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Native Hardwood Tree Seedling Establishment Following Invasive Autumn-Olive (*Elaeagnus umbellata*) Removal on a Reclaimed Coal Mine

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Abstract

The Appalachian region of the United States is home to the largest temperate deciduous forest in the world, though surface mining has caused significant forest loss. Many former coal mines are now dominated by invasive plants, which often inhibit establishment of desirable species, especially slower-growing native trees. Autumn-olive (*Elaeagnus umbellata* Thunb.) is a nonnative, nitrogen-fixing shrub that was historically planted on former coalfields, but now impedes reclamation. To better understand the influence of *E. umbellata* management practices on hardwood establishment, we evaluated two common management practices: cutting and cut stump herbicide treatment. Planted native tree species, including black cherry (*Prunus serotina* Ehrh.), pin oak (*Quercus palustris* Münchh.), and red maple (*Acer rubrum* L.), were monitored for survival and performance over two growing seasons following *E. umbellata* removal. In each plot, we also measured plant-available nitrate (NO_3^-) and ammonium (NH_4^+) in soils using ionic exchange membranes. At the end of the first growing season, native tree survival was high, and the presence or absence of *E. umbellata* had little effect on tree survival or growth, despite the higher plant-available nitrate where *E. umbellata* was present. By the end of the second growing season, native tree survival dropped to 20% to 60% and varied among *E. umbellata* treatments. Survival was highest when *E. umbellata* was cut and treated with herbicide, though tree growth was similar across all treatments without *E. umbellata*. When establishing native trees to replace *E. umbellata*, cutting and herbicide application treatment of the invader resulted in the highest overall efficacy (100% control), though the most cost-effective method may be to simply cut mature stands despite regrowth, as this resulted in equivalent native tree growth over 2 yr. While this allowed *E. umbellata* regeneration, it provided sufficient invader control to allow initial tree establishment. Cutting and herbicide application treatment resulted in less *E. umbellata* regeneration and appears to provide greater assurance that established trees will persist over the long term.

Introduction

The Appalachian region of the United States is home to the Earth's largest temperate deciduous forest, housing some of the most biologically diverse forest systems in nontropical regions (Ricketts et al. 1999). Appalachian forests provide many ecosystem services, such as water-quality protection, carbon sequestration, and wildlife habitat, and economic benefits, such as timber production. Surface mining for coal, however, has caused large-scale disturbances, net loss of productive forests, and forest fragmentation (Drummond and Loveland 2010; Wickham et al. 2007). Coal mining in particular has affected >600,000 ha in Appalachia, the majority of which has not been returned to forests or any other type of productive land use, often resulting in unmanaged lands that are invaded by nonnative plants (Zipper et al. 2011a).

Severe erosion, sedimentation, and landslides were significant concerns for Appalachian coal surface mines before 1977 (Skousen and Zipper 2014). As a result, the U.S. Congress passed the Surface Mining Control and Reclamation Act (SMCRA, Public Law 95-8) to standardize and mandate reclamation practices. SMCRA required coal-mining companies to obtain a permit and a performance bond before mining to ensure land reclamation adequate to restore an area to its original use or a use of higher value [Sect. 515(b)(2)]. In Appalachia,

Management Implications

Surface mining is widespread globally and represents a severe and often long-term disturbance. Following mining, as with most disturbed sites, these lands are colonized by exotic plants. However, in the United States, mining companies are required to reclaim former coalfields to specific standards—often to native forests. Thus, rapidly colonizing exotic invasive plants often interfere with reclamation goals; such interference can include competing with planted tree seedlings. Autumn-olive (*Elaeagnus umbellata* Thunb.) is one of the most common invasive plants on former coalfields in the eastern United States. This fast-growing, nitrogen-fixing shrub tolerates poor soils and is readily dispersed by animals. Land managers often find it necessary to remove *E. umbellata* before establishing native trees but lack efficacious management practices.

