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Evaluation of Four Herbicides and Tillage for Weed Control on 1-0 Planted Tree Seedlings

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ABSTRACT: *Azafenidin, sulfometuron, pendimethalin, and simazine were applied alone and in combination to 1-0 seedlings of nine hardwood and one conifer species. Percent bare ground at 30, 60, and 90 days, diameter and height growth of the seedlings were determined for 16 herbicide treatments, tillage and a control. Azafenidin applications alone and in combination with sulfometuron resulted in about 85% bare ground 90 days post-treatment. There were significant differences for diameter, height growth, and volume among the treatments for every species. No single treatment ranked best for all species, but comparison of the mean ranks of the treatments for all species indicated that azafenidin and pendimethalin resulted in the most growth. Azafenidin-treated seedlings also had the greatest volume at the end of the season. North. J. Appl. For. 19(3):101–105.*

Key Words: Weed control, hardwood, black cherry, black walnut, yellow poplar, red oak, white oak, white ash, eastern white pine, flowering dogwood, northern bayberry, Siberian crabapple.

Weed control is important to the early diameter and height growth of hardwood seedlings, and pre-emergent herbicides can reduce the total number of weeds in nursery plantings (Akers et al. 1984). The early success of a hardwood plantation is often dependent on the ability of seedlings to compete for soil moisture and nutrients (Byrnes et al. 1973). In the late 1960s, Erdmann and Green (1967) demonstrated the necessity of weed control for four hardwood species. More recent studies (von Althen 1989, Seifert 1993) have continued to demonstrate the importance of weed control for the survival and subsequent development of hardwood plantations.

Azafenidin (AZ) and sulfometuron (SF) are relatively new pre-emergent herbicides that have been tested alone and in combination with other herbicides in the southern United States for use in hardwood plantations (Muir and Glover 1998, Muir and Zutter 1999). Both herbicides were effective at reducing weed cover and resulted in improved first-year height growth. Pendimethalin (PM) and simazine (SM) have been tested more extensively and are commonly recommended for hardwood plantation establishment (Seifert 1997).

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Our objective was to compare and evaluate new and standard pre-emergent herbicides for use in state nurseries and in hardwood plantation establishment. We were especially interested in weed control efficiency by individual products and by combination treatments, growth response of the seedlings to the treatments, and the relationship between weed control and toxicity. Finally, because many midwestern United States hardwood plantations contain multiple species, we wanted to determine if we could identify the best treatment for the greatest number of species in a mixed planting. We included eastern white pine seedlings in this study because this species is often used as a companion in mixed hardwood plantings.

Material and Methods

Study Area

The study was established in the spring of 2000 at the Southeast Purdue Agricultural Center (SEPAC), located in southeastern Indiana. The soil at the study site is a Parke silt loam with less than 1% organic matter and 6.5 pH. The study site had been used previously as a cornfield.

Experimental Design

A total of 5,400 tree seedlings of black cherry (*Prunus serotina* Ehrh.), black walnut (*Juglans nigra* L.), eastern white pine (*Pinus strobus* L.), flowering dogwood (*Cornus florida* L.), northern bayberry (*Myrica pensylvanica* L.), red

Table 1. Common, trade, and chemical names of herbicides used in this study.

Common name	Trade name	Chemical name
Azafenidin	Milestone	2-[2-4-dichloro-5-(2-propynyloxy)phenyl]-5,6,7,8-tetrahydro- 1,2,4-triazolo{4,3-A]pyridin-3 (2H)-one
Sulfometuron	Oust	{Methyl2-[[[(4,6dimethyl-2-pyrimidinyl)amino]carbonyl]sulfonyl]benzoate}
Pendimethalin	Pendulum	(N-(1-ethylpropyl)-3,4-dimethyl)1-2-6-dinitro-benzenamine
Simazine	Princep 4L	2-chloro-4,6-bis(ethylamino)-s-triazine

