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Long-term effects of organic matter removal, compaction, and vegetation control on tree survival and growth in coarse-textured, low-productivity soils

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ABSTRACT

The Long-Term Soil Productivity Network is providing a systematic examination of the effects of organic matter removal and compaction on a variety of different soils and forest types across North America. Here we report on the 22nd-year survival and height growth of white oak (*Quercus alba*), northern red oak (*Q. rubra*), and shortleaf pine (*Pinus echinata*) on rocky, nutrient-poor soils that have a low to moderate water holding capacity in the Missouri Ozark Highlands. Treatments included three levels of organic matter removal (sawlog, whole tree, and whole-tree plus forest floor) and three levels of soil compaction (none: bulk density = 1.34 g cm^{-3}; moderate: bulk density = 1.65 g cm^{-3}; and severe: bulk density = 1.78 g cm^{-3}) each with and without vegetation control. Following treatments, bareroot, 1–0 white oak, northern red oak, and shortleaf pine seedlings were planted at a 3:3:1 ratio, approximating the distribution of these species in this region. Within half of each plot, a vegetation control treatment was applied for the first 10 years by treating competing vegetation with herbicide. After 22 years, vegetation control significantly increased biomass and height of all planted species. The average height for northern red oak with vegetation control treatments was 884 cm with vs. 606 cm without; white oak was 837 cm with vs. 424 cm without; shortleaf pine was 1339 cm with vs. 1220 cm without. Moderate compaction increased average white oak height by 15% and severe compaction increased average height by 18% compared to no-compaction treatments. Compaction was not a significant treatment for red oaks or for shortleaf pines. However, the coarse fragments in the study soils appear to have muted much of the compaction to the soil's fine-earth fraction and may have had the unintended effect of providing partial vegetation control. Whole-tree removal reduced average shortleaf pine heights by 6% vs. sawlog-only removal, while whole-tree + forest floor removal increased heights 3% compared to sawlog harvests. Organic matter removal was not a significant treatment for either oak species. Red oak survival probability was 0.79 with vegetation control vs. 0.34 without; white oak was 0.81 with vs. 0.65 without; shortleaf pine was 0.49 with vs. 0.45 without. Overall, vegetation control was the dominant factor driving survival and growth of oaks, and to a lesser degree, growth of shortleaf pine. Organic matter removal and compaction treatments had relatively little negative effect on height, indicating the resilience of these species to harvest-related disturbances in Ozark Highlands soils.

1. Introduction

Nutrient depletion and soil compaction associated with timber harvesting have long been concerns (Powers et al., 1990, 2005; Thiffault et al., 2011). Substantial quantities of nutrients stored in tree boles and bark are removed during sawlog harvests (Kabrick et al., 2013; 2019). Emerging interests in biofuel or bioproducts has raised additional concerns because of the potential to remove branches, tops, and other residues that ordinarily would remain on forest floor after traditional sawlog-only harvests (Goerndt et al., 2014). These nutrient losses can reduce stand productivity where removals exceed inputs (Kabrick et al., 2013). Soil compaction caused by harvesting equipment can further reduce productivity by increasing bulk density and reducing microporosity, collectively decreasing aeration, infiltration, and water-holding

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capacity (Ponder, 2007). Severe compaction has been shown to limit root growth where bulk density levels exceed specific thresholds associated with soil texture (Daddow and Warrington, 1983). However, despite years of study, there are no consistent or universal effects of harvest removals or soil compaction on long-term site productivity because the effects appear to differ by climate or microclimate, by soil properties such as texture and organic matter content, and/or by forest type (Thiffault et al., 2011; Ponder et al., 2012). Powers et al. (1990) stated that a systematic and coordinated approach was needed for a comprehensive examination of the fundamental effects of organic matter removal and compaction on forest growth, leading to the development of the Long-Term Soil Productivity (LTSP) network of studies (Powers and Van Cleve, 1991; Powers et al., 2005; Ponder et al., 2012).

One of the many strengths of the LTSP study network is that it includes more than 100 sites across a wide range of forest types and soils, facilitating analyses of the long-term treatment effects on many different tree species and soil properties in different climates (Powers et al., 1990; Powers and Van Cleve, 1991). In this paper, we report on the 22-year effects of the three levels of organic matter removal, three levels of soil compaction, and two levels of vegetation control on tree survival and growth in the Ozark Highlands installation in southeastern Missouri, USA. This LTSP installation is in an oak – pine forest type and included northern red oak (*Quercus rubra*), white oak (*Q. alba)*, and shortleaf pine (*Pinus echinata*) planted in soils with an abundance of coarse fragments that are nutrient-poor and well drained. Five- and ten-year results for this study site and for all LTSP study sites have been reported elsewhere (Fleming et al., 2006; Ponder et al., 2012).

2. Methods

2.1. Site description

The study is in the Current River Conservation Area in Shannon County, MO (N 37°10′48″, W 91°06′36″*)*. Soils at the Missouri site are primarily Clarksville gravelly silt loam (loamy-skeletal, siliceous, semiactive, mesic Typic Paleudults), but includes Scholten gravelly silt loam (loamy-skeletal, siliceous, active, mesic Typic Fragiudults), and Poynor gravelly silt loam (loamy-skeletal over clayey, siliceous, semiactive, mesic Typic Paleudults). These soils occur extensively in the Ozark Highlands and are mapped on more than 1.1 million ha in the region. The soils formed in cherty hillslope sediments overlying clayey residuum from dolostone. Gravel-and cobble-sized chert fragments occur throughout the profile. They are well drained and have a low to moderate water-holding capacity (https://casoilresource.lawr.ucdavis.edu/soilweb-apps/, accessed 22 March 2021). Data from our study sites indicated that coarse fragments comprise 23 to 64% of the volume of the upper 30 cm of soil, the base cation saturation ranges from 23 to 42%, and the pH ranges from 5.4 to 5.7. Prior to study initiation, the site was occupied by a mature second-growth oak (*Quercus* spp.)- hickory (*Carya* spp.) forest (Ponder and Mikkelson, 1995). Site index at 50 years (*Q. velutina* basis) ranges from 22 to 24 m (Ponder, 1997). Weather data collected on-site from February 2001 to November 2020 indicated a mean annual temperature at the site of 14.0 ^{0}C, and an average annual precipitation of 1130 mm.

