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Vegetation community responses to different establishment regimes in loblolly pine (*Pinus taeda*) plantations in southern MS, USA

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ABSTRACT

Management treatments involving multiple herbicide applications are standard procedure on most industrial pine plantation sites in the southern USA, raising concerns about biodiversity impairment. Management decisions impact not only plant communities but also the habitat potential they create for wildlife. We tested the effects of five intensities of stand establishment treatments on vegetation communities in loblolly pine plantations ($n = 4$) to age 5 in the Middle Coastal Plain (MCP) of Mississippi. Measurements were species richness, diversity, coverage, and community composition. Treatments were combinations of mechanical site preparation (MSP), chemical site preparation (CSP), and herbaceous weed control (HWC) both banded or broadcast for 1 or 2 years using the same herbicide mixtures. Tree richness and diversity were reduced by increasing treatment intensity; tree coverage, which included crop and non-crop trees, was less in moderate-intensity treatments. Vine richness and coverage were less in more intensive treatments, but 2 diversity indices differed on whether vine diversity was likewise affected. Richness and coverage of forbs and graminoids was lessened by broadcast HWC, with effects mostly limited to the year of application. Plant communities differed in all 5 years, with CSP acting as the primary factor for years 2–5. Early seral communities were favored by CSP, but broadcast HWC suppressed resulting herbaceous plants. Though CSP may somewhat reduce stand-level plant diversity, it may increase overall biodiversity within plantation-dominated landscapes by creating early succession plant communities that enhance wildlife habitat.

1. Introduction

Intensively managed pine plantations in the southern USA will play an important role in providing wood products for the foreseeable future (Prestemon and Abt, 2002). The USA produces 25% of total world roundwood supply, with 60% of this coming from the 13 southern states (Prestemon and Abt, 2002). Although industrial forest management strategies change in response to silvicultural, economic, and social issues, future strategies likely will include increased use of herbicides (Wigley, 2000). Management regimes will consist of tank mixes of multiple herbicides prior to planting and one or more post-planting herbaceous weed control treatments. In 2002, approximately 286,000 ha of southern pine plantations received applications of herbaceous weed control, and 433,000 ha received chemical site preparation (Dubois et al., 2003), mostly relying on tank mixes of 2 or 3 herbicides (Shepard et al., 2004).

Trade-offs exist among timber yields, competing vegetation control, and biodiversity. Control of competing vegetation with herbicides typically produces increases of up to 150% in volume for pine species in the southeastern United States (Wagner et al., 2004). However, increasing intensity of site preparation can reduce abundance and diversity of woody and herbaceous plant species depending on herbicide type (Miller et al., 1999), rate (Zutter and Zedaker, 1988), proportion of the area receiving treatment (Schabenberger and Zedaker, 1999), and the additive effects of mechanical site preparation (Harrington and Edwards, 1996).

Preserving biodiversity in managed forests is a major challenge for sustainable forest management (Hartley, 2002; Guynn et al., 2004; Stephens and Wagner, 2007), and forest certification systems place emphasis on maintaining and enhancing biodiversity (Brown et al., 2001; Cauley et al., 2001). Early succession environments in the southeastern U.S. have declined in recent decades due to fire suppression and reforestation of abandoned farmland (Trani et al., 2001). Consequently, young pine plantations may provide most of the early succession environments potentially suitable for disturbance-dependent wildlife species in landscapes dominated by commercial pine management. Because intensive

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pine management involves reducing competition from non-pine vegetation and shortening the period before crown closure, it is appropriate to consider the impact such management has on this community. This research is a subset of a larger project investigating effects of intensive loblolly pine plantation management on wildlife habitat quality (Edwards, 2004; Hanberry, 2005, 2007; Jones, 2008).

Previous studies of vegetation communities following pine stand establishment have focused on controlling different categories of competing vegetation (Swindel et al., 1989; Miller et al., 1995), response to varying methods of mechanical (Conde et al., 1983a,b; Swindel et al., 1983; Stransky et al., 1986; Locascio et al., 1991) or chemical site preparation (Neary et al., 1990), and banded versus broadcast herbaceous weed control (Blake et al., 1987). There is as yet little information on the impact of tank mixtures of herbicides, multiple herbicide applications, and the combination of mechanical and chemical site preparation (Miller and Miller, 2004). This study was designed to investigate these treatment elements in a replicated experiment by incrementally increasing management intensity to reflect the range of commercial plantation establishment regimes as practiced in the southeastern USA. Our objectives were to test for differences in: (1) floristic diversity and richness, (2) coverage of plant growth-forms, and (3) plant community composition, and to identify indicator species for each treatment.

2. Methods

2.1. Study area

The Middle Coastal Plain (MCP) of Mississippi exhibits silvicultural challenges common throughout the southeastern U.S. Mechanical site preparation using a combination plow to subsoil, disk, and bed is an effective (Morris and Lowery, 1988) and widely used (Smidt et al., 2005) method to address issues of poor drainage and soil compaction common in the region. The warm, moist climate promotes vigorous vegetative competition with planted pines. For this reason, some level of chemical competition control during stand establishment is standard procedure.

