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Controlling Japanese barberry (*Berberis thunbergii* DC) in southern New England, USA

Jeffrey S. Ward [a,*], Thomas E. Worthley [b], Scott C. Williams [a]

[a] The Connecticut Agricultural Experiment Station, Department of Forestry and Horticulture, PO Box 1106, New Haven, CT 06504, United States
[b] University of Connecticut, Department of Extension, 1066 Saybrook Road, Box 70, Haddam, CT 06438, United States

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ABSTRACT

Dense Japanese barberry (*Berberis thunbergii*) stands have spread beyond manicured landscapes and are associated with a paucity of both tree regeneration and herbaceous plants in some forest stands. Studies over 2 years evaluated the effectiveness of various treatment alternatives to control barberry. A total of 375 barberry clumps at three study areas were selected for the first study in 2006. Treatments included directed flame using a 100,000 BTU propane torch on the following schedule: (1) pre-leafout and no follow-up treatment in July, (2) pre-leafout with directed flame in July, (3) post-leafout and no follow-up treatment, (4) post-leafout with follow-up treatment, and (5) untreated controls. Clumps treated once had higher mortality (45%) than untreated clumps (3%), but timing of initial treatment did not affect clump mortality. Clumps treated twice had the highest mortality of all (74%). All propane torch treatments reduced clump size, on average, by nearly 75%. Size of untreated clumps increased by 13%.

In 2007, a two-step process to control barberry was examined for 1100 clumps at six study areas. Initial treatments (prescribed burning, mechanical mowing with a drum chopper or with a brush saw) were applied to reduce the size of established barberry clumps. The second, follow-up treatments in mid-summer that treated new sprouts included foliar application of triclopyr or glyphosate, directed flame, and untreated controls. All initial treatments were equally effective in reducing clump size. Mortality differed among follow-up treatments: untreated controls (14%), directed flame (40%), and herbicide (93%). Surviving clumps having no follow-up treatment recovered to half of their original size by the end of the growing season. Size of surviving clumps did not differ among the other follow-up treatments and averaged 20% of the original size. Excellent control of Japanese barberry can be achieved using either propane torches or herbicides. Propane torches provide a non-chemical alternative where in parks, nature preserves, or forests where herbicide use is restricted and where barberry infestations are still light.

1. Introduction

Japanese barberry (*Berberis thunbergii*) is an aggressively invasive, non-native shrub that has spread and become established well beyond managed landscapes and is naturalized in at least 31 states and 5 Canadian provinces (USDA, NRCS, 2008). Throughout the region, especially where white-tailed deer (*Odocoileus virginianus*) populations are high, dense barberry stands can develop in the forest understory (Ehrenfeld, 1997; Silander and Klepeis, 1999). Such dense barberry stands are associated with a paucity of desirable tree regeneration and herbaceous plants. Barberry may alter nitrogen cycling and thereby affect soil biota (Kourtev et al., 1999; Ehrenfeld et al., 2001) as well as soil structure and function (Kourtev et al., 2003). A Maine study reported blacklegged tick (*Ixodes scapularis*) populations were twice as numerous in barberry-infested forests than in adjacent forests without barberry (Elias et al., 2006). Blacklegged ticks are the major vectors for several disease agents that cause Lyme disease, human granulocytic anaplasmosis, and human babesiosis (Magnarelli et al., 2006), thus barberry infestations may have an indirect, adverse effect on human health.

Current recommendations to reduce barberry include root wrenching, herbicide applications to cut stems, and foliar applications of herbicide to intact plants. The first two measures, while effective, are primarily applicable to smaller infestations because they require substantial physical labor. Foliar herbicide applications cannot be used in areas where the potential exists for damaging non-target plants or where herbicide use is restricted by regulation or deed (e.g., adjacent to drinking water supplies). While there are several anecdotal accounts of controlling barberry

* Corresponding author. Tel.: +1 203 974 8495; fax: +1 203 974 8502.
E-mail address: jeffrey.ward@po.state.ct.us (J.S. Ward).