2.2. Experimental design

There are nine treatments in a 3x3 split-plot factorial design including three levels of organic matter removal (OM) in whole plots, three levels of soil compaction (C) in whole plots, and one of two levels of understory vegetation control (VC) in half of each treatment unit in split plots. The three levels of OM removal were bole only (OM_0), where branches, tops and litter remained on-site after harvest; whole-tree (OM_1), where the entire above-ground biomass was removed; whole-tree plus forest floor (OM_2), which includes whole-tree removal, plus the raking of forest floor litter down to the mineral soil.

Table 1
Whole-soil (Dbw) and fine-earth bulk densities (Dbf) for the Missouri LTSP study (least square means ± 1 standard error). Within columns and depth classes, different letters indicate significant differences (P < 0.05).

Treatment	Depth (cm)	Dbw (g cm^{-3})	Dbf (g cm^{-3})
0 years post-treatment			
C_0	0–10	1.34	0.96
C_1	0–10	1.65	1.29
C_2	0–10	1.78	1.43
8 years post-treatment			
C_0	0–10	1.37 ± 0.13 a	0.86 ± 0.13 a
C_2	0–10	1.49 ± 0.14 a	1.06 ± 0.15 a
C_0	10–20	1.40 ± 0.12 a	0.89 ± 0.09 a
C_2	10–20	1.84 ± 0.21b	1.41 ± 0.27b
C_0	20–30	1.70 ± 0.16 a	1.18 ± 0.18 a
C_2	20–30	1.79 ± 0.21 a	1.20 ± 0.22 a

Soil compaction levels were no compaction (C_0) with a whole-soil bulk density (Dbw) of 1.37 g cm^{-3}, moderate compaction (C_1) with a Dbw = 1.65 g cm^{-3}, and severe compaction (C_2) with a Dbw = 1.78 g cm^{-3}. Soil compaction was applied using a 14-ton vibrating sheep's foot roller, with field measurements of soil bulk density performed after each pass of the roller. Moderate compaction plots received three passes, while C_2 plots received between five and eight passes. Changes in bulk density were not observed beyond five passes (Ponder 1997). Plots designated for C had post-harvest forest floor removed and stored prior to treatment, after which the forest floor was returned to the plot. In the C_0 plots harvested biomass was removed by a cable yarding system to minimize potential soil disturbance from logging equipment. At study inception, bulk densities were based upon whole-soil (rather than fine-earth) fractions. However, because rooting occurs in the fine-earth fraction, bulk densities of the fine-earth fraction (Dbf) were recalculated using the original laboratory texture data where available or approximated using a regression equation developed from pre-treatment data (Table 1). Whole-soil Db values are from Ponder (2007) although source data were not available for analysis; Dbf values were estimated with empirical relationship for pre-treatment soils where Dbf = 1.07Dbw – 0.47 ($P = 0.001$, $R^2 = 0.73$).

In the split plots designated for VC treatment, herbicides were applied to the VC_1 treatment, while the other plot half was left untreated (VC_0) to allow natural regeneration to develop along with the planted trees. In the VC_1, treatment, a glyphosate-simazine mixture was applied annually to all but planted seedlings during the first ten growing season, preventing the establishment of competing vegetation. The understory in the VC_1 treatment remained free of herbaceous and woody vegetation, despite the cessation of herbicide applications over a decade ago (Fig. 1). In the VC_0 treatment, hardwoods that naturally regenerated included white oak, northern red oak, scarlet oak (*Q. coccinea*), black oak, (*Q. velutina*), post oak (*Q. stellata*), shortleaf pine, red maple (*Acer rubrum)*, blackgum (*Nyssa sylvatica)*, hickories (*Carya* spp.), and dogwood (*Cornus florida)*.

Pre-treatment harvesting took place in early 1994. Treatment application and seedling planting occurred in Spring 1995. All seedlings were 1–0 bareroot stock from the George O. White State Nursery in Licking, MO. About 2,380 northern red oak, 2467 white oak, and 763 shortleaf pine, were planted 2.5 m apart in rows that were 3.0 m apart in a 3:3:1 ratio, respectively, to approximate their relative distribution at the initiation of the study. A 1 m-radius area around all seedlings, regardless of treatment, was sprayed with the same herbicide mixture used in the VC_1 treatment for two growing seasons. The spring of 1995 was extremely dry, resulting in high mortality during the first growing season, especially of shortleaf pine (approximately 29% of planted seedlings died). Subsequently, seedlings were watered once in late 1995 (Ponder, 1997). Further, tree shelters were placed around each seeding due to recurring rodent damage during the first growing season (Ponder, 1997). It is not known how long these shelters remained in place. For a

Fig. 1. Missouri LTSP study site after 22 growing seasons in the OM_2C_2 treatment in the (a) VC_1 subplot (planted trees only) and the (b) VC_0 subplot (planted and naturally regenerated trees).

Table 2
Soil organic matter, nutrient concentrations, and pH (0–10 cm depth) by treatment (least square means ± 1 standard error) determined at year 15. Within columns and treatment, different letters indicate significant differences ($P < 0.05$).

