Influence of Herbicide Site Preparation on Longleaf Pine Ecosystem Development and Fire Management

Robert N. Addington, Thomas A. Greene, Michele L. Elmore, Catherine E. Prior, and Wade C. Harrison

ABSTRACT

Herbicide site preparation is common in longleaf pine artificial regeneration and restoration to reduce competition and promote seedling establishment. However, few studies have evaluated longer-term influences of herbicide site preparation on ecosystem development and fire management. We report results from a field study on Fort Benning, Georgia, initiated in 2003 to evaluate the response of longleaf pine seedlings, woody plant stem density, herbaceous vegetation cover, species richness, and fine fuels to two herbicide site preparation treatments: imazapyr/glyphosate and hexazinone. Both treatments clearly enhanced longleaf pine seedling growth compared with an untreated control, primarily by reducing hardwood stem densities. By 2009, hardwood stem density was 5 times as high on control plots compared with treated plots. Vegetation composition and structure were otherwise similar, with no differences in shrubs and woody vines, perennial bunch grasses, or species richness on treated versus control plots. Total herbaceous fuels were enhanced by hexazinone in particular, which bodes well for fire management and continued hardwood control. Alternatively, increased woody litter on control plots appeared to modify the fuel bed in ways that may inhibit fire management. Overall, results suggest that treated plots are better poised than control plots for restoration success without additional treatments beyond fire.

Keywords: *Pinus palustris*, restoration, herbicides, prescribed fire, fuels

Herbicides are commonly used in forest management and restoration to alter vegetation composition and structure in desirable ways consistent with management objectives. In the southeastern United States, herbicides are often used in longleaf pine (*Pinus palustris* Mill.) ecosystem restoration to reduce and control woody plant encroachment that may occur because of fire exclusion. In the absence of fire, longleaf pine ecosystems succeed to hardwoods and lose the plant and animal diversity that is the hallmark of the ecosystem (Landers et al. 1995, Van Lear et al. 2005).

At the time of European settlement, longleaf pine ecosystems occupied an estimated 37 million ha from southern Virginia to eastern Texas (Frost 2006). By 1930, most of this land area had been cleared for agriculture and other uses (Van Lear et al. 2005, Frost 2006). Establishment of pine plantations for commercial timber production began on a large scale in the 1940s and 1950s, using fast-growing pines such as loblolly (*Pinus taeda* L.) instead of longleaf (Frost 2006). In recent years, however, conversion of such sites back to longleaf pine has become a management goal for many land owners for a variety of reasons, including habitat restoration for rare species such as the federally endangered red-cockaded woodpecker (*Picoides borealis*). This is the case on many military installations in the southeastern United States (Stein 2008).

Longleaf pine restoration often requires artificial regeneration because of scarcity of longleaf pine seed trees and lack of natural regeneration. Longleaf pine seedlings are intolerant of competition (Boyer 1990a), and herbicide site preparation has been shown to be effective in reducing competition and improving seedling establishment and growth (Hainds 1999). Hexazinone, imazapyr, glyphosate, and triclopyr are all commonly used herbicides in southern pine systems (Hainds 1999, Nelson and Cantrell 2002). For sandhill longleaf pine sites, hexazinone is popular because of its effectiveness on oaks (*Quercus* spp.) in particular, and because desirable species such as blueberry (*Vaccinium* spp.) are unaffected (Brockway et al. 1998, Hainds 1999, Hay-Smith and Tanner 1999). Hexazinone applied at low rates has also been shown to enhance herbaceous vegetation, which is important for fire management because young pine plantations lack pine needle fuels (Brockway and Outcalt 2000). Imazapyr is also commonly used in longleaf pine restoration, as it can be applied across a range of soil textures and is particularly effective for sweetgum (*Liquidambar styraciflua* L.) control, as well as for enhancement of forbs and other herbaceous species (Nelson

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Manuscript received March 25, 2011; accepted August 29, 2011. http://dx.doi.org/10.5849/sjaf.11-012.

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We thank Fort Benning's Environmental Management Division, specifically Bob Larimore, James Parker, Pete Swiderek, and John Brent, for their support of this project. We are particularly indebted to Mark Byrd for help with site selection and herbicide application. We also thank Bob Mitchell and Jason McGee for help with processing fuel samples, John Britt for site history information, and Matt Nespeca and Ben Knapp for reviewing the manuscript. The manuscript was also significantly improved by comments from three anonymous reviewers. Funding for this project was provided by the US Department of Defense, through The Nature Conservancy-Fort Benning Cooperative Agreements DAMD17-00-2-0017 and W81XWH-04-2-0051.

This article uses metric units; the applicable conversion factors are: millimeters (mm): 1 mm = 0.039 in.; centimeters (cm): 1 cm = 0.39 in.; meters (m): 1 m = 3.3 ft; square meters (m^2): 1 m^2 = 10.8 ft^2; hectares (ha): 1 ha = 2.47 ac; kilograms (kg): 1 kg = 2.2 lb; liter (L): 1 L = 61.02 $in.^3$, = 0.908 quart (dry), = 1.057 quart (liquid).

and Cantrell 2002, Jones and Chamberlain 2004, Shephard et al. 2004). Tank mixes are also popular as they afford broad-spectrum control, but they also may be more likely to negatively affect nontarget species.

