Improving the Composition of Beech-Dominated Northern Hardwood Understories in Northern Maine

Andrew S. Nelson and Robert G. Wagner

ABSTRACT

The natural regeneration that develops following the shelterwood and selection harvesting of northern hardwood stands across the Northeast is often plagued by an overabundance of American beech infected with beech bark disease. This regenerating beech typically dominates and interferes with the regeneration of more desired hardwood species (sugar maple, yellow birch, and red maple), lowering the productivity and value of future stands. We tested factorial combinations of glyphosate herbicide (Accord Concentrate) rate and surfactant (Entrée 5735) concentration to identify an optimal treatment that would maximize beech control while minimizing sugar maple injury. Third-year posttreatment results revealed that glyphosate rate was a more important factor than surfactant concentration in reducing beech abundance and preserving sugar maple. The optimal treatment (0.56–1.12 kg/ha of glyphosate plus 0.25–0.5% surfactant) selectively removed 60–80% of beech stems, whereas sugar maple control was less than 20%. The five dominant hardwood species differed substantially in their susceptibility to the treatments in the following decreasing order: beech > striped maple > yellow birch > red maple > sugar maple. Similar results produced using a backpack mistblower suggested transferability of treatment effects to operational applications using a tractor-mounted mistblower. Our findings indicate that this relatively low-cost and effective treatment can substantially improve the understory composition of northern hardwood stands.

Keywords: American beech, sugar maple, glyphosate herbicide, hydraulic nozzle, mistblower

Many thousands of acres of northern hardwood stands in Maine and other Northeastern states are plagued by an overabundance of naturally regenerated American beech (*Fagus grandifolia* Ehrh.) following natural overstory disturbance and harvesting. A majority of the beech regeneration is of root sucker origin (Farrar and Ostrofsky 2006) from trees infected with beech bark disease (*Nectria coccinea* var. faginata Lohman, Watson, and Ayers and *Nectria galligena* Bres.). The overabundant beech regeneration typically dominates and interferes with the regeneration of more desirable species, such as sugar maple (*Acer saccharum* Marsh.), yellow birch (*Betula alleghaniensis* Britt.), and red maple (*Acer rubrum* L.). These conditions are widespread following the shelterwood and selection harvest of many northern hardwood stands. Thus, an effective and low-cost treatment is needed that can selectively reduce beech abundance while preserving maple and birch regeneration. A postharvest beech control method is particularly important for forests in Maine, where northern hardwood stands account for 44% of the forestland (McWilliams et al. 2005). Without an effective treatment, a significant proportion of these stands may need to be removed from production, thus negatively affecting future wood supplies.

The coexistence of the five dominant hardwood species in Maine northern hardwood stands, (beech, sugar maple, red maple, striped maple [*Acer pensylvanicum* L.], and yellow birch), suggest differences in regeneration and survival due to heterogeneous understory conditions (Forcier 1975). Beech and sugar maple are shade-tolerant (Godman et al. 1990, Tubbs and Houston 1990), but beech regeneration commonly occurs as root suckers (Beaudet and Messier 2008), whereas sugar maple regenerates primarily from seed. In undisturbed understories, the height growth of beech saplings tends to be greater than sugar maple (Poulson and Platt 1996), which often results in stratified understories (vertical dominance of beech over sugar maple) dominated by beech. Red maple and striped maple are also shade-tolerant (Gabriel and Walters 1990, Walters and Yawney 1990). Yellow birch is the only coexisting species considered mid-tolerant of shade and typically regenerates following larger gap disturbances (Erdmann 1990). Following overstory disturbances, beech saplings may continue to overtop other hardwood species (Nelson 2010), requiring silvicultural intervention to promote the development of more desirable understories (sugar maple, yellow birch, and red maple).

American beech dominance has become a major problem following landscape-level infection of Northeastern forests with beech bark disease, and silvicultural methods have been developed to promote desirable species (Kelty and Nyland 1981, Horsley 1994, Leak 1999, Nolet et al. 2008) and reduce disease severity (Ostrofsky and McCormack 1986, Ostrofsky and Houston 1988, Houston 2001, Ostrofsky 2004). Uneven-aged selection harvesting often increases

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This article uses metric units; the applicable conversion factors are: kilometers (km): 1 km = 0.6 mi; hectares (ha): 1 ha = 2.47 ac; kilograms (kg): 1 kg = 2.2 lb.