Treatment	Organic matter	Nitrogen	Calcium	Magnesium	Potassium	pH
	%	$mg\ kg^{-1}$				
OM_0	3.7 ± 1.1	2034 ± 1	1149 ± 147	75 ± 1	87 ± 1	5.7 ± 0.1
OM_1	3.5 ± 1.1	1999 ± 1	1012 ± 146	67 ± 1	95 ± 1	5.4 ± 0.2
OM_2	3.7 ± 1.1	2840 ± 1	926 ± 146	80 ± 1	102 ± 1	5.5 ± 0.1
C_0	3.7 ± 1.1	2075 ± 1	857 ± 146	62 ± 1	88 ± 1	5.4 ± 0.2
C_1	3.4 ± 1.1	2051 ± 1	990 ± 146	73 ± 1	92 ± 1	5.5 ± 0.2
C_3	3.8 ± 1.1	2714 ± 1	1240 ± 147	89 ± 1	103 ± 1	5.7 ± 0.2
VC_0	3.8 ± 1.1	2402 ± 1	1078 ± 116	95 ± 1[a]	104 ± 1[a]	5.5 ± 0.1
VC_1	3.5 ± 1.1	2127 ± 1	980 ± 116	57 ± 1[b]	86 ± 1[b]	5.6 ± 0.1

complete description of the site characteristics and experimental design, see Ponder and Mikkelson (1995).

2.3. Tree measurements

Tree height, basal diameter (until height exceeded 1.37 m), or diameter at 1.37 m above ground line (DBH) of living trees were measured annually for the first 10 growing seasons and periodically afterwards. Here we used the most recent inventory completed after the 22nd growing season in 2016. In April 2019, the VC_0 split plot was inventoried in 0.04-ha fixed-radius circular plots to provide an estimate of stocking and biomass of all woody vegetation developing in the absence of vegetation control. Data collected included DBH and crown class by species for trees > 1.37 m tall. For all datasets, biomass was calculated using the equations by Jenkins et al. (2003) for per hectare estimates and equations by Chojnacky et al. (2013) for the planted oaks and pines. We also estimated treatment unit stocking (*sensu* Gingrich 1967) using parameters of Gingrich (1967) for hardwoods and Rogers (1983) for shortleaf pine.

2.4. Soil nutrient analyses

Replicate soil samples (0–10 cm depth) were collected at year 15 and sent to the University of Arkansas Agricultural Diagnostic Laboratory soil testing laboratory for determination of organic matter content (weight loss on ignition), total nitrogen (dry combustion), exchangeable cations (Mechlich III extraction, 1:10 soil to solution ratio), and pH (1:2 soil to water ratio) (Table 2). Methods follow Sikora and Moore (2014).

2.5. Data analyses

Survival probabilities for each species in relation to C, OM, and VC were determined using logistic regression for the 22nd-year data collection. We used a generalized linear mixed model with a binary distribution (survival = 1, mortality = 0), logit link function, and random intercept using PROC GLIMMIX in SAS 9.4 software (SAS Institute, Inc., Cary, NC). Treatment effects on above-ground biomass, tree heights, and soil nutrients were analyzed using a generalized linear mixed model with PROC GLIMMIX in SAS 9.4 software (SAS Institute, Inc., Cary, NC). The best fit models were identified through a standard

Table 3
Stocking and above-ground tree biomass (least square means ± 1 standard error) by treatment. Within columns and treatment, different letters indicate significant differences ($P < 0.05$).

	Stocking (%)	Above-ground biomass (Mg ha^{-1})	Stocking (%)	Above-ground biomass (Mg ha^{-1})	Above-ground biomass per tree (kg)
	All trees, VC_0 treatment only		Planted trees only, all treatments		
OM_0	112 ± 12	15.9 ± 1.1	80 ± 6	21.9 ± 1.2	81.4 ± 13.3
OM_1	104 ± 12	13.5 ± 1.1	76 ± 6	21.1 ± 1.2	74.9 ± 12.4
OM_2	116 ± 12	16.9 ± 1.1	81 ± 7	25.9 ± 1.2	80.4 ± 13.5
C_0	103 ± 12	15.1 ± 1.1	67 ± 6[a]	13.6 ± 1.2[a]	66.9 ± 13.1
C_1	108 ± 12	14.7 ± 1.1	82 ± 6[b]	27.5 ± 1.2[b]	80.0 ± 13.1
C_2	122 ± 12	16.4 ± 1.1	88 ± 6[b]	32.0 ± 1.2[b]	89.7 ± 13.1
VC_0	111 ± 7	15.9 ± 1.0	33 ± 6[a]	9.6 ± 1.1[a]	39.8 ± 10.7[a]
VC_1	–	–	125 ± 6[b]	54.5 ± 1.1[b]	117.9 ± 10.7[b]

residuals analysis and a Levene's test to ensure that response variable distributions were specified correctly and that model assumptions were met. For all models, we examined the fixed effects of C, OM, and VC, as well as all first-order interactions. For OM and C treatments (whole plot effects), the random effect "block" was the error term and for VC (split-plot effects) and interactions with VC, the residual error was used. Least-square means were subjected to pairwise comparisons using T-grouping at $\alpha = 0.05$.

3. Results

3.1. Total stocking and biomass

All plots were fully stocked regardless of treatment and stocking exceeded 100% in the VC_0 treatment where natural regeneration developed along with the planted trees (Table 3). In the VC_1 treatment which included only planted trees, the overall stocking was greater (125%) suggesting that it exceeded full growing space utilization (Fig. 1). Total above-ground biomass ranged from 13.5 to 16.9 Mg ha^{-1} in the VC_0 split plots among the OM and C treatments but was 54.5 Mg ha^{-1} in the VC_1 split plots where planted trees were growing in the absence of competing vegetation. For the planted trees in the VC_1 treatment, the stocking and above-ground biomass were four to five times greater ($p < 0.001$) than those in the VC_0 treatment. Moderate and severe compaction treatments (C_1 and C_2) also had greater planted-tree stocking and biomass ($p < 0.001$) compared to C_0. There were no significant interactions of OM, C, and VC ($p > 0.091$).

