Riparian Forest Restoration: Increasing Success by Reducing Plant Competition and Herbivory

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Abstract

The reestablishment of riparian forest is often viewed as "best management practice" for restoring stream ecosystems to a quasi-natural state and preventing non-point source contaminants from entering them. We experimentally assessed seedling survivorship and growth of *Quercus palustris* (pin oak), *Q. rubra* (red oak), *Q. alba* (white oak), *Betula nigra* (river birch), and *Acer rubrum* (red maple) in response to root-stock type (bare root vs. containerized), herbivore protection (tree shelters), and weed control (herbicide, mowing, tree mats) over a 4-year period at two riparian sites near the Chester River in Maryland, U.S.A. We started with tree-stocking densities of 988/ha (400/ac) in the experimental plots and considered 50% survivorship (i.e., a density of 494/ha [200/ac] at crown closure) to be an "acceptable or minimum" target for riparian restoration. Results after four growing seasons show no significant difference in survivorship and growth between bare-root and containerized seedlings when averaged across all species and treatments. Overall survivorship and growth was significantly higher for sheltered versus unsheltered seedlings (49% and 77.6 cm vs. 12.1% and 3.6 cm, respectively) when averaged across all species and weed control treatments. Each of the five test species exhibited significantly higher 4-year growth with shelter protection when averaged across all other treatments, and all species but river birch had significantly higher survivorship in shelters during the period. Seedlings protected from weeds by herbicide exhibited significantly higher survivorship and growth than seedlings in all other weed-control treatments when averaged across all species and shelter treatments. The highest 4-year levels of survivorship/growth, when averaged across all species, was associated with seedlings protected by shelters and herbicide (88.8%/125.7cm) and by shelters and weed mats (57.5%/73.5 cm). Thus, only plots where seedlings were assisted by a combination of tree shelters and either herbicide or tree mats exhibited an "acceptable or minimum" rate of survivorship (i.e., >50%) for riparian forest restoration in the region. Moreover, the combined growth and survivorship data suggest that crown closure over most small streams in need of restoration in the region can be achieved most rapidly (i.e., 15 years or less) by protecting seedlings with tree shelters and controlling competing vegetation with herbicides.

Key words: forest buffer, weed control, plant competition, riparian, seedling, stream restoration, tree growth, tree shelter, herbivory, Quereus, survival.

Introduction

Forest was the predominant vegetation on a large proportion of North America during most of the past 10,000 years (Williams 1989). In the aftermath of the periodic deforestation and afforestation that has characterized many temperate watersheds in North America (Matlack 1997), fewer than half of the historically forested riparian areas in the Continental United States exist today, and most of that land is adversely impacted by human activities (Fredrickson & Reid 1986). Because the deforestation of riparian areas has been a major factor in the decline of water and habitat quality in stream ecosystems of North America (Sweeney 1992, 1993), the reestablishment of natural riparian forests (i.e., forest buffers) is now considered "best management practice" for restoring stream and river ecosystems to their natural or quasi-natural states (United States Environmental Protection Agency 1995; Lowrance et al. 1995, 1997). This designation reflects, at least in part, a growing recognition that "ecosystem services" provided by riparian forests, such as watershed protection, stream ecosystem enhancement, wildlife

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conservation, and carbon sequestration, can in many landscapes outweigh the economic benefits of agriculture or logging (Bonnie et al. 2000).

Although there are many compelling reasons for reforesting riparian areas, reestablishing natural forests can be a slow and difficult process, particularly in landscapes where competition with foreign invasive plants and mammalian herbivores produces high seedling mortality rates (Marquis 1977; Marquis & Brenneman 1981; Davies 1987; Opperman & Merenlender 2000). Moreover, the challenge of reestablishing the original species is further exacerbated by a reduced local seed pool and by perturbed site conditions caused by grazing, plowing, cultivation, pesticides, and fertilizers (Bormann & Likens 1979). Consequently, improving water quality and stream ecosystem function with forest buffers depends on developing afforestation practices that maximize seedling survivorship and growth and that provide natural diversity in the riparian canopy.

During the past decade several new experimental techniques have been developed to increase afforestation success in both upland and riparian areas. Most of these techniques have targeted either protecting seedlings against herbivory by the use of tree shelters and fencing or reducing competition from invasive plants with tree mats. The available data, which come primarily from upland habitats, suggest that seedling growth and/or survivorship can be significantly increased by either fencing (Opperman & Merenlender 2000) or tree shelters (Sweeney 1992, 1993; Buresti & Sestini 1994; Kjelgren et al. 1994; Lantagne 1995; West et al. 1999; Dubois et al. 2000; Weitkamp et al. 2001). The increased growth attributed to shelters has been related to reduced water stress (Peterson et al. 1994; Kjelgren et al. 1994) and accelerated stem elongation and reduced tapering due to suppression of lateral branching (Schuler & Miller 1996). Enhanced survivorship of seedlings protected by shelters seems largely due to reduced herbivory by deer (Stange & Shea 1998; Dubois et al. 2000), mice, and voles (Weitkamp et al. 2001). On the other hand, the use of tree mats to increase growth and survivorship by reducing plant competition has been largely unsuccessful because of a concomitant increase in herbivory by deer on the highly exposed plants (Stange & Shea 1998).