We studied vascular vegetation communities on loblolly pine plantations established at 4 industrial forest sites in the Mississippi MCP (Fig. 1). Previous stands were harvested between September 2000–February 2001 and averaged 66 ha in size. The climate is subtropical, with temperatures ranging from a mean daily minimum of 3 °C in January to a mean daily maximum of 33 °C in July, mean annual rainfall of 159 cm, and frost-free periods of 216–241 days (NOAA, 2008). Soils at two sites were completely comprised of Susquehanna series, a somewhat poorly drained fine, smectitic, Vertic Paleudalf. A third site consisted entirely of McLaurin series, a deep, well-drained, coarse-loamy, siliceous, subactive, thermic Typic Paleudult. The fourth site was characterized by a mixture of McLaurin, Freestone (a very deep, moderately well-drained, fine-loamy, siliceous, semiactive, thermic Glossaquic Paleudalf), and Baxter (a very deep, well-drained, fine, mixed, semiactive, mesic Typic Paleudalf) soils. Elevations were 40–121 m above sea level; topography was gently undulating with site-specific elevational differences of 10–12 m (3 sites) to 27 m (1 site). All sites had been managed as commercial pine forests for at least 40 years prior to this study.

Vegetation at all sites was representative of the Outer Coastal Plain Mixed Forest Province (Bailey, 1980). Common trees included sweetgum (*Liquidamabar styraciflua*), various oaks (*Quercus* spp.), and common persimmon (*Diospyros virginiana*); tungoil tree (*Vernicia fordii*) was present on two sites which had previously been tungoil plantations. Shrub species included various hollies (*Ilex* spp.), eastern baccharis (*Baccharis halimifolia*), blueberries (*Vaccinium* spp.), wax myrtle (*Myrica cerifera*), and American beautyberry (*Callicarpa americana*). Common vines and semi-woody plants included lianas such as poison ivy (*Toxicodendron radicans*), muscadine (*Vitis rotundifolia*), Virginia creeper (*Parthenocissus quinquefolia*), yellow jessamine (*Gelsemium sempervirens*), and greenbriers (*Smilax* spp.), and early seral species such as sawtooth blackberry (*Rubus argutus*), southern dewberry (*R. trivialis*), and Japanese honeysuckle (*Lonicera japonica*). Herbaceous associates included threeawngrass (*Aristida* spp.), broomsedge (*Andropogon virginicus*), and various panic grasses (*Dicantheleum* spp.); forb communities were characterized by *Eupatorium* spp. and numerous asters (*Aster* spp., *Solidago* spp., and *Euthamia tenuifolia*). Two more poorly drained sites exhibited strong sedge (*Carex* spp. and *Cyperus* spp.) and rush (*Juncus* spp.) components.

2.2. Study design

Treatments were combinations of chemical site preparation (CSP), mechanical site preparation (MSP), and herbaceous weed control (HWC) designed to reflect the range of operational intensities used on industrial forests of the southeastern USA. Chemical site preparation was applied during July–August 2001 (year 0) using a mixture of: (1) 0.55 kg a.i. ha^{-1} of imazapyr in the form of Chopper Emulsifiable Concentrate® (BASF Corp., Research Triangle Park, NC, USA), (2) 1.68 kg a.i. ha^{-1} of glyphosate in the form of Accord® (Dow AgroSciences LLC, Indianapolis, IN, USA), and (3) 1.68 kg a.i. ha^{-1} of triclopyr in the form of Garlon 4® (Dow AgroSciences LLC, Indianapolis, IN, USA). Herbicides were applied with 1% volume-to-volume ratio of 90/10 non-ionic surfactant (Timberland 90®, UAP Timberland LLC, Monticello, AR, USA) in a broadcast spray solution of 93.6 L ha^{-1}. Mechanical site preparation was applied during September–December 2001 (year 0) using a combination plow pulled by a bulldozer. The combination plow ripped and shattered any compacted layers to a depth of approximately 40 cm, disked planting rows to improve soil tilth and rooting volume, and created a raised bed (15–20 cm). The result was a pattern of alternating 1.5 m strips of disturbed and undisturbed soil. Herbaceous weed control was applied during March–April 2002 (year 1) and March–May 2003 (year 2), and consisted of 0.11 kg a.i. ha^{-1} of sulfometuron methyl and 0.56 kg a.i. ha^{-1} hexazinone as Oustar® (E. I. du Pont de Nemours and Company, Inc., Wilmington, Delaware, USA); HWC was either applied in a 1.5 m band over the tops of pine seedlings, resulting in 50% total coverage, or broadcast aerially over the entire experimental unit.

Treatments were combinations of MSP, CSP, and HWC (Table 1). We randomly assigned each of the 5 treatments to an area $\geq$8 ha, each treatment occurring once per stand, for 4 replications per treatment in a randomized complete block design. We divided stands so as to minimize differences in topography and contact with drainages among experimental units. A pre-treatment survey in June 2001 (year 0) measured plant species coverage using 5 randomly placed 30 m transects in each experimental unit and indicated there were no pre-treatment differences in community composition (P. Jones, Mississippi State University, unpublished data).

Loblolly pines were planted on each site during the winter of 2001–2002 using 3.0 m × 2.1 m spacing (1551 trees ha^{-1}); each participating company used its own seedlings. Two sites were machine planted, and 2 sites were hand planted due to high coarse woody debris loads. All stands were fertilized in April 2002 with a broadcast application of di-ammonium phosphate at 280 kg ha^{-1}.