Although there are many studies in the literature that document the initial effects of herbicide site preparation on vegetation and pine seedlings, particularly for loblolly pine (e.g., Shiver et al. 1990, Harrington et al. 1998, Miller and Chamberlain 2008), fewer studies evaluate site preparation effects for longleaf pine (Boyer 1988, Hainds 1999, Knapp et al. 2006), and even fewer address longer-term effects and implications for ecosystem development and fire management (reviewed in Litt et al. 2001). In this study, we evaluated the role of two commonly used herbicide site preparation treatments—hexazinone and imazapyr + glyphosate—in advancing longleaf pine restoration objectives on Fort Benning, a Department of Defense Army training installation located in the Fall Line Sandhills region of Georgia. Fort Benning began restoring longleaf pine to nearly 35,000 ha of upland forest in the mid-1990s (US Army Infantry Center 2006). Roughly 500 ha are planted to longleaf pine on Fort Benning per year; nearly 8,000 ha have been planted since 1994. These areas are site-prepared with herbicide, allowed to brown out, burned by prescribed fire, planted, and then burned every 2–3 years thereafter as part of the installation's prescribed fire program. Restoration objectives include successfully establishing and accelerating growth of longleaf pine seedlings, reducing woody plant competition, and maintaining or enhancing herbaceous vegetation cover and richness. Specifically, we sought to evaluate the effects of herbicide site preparation on planted longleaf pine seedling growth and density, woody plant stem density, herbaceous vegetation cover, plant species richness, and fine fuels. We compared the two herbicide treatments to one another and to an untreated control, and we carried the study through two prescribed fire cycles over a 6-year period to evaluate interactions among herbicide treatments and fire. We hypothesized that longleaf pine seedling establishment and growth would be enhanced on herbicide-treated plots because of reductions in woody plant competition and that competitive release of grasses and other herbaceous fuels would enhance fire management and the ability of treated sites to be managed with fire alone into the future.

Methods

Study Sites

The study was conducted on Fort Benning, a 74,000-ha Army training installation located in west-central Georgia and eastern Alabama (32.4°N latitude, 84.8°W longitude). Fort Benning's topography is characterized as rolling, with elevation varying from 58 to 226 m above sea level (US Army Infantry Center 2006). The climate is temperate, with a mean summer temperature of 26°C and a mean winter temperature of 8°C (Green 1997). Precipitation in the region averages 1,320 mm annually. Fort Benning is located north of the range of wiregrass (*Aristida stricta* Michx.) within the longleaf pine-bluestem system described by Frost (2006). Dominant perennial bunch grasses include bluestems (*Andropogon* spp., *Schizachyrium scoparium* Michx.) and Indian grasses (*Sorghastrum* spp.).

The area selected for study was a large loblolly pine plantation located on the southern end of Fort Benning that was clearcut in 2002 and slated for longleaf pine planting by Fort Benning's Land Management Branch. The area was part of an approximately 2,100-ac land exchange that occurred between Fort Benning and the city of Columbus, Georgia, in 2000. Prior to Fort Benning's ownership, the area had been owned and managed by various timber companies as commercial timberland. Some history of cultivation—primarily cotton farming by small tenant farmers—is also documented, prior to the area being converted to timberland in the mid-1900s (US Department of the Army 1999). At the time of acquisition by Fort Benning, most stands contained young (<25 years old), densely planted loblolly pine, with understories dominated by sand blackberry (*Rubus cuneifolius* Pursh.), winged sumac (*Rhus copallinum* L.), American beautyberry (*Callicarpa americana* L.), lespedeza (*Lespedeza* spp.), muscadine (*Vitis rotundifolia* Michx.), and greenbrier (*Smilax* spp.) (US Department of the Army 1999). Site fire history prior to Fort Benning's ownership could not be determined from historical records. Soils on the study sites are Ultisols and include Troup and Ailey loamy sands (Loamy, kaolinitic, thermic Grossarenic Kandiudults and Loamy, kaolinitic, thermic Arenic Kanhapludults, respectively; Green 1997), representative of the dominant soils on Fort Benning.

Experimental Design and Treatments

Study sites were established in May to June 2003 using a randomized complete block design with four replicates (blocks), two herbicide treatments, and an untreated control, for a total of 12 plots. Each block was 0.25 ha and contained three plots, each 20 × 40 m. Within each block, plots were randomly selected for herbicide treatment. Hexazinone (Velpar ULW; [3-cyclohexyl-6-[dimethylamino]-1-methyl-1,3,5-triazine-2,4[1H,3H]-dione]) was applied granularly at a rate of 3.36 kg per ha active ingredient during May 2003 using a skidder-mounted applicator. Imazapyr/glyphosate (Arsenal AC + Accord; [2-[4,5-dihydro-4-methyl-4-[1-methylethyl]-5-oxo-1H-imidazol-2-yl]-3-pyridinecarboxylic acid] + [*N*-[phosphonomethyl] glycine]) was applied in August 2003 as a tank mix at a rate of 1.15 L per ha formulated product of imazapyr and 9.35 L per ha of glyphosate, plus 0.5% nonionic surfactant. All sites were burned following vegetation brown out. Nursery-grown, containerized longleaf pine seedlings were hand planted in November 2003 at a target spacing of 1.8 × 3.6 m to achieve an initial density of 1,500 seedlings per ha, consistent with recommended planting densities found in the literature (Brockway et al. 2006). Seedlings came from a regional supplier (International Forest Company, Moultrie, GA) and were 8–9 months old at the time of planting.