Here we evaluate the effects of seedling root-stock type (bare root vs. containerized), herbivore protection (plastic tree shelters), and control of competing vegetation (i.e., "weed treatment" by herbicides, mowing, and tree mats) on the survivorship and growth of seedlings planted in large experimental plots adjacent to a river and a lake in the coastal plain of eastern Maryland, U.S.A. Our goal was to determine the quickest and most successful combination of seedling stock, herbivore protection, and weed abatement to ensure full crown closure over small streams in the mid-Atlantic region.

Study Sites

The study was conducted at Chino Farms, Inc. on the Eastern Shore of Maryland, U.S.A. Treatments were applied in a split-plot design with the following variables: site location, species, root-stock type, tree shelter use, and weed treatment. Nine replicate plots were established at a riverine site (39°12′51″N; 76°00′58″W), and 13 replicate plots were established at a lakefront (39°13′49″N; 75°59′22″W) site. Plots at the riverine site were within 5 to 10 m of the Chester River, whereas lakefront plots were about 30 m from the edge of a reservoir on an unnamed tributary of the Chester River. Weed treatments, which were applied at the plot level, consisted of mowing (weed eater), tree mats (VisPore, Tredegar Corporation, Richmond, VA, U.S.A.), herbicide application (Roundup, Monsanto Co., St. Louis, MO, U.S.A.), or control (no treatment). Five tree species were planted in each plot: *Quercus palustris* (pin oak), *Q. rubra* (red oak), *Q. alba* (white oak), *Acer rubrum* (red maple), and *Betula nigra* (river birch). Half the seedlings for each species were bare-root stock and half were containerized. Tree shelters were placed over every other root-stock type and species combination. Each plot was planted in four rows of 10 seedling each, making a total of 1,000 seedlings in the 25 plots.

Because all sites were plowed and disked before planting, they were initially weed free. Plots at the riverine site consisted of Galestown loamy sand soils (type B) with clayey substratum and slopes of 0 to 5%. Soils at the lakefront site were mostly Galestow (type C). However, 5 of the 16 lakefront plots consisted of Sassafras (type C3) sandy loam with slopes of 2 to 5%. At the corners of each experimental plot, fence posts were labeled to facilitate the weed treatments and the subsequent location of seedlings. Invasive grasses and woody vegetation, including *Rosa multiflora* (multiflora rose), *Celastrus scandens* (bittersweet), and *Lonicera canadensis* (honeysuckle), were present at both sites.

Methods

Bare-root seedlings were obtained from Natural Landscapes Nursery and containerized seedlings from Octarara Wetlands Nurseries, Inc., both in Chester County, Pennsylvania. All seedlings were approximately 2 years old and were hand planted on 5 to 6 April 1997 using a dibble bar with 3 × 3-m spacing. One Right Start Fertilizer Packet (Treesentials Inc., Mendota Heights, MN, U.S.A.) was placed in each hole before planting.

Tree species were chosen for their site suitability and potential benefits. All planted species are native to the region and will provide food and habitat for stream macroinvertebrates. Specifically, river birch and red maple are adapted to wet conditions, and their broad root systems will provide stream bank stabilization. The oak species will not only benefit the stream through their leaves, fruits, and shade, but they also represent a potential cash crop. Most riparian areas occur on private lands, and landowners, especially farmers, may be unable or unwilling to reforest these areas due to financial or other constraints. Consequently, oaks were included because they could eventually provide landowners with a source of income, albeit not every year. The three oak species represent an adaptation gradient for wet conditions, with pin oak being the most tolerant and white oak the least.

Tubex (Aberaman Park, Aberaman, South Wales, U.K.) tree shelters (1.2 m tall and tan) were placed over half the seedlings at planting (every other root-stock type–species combination). Shelters were pushed into the soil approximately 3 to 4 cm and fastened with plastic ties to 1.2 m tall by 2-cm diameter plastic stakes driven into the ground approximately 0.3 m. Coarse (~2 cm mesh) plastic netting was placed over the top of the shelters to prevent birds from becoming trapped inside.

