



Higher Intensities of Mulching-Head Treatments Limit the Response of a Target Invasive Shrub (*Lonicera maackii*) and Promote Herbaceous-Layer Species Diversity

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Abstract

Amur honeysuckle (*Lonicera maackii* [Rupr.] Herder) and other invasive shrubs represent a serious threat to the biodiversity and ecosystem services of forests in the eastern United States. Treating invasive shrubs can be costly and time consuming, highlighting the need for efficient techniques to control heavy invasions across large areas of forest. Mulching-heads have shown promise for efficiently controlling multiple species of invasive shrubs, including Amur honeysuckle, potentially aiding the restoration of suppressed herbaceous-layer plant communities. In this study, we examined how mulching intensity (i.e., treatment depth below the soil surface) affects Amur honeysuckle sprouting response, as well as the post-treatment response of the plant community. We found that deeper applications of a mulching-head inhibited the post-treatment regrowth of Amur honeysuckle sprouts. According to NMDS analysis, post-treatment species composition became more similar across plots and shifts in post-treatment axis values were associated with increased species diversity and floristic quality, a measure of species conservation value. Additionally, a canonical correspondence analysis revealed that deeper mulching-head intensities were correlated with increased herbaceous-layer plant species diversity and floristic quality. We conclude that mulching-head treatments are an effective technique for controlling invasive shrubs without degrading native plant communities, and deeper treatments reduce the rate of post-treatment sprouting.

Keywords Community composition · Floristic quality · Invasive control · Sprouting

Introduction

Invasive shrubs are ubiquitous and a threat to the health of forest ecosystems in the eastern United States, particularly shrub species originating from East Asia (Webster et al. 2006; Ricklefs et al. 2008); Iannone et al. 2015, 2016). These invasive shrubs

threaten native plant species in a myriad of ways. Most notably, their extended leaf phenology allows additional carbon fixation earlier and later in the year, resulting in a longer growing season and greater potential to shade out competitors in the understory (Fridley 2012). Not only are invasive shrubs directly harmful to forest ecosystems, but they are also extremely difficult to control across landscapes (Webster et al. 2006). The vigorous root growth and a propensity to sprout new stems after treatment make invasive shrubs a costly and persistent challenge for control efforts by land managers (Rathfon and Ruble 2007; McNeish and McEwan 2016). For example, between 1994 and 2005, Great Smoky Mountains National Park alone spent over 17,000 worker-hours controlling woody invasive plant species, including shrubs (Webster et al. 2006). Developing efficient and cost-effective invasive shrub control techniques is critical to restoring and protecting the forest ecosystems of the eastern United States and elsewhere.

Amur honeysuckle (*Lonicera maackii* [Rupr.] Herder) is an archetypal invasive shrub that was deliberately introduced in the United States multiple times for many reasons, including soil stabilization, horticultural value, and wildlife habitat, and has become nearly ubiquitous in Ohio River watershed and lower Midwest forests (Luken and Thieret 1996). Similar to other invasive shrubs from East Asia, Amur honeysuckle is noted for having an extended leaf phenology (Wilfong et al. 2009; McNeish and McEwan 2016), the ability to alter nutrient cycling (Schuster and Dukes 2017), and early developing and prolific reproductive capabilities (Luken and Thieret 1996; Deering and Vankat 1999; Lieurance 2004; Gorchovet et al. 2014). Additionally, there is evidence that Amur honeysuckle may be allelopathic (Bauer et al. 2012; Cipollini and Greenawalt Bohrer 2016).

Control techniques for Amur honeysuckle and other invasive shrubs tend to employ one or more of four treatment categories: physical removal of individuals, biological control, fire, and herbicide treatments. Root wrenching, lopping, root severing, and brush-cutting are all common examples of physical removal (Frank et al. 2018). Goat grazing has recently been suggested as a potential means to biologically control shrub invasions (Luginbuhl et al. 1998; Elias and Tischew 2016; Rathfon et al. 2021). Prescribed fires are also commonly used to treat invasive shrubs (Mandle et al. 2011). In addition, studies have shown that direct fire treatment from propane torches can be effective in controlling Japanese barberry (*Berberis thunbergii* DC) in forests of the northeastern United States when applied multiple times (Ward and Williams 2011) or used with herbicides (Ward et al. 2009). Herbicide applications, such as foliar spraying, hack and squirt, girdling, stem injections, and cut-stump applications, are the most common means of invasive shrub control and often also involve a method of physical removal (Hartman and McCarthy 2004; Webster et al. 2006; Rathfon and Ruble 2007; Howle et al. 2010; Bailey et al. 2011; Rivera et al. 2022).

While all of these methods can be effective in controlling invasive shrubs, they also all have major drawbacks. Physical removal techniques often require specialized equipment and are one of the most inefficient control methods (Bailey et al. 2011). While goats and other forms of biological control show potential (Luginbuhl et al. 1998; Elias and Tischew 2016; Rathfon et al. 2021), the techniques are still relatively untested and potential non-target effects are not fully understood.