oak (*Quercus rubra* L.), Siberian crabapple (*Malus baccata* [L.] Borkh), white ash (*Fraxinus americana* L.), white oak (*Q. alba* L.), and yellow poplar (*Liriodendron tulipifera* L.) were planted as 1-0 seedlings on May 15, 2000 with a machine planter. Sixteen herbicide treatments, along with a tilling treatment and an untreated control (Tables 1, 2) were established using ten species in a randomized complete block design with three replications and ten seedlings per species per plot. Herbicide treatment rates were chosen based on previous experience at SEPAC. The rates for PM and SM (Table 2) were chosen to maximize the number of days that weeds would be controlled without suppression of tree growth (Seifert, personal observation).

Pre-budbreak herbicide treatments were applied as sprays 10 in. from the base of the trees on May 29 in a carrier of 25 gal of water per acre using a CO_2 plot sprayer. Sprays applied after budbreak were applied over the top of the trees. About 1/2 in. of rain fell within seven days of the application of the pre-emergence herbicide/combination treatments, ensuring penetration and incorporation of the chemicals into the soil. Post-budbreak (post-germination) applications of herbicides were made on June 20, when weeds were 12 to 24 in. tall but not flowering. Tilled plots were tilled four times through the growing season (once monthly). The control plots were not treated or tilled after planting.

Weed control was visually estimated by one of the authors (Seifert) as percent bare ground for each treatment in each block 30, 60, and 90 days after treatment. Plots that received post-budbreak applications were evaluated on the same days as the pre-budbreak plots. Initial seedling height was taken at the time of planting. Groundline diameter and incremental height growth were measured by two technicians in October after leaf fall.

Statistical Analysis

We used SAS V. 8.1 (SAS Institute, Cary, NC) for all statistical analyses. Seedling volumes were approximated using the formula 1/3(basal area) × (height). Because of extreme variance heterogeneity and nonnormality in the growth variables, data transformations (arcsin, $\ln_e$, or PROC RANK with default options) were used to prepare the data for subsequent analysis. The RANK procedure assigns the lowest rank to the highest response, i.e., the treatment that produced the greatest growth was ranked 1, the second best was ranked 2, and so forth. We used ANOVA (Proc GLM) on volume, height change, diameter, and ranks to evaluate differences among treatments. Means and rank means were separated using Duncan's multiple range test, $\alpha = 0.05$. PROC VARCOMP was used to estimate the proportion of variance attributable to treatments, weed control and other effects. PROC REG was combined with GLM for analysis of residuals (Cody and Smith 1997).

Results

Survival

An average of 529 of the 540 trees of each species survived the first year of the study (98%). Only flowering dogwood, with 450 trees surviving (83%), had significantly lower survival than the other species. Differences among treatments for survival were small and not statistically significant.

Table 2. Weed control by herbicide treatments at 30, 60, and 90 days after treatment (DAT).

Treatment	Application rate (ai/ac)	Pre- or post-budbreak	Bare ground 30 DAT	60 DAT	90 DAT
			(%)*		
Control			98 ± 3	0.0	0.0
Tilled			100	100	100
Azafenidin	2.0 oz	Pre	100	53 ± 12	12 ± 6
Azafenidin	4.0 oz	Pre	100	77 ± 8	37 ± 3
Azafenidin	6.0 oz	Pre	100	93 ± 3	62 ± 3
Azafenidin	8.0 oz	Pre	100	96 ± 1	85 ± 0
Azafenidin	16.0 oz	Pre	100	97 ± 0	90 ± 0
Sulfometuron	0.562 oz	Pre	100	57 ± 12	35 ± 3
Sulfometuron	0.750 oz	Pre	100	82 ± 3	65 ± 0
Azafenidin + Sulfometuron	2.0 + 0.375 oz	Pre	100	72 ± 13	35 ± 8
Azafenidin + Sulfometuron	2.0 + 0.562 oz	Pre	100	92 ± 4	81 ± 3
Azafenidin + Sulfometuron	2.0 + 0.750 oz	Pre	100	94 ± 4	83 ± 3
Azafenidin + Sulfometuron	4.0 + 0.375 oz	Pre	100	93 ± 3	88 ± 6
Azafenidin + Sulfometuron	4.0 + 0.562 oz	Pre	100	96 ± 1	83 ± 3
Azafenidin	4.0 oz	Post	100	47 ± 12	5 ± 0
Sulfometuron	0.75 oz	Post	100	40 ± 0	10 ± 0
Pendimethalin	3.3 lb	Pre	100	68 ± 14	28 ± 14
Simazine	4.0 lb	Pre	100	57 ± 25	20 ± 9