One of the four weed treatments was applied to each plot to examine the effects of weed competition on seedling survivorship and growth. Plot treatment locations were randomly determined. At the riverine site three plots received the mow treatment and two each received the tree mat, herbicide, and control treatments. At the lakefront site there were four plots for each treatment. All treatments took place in an area between 0.8 to 1.0 m^2 around the seedling base. Black VisPore tree mats were placed at planting. Mowing and herbicide treatments were applied twice each growing season for the 4 years of study. Plots were mowed on 16 June and 22 July 1997, 8 June and 4 August 1998, 3 June and 11 August 1999, and 5 June and 9 August 2000 at the riverine site and 24 June and 29 July 1997, 8 June and 5 August 1998, 3 June and 11 August 1999, and 6 June and 9 August 2000 at the lakefront site. In herbicide-treated plots, Roundup® (glyphosate) was used because the habitat was classified as non-wetland. (In wetland habitats other herbicides, such as Rodeo®, should be substituted for Roundup®.) Herbicide treatments were applied on 17 June and 23 July 1997, 8 June and 4 August 1998, 3 June and 9 August 1999, and 5 June and 14 August 2000 at the riverine site and 25 June and 29 July 1997, 8 June and 5 August 1998, 3 June and 11 August 1999, and 6 June and 17 August 2000 at the lakefront site.

Seedling height was measured at planting and at the end of each growing season, when survival rates were also measured. Here we only report results after the first and fourth growing season (i.e., for monitoring dates 30 September 1997 and 30 August 2000, respectively).

Survivorship Analysis

Survival data were analyzed with repeated measures logistic regression models (Proc GENMOD; SAS Institute Inc. 1989). The models included all main effects and two-way interactions, with survival as the dependent variable and species, root-stock type, tree shelter use, and weed treatment as independent variables. Because seedling height at planting varied within and between species, ranging from 25.6 ± 6.1 cm (mean ± SD) for white oak to 120.4 ± 16.6 cm for river birch, initial seedling height was also included as an independent variable to ensure that other parameter estimates would not be influenced by the initial height variable. The repeated structure was ignored for fourth-year survival data because of problems with model convergence as a result of highly separated data. Probabilities of seedling survival were calculated by back transformation of the least-squares mean (LSM) from the logistic models ($e^{LSM}/(1 + e^{LSM})$.

Growth Analysis

Seedling growth was estimated by subtracting the initial height (at planting) from the height at the end of the first and fourth growing seasons. Growth measures were analyzed with linear regression models (Proc MIXED; SAS Institute Inc. 1989). The models included all main effects and two-way interactions, with seedling growth as the dependent variable and species, root-stock type, tree shelter use, and weed treatment as independent variables. As with survival analyses initial seedling height was included as a covariate in the models. Results of seedling growth are presented as LSM ± SE.

Results

First Year Survivorship

Significant main effects included shelter use, species, and weed treatment (Table 1). More detailed analyses showed that (1) seedlings protected by tree shelters were roughly twice as likely to survive (averaged across species and weed treatments) than those without shelters; (2) overall survivorship (averaged across treatments) of pin oak, red oak, and white oak was about double that of river birch or red maple; and (3) seedlings (averaged across species) in plots with herbicide weed treatment had significantly higher survivorship than those in plots with all other weed treatments (Table 2, Figs. 1 and 2).

Two significant interactions were observed (Table 1): (1) The site location by shelter interaction resulted because seedlings (when averaged across all species) with tree shelters had significantly higher survivorship than those without shelters at both the riverine (75.2% vs. 26.8%) and lakefront (74.2% vs. 50.1%) sites and (2) the species by tree shelter interaction resulted because there was no difference in survivorship among oaks for sheltered seedlings, but survivorship was significantly lower for unsheltered white oak relative to unsheltered pin oak seedlings (Fig. 1).

Fourth Year Survivorship

Significant main effects after 4 years included tree shelter use, species, weed treatment, and site location (Table 1). More detailed analyses showed that (1) survivorship (averaged across species and weed treatments) was substantially lower after the fourth year relative to the first for both sheltered seedlings and unsheltered seedlings; (2) survivorship for seedlings with shelters (when averaged across all species) was significantly higher than for those without shelters; (3) the relative pattern of survivorship among species after 4 years was similar to that after 1 year; (4) overall survivorship declined between the first and fourth year for each species; and (5) the relative pattern of survivorship among seedlings in plots with different weed treatments after 4 years was similar to that after 1 year. In addition, unlike the first season when there was no significant overall site effect, seedlings at the lakefront site had higher survivorship after 4 years than those at the riverine site (32.0% [C.I.: 27.6, 36.6] vs. 22.0% [C.I.: 16.6, 28.4], respectively) (Table 2, Figs. 1 and 2).