Prescribed burns are very efficient in terms of time and cost (Ward and Williams 2011; Ward et al. 2013), but the technique may have limited effectiveness for some invasive shrubs and may even favor some invasive plant species (Mandle et al. 2011; Ward and Williams 2011; Rebbeck 2012; Ward et al. 2013; Guthrie et al. 2016). Herbicide application is a highly effective control technique for invasive shrubs. However, the cost of application can be limiting (Bailey et al. 2011), and landowners are often cautious about the potential dangers of herbicide application (Ma et al. 2018). Glyphosate, which is the most heavily used herbicide in the world and known to be relatively benign compared to other herbicides (Baylis 2000; Tarazona et al. 2017), has been the subject of multiple lawsuits, with awards averaging \$47.6 million (Benbrook 2020), and research has found evidence of non-target environmental effects (Busse et al. 2001; Tsui and Chu 2003; Bai and Ogbourne 2016; Gill et al. 2018). While herbicides will continue to be widely used in the control of invasive plants, control techniques that reduce the amount of herbicide applied can reduce the cost of control, while also helping to assuage public concerns.

Mechanical control of invasive shrubs offers an efficient control technique that can be applied to heavy invasions across large areas. Recently, mulching-head treatments (also known as rotary mulching-heads, forestry heads, wood shredders, or mastication heads) have gained attention as an efficient method of controlling dense thickets of invasive shrubs (Hanula et al. 2009; Bailey et al. 2011; Ward et al. 2013; Frank et al. 2018). Conceptually, the treatment should be able to shatter the root collar of the shrub, inhibiting the post-treatment sprouting from stumps (Frank et al. 2018). The effectiveness of mulching-head treatments seems to vary by species. A study comparing mulching-head treatments to stem cutting and removal without herbicide for the treatment of Japanese barberry found the two treatments to be equally effective (Ward et al. 2013). Hanula et al. (2009) found both of these methods failed to significantly reduce the herbaceous-layer cover of Chinese privet (*Ligustrum sinense* Lour.) but did significantly increase cover of non-privet plant species within a year after treatment. Foliar application a year after either treatment nearly eliminated Chinese privet from the treated sites (Hanula et al. 2009). While the effects of mulching-head treatment on the herbaceous-layer plant community have received little attention, Hudson et al. (2014) found that species richness was higher following treatment of Chinese privet with mulching-heads compared to cut-stump treatment.

Frank et al. (2018) found that mulching-head treatments were nearly as effective as cut-stump in controlling Amur honeysuckle invasions. They also observed increased herbaceous-layer plant species diversity and conservation value in mulching treatments, compared to the cut-stump method. However, the authors noted that Amur honeysuckle sprouted prolifically, highlighting the need to examine how the intensity of mulching-head treatments affects post-treatment sprouting. Moreover, they identified a negative relationship between depth of mulching-head treatment and the volume of sprouts on treated Amur honeysuckle stumps in the spring following a winter treatment. However, whether this relationship would persist across multiple years was not evaluated. Additionally, increased intensity (depth) of treatment may damage below-ground plant structures and seeds, which could affect the response of post-treatment herbaceous-layer species composition and diversity as well as promote the establishment of ruderal or exotic species (Frank et al. 2018).

In this study, we used plots previously established by Frank et al. (2018) to examine the multi-year response to mulching-head intensity – as measured by treatment depth below the soil surface. Specifically, we examined how intensity affects the multi-year sprouting of treated Amur honeysuckle stumps, as well as the species composition and diversity of the herbaceous layer. We predicted that more intense treatment would reduce Amur honeysuckle sprouting vigor by more thoroughly destroying or damaging preformed, vegetative buds around the root collar. However, we also predicted that more intense treatments would shift herbaceous layer species composition toward greater importance of early seral and non-native species, such as garlic mustard (*Alliaria petiolata* [M. Bieb.] Cavara & Grande), which often increases in cover after Amur honeysuckle removal (Shields et al. 2015).

Methods

In the autumn of 2016, we established a field experiment to examine the effects of mulching-head intensity, with three replicates at two sites in west-central Indiana, near West Lafayette. One replicate was established at the Purdue Wildlife Area (PWA; 40.4562, –87.0592) and two other replicates were established at the Richard G. Lugar Forestry Farm (40.4289, –86.9534; henceforth referred to as “Lugar Farm”). At each site, we also sampled a single, untreated reference area for comparison to the replicates at that site. Prior to treatment, understories of the replicates and reference areas were dominated by Amur honeysuckle and had received no prior invasive-species treatments (Frank et al. 2018).

At each treatment and reference area, eight plots were established with four plots in two parallel rows: plot centers 8 m apart. Prior to any treatment, the percent cover of each herbaceous-layer species was visually estimated in four 1-m² quadrats positioned one meter away from plot center in all four cardinal directions (north, east, south, and west). Aside from grass species, which were combined into a single taxonomic group, all plants were identified to at least the genus level, and most were identified to the species level (USDA Plants Database 2021). The percentage of ground cover by substrate type (leaf litter, fine woody debris, coarse woody debris, bare ground, and tree bole) was also estimated in these quadrats.