This study was designed to remove mature *E. umbellata* and establish native tree seedlings. We evaluated two common management practices, cutting and cut stump herbicide application, for their efficacy in managing *E. umbellata*, as well as how they compared with no *E. umbellata* removal and an *E. umbellata*–free area for native tree sapling establishment. After 2 yr, the cutting plus herbicide treatment resulted in complete *E. umbellata* control and had the highest native tree seedling survival and growth. However, the more cost-effective cutting-only treatment provided only slightly poorer performance and may be the preferred choice for reclamation of large, heavily infested areas.

common ways of meeting SMCRA reclamation requirements are reestablishment of native hardwood forest or creation of livestock pasture (Skousen and Zipper 2014).

However, under SMCRA, reclamation assessment may occur only 5 yr after reclamation has been completed. Historically, this resulted in many projects focusing on short-term mitigation and not on restoration of native forest ecosystems (Angel et al. 2005). In recent years, landowners and mine operators have been embracing mine reclamation using the Forestry Reclamation Approach that attempts to restore native forest trees (Burger et al. 2005). However, these techniques use herbaceous plants that minimize competition with native trees and may leave the mine sites more vulnerable to invasion by exotic plants (Fields-Johnson et al. 2012). As such, invasive exotic plants have become a primary concern for those responsible for reclamation. Furthermore, exotic plants have become widespread and are implicated in a variety of negative ecosystem impacts, including acting as impediments to reclamation success (Barney et al. 2013).

On former coal mines in the Appalachian region, autumn-olive (*Elaeagnus umbellata* Thunb.) is one of the most common invasive exotic plants (Lemke et al. 2013; Oliphant et al. 2017; Zipper et al. 2011b). *Elaeagnus umbellata* was brought to the United States in 1830 and is native to Pakistan, China, and eastern Asia (Ahmad et al. 2006). In the 1960s, it was intentionally planted for erosion control, as a nurse species for tree plantations, and to provide wildlife habitat and food on disturbed lands (Fowler and Fowler 1987; Lemke et al. 2013). These factors, and ease of establishment, resulted in widespread planting of *E. umbellata* on reclaimed mine sites. Although it is no longer commonly planted today, *E. umbellata* is widespread and continues to invade and proliferate on former Appalachian mine sites (Lemke et al. 2013; Oliphant et al. 2017; Zipper et al. 2011b).

Elaeagnus umbellata has many traits that contribute to its success on reclaimed mine sites, including the ability to fix atmospheric nitrogen, produce numerous drupes, and grow in acidic, loamy soils (Ahmad et al. 2006). This large shrub has the potential to produce multiple stems from the main root (Moore et al. 2013) and quickly forms a broad, dense crown (Evans et al. 2013) that suppresses native species through intense shade (Lemke et al. 2013) and formation of dense patches (Catling et al. 1997). *Elaeagnus umbellata* establishment and proliferation on mine sites interferes with forest restoration (Evans et al. 2013) and can be expensive and time-consuming to remove. It can be managed on reclamation sites by physical cutting with large equipment, but little information exists regarding management efficacy or the subsequent effects on planted native trees.

We investigated the consequences of the presence and management of *E. umbellata* on native hardwood tree seedling establishment and growth. Specifically, we had the following objectives: (1) compare hardwood seedling survival and growth over 2 yr in reclaimed areas where mature *E. umbellata* was left unmanaged, reclaimed areas where *E. umbellata* was never present, and reclaimed areas where *E. umbellata* was managed in two different ways: mechanical removal alone and mechanical removal plus cut stump herbicide application; (2) evaluate whether *E. umbellata* changes plant-available soil nitrogen, which may affect tree growth; (3) identify which scenario achieves the best, most effective approach for native tree seedling growth. This study is intended to inform both management and reclamation practices and to improve understanding of basic ecological interactions among invasive and native woody plants.

Materials and Methods

The following experiments were carried out at the Powell River Project, a 445-ha area located in Wise County, VA, and used cooperatively by Virginia Tech, natural resource industries, and other educational institutions to conduct mine-reclamation research.

To meet our objectives, we conducted an experiment to investigate hardwood tree seedling growth on reclaimed lands in response to four different *E. umbellata* treatments. All *E. umbellata* used in this study were large, mature, multistemmed shrubs, approximately 3- to 4-m tall with dense canopies. The study area was a previously reclaimed mine area that included dense patches of mature *E. umbellata* interspersed with areas with no known presence or history of *E. umbellata*. Each 8 by 8 m block was 75% covered with *E. umbellata* and 25% open area. Eight blocks were randomly located within the same 1-ha area described above. Each block was subdivided into four 3 by 3 m plots with 2-m buffers between plots within each block.