Three significant interactions were observed for survivorship after 4 years (Table 1). First, the tree shelter by weed treatment interaction resulted because (1) the poorest survivorship occurred in mow plots for unsheltered seedlings compared with control plots for sheltered seedlings and (2) sheltered seedlings in tree mat plots had higher survivorship than those in mow or control plots, a difference not seen for unsheltered seedlings (Fig. 2). Second, the species by root-stock interaction resulted because (1) survivorship of bare-root pin oak (38.1% [C.I.: 26.2, 51.6]) and bare-root red oak (51.0% [C.I.: 38.0, 63.7]) seedlings was significantly higher than for bare-root red maple (15.5% [C.I.: 7.9, 28.0]), whereas bare-root red oak (51.0% [C.I.: 38.0, 63.7]) had significantly higher survivorship than bare-root white oak (18.9% [C.I.: 8.7, 36.2]) and (2) no significant differences in survivorship were observed among the five species for containerized seedlings. Finally, the root-stock type by weed treatment interaction resulted because (1) survivorship of both containerized and bare-root seedlings in herbicide (66.3% [C.I.: 52.5, 77.8] and 46.4% [C.I.: 33.9, 59.4], respectively) and tree mat (39.4% [C.I.: 29.5, 50.4] and 34.4% [C.I.: 25.0, 45.1], respectively) plots were significantly higher than in mow (11.7% [C.I.: 7.0, 18.9] and 16.3% [C.I.: 10.5, 24.6], respectively) or control (9.9% [C.I.: 5.4, 17.2] and 15.6% [C.I.: 9.6, 24.5], respectively] plots and (2) survivorship only differed significantly between herbicide (66.3% [C.I.: 52.5, 77.8]) and tree mat (39.4% [C.I.: 29.5, 50.4]) plots for containerized seedlings.

First Year Growth

Significant main effects after 1 year included tree shelter use, species, weed treatment, and root-stock type (Table 1). More detailed analyses showed that (1) there was a slight but significant increase in height for seedlings in tree shelters (when averaged across all species and treatments), whereas seedlings without shelters actually lost height (due to herbivory); (2) differences in growth among species were highly significant, with river birch and red maple increasing in height and red oak, pin oak, and white oak decreasing in height when averaged across treatments; (3) height change for river birch was significantly greater than all species except red maple which were only slightly smaller; (4) seedlings in herbicide and tree mat plots exhibited an increase in height compared with control or mow plots, which decreased

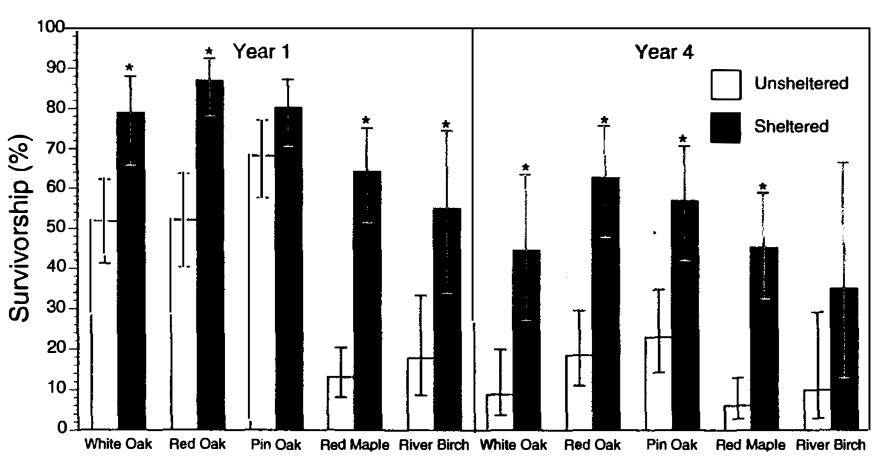

Figure 1. Effects of tree shelter presence or absence on mean seedling survivorship (% ± confidence limits) for each weed treatment when averaged across all species after the first and fourth growing seasons. Asterisks indicate significant differences between sheltered and unsheltered pairings.

Table 1. Results from regression models analyzing seedling survivorship and growth after the first and fourth growing seasons.

		Survival				*Growth*			
		First Year		*Fourth Year*		*First Year*		*Fourth Year*	
Source	df	*F*	p	*F*	p	*F*	p	*F*	p
Tree shelter	1	15.33	<0.001	107.27	<0.001	7.11	0.008	87.71	<0.001
Species	4	16.14	0.003	18.02	0.001	3.19	0.013	2.44	0.047
Weed treatment	3	13.03	0.005	92.69	<0.001	7.72	0.002	7.03	0.001
Site	1	1.90	0.168	7.21	0.007	0.54	0.472	8.03	0.006
Root stock type	1	0.90	0.343	0.02	0.877	11.11	0.001	0.29	0.588
Initial height	1	0.06	0.812	0.32	0.573	19.51	<0.001	0.66	0.417
Site × tree shelter	1	6.37	0.012	1.21	0.272	0.98	0.322	1.68	0.196
Species × tree shelter	4	12.26	0.016	4.34	0.361	1.70	0.148	4.12	0.003
Site × species	4	9.24	0.055	5.13	0.274	0.72	0.579	2.77	0.028
Site × weed treatment	3	6.90	0.075	4.65	0.199	1.70	0.204	0.78	0.519
Tree shelter × weed treatment	3	6.67	0.083	34.91	<0.001	5.76	0.001	6.49	<0.001
Species × root stock type	4	6.68	0.154	9.70	0.046	0.32	0.867	2.84	0.025
Species × weed treatment	12	16.33	0.177	13.20	0.355	1.49	0.125	0.49	0.919
Site × root stock type	1	0.62	0.430	0.08	0.777	4.09	0.044	0.17	0.681
Root stock type × tree shelter	1	0.36	0.546	0.63	0.427	1.14	0.286	0.00	0.988
Root stock type × weed treatment	3	1.53	0.677	8.86	0.031	0.94	0.420	2.60	0.053