3.2. Treatment effects on species

3.2.1. Survival

Twenty-one years after planting, northern red oak survival was significantly affected by VC ($p < 0.001$), with survival probability more than doubling from 0.34 to 0.79 where competing vegetation was absent, and by C ($p = 0.002$), where moderate compaction (C_1) increased survival probability by 0.13 compared to the non-compacted (C_0) treatment (Fig. 2). Also significant were the interactions of C × VC ($p = 0.046$) and OM × C ($p = 0.004$) (Fig. 3). Organic matter removal alone was not significant ($p = 0.297$), nor were the interactions of OM × VC ($p = 0.424$) and overall treatment interactions, OM × C × VC ($p = 0.307$).

White oak survival after 22 years was significantly impacted by all main effects. Vegetation control increased survival probability by 16% ($p < 0.001$), while C_2 increased survival probability by 12% ($p < 0.001$). Organic matter removal was also significant ($p = 0.022$), with increasing levels of OM removal increasing survival probability (Fig. 4). Two interactions were significant. For C × VC, compaction increased survival significantly in VC_0 treatments, with severe compaction probabilities equal to those of the VC_1 treatment ($p = 0.010$) (Fig. 3). For OM × C, compaction significantly increased survival probability in OM_0 and OM_1 but had a mixed effect in OM_2 ($p = 0.004$) (Fig. 3). Interactions between OM × VC, as well as overall main treatment effects were not significant ($p = 0.180$ and $p = 0.608$, respectively).

Shortleaf pine 22nd year survival probability was not significantly affected by VC ($p = 0.294$) but was significantly increased by compaction ($p < 0.001$), while OM removal had a significant, though non-linear, effect ($p = 0.013$) (Fig. 5). The OM × C interaction was significant ($p = 0.009$) indicating that compaction increased survival when only sawlogs were removed (OM_0) but had a mixed effect with higher levels of OM removal (Fig. 3). The C × VC interaction was also significant ($p = 0.006$) indicating that where compaction treatments were not applied (C_0), VC_0 had nearly doubled survival probability vs VC_1, while

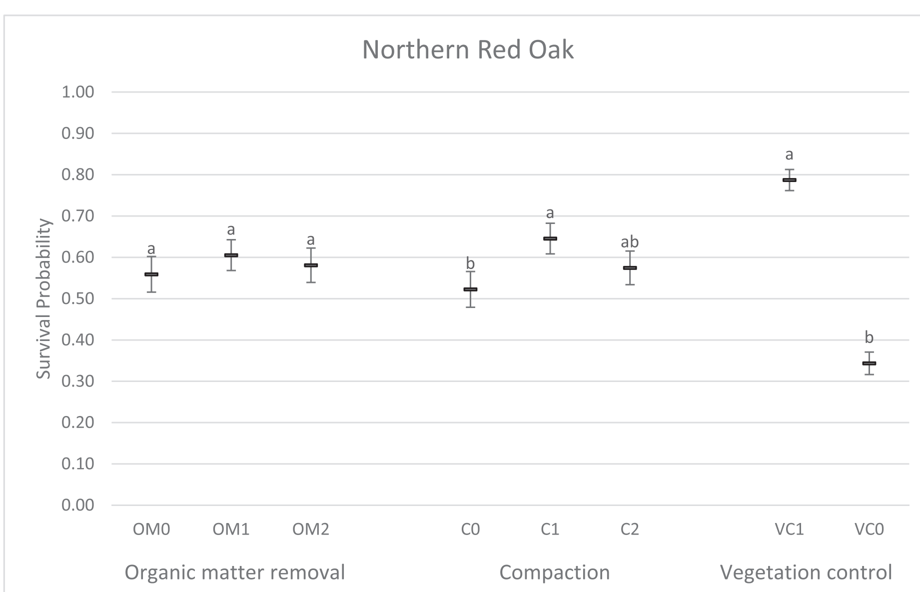

Fig. 2. Northern red oak survival probability by treatment main effects after 22 growing seasons. Bars are ± 1 standard error. Within treatments, different letters indicate significant differences. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