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with herbicides, there are few published references (Silander and Klepeis, 1999).

Fire has been demonstrated to have both positive and negative affects on invasive species abundance. Studies of sites disturbed by fires in the western United States indicate that such disturbances can create conditions favorable to invasion by non-native species (Dodson and Fiedler, 2006; Keeley, 2006). Also, in an eastern deciduous forest experiment in Ohio, the combination of prescribed fire and canopy disturbance appeared to facilitate the establishment of two invasive species, *Microstegium vimineum* and *Rosa multiflora* (Glasgow and Matlack, 2007).

On the other hand, in studies where populations of invasive species were already in existence, fire was an effective control mechanism. Annual summer burning (four growing seasons) controlled *Centaurea maculosa* in a prairie restoration experiment in Michigan (Emery and Gross, 2005). When integrated with mechanical and biological treatments, fire successfully controlled the wetland invasive shrub *Mimosa pigra* in Australia (Paynter and Flanagan, 2004). A review of several studies focused on eastern oak (*Quercus*) communities suggests that repeated prescribed burning may be effective for controlling some invasive alien species, including Japanese barberry (Huebner, 2006). A Massachusetts study found prescribed burning and mechanical control did not kill barberry, but did dramatically reduce cover and height (Richburg, 2005).

The goal of this project was to compare the effectiveness of various combinations of selected methods for controlling Japanese barberry including herbicides, burning, flaming, and mechanical control. Considering the constraints imposed by labor requirements, expense and administrative details associated with conducting a controlled burn, special emphasis is placed on the non-chemical option of directed flame using a propane torch to simulate the effects of an intense fire on individual plants without actually having a prescribed fire. Objectives of the studies included quantifying control method effectiveness by measuring clump mortality and size after treatment, testing the seasonal effectiveness of flame treatments, and comparing integrated (two-step) treatments that combine mechanical treatments with herbicide and flame application follow-ups. Results of this study will be of value to private and public natural resource managers when selecting among barberry control alternatives that will best achieve the management goals of the landowner while adhering to potential management constraints.

2. Methods

2.1. Study areas

Three study areas were established for the treatment timing study in 2006 (Table 1). The first study area (Lyme) was at Lord Creek Farm in Lyme, CT. The second study area (Gaillard) was on a South Central Connecticut Regional Water Authority (RWA) property in North Branford and the third study area (Fenton) was on University of Connecticut Forest land in Mansfield, CT.

Six study areas were established for the control alternatives study in 2007 (Table 1). Two study areas (Tommy and Icehouse) were established on a RWA property in North Branford, CT. Two study areas (Egypt and Redding) were established on the Centennial Watershed State Forest in Redding, CT, a tract that is jointly managed by the Connecticut Department of Environmental Protection, the Aquarion Water Company, and The Nature Conservancy. The fifth study (Barnhill) area was established in Storrs, CT on University of Connecticut Forest land. A sixth study area (Reservoir) was established in Salisbury, CT on lands managed by The Nature Conservancy.

All study areas were agricultural fields or pastures abandoned in the early 1900s, except Egypt which was abandoned in the 1940s. Upper canopies were primarily sugar maple (*Acer saccharum*) with mixed oak, white ash (*Fraxinus americana*), and scattered yellow poplar (*Liriodendron tulipifera*) on all plots, except Barnhill, Lyme, and Egypt where ash, red maple (*Acer rubrum*), and oak predominated, and Reservoir which was replanted with white pine (*Pinus strobus*) in the early 1900s. Management was negligible (fuelwood harvests of declining and subcanopy trees), except on Tommy where ~70% of basal area was removed during a salvage harvest of eastern hemlock (*Tsuga canadensis*) in early 1990s. All study areas had medium to dense stands of mature Japanese barberry that were excluding desirable forest regeneration and native herbaceous vegetation.