Models include all main effects and two-way interactions with initial seedling height as a covariate.

in height; and (5) containerized seedlings (when averaged across all species) exhibited greater growth compared with bare-root seedlings, which lost height during the first year (Table 2, Figs. 3 and 4).

Two significant interactions were observed for growth after the first year (Table 1). First, the tree shelter by weed treatment interaction resulted because (1) tree shelters had a significant positive effect on seedling growth only in tree mat and herbicide plots, (2) sheltered seedlings (averaged across species) in herbicide and tree mat plots had higher growth than those in control or mow plots, and (3) there were no differences between the four weed treatment plots when seedlings were unsheltered (Fig. 4). Second, the site location by root-stock interaction resulted because containerized seedlings at the lakefront site significantly increased in height compared with bare-root seedlings (6.6 ± 2.5 vs. –7.3 ± 2.3 cm, respectively), whereas no difference was observed at the riverine site.

Fourth Year Growth

Significant main effects after 4 years included tree shelter use, species, weed treatment, and site location (Table 1). More detailed analyses showed that (1) when averaged across species and treatments, seedlings with tree shelters grew 21 times faster than unsheltered seedlings; (2) river birch and pin oak were the fastest growers, whereas white oak and red oak were the slowest; (3) the general growth pattern after 4 years among all species but pin oak was similar to the pattern after the first year (viz. growth of river birch > red maple > red oak > white oak); (4) seedlings in herbicide treated plots exhibited greater growth after 4 years than those in any other weed treatment plots when averaged across species; and (5) growth (when averaged across species) was about twice as great at the riverine site as at the lakefront site (52.0 ± 7.3 vs. 29.2 ± 3.9 cm, respectively) due primarily to the significantly higher growth of river birch at the lakefront site than at the riverine site (94.7 ± 25.8 vs. 39.1 ± 22.9 cm, respectively) (Table 2, Figs. 3 and 4).

Four significant interactions were observed for growth after 4 years (Table 1). First, the tree shelter by weed treatment interaction resulted because (1) differences in growth were significant for only the tree mat, herbicide, and control plots; (2) seedlings planted with shelters in plots treated with herbicide experienced the highest 4-year growth rates (2.1 times greater than sheltered seedlings in control plots with no weed abatement and 18 times greater than unsheltered seedlings in herbicide plots); and (3) there were no differences among weed treatments for unsheltered seedlings (Fig. 4). Second, the species × site interaction resulted because (1) growth, when averaged across species, was greater at the riverine site than the lakefront site (52.0 ± 7.3 vs. 29.2 ± 3.9 cm, respectively) and (2) although all species exhibited this pattern differences were significant only for river birch. Finally, the species by root-stock interaction resulted because the growth of bare-root seedlings of pin oak (60.1 ± 9.9 cm) after 4 years was significantly greater than those of white oak (6.3 ± 17.0 cm), but there was no significant difference in growth among the five test species for containerized seedlings.

Table 2. Comparison of seedling survivorship (mean % [confidence limits]) and growth (mean cm [± SE]) after the first and fourth growing season.

	Survivorship		*Growth*	
	First Year	*Fourth Year*	*First Year*	*Fourth Year*
Shelter				
Unsheltered	37.8A	12.1A	−5.3A	3.6A
	(31.7, 44.3)	(9.0, 16.0)	(± 2.7)	(± 7.2)
Sheltered	74.7B	49.0B	2.0B	77.6B
	(68.9, 79.7)	(42.7, 55.4)	(± 2.1)	(± 4.0)
Species				
River birch	34.0A	19.8AB	23.0C	66.9AB
	(18.7, 53.6)	(6.7, 45.9)	(± 9.9)	(± 23.2)
Red maple	34.2A	18.9A	1.8BC	38.8AB
	(26.0, 43.5)	(12.2, 28.1)	(± 4.4)	(± 10.8)
White oak	66.8B	21.9AB	−17.9A	20.6AB
	(56.9, 75.4)	(11.8, 37.2)	(± 4.3)	(± 14.0)
Red oak	72.9B	38.3B	−6.3B	26.0A
	(64.0, 80.4)	(27.8, 50.1)	(± 2.8)	(± 8.3)
Pin oak	74.7B	38.7B	−9.0AB	50.8B
	(66.2, 81.7)	(28.4, 50.1)	(± 2.8)	(± 8.2)
Weed treatment				
Control	35.3A	12.5A	−5.5A	27.5A
	(26.3, 45.4)	(8.2, 18.4)	(± 4.2)	(± 10.1)
Mow	37.7A	13.9A	−12.7A	32.3A
	(31.6, 44.2)	(9.6, 19.5)	(± 3.7)	(± 9.3)
Tree mat	58.6B	36.9B	4.1B	36.3A
	(50.7, 66.1)	(29.6, 44.7)	(± 3.5)	(± 6.1)
Herbicide	87.3C	56.6C	7.6B	66.3B
	(78.7, 92.8)	(46.7, 66.0)	(± 3.0)	(± 5.7)

