Canadian Journal of
Forest Research

Note

Limited effects of biochar application and periodic irrigation on jack pine (*Pinus banksiana*) seedling growth in northern Minnesota, USA

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Abstract

We tested the effect of biochar application on growth of planted jack pine on a sandy soil in northern Minnesota. Biochar was applied in combination with compost and with or without manual irrigation in a factorial design to isolate possible effects associated with nutrient or water availability. There were no differences among treatments in seedling annual diameter or height growth after 4 years. Watering increased mean needle mass, indicating the treatment was somewhat effective at increasing water availability and seedling performance. Watering increased foliage Mg and K concentrations and content, possibly indicating that these elements are limiting to jack pine growth on sandy soils. Biochar-only application decreased foliage Ca concentration relative to controls, likely due to increased nutrient immobilization when biochar is applied without a nutrient source. These findings and others from the region highlight that biochar does not increase planted jack pine seedling survival or growth on sandy soils.

Key words: nutrient immobilization, Great Lakes region, foliar analysis, artificial regeneration, potassium limitation

Introduction

Reforestation via planting is increasingly being used to establish stands following disturbance and as part of climate adaptation strategies to increase forest resilience over time (Bastin et al. 2019; Fargione et al. 2021). Planted seedlings face many pressures that inhibit establishment, including browse, competition, and drought stress. Drought stress in particular can increase seedling mortality in the first few years after planting because planted seedlings have poorly developed root systems initially (Niinemets 2010; Grossnickle 2012). Because of this, new practices and approaches are being evaluated to reduce drought stress, including the use of new stock types (Pinto et al. 2018) and timing of planting (Grossnickle and MacDonald 2021), among others.

One practice of interest is amending soil at time of planting with biochar, which is a carbon-rich material created during pyrolysis of organic matter such as wood and agricultural residues (Lehmann and Joseph 2015). Biochar has unique properties that may increase soil water holding capacity and subsequent resilience of seedlings to drought events. These properties include a high C content, high surface area and pore space, and high cation exchange capacity (Page-Dumroese et al. 2017; Sohi et al. 2010). In regard to water holding capacity, it is thought that the high specific surface area may increase water content via adhesion, or possibly increase water content through enhanced pore structure and distribution (Li et al. 2021). The magnitude of any effect is thought to vary with soil properties such as soil texture; using meta-analysis of 37 studies, Edeh et al. (2020) found that the positive effects of biochar on available soil water were greatest in sandy, coarse-textured soils when 30–70 Mg ha^{-1} of biochar were applied. Because of its high cation exchange capacity, biochar is often applied in combination with other nutrient amendments (e.g., compost) to ensure that nutrient availability does not decrease following application.

Despite the above, biochar effects on tree seedling survival and growth have been inconsistent in studies to date. Slightly positive (Robertson et al. 2012; Palviainen et al. 2020; Grau-Andrés et al. 2021) and more often neutral to contrasting responses (McElligott 2011; Sherman et al. 2018; Sauer et al. 2019; Slesak et al. 2022; Vannini et al. 2022) have been observed following a range of biochar application rates in both greenhouse and field settings. Using meta-analysis, Thomas and Gale (2015) concluded that tree response (mostly of planted seedlings in pot studies) to biochar is more evident in tropical than temperate regions and higher in broadleaf species than conifers.

Within northern temperate regions, there continues to be interest in using biochar to increase planted seedling survival, particularly at sites susceptible to drought such as those with sandy soils that have innately low water holding capacity. Based on the findings of Edeh et al. (2020), biochar should be an effective mean to increase drought tolerance at sites with these soils. However, Slesak and colleagues (2022) reported limited effects of biochar and manual vegetation control on jack pine (*Pinus banksiana* Lamb.) survival and growth after 5 years across three sites in northern MN, USA. Additionally, in a greenhouse study that simulated different drought treatments on sandy soils, biochar did not increase seedling survival or growth (Reuling et al. 2023). Here, we expand on this research to determine how irrigation and biochar treatments influence growth and survival of planted jack pine seedlings to determine whether there are any effects of these practices. Based on previous work, we hypothesized that effects of irrigation would be positive but effects of biochar would be neutral.