A description of soils and topography for all study areas is given in Table 1. Elevations ranged from 55 to 355 m above mean sea level. Climatic data (NOAA, 1991) were from Hartford, CT, geographically centered among the study areas, which are within the northern temperate climate zone. Mean monthly temperature ranged from −3 °C in January to 23 °C in July. There was an average of 176 frost-free days per year. Average annual precipitation was 1128 mm per year, evenly distributed over all months. Soils were coarse-loamy, mesic Typic Dystrudepts and Oxyaquic Dystrudepts; stony to extremely stony; derived from gneiss, schist, and granite glacial tills.

2.2. Design and measurements

The initial study in 2006 examined combinations of treatment timing. At each study site 125 barberry clumps representative of the range of clump sizes were selected and measured, making a total for the three study sites of 375 clumps. A numbered aluminum tag was placed adjacent to each clump for positive identification. After measurement (see below), clumps were stratified into groups of five by size. One clump in each group of five was randomly assigned one of five treatments: (1) pre-leafout and no follow-up treatment in July, (2) pre-leafout with directed flame in July, (3) post-leafout and no follow-up treatment, (4) post-leafout with follow-up treatment, and (5) untreated controls.

Table 1
Description of study area locations, soils, and initial barberry cover (%).

Study area (initial treatment)	Soil classification	Elevation (m)	Latitude	Longitude	Initial cover
Gaillard	Cheshire	80	41.34	−72.76	–
Lyme	Canton and Charlton	55	41.35	−72.34	–
Fenton	Sutton	115	41.83	−72.25	–
Icehouse	Wethersfield	70	41.35	−72.76	11%
Redding	Paxton and Montauk	105	41.28	−73.37	67%
Barnhill	Paxton and Montauk	190	41.82	−72.25	53%
Egypt	Canton and Charlton	150	41.28	−73.37	43%
Tommy	Cheshire-Holyoke complex	85	41.37	−72.77	48%
Reservoir	Dummerston	355	41.98	−73.47	12%

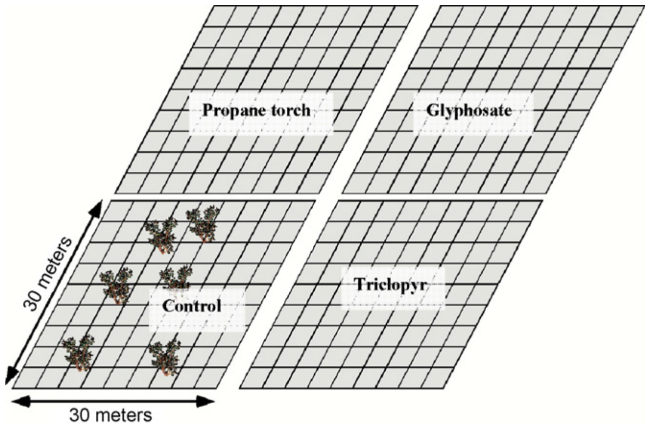

Fig. 1. Schematic of plot layout for 2007 control alternatives study. A possible scenario for follow-up treatments is shown.

The following measurements were recorded for each clump: crown height (cm), average crown width (cm), basal diameter (cm), number of live stems, and diameters (mm) of the three largest ramets (individual stems of a clump). Basal diameter is the diameter of the area from which ramets emerge. Clump size was arbitrarily defined as the average of crown height and crown diameter. Prior to follow-up treatments in July, crown height, and the number of surviving and new (sprout) ramets for each clump were also recorded. In October, crown height, crown width, and the number of new and surviving ramets of each clump were measured.

The second study in 2007 examined control alternatives. Initial treatments were prescribed fire, mechanical mowing, and brush saw; treatment details are given below. The follow-up steps that treated surviving and new ramets in July were: directed flame (propane torch), foliar applications of herbicide (triclopyr or glyphosate), and no follow-up treatment (control).

Initial treatment plots were comprised four contiguous 30 m $\times$ 30 m square subplots (Fig. 1). Each subplot was randomly assigned one of the distinct follow-up treatments. Each follow-up treatment was applied over each initial treatment, i.e., separate subplots of drum chopped plots were treated with triclopyr, glyphosate, propane torch, or left untreated.