Values in a given column followed by the same letter are not significantly different within the grouping variables shelter, species, and weed treatment.

Discussion

A primary goal of riparian forest restoration efforts is to establish a sufficient number of trees to create forest conditions along the stream as quickly, efficiently, and economically as possible. Managed restoration, including proactive site preparation and tree planting, as opposed to natural regeneration is desirable and/or necessary at many locations because of a high local incidence of herbivores and/or invasive plant competitors, an insufficient quantity or poor diversity of local seeds for desirable tree species, and a need to quickly restore habitat and water quality of the local stream. As a result, there is an urgent need to expand the cadre of tools available to improve both the rate of regeneration and the overall success of managed restoration projects.

In our study we stocked seedlings at an initial density of 988 trees/ha (400/ac), which Pannill et al. (2001) found to be a "desirable" level for restoring forests, based on "past policies, current spacing practices, review of other reforestation studies, and criteria for funding programs such as the Conservation Reserve Enhancement Program and the Buffer Incentives Program." They considered a density of 494 trees/ha (200/ac), which results in crown closure when trees are 4.6 m (15 ft) tall, as an "acceptable or minimum" stocking density. Furthermore, their field study of riparian restoration elsewhere in Maryland suggests that survivorship of seedlings after the fourth growing season is fairly stable. Therefore, a 50% level of survivorship at our initial stocking density after 4 years would indicate that the acceptable or minimum stocking density would likely be achieved at the normal crown closure height of the trees.

In our experiments when averaged across all study species only a combination of tree shelter use with either herbicide or tree mats produced survivorship rates greater than 50% after 4 years (88.8% and 57.5%, respectively). In addition, the highest 4-year growth rate, which would produce the shortest theoretical time to achieve crown closure at an acceptable stocking density, resulted when tree shelter use was combined with herbicide treatment (125.7 cm growth in 4 years; about 15 years to crown closure). Tree shelter use with tree mats resulted in slower growth and thus longer time to crown closure (73.5-cm growth in 4 years; about 25 years to crown closure). Our results suggest that using

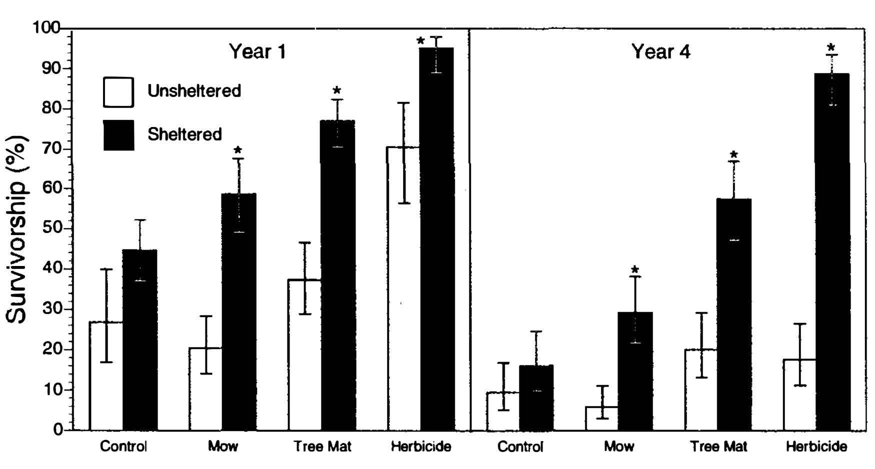

Figure 2. Effects of tree shelter presence or absence on mean seedling survivorship (% ± confidence limits) of each species when averaged across all weed treatments after the first and fourth growing seasons. Asterisks indicate significant differences between sheltered and unsheltered pairings.