Field Measurements

Within each plot, a 45-m-long diagonal transect was established. All field measurements were conducted along this transect, beginning at the 9-m mark and ending at the 36-m mark to provide some buffer from adjacent plots. Density of longleaf pine seedlings was measured in June 2005, March 2006, and February 2009. Seedlings were tallied within a 4-m-wide belt transect along each plot's diagonal transect for a total area of 108 m^2. Rootcollar diameter (RCD) was measured for each seedling to the nearest 1 mm using calipers. Seedling height was measured to the nearest 1 cm.

Woody plant density was measured within ten 1 m^2 sampling quadrats placed every 3 m along each transect, for a total area of 10 m^2. All hardwood trees, shrubs and woody vines rooted within each quadrat were tallied by species. Measurements were made in May to June 2003 (prior to herbicide treatments) and in the summers of 2005, 2006, and 2009. In 2009, a larger-scale sample of hardwood tree density across plots was made within the same 4-m-wide belt transects used for measuring longleaf pine seedlings. This sample was restricted to stems greater than 1.4 m in height (breast height).

Foliar cover (%) of all grasses was estimated in each 1-m^2 quadrat coincident with woody plant density measurements. Emphasis was placed on grasses because of their importance for fire. Foliar cover was estimated visually within percentage classes (1% classes up to 5% and then 5% classes thereafter, i.e., 1, 2, 3, 4, 5, 5–10, 10–15, 15–20%, etc.). Grasses were divided into two groups: large, C4 bunch grasses, such as bluestems, and what we termed "other grasses," which primarily included *Dichanthelium* species. Although the *Dichanthelium* genus also includes bunch grasses, their growth form tends to produce a lower fuel load and is less conducive to fire spread. In 2009, plant species richness was measured across plots by tallying the number of unique species in each 1-m^2 quadrat within each plot, followed by a meander survey of the whole plot. Voucher specimens were not collected.

All plots were burned in January 2006 and February 2009. Foliar cover of herbaceous and woody fine fuels (1-hour fuels, <0.635 cm in diameter) was measured in December 2008, prior to the 2009 burn, within the same quadrats used for previous measurements. Following each burn, percentage cover of unburned fuel was measured and a qualitative assessment of burn severity based on fuel consumption was conducted. Burn severity was evaluated using a coding matrix developed by the US National Park Service (US Department of the Interior National Park Service 2003). Quadrats were scored on a scale of 1 to 5, with 1 being heavily burned and 5 being unburned. Qualitative descriptions of consumption for both vegetation and substrate accompany each code as described in more detail in US Department of the Interior National Park Service (2003).

Statistical Analysis

Treatment effects on longleaf pine seedlings, understory vegetation, and fine fuels were analyzed using analysis of variance (ANOVA) in SAS version 9.2 (SAS Institute, Cary, NC). Specific response variables included longleaf pine rootcollar diameter, height, and density; woody stem density; graminoid percentage cover; plant species richness; and fine fuel cover. For woody stem density, dominant species were also analyzed individually. Results from all analyses were considered significant at $\alpha = 0.05$. When only 1 year of data was present, an ANOVA with block and treatment as factors was performed. Where treatment effects were significant, post hoc tests using Tukey's honestly significant difference test were conducted to evaluate differences among treatments. Where multiple years of data were present, repeated-measures (RM) ANOVA was conducted. The sphericity assumption of RM ANOVA was evaluated using Mauchly's test and Huynh-Feldt corrected probabilities were used where needed. When RM ANOVA models yielded significant treatment × time interactions, treatment effects within each year and year effects within each treatment were evaluated separately. In some cases, ANOVA tests were conducted on 2005 data only to evaluate the more immediate effects of treatments. When available, pretreatment (2003) data were considered for use as a covariate by evaluating regression relationships among pre- and posttreatment data. Where these relationships were significant, pretreatment data were incorporated as a covariate and tests for slope homogeneity were carried out. Data were transformed as needed to meet normality and constant variance assumptions associated with parametric tests. Both arcsine and log transformations were used.

To evaluate relationships among response variables, linear regression was conducted using SigmaPlot version 11.0 (Systat Software, Inc., San Jose, CA). Longleaf pine seedling size (rootcollar diameter and height) was evaluated against several independent variables, including hardwood density and graminoid cover. Relationships among hardwood stem density and fuels, and fuels and fire effects were also evaluated using linear regression.

Results

Longleaf Pine Seedlings

Longleaf pine RCD responded significantly to herbicide treatment ($P < 0.01$) and over time ($P < 0.001$), and there was a significant interaction between treatment and time ($P < 0.001$). Post hoc tests showed that seedlings on both hexazinone and imazapyr/glyphosate plots were similar to one another, and both had significantly higher RCD compared with control plots by 2009 (Figure 1A). Mean RCDs in 2009 were 6.0, 6.7, and 4.1 cm for imazapyr/glyphosate, hexazinone, and control plots, respectively. Treatments likewise had a significant effect on longleaf pine seedling height ($P < 0.01$), with both time and treatment × time significant as well ($P < 0.001$ and $P < 0.01$, respectively; Figure 1B). Mean seedling height on both hexazinone and imazapyr/glyphosate plots exceeded 2 m by 2009, whereas mean height for seedlings on control plots was less than 1 m. Seedling density was not affected by treatments ($P = 0.163$), nor did it change significantly over time ($P = 0.839$; Figure 1C), and there was no interaction between treatment and time ($P = 0.298$).