Within each subplot, 25 barberry clumps representative of the range of clump sizes were selected and measured. A numbered aluminum tag was placed adjacent to each clump for positive identification. Measurement protocols of individual clumps were identical to those for first study, except that no measurements were made in July. A total of 1100 clumps were selected and measured prior to treatment assignment for this study. Japanese barberry cover was assessed using one hundred 0.5 m^2 samples for each 30 m $\times$ 30 m plot (4400 total points).

2.3. Treatment descriptions

For the 2006 treatment timing study, the treatment applied in each case was comprised 20 s of flame applied to the base of each clump using a 100,000-BTU propane torch (BP 223C, Flame Engineering Inc., LaCrosse, KS). Pre-leafout treatments were applied on 4 April (Gaillard and Lyme) and 10 April (Fenton). Post-leafout treatments were applied on 18 May (Lyme), 23 May (Gaillard), and 30 May (Fenton). The second treatment was applied on 2 July (Gaillard and Lyme) and 25 July (Fenton).

For the second study in 2007, three types of initial treatments were used to reduce the size of established barberry clumps. These were mechanical mowing with a drum chopper, mechanical mowing with a brush saw, and prescribed burning. The mechanical mowing with a drum chopper was completed in March 2007. A drum chopper utilizes a cylinder with attached teeth rotating at high speed to pull vegetation against a fixed cutting blade. The hydraulically powered unit is mounted to the front of a small tractor with rubber tracks. Equipment used on this project was Fecon Bull Hog® mulcher (Model BH74FM, Lebanon, OH) with a total width of 188 cm and a cutting width of 155 cm. The tractor was a Bobcat® T300 compact track loader (West Fargo, ND). All study areas were accessible to this equipment. Barberry clumps missed by the drum chopper (adjacent to trees, stone walls, or large rocks) were cut using a brush saw. Plots that received brush saw treatments were completed in April 2007.

Plots receiving prescribed burns were also completed in April 2007. Initial plans for the prescribed fires called for ring fires ignited by a drip torch. Low flame heights and low rate of spread following initial ignitions required strip ignitions at 10–100 m intervals. Connecticut Department of Environmental Protection foresters supervised and assisted with all prescribed burns. Treatment dates for the second study are shown in Table 2.

Virtually all of the clumps cut or burned had new ramets (resprouts) after the initial treatments. The follow-up steps used to treat the new ramets were: directed flame with a propane torch, foliar application of glyphosate, foliar application of triclopyr, and no follow-up treatment (control).

Per company policy, herbicides were not tested on RWA study areas (Tommy and Icehouse). Therefore, the triclopyr treatment was replaced with directed flame following initial spring flush in early-June, and the glyphosate treatment was replaced with directed flame following initial spring flush and again in early-August.

Based on observations from the 2006 treatment timing study, duration of flame treatments during the 2007 study were varied according to clump size. Flame was applied until all leaf litter at the base of each clump was consumed and individual ramets became carbonized and began to glow. Treatment times varied from 10 s for the smallest clumps to 40 s for the largest clumps. All directed flame treatments were completed on days when the leaves were

Table 2
Treatment schedules for 2007 control alternatives study. Initial treatments: mechanical mowing with a drum chopper (DCh), mechanical mowing with a brush saw (BrS), and prescribed burning (PBu). Follow-up treatments: directed flame with a propane torch (Pro), foliar application of glyphosate (Gly), foliar application of triclopyr (Tri), directed flame following initial spring flush in early-June (PrF), and directed flame following initial spring flush and again in early-August (Pr2).

Study area	Initial treatments			Follow-up treatments				
	DCh	BrS	PBu	Pro	Gly	Tri	PrF	Pr2
Icehouse	23 February	13 March	–	29 June	–	–	4 June	30 July
Redding	22 February	30 March	–	19 June	29 June	29 June	–	–
Barnhill	26 February	25 March	–	5 July	26 July	26 July	–	–
Egypt	21 February	–	11 April	11 July	29 June	29 June	–	–
Tommy	23 February	–	24 April	27 June	–	–	6 June	3 August
Reservoir	–	2 May	–	12 July	25 July	25 July	–	–

damp or wet. Indeed, we treated on some days during light to moderate rain showers.