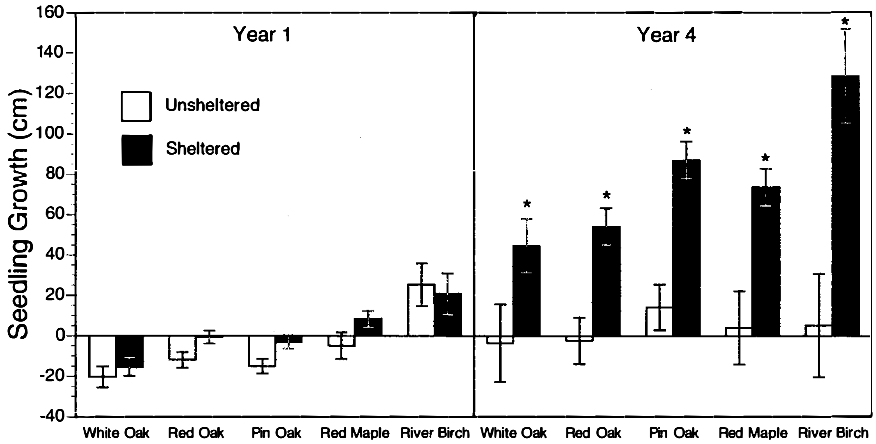

Figure 3. Effects of tree shelter presence or absence on mean change in overall seedling height (cm ± SE) for each weed treatment from the time of planting when averaged across all species after the first and fourth growing seasons. Asterisks indicate significant differences between sheltered and unsheltered pairings.

tree shelters while controlling competing vegetation through mowing would not result in adequate survivorship (29.4%). Furthermore, even if survivorship met the acceptable minimum level, growth after 4 years (52.6 cm) suggests that crown closure would require 35 years. As noted above, these results have been averaged across five study species whose 4-year survivorship levels were similar but whose growth rates differed significantly, especially for sheltered seedlings (Figs. 1 and 4). Thus, riparian areas reforested with monocultures of certain individual species (e.g., river birch) might achieve crown closure quicker than discussed above. However, afforestation of riparian areas as a monoculture is not acceptable for a variety of ecological reasons (Sweeney 1993).

The positive effect of tree shelters on seedling survivorship and growth observed during this study is consistent with previous studies and is likely related to one or more of the following factors: protection from herbicide drift during weed treatment, defense against mammal herbivory, reduced mechanical damage, lateral branch suppression, reduced trunk tapering, and lower water stress (Potter 1991; Sweeney 1992, 1993; Buresti & Sestini 1994; Dunn et al. 1994; Kjelgren et al. 1994; Peterson et al. 1994; Lantagne 1995; Ward & Stephens 1995; Schuler & Miller 1996; Ward 1996; Stange & Shea 1998; West et al. 1999; Dubois et al. 2000; Ward et al. 2000; Weitkamp et al. 2001). Earlier studies found that once seedling height reaches or slightly exceeds the shelter top, vertical growth slows to "normal" and stem diameter increases (Tuley 1983; Kelty & Kittredge 1986). However, our results suggest that shelters continue to enhance growth and survivorship of seedlings even after they have outgrown the shelter. For example, sheltered river birch seedlings exhibited the greatest height increase over four growing seasons (mean increase, 128.6 ± 23.3 cm) , even though the average height at planting (mean initial height, 120.4 ± 16.6 cm) was virtually equal to the shelter height (120 cm). In this case, shelters prevented the predominant local herbivore, white tail deer (*Odocoileus virginianus*), from grazing seedlings below 1.2 m, thus enabling seedlings with established root structure to eventually "outgrow" them.

Many seedlings initially lost height but then gained substantially over the 4 years of the study, especially when they were protected by shelters or relieved of plant competition through weed control. Initial height loss was most likely due to browsing by herbivores or

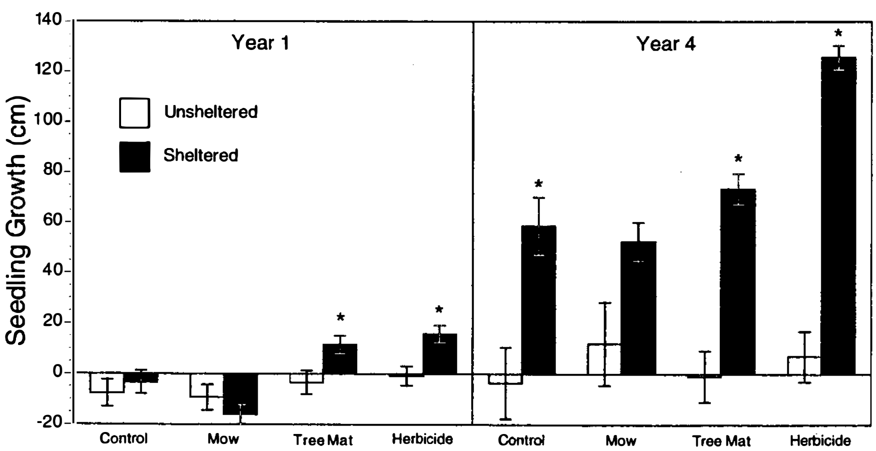

Figure 4. Effects of tree shelter presence or absence on mean change in overall seedling height (cm ± SE) for each species from the time of planting when averaged across all weed treatments after the first and fourth growing seasons. Asterisks indicate significant differences between sheltered and unsheltered pairings.

damage to the seedlings' stems or roots associated with handling before and during planting. Because all seedlings were handled in the same manner, the probability of sustaining damage at planting was likely equal and random for all seedlings. Herbivory, on the other hand, was less likely to have been random or equally probable because white tail deer have preferences for certain species of plants.