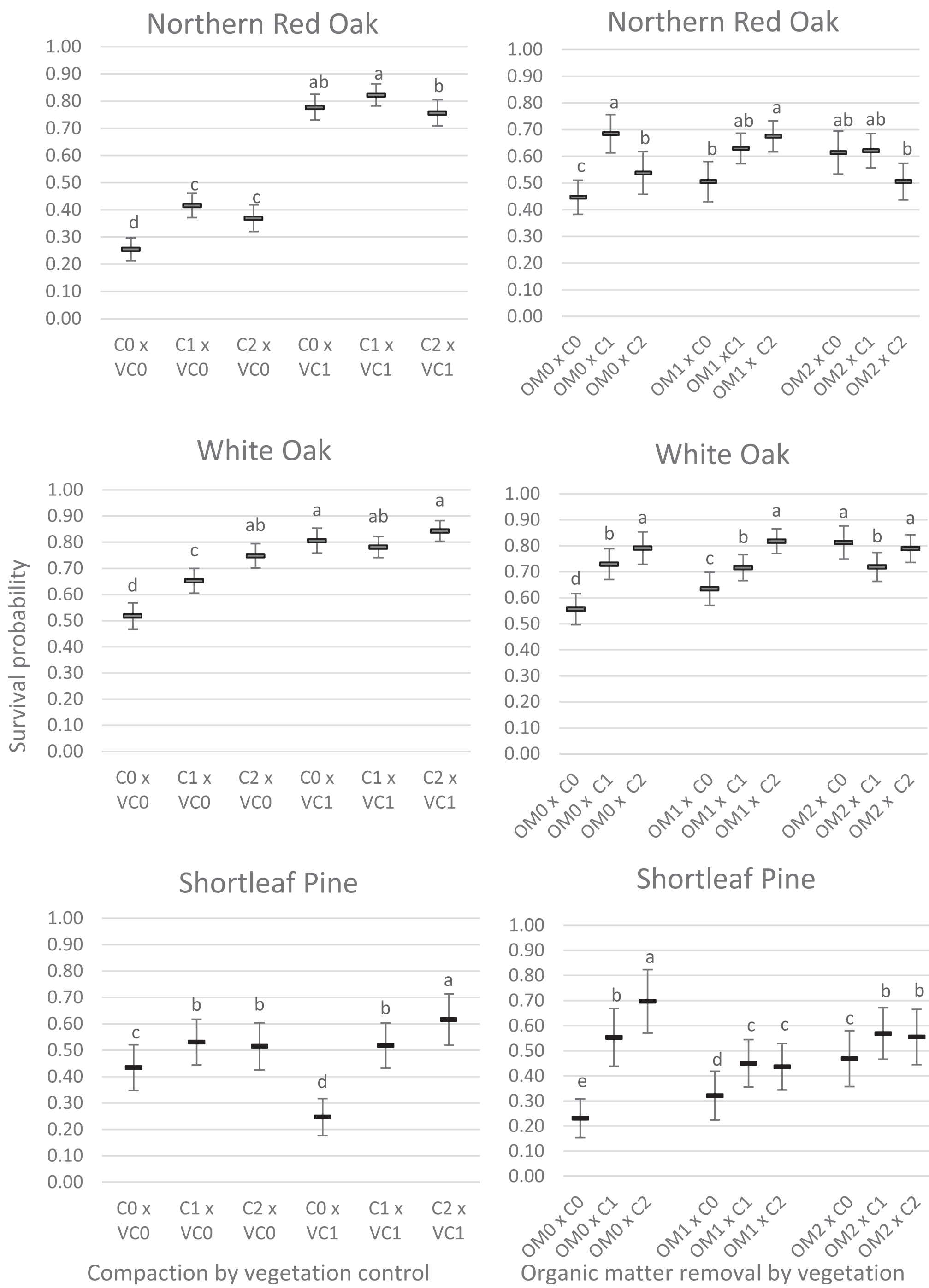

Fig. 3. Survival probabilities by treatment interactions after 22 growing seasons. Bars are ± 1 standard error. Within treatments, different letters indicate significant differences.

in the C_2 treatment, VC_1 survival probability was 10% greater than VC_0 (Fig. 3).

3.2.2. *Height growth by species*

Vegetation control significantly increased heights of all species ($p < 0.001$). In northern red oak, heights of trees in VC_1 plots were 32% greater than in VC_0; white oak height nearly doubled with VC_1 from 424 cm to 837 cm; shortleaf pine height increased by 9% (119 cm) in VC_1 treatments (Fig. 6).

Compaction significantly increased the height of white oak ($p = 0.001$), and marginally increased the height of shortleaf pine ($p = 0.056$) but did not affect northern red oak ($p = 0.174$) (Fig. 7). Organic matter removal was marginally significant for shortleaf pine ($p = 0.038$), where whole-tree removal decreased average height, while whole-tree plus forest floor removal increased planted tree height. Organic matter removal was not significant for northern red oak ($p = 0.357$) or white oak ($p = 0.643$) (Fig. 7). The interaction of C × VC was significant in white oak ($p = 0.002$) and shortleaf pine ($p = 0.006$) but not northern red oak ($p = 0.704$) (Fig. 8). Overall, the three-way interaction among OM × C × VC was significant for shortleaf pine ($p = 0.035$) but not northern red oak ($p = 0.401$) or white oak ($p = 0.905$). No other interactions were significant ($p > 0.100$).

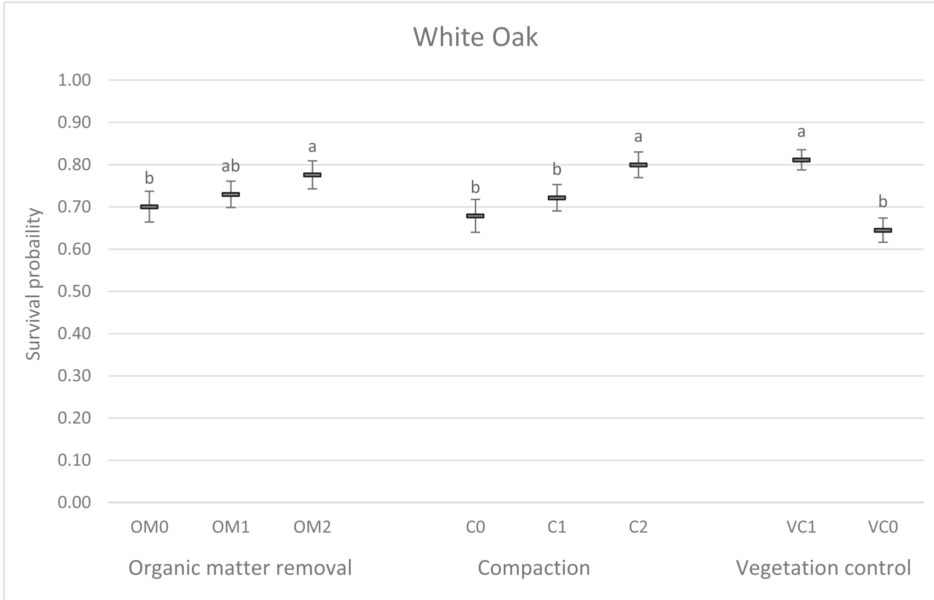

Fig. 4. White oak survival probabilities after 22 growing seasons by treatment main effects. Bars are ± 1 standard error. Within treatments, different letters indicate significant differences.