Herbicide sprays were applied using backpack-pressurized sprayers. Each herbicide treated subplot (Fig. 1) was treated with only one herbicide. Herbicides were sprayed on all barberry clumps within a subplot. The following herbicides were sprayed on target foliage until wet: 'Glyphomax Plus' [glyphosate, N-(phosphonomethyl) glycine, isopropylamine salt (41% a.i.)]: (2.0% solution); 'Garlon 3A' [triclopyr, 3,5,6-trichloro-2-pyridinyloxyacetic acid, triethylamine salt (44.4% a.i.)]: (4.6% solution); and 'Crossbow' [2,4-dichlorophenoxyacetic acid, butoxyethyl ester (75% a.i.), triclopyr, 3,5,6-trichloro-2-pyridinyloxyacetic acid, butoxyethyl ether (15.5% a.i.)]: (2.3% solution). A dye was added to the tank mixes to prevent spraying clumps more than once and to identify clumps that had not been treated.

2.4. Analyses

For the 2006 treatment timing study, experimental design was a two-factor (study area and treatment) analysis of variance with initial clump size as a covariate. Chi-square statistics were used to determine whether mortality differed among treatments. Mortality in the following sections refers to clumps that had no live aboveground sprouts at the end of the growing season, it does not refer to mortality of individual ramets (or sprouts) of a given clump (genet). When mortality differed among treatments, the following procedures (Neter et al., 1982, pp. 325–329) were used to determine which treatments differed:

$$p' = \frac{n_1 \bar{p}_1 + n_2 \bar{p}_2}{n_1 + n_2} \tag{1}$$

$$s^2\{\bar{p}_2 - \bar{p}_1\} = p'(1 - p')\left(\frac{1}{n_2} + \frac{1}{n_1}\right) \tag{2}$$

$$z* = \frac{\bar{p}_2 - \bar{p}_1}{s^2\{\bar{p}_2 - \bar{p}_1\}} \tag{3}$$

where n_i is the sample size of treatment i, $\bar{p}_i$ is the mortality of treatment i, and z^* is the standardized test statistic. Differences for all comparisons were considered significant at $p \leq 0.05$.

For the 2007 control alternatives study, a two-factor (study area and initial treatment) analysis of variance with initial clump size as a covariate was used to compare the influence of initial treatments on clump size at the end of the growing season in 2007. Only those subplots without follow-up treatments were included in the analysis. Tukey's HSD test was used to test for significant differences among initial treatments. Differences were judged significant at $p \leq 0.05$. Chi-square statistics were used to determine whether clump mortality differed among treatments. When clump mortality differed among treatments, procedures in Neter et al. (1982) were used to determine which treatments differed.

Because treatment randomization was restricted by subplot, each 30 m × 30 m subplot was considered a replicate to avoid potential pseudo-replication (there were 25 clumps identified and measured within each subplot). Therefore, average clump size for each subplot (replicate) was used in the statistical analysis rather than the size of individual clumps.

Site and company policy restrictions did not permit all treatment combinations to be evaluated at all study sites for the control alternatives study in 2007. Therefore, the effects of the follow-up treatments were examined as two separate analyses. The four study areas where herbicides were used were analyzed separately from the two study areas where herbicides were not used. All initial treatments reduced clump size, but clump mortality and final clump sizes did not differ significantly among treatments. Therefore, initial treatment was not included as a factor in the analysis of the effects of follow-up treatments.

Barberry clump measurements from four study areas (Egypt, Redding, Barnhill, and Reservoir) were included in the comparison of propane torches, glyphosate, and triclopyr. A two-factor (study area and follow-up treatment) analysis of variance with initial clump size as a covariate was used to compare influence initial treatments on clump size at the end of the growing season in 2007. Tukey's HSD test was used to test for significant differences among initial treatments. Differences were judged significant at $p \leq 0.05$. Chi-square statistics were used to determine whether clump mortality differed among treatments. When clump mortality differed among treatments, procedures in Neter et al. (1982) were used to determine which treatments differed. Barberry clump measurements on two study areas (Icehouse and Tommy) were included in the comparison of timing of directed flame treatments using propane torches. Analyses were completed as described for the study areas where herbicide was used.