Mulching-head treatments of the two replicates at Lugar Farm and one at PWA occurred in the winter of 2017 using a skidsteer-mounted forestry mulching head (Bull Hog®; Fecon Inc., Lebanon, OH, USA). We attempted to clear all honeysuckle shrubs while avoiding damage to native saplings and trees by removing honeysuckle shrubs too close to native trees with a clearing saw. To measure mulching-head treatment intensity, we established a 9×5 grid of pre-marked wooden stakes on four meter spacing, overlaid on the grid of vegetation plots (Frank et al. 2018). Stakes were hammered into the soil with 10 cm left above ground and had markings at 1-cm intervals above- and below ground for measuring treatment depth. After treatment, we recorded depth values from the remaining portion of each stake. While the mulching head completely pulled some stakes out of the ground, at least three out of the nine stakes nearest each plot center (≤ 6 m) remained measurable after treatment

(median 4.5). We calculated the mean depth of the remaining stakes within 6 m of each plot center and used this as the measurement of treatment intensity.

In the autumn of 2019 (two years post-treatment), we remeasured herbaceous-layer cover by species during the same time of year and using the same methodology as Frank et al. (2018), except that a rock cover type was estimated, and bole cover was not estimated following treatments. In the fall of 2020 (three years post-treatment), we visually estimated the percentage of midstory (1.01 to 5 m) Amur honeysuckle cover in 2×2 m quadrats randomly placed at each plot. We also measured the number of stems sprouting from treated Amur honeysuckle stumps in 40-m² circular plots extending from each plot center. The height, crown length, and crown width of each sprout were measured and used to calculate the ellipsoidal volume of the individual shrub. We summed volumes of all sprouts at each plot as a measure of Amur honeysuckle response to mulching treatment. Total shrub volume is considered a more informative metric for stump response, as it combines stem density and shrub cover into a single measurement (Frank et al. 2018).

Statistical Analysis

Effect of Intensity of Treatment on Honeysuckle

Finally, we wanted to focus on the relationship of treatment intensity to the response of Amur honeysuckle. Similar to an analysis of short-term response to mulching-head treatments (Frank et al. 2018), we used linear regression to evaluate the correlation between treatment intensity and the volume of shrubs found at each plot two years post-treatment. A Shapiro–Wilk normality test revealed that shrub volume was not distributed normally ($W=0.84407$, $p=0.002$). We applied a natural log transformation, re-tested the data for departures from normality ($W=0.9577$, $p=0.394$), and fit a linear regression for the effect of treatment intensity on shrub volume. All statistical analyses were performed in R (version 3.6.3).

Effect of Treatment on Community Metrics

We first evaluated the overall effect of treatment on herbaceous-layer community responses by comparing community metrics from pre- and post-treatment surveys in treatment plots. Based on the percent herbaceous-layer cover, we calculated taxonomic species richness (richness), Shannon's Diversity Index (diversity), and Pielou's Evenness Index (evenness) for each plot both before and after mulching-head treatment. We also determined the average coefficient of conservatism (C-value) and floristic quality index (FQI), according to Indiana state guidelines (Rothrock and Homoya 2005). C-value represents the sensitivity of each species to habitat degradation (Rothrock and Homoya 2005), and we calculated the average C-value across all species present in the plot with all species weighted evenly. FQI integrates C-value with species richness (Rothrock and Homoya 2005) and was derived by multiplying the average C-value of a plot by the square root of plot species richness. To make these metrics comparable to a previous study, we also excluded grasses (Poaceae),

sedges (*Carex* spp.), and unidentified taxa from C-value calculations, assigned exotic species a C-value of 0, and averaged possible C-values for other taxa only identified to genus (Frank et al. 2018).

To visualize how the herbaceous layer responds to mulching-head treatment across the full range of treatment intensities, we used non-metric multidimensional scaling (NMDS) to fit herbaceous-layer community metrics (richness, diversity, evenness, average C-value, and FQI) and the ground-cover types (bare ground, coarse woody debris, fine woody debris, and litter) from only the treated plots both before and after treatment within a single ordination. Analysis was conducted using the ‘vegan’ package in R (Oksanen et al. 2025). The data were square-root and Wisconsin transformed and constrained into two axes and based on Bray–Curtis dissimilarity. A maximum of 100 attempts were allowed to find a convergent solution to the ordination. The linear R^2 and stress of the ordinations were recorded as measures of how much of the dissimilarity matrix was preserved in the ordination. We considered a stress < 0.2 to indicate adequate representation of the original data (Oksanen et al. 2025).

After a stable NMDS ordination was derived, we plotted the ordination with vector arrows drawn connecting each treatment plot’s pre-treatment location within the ordination to its location post-treatment to visualize changes in herbaceous-layer species composition after treatment. The weights of each community metric were also plotted to visualize which factors shifted after treatment. To statistically determine if there were differences in pre- and post-treatment plots, we used the “adonis” analysis (also referred to as a PERMANOVA) from the ‘vegan’ package in R ($\alpha = 0.05$). The “adonis” analysis provides an analysis of variance for distance matrices. We tested if measured metrics of diversity and ground-cover types varied between pre- and post-treatment plots within a Gower’s dissimilarity matrix using 999 permutations. To determine what variables (community metrics or ground-cover types) contributed most to the dissimilarity of the two groups, we used a similarity percentage analysis (“simper” command in ‘vegan’; also known as a SIMPER analysis). This analysis revealed which variables (community metrics or ground-cover types) contributed significantly to the compositional divergence of groups (pre- and post-treatment plots) in a Bray–Curtis dissimilarity matrix ($\alpha = 0.05$).

