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Research Article

Silviculture

Effect of Biochar and Manual Vegetation Control on Early Growth and Survival of Planted Jack Pine (*Pinus banksiana* Lamb.) Seedlings in Northern Minnesota

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Abstract

Survival of planted seedlings following a regeneration harvest can be challenging and early interventions through silvicultural treatments may be required for successful stand establishment. We tested the influence of soil amendment (biochar plus compost, compost-only, or control) and vegetation control (VC; applied either initially or annually for five years using brush saws) on the growth and survival of jack pine at three sites in northern Minnesota. Application of the biochar plus compost soil amendment increased seedling survival by 30% relative to the control in the first year, but there was no significant difference in survival among soil amendment treatments after five years. Both soil amendments increased diameter growth relative to the control (14% increase with biochar plus compost, 10% increase with compost only), with most of the biochar plus compost effect attributed to the compost. Annual VC increased diameter growth by 17% relative to initial VC, but overall effects on survival and growth were generally small relative to reported effects of VC via herbicide. The limited short-term influence of biochar and manual VC on growth and survival of jack pine indicates that these practices are likely not an effective means to increase jack pine establishment, but other benefits (e.g., increased carbon storage) may become apparent with time.

Study Implications: Emerging changes to forest conditions and climate are likely to create challenges for successful regeneration in even-aged silvicultural systems. Early interventions such as application of soil amendments and vegetation control may be required to increase seedling survival. However, our findings indicate that biochar application and manual vegetation control were not very effective at increasing survival and growth of planted jack pine seedlings across a range of site conditions in northern Minnesota. Further study is warranted to determine whether other biochar application rates and techniques or other forms of vegetation control are more effective for successful jack pine establishment.

Keywords: regeneration, drought, weed control, brush saws, compost

Successful establishment of tree regeneration following stand replacing disturbances is becoming more challenging as managers must address new threats associated with a changing climate (e.g., drought), altered disturbance regimes, the spread of invasive species, and the numerous interactions among them (e.g., North et al. 2019, Palik et al. 2021). In Minnesota, USA, one species that managers are actively trying to plant and restore across the landscape is jack pine (*Pinus banksiana* Lamb.) (Windmuller-Campione et al. 2019) because it is ecologically and commercially important; jack pine's extent has been greatly reduced since European colonization (approximately 60% remaining; Frelich 2002). Jack pine is prominent in north-central forests of the Great Lakes Region (GLR) of the United States (Minnesota, Michigan, Wisconsin) and Canada (Ontario) where it occurs on outwash, coarse sandy soils which are a common soil type of the region (Anderson et al. 1999). Jack pine is a shade-intolerant pioneer tree species that is well adapted to fire because it has serotinous cones with high seed germination on exposed mineral soils coupled with high survival when competition is reduced after fire (Smirnova et al. 2008).

In a recent survey of natural resource managers in Minnesota, jack pine was rated as the most difficult species to regenerate (Windmuller-Campione et al. 2019), possibly because of suppression of natural fire regimes and limited use of prescribed fire during site preparation activities. Predicted increases in drought frequency and duration during the growing season within the GLR are likely to make successful regeneration of jack pine even more difficult (Handler et al. 2014). There is a need to evaluate alternative silvicultural tools to increase survival and resilience of jack pine following planting under current and changing climatic conditions.

Jack pine is generally considered a drought tolerant species, but drought-related mortality during the initial years after planting is common because root systems are poorly developed (Grossnickle 2012) and associated soils generally have very low water holding capacity (e.g., coarse-textured sands). Practices that increase the availability of water and other growth-limiting resources, such as application of soil amend-

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ments at time of planting, may lead to increased survival and growth. One promising amendment to increase resource availability is biochar, a bio-based product obtained during thermal decomposition of organic matter in a low-oxygen environment, which is similar to charcoal (Lehmann and Joseph 2015). Biochar has characteristics that can increase water and nutrient availability in soils, including high carbon content, high surface area and pore space, and high cation exchange capacity (Sohi et al. 2010, Page-Dumroese et al. 2017, Edeh et al. 2020). Because of its high capacity to sorb available nutrients, it is often applied in combination with other nutrient amendments (e.g., compost) to ensure that nutrient availability is not decreased following application.

Biochar has been used for centuries in tropical environments to increase soil productivity (Lehmann et al 2003, Sohi et al. 2010, Lehmann and Joseph 2015), and many studies have demonstrated its utility in modern agricultural production systems (Spokas et al. 2012, Biederman and Harpole 2013). Biochar also has potential for use in forest ecosystems (Page-Dumroese et al. 2017), but findings from existing studies are not consistent. Both Sherman et al. (2018) and Sarauer et al. (2019) found limited effects of biochar application on midrotation growth in mixed stands following thinning in the Intermountain West, USA. In contrast, Palviainen et al. (2020) observed ~10%–20% increase in growth in Scotch pine (*Pinus sylvestris* L.) stands in Finland growing on relatively poor-quality sites, where effects may be expected to be more pronounced (El-Naggar et al. 2019). Using metanalysis, Thomas and Gale (2015) concluded that tree response to biochar is more evident in tropical than temperate regions and higher in broadleaf species than conifers. Varied response to biochar application is likely also a result of differences in biochar type (feedstock type, pyrolysis conditions, etc.) and their influence on water and nutrient availability (Xiapu et al. 2014, Ippolito et al. 2020) in combination with variations in existing soil properties that may mediate the response (Streubel et al. 2011, Aller et al. 2017, Edeh et al. 2020). The applicability of the above findings to recently planted jack pine is unclear, underlying a need to evaluate the effects of biochar on jack pine survival and growth across a range of site conditions (Li et al. 2018).