3. Results and discussion

Mean initial size of barberry clumps was 133 cm and ranged from 97 cm at Fenton to 166 cm at Tommy and Reservoir (Table 3). Basal (groundline) diameter of clumps averaged 16 cm. On average, clumps had 19 ramets and the largest ramet had a basal diameter of 10 mm.

3.1. Treatment timing study

Clump mortality differed significantly among treatments (χ^2 = 113.7, d.f. = 4, $p < 0.001$). Only 2 of the 75 untreated clumps died during the initial study of treatment timing in 2006. Both pre-

Table 3
Mean initial sizes of barberry clumps by study area. Diam—diameter (mm) of largest ramet, Count—number of live ramets per clump, *N*—number of clumps in each study area.

Study area	Crown size (cm)			Basal width (cm)	Ramets		
	Height	Width	Size		Diam	Count	*N*
Treatment timing study							
Gaillard	119 (2.6)	135 (3.1)	127 (2.5)	15 (0.2)	0.9 (0.02)	23 (1.2)	125
Lyme	111 (2.7)	125 (3.5)	118 (2.8)	11 (0.2)	0.9 (0.02)	16 (0.8)	125
Fenton	91 (2.1)	104 (2.5)	97 (2.0)	9 (0.1)	0.9 (0.05)	12 (0.5)	125
Control alternatives study							
Icehouse	114 (2.1)	130 (3.0)	122 (2.4)	20 (0.8)	0.9 (0.19)	20 (0.9)	200
Redding	131 (2.5)	122 (3.1)	127 (2.6)	17 (0.6)	1.0 (0.25)	20 (0.8)	200
Barnhill	132 (2.1)	155 (2.6)	144 (2.1)	13 (0.4)	1.0 (0.29)	18 (0.7)	200
Egypt	127 (2.3)	152 (3.0)	140 (2.3)	11 (0.4)	0.9 (0.20)	18 (0.7)	200
Tommy	153 (2.4)	178 (3.2)	166 (2.5)	17 (0.6)	1.3 (0.24)	22 (0.8)	200
Reservoir	168 (3.8)	164 (5.2)	166 (4.2)	22 (1.0)	1.4 (0.76)	21 (1.5)	100

Table 4
Clump mortality and mean (standard error) of initial and final size of barberry clumps by treatment timing in Connecticut.

Treatment	Mortality[a]	Initial size (cm)	Final size (cm)	N
Control	3% a	114.1 (3.35) a	129.2 (3.84) a	75
Pre-leafout and none	41% b	118.9 (3.26) a	42.1 (3.88) b	75
Post-leafout and none	48% b	115.1 (3.27) a	30.7 (3.20) bc	75
Pre-leafout and July	76% c	111.2 (3.88) a	26.9 (4.67) c	75
Post-leafout and July	72% c	111.6 (3.67) a	28.4 (4.14) bc	75

[a]Column values followed by same letter were not significantly different at $p \leq 0.05$.

and post-leafout burning without a follow-up treatment were effective in killing aboveground stems (Table 4), averaging 41% and 48% mortality, respectively. The second, follow-up treatment in July increased mortality to 77% for clumps first treated before leafout and 72% for clumps first treated after leafout. The observed mortality rates for clumps that had been treated twice were significantly higher than for the clumps that had only been treated once.

The size of barberry clumps differed among treatments at the end of the growing season ($F = 239.0$, d.f. = 4, $p < 0.001$). Untreated barberry clumps grew an average of nearly 19 cm during 2006. Both a single and double application of directed flame greatly reduced the size of surviving clumps (Table 4). At the end of the 2006 growing season, average post-treatment clump height was less than 40 cm compared with 132 cm for untreated clumps. The greatly reduced size of barberry clumps following treatment should increase available growing space and reduce competition for the establishment of desirable forest regeneration and native herbaceous vegetation.

