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Long-Term Soil Productivity Study: 25-Year Vegetation Response to Varying Degrees of Disturbance in Aspen-Dominated Forest Spanning the Upper Lake States

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ABSTRACT.—Installations of the Long-Term Soil Productivity Study were established in northern Minnesota and Michigan at the Chippewa, Ottawa, and Huron-Manistee National Forests (NFs) in the early 1990s and have since provided a wealth of data for assessing the response of aspen-dominated forest ecosystems to varying levels of organic matter removal and soil compaction. An assessment of 25-year standing woody biomass indicates that neither whole-tree harvest nor whole-tree harvest combined with forest floor removal reduced forest productivity on silt-loam soils compared with conventional, stem-only harvest; however, moderate and heavy compaction did negatively impact aspen biomass and stem densities. In contrast, whole-tree harvest reduced standing biomass of aspen and all species combined on sandy soils at the Huron NF while compaction had no discernable impact. Neither treatment factor affected vegetation response at the Ottawa NF (clay soils), but reduced sample size at this site may have increased variability. Over all, the response of standing biomass and forest structure to organic matter removal and compaction treatments demonstrate that the sustainability of practices such as whole-tree harvesting and associated potential for soil impacts varies with site conditions, even when stands are dominated by the same species (e.g., *Populus tremuloides*).

INTRODUCTION

Scientists established the Long-Term Soil Productivity (LTSP) program in 1989 in part to provide data for assessing whether forest management practices degraded productivity as mandated in the 1976 National Forest Management Act (NFMA) (Powers 2006). While the basic questions underlying the LTSP Study were developed over 30 years ago, they remain no less relevant today. Increasing concern related to climate change has renewed interest in sourcing renewable, bioenergy feedstocks from forests (Becker et al. 2009, Berger et al. 2013, Janowiak and Webster 2010, Millar et al. 2007) and may lead to more frequent harvests and greater likelihood of residue removal in some regions. Additionally, changing climatic conditions have potential to influence the length of winter and associated frozen-soil logging season where soils tend to be wet, fine-textured, and prone to compaction (Rittenhouse and Rissman 2015, Wolf et al. 2008). Together, these factors have potential to reduce forest site quality through a reduction in nutrients and increased physical impacts to soils.

Compared to presettlement conditions, quaking aspen (*Populus tremuloides*) has become more dominant across the Upper Lakes States region, having regenerated successfully after extensive harvesting and associated fires that occurred during the late 19th and early 20th

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centuries (Friedman and Reich 2005, Schulte et al. 2007). Quaking aspen is now one of the most abundant tree species across this landscape and has become economically important, particularly in Minnesota. Both quaking aspen and big-toothed aspen (*P. grandidentata*) are shade intolerant, pioneer species that respond favorably to disturbance through the production of prolific root suckers (Frey et al. 2003, Graham et al. 1963). Perhaps for this reason, they are widely characterized as resilient and managed accordingly, typically with a coppice system (Burns et al. 1990, Graham et al. 1963, Stone 2001).

The effects of whole-tree harvest on tree regeneration and forest productivity have been studied across temperate and boreal forests of North America and Europe, but little consensus about the sustainability of such practices exists because results vary depending on forest type, site quality, time since disturbance, and land-use history (Thiffault et al. 2011). On nutrient-poor soils, particularly where harvests have already occurred one or more times, whole-tree harvest can reduce soil nutrient availability and tree growth (Helmisaari et al. 2011, Morris et al. 2014, Walmsley et al. 2009). Importantly, negative impacts may take 10–20 (or more) years after harvest to emerge (Mason et al. 2012, Thiffault et al. 2011). In forests with greater nutrient availability, the practice of removing harvest residues may not negatively impact nutrient availability in the soil organic layer (Smolander et al. 2010) or subsequent vegetative growth (Muñoz Delgado et al. 2019, Roxby and Howard 2013). In a broad analysis of vegetative response across the entire LTSP network, 10-year results suggested no negative impact of biomass removal on vegetative growth (Powers et al. 2005). In the present study, we assessed the 25-year impact of organic matter removal and compaction on tree density and standing biomass at 3 LTSP sites dominated by aspen species in the Upper Lake States region.

STUDY AREAS

We present results based on data collected from three USDA Forest Service installations of the LTSP Study distributed across the Laurentian Mixed Forest Province. Sites included the Chippewa, Ottawa, and Huron National Forests in Minnesota and Michigan. Aspen (*Populus tremuloides* and *P. grandidentata*) dominated all forest stands prior to harvest, but sites differed in soil texture, ranging from clayey to sandy (Table 1). Consistent with the original intent of the LTSP Study, we compared responses across site types that vary in quality for the dominant tree species, aspen (Powers 2006, Stone 2001).

Table 1.—Site characteristics

	Harvest year	Location	Site index[a]	Soil texture	Dominant tree species prior to harvest
Chippewa NF	1993	Minnesota 18’47’N, 94 31’W	23	silt loam	Trembling aspen (*P. tremuloides*), red maple (*Acer rubrum*), sugar maple (*A. saccharum*), basswood (*Tilia americana*), northern red oak (*Q. rubra*), eastern white pine (*Pinus strobus*)
Huron NF	1994	Michigan 44 38’N, 83 31’W	19	sand	Trembling aspen, big-tooth aspen (*P. grandidentata*), red maple, black cherry (*P. serotina*), northern red oak, white pine (*P. strobus*)
Ottawa NF	1992	Michigan 46 37’N, 89 12’W	17-18	clay	Trembling aspen, balsam fir (*Abies balsamea*), white spruce (*Picea glauca*), red maple

[a]Aspen, base age 50 (Lundgren and Dolid 1970).