* Mean of three blocks containing eighteen ten-tree plots each ± standard deviation.

Survival differed significantly among blocks, with the best survival (1,774 out of 1,800 trees per block) in the block farthest from a nearby woodlot, and the worst (1,750 surviving) in the block closest to the woodlot. There was no apparent spatial pattern to the distribution of dead seedlings within the blocks.

Weed Control

At the time of the earliest evaluation, 30 days after treatment (DAT), there was essentially no aboveground weed growth, even in the untreated (control) plots (Table 2). By 60 DAT, all of the plots treated with tillage or herbicides were less weedy than control plots, and differences in weed control among the treatments were apparent and very highly significant ($P \leq 0.0001$). The most prevalent weeds were crabgrass (*Digitaria* spp.), horseweed (*Erigeron canadensis*), giant foxtail (*Setaria faberii*), and yellow foxtail (*Setaria glauca*). Tillage provided the greatest amount of weed suppression, followed closely by the higher rates of AZ and AZ + SF in combination. At 90 DAT, azafenidin 2.0 plots (AZ 2.0) had 12 ± 6% bare ground, and SF 0.562 plots had 35 ± 3% bare ground, but the plots treated with the two herbicides in combination (AZ 2.0 + SF 0.562 rate) had 81 ± 3% bare ground, about 30% more weed control than might be expected if the two herbicides worked in a simply additive manner. At 60 and 90 DAT, AZ 16.0 produced the greatest amount of weed control (97 and 90%, respectively), but much lower rates of herbicides, e.g., AZ 8.0 and AZ 4.0 + SF 0.375, were very nearly as effective (Table 2). The highest rates in combination treatments did not result in the greatest amount of weed control 90 DAT. For example, AZ 4.0 + SF 0.562 provided no better weed control than AZ 2.0 + SF 0.562, or AZ 4.0 + SF 0.375. Post-budbreak application of AZ or SF was much less effective than pre-budbreak applications of the same herbicides at both 60 and 90 days. Weed control by PM and SM was comparable to that provided by the lowest rates of AZ and SF at both 60 and 90 days.

Treatment Differences

Most, but not all, of the species showed a significant volume benefit from control of the aboveground growth of weeds. The effect of treatment on volume, diameter, and height growth was very highly significant when ANOVA was performed without regard to weed control, whether the analysis was performed with each species separately (17 df for treatment, N ≈ 520, Table 2), or across all species together (17 df, N ≈ 5,180). Thus, trees grew better after some herbicide treatments than others. This was true of each species separately and of all species taken together. There were two exceptions: herbicide treatments had a significant effect on diameter and volume of red oak but no significant effect on height growth; and there were no significant differences among treatments for volume of northern bayberry. Significant species × treatment interactions were found when all the species were pooled in a single analysis. This potentially complicates mixed hardwood plantation management, since it may not be possible to use different herbicides for each species.

The practical importance of the statistical differences among treatments can be evaluated by comparing the best and worst treatments for diameter and height growth with the control (Table 3). For example, for white oak, the difference in height growth between the control and the best treatment (0.3 cm) was probably not biologically or economically meaningful (Table 3). The same may be true for height growth of eastern white pine, for which the difference between the best treatment and the control was only about 2 cm. In most cases, the control plots had the smallest diameter (i.e., highest rank for diameter) as compared to the herbicide treatments (Table 3 and 4). In contrast, for height growth, several of the treatments were worse than the control for several species, notably the oaks.