Treatment timing (pre-leafout vs. post-leafout) both with and without follow-up treatment had no significant effect on clump mortality and minimal effect on clump size. This suggests that the period of initial treatments can span from early-April through late-May. In Connecticut, this roughly corresponds to the 1 month before and 1 month after full leaf expansion.

3.2. Control alternatives study

The treatment timing study in 2006 indicated that a two-step process could effectively control Japanese barberry in areas where foliar application of herbicide to intact plants is prohibited or severely restricted. Mortality was low for barberry clumps that received only the initial treatment (Table 5). Clump mortality did not differ among initial treatments ($\chi^2 = 1.2$, d.f. = 2, $p = 0.549$). Virtually all of the single-treatment barberry clumps had new sprouts by the end of the growing season. While the initial treatments did not kill barberry, the treatments were successful in reducing the size of the barberry clumps.

At the end of the growing season, the average clump size had been reduced by slightly more than half of the original size. Because site (study area location) had no significant effect on final size ($F = 0.712$, d.f. = 5, $p = 0.672$), it was not included in the final analysis. Initial treatment method had no significant effect on final size ($F = 0.089$, d.f. = 2, $p = 0.919$). Similar results were noted in Massachusetts where barberry was not killed by mechanical control and prescribed burning (Richburg, 2005).

Table 5
Clump mortality and mean (standard error) of initial and final size of barberry clumps by initial treatment for clumps that had no second, follow-up treatment in Connecticut.

Initial treatment	Mortality[a]	Initial size (cm)	Final size (cm)	N
Brush saw	10% a	139.9 (4.04) a	72.3 (3.41) a	100
Drum chopper	18% a	147.0 (3.34) a	69.5 (2.86) a	125
Prescribed fire	20% a	138.9 (6.49) a	64.3 (5.64) a	50

[a]Column values followed by same letter were not significantly different at $p \leq 0.05$.

When one examines the data associated with initial (flame) treatments in the treatment timing study in relation to initial (mechanical) treatments from the control alternatives study, it can be observed that a single application of direct heating with propane torches (Table 4) resulted in both higher clump mortality and smaller clumps than was observed using a brush saw, drum chopper, or prescribed fire (Table 5). While all initial treatments removed nearly all aboveground ramets, it seems likely that the directed flame resulted in higher mortality of the latent buds or meristematic tissues that produce the new ramet following treatment.

The second, follow-up steps treated the new, smaller clumps that developed after the initial treatment. Herbicide application was permitted on four of the six study areas (Table 2), and the effectiveness of the follow-up treatments on these areas was analyzed separately from the areas where herbicides were not tested.

All follow-up treatments resulted in both increased mortality of clumps and smaller surviving clumps compared to clumps that had no follow-up treatment (Table 6). Clump mortality did differ significantly among follow-up treatments ($\chi^2 = 350.4$, d.f. = 3, $p < 0.001$). Foliar herbicide application resulted in very high clump mortality and was more effective than directed flame using propane torches. However, directed flame did kill 39% of clumps. Another study reported spring application of glyphosate resulting in complete control of barberry on a small (3 m $\times$ 5 m), unreplicated plot (Silander and Klepeis, 1999).

The final size of barberry clumps did differ among follow-up treatments ($F = 11.1$, d.f. = 3, $p < 0.001$). On average, the clumps that survived follow-up treatment were only 20% of their original size compared with 47% for clumps that had no follow-up treatment. Final size did not differ among clumps treated with propane torches, glyphosate, or triclopyr.

The two study areas where herbicides were prohibited were used to examine different timing alternatives for follow-up treatments with propane torches (Table 2). The July treatment in Table 7 is synonymous with, and occurred at the same time as the propane torch treatment in Table 6. Clump mortality rates differed among follow-up treatments ($\chi^2 = 46.9$, d.f. = 3, $p < 0.001$), but surprisingly, mortality of clumps treated in June

Table 6
Clump mortality and mean (standard error) of initial and final size of barberry clumps by second, follow-up treatment on study areas where herbicide was used in Connecticut.