We set up the following four treatments in fall 2014 in a randomized complete block design:

1. *Elaeagnus umbellata* unmanaged;
2. mechanical control of *E. umbellata* (cut only);
3. mechanical control of *E. umbellata* followed by cut stump herbicide application (cut and sprayed); and
4. *Elaeagnus umbellata* never present (no *E. umbellata*).

Treatments 1 to 3 were sited within the 75% of the block that was covered by *E. umbellata*. Treatment 4 was in the 25% of the block where *E. umbellata* was never present. To simulate how *E. umbellata* could be managed on a large scale, we cut *E. umbellata* with a chainsaw at 10 to 15 cm above the soil surface for Treatments 2 and 3, and the biomass was removed from the site. For Treatment 3, we also applied triclopyr (Garlon® 4 Ultra, 480 g ae L^{-1}, Dow AgroSciences, Indianapolis, IN) at 20% v/v in basal oil (Alligare, Opelika, AL) to the cut stumps. The ground cover in Treatments 1 to 3 was bare ground throughout the experiment, while all blocks in Treatment 4 were 80% to 90% sericea lespedeza [*Lespedeza cuneata* (Dum. Cours.) G. Don] and tall fescue [*Lolium arundinaceum* (Schreb.) Darbysh.], which commonly occur on reclaimed mines throughout Virginia coal-mined areas, with the remaining 10% to 20% being bare ground. The ground cover composition did not change over the course of the experiment. Due to restrictions of the location where the experiment was conducted, we were unable to replicate the experiment in space. This is an active mine site with a variety of restrictions on what can be done. Thus, we were limited to a single site-year.

Reclamation specialists typically hand transplant 1-yr-old bare-rootstock seedlings in late winter. Therefore, we used 1-yr-old bare-rootstock seedlings of three native species, pin oak (*Quercus palustris* Münchh.), red maple (*Acer rubrum* L.), and black cherry (*Prunus serotina* Ehrh.), which were chosen for their local use and rapid growth rate on reclaimed mine sites (Davis et al. 2012). Three individuals of each species were planted haphazardly into each treatment in each block in mid-March 2015, spaced 0.5 to 1 m apart. For Treatment 1, tree seedlings were planted under the existing *E. umbellata* canopy. All trees were obtained from the same supplier and were of similar size: *P. serotina* mean height was 43 cm, *Q. palustris* mean height was 44 cm, and *A. rubrum* mean height was 15 cm. Within each plot, we monitored survival in October 2015 and 2016 for each native tree seedling. In October 2016 (the end of the second growing season), we recorded native tree seedling height and stem diameter at ground level, and all surviving planted hardwoods were excavated, separated into above- and belowground sections, and dried at 70 C until constant weight. Basal tree diameter was strongly correlated ($r^2 = 0.76$) with tree height and biomass and was therefore not analyzed. We also recorded whether *E. umbellata* regrew (for Treatments 2 and 3) in October 2015 and 2016. In all blocks, Treatment 2 (cut-only) *E. umbellata* regrew, and in Treatment 3 (cut stump) we observed no regrowth. We did not record additional measures, as the treatment effect was absolute.