A more common practice to increase seedling survival and growth is the use of competing vegetation control (VC), which increases resource availability (light, water, and nutrients) to the target species (Harrington and Tappeiner 1991, Dinger and Rose 2009). Vegetation control is generally very effective at increasing survival and growth across a wide range of site and climate conditions (Walstad and Kuch 1987, Fleming et al. 2006, Wagner et al. 2006), but effectiveness is greatest at sites where available resources are low (e.g., coarse textured, low fertility soils; Harrington et al. 2020). Wagner and Robinson (2006) reported increased volume of 117% (relative to controls) in jack pine after five years of VC, but no significant effect on survival. In a longer study, Fleming et al. (2018) also found beneficial effects of VC that diminished with time (from 10 to 20 years), but with slight negative effects on survival that were attributed to indirect effects of vegetation removal on the microenvironment. The above studies focused on VC via use of herbicides, which is the predominant form of VC used in operational practice, but there has been increased interest in using other means to control vegetation because of policies or negative perceptions against the use of herbicides (Thiffault et al. 2012). The relative efficacy of alternative weed control methods, such as mechanical removal with brush saws (Jobidon and Charette 1997), is generally variable and dependent on characteristics of the competing vegetation (e.g., herbaceous versus woody). Although there has been extensive work on the influence of VC on forest establishment, there are no studies of which we are aware that explore the potential interactions of biochar and VC.

The overarching goal of our study was to evaluate methods to increase the survival and early growth of jack pine. Specially, our objective was to assess whether short-term (five years) survival and growth of planted jack pine seedlings on sandy, nutrient poor soils is influenced by soil amendment or VC treatments. We hypothesized that there would be beneficial effects of both biochar application and annual VC on survival and growth, with greatest benefits achieved when these practices were applied in tandem.

Methods

Study System

The experiment was conducted in the Superior National Forest (SNF) located in northeastern Minnesota in the Laurentian mixed forest province. Jack pine forests currently cover approximately 2% of forested land in Minnesota (~140,000 ha), which is a significant decrease from its extent prior to European colonization and lumber exploitation (Miles 2017). Jack pine is a minor component in numerous pine and hardwood forest types within Minnesota and the GLR, providing valuable ecological and economic resources (Benzie 1977). Historically, fire was a major form of disturbance in jack pine forests, with low intensity, high frequency fires that decreased competition and aided mineral soil exposure and heat for natural regeneration of jack pine (Cayford and McRae 1983). Management within the SNF is currently focused on restoring jack pine via planting (SNF 2004). The climate is continental, with a mean annual growing season temperature of 15°C and annual precipitation of approximately 700 mm (Slesak 2013). During the growing season (May–Sept.) of the project period (2016–2020), mean monthly temperature was 18.1°C and mean monthly precipitation was 26 mm (PRISM Climate Group). Soils in the region are glacially deposited, typically shallow unsorted glacial till underlain by Precambrian sedimentary bedrock.

Three sites were selected from a pool of sites identified for planting by the SNF (Table 1). Our study represents a small portion of the overall number of stands being regenerated on the SNF. We nonrandomly selected sites that had suitable access and relatively uniform conditions (soils, topography, preharvest stand composition). The three sites varied in preharvest stand composition and postharvest site preparation practices related to slash management (Table 1). The associated slash practice of a given site was uniformly applied and soil disturbance after site preparation was low. Soils were typical for the region, being generally coarse textured, well drained, and low in carbon and nutrients (Table 1).

Experimental Design

At each site, jack pine seedlings (2-0 bare root) sourced from the Minnesota Department of Natural Resources were planted in May of 2016 in a 2 × 3 m grid (2 m between trees within a row, 3 m between rows) using a randomized factorial design with two factors. The first factor was soil amendment with three levels: biochar plus compost (1 l mix with equal parts biochar and compost mixed immediately before

Table 1. Site characteristics and soil chemical properties from 0 to 30 cm depth for the three biochar study sites (Standard error in parenthesis, n = 4).

Characteristic or property	Site 1	Site 2	Site 3
Location (lat., long.)	47.669101, –92.811013	47.603004, –92.805684	47.602057, –92.808743
Preharvest cover type	Jack pine	Quaking aspen, white spruce	Quaking aspen
Site-preparation practice	Burned	Scattered slash	Piled slash
Stand size (ha)	8.10	4.82	4.50
NRCS soil series	Graycalm-Biwabek complex	Beargrease	Greatscott-Nashwauk -Balkan complex
Texture [a]	Loamy sand	Very stony loam	Stony loam
Drainage class [a]	Excessively drained	Well drained	Well drained
C (%) [b]	0.69 (0.21)	1.75 (0.37)	1.10 (0.25)
N (%) [b]	0.03 (0.01)	0.10 (0.02)	0.06 (0.01)
Ca (mg kg^{-1}) [b]	176 (73)	523 (194)	315 (61)
K (mg kg^{-1}) [b]	30 (5)	106 (46)	56 (12)
Mg (mg kg^{-1}) [b]	18 (5)	79 (22)	76 (19)
P (mg kg^{-1}) [b]	1.5 (0.2)	1.9 (0.3)	2.1 (0.3)

[a] From NRCS official series descriptions of associated units
[b] From soil samples collected at each site from three locations per site

Table 2. Biochar characteristics.

Property	Value	Property	Value
Organic C (%)	66.8	Bulk density (g cm^{-3})	0.33
Hydrogen:carbon	0.32	Particle size:	
Total ash (%)	26.4	4–8 mm (% of total)	1.4
Volatile matter (%)	18	2–4 mm (% of total)	11.1
pH	7.8	1–2 mm (% of total)	15.2
Total N (%)	0.56	0.5–1 mm (% of total)	22.9
Total P (mg kg)	3120	<0.5 mm (% of total)	49.4
Total K (mg kg)	580		

* Analyses conducted by Control Laboratories, Watsonville, CA, USA.

planting), compost-only (0.5 l), and a no amendment control. Our primary focus was to determine the effect of the biochar; the compost was included in treatments because application of raw biochar can reduce nutrient availability (Brtnicky et al. 2021), which could confound interpretation of any response. Amendments were applied by placing the material at the base of the planting hole (using a planting bar; hole was ~20 cm deep) and then backfilling with native soil. At time of planting, the biochar and compost were moist. Treatment application rates and techniques are similar to those used by Richard et al. (2017) because this is one option that could be applied during operational reforestation efforts. Planting locations were located away from any residual overstory trees to minimize variations in the light environment.