Vegetation

Herbicide treatments had a significant effect on total hardwood stem density ($P < 0.01$), and there was a significant change over time as well ($P < 0.05$), but there was no interaction between treatment and time ($P = 0.377$; Table 1). Imazapyr/glyphosate and hexazinone plots were similar to one another, and both had significantly fewer hardwood stems than control plots (Table 2). Mean hardwood stem density from 2005 to 2009 was 0.8, 0.6, and 2.7 stems per m^2 on imazapyr/glyphosate, hexazinone, and control plots, respectively. Southern red oak (*Quercus falcata* Michx.) was the most abundant hardwood present and was affected by hexazinone in particular (Table 2). Sweetgum was significantly reduced by both herbicide treatments initially in 2005 ($P < 0.05$; Table 2), but by 2009, sweetgum had recovered across plots and treatment effects were not significant in the full RM ANOVA ($P = 0.247$; Table 1). Persimmon (*Diospyros virginiana* L.) was significantly reduced by both herbicide treatments as well ($P < 0.05$; Table 1), and in this case differences between treated and control plots remained throughout the study period (Table 2). By 2009, hardwood stems on control plots had grown well into the midstory vegetation layer. Control plots contained 5-fold higher density for hardwood stems greater than 1.4 m sampled within the belt transect in 2009 ($P < 0.001$; Figure 2).

Shrub density was fairly variable among treatments and over time. There was no significant treatment effect in the full RM ANOVA ($P = 0.187$), but there was a significant change through time across plots ($P < 0.001$), as well as a significant interaction between treatment and time ($P < 0.01$; Table 1). No differences in total shrub density among treatments were detected within individual years (Table 2). For individual species, sand blackberry was by far the most abundant across plots. There was a significant treatment effect ($P < 0.01$), time effect ($P < 0.01$), and interaction between

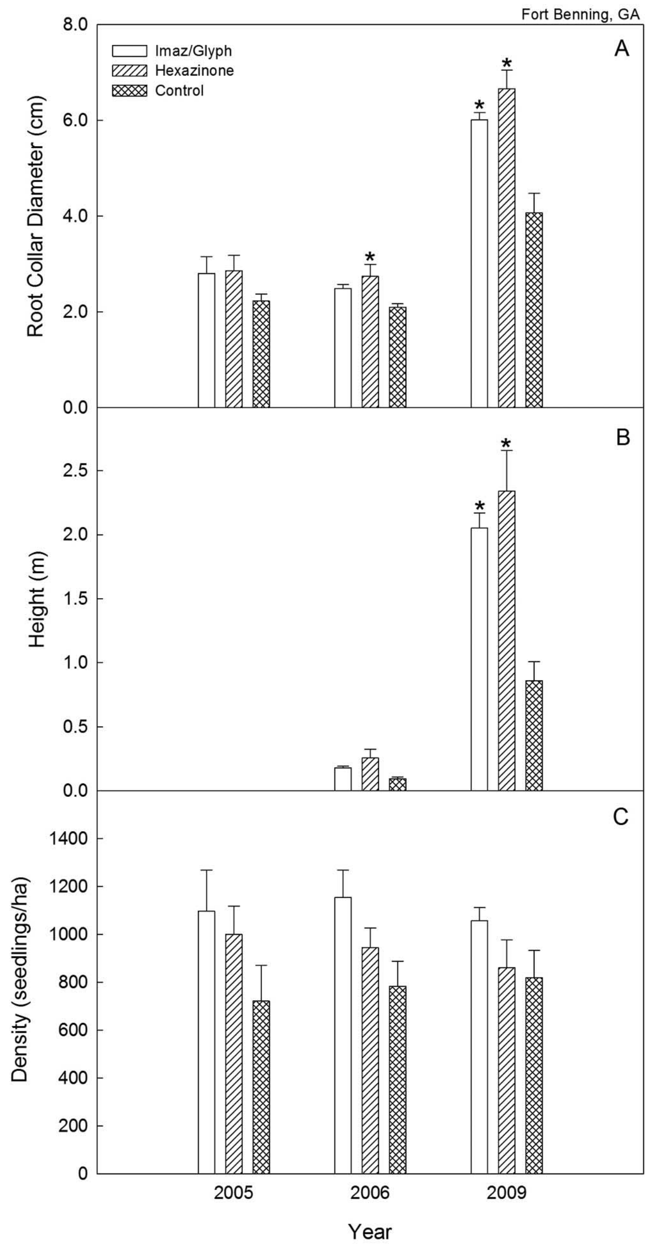

Figure 1. Longleaf pine seedling rootcollar diameter (A), terminal bud height (B), and density (C) for 2005, 2006, 2009 across treatments. Seedlings were planted in 2003. Height growth out of the grass stage was not observed until 2006. Values represent treatment means ($n = 4$ replicates per treatment; ±1 SE). An asterisk denotes a treatment effect significantly different from the control at $\alpha = 0.05$. Imaz/Glyph, imazapyr/glyphosate.

treatment and time ($P < 0.001$) for blackberry (Table 1). Blackberry was significantly higher on imazapyr/glyphosate plots compared with control plots in both 2005 and 2006 (Table 2). By 2009, however, there was no difference in blackberry density between imazapyr/glyphosate and control plots. Winged sumac showed initial resistance to hexazinone (Table 2), but there was no significant treatment effect in the full RM ANOVA ($P = 0.09$; Table 1). Similarly, beautyberry appeared resistant to hexazinone, and in this case treatment effects were significant ($P < 0.05$; Table 1). No effect of either herbicide treatment was detected for blueberry species ($P = 0.998$; Table 1).