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regeneration and pole-sized beech densities (Jones et al. 1989, Bohn and Nyland 2003, Nolet et al. 2008), but with larger gap/patch openings, beech densities can be reduced while allowing shade-tolerant sugar maple to grow beneath shade-intolerant species that establish after harvest (Leak 1999). Subsequent timber stand improvement can then be used to shift species compositions to sugar maple and yellow birch (Leak and Smith 1997).

Shelterwood harvests can favor beech-dominated understories when residual beech regeneration remains, root suckering increases, and harvests occur on mid-quality sites, because beech is typically more competitive than sugar maple on sites low in calcium and nitrogen (Boerner and Koslowsky 1989, Long et al. 1997). Preharvest site preparation (Kelty and Nyland 1981) and postharvest herbicide applications (Ostrofsky and McCormack 1986) can be effective strategies for promoting the establishment of sugar maple and yellow birch when combined with even-aged management. Advances in forest herbicide technology, including precise application rates, make it possible to test the performance of treatments designed to release desirable hardwood species from understory beech cover, similar to northern conifer release treatments (*sensu* Newton et al. 1992, Wagner and Robinson 2006).

The high susceptibility of beech and low susceptibility of sugar maple to moderate glyphosate rates (Ostrofsky and McCormack 1986, Pitt et al. 1992, 1993) makes this herbicide an ideal candidate for testing the selective removal of beech and preservation of sugar maple following shelterwood harvests. We hypothesized that by systematically adjusting the glyphosate rate and surfactant concentration that a treatment combination could be identified that produced maximum beech control and minimal injury to sugar maple and other desirable hardwood species. The objectives of this study were to (1) document the relative susceptibility of five major hardwood species in Maine northern hardwood stands (beech, sugar maple, red maple, striped maple, and yellow birch) to various combinations of glyphosate herbicide (Accord Concentrate) and surfactant (EnTreé 5735); (2) identify an optimal combination of glyphosate rate and surfactant concentration that produced the highest level of beech control and lowest level of sugar maple injury; and (3) determine whether the results produced using hydraulic nozzle applications (which were required to precisely control herbicide and surfactant application rates) were transferable to mistblower applications that would typically be used for industrial herbicide applications.

Methods

Study Sites

Three hardwood stands with beech-dominated understories were selected in north-central Maine. The sites are located within ~20 miles of Millinocket, ME, and managed by three different industrial landowners. Site T2R7 is located at 45°49′N, 68°33′W, site T2R8 at 45°47′N, 68°42′W, and site TAR7 at 45°35′N, 68°36′W. Mean monthly temperatures at Millinocket are −10.0°C (14.0°F) in January and 19.8°C (67.6°F) in July, with an annual mean of 5.3°C (41.5°F) (Baron et al. 1980). Precipitation is evenly distributed throughout the year, with an average of 1,058 mm (41.6 in) per year (Baron et al. 1980). Soils at all sites are of glacial till origin, Typic Haplorthods stony sandy-silty loams, with slopes between 0 and 15% (USDA Natural Resources Conservation Service 2007).

Initial shelterwood harvests were performed at all three sites between 2002 and 2004 with the objective of removing mid-stories and enough overstory basal area to stimulate natural regeneration. Preharvest basal areas among the stands ranged from 30 to 34 m^2/ha acid equivalent (a.e.) (130–148 ft^2/ac), and residual basal areas following the harvest were between 9 and 20 m^2/ha (39–89 ft^2/ac). No data were available for preharvest understory conditions, but when pretreatment inventories were conducted in 2006, all three stands were dominated by tens of thousands of stems per hectare of beech, sugar maple, yellow birch, red maple, and striped maple regeneration (Table 1).

Table 1. Pretreatment regeneration density (stems/ha) of the five dominant hardwood species for the 13 treatments. Treatments are represented by their herbicide rate (0.56, 1.12, and 1.56 kg/ha a.e.) and surfactant concentration (0%, 0.25%, 0.5%, and 1%). Analysis of variance was used to test for differences among the treatments for each species, but there were no significant values at $\alpha \leq 0.05$. Values in parentheses represent 1 standard error.