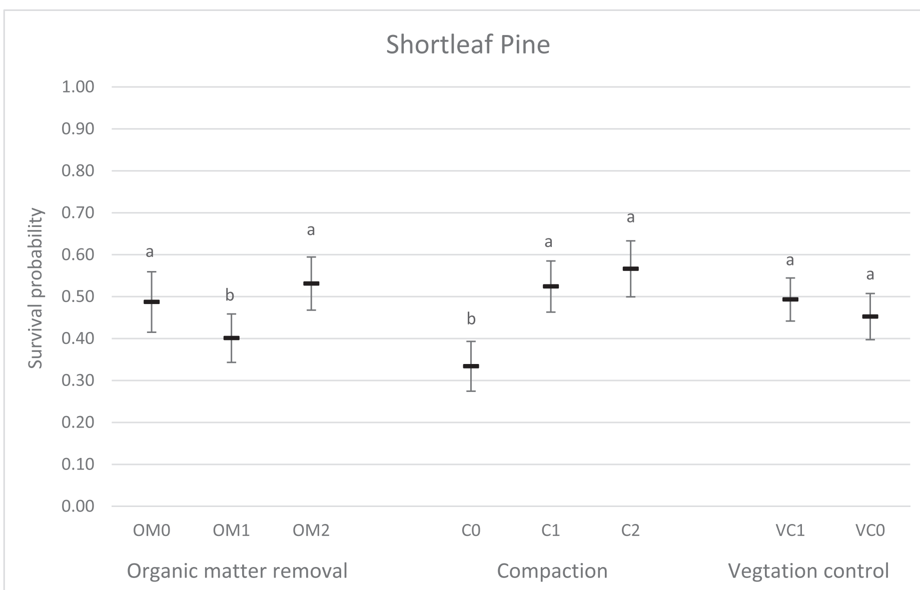

Fig. 5. Shortleaf pine survival probabilities after 22 growing seasons by treatment main effects. Bars are ± 1 standard error. Within treatments, different letters indicate significant differences.

4. Discussion

4.1. Vegetation control

Vegetation control had the most substantial effect on planted trees, increasing the twenty-two-year biomass, height growth, and survival of the planted oak species, while only increasing the height of shortleaf pine. The presence of competing vegetation reduced the mean height of the planted trees. Competing vegetation also reduced the survival of the planted oaks. The VC treatment was not a significant factor in shortleaf pine survival, although overall survival was nominally reduced when competing vegetation was present.

Survival was also affected when a total of 34 shortleaf pines were removed (harvested) from the site following the 6th growing season after abnormal growth was noted due to ice damage occurring during the previous year. All but one of these trees were in VC_1 plots (Ponder, 2007). Because we do not know the plots from which these trees were removed, it is possible that this ice storm, or other extreme weather conditions, disproportionately impacted shortleaf pine survival in the OM_0C_0 treatment, as survival probability averaged only 0.25 after 22 years (Fig. 3). Ponder (1997) reported that due to a drought at time of planting, short-term irrigation was applied. These non-treatment effects may have increased the survival of shortleaf pine, as the survival probabilities in C_1 and C_2 were statistically the same between VC_1 (0.53) and VC_0 (0.52) but were significantly higher in C_2 where VC was applied (0.62 survival) compared to where there was no VC (0.51 survival). Similarly in a separate study, Kabrick et al. (2015) found no correlation between shortleaf pine seedling survival and overstory competition,

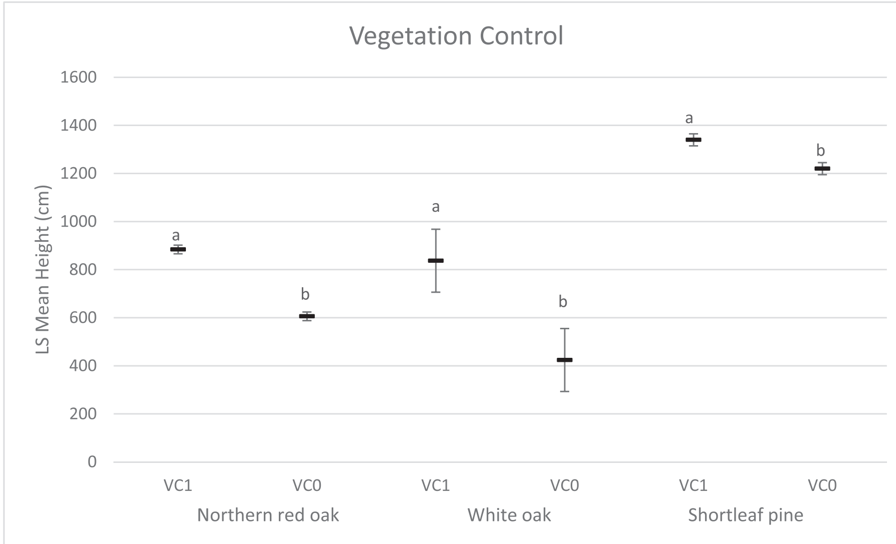

Fig. 6. Vegetation control effects by species. Bars are ± 1 standard error. Within treatments, different letters indicate significant differences.