Table 1. Significance probabilities for treatment effects, year effects, and treatment × year interactions from repeated measures analysis of variance for woody density (stems/m^2) and graminoid percentage cover. Pretreatment (2003) data were evaluated for use as a covariate for each test; where significant, pretreatment data were incorporated into the analyses as a covariate.

	Pretreatment	Treatment	Year	Treatment × year
	. . . . (*P* value)			
Woody stem density				
Combined hardwood trees	0.358	0.002	0.016	0.377
Combined shrubs	0.189	0.187	<0.001	0.006
Combined woody vines	0.005	0.121	0.107	0.177
Liquidambar styraciflua	0.964	0.247	0.085	0.674
Quercus falcata	0.007	0.050	0.669	0.175
Diospyros virginiana	0.679	0.002	0.218	0.409
Quercus nigra	0.117	0.473	0.111	0.318
Quercus incana	<0.001	0.431	0.886	0.849
Rubus cuneifolius	0.533	0.009	0.001	<0.001
Rhus copallinum	0.102	0.091	<0.001	0.196
Callicarpa americana	0.298	0.021	0.379	0.258
Morella cerifera	0.056	0.141	0.114	0.083
Vaccinium spp.	0.567	0.911	0.010	0.998
Gelsemium sempervirens	0.067	0.004	0.007	0.006
Vitis rotundifolia	0.008	0.129	0.295	0.334
Smilax spp.	0.593	0.395	0.042	0.098
Graminoid percentage cover				
Bunch grasses	0.259	0.513	<0.001	0.684
Other grasses	0.203	0.474	0.003	0.322
Combined grass cover	0.832	0.168	<0.001	0.032

No significant difference was found among treatments ($P = 0.121$) or over time ($P = 0.107$) for total woody vine density, and there was no interaction between treatment and time ($P = 0.177$; Table 1). For individual species, Carolina jessamine (*Gelsemium sempervirens* L.) showed some susceptibility to imazapyr/glyphosate but appeared to be resistant to hexazinone (Table 2). Muscadine and greenbriers appeared resistant to both herbicide treatments.

Bunch grass cover increased significantly across plots from 2003 to 2009 ($P < 0.001$), with no differences among treatments ($P = 0.513$) and no interaction between treatment and time ($P = 0.684$; Table 1). Foliar cover of other grasses also increased significantly by 2009 ($P < 0.01$), with no treatment effect ($P = 0.518$) and no treatment × time interaction ($P = 0.405$; Table 1). A significant interaction did emerge, however, when the data were summed to represent all grasses ($P < 0.05$; Table 1). Within-year analyses showed that total grass cover was significantly higher on hexazinone plots compared with control plots by 2009, with imazapyr/glyphosate plots intermediate (Table 2). Total grass percentage cover was 25.2, 20.8, and 15.8% for hexazinone, imazapyr/glyphosate, and control plots, respectively, in 2009.

There was no significant difference in total species richness among plots by 2009 at either the quadrat or whole-plot scale ($P = 0.867$ and 0.617, respectively; Table 3). Mean quadrat-scale richness was 12.8, 13.6, and 13.5 for imazapyr/glyphosate, hexazinone, and control plots, respectively, whereas whole-plot richness averaged 57.3, 60.0, and 56.5 for imazapyr/glyphosate, hexazinone, and control plots, respectively. Some differences in functional group richness were present, however, at the quadrat scale. Woody plant richness was higher on control plots relative to treated plots ($P < 0.01$; Table 3). Herbaceous richness tended to be higher on treated plots relative to controls, but results were not statistically significant ($P = 0.412$).

Table 2. Means by year and among treatments for woody density (stems/m²) and graminoid percentage cover for individual species and vegetation groups where analysis of variance (ANOVA) models yielded significant results. Analyses were first restricted to data from 2005 to evaluate more immediate effects of herbicide treatments on vegetation. Longer term herbicide effects (2005–2009) were then analyzed using repeated measures ANOVA. In both cases, pretreatment (2003) data were evaluated for use as a covariate.