	Density				
Treatment	American Beech	Striped maple	Yellow birch	Red maple	Sugar maple
	. . . . (Thousand stems/ha).				
Untreated control	54 (18)	18 (6)	14 (7)	23 (6)	27 (12)
0.56 kg/ha, 0%	38 (19)	12 (4)	38 (33)	13 (6)	27 (19)
0.56 kg/ha, 0.25%	47 (16)	15 (7)	31 (28)	8 (5)	33 (7)
0.56 kg/ha, 0.5%	25 (12)	22 (12)	20 (15)	10 (6)	44 (9)
0.56 kg/ha, 1%	45 (18)	17 (4)	12 (11)	13 (6)	56 (17)
1.12 kg/ha, 0%	49 (34)	9 (2)	26 (17)	19 (10)	37 (30)
1.12 kg/ha, 0.25%	42 (20)	19 (4)	34 (27)	15 (3)	21 (5)
1.12 kg/ha, 0.5%	45 (14)	21 (10)	7 (3)	15 (6)	30 (9)
1.12 kg/ha, 1%	30 (10)	6 (3)	22 (10)	25 (14)	54 (45)
1.68 kg/ha, 0%	46 (17)	15 (3)	11 (6)	9 (6)	33 (22)
1.68 kg/ha, 0.25%	35 (20)	13 (6)	32 (24)	23 (15)	26 (14)
1.68 kg/ha, 0.5%	40 (23)	9 (4)	28 (9)	6 (3)	53 (39)
1.68 kg/ha, 1%	38 (27)	11 (6)	16 (7)	9 (5)	39 (46)

Herbicide Treatments

A 3 × 4 factorial combination of glyphosate herbicide (Accord Concentrate) and surfactant (Entrée 5735) was tested that included glyphosate rates of 0.56, 1.12, and 1.68 kg/ha (0.5, 1, and 1.5 lb/ac), acid equivalent (a.e.), and surfactant concentrations of 0.0, 0.25, 0.5, and 1% (v/v) applied in aqueous solution at 93.5 L/ha (10 gal/ac). Treatments were applied using two identical CO_2-pressurized backpack sprayers equipped with a KLC-9 Floodjet nozzle attached to the end of an 11-ft-long boom (R&D Sprayers, Inc., model 4F). All herbicide and surfactant mixtures were prepared in 2-L bottles in a laboratory before application. Both sprayers were calibrated prior to application, and walking time across each plot during spraying was closely monitored using a stopwatch to ensure precise application. The effective swath width of each sprayer was equal to the width of the treatment plot, 7.6 m (25 ft), so only one swath was needed to treat each plot. Each sprayer was calibrated to deliver 46.8 L/ha (5 gal/ac), or half of the target delivery rate, so that each plot could be sprayed in two passes in opposite directions to ensure good coverage of all plants in the treatment plot. The sprayers were rinsed with water between treatment applications. The volume of unused spray mixture remaining after treating each plot was measured, and the precise amounts of herbicide and surfactant actually applied to each treatment plot were calculated. All treatments were applied to within 2.2% of their target volume, with all but five of the 72 plots being applied within 10% of the target rate. The range of applied amounts was between −16.6% and + 6.2%, with variance of 2.5% among all 72 plots. All three sites were treated on Aug. 17, 2006. The average temperature during application was 24°C, the average relative humidity was 44%, and the average wind speed was 2.6 km/hour. No rain occurred for at least a week after application. Late summer is the optimum time to control woody vegetation with glyphosate in the Northeast (Horsley and Bjorkbom 1983) because of high phloem transport rates to root systems in preparation for the dormant season.

To test whether the results using the CO_2-pressurized backpack sprayer with a hydraulic nozzle would be transferable to a tractor-mounted mistblower (the method commonly used operationally for treatment of forest understories), we selected three of the factorial treatments (0.56 kg, 0.25%; 1.12 kg, 0.5%; and 1.68 kg, 1%) and applied them using a Solo motorized backpack mistblower. The mistblower treatments were applied to all sites on Aug. 22, 2006, with clear weather. As with the CO_2 sprayer, the volume of unused spray mixture remaining was measured, and the precise amount of herbicide and surfactant actually applied to each mistblower plot was calculated. Because the delivery rate of the mistblower could not be easily controlled, it applied about 3-fold as much herbicide mixture on average than the CO_2 sprayer. Thus, the actual glyphosate rates applied with the mistblower were 1.68, 3.36, and 5.04 kg/ha for the three treatments. Surfactant concentrations remained the same (0.25%, 0.5% and 1%).

Experimental Design

Sixteen treatment plots were located across each of the three sites (48 plots total) that were dominated by five hardwood species (beech, striped maple, yellow birch, red maple, and sugar maple) (Table 1). Each treatment plot consisted of two half-plots that were 18 m (59 ft) × 7.6 m (25 ft) in size and located next to one another. The treatment plots were divided in half so that harvest trails could be avoided to ensure uniform vegetation conditions. The total treated area for each treatment plot was 36 m (118 ft) × 7.6 m (25 ft), or 0.027 ha (0.068 ac).