Methods

Site description

The study was conducted at the University of Minnesota's Cloquet Forestry Center, located in Carlton County, approximately 43 km southwest of Duluth, MN, USA. The Cloquet Forestry Centers lies wholly within the reservation Fond Du Lac Reservation. The climate is continental, with a mean annual growing season temperature of 15 °C and annual precipitation of approximately 700 mm (Slesak 2013). The experimental site was previously occupied by a mix of conifer species, including jack pine, red pine (*Pinus resinosa*), and balsam fir (*Abies balsamea* Lamb.). The site was clearcut in the summer of 2016, followed by site preparation that included scarification with a roller-disker, and then treated with herbicide (glyphosate mixed with a surfactant) via backpack sprayer as needed throughout the growing season to achieve complete removal of competing vegetation for the duration of the project. Soils at the site were derived from glacial outwash and have a texture of sand to fine sand with almost no coarse fragments. Soils are classed as the Omega series, with a taxonomic classification of sandy, mixed, frigid Typic, and Haplorthods (NRCS 1996). Soil fertility is low; mean total soil C and N from 0-30 cm was 0.80% (+/−0.09) and 0.04% (∗/− 0.005), respectively.

Design

A two-way factorial design was used with individual jack pine seedlings as the experimental unit; 2 year old bare root seedlings were acquired from MN Department of Natural Resources nursery and planted in a grid at 3 × 3 m spacing. Factor 1 was soil amendment with four levels: biochar only (0.5 L), compost only (0.5 L), biochar + compost (1 L mix, 50:50 biochar:compost), and control (no amendment). The biochar was produced using gasification (Cha et al. 2016) of lodgepole pine (*Pinus contorta* Doug.) in a low-oxygen environment for 5 min at 600 °C (Table 1). Compost was sourced from a commercial supplier and composed of cow manure, garden compost, and peat, and contained 0.5% nitrogen, 0.5% phosphorus, and 0.25% potassium by mass. We included the compost treatment because application of raw biochar can reduce nutrient availability (Brtnicky et al. 2021), which we wanted to evaluate with application of an additional nutrient source. If the amendments had been uniformly applied across an area in the same manner, the approximate application rate was 18 Mg ha^{-1} for biochar, 220 kg ha^{-1} N and P in the compost, and 110 kg ha^{-1} K in the compost. Soil amendments were applied by hand by mixing the material evenly with native soil in the hole at time of planting to maximize root contact. This application method has been used in other studies to evaluate biochar application at time of planting (Richards et al. 2017; Slesak et al. 2022). Factor 2 was irrigation with two levels: periodically irrigated or not irrigated (as control) but receiving ambient precipitation. For the irrigation treatment, 3 L of water was manually applied three times per week to each seedling throughout the growing season. Each treatment combination was replicated 10 times (80 tree seedlings total). Seedlings were planted in May 2016 and mesh tubing (rigid seedling protector tubes) was placed around each seedling to inhibit browse for the first 3 years of the study. Seedlings that experienced mortality in 2016 were replaced with new seedlings planted in 2017 (21 across all treatments).

Table 1. Characteristics of biochar used in this study.

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^{-1}))	3120	<0.5 mm (% of total)	49.4
Total K (mg kg^{-1})	580		

Measurements

Basal diameter and height were recorded at the time of planting and at the end of the growing season in each year thereafter (typically in October) for 4 years. Mortality and seedling condition were also recorded at the end of each growing season. Volumetric soil water content (SWC) was monitored on a subset of treatments in 2019 and 2020 using dialectic soil sensors (model 10-HS, METER Group) attached to data loggers (model EM50, METER Group). Sensors were installed laterally into the soil at a depth of 30 cm and approximately 15 cm away from the tree. SWC was logged hourly on three seedlings in each of the following treatments: biochar + compost + water, biochar + compost + no water, control + water, and control + no water.

Foliage was collected at the end of the project period in the fall of 2020 to assess treatment effects on tree nutrition. Mean needle mass was determined on a subsample of 100 needles, which were dried to 65 °C; needles were then ground in Wiley mill prior to chemical analysis. Macronutrient concentrations were determined using inductively coupled plasma - optical emission spectrometry (iCap 7600 Duo ICP-OES, Thermo Scientific, Bothell, WA) and total N was determined using the Dumas method on a Elementar vario MAX cube (Elementar Americas Inc., Ronkonkoma, NY) to determine the total amount of nitrogen per sample.