	Treatment	Year 2003	2005	2006	2009	Mean, 2005–2009
Woody stem density						
Combined hardwood trees	Imaz/gly	3.9	0.7	0.5	1.3	0.8[a]
	Hex	1.5	0.3[a]	0.7	0.8	0.6[a]
	Control	2.8	1.7	2.5	3.8	2.7
Combined shrubs	Imaz/gly	7.4	8.3	14.9	8.5	10.6
	Hex	6.4	3.1	6.6	11.2	6.9
	Control	9.3	5.5	8.3	9.4	7.7
Liquidambar styraciflua	Imaz/gly	1.5	0.03[a]	0.03	0.1	0.2
	Hex	0.7	0.0[a]	0.4	0.5	0.3
	Control	0.6	0.4	0.5	0.9	0.6
Quercus falcata	Imaz/gly	0.9	0.1	0.2	0.6	0.3
	Hex	0.3	0.0[a]	0.0	0.0	0.0[a]
	Control	0.7	0.2	0.3	1.1	0.5
Diospyros virginiana	Imaz/gly	0.5	0.0[a]	0.0	0.08	0.03[a]
	Hex	0.1	0.0[a]	0.0	0.03	0.01[a]
	Control	0.4	0.4	0.2	0.9	0.5
Rubus cuneifolius	Imaz/gly	5.5	8.0[a]	14.6[a]	5.8	9.5[a]
	Hex	5.6	1.2	4.5	7.4	4.4
	Control	7.3	3.2	5.0	4.2	4.1
Rhus copallinum	Imaz/gly	0.7	0.0[a]	0.2	1.7	0.6
	Hex	0.5	1.0	1.2	1.6	1.3
	Control	1.1	1.6	2.1	2.5	2.1
Callicarpa americana	Imaz/gly	0.5	0.05	0.03	0.0	0.03
	Hex	0.0	0.2	0.4	0.5	0.4[a]
	Control	0.4	0.05	0.0	0.08	0.04
Gelsemium sempervirens	Imaz/gly	0.0	0.03	0.0[a]	0.3	0.1[a]
	Hex	0.03	1.0	1.2	0.8	1.0
	Control	0.08	0.4	1.6	1.7	1.2
Graminoid percentage cover						
Combined grass cover	Imaz/gly	6.0	14.0	12.0	20.8	15.6
	Hex	13.9	21.9	16.2	25.2[a]	21.1
	Control	3.4	20.4	10.7	16.2	15.8

ANOVA, analysis of variance; Imaz/gly, imazapyr/glyphosate; Hex, hexazinone.

[a] Significantly different from control plots within columns at $\alpha = 0.05$.

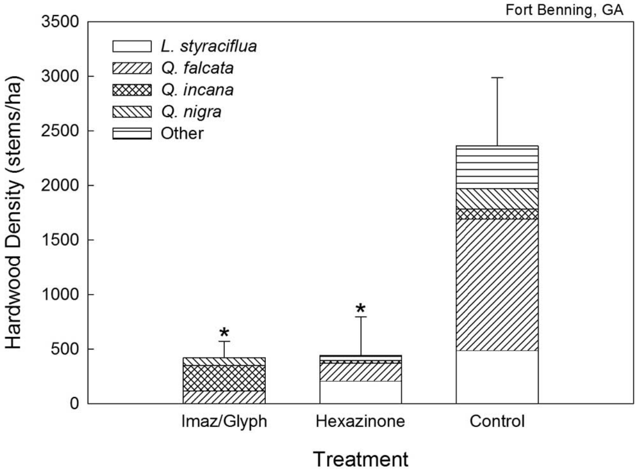

Figure 2. Hardwood stem density for stems >1.4 m in height measured within belt transects in 2009, averaged by treatment (n = 4 replicates per treatment; ±1 SE). In addition to the species listed, other species included *Crataegus flava* (Aiton), *Diospyros virginiana*, *Quercus hemisphaerica* (Bartram ex Willd.), and *Acer rubrum* (L.). Error bars are for the mean of all species combined. An asterisk denotes a treatment effect significantly different from the control at $\alpha = 0.05$. Imaz/Glyph, imazapyr/glyphosate.

Table 3. Species richness by vegetation functional group at the quadrat (1 m²) scale and the whole-plot (800 m²) scale. Values represent means of n = 4 plots.

	Quadrat-scale richness (spp/m²)			Whole-plot richness (spp/800 m²)		
Functional group	Imaz/gly	Hex	Control	Imaz/gly	Hex	Control
Bunch grasses	0.9	1.0	0.9	2.0	2.0	2.3
Other grasses	2.5	2.6	2.1	8.8	9.3	7.5
Legumes	1.6	1.7	1.7	6.8	8.3	7.5
Other forbs	5.3	5.3	3.9	22.0	22.5	17.8
Hardwood trees	0.4	0.2[a]	0.9	5.0	4.8	5.0
Shrubs	1.6[a]	2.0	2.6	7.0	8.3	10.3
Vines	0.6	0.9	1.5	5.8	5.0	5.8
Total herb	10.2	10.5	8.5	39.5	42.0	35.0
Total woody	2.6[a]	3.1[a]	5.0	17.8	18.0	21.5
Total	12.8	13.6	13.5	57.3	60.0	56.5

Imaz/gly, imazapyr/glyphosate; Hex, hexazinone.

[a] Significantly different from control plots within rows at $\alpha = 0.05$.