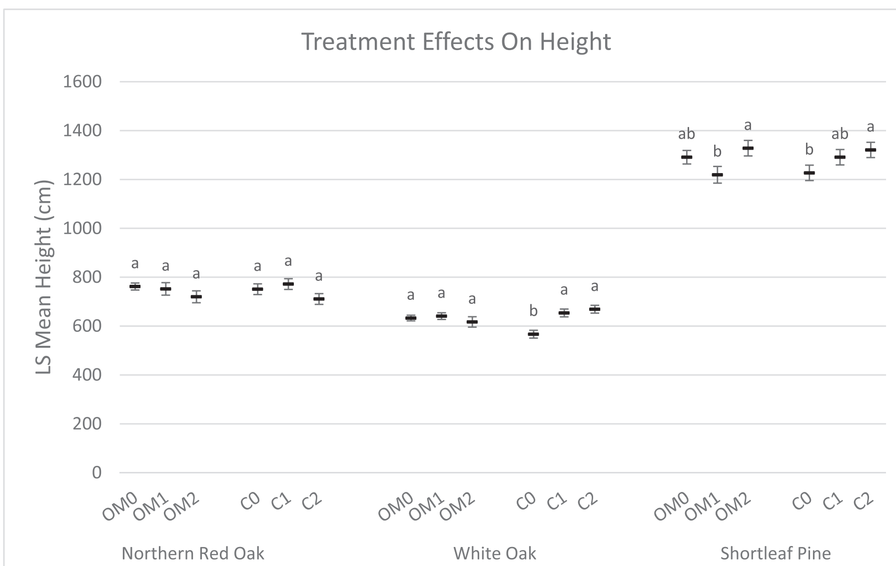

Fig. 7. Treatment main effects on height after 22 growing seasons. Bars are ± 1 standard error. Within treatments, different letters indicate significant differences.

suggesting additional contributing factors influenced survival. Vegetation control, although only statistically significant for northern red and white oak survival probabilities, appears to have reduced competition for light, water, and nutrients, allowing the seedlings to become established.

4.2. Soil compaction

Soil compaction had either no significant impact on mean height (northern red oak), or compaction increased mean height (white oak and shortleaf pine). Compaction consistently increased survival in all species, but most notably in shortleaf pine, where severely compacted soils (C_2) had a 22-year survival probability of 0.57, while survival in the non-compacted (C_0) treatment was only 0.33. These long-term findings in survival reverse a non-significant trend at this LTSP installation observed by Ponder (2004, 2007), who reported survival probability of shortleaf pine seedlings to be nominally lower in the compaction treatments (C_1 and C_2) compared to no compaction (C_0) during each of the first nine growing seasons. Schubert et al. (2004) found mean shortleaf pine survival of 56.2% after 22 years in the Highland Rim in Tennessee in plantations having a similar planting spacing as in our study. Though conifer response to compaction is generally positive (Brais, 2001; Gomez et al., 2002; Powers et al., 2005; Ponder et al., 2012), it was notable that northern red oak and white oak survival probabilities, and white oak height were also positively affected by the compaction.

The observed biomass and height increase in the C_1 and C_2 treatments were probably not caused by compaction per se but resulted from unintended competition control resulting from mechanical damage to residual stumps and stems caused by the roller used to apply the compaction treatment. Multiple passes with the roller appear to have initially reduced the sprouting of hardwood stumps. Ponder (2008) reported that the density of competing trees in the severe compaction treatment (C_2) measured 6 and 8 years after the study was initiated was reduced by 50% and 42% compared to the no-compaction (C_0). However, this effect appears to have been temporary because presently there is no difference in the stocking levels among compaction treatments (Table 3). In addition, the soils at this site can contain as much as 64%