Biochar was produced by Biochar Solutions (LaFayette, CO) using gasification of Rocky Mountain lodgepole pine (*Pinus contorta* Doug.) in a low-oxygen environment for 5 minutes at 600°C. Biochar characteristics are shown in Table 2. Compost was formed from manure, sourced from a commercial supplier, and contained 0.5% nitrogen, 0.5% phosphorus, and 0.25% potassium by mass. The second factor was VC at two levels (either initial VC or annual VC application). All seedlings received initial VC in July 2016, and those assigned to the annual VC treatment received treatment two times (generally in May and July) during each of the subsequent growing seasons. VC was manually applied with motorized brush saws (Stihl model FS 250) which were used to remove all aboveground vegetation within an area of 2.25 m^2 centered on each tree. Manual VC methods were used, as this is the method of VC commonly used on the SNF and there is interest in quantifying its efficacy. Each of the treatment combinations were replicated 15 times at each site (n = 270 across all sites).

All seedlings were protected from deer browse using mesh tubing (Rigid Seedling Protector Tubes, Forestry Suppliers) held in place with bamboo stakes. Seedlings that suffered mortality in the first growing season (2016) were replanted during the spring of 2017 using the same stock type and nursery source. At the time of planting, the height (nearest cm) and basal diameter (two dimensions measured with calipers to nearest 0.01 cm) of each seedling was recorded. After the seedlings hardened at the end of each subsequent growing season (mid-October), mortality status was recorded and heights and basal diameters were measured. Annual growth was determined by subtracting the previous measurement from the most recent measurement.

Analysis

Data from the three sites were pooled for all analyses. Treatment effects on seedling survival at one and five years were assessed for the initial cohort that survived (i.e., no replants were included); these two time periods were used in the analysis because they represent two common time periods where natural resource managers would assess regeneration. Treatments were analyzed with a mixed effects model using site-level means for each treatment (n = 3 for each treatment across sites), with site coded as a random effect and soil amendment, VC, and the interaction between amendment and VC coded as fixed effects. Visual inspection of the residuals indicated assumptions of normality were met. Treatment effects on growth were also assessed with a mixed effects model (n = 45 for each treatment across sites) with site coded as a random effect and soil amendment, VC treatment, time, and their interactions coded as fixed effects. Repeated measures analysis was incorporated in the model to account for serial correlation using an AR(1) covariance matrix and

Table 3. F statistic probabilities for fixed treatment effects on one- and five-year site-level survival.

Effect	Numerator DF	Denominator DF	One-year *P*-value	Five-year *P*-value
Amendment	2	10	0.014	0.060
Vegetation control (VC)	1	10	0.131	0.291
Amend*VC	2	10	0.965	0.955

initial height or diameter were used as covariates. Diameter and height data were log-transformed to meet assumptions of variance normality; values were back transformed for presentation and are therefore estimates of the median. When ANOVA results indicated significant treatment effects, multiple comparisons with Tukey's adjustment were conducted to determine what treatments differed. An alpha level of 0.05 was used to determine significance in all tests. All analyses were conducted in SAS V9.4.

Results

Survival

Seedling survival was low across all sites, with a mean of 48.5% survival across all treatments in the first year after planting. There was a significant effect of soil amendment on first year survival, but no effect of VC and no interaction between the treatment factors (Table 3). Survival was significantly higher in the biochar plus compost treatment relative to the control (diff. = 30%, ±8.2%; adj. $P = 0.012$, Table 4), but there was no difference between the biochar plus compost and compost-only treatments (adj. $P = 0.105$). After five years, survival was much lower overall across all sites and there were no differences among soil amendment treatments (Tables 3 and 4). There was no effect of VC treatment on survival at either one or five years (Tables 3 and 4). Examination of site level treatment means indicated that all sites responded in a similar manner as described above (data not shown).

Growth

Across all sites, planted seedlings had initial diameter of 5.1 cm (sd = 1.6 cm) and initial height of 23.9 cm (sd = 7.2 cm). ANOVA results indicated that initial diameter and height had significant effects on diameter and height growth during the project period (Table 5). There were significant main effects of both soil amendment and VC on diameter growth across all sites, with no interaction between the factors or with time. Note that individual sites responded in a similar manner (see the Supplemental Material for site-specific ANOVA tables). For the soil amendments, both biochar plus compost and compost-only treatments had greater diameters than the control treatment, where biochar plus compost increased diameter by 1.34 cm (an increase of ~14% relative to control; Figure 1) and compost-only increased diameter by 0.94 cm (~10% relative to control). For the VC treatment, diameter in the annual VC treatment was 1.64 cm greater than the initial VC treatment (an increase of ~17% relative to initial VC). There was no difference in diameter between the biochar plus compost and compost treatments. For height, there was a significant effect of amendment on growth but not VC and there was

Table 4. Mean survival of jack pine seedlings at the site level one and five years after planting. Means within a treatment factor containing different letters are significantly different (standard error in parenthesis, $n = 3$).

Treatment	One-year survival (%)	Five-year survival (%)
Soil amendment		
Biochar + compost	62.2 (4.1) b	35.6 (3.7) a
Compost only	51.1 (7.0) ab	38.9 (7.8) a
None	32.2 (6.7) a	20.0 (3.85) a
Vegetation control		
Annual	42.9 (6.0) a	28.2 (4.0) a
Initial	54.1 (6.4) a	34.8 (6.0) a

no interaction between the factors or with time (Table 5). The biochar plus compost treatment had significantly greater height growth than the control treatment (by 6.9 cm or ~15% relative to control), but no difference with the compost-only treatment (Figure 1).

Discussion

Successful establishment of regeneration in forest ecosystems following disturbance is likely to become increasingly challenging as disturbances become more varied and severe (e.g., following pest outbreaks or intense wildfire) and climate conditions less suitable for seedling survival (e.g., extreme drought events) (McKenney et al. 2009, Duveneck et al. 2014). Because of this, forest managers may need to invest more time or resources in silvicultural strategies during the establishment phase to increase survival and growth of newly planted seedlings, including the use of soil amendments and VC (Clark et al. 2016). Biochar is a promising amendment for jack pine because it has potential to mimic some of the effects of charcoal inputs on soil properties that are associated with the fires common to jack pine ecosystems (Licht and Smith 2020). Here, we found that application of biochar plus compost and compost-only caused modest increases in jack pine growth and survival over a period of five years after planting across three sites that spanned a range of operational conditions. In contrast, the effects of VC were limited to an increase in diameter growth with annual VC compared with initial VC only. We examine these responses and implications in more detail below.