The twelve CO_2-sprayer treatments and untreated check plot (13 treatments) were randomly assigned at each site. The remaining three backpack mistblower treatments were randomly assigned to three plots that were physically separated from the CO_2-sprayer treatment plots to avoid spray drift to the other plots.

Vegetation Sampling

Within each treatment plot, 10 circular sample plots 1.2 m (4 ft) in radius were established tangential to a center line on the long axis of each treatment plot. Five of the plots were located in each of the two half-plots, with a 5-m (16.4-ft) buffer at each end. Each sample plot was spaced 2 m (6.6 ft) apart within the half-plot. Because the edge of the sample plots was tangential to the long axis of the half-plot, the vegetation in the sample plots was not disturbed by the spray applicator walking down the centerline of the half-plot.

All regenerating hardwood stems ≤2 m in height were tallied by species. Pretreatment measurements were made in mid-July 2006, and three subsequent posttreatment measurements were made in July 2007, 2008, and 2009. The complete experiment included 16 treatment plots with 160 vegetation sample plots on three sites (480 vegetation sample plots total).

Analysis

The purpose of this study was to compare the relative efficacy among herbicide treatments. One challenge in quantifying the efficacy of herbicide treatments is using an appropriate measure of vegetation change relative to the untreated (or control) condition. A simple difference in plant cover or density relative to pretreatment condition is not an appropriate metric because the future dynamics of vegetation development that the treatment interrupted needs to be included in the assessment over time. To overcome this limitation, various methods have been developed to standardize measures of vegetation control for forest herbicide research (Zedaker and Miller 1991). A regression-adjusted approach that bases percentage of control on the ratio of the cover or density in treated plots to the cover or density in untreated plots has been developed and tested (Knowe et al. 1990, Zedaker and Miller 1991). This approach provides a better measure of herbicide treatment efficacy over time and has been used in other forest herbicide studies (Shiver et al. 1991, Wagner and Rogozynski 1994, Harrington and Miller 2005).

Although we measured both percentage of cover and stem density changes in this study, we used changes in hardwood stem density as the primary variable of treatment efficacy because we were interested in treatments that increased the regenerating stem density of desired hardwood species (sugar maple, yellow birch, and red maple) and reduced the stem density of beech. Therefore, we used a linear regression-adjusted approach to estimate the number of stems that treated plots would have had in the absence of treatment as described by Knowe et al. (1990) and Zedaker and Miller (1991)

$$D_{\text{projected}} = \beta_0 + \beta_1 \times (D_{\text{pre}}),$$

where $D_{\text{projected}}$ is projected stem density of the treated plot in the absence of herbicide application, D_{pre} is pretreatment stem density of the treated plot, β_0 is intercept of the regression line of the densities in the untreated plot, and β_1 is the slope. Percentage of control was then calculated as

$$\text{Percent control} = \frac{(D_{\text{projected}} - D_{\text{post}})}{D_{\text{projected}}} \times 100\%,$$

where D_{post} is the 3rd-year posttreatment stem density in the treated plots. This regression-adjusted approach may be biased if initial stem densities are different (Zedaker and Miller 1991). However, we found no difference in initial stems densities among treated and untreated plots for the five tree species examined (Table 1).

A randomized complete block design, mixed-effects analysis of variance (ANOVA) with site as a random factor was used to test for differences in percentage of control for glyphosate rate, surfactant concentration, and their interaction for all five hardwood species. All analyses were evaluated at the $\alpha = 0.10$ level. If factors were significant in the ANOVA, Tukey's honestly significant difference pairwise comparisons were used to investigate differences among the treatment rates at the $\alpha = 0.10$ level. Percentage of control was arcsine-squareroot transformed for all species to improve residual variance, as recommended by Gomez and Gomez (1984). All statistical analyses were performed in R (R Development Core Team 2010).

Mixed-effects ANOVA was also used to test for differences in control between the hydraulic nozzle and mistblower application techniques. The model factors were site as a random factor and application technique (hydraulic versus mistblower) as a fixed factor. Treatment rate was not included in the model because the concentrations of the mistblower application were triple those of the hydraulic sprayer and therefore could not be assumed to be the same for each treatment level.