2.3. Sampling

We quantified vegetation communities during June 2002–2006 using 10 randomly placed 30 m transects to measure cm of species

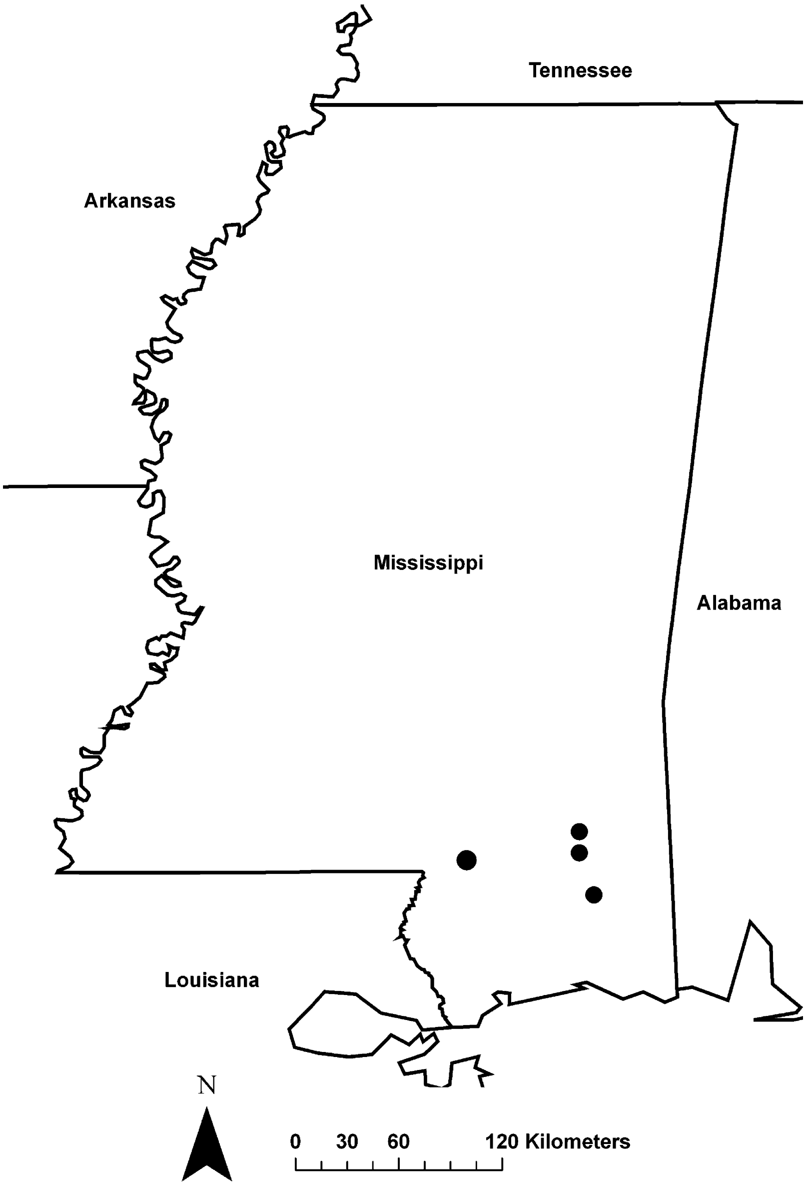

Fig. 1. Location of 4 loblolly pine plantations sampled for vegetation composition 1–5 years following establishment using various levels of intensive management in southern Mississippi, USA, 2002–2006.

coverage and 40 randomly placed 1 m^2 circular plots to document species occurrence in each experimental unit. We did this by laying a numbered grid over each experimental unit containing 20 0.4 ha squares and randomly selecting 10 squares to sample. At the center of each square, we randomly selected an azimuth for the transect. Four circular plots were located at the vertices of a 15 m × 20 m rectangle centered on each transect. We determined species richness by species count from transects and circular plots combined. We identified all plants to the species level with the exceptions of wiregrass (*Aristida* spp.) and yellow-eyed grass (*Xyris* spp.). Each plant species was assigned to 1 of 5 growth-form categories (i.e., forb, graminoid, shrub, tree, vine) for further analysis. To minimize potentially confounding edge effects, we excluded from sampling a 30 m buffer strip inside plot boundaries.

Table 1
Treatments applied to establish loblolly pine plantations on four industrial forest sites in the Middle Coastal Plain of Mississippi.

Treatment	Site preparation		Herbaceous weed control[a]	
	Mechanical[b]	Chemical[c]	Banded	Broadcast
M-Ba	x		Yr 1	
C-Ba		x	Yr 1	
MC-Ba	x	x	Yr 1	
MC-Br	x	x		Yr 1
MC-Br2	x	x		Yrs 1 and 2

[a] Consisted of 0.11 kg a.i. sulfometuron methyl and 0.56 kg hexazinone ha^{-1}. Banded treatments covered the width of the planting bed (1.5 m).
[b] Combination plow to subsoil, disk, and bed.
[c] Tank mix of 0.55 kg a.i. imazapyr, 1.68 kg a.i. glyphosate, and 1.68 kg a.i. triclopyr ha^{-1}.

