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Sapling white pine (*Pinus strobus* L.) exhibits growth response following selective release from competition with glossy buckthorn (*Frangula alnus* P. Mill) and associated vegetation

Nicholas B. Lanzer*, Thomas D. Lee, Mark J. Ducey, Stephen E. Eisenhaure

Department of Natural Resources and the Environment, University of New Hampshire, 114 James Hall, 56 College Rd, Durham, NH 03824, USA

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ABSTRACT

Invasive glossy buckthorn (*Frangula alnus*) hampers management of white pine (*Pinus strobus*) in the northeastern USA, especially when these species co-establish following harvest activities. Our objective was to test the effects on pine sapling growth of a simple, quick, and novel silvicultural procedure involving local buckthorn stem removal. We identified 75 five-year-old pine saplings in a Durham, NH, forest regeneration area that was clear-cut in 2009 and which was heavily invaded by buckthorn. All selected pine saplings were surrounded primarily by glossy buckthorn. Around each of 50 of these pine saplings, a 1 m radius was cleared ('cut only' treatment) and for half of these there was a follow-up herbicide application ('cut + herbicide' treatment). Remaining saplings were untreated controls. After one growing season, pines responded to treatment with increased terminal leader biomass (+75%), basal stem diameter (+12%) and bark starch (+140%). Treated pines displayed even greater diameter increase (+29%) after two growing seasons. None of these variables differed across the two treatments. Height of treated pines did not differ from controls, even after the second growing season. When herbicide was used, there were 86% fewer buckthorn sprouts in treated areas, but pine mortality was five times greater ($n = 5$) than in the cut only treatment ($n = 1$). Our results show that, regardless of herbicide use, those pines cleared of surrounding vegetation and not subject to post-treatment mortality exhibited increased vigor and growth, suggesting a greater potential to eventually outgrow competing buckthorn and thus more rapidly reach commercial size.

1. Introduction

Non-native invasive woody plants, increasing both in overall abundance and number of species within eastern United States forests, present a challenge to forest management (Webster et al., 2006). Invasive plants often establish in high densities and can displace native forest vegetation through competition (Bais et al., 2003; Stinson et al., 2006). Such displacement can reduce the abundance or growth of native flora (e.g., Forseth and Innis, 2004; Hamelin et al., 2016, 2017) and wildlife species dependent on them (e.g., Burghardt et al., 2010; Fickenscher et al., 2014) and may encourage additional invasion (Simberloff and Von Holle, 1999). Invaders can compromise ecosystem services, such as hydrologic cycling (Levine et al., 2003), fire regimes (Mack et al., 2000), carbon sequestration (Peltzer et al., 2010), and nutrient cycling (Ehrenfeld et al., 2001; Evans et al., 2001; Heneghan et al., 2006), with potentially expensive consequences. Traditional goals of forestry (timber, water quality, wildlife, and recreation) are sometimes difficult to achieve with non-native plants present and such difficulties, as well as the spread of the plants that cause them, are not explicitly addressed by traditional silvicultural methods. Accounting for invasive plant proliferation and potentially diverse impacts makes for a complex management calculus.

One important invader is glossy buckthorn (*Frangula alnus*, hereafter "buckthorn"), a shrub originating in Europe and now common in much of the eastern U.S. and southeastern Canada. With its rapid growth (Webster et al., 2006) and early leaf-out (Godwin, 1943), buckthorn can establish dense thickets which inhibit the development of native seedlings (Fagan and Peart, 2004; Hamelin et al., 2016; Lee et al., 2016). Moderately shade tolerant (Frappier et al., 2003; Cunard and Lee, 2009), buckthorn poses a particular threat to forests of eastern white pine (*Pinus strobus*), where it commonly invades and regenerates (e.g., Lee and Thompson, 2012), outcompeting pine seedlings (Frappier et al., 2004). Like many of the other non-native woody plants in eastern US forests (Webster et al., 2006), for example the invasive shrub Amur honeysuckle, (*Lonicera maackii*, Collier et al., 2002), a buckthorn invasion can suppress tree establishment and thus potentially reduce

* Corresponding author at: 500 Pond Hill Rd, Strafford NH 03884, USA.
E-mail address: nlanzer@wildcats.unh.edu (N.B. Lanzer).

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production of harvestable trees.

Spread of buckthorn following colonization can be swift as buckthorn seeds remain viable for upwards of three years, and stems sprout vigorously when damaged (Godwin, 1943). Canopy disturbances increase stem density (Burnham and Lee, 2010) probably by creating conditions favorable to germination of dormant seeds (e.g., increased light and warmth at soil level). Without careful pre-harvest control, logging may in fact facilitate invasion (Frappier et al., 2003; Fagan and Peart, 2004; Burnham and Lee, 2010; Lee and Thompson, 2012; Lee et al., 2016), unintentionally promoting buckthorn thickets and seed banks which challenge future forest stand development.

Given the impact of buckthorn on forests, various methods of control have been considered. Chemical methods (e.g., herbicides such as glyphosate or triclopyr), mechanical means (e.g., pulling or cutting), and targeted burning are often effective, and a combination of two or more methods is commonly employed (Reinartz, 1997; Pergams and Norton, 2006; Lee et al., 2016). Timing of any buckthorn control treatment is an important consideration due to its ability to sprout (Reinartz, 1997; Zuidema, 2014). Typically, chemical and mechanical controls are applied on a stand-wide basis and can reduce buckthorn abundance if repeated within a growing season (Zuidema, 2014; Lee et al., 2016).