Analysis

Soil sensor readings were converted to SWC values using the manufacturer calibration equations. Values were first averaged by day, and then by week. Weekly mean SWC was expressed relative to the first week to account for spatial variation in SWC associated with sensor placement; positive values indicate higher SWC relative to the first week of measurement, and negative values indicate lower SWC relative to the first week of measurement. Treatment effects on weekly relative SWC were assessed using Analysis of variance (ANOVA) with repeated measures analysis with an AR(1) correlation matrix; each year was analyzed independently. When *F*-statistics indicated significant main effects, means between treatment levels at a given week were compared using the slice command in SAS (SAS Institute, Inc., 2013), which limits comparisons to within a week instead of multiple comparisons across all week and treatment combinations.

We report needle mass, nutrient concentration, and nutrient content to assess whether treatments increased needle growth, nutrient acquisition, or both (Timmer and Stone 1978). Foliage nutrient content was calculated as the product of needle mass and nutrient concentration. ANOVA was used to assess treatment effects on foliage variables. When significant effects were indicated, multiple comparisons were made to determine differences among treatments using a Tukey's adjustment. Treatment effects on annual diameter and height growth over time were assessed using ANOVA with repeated measures analysis with an AR(1) covariance matrix and using the initial diameter or height growth measurement as a covariate. For this analysis, seedlings replanted in the second year following mortality were coded as missing in the initial year, and then annual growth measures were used in subsequent years. Diameter and height data were log-transformed to meet assumptions of variance normality. When *F*-statistics indicated significant treatment effects, multiple comparisons with Tukey's adjustment were conducted to determine differences among treatments. An alpha level of 0.1 was used to determine significance in all tests to account for high variability among replicates and reduce the probability of type 2 errors occurring. All analyses were conducted in SAS V9.4 (SAS Institute, Inc., 2013).

Results

Treatment effects on SWC

Weekly mean SWC ranged from 0.22 to 0.27 $m^3\ m^{-3}$ in 2019 (mean 0.25 $m^3\ m^{-3}$ +/− 0.003) and ranged from 0.14 to 0.27 $m^3\ m^{-3}$ in 2020 (mean 0.23 $m^3\ m^{-3}$ +/− 0.008) across all treatments. There was significant interaction between irrigation treatment and week in 2019 ($p < 0.001$, Table S1), which manifested as larger reduction in SWC in the no water treatment compared to the watering treatment in growing season weeks 10, 11, 14, and 15 (Fig. 1). Similar trends were observed throughout 2020, but they were not significantly different (Table S1). There were no effects of soil amendment or any associated interaction in either year (Table S1).

Effects on seedling survival and growth

Seedling survival at the end of the study period was 95%, 100%, 80%, and 90% in the biochar, compost, biochar + compost, and control treatments, respectively; it was 92.5% and 90% for water and no water treatments, respectively. Across all treatments, mean seedling diameter was 5.5 mm (+/− 1.2) and 22.2 mm (+/− 2.8) in 2017 and 2020, respectively. ANOVA results (Table S2) indicated a significant three-way interaction among irrigation, soil amendment, and year on diameter. However, multiple comparisons failed to detect any differences among treatments and there were no clear patterns or trends among the treatment levels (Fig. 2). There was no effect of any treatment on seedling height over the course of the study (Table S2).