Treatment Effects on Survival

Jack pine survival was generally low regardless of treatment, averaging just ~50% across the three study sites after the first year of planting. For context, other studies report survival rates of jack pine between 70–95% (Wagner and Robinson 2006, Fu et al. 2007, Fleming et al. 2018). The low survival we observed is likely a combination of soil conditions (low water holding capacity; Table 1) and low precipitation in the year of planting (R. Slesak, personal observation), which, in combination, would have greatly increased drought stress of the seedlings. These conditions are already common on sites with sandy, outwash soils and the impact to trees is likely to become more prevalent in the future as drought events increase in occurrence and severity (Winkler et al. 2012, Tam et al. 2018).

Table 5. F-statistics probabilities for fixed effects of treatment on diameter and height growth.

Effect	Numerator DF	Denominator DF	Diameter *P*-value	Height *P*-value
Covariate	1	892	<0.001	<0.001
Amendment	2	892	0.001	0.003
Vegetation control (VC)	1	892	<0.001	0.498
Amend*VC	2	892	0.080	0.197
Year	4	892	<0.001	<0.001
Amend*year	8	892	0.142	0.456
VC*year	4	892	0.053	0.520
Amend*VC*year	8	892	0.600	0.678

* Analysis conducted across sites, but all sites responded in a similar manner (See Supplementary Material)

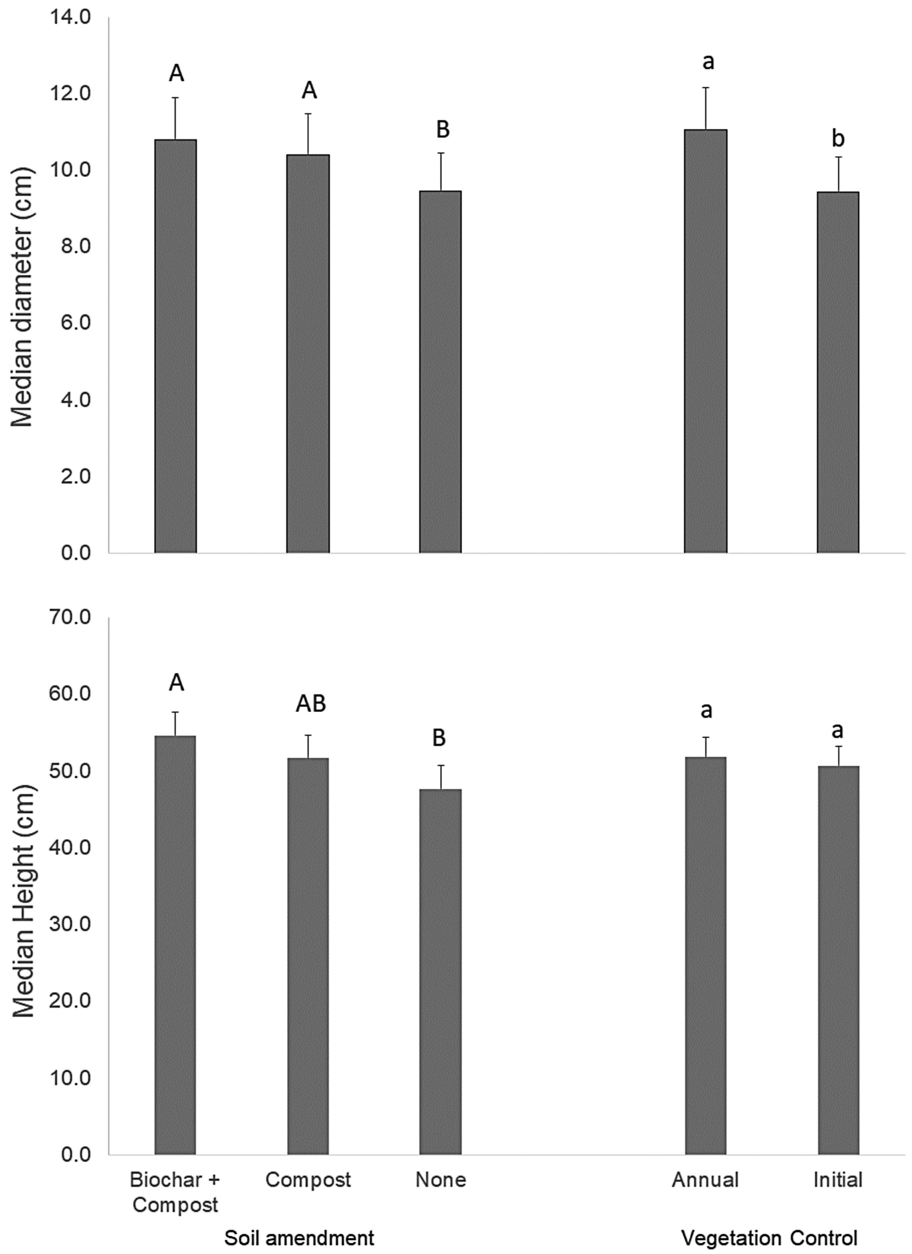

Figure 1. Effects of soil amendment and vegetation control on median annual diameter (upper panel) and height (lower panel) growth of jack pine seedlings during the five-year study period. Treatments within each factor containing different letters are significantly different (error bars are standard error of the mean).

The significant increase in survival with biochar plus compost addition in the first year after planting was large relative to control. Given the similarity in survival between the compost only and biochar plus compost amendments (Table 3), we attribute much of this effect to the compost rather than the biochar. Similar nonsignificant patterns at the end of the study support this, as the compost-only treatment had higher survival than the biochar plus compost treatment. A positive effect of the two soil amendment treatments on survival is likely associated with increased water availability to the seedlings, as both of these amendments are known to increase soil water holding capacity (Liu et al. 2012, Razzaghi et al. 2020), and seedling mortality is commonly associated with drought stress (Grossnickle 2012). Our application method would have enhanced this effect, as the materials were in close contact with tree roots compared with surface applications. The lack of significant differences between the compost-only and control treatments in year 1 and among all treatments in year 5 is most likely due to low statistical power arising from the low replication (n = 3).