Effect of Intensity of Treatment on Community Metrics

After evaluating the overall effect of mulching-head treatment on herbaceous-layer community metrics, we then aimed to understand the role of treatment intensity on those metrics. To do this, we performed a canonical correspondence analysis (CCA) in order to understand how mulching-head intensity and other factors drove changes in the herbaceous species response within treatment plots. A CCA combines regression and ordination techniques where a matrix of explanatory (independent) variables are constrained by a matrix of response (dependent) variables (Borcard et al. 2011). This technique allowed us to directly examine the influence of both pre-treatment variables and intensity of treatment on those same metrics after treatment. This technique allows us to understand what happened to each plot based on how it was before treatment and the intensity of mulching.

To determine how the post-treatment herbaceous community was related to the pre-treatment herbaceous-layer community (richness, diversity, evenness, average C-value, and FQI); site; ground-cover type (bare ground, bole, coarse woody debris, and fine woody debris); and intensity of mulching-head treatment, we utilized an explanatory matrix consisting of these variables. Our response matrix consisted of post-treatment measures of the same metrics of herbaceous-layer communities (richness, diversity, evenness, average C-value, and FQI), along with measures of Amur honeysuckle sprouting (Amur honeysuckle volume, number of sprouting stems on treated Amur honeysuckle stumps, and Amur honeysuckle midstory cover). To determine if our matrix of explanatory variables significantly predicted our matrix of response variables, we used the “anova.cca” command from ‘vegan’ to derive overall model significance ($\alpha=0.05$) and determine the amount of variance the model explained (pseudo- R^2). In addition, “anova.cca” was used to examine the significance of individual explanatory variables ($\alpha=0.05$) in contributing to the constrained ordination. A triplot of the CCA was created to demonstrate which explanatory variables correlated with which response variable.

Effect of Intensity of Treatment on Herbaceous Plant Community Composition

We then aimed to understand how treatment impacted the composition of specific plant species between treatment and reference plots. Since reference plots did not fall along the spectrum of intensity of treatment (a value of 0 would not be equivalent to a reference plot since its soil was not impacted rather than the disturbance averaging out to 0), we assigned each plot into three categorical levels of treatment: reference, above soil surface, and below soil surface. These were based on the average break-age point of our recoverable wooden stakes occurred during treatment for each plot (~4.5 wooden stakes per plot). To understand how the composition of plant species varied with intensity of treatment, we first used NMDS to ordinate all post-treatment plots with a Bray–Curtis dissimilarity matrix of the percent cover of all plant species and ground-cover types (litter, fine woody debris, coarse woody debris, bare ground, and rock) found in post-treatment plots. The parameters of this ordination were similar to the previous NMDS ordinations we created: two axes, all data were Wisconsin and square-root-transformed, 100 attempts were allowed to find a convergent solution, and a stress above 0.2 being considered inadequate for analysis.

After a stable ordination of herbaceous-layer species percent cover was created, we assigned all plots to one of three intensity classes based on the values for depth of treatment: above soil surface (less intense), below soil surface (more intense), and reference (untreated). We plotted the different intensity classes within the ordination to display differences. To statistically determine if there were differences in species composition between intensity classes, we again used the “adonis” analysis from the ‘vegan’ package in R ($\alpha=0.05$). We tested if herbaceous-layer species composition varied among intensity classes within a Bray–Curtis dissimilarity matrix using 999 permutations. Following this, we evaluated pairwise differences between intensity classes using the command “pairwise.adonis” from the package ‘pairwiseAdonis’ with 999 permutations within a Bray–Curtis dissimilarity matrix ($\alpha=0.05$). Finally, to determine which plant species or ground-cover types varied between each

intensity class, we performed a similarity percentage analysis (“*simper*” command in ‘*vegan*’). This analysis revealed which variables (plant species or ground-cover types) contributed significantly to the compositional divergence of groups (intensity classes) in a Bray–Curtis dissimilarity matrix ($\alpha=0.05$).

Results

Effect of Intensity of Treatment on Honeysuckle

The relationship between the intensity of mulching-head treatment and the natural log of resprouting Amur honeysuckle volume was significant in our study ($F_{1,22}=16.69$, $R^2=0.406$, $p<0.001$), displaying a negative relationship between intensity and volume (Fig. 1). This is congruent with the previous study, which found a similar short-term trend (Frank et al. 2018). Differences in intensity between sites also became apparent, with Lugar Farm having a mean intensity of 0.2 cm above the soil surface and PWA having a less intense average treatment intensity of 1.4 cm above the soil surface.