We used an estimate of seedling volume to determine the best overall treatment for each species, but no single treatment ranked best for volume for all species (Table 4). Treatments were ranked for volume within species (columns in Table 4). Mean treatment ranks across all species (rows in Table 4) were calculated, and ANOVA on the ranks revealed significant differences among treatments. The best (lowest ranking) treatment for all species combined for seedling volume was AZ 16.0, followed closely by AZ 6.0 and PM. Tillage was a particularly good treatment for white ash, black cherry, and yellow poplar, but not for eastern white pine or the oaks. Pendimethalin was comparable to AZ 16.0 for overall seedling volume, and was better than AZ 16.0 for eastern white pine, black walnut, white oak, and flowering dogwood. Sulfometuron and AZ + SF combinations resulted

Table 3. Diameter and height growth of ten tree species with best and worst treatment, and control.

	Diameter (mm)*			Height growth (cm)		
Species	Control	Best treatment†	Worst treatment	Control	Best treatment	Worst treatment
White ash	12.2 ± 2.7	17.4 ± 3.8	Control†	34.4 ± 13.0	47.1 ± 19.0	15.4 ± 12.2
Siberian crabapple	12.2 ± 3.3	17.7 ± 5.0	Control	47.1 ± 25.6	50.4 ± 14.9	22.0 ± 10.8
Northern bayberry	6.9 ± 2.3	8.2 ± 1.1	6.6 ± 1.8	29.5 ± 24.7	Control	11.0 ± 4.8
Black cherry	11.2 ± 3.4	23.6 ± 3.6	Control	32.0 ± 13.8	85.3 ± 34.6	28.4 ± 12.7
Eastern white pine	4.9 ± 0.9	7.4 ± 2.0	Control	12.6 ± 4.5	14.3 ± 6.1	8.6 ± 3.8
Black walnut	8.9 ± 2.3	15.4 ± 3.1	Control	5.8 ± 3.0	14.7 ± 7.8	5.3 ± 4.2
Yellow-poplar	10.5 ± 1.7	24.8 ± 3.0	Control	33.6 ± 17.7	85.3 ± 34.6	Control
White oak	8.1 ± 2.0	11.5 ± 2.8	Control	25.0 ± 8.3	25.3 ± 11.2	18.8 ± 7.5
Flowering dogwood	5.8 ± 1.5	10.7 ± 2.9	5.8 ± 1.5	18.9 ± 11.0	21.7 ± 10.1	5.5 ± 3.7
Red oak	7.9 ± 1.7	9.3 ± 2.1	7.2 ± 2.0	12.9 ± 10.8	13.2 ± 12.2	9.6 ± 6.1

* Mean ± standard deviation.

† Best and worst treatment based only on largest or smallest diameter or height growth, respectively. "Control" was tabulated when control plots showed the best or worst diameter or height growth.

Table 4. Herbicide treatments ranked for seedling volume for ten species and mean rank for each treatment.

		Species									
Treatment	Mean rank*	White ash	Siberian crabapple	Northern bayberry	Black cherry	E. white pine	Black walnut	Tulip tree	White oak	Flowering dogwood	Red oak
Azafenidin 16.0	3.9A	3	2	1	1	2	7	2	9	9	3
Azafenidin 6.0	4.0A	5	9	4	4	7	1	3	1	1	5
Pendimethalin	4.0A	6	2	3	5	1	2	4	6	4	6
Azafenidin 4.0	4.9AB	9	4	2	6	3	3	5	3	5	9
Azafenidin 8.0	5.1AB	4	1	1	3	8	6	6	8	2	2
Azafenidin 2.0	7.1ABC	1	5	12	10	13	4	7	4	3	12
Tillage	7.6BCD	2	7	7	2	15	5	1	12	10	15
Simazine	9.4CD	15	8	10	14	4	9	9	7	7	11
Azafenidin 2.0 + Sulfometuron 0.75	9.8CDE	10	12	13	7	5	11	13	5	15	7
Azafenidin 2.0 + Sulfometuron 0.375	10.0CDE	11	16	5	9	6	10	8	11	8	16
Azafenidin 4.0 + Sulfometuron 0.562	10.7DE	7	11	17	11	11	12	12	10	12	4
Sulfometuron 0.562	11.2DEF	8	14	16	13	16	13	16	2	6	8
Azafenidin 4.0 + Sulfometuron 0.375	11.2DEF	12	15	6	8	14	8	11	14	11	13
Azafenidin 2.0 + Sulfometuron 0.562	13.3EFG	14	13	9	12	9	14	15	16	17	14
Azafenidin post	13.4EFG	13	6	15	15	12	15	10	18	13	17
Sulfometuron post	14.7FG	18	18	18	17	10	18	14	15	18	1
Control	14.7FG	17	10	8	18	18	17	18	17	14	10
Sulfometuron 0.75	16.0G	16	17	14	16	17	16	17	13	16	18