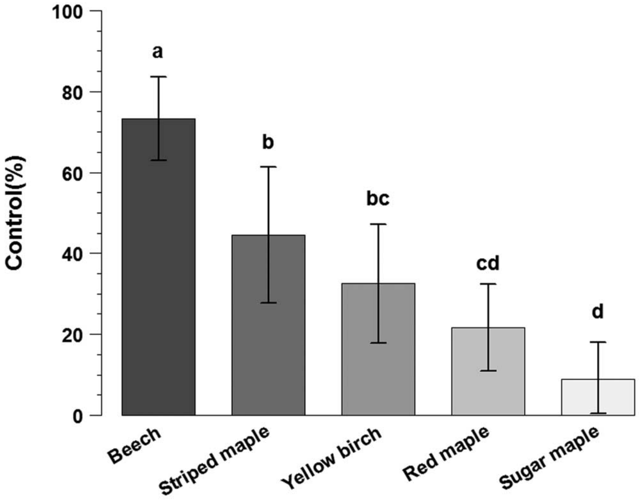

Figure 1. Third-year posttreatment control of five dominant hardwood species from all glyphosate treatments combined. Same letters above bars (a, b, c) indicate species that were not different at $\alpha = 0.10$. Error bars represent 1 SD above and below the mean.

Table 2. *P* values from mixed-effects analysis of variance on 3rd-year posttreatment control by experimental factor for each of the five dominant hardwood species. Mixed-effects models were used to allow site to be a random factor. The random factor of site is a measure of variance among site means and all possible sites that could have been used for the investigation. The *P* values of the fixed factors were evaluated at $\alpha = 0.10$. df, degrees of freedom.

	df	American beech	Striped maple	Yellow birch	Red maple	Sugar maple
Random effect						
Site		0.13	0.18	0.18	0.13	0.18
Fixed effects						
Glyphosate	2	0.02^{a}	0.25	0.83	0.06^{a}	0.06^{a}
Surfactant	3	0.95	0.86	0.68	0.53	0.04^{a}
Glyphosate × surfactant	6	0.91	0.59	0.96	0.32	0.62
Error	22					
Total	35					

[a] Significant factor.

Results

Glyphosate susceptibility was determined by averaging percentage of control among all treatments for each of the five species. American beech was most susceptible (73% control), followed by striped maple (45%), yellow birch (32%), red maple (22%), and sugar maple (9%) (Figure 1). Beech control was greater than for the other four species ($P < 0.10$), while striped maple was more susceptible than red maple, and sugar maple was less susceptible than striped maple and yellow birch ($P < 0.10$).

The interaction between glyphosate rate and surfactant concentration was not significant for any of the species ($P \geq 0.32$) (Table 2). Glyphosate rate increased control of beech ($P = 0.02$), sugar maple ($P = 0.06$), and red maple ($P = 0.06$), while the control of yellow birch or striped maple did not differ among rates ($P > 0.25$). The maximum control levels of beech, red maple, and sugar maple were 80%, 31%, and 12%, respectively (Table 3). Sugar maple was the only species that was influenced by surfactant concentration ($P = 0.04$), with maximum average control of 13% with 0.5% surfactant.

Table 3. Third-year posttreatment control (percentage) of the five dominant hardwood species by glyphosate rate and surfactant concentration. Mixed-effects models with site as a random variable were used for the analysis of variance.

	Control				
	American beech	Striped maple	Yellow birch	Red maple	Sugar maple
	(%)				
Glyphosate rate					
0.56 kg/ha (0.5 lb/ac)	64^{a}	32^{a}	37^{a}	13^{a}	5^{a}
1.12 kg/ha (1.0 lb/ac)	80^{b}	36^{a}	49^{a}	21^{ab}	9^{b}
1.68 kg/ha (1.5 lb/ac)	76^{ab}	29^{a}	48^{a}	31^{b}	12^{b}
Surfactant (% v/v)					
0.0	70^{a}	32^{a}	47^{a}	18^{a}	4^{a}
0.25	75^{a}	34^{a}	42^{a}	21^{a}	7^{a,b}
0.5	76^{a}	35^{a}	46^{a}	17^{a}	13^{b}
1.0	72^{a}	29^{a}	44^{a}	30^{a}	11^{b}

[a,b,c] For each factor, values within columns with the same letters were not different at $\alpha = 0.10$.

Table 4. Third-year posttreatment control (%) of the five dominant hardwood species for each of the 12 treatments. None of the treatment combinations differed from one another ($P > 0.10$) because the interaction was not significant in the mixed-effects analysis of variance model with site as a random variable.