2.4. Data analysis

We calculated 2 diversity indices used widely in community ecology studies. The Shannon index (H'; Shannon and Weaver, 1949) indicates the level of uncertainty associated with predicting the species of an individual selected at random from a given community. It ranges from 0 when there is no diversity to ~5 in the most diverse communities. The Simpson index (D; Simpson, 1949) measures the probability that 2 individuals selected at random from a given community will be of different species; it ranges from 0 (no diversity) to a theoretical maximum of 1. We calculated both indices based on plant species coverage in each experimental unit.

We used a mixed model with repeated measures design to test for main effects of year and treatment and year $\times$ treatment interaction for species diversity, species richness, and coverage of forbs, graminoids, shrubs, vines, trees, and total vegetation. We compared means among treatments ($n = 5$) and years ($n = 5$) in SAS PROC MIXED (SAS Institute, 2000). Stands represented our blocking factor, so we included stand ($n = 4$) as a random effect. Year was the repeated effect, and treatment $\times$ stand was the subject. For each analysis, we selected the best combination of data transformation, covariance structure, and use of the random statement, choosing the combination that minimized AIC_C (Akaike's Information Criterion corrected for small sample size; Littell et al., 2006; Gutzwiller and Riffell, 2007). This is not a case of mixing analytical paradigms as warned against in Anderson et al. (2001); the AIC_C is not used for model selection, but rather to determine which analysis procedure makes the best use of the data for each particular analysis (i.e., no single combination was used for all analyses.) We first determined if square-root transformation reduced AIC_C and used it accordingly. We then selected the best covariance structure from among: autoregressive covariance with treatment as a group, autoregressive covariance without treatment as a group, and unstructured covariance. We then assessed the utility of the random statement, and chose whether to retain it based on lesser AIC_C value. We used the Kenward-Roger correction in denominator degrees of freedom for repeated measures to avoid inflated Type I error (Littell et al., 2006; Gutzwiller and Riffell, 2007). We considered differences significant if $P \leq 0.05$. We used LSMEANS SLICE to identify a treatment effect within years following a significant interaction (Littell et al., 2006). We compared means using Fisher's least significant difference with the LSMEANS PDIFF option (Littell et al., 2006). For ease of data interpretation, we present actual means although we conducted some analyses on transformed data.

To test the hypothesis that plant community composition did not differ among treatments within years, we conducted blocked multi-response permutation procedures (MRBP; Biondini et al., 1988) in PC-ORD 4.0 on species coverage data. We square-root transformed species coverage to dampen the effects of dominant species, selected Euclidean distance as the distance measure (Mielke, 1991) and used median alignment within-blocks to focus analysis on within-block differences (McCune and Grace, 2002). Though similar to parametric procedures such as discriminant analysis and multivariate ANOVA, MRBP does not require assumptions of multivariate normality or homogeneity of variance, which are often not met by community data (McCune and Grace, 2002). The MRBP first calculates a weighted mean within-group distance (δ) in species space. Then a T statistic is calculated as the difference between the observed and expected δ divided by the standard deviation of the expected δ. The T statistic describes the separation between groups, which increases as T becomes more negative. Next, a P-value indicates the probability of a getting a δ as or more extreme than that observed. Lastly, an agreement statistic (A) is calculated to describe within-group homogeneity compared with random expectation. When all plots are identical within groups (i.e., maximum homogeneity), $A = 1$; if heterogeneity within groups equals expectation by chance, then $A = 0$. Values of $A > 0.3$ are considered relatively high, while values < 0.1 are relatively common in community ecology, even when P-values indicate significance (McCune and Grace, 2002). To reduce noise we excluded species that occurred in $\leq 5\%$ of the experimental units (McCune and Grace, 2002), resulting in 135–188 species used for analysis, depending on year. We screened data for outliers by block using the Outlier Analysis function in PC-ORD 4.0 and found no samples >2 standard deviations from block means; therefore, we retained all samples for analysis. If within-year tests indicated a treatment effect, we performed separate post hoc MRBP analyses to determine which pairs of treatments differed (McCune and Grace, 2002).

As a complement to the MRBP analysis, we determined indicator species (i.e., characteristic species found mostly in a given treatment and present in most samples from that treatment [Dufrêne and Legendre, 1997]) within each year using PCORD 4.0. Dufrêne and Legendre's (1997) method relies on proportional abundance and proportional frequency of a species to calculate an indicator value (*IV*) for each species within each treatment, which represents the percentage of perfect indication. The greatest *IV* for each species is then tested for statistical significance against the random expectation calculated by Monte Carlo permutation. Species with few occurrences never yield an *IV* stronger than expected by chance (McCune and Grace, 2002), thus precluding the selection of rare species. We tested *IV*s for significance using 1000 randomizations and accepted significance if $P \leq 0.05$.

3. Results

3.1. Growth-form metrics

Treatment differences due to varying levels of HWC were typically found in forbs and graminoids, and these tended to be restricted to the season following treatment. Conversely, vines and woody species were more affected by site preparation, and these impacts were consistent across the 5-year study period.