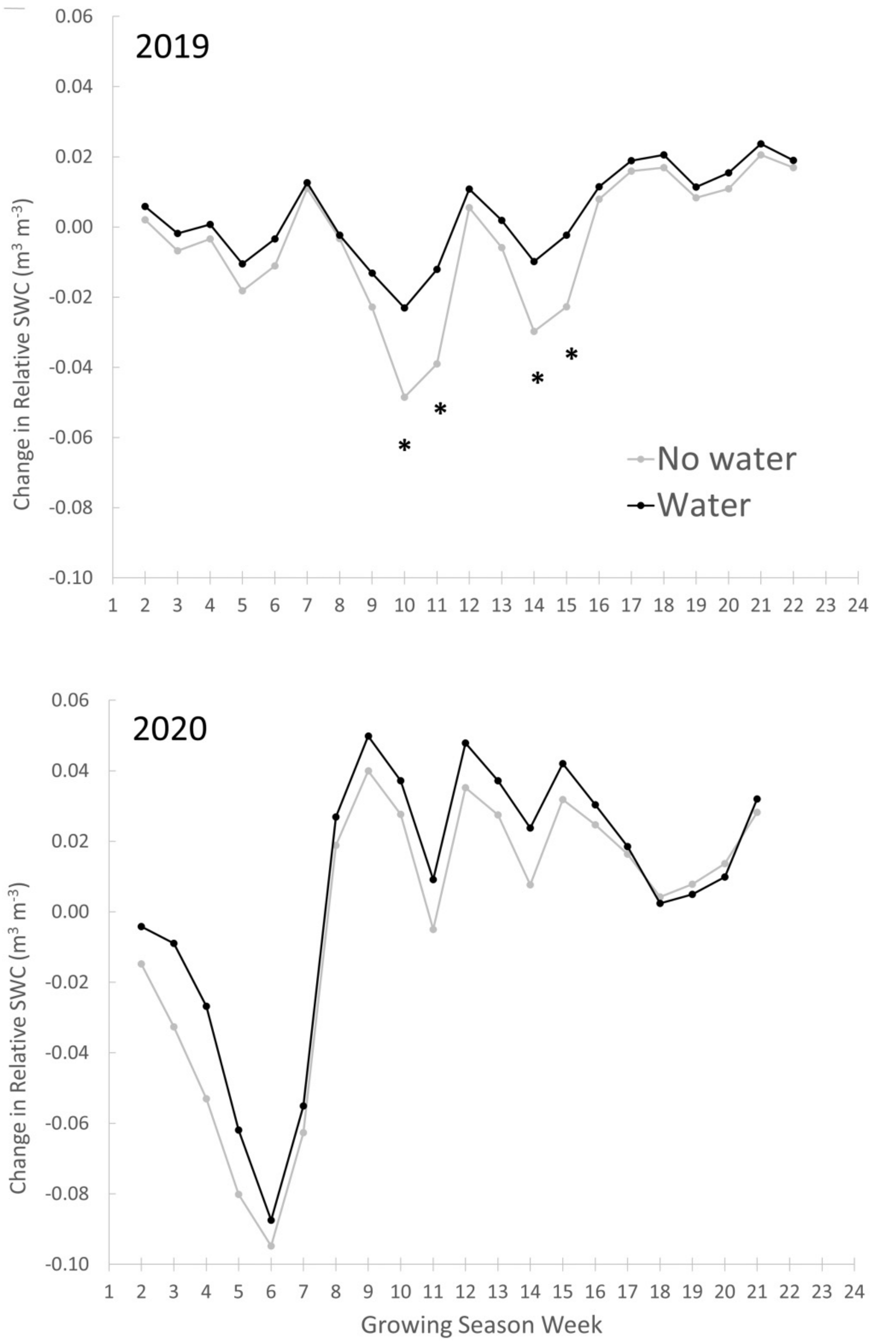
Effects on foliage mass and chemistry

Watering via irrigation significantly increased needle mass by the end of the study period; mean needle mass was approximately 25% greater in the water treatment relative to the no water treatment (Table 2). There was no effect of soil amendment or interaction between the two factors on needle mass (Table S3). Nutrient content increased with watering for both Mg and K (Tables S3 and 2). In the case of Mg, the increase in content resulted from the increase in needle mass coupled with increased concentration. For K, the increase in content was largely caused by the increase in needle mass alone. Watering also caused a significant reduction in foliage Ca concentration, but no concurrent effect on Ca content (Table 2). There was a significant effect of soil amendment treatment on soil Ca concentrations, which manifested as significantly lower Ca concentrations in the biochar-only treatment compared to the control treatment (Table 2). There were no other effects of soil amendment or interaction between irrigation and soil amendment on nutrient concentration or content.

Discussion

Biochar soil amendments to coarse, sandy soils did not have any positive effects on growth or foliar nutrition of jack pine seedlings in the initial years after planting. These results align with other studies conducted in the region focused on jack pine and biochar (Slesak et al. 2022; Reuling et al. 2023) and studies conducted elsewhere (McElligott 2011; Sherman et al. 2018; Sauer et al. 2019; Vannini et al. 2022). Biochar application may have large benefits to carbon sequestration because of its long residence time in soil (Spokas 2010), but our data do not support using it as a practice to increase seedling establishment and growth following planting on sandy soil where biochar is added into a planting hole at the rate that we used. It is possible that higher application rates or different application methods could provide some benefit to tree growth, and further study may be warranted.