The lack of any effect of VC treatment on survival at one or five years aligns with other studies that have reported either no or minor effects of VC on jack pine survival. Wagner and Robinson (2006) found only a ~10% increase in jack pine survival after 10 years after five years of annual VC compared with control treatments. In contrast, Fu et al. (2008) found no effect of annual VC on jack pine survival after 10 years, and Fleming et al. (2018) found a decrease in jack pine survival with VC, which was attributed to changes in the microsite conditions rather than direct injury from application. The above studies all used herbicide for VC compared with our use of manual control via motorized brush saws. Given the lack of positive response in jack pine survival with VC (herbicide or manual control), factors other than competition are likely more critical to consider for survival of planted jack pine seedlings.

Treatment Effects on Growth

A number of studies have evaluated the use of organic soil amendments to increase growth in forestry applications, but most studies focus on wood ash application (e.g., Emilson et al. 2019) or use of composted sludge or manure (Larney and Angers 2012). Only a few have evaluated the utility of biochar application, with most of those focused on midrotation stand response (e.g., Sarauer et al. 2019, Somerville et al. 2020). Our results show that biochar-compost amendments can increase early height and diameter growth of planted jack pine. Given the similarity of response between the biochar plus compost and compost-only treatments on short-term growth, most of this effect can be attributed to the influence of compost with only minor contribution from the biochar. This finding aligns with other studies that have observed limited effects of biochar application on tree growth, including studies on midrotation stand response (Sarauer et al. 2019, Sherman et al. 2018, Somerville et al. 2020), seedling response in the field (Glisczynski et al. 2016), and seedling responses in greenhouse or microcosm studies (Robertson et al. 2012, Noyce et al. 2017). The above studies used a wide range of biochar application rates and were set in temperate regions but were generally limited to assessment of short-term responses (four months to ~five years). In a meta-analysis, Thomas and Gale (2015) also noted that most tree-biochar studies are short in duration and that effects are limited in temperate regions. It is possible that effects on growth may become more pronounced with time as jack pine demand for soil resources increases, given the positive effects that biochar has on soil properties (Richard et al. 2017) and its long residence time in soil (Spokas 2010). For example, Grau-Andrés et al. (2021) found that biochar increased growth of *Pinus sylvestris* by 19% after a period of nine years at a boreal forest in northern Sweden.

The limited effect of VC on growth was surprising, as most studies have shown a large and positive effect of VC on tree growth, particularly during the early years of stand establishment and when applied continuously over the course of multiple years (Wagner 2006, Fleming et al. 2018). Wagner and Robinson (2006) reported that jack pine had the smallest increase in diameter growth with continuous VC for five years compared with red pine (*Pinus resinosa* Ait.), white pine (*Pinus strobus* L.), and black spruce (*Picea mariana* Mill.). In that study, jack pine diameter was 39% greater with VC relative to control, which is more than double the 17% we observed in this study. Other studies have reported much higher increases in diameter growth for jack pine seedlings following continuous VC (200%+; Burgess et al. 2010, Fleming et al. 2018). The small diameter response and lack of any effect on height in our study may be due to our use of manual VC with brush saws, which would have been effective at removing woody competitors but likely less so at herbaceous species, which can be significant competitors for water and nutrients (Bell et al. 2000). In a comparison of VC techniques, Pitt et al. (2000) found that brush saws and other manual methods were much less effective at increasing jack pine growth than herbicides, and others have found manual methods to be ineffective or suboptimal at increasing tree growth compared with herbicides (Thiffault et al. 2012). A limitation of our study was that we were unable to include a herbicide treatment for direct comparison with the manual VC treatment. Additional research directly comparing these techniques for jack pine is necessary to quantify the tradeoffs for natural resources managers to consider when developing VC practices.

Implications for Operational Application

Although the biochar plus compost treatment in our study had marginal influence on short-term growth (diameter or height) or survival compared with compost-only for jack pine seedlings, the addition of biochar may have other long-term benefits related to climate change and ecosystem function. Notably, biochar has high potential to increase carbon storage in soils because of its stability and slow turnover time compared with other organic matter pools in soil (Spokas 2010). Because of this, biochar application has been suggested as a possible practice to mitigate the effects of climate change, but application of biochar in forested settings is still extremely limited because of high costs and limited effects on tree growth (Page-Dumroese et al. 2017, Sarauer et al. 2019). Richard et al. (2017) applied biochar using a similar technique to ours and estimated that that it would increase planting costs by a factor of 20. Given this, and the limited effect on survival and growth over the study period, it does not seem feasible that biochar could be used operationally to increase jack pine seedling establishment unless application costs could be reduced (e.g., mechanized application; Page-Dumroese et al. 2016) and new markets or favorable policy for carbon sequestration emerges. It is possible that a higher biochar application rate than used in our study or different types of biochar (different feedstocks, pyrolysis conditions, etc.; Ippolito et al. 2020, Huang et al. 2021) could have larger positive effects on jack pine establishment and growth. Further evaluation is warranted to fully understand biochar's potential as a forest soil amendment.

The effects of annual VC and related implications are similar to those discussed above, as the modest increase in diameter growth probably does not justify the annual costs associated with VC application via brush saws. Although manual VC methods may be more acceptable to some than use of herbicides, the limited efficacy of brush saws as shown here should be considered when developing silvicultural strategies to increase the survival and growth of planted jack pine. Other forms of manual vegetation control may be more effective and should be explored as options for increasing the establishment of jack pine.