3.1.1. Species richness

Species richness was affected primarily by level of herbicide application (Table 2). Broadcast HWC reduced species richness primarily in herbaceous plants. Forb richness was 2.4 times greater in treatments receiving banded HWC than in treatments with broadcast HWC, but only during the years in which broadcast HWC was applied. Forb richness was similar among treatments from years 3–5, indicating resilience to the levels of herbicide applied in this study. Graminoid richness was reduced 44% by broadcast HWC, but, as with forbs, recovered the year following application to become similar to banded treatments. Because forbs represented half of all species identified, forb richness was the primary factor responsible for treatment differences in total species richness. Total richness was reduced by broadcast HWC, and the impacts of the year 2 application in MC-Br2 extended into year 3. Total richness was also reduced by the combination of MSP and CSP relative to MSP alone, but only in year 1.

Both tree and vine richness differed among treatments across all years. Tree richness was greater in treatments receiving either CSP or MSP alone ($\bar{x} = 10.2$ species) than in treatments with both ($\bar{x} = 7.6$ species). Vine richness was reduced by CSP from 12 to 9.5 species, and reduced again to 7 species by repeated broadcast HWC. Shrub richness did not differ among treatments ($P = 0.051$).

3.1.2. Coverage

In most ways, growth-form coverage was affected similarly to species richness (Table 3). Forb coverage in treatments with banded HWC was 9.5 times greater than in treatments with broadcast HWC in year 1. In year 2, MC-Br recovered to parity with other treatments receiving a single HWC application, and the second broadcast HWC application reduced forb coverage in MC-Br2 by 74%. This pattern shifted in year 3, when forb cover was greatest in treatments with CSP and a single HWC application, regardless of whether HWC was broadcast or banded. Graminoid

Table 2
Categories of mean plant species richness expressing statistical differences ($P \leq 0.05$) in 5 loblolly pine (*Pinus taeda*) plantations 1–5 years following establishment treatments[a] ranging from low (M-Ba) to high (MC-Br2) intensity in the Middle Coastal Plain of Mississippi, 2002–2006[b].

Life form	Year	Treatment[c]										*P*-value[d]
		M-Ba		C-Ba		MC-Ba		MC-Br		MC-Br2		
		$\bar{x}$	SE	$\bar{x}$	SE	$\bar{x}$	SE	$\bar{x}$	SE	$\bar{x}$	SE	
Forb	1	29.0^{A}	6.7	28.3^{A}	10.1	28.0^{A}	5.8	12.3^{B}	2.5	10.0^{B}	2.9	≤0.001[e]
	2	32.3^{A}	5.6	29.3^{A}	6.0	34.8^{A}	5.1	30.8^{A}	6.5	13.8^{B}	5.3	≤0.001[e]
Graminoid	1	7.8^{A}	0.6	8.8^{A}	1.4	6.0^{AB}	0.4	4.3^{B}	0.9	5.0^{B}	1.5	0.003[e]
	2	9.0^{A}	2.0	11.3^{A}	1.1	11.5^{A}	1.7	11.2^{A}	1.7	6.0^{B}	0.9	≤0.001[e]
Vine	All	12.1^{A}	0.5	9.2^{B}	0.8	9.5^{B}	0.8	9.8^{B}	0.9	7.0^{C}	0.8	≤0.001
Tree	All	10.7^{A}	0.7	9.7^{A}	0.6	7.4^{B}	0.7	7.8^{B}	0.7	7.6^{B}	0.5	0.002
Total	1	64.3^{A}	7.6	55.5^{AB}	12.0	50.8^{B}	4.8	30.3^{C}	1.8	27.8^{C}	4.2	≤0.001[e]
	2	68.0^{A}	4.6	63.8^{A}	6.8	68.0^{A}	3.9	62.5^{A}	4.5	35.3^{B}	4.5	≤0.001[e]
	3	84.3^{A}	8.4	85.3^{A}	10.3	79.0^{A}	6.7	82.5^{A}	8.3	65.5^{B}	9.2	0.036[e]

[a] See Table 1 for treatments.
[b] Actual means presented. Analyses were performed on square-root transformed data. *P*-values refer to least square means.
[c] Differences among treatment means are designated by different letters within rows.
[d] Degrees of freedom were as follows: Forb = 4, 5.77; Graminoid = 4, 17.6; Tree = 4, 14.2; Vine = 4, 14.9; Total = 4, 14.1.
[e] Interaction was significant; Trt *P*-value is for within-year comparison.

coverage was reduced 89% by broadcast HWC in year 1, and by 63% in year 2, after which all treatments were similar. Total plant coverage was reduced by broadcast HWC in the years it was applied, with some residual effects in later years. In year 3, total plant coverage in MC-Br2 increased by 92%, yet continued to be less than in all treatments except C-Ba. In year 4, total plant coverage averaged 137% across all treatments; differences reappeared in year 5, when C-Ba and MC-Br2 decreased to 121% coverage whereas M-Ba remained stable at 158%.

Vines and trees again exhibited treatment differences consistently across all years. Vine coverage was reduced by CSP from 49 to 29%, and further reduced to 16% by repeated broadcast HWC. Tree coverage was greater in treatments with MSP only (M-Ba), which allowed resprouting of some residual species, and in treatments with broadcast HWC (MC-Br and MC-Br2), which released planted pines from herbaceous competition. Shrubs again did not differ among treatments ($P = 0.283$).