Effect of Treatment on Community Metrics

The NMDS, including metrics of plant diversity and ground-cover types in both pre- and post-treatment plots, found a convergent, two-axis solution in 20 attempts with a stress of 0.11 and a linear R^2 of 0.973, which was acceptable for this analysis. We

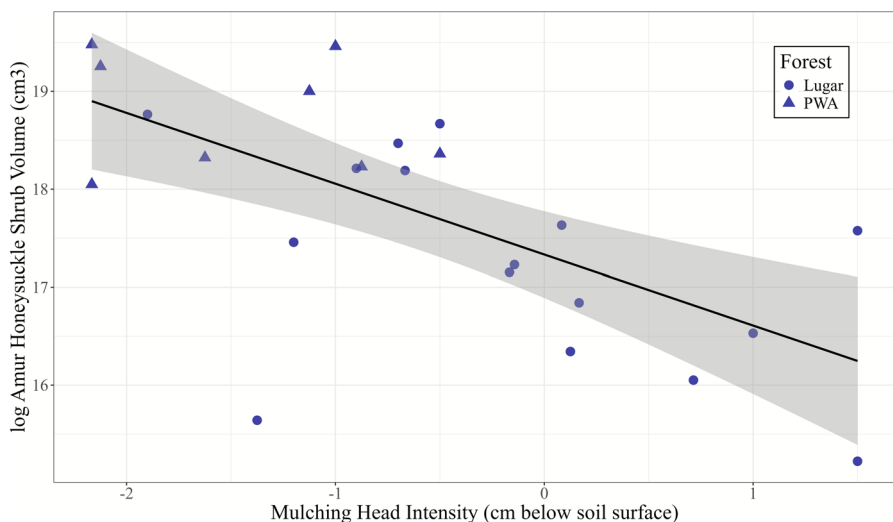


Fig. 1 The negative relationship between mulching-head intensity and volume of sprouting Amur honeysuckle stems ($F_{1,22}=16.69$, $R^2=0.406$, $p<0.001$). Negative x-axis values indicate height above soil level

then compared the plots prior to treatment to the plots after treatment. The pre- and post-treatment plots were significantly separate from one another in the “adonis” analysis ($F_{1,47}=23.881$, $p=0.001$, $R^2=0.380$) and the post-treatment sites were clustered within the ordination (Fig. 2). Plots converged post-treatment, displaying largely unidirectional movement in ordination space. Overall, the dispersion of plots decreased post-treatment. The weights of species richness, diversity, average C-value, and FQI all trended in the same direction, as the cluster of post-treatment plots with all other factors trending away from the cluster (Fig. 2). The SIMPER analysis confirmed this trend, with richness, diversity, evenness, average C-value, and FQI all significantly correlated with post-treatment plots in the ordination (Table 1). These were confirmed to be statistically significant drivers of the difference between pre- and post-treatment groups with p values <0.05 . Leaf litter was the most strongly contributed to the difference between pre- and post-treatment plots and decreased after treatment. Bare ground and coarse woody debris also significantly decreased after treatment, but to a lesser extent. Fine woody debris, however, did not significantly contribute to the difference between pre- and post-treatment plots.

Effect of Intensity of Treatment on Community Metrics

The CCA we fit to examine response to mulching-head intensity explained a significant amount of variation in post-treatment plots ($F_{12,11}=4.232$, $R^2=0.822$, $p=0.001$). Our dependent variables (post-treatment diversity, richness, evenness, FQI, average C-value, number of sprouts on treated Amur honeysuckle stumps,

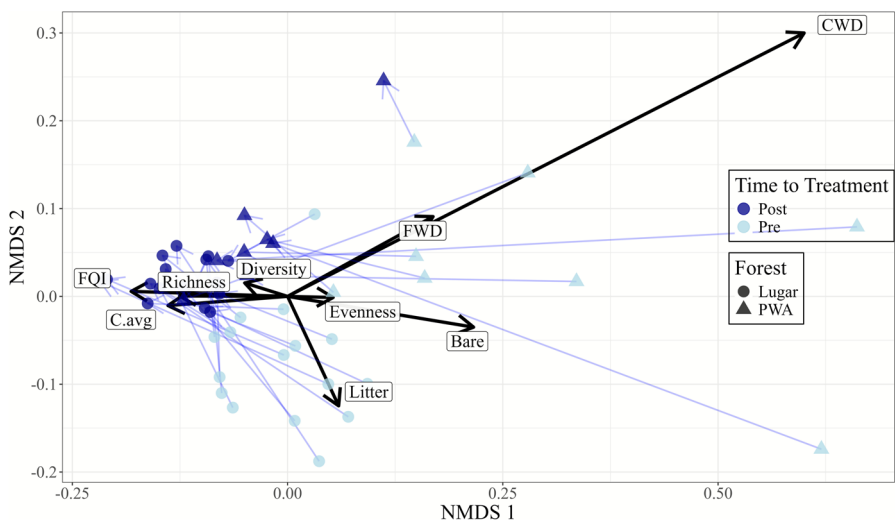


Fig. 2 A non-metric multi-dimensional scaling comparing the plots pre- and post-mulching-head treatment. The smaller, blue lines connect measurements of plots before treatment to measurements after treatment. Thicker, black lines represent the weights variables within the ordination

Table 1 Results of a SIMPER analysis ($\alpha=0.05$) comparing the variables which contributed to the difference between pre- and post-treatment plots

Contributing Species	Mean Difference	% Contribution	p-value
Litter	−26.17	13.47%	0.001*
Fine Woody Debris	7.08	6.23%	0.357
Bare Ground	−10.38	5.67%	0.001*
Richness	11.33	5.37%	0.001*
FQI	5.91	2.78%	0.001*
Coarse Woody Debris	−0.67	0.48%	0.031*
Diversity	0.96	0.45%	0.001*
Average C-value	0.68	0.39%	0.001*
Evenness	0.15	0.09%	0.001*

Mean difference compares the post-treatment plot means of each variable to those of pre-treatment plots. Asterisks denote the significance of the variables.