Fine Fuels and Fire Effects

Total herbaceous fine fuel cover was significantly higher on hexazinone plots compared with control plots, with imazapyr/glyphosate plots intermediate ($P < 0.05$; Figure 3). Foliar cover of woody fuels, mainly woody litter, was 3-fold higher on control plots

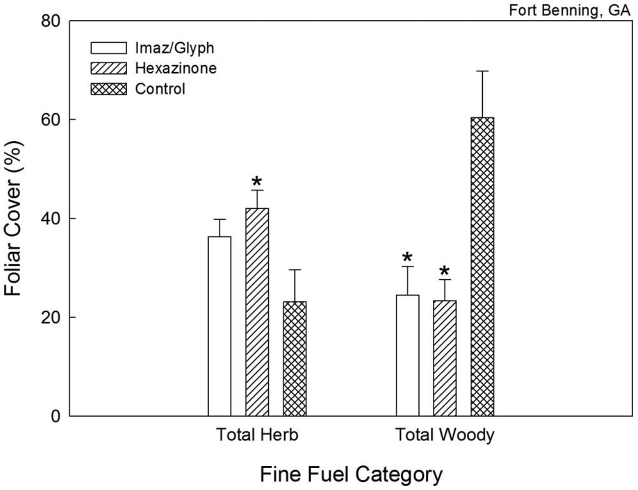

Figure 3. Percentage cover of herbaceous and woody fine fuels (1-hour fuels, <0.635 cm in diameter) measured in December 2008 prior to sites being burned in January 2009. Values represent treatment means (n = 4 replicates per treatment; ±1 SE). An asterisk denotes a treatment effect significantly different from the control at $\alpha = 0.05$. Imaz/Glyph, imazapyr/glyphosate.

Table 4. Mean burn severity code and percentage cover of unburned fine fuel (1 hour of fuel) following prescribed fires in 2006 and 2009. Severity codes were adapted from US Department of the Interior National Park Service (2003), with 1 = heavily burned and 5 = unburned. Values are averages by treatment (n = 4 repetitions per treatment). No significant differences among treatments within years were present for either burn severity or percentage cover of unburned fuel.

	Treatment	2006	2009
Burn severity code	Imaz/gly	3.5	2.8
	Hexazinone	3.3	2.6
	Control	4.2	3.3
Percentage cover unburned fuel	Imaz/gly	29.8	13.4
	Hexazinone	26.9	13.2
	Control	33.5	23.4

Imaz/gly, imazapyr/glyphosate.

compared with treated plots ($P < 0.01$; Figure 3). There were no significant differences among treatments in burn severity and percentage cover of unburned fuel following the burns in 2006 and 2009 (minimum $P = 0.120$; Table 4), though burn severity scores tended to be lower (more severe) and there tended to be less unburned fuel on treated plots relative to control plots.

Relationships among Variables

Statistically significant results from regression analyses among response variables are presented in Table 5. Of the variables evaluated against longleaf pine seedling size, hardwood stem density (for stems greater than 1.4 m height) from 2009 was by far the most highly significant. Strong relationships were found between hardwood stem density and longleaf pine seedling rootcollar diameter ($r^2 = 0.72$, $P < 0.001$) and height ($r^2 = 0.75$, $P < 0.001$). As expected, strong relationships were found between hardwood density and woody fuel percentage cover ($r^2 = 0.77$, $P < 0.001$), verifying the effect of hardwoods on the composition of the fuel bed. Significant relationships were also found between fuel bed composition and fire effects, such that as percentage cover of woody fuels increased, burn severity code increased (became less severe), and percentage cover of unburned fuel also increased, indicating lower fuel consumption. Similarly, as herbaceous fuels increased, burns became more severe and fuel consumption increased.

Discussion

Herbicide site preparation in this study adjusted vegetation composition and structure in desirable ways, with important implications for ecosystem development and longer-term fire management. The most apparent outcome of the treatments was the reduction in hardwoods, which had important consequences for longleaf pine seedling growth and fuel bed composition in particular. The accelerated seedling growth we observed on treated plots is desirable, as longleaf pine seedlings that are out of the grass stage are less susceptible to mortality caused by fire, brown-spot needle blight, or feral hogs (Croker and Boyer 1975, Lipscomb 1989, Boyer 1990a). Furthermore, pine needle contribution to the fuel bed will occur more quickly on treated plots compared with control plots, which will further enhance the ability of these sites to be managed with fire alone into the future. Alternatively, the increase in woody fuels, woody litter in particular, on control plots may modify the burning characteristics of the fuel bed in ways that make hardwood control by fire even more difficult (e.g., Provencher et al. 2001a, Kane et al. 2008). Though many woody species, such as deciduous oaks, produce litter with burning characteristics that facilitate fire (Kane et al. 2008), we also had an abundance of woody species such as water oak (*Quercus nigra* L.) that may impede fire.

Herbaceous vegetation and fuels, perennial bunchgrasses in particular, were not negatively affected by herbicide treatments, which also bodes well for continued fire management on treated plots. Other studies have shown enhancement of grasses following herbicide treatments, presumably due to release from woody plant competition. Brockway and Outcalt (2000) reported an increase in wiregrass following hexazinone and fire in north Florida. Miller and Chamberlain (2008) reported an increase in bluestem grasses in Louisiana following imazapyr. Haywood (2000) and Provencher et al. (2001a) also showed positive responses of bluestems to hexazinone, though Provencher et al. (2001a) detected an initial negative effect on little bluestem, followed by an increase after sites were burned.

Understory plant species richness was similar among treated and control plots as well, which is favorable for meeting restoration objectives with regard to species diversity. Although several studies have documented declines in richness following herbicide treatments (Wilkins et al. 1993, reviewed in Litt et al. 2001), longer-term studies often show recovery, particularly when treatments are followed by prescribed fire (Brockway et al. 1998, Miller and Chamberlain 2008, Freeman and Jose 2009). At the quadrat scale, species richness in our study was similar to that documented on high-quality reference sites elsewhere on Fort Benning by Mulligan and Hermann (2004). Our sample, however, contained more ruderal and old-field species, such as dog fennel (*Eupatorium capillifolium* Lam.), horseweed (*Conyza canadensis* L.), and ragweed (*Ambrosia artemisiifolia* L.), which are indicators of disturbance and less emblematic of high-quality longleaf sites (Dale et al. 2002, Rasser 2003, Kirkman et al. 2004). As our sites continue to develop, though, they will presumably continue to gain desirable species, or they may be further enhanced by active reintroduction of desirable species via seed broadcasts and plug planting.