		Control				
Glyphosate (kg/ha)	Surfactant (% v/v)	American beech	Striped maple	Yellow birch	Red maple	Sugar maple
		(%)				
0.56	0.0	58	35	31	9	5
0.56	0.25	61	26	34	4	2
0.56	0.5	73	42	35	21	8
0.56	1.0	65	27	49	20	3
1.12	0.0	74	35	45	16	3
1.12	0.25	80	42	49	30	7
1.12	0.5	83	34	60	16	14
1.12	1.0	81	32	42	21	12
1.68	0.0	78	27	65	28	3
1.68	0.25	83	33	42	29	12
1.68	0.5	73	29	42	15	17
1.68	1.0	71	29	40	41	19

Although interactions were not statistically significant, meaningful differences were apparent among treatment combinations. The lowest glyphosate rate (0.56 kg/ha) controlled beech stems by 58% without surfactant, but control increased to 73% with 0.5% surfactant (Table 4). The greatest beech control occurred with 1.12 kg/ha + 0.5% and 1.68 kg/ha + 0.25% rates, averaging 83%. In contrast to the consistent high rates of beech control, sugar maple control did not exceed 19% for any treatment (Figure 2). Control of the other three species was intermediate between beech and sugar maple (Table 4). Striped maple control did not increase ($P > 0.10$) with the addition of surfactant, except at the 1.68 kg/ha rate, whereas yellow birch control did not exceed 42%. Red maple control ranged between 4% at the 0.56 kg/ha + 0.25% rate and 30% at the 1.12 kg/ha + 0.25% rate, but control was greatest at the highest rate tested, with 51% control.

Changes in regeneration density over time (Figure 3) were consistent with the 3rd-year control results. The density of all species, except sugar maple and red maple, were initially reduced. Three years following herbicide application, site T2R7 became dominated by sugar and red maple; T2R8 by sugar maple and moderate densities of residual beech; and TAR7 by sugar maple, red maple, and yellow birch. Striped maple densities were initially reduced and remained low following the treatments at all three sites. Beech remained dominant in the untreated control plots at all three of the sites.

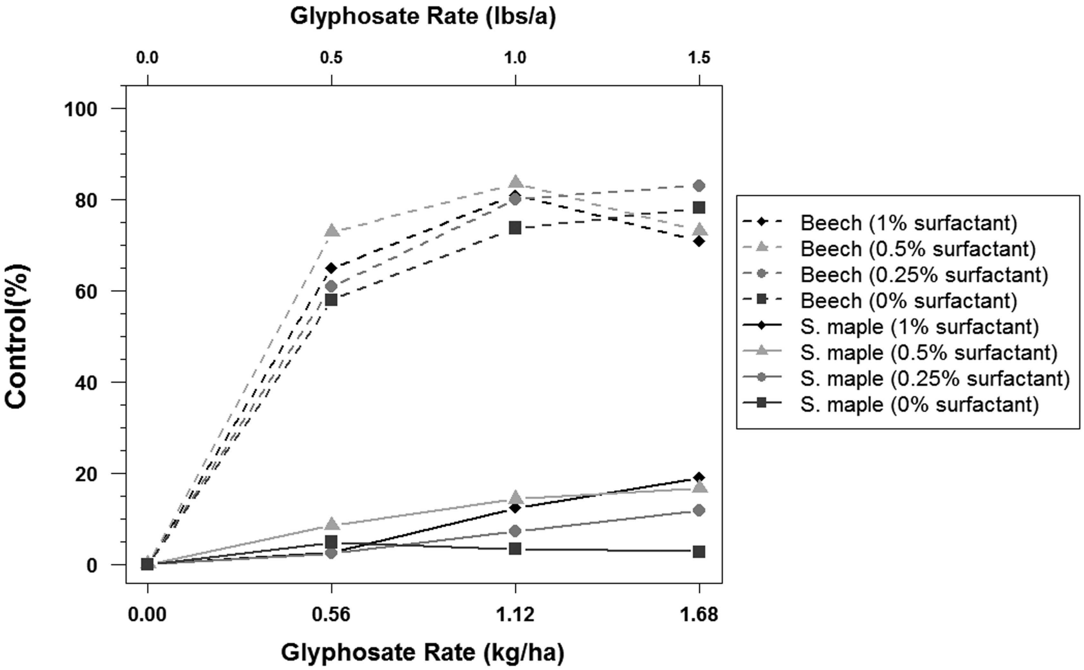

Figure 2. Third-year posttreatment control of beech and sugar maple for all glyphosate rates (lb/ac) and surfactant concentrations tested. Beech is indicated by dashed lines and sugar maple (S. maple) by solid lines.