Amur honeysuckle volume, and Amur honeysuckle midstory cover) were significantly predicted by our explanatory variables (Table 2). Specifically, site, C average prior to treatment, and intensity significantly influenced the constrained post-treatment ordination (Table 2). Graphing the CCA reveals that increasing intensity of treatment is tightly correlated with increasing diversity, richness, evenness, average C-value, and FQI in post-treatment plots (Fig. 3). The Lugar Farm and PWA sites were ordinated in opposite directions from one another. While the greater number of sprouts on treated Amur honeysuckle stumps was greater at the Lugar Farm sites, Amur honeysuckle volume and midstory cover were higher at the PWA sites. The average C-value of pre-treatment plots displayed a weak relationship to our explanatory variables but was strongly associated with the second axis of the CCA, which explained a smaller portion of the variation in the model (21.3%) compared to the

Table 2 Pre-treatment explanatory variables and the contribution made to a canonical correspondence analysis explaining post-treatment variables at each plot ($\alpha=0.05$)

Explanatory Variable	Df	χ^2	F	p-value
Site	1	0.113	26.641	0.001*
Intensity	1	0.031	7.396	0.004*
Bare Ground	1	0.008	1.784	0.149
Tree bole	1	0.004	0.935	0.352
Coarse Woody Debris	1	0.007	1.653	0.162
Fine Woody Debris	1	0.006	1.456	0.203
Litter	1	0.005	1.231	0.272
Richness	1	0.006	1.332	0.221
Diversity	1	0.006	1.350	0.250
Evenness	1	0.004	0.910	0.380
C Average	1	0.016	3.813	0.025*
FQI	1	0.010	2.276	0.106
Residual	11	0.046		

Asterisks denote significance of the variable.

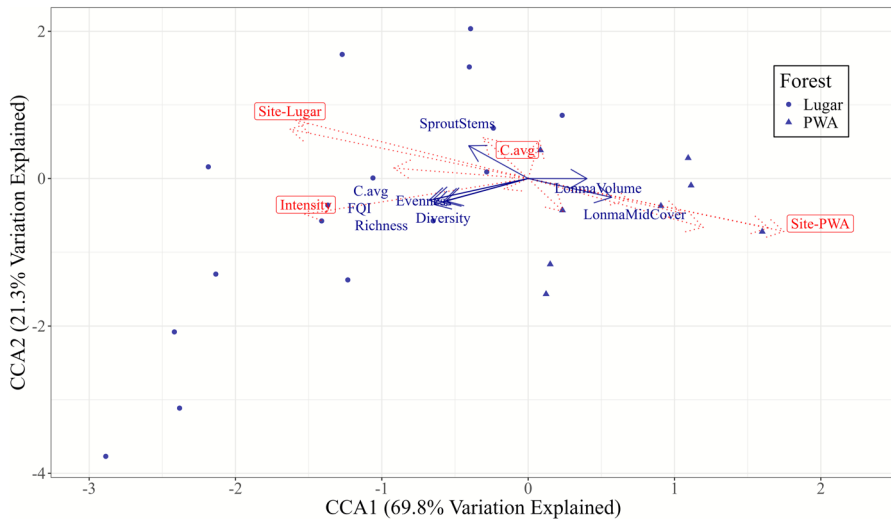


Fig. 3 Triplot of canonical correspondence analysis (CCA) explaining post-treatment plot measurements with pre-treatment plot measurements, site, and intensity. A triplot displays the location of each plot, the directionality of all predictor variables, and the directionality of all response variables in multidimensional space. Points represent post-treatment plots within the ordination with circles being plots in Lugar Farm and triangles plots at PWA. Full blue arrows show response (post-treatment) variables. Dotted red arrows represent explanatory variables with significant variables being labeled ($\alpha=0.05$)

first axis (69.8%). Although pre-treatment average C-value significantly contributed to explaining overall model variation, it was not strongly correlated with any post-treatment-dependent variables, including post-treatment average C-value.

Effect of Intensity of Treatment on Herbaceous Plant Community Composition

The NMDS we fit based on post-treatment herbaceous-layer species composition compiled after 28 attempts in two axes and exhibited low stress (0.109), as well as a linear R^2 of 0.951 showing that the ordination was acceptable for use in this analysis. An “adonis” analysis revealed significant differences between the three intensity groups ($F_{2,39}=15.362$, $p=0.001$, $R^2=0.454$). Within the ordination, the untreated reference sites are clearly dissimilar from both treatment intensities, but the above- and below-ground intensity groups have more overlap in the ordination (Fig. 4). The “pairwise.adonis” tests revealed significant differences in species composition between all intensity classes (Table 3). The SIMPER analysis revealed that the cover variables most responsible for the differences between intensity classes consist of variables with relatively low importance to conservation, such as Amur honeysuckle, ground-cover types, or plants with relatively low C-values (Table 3). The average C-value of the plants that contributed most to the dissimilarity between all intensity classes was 3.5 out of a possible 10. This indicates that while species composition does differ between intensity classes, the differences are not necessarily