Of the two treatments, hexazinone was slightly more effective than imazapyr/glyphosate in advancing restoration objectives,

Table 5. Relationships among variables. Hardwood stem density represents hardwood tree stems greater than 1.4 m in height tallied within belt transects in 2009. Equations are in the form $Y = a + bX$.

Y	X	a	b	r^2	P (<)	n
Longleaf RCD (cm)	Hwd density (stems/m^2)	6.551	−9.025	0.72	0.001	12
(log) Longleaf height (m)	Hwd density (stems/m^2)	0.371	−1.659	0.75	0.001	12
Woody fuel percentage cover	Hwd density (stems/m^2)	19.282	156.807	0.77	0.001	12
Burn severity code	Woody fuel percentage cover	2.042	0.024	0.56	0.005	12
Unburned fuel percentage cover	Woody fuel percentage cover	5.973	0.296	0.50	0.01	12
Burn severity code	Herb fuel percentage cover	4.524	−0.048	0.70	0.001	12
Unburned fuel percentage cover	Herb fuel percentage cover	33.322	−0.492	0.41	0.05	12

RCD, rootcollar diameter; Hwd, hardwood.

though differences were not statistically significant. Longleaf pine seedling growth was slightly higher on hexazinone plots compared with imazapyr/glyphosate plots. Herbaceous fuels, grass cover and species richness were all somewhat higher on hexazinone plots as well, and hardwood stem density was lower. Other anecdotal differences included a lower sweetgum but higher oak component on imazapyr/glyphosate plots, whereas there were more sweetgum stems and fewer oaks on hexazinone plots. Hexazinone is often used for oak control in particular (Brockway et al. 1998, Hay-Smith and Tanner 1999, Provencher et al. 2001b) and appeared effective at controlling oaks in this study as well. We also observed an initial release of blackberry following imazapyr/glyphosate treatments, consistent with other studies showing resistance of blackberry to imazapyr (Jones and Chamberlain 2004, Miller and Chamberlain 2008, Iglay et al. 2010). Beautyberry and winged sumac appeared resistant to hexazinone, also consistent with what other studies have found for these species (Wigley et al. 2002, Miller and Chamberlain 2008, Iglay et al. 2010). Similar to our study, Jones and Chamberlain (2004) reported increases in Carolina jessamine, muscadine, and greenbriers following imazapyr and fire treatments, and Hay-Smith and Tanner (1999) observed release of Carolina jessamine following hexazinone treatments. Though these species are capable of dense growth and may competitively exclude other desirable species, they appear manageable with fire alone on our study sites.

Hardwoods persisted and proliferated on control plots despite prescribed fires in both 2006 and 2009. Both burns were conducted during the dormant season, and cool season fires are often not an effective means of controlling hardwoods (Waldrop et al. 1992, Boyer 1993, Jacqmain et al. 1999), especially when conducted every 2–3 years as they are on Fort Benning. Although more frequent or more extreme fire management (i.e., growing season burns) may reduce hardwood stem densities on control plots (Boyer 1993, Rebertus et al. 1993, Provencher et al. 2001b), the risk of killing longleaf pine seedlings increases as well with more extreme fire management (Boyer 1990b, Provencher et al. 2001b). Site preparation treatments appear to have enabled more flexibility in fire management and more room for error, for example if a rotation is missed or if a burn is carried out under marginal conditions.

Despite the high hardwood component on control plots, we found no difference in longleaf pine seedling density among treated and control plots, suggesting that seedlings are still releasable if hardwood competition could be reduced and controlled. The fact that species richness was similar across plots also suggests that woody encroachment on control plots has not yet resulted in a decline in richness, likely because control plots have been burned as frequently as treated plots (Hiers et al. 2007). Thus, longleaf pine restoration objectives might be achieved in the absence of herbicide application, although at a slower rate and in this case presumably requiring some type of alternative treatment to reduce hardwoods.

Although control of woody competition is important, it is also important to point out that several of the woody species on our sites play a valuable role within longleaf pine ecosystems, particularly for wildlife. Hardwoods provide structural diversity, cover, and soft and hard mast for wildlife and are important for rare species such Sherman's fox squirrel (*Sciurus niger shermani*) (Perkins et al. 2008), as well as for desirable game species such as white-tailed deer (*Odocoileus virginianus*). Modest amounts of woody litter also likely provide microhabitat heterogeneity important for herpetofauna (Greenberg 2002). Lastly, although we demonstrate favorable effects of herbicide treatments, the introduction of chemicals into natural systems represents a novel treatment potentially leading to novel effects and influences on ecological processes (Menges and Gordon 2010), as well as possible unintended effects on nontarget species (Kaeser and Kirkman 2010). As such, we encourage practitioners to carefully develop herbicide prescriptions, considering both herbicide choice and concentration rates, based on the needs of individual sites, and to be careful and judicious in herbicide application.

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