Seedlings without shelters were completely exposed to browsing during the study and often demonstrated high resiliency to deer browse. In a few cases, seedlings initially scored as dead after the first growing season were actually still alive, but they were overlooked because they had been browsed to such a low level. Although seedlings with shelters were protected initially from herbivory, we did observe evidence of deer browse once they emerged from the tops of their shelters. Although these factors qualify our ability to confidently assign differences in observed growth to individual treatments, most treatment response patterns were clear, particularly after four growing seasons.

The relative influence of root-stock type on seedling growth and survivorship was minimal. Differences in survivorship among bare-root and containerized seedlings were not significant during the 4-year study. Moreover, the significantly greater growth of containerized seedlings (relative to bare-root seedlings when averaged across treatments and species) after the first year was quite small in magnitude (2.9 vs. –6.2 cm, respectively), and the difference was reversed—and insignificant—after 4 years (38.5 vs. 42.7 cm, respectively). We are not aware of any other studies directly comparing growth and survivorship of bare-root and containerized seedlings. In our study, the only experimental condition where containerized seedlings exhibited significantly better growth than bare-root seedlings was when plant competition was controlled effectively by herbicide use. Regardless, containerized seedlings may be worth the slightly higher investment in planting time and price because they seem less vulnerable than bare-root seedlings to death from root desiccation and poor handling before planting (Sweeney, personal observation). More importantly, containerized seedlings enable afforestation projects in temperate regions to take place from early spring to late fall, whereas bare-root seedlings are often lifted from nurseries and available for planting only during a narrow period in the spring.

Although differences in both survivorship and growth between the riverine and lakefront study sites were not significant after the first year, they were significant after 4 years. These differences were more likely related to local differences in herbivore intensity and/or weed competition because differences in soil type, topographic relief, solar input, rainfall, and agrocropping history were minimal at best between the two sites (although levels of herbivory or weeds were not quantified). Regardless, the site effect appeared to be cumulative (i.e., the same patterns of differences [albeit not significant] observed after the first year had become significant by the fourth year).

These data have important implications for stream restoration projects in eastern North America (and perhaps elsewhere). In general, streams in need of riparian restoration are usually small (first through third order) and therefore represent about 99% of the total number of streams on most landscapes (Leopold et al. 1964). Moreover, many of these streams, especially those located in historically forested landscapes, are likely to have unnaturally narrow stream channels because of the predominance of herbaceous grasses, rather than trees, along their banks (Zimmerman et al. 1967; Sweeney 1992, 1993; Davies-Colley 1997; Trimble 1997). For example, Sweeney (1992, 1993) showed that meadow reaches of first-, second-, and third-order streams in southeastern Pennsylvania are significantly narrower (averaging only 1.2, 1.4, and 2.8 m in width, respectively) than contiguous reaches flowing through forest. This means that most small streams in need of restoration are in a narrowed state, and seedlings planted along their banks will generally be 2.8 m or less apart. That spacing compares favorably with the 4.5-m spacing associated with the "acceptable or minimum" planting stock density of 494 seedlings per ha recommended by foresters. In other words, achieving the acceptable or minimum target would ensure full canopy cover at crown closure over most streams in need of restoration. Our data suggest that in the mid-Atlantic region this could be achieved in 15 years or less by initially planting the streamside areas at a density of 988 trees per ha and managing for an average of 4.6m of growth and ~50% survivorship during the period by using herbicides and tree shelters.

Acknowledgments

Supported by The Stroud Foundation, Pennswood No. 2 Research Endowment, Stroud Endowment for Environmental Research, and Chino Farms, Inc. We thank Dr. Harry Sears for providing the land, personnel, equipment, and supplies needed to establish and maintain the field experiments. We also thank Evan Miles, Salamon Romero, Jabier Tinoco, Henry Davis, Willard Kemp, Bob Spray, Jack Thomas, Ryan Abey, Tim Elbourn, Nick Huffer, John Kling, Evan Miles Jr., and Kevin Sweeney for invaluable assistance in the field during the project. The Potomac Watershed Partnership and Ducks Unlimited, Inc. supported analysis and manuscript development. Llowellyn Armstrong, Ducks Unlimited Canada, provided statistical assistance.

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