Despite the limited effects of soil amendments and VC on survival and growth of jack pine, these treatments do open the door to exploring alternative silvicultural treatments to increase successful establishment. Jack pine systems are commonly regenerated using clearcut harvest to allow for high light levels, which are presumed to favor establishment and growth of jack pine. However, Benzie (1977) notes the potential need for protection for seedlings from full sun during the initial years after planting. In support of this, Montgomery et al. (2013) observed the greatest growth of jack pine with retained dispersed residuals compared with no residuals. Thus, as the timing and frequency of drought continue to affect regeneration, natural resource managers may need to consider alternative silvicultural treatments, which may include increasing residuals and/or planting trees near protective features (e.g., stumps and downed wood) in combination with soil amendment or VC treatments.

Conclusion

Our findings indicate that soil amendments can increase survival and growth of jack pine seedlings in the first five years after planting across the range of conditions represented by our three study sites. There were limited differences between the biochar plus compost and compost-only treatments, indicating that compost is the more important component for short-term survival and growth. However, adding biochar with compost may provide additional long-term benefits including carbon sequestration and in our study, biochar did not negatively affect survival or growth of jack pine through year five. Manual application of annual VC with brush saws had no effect on survival and only modest increases in diameter growth over the five-year period. Because of this, annual VC with brush saws does not appear to be an effective means to increase establishment of planted jack pine. Given the relative recency of biochar use in forests systems in the GLR and interest in using manual VC, additional studies are warranted to determine whether these practices can be modified (e.g., other forms of manual VC) to improve overall efficacy related to individual tree species survival and growth, as well as broader influence on ecosystem processes.

Supplementary Material

Supplementary material is available at *Forest Science* online.

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Literature Cited

Aller, D.M., S. Rathke, D. Laird, R. Cruse, and J. Hatfield. 2017. Impacts of fresh and aged biochars on plant available water and water use efficiency. *Geoderma* 307:114–121.

Anderson, R.C., J.S. Fralish, and J.M. Baskin. 1999. *Savannas, barrens, and rock outcrop plant communities of North America*. Cambridge University Press, Cambridge, UK.

Bell F.W., M.T. Ter-Mikaelian, and R.G. Wagner. 2000. Relative competitiveness of nine early-successional boreal forest species associated with planted jack pine and black spruce seedlings. *Can. J. For. Res.* 30(5):790–800.

Benzie, J.W. 1977. *Manager's handbook for jack pine in the North Central states.* USDA Forest Service General Technical Report NC-32, North Central Forest Experiment Station, St. Paul, MN. 32 p.

Biederman, L.A. and W.S. Harpole. 2013. Biochar and its effects on plant productivity and nutrient cycling: A meta-analysis. *GCB Bioenergy* 5:202–214.

Brtnicky, M., R. Datta, J. Holatko, L. Bielska, Z.M. Gusiatin, J. Kucerik, T. Hammerschmiedt, *et al.* 2021. A critical review of the possible adverse effects of biochar in the soil environment. *Sci. Total Environ.* 796. doi:10.1016/j.scitotenv.2021.148756.

Burgess, D., Adams, G., Needham, T., Robinson, C., and R. Gagnon. 2010. Early development of planted spruce and pine after scarification, fertilization and herbicide treatments in New Brunswick. *For. Chron.* 86(4):444–454. doi:10.5558/tfc86444-4

Cayford, J.H., and D.J. McRae. 1983. The ecological role of fire in jack pine forests. P. 183–199 in *The role of fire in northern circumpolar ecosystems*, Wein R.W., and D.A. MacLean (eds). John Wiley and Sons, New York. 322 p.

Clark, J.S., L. Iverson, C.W. Woodall, C.D. Allen, D.M. Bell, D.C. Bragg, A.W. D'Amato, *et al.* 2016. The impacts of increasing drought on forest dynamics, structure, and biodiversity in the United States. *Glob. Change Biol.* 22(7):2329–2352.

Dinger, E.J., and R. Rose. 2009. Integration of soil moisture, xylem water potential, and fall-spring herbicide treatments to achieve the maximum growth response in newly planted Douglas-fir seedlings. *Can. J. For. Res.* 39:1401–1414.

Duveneck, M.J., R.M. Scheller, and M.A. White. 2014. Effects of alternative forest management on biomass and species diversity in the face of climate change in the northern Great Lakes region (USA). *Can. J. For. Res.* 44(7): 700–710.

Edeh, I.G., O. Mašek, and W. Buss. 2020. A meta-analysis on biochar's effects on soil water properties—New insights and future research challenges. *Sci. Total Environ.* 714. doi:10.1016/j.scitotenv.2020.136857.

El-Naggar, A., S.S. Lee, J. Rinklebe, M. Farooq, H. Song, A.K. Sarmah, A.R. Zimmerman, *et al.* 2019. Biochar application to low fertility soils: A review of current status, and future prospects. *Geoderma* 337:536–534.

Emilson, C.E., N. Bélanger, S. Brais, C.E. Chisholm, A. Diochon, R. Joseph, J. Markham, *et al.* 2019. Short-term growth response of jack pine and spruce spp. to wood ash amendment across Canada. *GCB Bioenergy* 12:158–167.

Fleming, R.L., J.-D. Leblanc, T. Weldon, P.W. Hazlett, D.S. Mossa, R. Irwin, M.J. Primavera, *et al.* 2018. Effect of vegetation control, harvest intensity, and soil disturbance on 20-year jack pine stand development. *Can. J. For. Res.* 48:371–387.

Fleming, R.L., R.F. Powers, N.W. Foster, J.M. Kranabetter, D.A. Scott, F. Ponder Jr., S. Berch, *et al.* 2006. Effects of organic matter removal, soil compaction, and vegetation control on 5-year seedling performance: A regional comparison of long-term soil productivity sites. *Can. J. For. Res.* 36:529–550.

Frelich, L.E. 2002. *Forest dynamics and disturbance regimes: Studies from temperate evergreen-deciduous forests.* Cambridge University Press, Cambridge.

Fu, S., Chen, H.Y.H., Bell, F.W., Sharma, M., Delaney, J.R. and G. Peterson. 2008. Effects of timing of glyphosate application on jack pine, black spruce, and white spruce plantations in northern Manitoba. *For. Chron.* 84(1):37–45. doi:10.5558/tfc84037-1

Grau-Andrés, R., M.R.A. Pingree, M.G., Öquist, D.A. Wardle, M.-C. Nilsson, and M.J. Gundale. 2021. Biochar increases tree biomass in a managed boreal forest, but does not alter N2O, CH4, and CO2 emissions. *GCB Bioenergy* 2021;13:1329–1342.