Because control of invasive plants is costly (Pimentel et al., 2005; Olson, 2006), the prospects of eradicating a particular species are usually small (Mack et al., 2000). Moreover, efforts to completely eradicate some invaders can negatively affect native species (Kettenring and Adams, 2011). More feasible in some systems is "maintenance control" (Mack et al., 2000), in which the abundance of one or several invasive species, through some degree of management, is kept at some acceptable level. Eradication of buckthorn from a pine forest, or following a harvest operation when both buckthorn and pine co-establish, would be challenging and expensive (Lee et al., 2016), especially if preserving any pine regeneration was a stated goal. It follows, then, that a conservative maintenance control scheme that promotes pine regeneration while minimizing time and cost expended to treat buckthorn (i.e., avoiding stand-wide application) may be ideal. This approach may be especially effective in the pine-buckthorn system, where a modest level of control might allow pine to emerge from and outpace the surrounding buckthorn thicket and, once relatively free of competition, continue on to grow to merchantable size. This motivates our research: is it possible to successfully manage for timber in the presence of an invasive species through a level of control that stops short of stand-wide eradication?

In this paper, we describe a simple silvicultural procedure combining elements of crop tree release with localized invasive species control—in effect, timber stand improvement (TSI) in miniature—in which individual pine saplings, selected for their vigor and economic potential, are liberated from direct competition with buckthorn and associated vegetation either by A: cutting adjacent vegetation, or B: cutting adjacent vegetation and applying herbicide to cut stumps, both within a small radius of the selected pine sapling. Pines treated in this way will have access to greater resources and thus should grow more quickly. The novelty of our approach lies in the single, localized treatment of invasive species as opposed to stand-wide eradication (e.g., Zuidema, 2014; Lee et al., 2016), the young age at which "crop trees" (saplings) are released, the targeted use of herbicide to suppress buckthorn recovery, and the acceptance of a persistent invasive population, without attempting eradication, provided aims of forestry remain achievable.

Here, we evaluate the effectiveness of the method using four pine physiological responses: growth (height and diameter), terminal leader biomass, foliar nitrogen concentration, and stem non-structural carbohydrates. *Growth:* Trees released from competition should grow faster in terms of radial (stem diameter) growth and overall height. *Terminal leader biomass:* Trees with access to higher resource levels should accrue biomass more rapidly than trees with limited access (Niinemets, 1997). Biomass of the terminal leader, which includes needles and stem tissue above the highest growth whorl, should serve as a reliable indicator of a tree's net photosynthetic capability (Reich et al., 1999). *Foliar nitrogen*: Trees with fewer competitors for soil nutrients should assimilate more nitrogen from the relatively larger pool of available resources, for instance to create chlorophyll or rubisco (Mooney et al., 1978; Field, 1983), and plants with higher foliar N should exhibit greater rates of net photosynthesis and accelerated growth (Chapin et al., 1987; Craine and Dybzinski, 2013). *Stem non-structural carbohydrates*: With greater photosynthetic capability, released trees should produce and store more non-structural carbohydrates (NSC: starch and sugars) than controls (Kozlowski et al., 1991). Our experiment examined NSC content of stem tissues (xylem and bark) only. The term "bark" as used here includes all tissues outside of the vascular cambium: secondary phloem, cortex, phelloderm, phellogen (cork cambium), and periderm.

We tested the following hypotheses. Following localized, spring cut and cut-and-herbicide treatments:

H1. After one growing season, treated pine saplings will respond to removal of adjacent stems by accruing additional leader biomass when compared to unreleased control specimens, indicating enhanced photosynthetic (and therefore growth) capacity.

H2. After one growing season, pine leaf nitrogen concentration will be greater in treated (released) pine saplings versus controls.

H3. After one growing season, stem non-structural carbohydrates in xylem and bark tissues of pine saplings will be found in greater concentrations in treated (released) pine saplings versus controls.

H4. After one and two growing seasons, (a) stem diameter and (b) height growth of treated (released) pine saplings will be greater than controls.

2. Methods

2.1. Site

Research was conducted at MacDonald Lot in Durham, New Hampshire, a forested 31.9-hectare property owned and managed by the University of New Hampshire. Soils are in the Scantic silt loam and Hollis-Charlton fine sandy loam series. Forest cover is white pine, pine-oak (red, black and white; *Quercus rubra*, *Q. velutina*, and *Q. alba*, respectively), and mixed hardwoods, which include white ash (*Fraxinus americana*), shagbark hickory (*Carya ovata*), black birch (*Betula lenta*) and red maple (*Acer rubrum*). Much of the understory, especially under white pine, is dominated by glossy buckthorn.

Pines studied here were located within four clearcut units created during the winter of 2009–2010. Because 2009 was a productive white pine seed year, pine established successfully following all cutting operations, alongside which buckthorn also established in dense thickets both from seed as well as through sprouting from stems crushed during harvesting (Lee et al., 2016). Prior to treatment, buckthorn density in some areas exceeded 30 stems m^{-2} (300,000 stems ha^{-1}). For this study, all research plots were set in areas of regenerating pine and buckthorn and with few other species present.

2.2. Study design

On May 18, 2015, 75 five-year-old pine saplings were identified, each meeting the following selection criteria: 1) ≥2 m from a canopy opening or cut edge, ≥5 m from a forest edge, and ≥3 m from next closest study pine; 2) ≥10 buckthorn stems of any diameter within a 1 m radius of pine sapling; 3) foliage at least as full as nearest pine saplings; 4) at least as tall as nearest pine saplings; 5) neither stunted, broken, nor chlorotic. These criteria were designed to ensure the possibility of competition between buckthorn and pine, and to mimic the