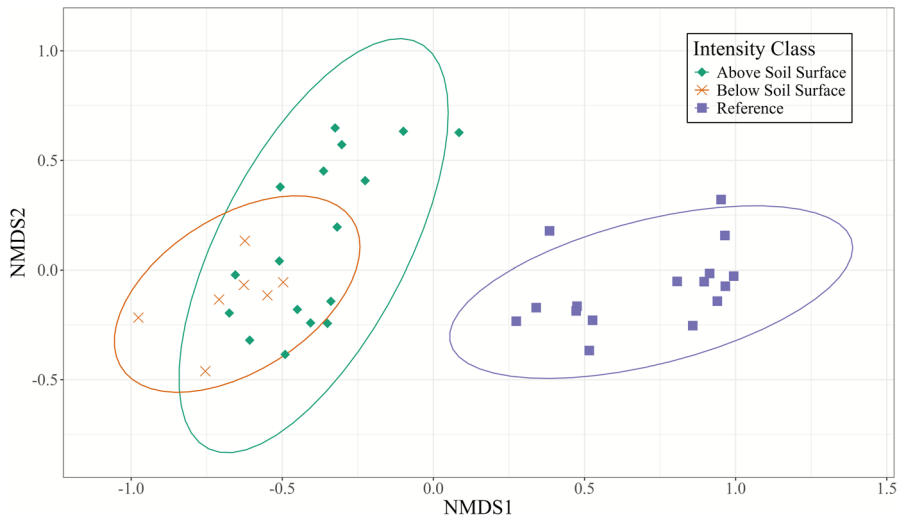


Fig. 4 A non-metric multidimensional scaling ordination comprised of percent cover of herbaceous-layer plant species and ground-cover types. Intensity classes of mulching-head treatment with 95% confidence interval ellipses surrounding them are displayed

driven by the establishment of plant species considered to be of particularly high value in conservation efforts.

Discussion

Our study confirmed the short-term results of Frank et al. (2018) by identifying a strong association between the intensity of mulching-head treatment and decreased volumes of sprout-origin Amur honeysuckle. This trend was confirmed immediately post-treatment (Frank et al. 2018), but differences persisted three years after treatment in our study (Fig. 1). Treatments deeper into the ground have the ability to inhibit the sprouting of treated stumps, most likely because deeper treatments resulted in greater damage to the root collar. Amur honeysuckle does not possess the ability to generate new sprouts from distal, horizontal roots (i.e. ‘root sucker’; B. Rivera, personal observation), so damaging the root collar likely reduces the number of dormant, preformed buds available for sprouting.

However, with soil disturbance – like those from mulching treatments – generally comes an increased risk of invasive or less-desirable species establishing in the disturbed seedbed of the treated area (Kulmatiski et al. 2006). Our results indicate that the number of species present in post-treatment plots was higher than in pre-treatment plots, regardless of intensity (Fig. 2, Table 1). However, increases in average C-value and FQI also were associated with post-treatment plots, indicating that species composition following mulching-head treatment did not include increased proportions of invasive plant species or more-weedy species

Table 3 Results from a “pairwise.adonis” comparison of species composition between intensity classes (**in bold**) and SIMPER analyses, comparing the five herbaceous-layer species or ground-cover types which most related to Bray–Curtis dissimilarity between intensity classes

Pairs	Contributing Species	C-value	Mean Difference in Percent Cover	% Contribution	Df	Sums Of Squares	F	R ²	p value
Below vs Above	-	-	-	-	1	0.457	5.104	0.188	0.006
	<i>Pilea pumila</i>	2	18.56	5.886%	-	-	-	-	0.018
	<i>Symphytotrichum</i> spp.	5.46	1.69	0.711%	-	-	-	-	0.031
	<i>Viola striata</i>	4	0.66	0.370%	-	-	-	-	0.044
	<i>Pericaria virginiana</i>	3	0.71	0.217%	-	-	-	-	0.001
Below vs Reference	<i>Populus tremuloides</i>	2	0.45	0.144%	-	-	-	-	0.031
	-	-	-	-	1	1.700	29.746	0.586	0.003
	<i>Fine Woody Debris</i>	NA	-34.33	12.348%	-	-	-	-	0.001
	Grasses	NA	29.00	10.308%	-	-	-	-	0.001
	<i>Pilea pumila</i>	2	26.82	9.368%	-	-	-	-	0.001
Above vs Reference	<i>Carex</i> spp.	NA	17.22	6.049%	-	-	-	-	0.001
	Bare ground	NA	-16.07	5.864%	-	-	-	-	0.001
	-	-	-	-	1	1.299	16.607	0.349	0.003
	Grasses	NA	21.21	7.063%	-	-	-	-	0.003
	<i>Lonicera maackii</i>	0	15.15	5.544%	-	-	-	-	0.003
	Bare ground	NA	-11.23	4.058%	-	-	-	-	0.005
	<i>Ageratina altissima</i>	2	4.90	1.688%	-	-	-	-	0.002
	<i>Vitis</i> spp.	4.86	3.88	1.272%	-	-	-	-	0.001

Species which contributed the most to the Bray–Curtis dissimilarity between two intensity classes as determined by the SIMPER analysis were listed in descending order of % Contribution underneath the “pairwise.adonis” comparisons of the same groups. All tests of significance were set at $\alpha = 0.05$.

of lower conservation value. While there may be unobserved negative effects from soil disturbances on the plant community, they seem to be outweighed by the effects of honeysuckle removal.