Grossnickle, S.C., 2012. Why seedlings survive: Influence of plant attributes. *New For.* 43(5–6):711–738.

Glisczynski, F.v., Pude, R., Amelung, W., and A. Sandhage-Hofmann. 2016. Biochar-compost substrates in short-rotation coppice: Effects on soil and trees in a three-year field experiment. *J. Plant Nutr. Soil Sci.* 179:574–583. doi:10.1002/jpln.201500545.

Handler, S., M.J. Duveneck, L. Iverson, E. Peters, Scheller R.M., K.R. Wythers, *et al.* 2014. *Minnesota forest ecosystem vulnerability assessment and synthesis: A report from the Northwoods Climate Change Response Framework Project.* USDA Forest Service, Gen. Tech. Rep. NRS-133, Northern Research Station, Newtown Square, PA. 228 p.

Harrington, T.B., and J.C. Tappeiner II. 1991. Competition affects shoot morphology, growth duration, and relative growth rates of Douglas-fir saplings. *Can. J. For. Res.* 21:474–481.

Harrington, T.B., R.A. Slesak, J. Dollins, S.H. Schoenholtz, and D. Peter. 2020. Logging-debris and vegetation-control treatments influence competitive relationships to limit 15-year productivity of coast Douglas-fir in western Washington and Oregon. *For. Ecol. Manage.* doi:10.1016/j.foreco.2020.118288.

Huang, H., N.G. Reddy, X. Huang, P. Chen, P. Wang, Y. Zhang, Y. Huang, P. Lin, and A. Garg . 2021. Effects of pyrolysis temperature, feedstock type and compaction on water retention of biochar amended soil. *Sci. Rep.* 11:7419.

Ippolito, J.A., L. Cui, C. Kammann, N. Wrage-Monnig, J.M. Estavillo, T. Fuertes-Mendizabal, M.L. Cayuela, *et al.* 2020. Feedstock choice, pyrolysis temperature and type influence biochar characteristics: a comprehensive meta-data analysis review. *Biochar* 2:421–438.

Jobidon, R. and L. Charette.1997. Effet, après 10 ans, du dégagement manuel simple ou répété et de la période de coupe de la vegetation de compétition sur la croissance de l'épinette noire en plantation. *Can. J. For. Res.* 27:293–305.

Larney, F.J. and D.A. Angers. 2012. The role of organic amendments in soil reclamation: A review. *Can. J. Soil Sci.* 92(1):19–38.

Lehmann, J., D. Kern, L. German, J. McCann, G.C. Martins, and A. Moreira. 2003. *Amazonian dark earths: Origin, properties, management. chapter 6: soil fertility and production potential.* Kluwer Academic, Dordrecht, The Netherlands.

Lehmann, J., and S. Joseph. 2015. *Biochar for environmental management: Science, technology and implementation*. 2nd ed. Routledge, New York. 976 p.

Licht, J., and N.G. Smith. 2020. Pyrogenic carbon increases pitch pine seedling growth, soil moisture retention, and photosynthetic intrinsic water use efficiency in the field. *Front. For. Glob. Change* 3(31). doi:10.3389/ffgc.2020.00031.

Li, Y., Hu, S., Chen, J., Müller, K., Li, Y., Fu, W., Lin, Z., and H. Wang. 2018. Effects of biochar application in forest ecosystems on soil properties and greenhouse gas emissions: a review. *J. Soils Sediments.* 18:546–563. doi:10.1007/s11368-017-1906-y.

Liu, J., H. Schulz, S. Brandl, H. Miehtke, B. Huwe, and B. Glaser. 2012. Short-term effect of biochar and compost on soil fertility and water status of a Dystric Cambisol in NE Germany under field conditions. *J. Plant Nutr. Soil Sci.* 175: 698–707.

McKenney, D., J. Pedlar, and G. O'Neill. 2009. Climate change and forest seed zones: Past trends, future prospects and challenges to ponder. *For. Chron.* 85(2):258–266.

Miles, P.D. 2017. *Forest Inventory EVALIDator web-application version 1.6.0.03.* USDA Forest Service, Northern Research Station, St. Paul, MN. Available online at http://apps.fs.fed.us/Evalidator/evalidator.jsp.

Montgomery, R.A., Brian, P.J., Suzanne B.B., and P.B. Reich. 2013. New cohort growth and survival in variable retention harvests of a pine ecosystem in Minnesota, USA. *For. Ecol. Manag.* 310:327–335. doi:10.1016/j.foreco.2013.07.055

North, M.P., J.T. Stevens, D.F. Greene, M. Coppoletta, E.E. Knapp, A.M. Latimer, C.M. Restaino, *et al.* 2019. Tamm review: Reforestation for resilience in dry western U.S. forests. *For. Ecol. Manage.* 432: 209–224.

Noyce, G.L., T. Jones, R. Fulthorpe, and N. Basiliko. 2017. Phosphorus uptake and availability and short-term seedling growth in three Ontario soils amended with ash and biochar. *Can. J. Soil Sci.* 97:678–691.

Page-Dumroese, D.S., M.D. Coleman, and S.C. Thomas. 2017. Opportunities and uses of biochar on forest sites in North America [Chapter 15]. P. 315–335 in *Biochar: A regional supply chain approach in view of climate change mitigation*, Bruckman, V., E.A. Varol, B. Uzun, and J. Liu, (eds.). Cambridge University Press, Cambridge, UK.

Page-Dumroese, D.S., N.M. Anderson, K.N. Windell, K. Englund, and K. Jump. 2016. *Development and use of a commercial-scale biochar spreader.* USDA Forest Service, Gen. Tech. Rep. RMRS-GTR-354, Rocky Mountain Research Station, Fort Collins, CO. 10 p.