No differences ($P > 0.10$) were found between the mistblower and hydraulic nozzle application methods for any species (Table 5). The variance among sites was greatest for yellow birch (0.16) and sugar maple (0.13), whereas the variance for beech was low (0.01), suggesting that beech control was high at all sites regardless of application method.

Discussion

The greater control of beech than sugar maple for all herbicide rates tested (Figures 1 and 2) indicated that beech was much more sensitive to glyphosate than sugar maple was. The mean reduction of beech density was from 40,000 to 8,000 stems/ha, whereas sugar maple densities were reduced by only 2,000 stems/ha. When glyphosate rate increased from 0.56 to 1.12 kg/ha, control of beech increased by 16%, whereas sugar maple control was increased by only 4%. Beyond the 1.12 kg/ha rate, sugar maple control continued to increase without an increase in beech control, suggesting that this was the optimal rate tested in our study. Horsley and Bjorkbom (1983) found that an August application of the same glyphosate rate controlled about 99% of beech less than 1.5 m tall. In addition, beech sensitivity to glyphosate has been demonstrated with direct injection and cut-stump treatments (Kochenderfer et al. 2001, 2004, 2006), with the additional benefit of reducing the density of beech root suckers. The low sensitivity of sugar maple to glyphosate also was shown by Pitt et al. (1993), who found that $>$0.5 kg/ha a.e. initially resulted in a 90% crown reduction of sugar maple, but the species dominated total crown area 2 years after treatment.

We found that 1.12 kg/ha glyphosate was the most effective rate; however, the other two rates also were successful at reducing beech (59 and 64% for 0.56 and 1.68 kg/ha, respectively) and preserving sugar maple abundance in postshelterwood harvested stands (Figure 2). Kelty and Nyland (1981) documented the regeneration dynamics of northern hardwoods stands treated with 2,4,5-T as a preharvest, site-preparation treatment in New York. As in our study, they found that sugar maple became the dominant species after treatment. Ray et al. (1999) investigated the 26-year posttreatment development of the New York stands and confirmed that the understory treatment increased the long-term stocking of desirable species.

Sugar maple was the only species in our study to show increased control with additional surfactant concentration. Although no other studies have documented greater sugar maple susceptibility to glyphosate with increasing surfactant concentrations, Horsley et al. (1992) found that Oust (sulfometuron methyl) treatments without surfactant controlled red maple germinants by 37%, whereas treatments with surfactant increased control to 49%.

Percentage of control of the other three species was intermediate between high beech control and low sugar maple control. Striped maple was the second most susceptible species to the treatments with 43% control (Figure 1), corresponding to a mean reduction from 14,000 to 5,000 stems/ha. Striped maple is commonly considered an undesirable species in regenerating northern hardwood stands (see review by Nyland et al. 2006). Glyphosate applied at a rate of 1.12 kg/ha controlled striped maple by 49% in this study, which is consistent with Wendel and Kochenderfer (1982), who achieved 51% control using the same rate. Yellow birch was shown to be susceptible to the glyphosate rates tested in this study, averaging 32% control with 0.56 kg/ha and 36% control with 1.12 kg/ha glyphosate. However, Figure 3 indicates that yellow birch densities have increased 3 years following treatment, most likely because the species typically disperses large quantities of seeds (Houle 1994) and establishes well under partial canopy openings (Erdman 1990), such as that created by shelterwood harvests.