* Means followed by the same letter are not significantly different ($\alpha = 0.05$) by Duncan's multiple range test.

in poor performance (had high ranks) for almost every species in the study. Post-budbreak applications of AZ and SF resulted in very poor seedling volume for nearly every species.

Suppression of Aboveground Growth of Weeds and Trees

Tillage resulted in the highest percent weed control but significantly less volume growth than AZ 6.0, which ranked eighth best for weed control. When considering just the herbicide treatments, AZ 16.0 resulted in the most weed control (90% bare ground 90 DAT) and also ranked best overall for seedling volume (Table 4), but other treatments that resulted in very high levels of weed control, i.e., AZ 2.0 + SF 0.562 and AZ 4.0 + SF 0.375, were among the worst treatments (ranked high) for seedling volume (Table 4).

For all species except northern bayberry and red oak, there was at least one herbicide treatment that significantly increased tree volume as compared to the control, but for seven of ten species at least one of the herbicides/combinations resulted in less volume than the control (Table 4), indicating that some treatments may have suppressed aboveground growth of the tree seedlings as well as weeds. The SF 0.75 treatment ranked worse than the control for volume for four of ten species, and had a mean rank higher than the control (Table 4). The suppression of aboveground growth of the tree seedlings (relative to the control) associated with herbicides/combinations was generally most apparent as a reduction in height growth (Table 3).

The association between weed control (as measured by percent bare ground) in the herbicide treated plots and seedling volume was species-dependent. For eight of the ten species; Siberian crabapple, northern bayberry, eastern white pine, black walnut, yellow poplar, white oak, flowering dogwood, and red oak, weed control was not significantly correlated with seedling volume ($r < 0.07$, $P > 0.10$ for all). For these species there was no clear relationship between the aboveground growth of the weeds in the herbicide treated plots and the volume of the trees.

There was a positive and significant linear relationship between percent bare ground in the herbicide treated plots and seedling volume for white ash and black cherry. To evaluate the importance of weed suppression versus other treatment effects on the growth of these two species, we used percent weed control as an independent variable in a regression using seedling volume as the dependent variable (regression $t = 2.5$, $P < 0.01$; $t = 5.34$, $P < 0.0001$, for white ash and black cherry, respectively), and then performed ANOVA on the residuals. This analysis showed that the treatment effects remained very highly significant ($F > 9.0$, $P \leq 0.0001$ for both species); indicating that the treatments had a very highly significant effect on volume even after the effect of weed control was removed. Overall, percent bare ground accounted for less of the variance in growth of the trees in the study than other effects of the treatments.

Site Effects

Although the study site was apparently uniform, block had a significant effect on the diameter of most species in the study (flowering crabapple and northern bayberry were the exceptions), and a significant effect on height growth for black cherry, eastern white pine, yellow poplar, and flowering dogwood. Block had a significant effect on the seedling volume of all the species except flowering crabapple, northern bayberry, and black walnut. There were highly significant block × treatment interaction effects on seedling volume, diameter and height growth for nine of the ten species in the study (northern bayberry was

the exception), even in cases when block effects alone were not significant. This may indicate that the optimal herbicide treatments for these species will depend on specific site conditions.