Elaeagnus umbellata is a nitrogen fixer and has the potential to alter nutrient cycles, which may affect tree seedling growth differently across treatments. Therefore, in each plot, ionic exchange membranes (IEMs; GE Osmonics, Trevose, PA) were used to measure soil nitrate (NO_3^-) and ammonium (NH_4^+) (Bowatte et al. 2008; Duran et al. 2013; Subler et al. 1995). All IEMs were cut into 5 by 10 cm rectangles and hole-punched at the top. IEMs were immersed in a 1 M solution of sodium chloride (NaCl), which allows either sodium (Na^+) or chloride (Cl^-) ions to fill all exchange sites. Anion and cation membranes were stored in the 1 M NaCl at 4 C in separate containers until put into the field. Before being placed in the field, membranes were rinsed with deionized (DI) H_2O. Within each plot, two IEMs (anion and cation) were installed at a 45° angle in the soil, ensuring no overlaps or wrinkles. After 30 d in the field during the month of August 2015, each membrane was placed into its own plastic bag, transported on ice back to the lab, and then stored at 4 C for <7 d. For the extraction of inorganic nitrogen, soil particles were rinsed off the membrane surface using DI H_2O, and then the IEMs were individually submerged in 1 M potassium chloride (KCl). They were then placed for 1 h on a reciprocal shaker at 22 rpm (Hangs et al. 2004; Subler et al. 1995). A TrAAcs 2000 Analytical Console (Bran + Luebbe, Analyser Division, Norderstedt, Germany) that was connected to an XY2 Auto sampler (SEAL Analytical, Mequan, WI) was used for the analysis of extracts for nitrate (NO_3^-) and ammonium (NH_4^+).

Data Analysis

To test for treatment effects on hardwood tree seedling survival, we conducted a logistic regression with tree species, treatment, and their interaction as fixed effects. To test for treatment effects on final height and total biomass of hardwood tree seedlings, we conducted a mixed model with blocks as a random effect; tree height at planting as a covariate (to account for tree species size differences); and tree species, treatment, and their interaction as fixed effects. In both cases, the interaction between treatment and tree species was not significant ($P > 0.05$) and was removed from the final model. A one-way ANOVA was conducted to test for the effect of *E. umbellata* control treatments on quantities of NO_3^- and NH_4^+. Means were separated using Tukey-Kramer honestly significant difference post hoc tests. All statistical analyses were conducted using JMP Pro 13.

Results and Discussion

Native Tree Survival

Survival was high (>80%) the first year and did not differ among the three native tree species, but survival did vary among treatments (Table 1). Hardwood tree seedlings had the highest survival in the *E. umbellata* cut-and-spray treatment compared with the no *E. umbellata* treatment (Figure 1A). By the second year, survival dropped precipitously for all three native tree species (Figure 1) and differed among treatments and among tree species (Table 1) with the smaller *A. rubrum* having the highest mortality rate. Survival was the same in all treatments that had *E. umbellata*, but higher when *E. umbellata* was cut and sprayed (>60%) than in the no *E. umbellata* treatment (~23%).

Hardwood Performance

Hardwood tree seedlings grew taller in plots where *E. umbellata* had been managed (both cut only and cut and spray) than in the unmanaged *E. umbellata* plots (Table 1; Figure 2A). With a somewhat different pattern, total biomass was greater in the cut-only and the no *E. umbellata* treatments than in the unmanaged *E. umbellata* treatment (Figure 2C). *Prunus serotina* and

Table 1. Logistic regression for tree survival and mixed-model analyses of tree height and total biomass at the end of the second growing season.

		Tree survival 2015	Tree survival 2016	Tree height	Tree biomass
	df	P-value	P-value	P-value	P-value
Block	7	0.0071	0.1937	0.5851	0.6188
Tree species (S)	2	0.1383	< 0.0001	< 0.0001	< 0.0001
Treatment (T)	3	0.0311	< 0.0001	0.0033	0.0219

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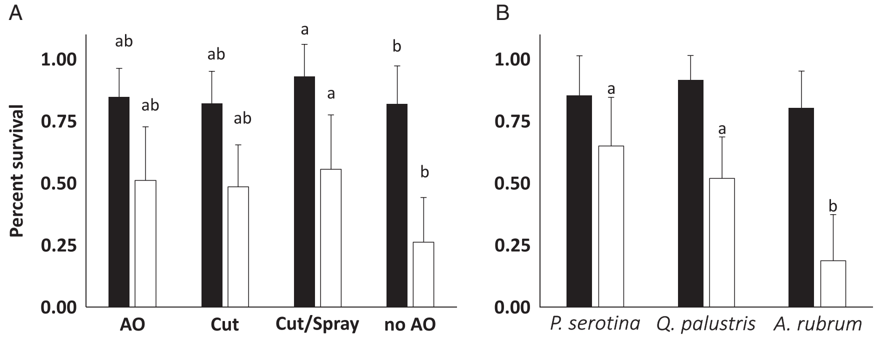

Figure 1. Percent survival of hardwood tree seedlings across the four treatments (A) and by species across all treatments (B) at the end of the first (filled bars) and second (open bars) growing season. In year 1, survival varied among treatments ($P = 0.031$) but not trees ($P > 0.05$), and in year 2 percent survival varied among treatments ($P < 0.0001$) and trees ($P < 0.0001$). Bars with different letters are significantly different ($P < 0.05$).