Fig. 1. Change in mean growing season weekly soil water content relative to initial water content by watering treatment in 2019 (upper panel) and 2020 (lower panel). Asterisks indicate weeks where significant differences between treatments occurred. In each year, week 1 corresponds to the second week in May.



Irrigation is not a practical forest management practice; we included it to separate possible effects of biochar on soil water availability versus nutrient availability. However, the response to irrigation does offer some insights on how limiting resources influence jack pine growth. The increase in needle mass with irrigation indicates that the seedlings were able to allocate more resources to foliage production when water is presumably less limiting to growth. The lack of any concurrent effect on diameter and height growth may be due to the limited effect of irrigation on weekly SWC (Fig. 1), which is likely a result of the relatively low amount of water that was applied and the low water holding capacity of sandy soils. The limited effect may also be associated with above average growing season precipitation during the study (∼10%–20% higher than the 20 year average; PRISM Climate Group 2023), which may have alleviated water limitations to seedling growth. For foliage Mg and K, the concurrent increase in needle mass, concentration, and content for these elements is commonly interpreted to indicate that the nutrient is limiting to growth (Haase and Rose 1995). Compared to

 Can. J. For. Res. **54:** 245–251 (2024) | dx.doi.org/10.1139/cjfr-2023-0092

Fig. 2. Mean seedling diameter by treatment combination during the study period. Values were back-transformed from a log transformation for display purposes. Multiple comparisons failed to detect any significant differences among treatments and time periods. NW = no water treatment; W = watering treatment.

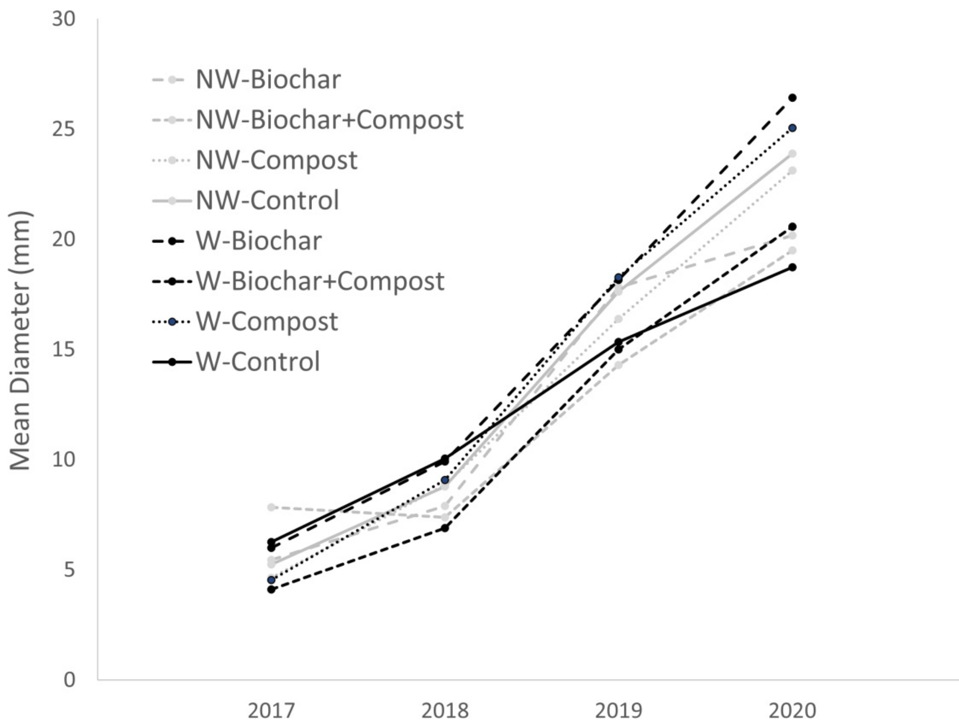


Table 2. Mean needle mass, foliage nutrient concentration, and foliage nutrient content by water and soil amendment treatment.