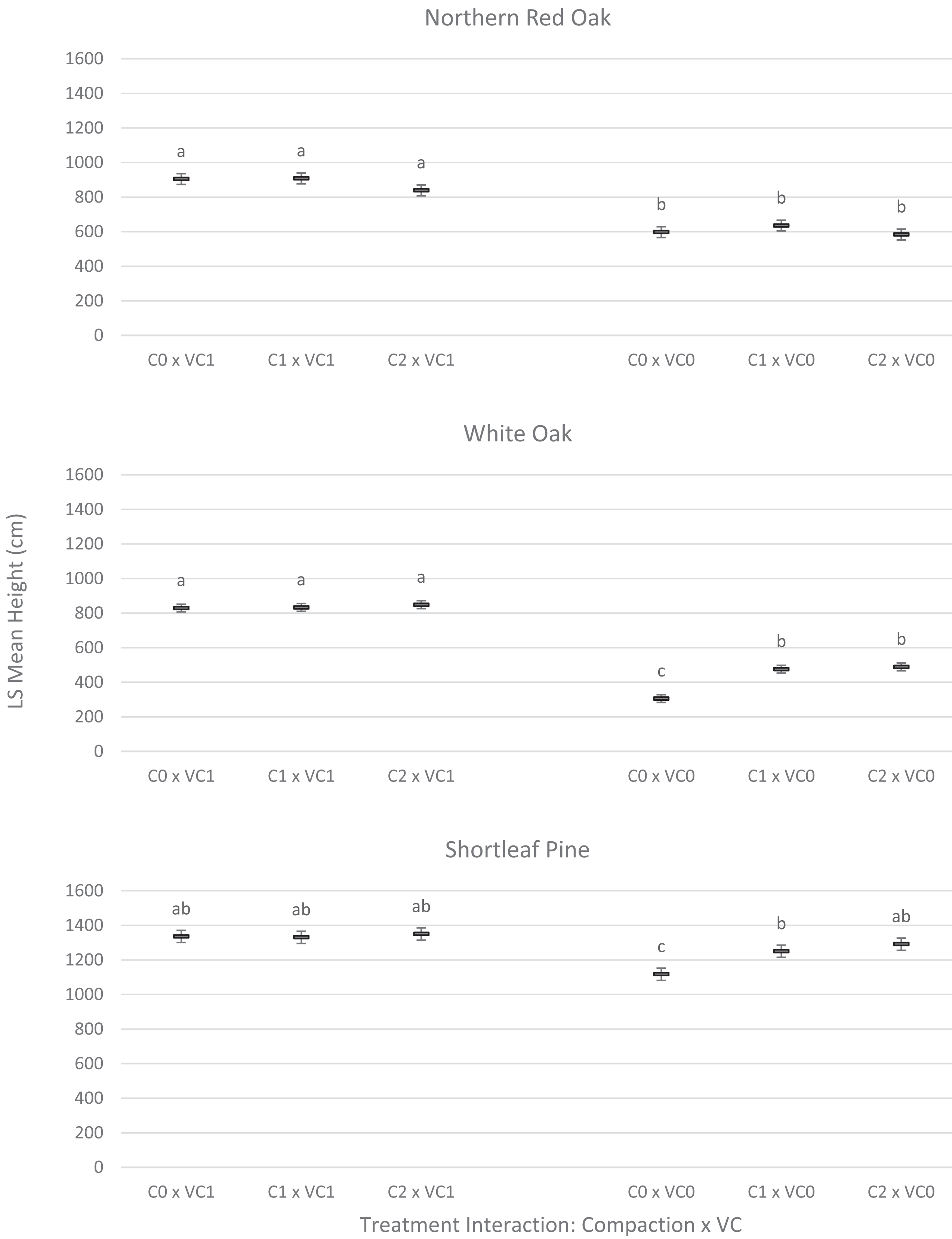

Fig. 8. Mean heights after 22 growing seasons by treatment interaction. Bars are ± 1 standard error. Within treatments, different letters indicate significant differences.

coarse fragments by volume in the upper 30-cm, providing a buffer to resist compaction of the fine-earth fraction. Because rooting only occurs in the fine-earth fraction in these soils, a better assessment of compaction is the bulk density of the fine-earth fraction. Bulk density determined on a fine-earth fraction basis (Table 1) shows that only in the severe compaction treatment (C_2) did the bulk density approach levels that are associated with reduced tree growth in silty soils (see Daddow and Warrington, 1983; Morris and Lowery, 1988).

Compacted forest soils can require several decades to recover to a non-compacted bulk density (Sands et al., 1979). Recovery can be affected by several factors including repeated exposure to compacting events (e.g., timber harvesting), soil moisture, coarse fragment content, and cryoturbation (Liechty et al. 2002). Additionally, sampling error caused by the soil coring device compressing the sample may have caused an overestimation of the bulk density when measured during treatment implementation (Lichter and Costello, 1994; Ponder, 2007). Subsequent bulk density measurements made using the polyurethane foam method (Table 1) indicated soil compaction recovery of the 0–10 cm depth 8 years after compaction treatments were applied (Ponder et al., 1999, 2012; Ponder., 2007).

4.3. Organic matter removal

The absence of long-term height reductions of the planted trees under increasing levels of OM removal was notable. In other studies, whole-tree harvest removals have been shown to reduce the growth of subsequent tree crops (Proe and Dutch, 1994) although effects are not always consistent among studies (Thiffault et al., 2011). However, our findings generally follow those of Ponder et al. (2012) who reported few OM removal treatment effects on the 10th-year biomass in a continent-wide analysis that included 45 of the LTSP sites. Ponder et al. (2012) suggested that competition for nutrients may become acute after canopy closure when there is a corresponding increase in nutrient demand for continued tree growth and canopy development, particularly on sites having lower fertility such as those at the Missouri LTSP installation. Our observations (Fig. 1) and stocking measurements (Table 3) confirm that canopy closure and full growing space occupancy has occurred or has been exceeded but without measurable reductions in growth associated with increasing levels of OM removal. An analysis of soil samples collected during year 15 indicated few measurable differences in the organic matter content, concentrations of macronutrients, and pH among treatments (Table 2), which may explain why growth reductions among OM treatments were not observed. These findings also suggest that changes in long-term nutrient availability after a single OM-removal event may not be detectable, even though the soils of our study sites have inherently low fertility.

4.4. Interactions

The survival probabilities of all species were affected by two interactions: C × VC, and OM × C. With both oak species, compaction increased survival probability in VC_0 plots; while shortleaf pine survival probability was increased by C in both VC_0 and VC_1 treatments. Where OM removal interacted with C, results were more variable. Northern red oak survival increased with moderate (C_1) and severe compaction (C_2) in the sawlog (OM_0) and whole-tree removal (OM_1) treatments, but C had a neutral or negative effect when the whole-tree plus forest floor (OM_2) were removed. White oak behaved similarly, though C had a less significant effect in the most extreme OM removal treatment. In all levels of OM removal, shortleaf pine survival was increased by C (Fig. 3). Growth was less affected by interactions than survival, with the C × VC interaction significantly impacting white oak and shortleaf pine. Height growth of white oak and shortleaf pine was increased by C × VC_0, but unaffected by VC_1 treatment. This interaction did not affect northern red oak.

5. Conclusion

In the coarse-texture and nutrient-poor soils of the Ozark Highlands, vegetation control had the greatest impact on total biomass, planted tree survival, and planted tree height growth, significantly increasing the planted oak survival and growth, and significantly increasing the growth of planted shortleaf pine. Compaction also affected survival and growth, but in unexpected ways by increasing the growth of shortleaf pine and white oak and having no significant effect on the growth northern red oak. The lack of long-term decreases in productivity associated with organic matter removal suggests that excessive nutrient removals associated with whole-tree harvests and forest floor removal may have few measurable effects when conducted only one time.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Disclaimers

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