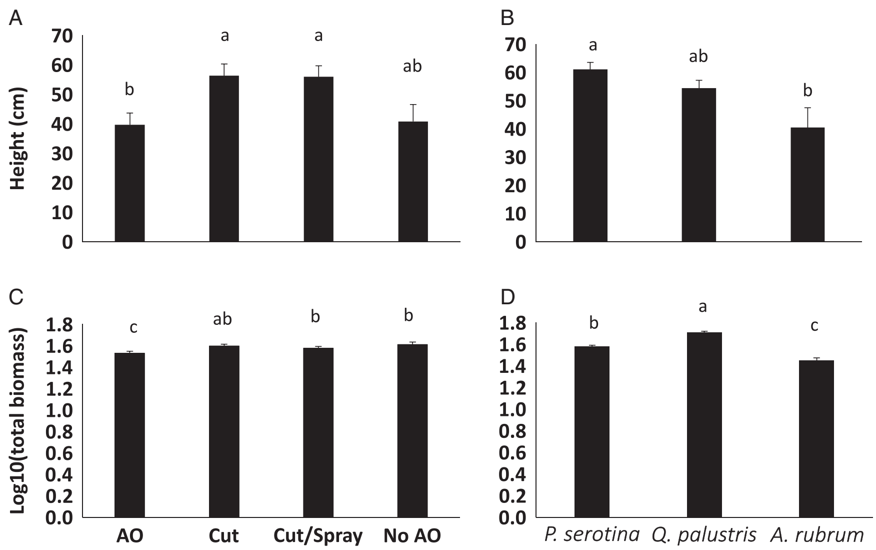

Figure 2. Mean height and total biomass (aboveground + belowground, log_{10} transformed) after two growing seasons of the planted native trees across treatments (A, C) and by tree species (B, D). Bars with different letters are significantly different ($P < 0.05$).

Q. palustris heights did not differ from one another, and *P. serotina* was taller than *A. rubrum* across all treatments (Figure 2B). *Quercus palustris* had the most total biomass, and *P. serotina* had more biomass than *A. rubrum* (Figure 2D). Interestingly, root biomass was 10% higher in plots with *E. umbellata* than in plots with no *E. umbellata* ($P = 0.03$, unpublished data).

IEMs

Plant-available soil nitrogen as nitrate (nitrate-N) was more than two times greater where *E. umbellata* was still intact (unmanaged *E. umbellata* treatment) than in the no *E. umbellata* treatment ($P = 0.0202$; Figure 3), but soil nitrate-N levels in the cut-only and cut-and-spray treatments did not differ statistically from those of other treatments. There was no significant difference among treatments in plant-available soil ammonium N (NH_4^+ -N) ($P = 0.9351$, unpublished data). Overall, we found that a single management activity of the invasive *E. umbellata* resulted in improved performance of transplanted native tree seedlings in a reclaimed coal mine. However, contrary to our expectations, we did not see clear soil nitrogen contributions from *E. umbellata*, a nitrogen fixer, that we expected to benefit tree performance.

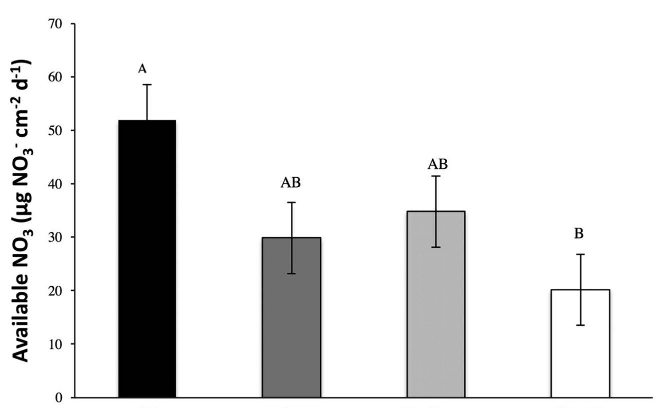

Figure 3. Plant-available soil nitrogen as nitrate (NO_3^-) (mg N cm^{-2} d^{-1}) within each management plot with SE.