Not only did increasing intensities of mulching-head treatment correlate to decreasing volumes of sprout-origin Amur honeysuckle, but our results also indicate that more intense mulching-head treatments correlated with increasing herbaceous-layer species diversity, richness, evenness, FQI, and average C-value (Fig. 3). However, the question remains whether this trend would continue with even deeper applications of the mulching head. Managers implementing treatments for our study avoided maximizing soil disturbance and damage to native saplings (Frank et al. 2018), which could have led to a lower intensity of treatment compared to techniques where those precautions were not taken. This does, however, likely replicate how land managers would implement this technique. The maximum mean intensity/depth for a plot was 1.5 cm below the soil surface (Fig. 1). It is unclear if even deeper treatments would increase the susceptibility of a plot to invasive species establishment and may warrant future study. Increases in plant species diversity, richness, evenness, average C-value, and FQI are likely being driven by decreasing dominance of Amur honeysuckle stump sprouts at sites with more intense treatments. Less competition from Amur honeysuckle sprouts when stumps are treated with herbicide can lead to a more vigorous short-term response from the herbaceous layer (Shields et al. 2015), and our study shows this trend also occurs with increased intensity of mulching-head treatments. Amur honeysuckle is known to inhibit understory plant growth through shading (McNeish and McEwan 2016), and is potentially allelopathic (Bauer et al. 2012), so with less Amur honeysuckle present in more intensely treated areas, more native plants have the opportunity to become established.

While the conservation value of these communities increased with treatment and was correlated with more intense mulching-head treatments, neither pre- nor post-treatment plots exhibited particularly high average C-values (means of 2.05 and 2.73, respectively). According to Rothrock and Homoya (Rothrock and Homoya 2005), forested natural areas occurring in the same region as our study sites exhibited average C-values ranging between 3.8 and 4.1. Both of these sites (Lugar Farm and PWA) are typical forests in the Central Hardwood Region, which has a long history of human disturbance in its forests (Jenkins 2013). Agricultural use and abandonment, livestock grazing, high-grade logging, and surface fires have long altered the species composition of this region, and, thus, the existing species pool in the seed bank or dispersal from the local area may not include plant species of high conservation value. While *Pilea pumila* may be considered an early seral species, many of the plant species responsible for the increases in diversity we observed following treatment, such as *Ageratina altissima* (Jenkins and Parker 1999), are often associated with these historical disturbances rather than more recent disturbances (Table 3). Deer browsing may have lowered the overall C-value of our plots since we did not fence the treatments and could be an area of future research. Overall, the species driving changes between the different intensity classes (above soil surface, below soil surface, and untreated reference sites) were also of low conservation value in Indiana. More intense mulching treatments do, however, create opportunities for

the establishment of more plant species, which could include active post-treatment seeding by land managers.

Our results show that short-term (< 1 year) observations of reduced honeysuckle sprouting with greater treatment intensity (Frank et al. 2018) persisted after three years. Mulching-head treatments appear to be an effective and efficient technique to control heavy invasions of Amur honeysuckle, especially when applied with deeper intensity. Not only did more intense mulching-head treatment reduce Amur honeysuckle sprouting (Fig. 1), but it also led to increased plant diversity and conservation value in the herbaceous layer. A common relationship exists between the treatment of Amur honeysuckle and the emergence of invasive garlic mustard after treatment (Shields et al. 2015), indicating that the control of one invasive plant can lead to the establishment of other invasive plants after treatment. However, no such relationship was found in our data, with no clear increase in any particular invasive plant species after treatment. Future studies should examine the effects of deeper treatment intensities in less historically disturbed forest. Additionally, determining the relationship of mulching treatments with post-treatment invasive species establishment in forests with less historical disturbance than in this study will help show how broadly this control technique can be applied in other forest systems. Sensitive plant species are not common at our sites may be more vulnerable to non-target effects of mulching-head treatments. Native tree regeneration could also be affected and examined in future studies.

Finally, land managers should strongly consider adding intense mulching-head treatments to their suite of techniques to control heavy shrub invasions in historically disturbed forests. Amur honeysuckle is an archetypal invasive woody shrub (Luken and Thieret 1996) which suggests that this treatment technique will be effective against an array of other East Asian shrub species. While the cost of mulching rental may be prohibitive in some cases (Bailey et al. 2011), it is a fixed cost, and rapid treatment means that scaling up to large invasions may be cost-effective. Reduced sprouting of treated stumps in more intense mulching-head treatments allows for less herbicide usage in initial and follow-up treatments. Foliar applications a year after mulching treatment have been effective in greatly reducing Chinese privet densities and may be a recommendable strategy for controlling other invasive shrubs following mulching treatments (Hanula et al. 2009). In summary, mulching-head treatment is a promising technique for controlling invasive shrubs, and its effectiveness can be improved by increasing intensity without negatively impacting herbaceous-layer responses.

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Data Availability Data is available upon request.

Declarations

Conflict of interest The authors declare no conflict of interest.

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