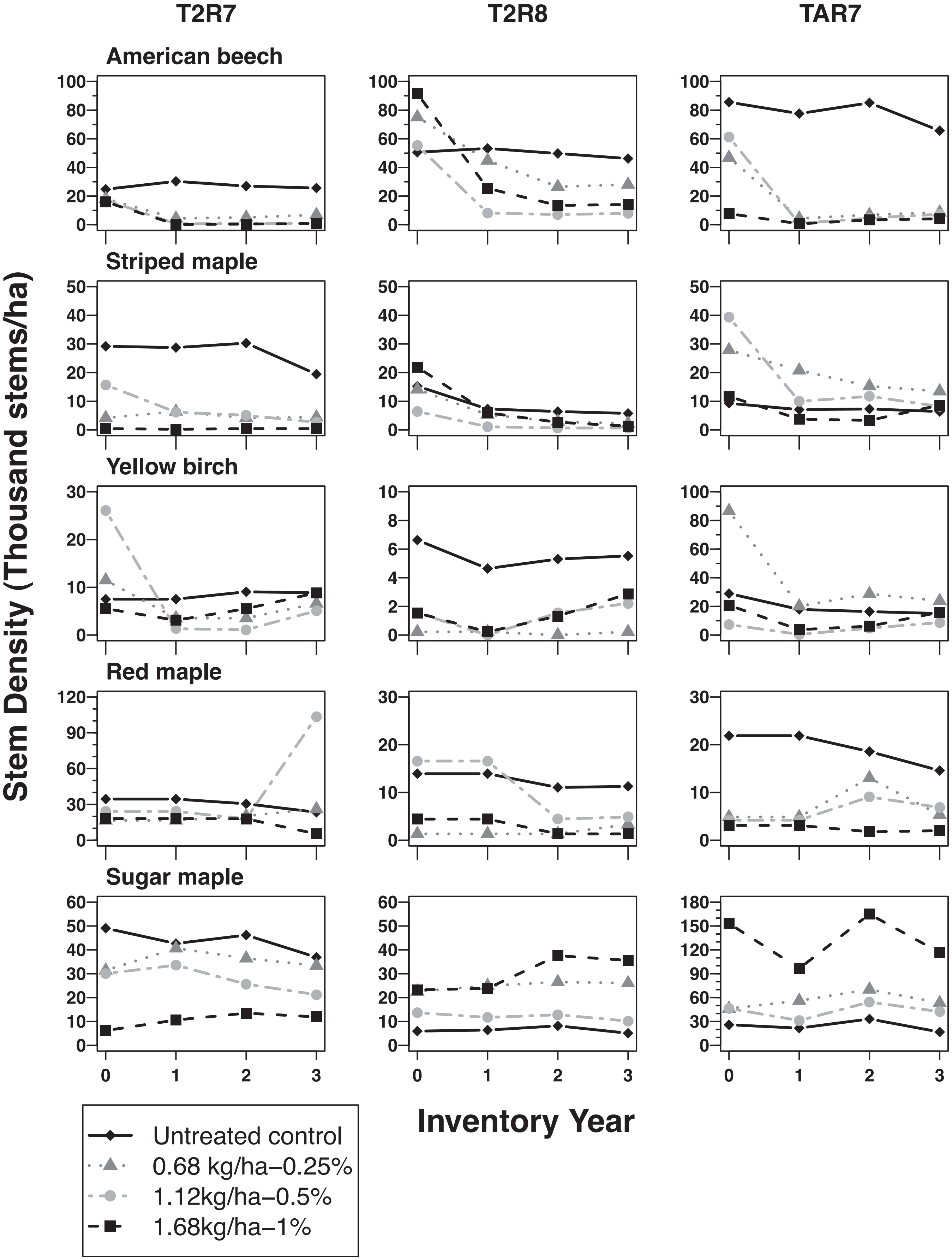

Figure 3. Change in stem density (thousand stems/ha) for the five dominant hardwood species at each study site (T2R7, T2R8, and TAR7) before treatment (year 0) and for 3 years following treatment. Note the difference in *y*-axis scales.

Table 5. Comparison of backpack mistblower and hydraulic nozzle application methods on 3rd-year posttreatment control for the five dominant hardwood species. Mixed-effects analysis of variance was used to compare application methods, with site as a random variable. Application method is expressed by the average control (percentage) of the species among treatments included in the comparison (0.56 lbs/ac, 0.25%; 1.12 kg/ha, 0.5%; and 1.68 kg/ha, 1.0%). Application methods were not different for any species at the $\alpha > 0.10$ level.

	Control				
	American beech	Striped maple	Yellow birch	Red maple	Sugar maple
Application method	. . . .	. . . .	(%)	. . . .	. . . .
Hydraulic	72	43	30	23	12
Mistblower	82	39	43	19	20
Random factor					
Site	0.01	0.10	0.16	0.00	0.13

We found no difference in percentage of control between hydraulic nozzle and mistblower application methods. Overall, levels of control for all five species were similar despite a 3-fold higher rate of glyphosate and surfactant with the mistblower treatment. This result strongly suggested that the patterns observed in this study are likely to be relatively robust across the wide range of conditions that are typically encountered in an operational setting when using a tractor-mounted mistblower. The three most desirable species (sugar maple, yellow birch, and red maple) were the least susceptible to glyphosate, suggesting that moderate glyphosate rates mixed with low surfactant concentrations can successfully shift species composition to more desirable species by reducing densities of beech and striped maple. This conclusion is supported both by the percentage of control variable (Table 4) and by changes in stem densities over time (Figure 3).

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