Second treatment	Mortality[a]	Initial size (cm)	Final size (cm)	N
None	14% a	141.2 (2.85) a	66.1 (2.11) a	175
Propane torch	39% b	148.4 (2.93) a	26.3 (2.55) b	175
Glyphosate	90% c	146.3 (2.86) a	22.2 (6.23) b	175
Triclopyr	96% c	140.4 (2.35) a	39.7 (9.65) b	175

[a]Column values followed by same letter were not significantly different at $p \leq 0.05$.

Table 7
Clump mortality and mean (standard error) of initial and final size of barberry clumps by timing of follow-up propane treatment on study areas where herbicide was not used.

Second treatment	Mortality[a]	Initial size (cm)	Final size (cm)	N
None	19% a	148.2 (4.18) a	81.3 (2.42) a	125
June	34% ab	146.5 (4.87) a	50.1 (4.62) b	50
July	38% b	144.8 (3.50) a	28.9 (2.77) c	125
June and August	63% c	146.7 (3.85) a	11.7 (4.05) d	100

[a]Column values followed by same letter were not significantly different at $p \leq 0.05$.

did not differ significantly from clumps treated in July that had no follow-up treatment (Table 7). Mortality of clumps treated in July (38%) was higher than untreated clumps (19%), but less than clumps that were treated in both June and August (63%).

The final size of barberry clumps did differ among follow-up treatments using a propane torch ($F = 86.7$, d.f. = 3, $p < 0.001$). This study indicates that June is not the optimal time to use a propane torch as a follow-up to pre-leafout mechanical treatment. Mortality did not differ from clumps that received no follow-up treatment, and final clump size was significantly larger than that of clumps treated in July (Table 7). Propane flaming applied in both June and August as a follow-up to the initial mechanical treatments resulted both in clump mortality that approached the rates resulting from herbicides and also in very small (<12 cm) surviving clumps.

4. Conclusions

A two-step process can effectively control Japanese barberry in areas where herbicide use is restricted and in areas where management objectives include minimizing herbicide applications. Integrating an initial pre- or early-season mechanical (cutting), prescribed fire, or directed flame treatment with a mid-to-late growing season follow-up treatment such as light, targeted herbicide applications, or directed flame can achieve effective control in a single growing season. The choice of the initial treatment to reduce clump size by killing aboveground ramets will depend on such factors as the availability of local assets (e.g., personnel qualified for prescribed burning and equipment), the size and extent of the treatment area, and the relative height and density of the infestation.

We recommend using medium (drum chopper) or heavy (bulldozer) equipment to cut or flatten corridors in large, dense barberry infestations that are waist high or taller. Using a brush saw in tall barberry clumps is very frustrating after the first hour. It is likely that productivity of hourly employees, or volunteers, cutting tall barberry clumps would quickly decrease if more than a small patch was being treated. However, use of medium and heavy equipment may be limited by terrain, rockiness, forest density, operator experience, and other factors that need to be considered by the local natural resource manager. In this study for example, treatment with the drum chopper was completed in February when soil was frozen to minimize soil disturbance on steeper slopes (~25%).

Propane torches provide a non-chemical alternative for both the initial and follow-up treatments in parks, nature preserves, and forests where herbicide use is restricted and where barberry infestations are still light, and can mimic the effects of a controlled burn without the logistical constraints and expense. As per our experience with student interns however, quality control is essential when using a propane torch. Top killing live stems without simultaneously killing latent basal buds are a waste of time and resources that will result in poor control. Flame treatments conducted when conditions are damp are both effective and eliminate the risk of a wildfire in deciduous forests.

Foliar application of herbicides on new sprouts resulted in higher clump mortality than direct flaming with propane torches, though all treatments resulted in reductions of average surviving clump size. Personnel availability for herbicide application may be limited in jurisdictions that require applicator certification. Use of a marker dye in herbicide solutions can greatly reduce the volume of herbicide used, missed clumps, clumps sprayed more than once, and mis-application to non-target vegetation.

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