Native tree seedlings performed as well in plots following *E. umbellata* management as in plots that had no history of *E. umbellata*, though long-term performance would be impacted by potential *E. umbellata* regrowth, particularly in plots where no herbicide treatment was applied.

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In line with our results for *E. umbellata* management, Byrd et al. (2012) found that mechanical removal with herbicide treatment of stumps provided greater *E. umbellata* control on mined lands than did mechanical removal alone. Evans et al. (2013) also found that physical removal of *E. umbellata* without accompanying herbicide treatment failed to provide effective control. After four growing seasons, vigorous regrowth of *E. umbellata*, apparently from living rootstock as well as from seed, threatened survival of planted trees in some reforestation areas, as the *E. umbellata* had overtopped some of the planted trees with a spreading canopy (Evans et al. 2013).

Overall, native tree survival was initially high, but declined to 20% to 60% by the end of the second growing season. Planted tree survival appeared to be strongly reduced by competitive plant communities, whether *E. umbellata* was always present or regrown (cut-only treatment), as well as in the dense communities that lacked *E. umbellata*. Competitive herbaceous and forb communities are known to cause reduced survival and growth of trees planted on coal surface mines (Franklin et al. 2012). When reforesting former coal mines that have well-established vegetation, control of competing herbaceous vegetation is recommended until planted tree canopies are able to emerge from the competition (Burger et al. 2013).

The larger *P. serotina* and *Q. palustris* species responded similarly across the treatments, though the smaller *A. rubrum* had much lower survival across all treatments. Although not compared statistically, mean growth by *A. rubrum* (approximately 25 cm, on average, computed as change in height relative to average height for seedlings) was greater than for the other two species (<20 cm). We have reported height as our primary metric, however, because the planted trees' extension of canopy above competing vegetation is essential to persistence over longer terms. While hardwood seedling survival was highest when *E. umbellata* was cut and sprayed, there were no differences in seedling height or biomass among the *E. umbellata* management plots at the end of the second growing season. Though native tree seedlings were tallest in *E. umbellata* managed plots, they had more biomass in any treatment where *E. umbellata* was managed or never existed.

Elaeagnus umbellata creates root nodules that have a symbiosis with soil actinomycetes (*Frankia* spp.), giving them the ability to fix and use atmospheric nitrogen (Paschke et al. 1989). This symbiosis, combined with rapid growth rates and endozoochory, has allowed *E. umbellata* to thrive on degraded lands. In fact, there is evidence that in soils underneath *E. umbellata*, there are higher nitrification rates, and nitrate leaching underneath *E. umbellata* can be comparable to a fertilized cornfield (Baer et al. 2006). Nitrogen is one of the most important components of ecosystems worldwide, influencing ecosystem function (e.g., nutrient cycling) and structure (e.g., diversity) (Vitousek et al. 2002). Disturbance can often lead to pulses in plant nutrients, which can lead to invasion and change successional trajectories (Davis et al. 2000). However, in highly disturbed sites such as coal mines, which commonly use fractured bedrock as the growing medium, plant-available soil nitrogen is often lacking (Li and Daniels 1994). In many cases, disturbed nutrient-poor terrestrial ecosystems are commonly colonized by nitrogen-fixing exotic plants (Vitousek and Walker 1989; Vitousek et al. 1987).

Therefore, we expected the tree seedlings to grow better in plots with *E. umbellata*, managed or unmanaged, than in the plots where there is no *E. umbellata* present due to the increased concentration of plant-available nitrogen. The higher soil nitrogen under the growing *E. umbellata* was correlated with higher root production for all trees compared with those growing in plots with no *E. umbellata* history. This may have resulted from nitrogen foraging but did not translate to overall larger trees. Thus, it appears there is no ecologically relevant short-term effect of *E. umbellata* management on soil nitrogen. While nitrogen availability did not appear to affect tree seedling growth, as mentioned above, competition from other species appeared to have strong effects on tree performance. Additionally, in all cases where *E. umbellata* was only cut, it regrew the following year. Vigorous root suckering by *E. umbellata* following cutting appeared to reduce planted trees' survival, but had no effect on surviving trees' biomass over the first 2 yr.