Palik B.J., A.W. D'Amato, R.A. Slesak, D. Kastendick, C. Looney, and J. Kragthorpe. 2021. Eighth-year survival and growth of planted replacement tree species in black ash (Fraxinus nigra) wetlands threatened by emerald ash borer in Minnesota, USA. *For. Ecol. Manage.* 484(15):118958.

Palviainen, M., H. Aaltonen, A. Laurén, K. Köster, F. Berninger, A. Ojala, and J. Pumpanen. 2020. Biochar amendment increases tree growth in nutrient-poor, young Scots pine stands in Finland. *For. Ecol. Manage.* doi:10.1016/j.foreco.2020.118362.

Pitt, D.G., A.E. Morneault, P. Bunce, and F.W. Bell. 2000. Five years of vegetation succession following vegetation management treatments in a jack pine ecosystem. *North. J. Appl. For.* 17(3):100–109.

Razzaghi, F., Obour, P.B., and Arthur, E. 2020. Does biochar improve soil water retention? A systematic review and meta-analysis. *Geoderma* 361:114055.

Richard, R.P., L.R. Potvin, E.S. Kane, S.D. Handler, P.J. Smith, and D. Peterson. 2017. Biochar and wood ash amendments for forestry in the lake states: field report and initial results. *J. For.* 116(3):222–227.

Robertson, S.J., Michael, R.P., López-Gutiérrez, J.C., and H.B. Massicotte. 2012. Biochar enhances seedling growth and alters root symbioses and properties of sub-boreal forest soils. *Can. J. Soil Sci.* 92(2):329–340. doi:10.4141/cjss2011-066.

Sarauer, J.L., D.S. Page-Dumroese, and M.D. Coleman. 2019. Soil greenhouse gas, carbon content, and tree growth response to biochar amendment in western United States forests. *GCB Bioenergy* 11:660–671.

Sherman, L.A., D.S. Page-Dumroese, and M.D. Coleman. 2018. Idaho forest growth response to post-thinning energy biomass removal and complementary soil amendments. *GCB Bioenergy* 10:246–261.

Slesak, R.A. 2013. Soil temperature following logging-debris manipulation and aspen regrowth in Minnesota: Implications for sampling depth and alteration of soil processes. *Soil Sci. Soc. Am. J.* 77:1818–1824.

Smirnova, E., Y. Bergeron, and S. Brais. 2008. Influence of fire intensity on structure and composition of jack pine stands in the boreal forest of Quebec: Live trees, understory vegetation and dead wood dynamics. *For. Ecol. Manage.* 255:2916–2927.

Sohi, S.P., E. Krull, E. Lopez-Capel, and R. Bol. 2010. A review of biochar and its use and function in soil. *Adv. Agron.* 105:47–82.

Somerville, P.D., Farrell, C., May, P.B., and S.J. Livesley. 2020. Biochar and compost equally improve urban soil physical and biological properties and tree growth, with no added benefit in combination. *Sci. Total Environ.* 706:135736. doi:10.1016/j.scitotenv.2019.135736.

Spokas, K.A. 2010. Review of the stability of biochar in soils: Predictability of O:C molar ratios. *Carbon Manage.* 1(2):289–303.

Spokas, K.A., K.B. Cantrell, J.M. Novak, D.W. Archer, J.A. Ippolito, H.P. Collins, A.A. Boateng, *et al.* 2012. Biochar: A synthesis of its agronomic impact beyond carbon sequestration. *J. Environ. Qual.* 41:973–989.

Streubel, J.D., H.P. Collins, M. Garcia-Perez, J. Tarara, D. Granatstein, and C. Kruger. 2011. Influence of contrasting biochar types on five soils at increasing rates of application. *Soil Sci. Soc. Am. J.* 75:1402–1413.

Superior National Forest (SNF). 2004. *Land and resource management plan: Superior National Forest.* Duluth, MN. Available at https://www.fs.usda.gov/Internet/FSE_DOCUMENTS/fsm91_050593.pdf.

Tam, B., K. Szeto, B. Bonsal, G. Flato, A. Cannon, and R. Rong. 2018. CMIP5 drought projections in Canada based on the standardized precipitation evapotranspiration index. *Canadian Water Resources Journal/ Revue canadienne des ressources hydriques* 44(1):90–107.

Thiffault, N., B. Lafleur, V. Roy, and J. DeBlois. 2012. Large planting stock type and mechanical release effects on the establishment success of Picea glauca plantations in Quebec, Canada. *Int. J. For. Res.* doi:10.1155/2012/617392.

Thomas, S.C., and N. Gale. 2015. Biochar and forest restoration: A review and meta-analysis of tree growth responses. *New For.* 46:931–946.

Wagner, R.G., and A.P. Robinson. 2006. Critical period of interspecific competition for four northern conifers: 10-year growth response and associated vegetation dynamics. *Can. J. For. Res.* 36:2474–2485.

Wagner, R.G., K.M. Little, B. Richardson, and K. McNabb. 2006. The role of vegetation management for enhancing productivity of the world's forests. *Forestry* 79:57–79.

Walstad, J.D. and P.J. Kuch. (eds.). 1987. *Forest vegetation management for conifer production.* John Wiley & Sons, Inc., New York.

Windmuller-Campione, M.A., M.B. Russell, E.S. Sagor, and M.G. Rodman. 2019. *Current status and trends of silvicultural and forest health practices in Minnesota: A 2017 assessment.* Staff Paper Series No. 252. University of Minnesota College of Food, Agricultural and Natural Resources Sciences, Department of Forest Resources, St. Paul, MN.

Winkler, J.A., R.W. Arritt, and S.C. Pryor. 2012. Climate projections for the Midwest: Availability, interpretation and synthesis. in *U.S. National Climate Assessment Midwest Technical Input Report*, Winkler, J., J. Anderson, J. Hatfield, D. Bidwell, and D. Brown (eds.). Great Lakes Integrated Sciences and Assessment Center. Available online at http://glisa.msu.edu/docs/NCA/MTIT_Future.pdf.

Xiapu, G., H. Wang, J. Liu, L. Zhai, S. Liu, T. Ren, and H. Liu. 2014. Effects of feedstock and pyrolysis temperature on biochar adsorption of ammonium and nitrate. *PLoS One* 9(12):e113888.