Discussion

A goal of this research was to compare the performance of the relatively new herbicides AZ and SF with the more widely tested and used PM and SM. These results indicate that AZ was superior to both PM and SM for weed suppression at 90 days post-treatment, and that AZ resulted in better seedling growth than PM or SM for most of the species we tested. The sole exception was eastern white pine. Sulfometuron at the 0.750 rate provided better weed control than PM or SM, but both rates of SF resulted in less seedling volume than PM or SM (Table 4). The preferred weed control treatment for any situation depends on many factors. We used the term "best" treatment (Table 3) to indicate the treatment that resulted in the most growth. Conversely, we used "worst" to refer to the treatment that resulted in the least growth. We did not consider benefits and costs of weed control that are not related to growth, such as application costs, the role of weeds as refugia for beneficial insects or cover for birds and rodents. No single herbicide/combination treatment was best for all the tree species in the study (Table 4). Only PM ranked above average for seedling volume for every species in the study. If using multiple herbicides is a possibility, then matching an appropriate herbicide and rate with tree species will result in the most growth. If a single herbicide will be used in a mixed-species planting, then selecting herbicide/rate combinations that all the species will tolerate will help prevent loss of species from the mix.

Azafenidin and SM are typically applied as pre-emergence herbicides. We included a post-budbreak treatment for each of these compounds to determine if they can be used to rescue weedy nursery beds or planting sites when other weed control measures were inadequate, and to determine the amount of phytotoxicity that would result from post-emergence application. Horsley et al. (1992) found that a post budbreak application of SF resulted in a significant increase in damage to black cherry and white ash relative to controls, and damage increased the earlier in the year the application was made. In this study, post-budbreak applications of AZ and SF were among the worst treatments overall for seedling volume (Table 4). In several cases, application of these herbicides post-budbreak was little better or even worse than no treatment at all (controls). Our post-budbreak application was in mid-June. It is possible that the application of these herbicides later in the summer would have resulted in less injury to the tree seedlings (Horsley et al. 1992).

Environmental factors, especially rainfall (Muir and Zutter 1999) can influence the efficacy of herbicide treatments. Rainfall at our study site in the 2000 growing season was about average, permitting good growth of the seedling trees even when some weeds were present. If soil moisture had been limiting, it is possible that herbicide treatments/combinations and rates that resulted in fewer weeds would have performed better at promoting seedling growth. This may explain why SF alone did not perform as well as we expected. The seedlings treated with SM and PM had a volume that was comparable to or better than those treated with SF, but on sites with adequate moisture, weed control might be less important than phytotoxicity in determining the growth of some species. It is also possible the rates of SF we used were too high, since the 0.562 rate (the lowest rate we tested) outperformed the 0.750 rate for seedling volume for nearly every species.

Five of 16 herbicide treatments in this study were combinations of two herbicides. It would not be easy to predict the optimal rates for herbicide combinations based on the most effective rates of the herbicides alone, in part because the amount of weed control the combination treatments provided was not simply additive. The AZ 2.0 + SF 0.75 treatment controlled weeds somewhat better than the SF 0.75 treatment alone, but it seems unlikely that this improvement in weed control can explain why the AZ 2.0 + SF 0.75 ranked significantly better than the SF 0.75 treatment overall, and better for every species individually, even for species such as eastern white pine, for which AZ 2.0 alone ranked 13th best.

These results are from a single year's growth only, but they clearly indicate that AZ is suitable for hardwood establishment, and it is in many cases preferable to PM and SM, the herbicides conventionally used for this purpose. We expect that AZ would provide excellent weed control and support good growth in a mixed planting containing white oak, yellow poplar, black cherry, black walnut, and white ash, or a subset of these species. Eastern white pine interplanted on the same site would also perform acceptably. PM might be a good herbicide for a mixed planting containing just eastern white pine and black walnut.

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