3.1.3. Diversity

As herbicide use increased, total plant diversity as measured by both indices decreased consistently across all years (Table 4). Shannon diversity of vines was greater in M-Ba ($H' = 1.51$) than in treatments with CSP ($\bar{H}' = 1.01$; $P \leq 0.001$), but Simpson diversity was similar across treatments ($\bar{D} = 0.53$; $P = 0.397$). Both indices indicated differences in tree diversity reflective of differences in species richness; H' was greater in M-Ba and C-Ba ($\bar{H}' = 1.3$) than in treatments with both MSP and CSP ($\bar{H}' = 0.67$; $P = 0.003$), and D was greater in M-Ba (0.68) than in treatments with both MSP and CSP ($\bar{D} = 0.33$; $P = 0.007$). Shannon diversity was lower in shrubs receiving CSP ($\bar{H}' = 1.34$) than in M-Ba ($H' = 1.57$; $P = 0.039$). Neither forb nor graminoid diversity were affected by treatment. However, it is likely that non-significant responses of forb and graminoid diversity to varying levels of HWC contributed to the step by step response of total diversity to increasing herbicide use.

Table 3
Categories of mean plant growth-form coverage (%) expressing difference in 5 loblolly pine (*Pinus taeda*) plantations 1–5 years following establishment treatments[a] ranging from low (M-Ba) to high (MC-Br2) intensity in the Middle Coastal Plain of Mississippi, 2002–2006[b].

Life form	Year	Treatment[c]										*P*-value[d]
		M-Ba		C-Ba		MC-Ba		MC-Br		MC-Br2		
		$\bar{x}$	SE	$\bar{x}$	SE	$\bar{x}$	SE	$\bar{x}$	SE	$\bar{x}$	SE	
Forb	1	12.0^{A}	2.1	19.1^{A}	9.6	11.6^{A}	3.0	1.6^{B}	0.4	1.4^{B}	0.5	≤0.001[e]
	2	22.5^{A}	7.1	28.0^{A}	9.7	27.1^{A}	7.0	27.4^{A}	5.2	6.9^{B}	5.3	≤0.001[e]
	3	14.5^{BC}	3.7	20.8^{ABC}	7.6	24.7^{AB}	6.3	29.5^{A}	9.3	13.6^{C}	6.9	0.040[e]
Graminoid	1	15.0^{A}	3.4	18.0^{A}	5.8	8.8^{A}	1.8	1.9^{B}	0.7	1.1^{B}	0.4	≤0.001[e]
	2	28.7^{AB}	6.7	32.9^{A}	4.9	22.1^{AB}	6.4	21.4^{BC}	7.0	10.4^{C}	2.9	0.003[e]
Vines	All	49.0^{A}	5.4	24.8^{BC}	3.7	34.5^{B}	5.2	27.4^{B}	3.9	15.8^{C}	3.1	
Tree	All	27.2^{A}	4.8	19.8^{C}	3.9	21.4^{BC}	3.8	25.9^{AB}	4.7	28.3^{A}	5.2	0.017[e]
Total	1	46.2^{A}	5.8	45.0^{AB}	18.5	28.9^{B}	4.2	6.9^{C}	1.1	5.3^{C}	1.2	≤0.001[e]
	2	121.3^{A}	8.9	96.0^{B}	8.9	102.7^{AB}	11.3	90.4^{B}	3.7	29.0^{C}	7.5	≤0.001[e]
	3	173.4^{A}	16.8	141.6^{BC}	15.7	149.1^{AB}	14.1	158.6^{AB}	13.6	121.2^{C}	12.2	0.008[e]
	4	158.4^{A}	11.8	123.1^{B}	10.8	134.9^{AB}	8.7	140.6^{AB}	12.0	119.4^{B}	5.3	0.050[e]

[a] See Table 1 for treatments.
[b] Actual means presented. Analyses were performed on square-root transformed data. *P*-values refer to least square means.
[c] Differences among treatment means are designated by different letters within rows.
[d] Degree of freedom were as follows: Forb = 4, 15.2; Graminoid = 4, 16.6; Tree = 4, 18.2; Vine = 4, 15; Total = 4, 15.9.
[e] Interaction was significant, *P*-values is for within-year comparison.

Table 4
Mean Shannon (H') and Simpson (D) plant species diversity in 5 loblolly pine (*Pinus taeda*) plantations 1–5 years following establishment treatments[a] ranging from low (M-Ba) to high (MC-Br2) intensity in the Middle Coastal Plain of Mississippi, 2002–2006[b].

Diversity index	Treatment[c]										*P*-value[d]
	M-Ba		C-Ba		MC-Ba		MC-Br		MC-Br2		
	$\bar{x}$	SE	$\bar{x}$	SE	$\bar{x}$	SE	$\bar{x}$	SE	$\bar{x}$	SE	
H'	3.00^{A}	0.06	2.76^{AB}	0.09	2.69^{B}	0.07	2.64^{B}	0.07	2.30^{C}	0.02	0.005
D	0.91^{A}	0.01	0.88^{AB}	0.01	0.87^{B}	0.02	0.86^{B}	0.01	0.81^{C}	0.02	0.003

[a] See Table 1 for treatments.
[b] Actual means presented. Analyses were performed on square-root transformed data. *P*-values refer to least square means.
[c] Differences among treatment means are designated by different letters within rows.
[d] Degree of freedom were: H' = 4, 5.99; D = 4, 14.8.