The reduced size of planted trees in the unmanaged *E. umbellata* plots, relative to one (biomass) or both (height) management treatments and despite those soil nitrogen levels, may be evidence of competitive effects by the standing *E. umbellata* on the ability of planted tree seedlings to access essential resources such as sunlight. An ability to achieve rapid height growth is essential if planted tree seedlings are to successfully replace *E. umbellata*, given the capability of *E. umbellata* to reestablish, even if controlled initially, and to achieve rapid height growth and canopy cover once reestablished. Planted trees' survival on such mine sites will be affected negatively if they are overtopped by regenerating *E. umbellata*, as demonstrated by Evans et al. (2013), who found progressive declines of surviving planted tree numbers occurring over the second, third, and fourth growing seasons in association with rapidly expanding canopy cover by *E. umbellata* that had regenerated following mechanical removal with no herbicide treatment.

Once *E. umbellata* becomes established, eradication requires tremendous effort and expense. In fact, for most invasive species, eradication, or the complete elimination of the species in the area, scales exponentially with the size of the invasion (Rejmánek and Pitcairn 2002). The difficulties of *E. umbellata* eradication stem from prolific seed production, dispersal via wildlife, and the ability to resprout after cutting or damage (Kohri et al. 2002), resulting in aggressive colonization that hinders native woody species dispersal on reclaimed mine areas. Often, a single mechanical removal is used to control dense groves of *E. umbellata* on former coalfields that are hindering the establishment and growth of hardwood tree species (Byrd et al. 2012). However, mature *E. umbellata* is known to aggressively resprout when cut (Campbell et al. 1989), which is what we observed here—vigorous stand development from root suckers in the second year. *Elaeagnus umbellata* did not resprout when cut stumps were treated with herbicide, thus reducing competition with native trees. Though the similar responses of the native tree seedlings in the two *E. umbellata* management plots, whether sprayed or not, suggest that short-term survival and growth were similarly affected by competition with resprouting *E. umbellata* and other standing vegetation, long-term performance may change as the plant communities change with time. Cutting alone is more cost-effective than cutting and treating with herbicide, especially for managing large tracts of land with widespread invasions.

Elaeagnus umbellata also has the potential to impact ecosystem processes through nitrogen fixation and alteration of nutrient cycling (Schlesinger and Williams 1984), giving it the potential to impact the long-term development of forests (Moore et al. 2013). Successful management of *E. umbellata* with all techniques requires continual management (Byrd et al. 2012). Despite the known effects of *E. umbellata*, our results suggest that planted tree seedling survival and performance is highest when *E. umbellata* is cut and herbicide treated, although surviving tree seedling size is equivalent with cutting alone. It is unlikely that trees planted in mature *E. umbellata* stands will establish. In addition to its capacity for rapid proliferation and rapid growth and the dense shading produced by its canopy, *E. umbellata* can also suppress native plant establishment through allelopathic mechanisms (Orr et al. 2005). Thus, managers should prioritize preventing *E. umbellata* establishment when possible. Otherwise, cutting *E. umbellata* alone can appear as a cost-effective and practical management choice when attempting to establish native trees. However, prolific growth by *E. umbellata* resprouts from intact roots was observed in the cut-only management treatment, and prior research has demonstrated that *E. umbellata* can grow more rapidly than planted hardwood trees on coal surface mines, suggesting that survival may have been further impaired had we left the planted trees in place for longer than 2 yr. The cutting and herbicide treatment resulted in less *E. umbellata* resprouting and appears to provide a higher probability, relative to the cut-only treatment, that planted trees would be able to establish and persist successfully in the long term. Our results provide useful information for short-term *E. umbellata* management, but longer-term studies are needed to fully realize their ramifications on native tree growth and performance.

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