Treatment	Needle mass (g per 100)	N	Mg	Ca	K	P
		Nutrient concentration (% for N; mg kg for all others)				
Water	**1.299 (0.09)**	1.65 (0.03)	**1104 (33)**	**2994 (115)**	5615 (151)	**1799 (38)**
No water	**1.031 (0.09)**	1.58 (0.32)	**999 (34)**	**3443 (118)**	5818 (154)	**1898 (39)**
Control	1.053 (0.13)	1.68 (0.04)	1036 (47)	3577 (166)a	6028 (218)	1905 (55)
Biochar	1.084 (0.12)	1.60 (0.05)	1062 (46)	2930 (161)b	5460 (212)	1856 (54)
Compost	1.201 (0.12)	1.64 (0.04)	1058 (41)	3361 (145)ab	5758 (190)	1822 (48)
Bio-com	1.320 (0.14)	1.54 (0.06)	1052 (53)	3006 (184)ab	5622 (242)	1811 (61)
		Nutrient content (mg per 100 needles)				
Water		20.91 (1.48)	**1.43 (0.10)**	3.88 (0.32)	**7.42 (0.58)**	2.32 (0.17)
No water		17.99 (1.60)	**1.02 (0.10)**	3.57 (0.33)	**6.02 (0.59)**	1.96 (0.17)
Control		17.65 (2.10)	1.12 (0.14)	3.75 (0.47)	6.35 (0.83)	2.02 (0.24)
Biochar		17.96 (2.11)	1.12 (0.14)	3.16 (0.45)	5.92 (0.81)	2.00 (0.23)
Compost		19.91 (1.83)	1.27 (0.12)	4.12 (0.41)	7.03 (0.72)	2.21 (0.21)
Bio-com		22.27 (2.63)	1.39 (0.16)	3.89 (0.52)	7.58 (0.92)	2.34 (0.26)

Note: Means in bold within the water treatment are significantly different; mean concentrations containing different letters within the soil amendment treatment are significantly different. Standard error of the mean is shown in parenthesis. Bio-com = biochar-compost treatment.

nutrition criteria for lodgepole pine (*Pinus contorta* var. *latifolia*) (Brockley 2001, 2007) that is closely related to jack pine, Mg concentrations appeared to be sufficient for growth, but K concentrations would be classified as limiting. Watering increased the availability of growth-limiting nutrients, which may increase tree growth over time. The decrease in Ca concentration with watering is likely caused by dilution associated with larger needle mass as no concurrent change in total content occurred (Timmer and Stone 1978; Haase and Rose 1995).

Biochar has potential to decrease nutrient availability because of its high exchange capacity, which may sorb nutrients (Brtnicky et al. 2021); we included the compost treatment to quantify this possible effect. The reduction in foliage Ca concentrations with no concurrent change in needle mass in the biochar-only treatment indicates that Ca availability was reduced in that treatment, likely because it was immobilized by the biochar. This finding highlights the need to "charge" biochar prior to its application with a nutrient source such as the compost used in this study (Brtnicky et al. 2021) if the goal is to maintain or improve seedling nutritional status.

Despite our primary conclusion, it is possible that future work could develop a biochar that consistently improves seedling performance following planting, as demonstrated in some studies (Palviainen et al. 2020; Grau-Andrés et al. 2021). Biochar properties (and its related effects on resource supply) are known to be dependent on feedstock type, pyrolysis conditions used during production, and post-production processing (Ippolito et al. 2020; Huang et al. 2021). Future studies on trees and seedlings should focus on feedstocks and pyrolysis conditions that produce properties most favorable to increased plant resource supply. For soil water availability in coarse-textured soils, these properties are likely to include smaller particle sizes (<2 mm) and a high specific surface area (Edeh et al. 2020; Zhang et al. 2021).

Acknowledgements

We greatly acknowledge Sara Kelso, Kyle Gill, Lane Jonson, Rachael Olesiak, Christopher Bru, Wren Brien, and Elizabeth Ring with assistance in study initiation and treatment application. Measurements were conducted by Sara Kelso and Matt Lochner. Funding for this work was provided by the College of Food Agricultural and Natural Resource Science at the University of Minnesota, USDA NIFA Award Number 2018-10008-28583, MAES Project MIN-42-108, and the Minnesota Forest Resources Council.

Article information

History dates

Received: 20 April 2023
Accepted: 28 July 2023
Accepted manuscript online: 11 August 2023
Version of record online: 3 October 2023

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Data availability

Data are available upon reasonable request to the author.

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Investigation: RAS, MW
Methodology: RAS, MW
Supervision: MW
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Writing – review & editing: MW

Competing interests

The authors declare there are no competing interests.

Supplementary material

Supplementary data are available with the article at https://doi.org/10.1139/cjfr-2023-0092.

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