3.2. Plant communities

Plant community composition differed among treatments in all 5 years (Table 5) indicating the treatments created a broad range of vegetation communities. Large samples may produce significant *P*-values even with very small effect sizes; however, given our small sample size ($n = 4$), we believe these effects were biologically significant. Pair-wise comparisons from year 1 indicated that treatments receiving banded HWC differed from those receiving broadcast HWC. In years 2–5, lack of CSP separated M-Ba from all other treatments. In year 2, MC-Br2 received its second HWC application and was different from all other treatments, remaining so through year 3. Associations in year 4 were more complex and, except for no CSP in M-Ba, did not appear to correlate with any particular treatment element or combination of elements. Effect sizes between significance groups in year 4 were generally less than in other years. In year 5, community differences reflected clearly the establishment intensity gradient, indicating that some effects of both site preparation and HWC were still operative. Yearly effect sizes were moderate, ranging from 0.08 to 0.14. Within years, effect sizes of significant pair-wise comparisons were consistently greatest between M-Ba and MC-Br2, averaging 0.22.

Twenty-one species were classified as indicator species over the 5 years of the study (Table 6). Indicator status for M-Ba was conferred upon 7 vine, 4 tree, and 2 forb species. The remaining 8 indicator species, comprised of 3 graminoids, 2 forbs, 2 shrubs and 1 tree, were divided among the remaining 4 treatments. There were 5–7 indicator species each year in M-Ba, with 3 vine species acting as indicators for 4 years each. Among the remaining treatments, only C-Ba was assigned indicator species in more than 1 year, and no species acted as an indicator for multiple years.

Table 5
Significance groupings[a] and effect sizes (A) of plant communities in 5 loblolly pine (*Pinus taeda*) plantations 1–5 years following establishment treatments[b] ranging from low (M-Ba) to high (MC-Br2) intensity in the Middle Coastal Plain of Mississippi, 2002–2006.

Year	Treatment					*P*-value[c]	*A*
	M-Ba	C-Ba	MC-Ba	MC-Br	MC-Br2		
1	A	A	A	B	B	≤0.001	0.11
2	A	B	B	B	C	≤0.001	0.14
3	A	B	B	B	C	≤0.001	0.11
4	A	BD	BC	CE	DE	≤0.001	0.08
5	A	B	BC	CD	D	≤0.001	0.11

[a] Treatments within years designated by the same upper case letter did not differ ($\alpha = 0.05$).
[b] See Table 1 for treatments.
[c] *P*-values are equal to the probability of a smaller or equal δ resulting from blocked multi-response permutation procedure.

4. Discussion

4.1. Vegetation community

Plant species express differential susceptibility to herbicides, potentially resulting in distinctive communities (Harrington et al., 1998; Miller and Miller, 2004). In this study, all herbicide treatments were identical in composition and application rate. Community differences were therefore due to variations in herbicide coverage, number of HWC applications, or herbicide interaction with MSP.

Table 6
Indicator values[a] (*IV*) of designated indicator species for 5 loblolly pine (*Pinus taeda*) plantation establishment treatments[b] ranging from low (M-Ba) to high (MB-Br2) intensity in the Middle Coastal Plain of Mississippi, 2002–2006.

Species	Treatment	Year	*IV*	*P*-value[c]
Lonicera japonica	M-Ba	1	67	0.011
Parthenocissus quinquefolia	M-Ba	1	52	0.025
Rubus argutus	M-Ba	1	37	0.028
Smilax glauca	M-Ba	1	61	0.007
Vitis rotundifolia	M-Ba	1	83	0.003
Liquidambar styraciflua	M-Ba	2	57	0.019
Parthenocissus quinquefolia	M-Ba	2	60	0.023
Rubus argutus	M-Ba	2	36	0.012
Toxicodendron radicans	M-Ba	2	87	0.001
Vitis rotundifolia	M-Ba	2	59	0.001
Diospyros virginianus	M-Ba	3	50	0.001
Parthenocissus quinquefolia	M-Ba	3	56	0.003
Smilax rotundifolia	M-Ba	3	52	0.019
Toxicodendron radicans	M-Ba	3	73	0.001
Vitis rotundifolia	M-Ba	3	46	0.001
Diospyros virginianus	M-Ba	4	41	0.002
Eupatorium serotinum	M-Ba	4	38	0.026
Liquidambar styraciflua	M-Ba	4	48	0.018
Magnolia virginiana	M-Ba	4	47	0.050
Parthenocissus quinquefolia	M-Ba	4	52	0.004
Toxicodendron radicans	M-Ba	4	67	0.004
Vitis rotundifolia	M-Ba	4	39	0.004
Diospyros virginianus	M-Ba	5	46	0.004
Eupatorium leucolepis	M-Ba	5	73	0.008
Quercus phellos	M-Ba	5	49	0.043
Rhus copallina	M-Ba	5	39	0.050
Toxicodendron radicans	M-Ba	5	59	0.005
Ilex vomitoria	C-Ba	2	38	0.025
Digitaria ciliaris	C-Ba	3	54	0.028
Panicum anceps	C-Ba	4	58	0.044
Quercus marilandica	C-Ba	5	38	0.026
Dicanthelium scoparium	MC-Ba	3	33	0.043
Chamaechrista fasciculata	MC-Br	3	50	0.042
Hypericum drummodii	MC-Br2	4	59	0.030
Mecardonia acuminata	MC-Br2	4	61	0.019

[a] Indicator values represent the percentage of perfect indication by a given species.
[b] See Table 1 for treatments.
[c] Based on 1000 Monte Carlo randomizations of species coverage data.

Response differences among plant communities in this study can be understood as a combination of direct treatment impacts and interactions with seral stage. Similar to a report by Swindel et al. (1983), MSP failed to control a strong residual community, with subsequent long-term impact on community similarity. In addition, physical disturbance provided opportunity for pioneer species to establish, resulting in greater overall community diversity and species richness (Thompson and DeGraaf, 2001). Similar to results in other conifers (Lindgren and Sullivan, 2001; Biring et al., 2003), CSP was more effective than MSP at removing or suppressing species from the post-harvest stand, opening the way for a longer lasting response from early seral species like that reported by Miller et al. (1995) and creating communities with a more distinctively early succession character. Recovery of the forb community from HWC applied in year 1 was similar regardless of whether the application was banded or broadcast. However, by year 3 perennials began to dominate, leaving less growing space for recolonizing forbs suppressed by the second broadcast HWC application. This resulted in the continued separation of the MC-Br2 community, which was not fully overcome by year 5. The different rates at which treatments approached crown closure began to influence communities in year 4, by which time shading and litter from pines were most pronounced in MC-Br2, potentially speeding the decline of annual forbs (Moir, 1966; Monk and Gabrielson, 1985). These different successional dynamics may result in community differences even after crown closure, most particularly with M-Ba. This is supported by the relatively stable effect size (A) of M-Ba versus treatments receiving CSP, compared with decreasing effect sizes and a gradual erosion of pair-wise differences among the chemically site-prepared treatments, which indicates that communities in those treatments converged after year 1.

4.2. Growth-form metrics

Miller et al. (1995) maintained vegetation control regimes for 3–5 years after planting and compared resulting plant coverage. Complete herbaceous weed control reduced herbaceous cover to <15%, and accelerated the dominance of woody species (Miller et al., 1995). In our study, MC-Br and MC-Br2 had similarly low levels of herbaceous cover in the years they received broadcast HWC. Woody plants other than pines had already been eliminated or suppressed by CSP; thus, the primary woody species released by the broadcast HWC was loblolly pine (Jones et al., in press). Conversely, complete control of woody competition by Miller et al. (1995) increased the presence of grasses and forbs and led to longer dominance by the herbaceous component; in our study this response was most evident with forb coverage in treatments receiving CSP. Graminoids, however, were less responsive to release from woody competition, and expressed patterns independent of site preparation technique.

While the differences in diversity are important to note, it may be helpful to interpret those results in terms of predictability. Simpson diversity can be subtracted from 1 to give the probability of randomly selecting two individuals of the same species from a given community. Using the values of D (from Table 4), there was approximately half the probability of randomly choosing two conspecifics from M-Ba (0.09) as from MC-Br2 (0.19). Shannon diversity is less intuitive and cannot be directly interpreted. However, H' can be expressed in number of species by converting it as $N_1 = e^{H'}$, where N_1 equals the number of species that would, if each were equally common, yield the same H' value as the actual sample (MacArthur, 1965). The value of N_1 based on H' (from Table 4) would be 20.1 for M-Ba, and decrease through subsequent treatments to 10.0 for MC-Br2. Thus, the H' values indicate that there was again half the probability of randomly choosing two conspecifics from M-Ba (0.05) as from MC-Br2 (0.10). In both indices, values for the remaining treatments would be intermediate and somewhat clustered, indicating that CSP was a strong factor in reducing diversity, and that the second broadcast HWC added to this reduction.

4.3. Biodiversity

Opportunities for early successional communities were best created with CSP or CSP and MSP combined, which pushed the successional timeline farther back than MSP alone. However, following CSP with broadcast HWC suppressed the herbaceous component and released the planted pines to dominate the stand more quickly, similar to Miller et al. (2003). Limiting HWC to banded applications may increase expression of the early sere both in space and time.

Biodiversity also should be considered beyond the stand-level to include the landscape mosaic (Brown et al., 2001; Hartley, 2002). Using an assortment of stand establishment techniques should help conserve gamma diversity by creating a greater variety of plant communities and habitat characteristics. However, there may be legitimate limitations on these techniques. Broadcast HWC, especially when applied for >1 year, may reduce stand-level plant diversity below desirable levels without providing adequate habitat potential to compensate for that reduction. Haeussler et al. (1999) found a significant negative correlation between species diversity and volume of lodgepole pine (*Pinus contorta*) in 10-year-old stands established using a range of MSP intensities. This result is similar to our study, where more intensively established plantations expressed lesser diversity and greater crop tree heights and diameters (Jones et al., in press). Forest managers should be aware of these trade-offs to determine what constitutes an acceptable loss of stand-level diversity for a given increase in production, and consider whether use of certain treatments should be limited for the sake of biodiversity.

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