METHODS

Experimental Design and Field Sampling

This study assesses the impacts of two main factors on forest productivity, organic matter removal and soil compaction. The three organic matter removal treatments included: (1) stem-only harvest (SOH), the removal of all shrubs and merchantable stems and retention of harvest residues (nonmerchantable tops and branches) onsite; (2) whole-tree harvest (WTH), the removal of all aboveground portions of trees and shrubs; and (3) whole-tree harvest plus forest floor removal (FFR), the removal of all aboveground biomass. Compaction levels included: no additional compaction, representing operational conditions during a typical winter harvest (C0); moderate compaction (C1); and heavy compaction (C2). Both factors were fully crossed using a factorial design and replicated three times at the Chippewa and Huron NF sites. Replication at the Ottawa NF differed slightly, in part because of recent impacts from beaver. The Ottawa NF installation does not have the SOH/C2 treatment but includes five replicates of the WTH/C0 treatment, two replicates of SOH/C1, two replicates of FFR/C2, and three replicates of the remaining treatment combinations. Treatments were applied to 0.25 ha stands consisting of a 40 m × 40 m plot surrounded by a 5 m buffer. Overstory vegetation was sampled 25 years post-harvest in nine 1.78 m radius (10 m^2) circular subplots per stand. In these plots, the diameter and species for all woody stems with height greater than 15 cm were recorded. The analyses presented here only include data for overstory trees with diameter at breast height (d.b.h.; 1.37 m) greater than 10 cm. Harvest operations and treatment implementation are described in greater detail by Stone (2001).

Analysis

Aboveground biomass for all observed stems (d.b.h. >10 cm) was estimated using species-specific allometric equations (Jenkins et al. 2004). More detailed information about the equations used for species observed in this study are available in Curzon et al. (2017).

The influence of organic matter removal and compaction on tree standing biomass (all species) and on aspen standing biomass (all quaking and big-toothed aspen stems) was tested with mixed-effects ANOVA using the SAS MIXED procedure and the following statistical model: $Y_{ijk} = OMR + CPT + OMR*CPT + e_{ijk} + e'_{ijk}$ where OMR is the level of organic matter removal, CPT is the compaction level, and Y_{ijk} is aboveground woody biomass or stem density at the *i*th level of OMR, the *j*th level of CPT, and the *k*th level of plot. Plot was included as a random effect while OMR and CPT were treated as fixed effects. Type III sums of squares were used to account for the unbalanced design at the Ottawa NF. Each site was analyzed separately. Residuals were inspected visually to ensure assumptions for ANOVA had been met. Tukey-adjusted multiple comparisons were used to distinguish between treatment pairs where warranted.

RESULTS

The 25-year response of overstory trees at both the Chippewa NF and Huron NF suggests treatments have had a long-term impact on productivity, but results vary between the two sites. On silt-loam textured soils at the Chippewa National Forest, the no additional compaction treatment resulted in the greatest productivity in terms of aspen biomass while C1 and C2 reduced productivity by 46 percent and 73 percent, respectively (Fig. 2). Likewise, compaction decreased the density of aspen stems (C0 > C1, C2; Fig. 1). Reductions in mean stem density and standing biomass for all tree species, combined, were also observed (C1 and C2 reduced standing biomass by 18 percent and 33 percent, respectively), but differences were not statistically significant (Table 2; Figs. 1 and 2). Responses to the three organic matter removal treatments did not differ, nor was there an interaction between compaction and harvest treatment for any of the response variables assessed (Table 2).

In contrast to responses at the Chippewa NF, the removal of harvest residues associated with WTH negatively impacted total tree biomass (reduction of 39 percent) as well as aspen biomass, specifically (47 percent reduction) at the Huron NF. The additional removal of the forest floor (FFR) had a negligible impact on productivity relative to WTH at this site, and compaction did not impact either stem density or standing biomass (Figs. 1 and 2). No effects of organic matter removal or compaction on 25-year standing biomass or stem densities were observed at the Ottawa NF.

Table 2.—ANOVA results. Statistically significant effects (p<0.05) are shown in bold text

			Tree biomass		Aspen biomass		Stem density (all tree species)		Stem density (aspen)	
	Source	df	F	P-value	F	P-value	F	P-value	F	P-value
Chippewa NF	OMR	2	1.95	0.17	2.89	0.08	0.66	0.52	1.91	0.17
	CPT	2	3.21	0.06	**13.1**	**0.0004**	**10.2**	**0.001**	**21.85**	**< 0.0001**
	OMR*CPT	4	0.46	0.76	1.11	0.38	0.23	0.92	0.63	0.64
Huron NF	OMR	2	**3.77**	**0.04**	**4.12**	**0.03**	2.87	0.08	3.08	0.07
	CPT	2	1.17	0.33	1.35	0.28	1.84	0.18	1.74	0.20
	OMR*CPT	4	1.01	0.43	0.78	0.55	0.82	0.53	0.64	0.64
Ottawa NF	OMR	2	2.8	0.09	2.36	0.12	3.38	0.06	2.79	0.09
	CPT	2	0.24	0.78	0.26	0.77	0.41	0.66	0.48	0.62
	OMR*CPT	4	0.51	0.68	0.56	0.65	0.75	0.53	0.81	0.51

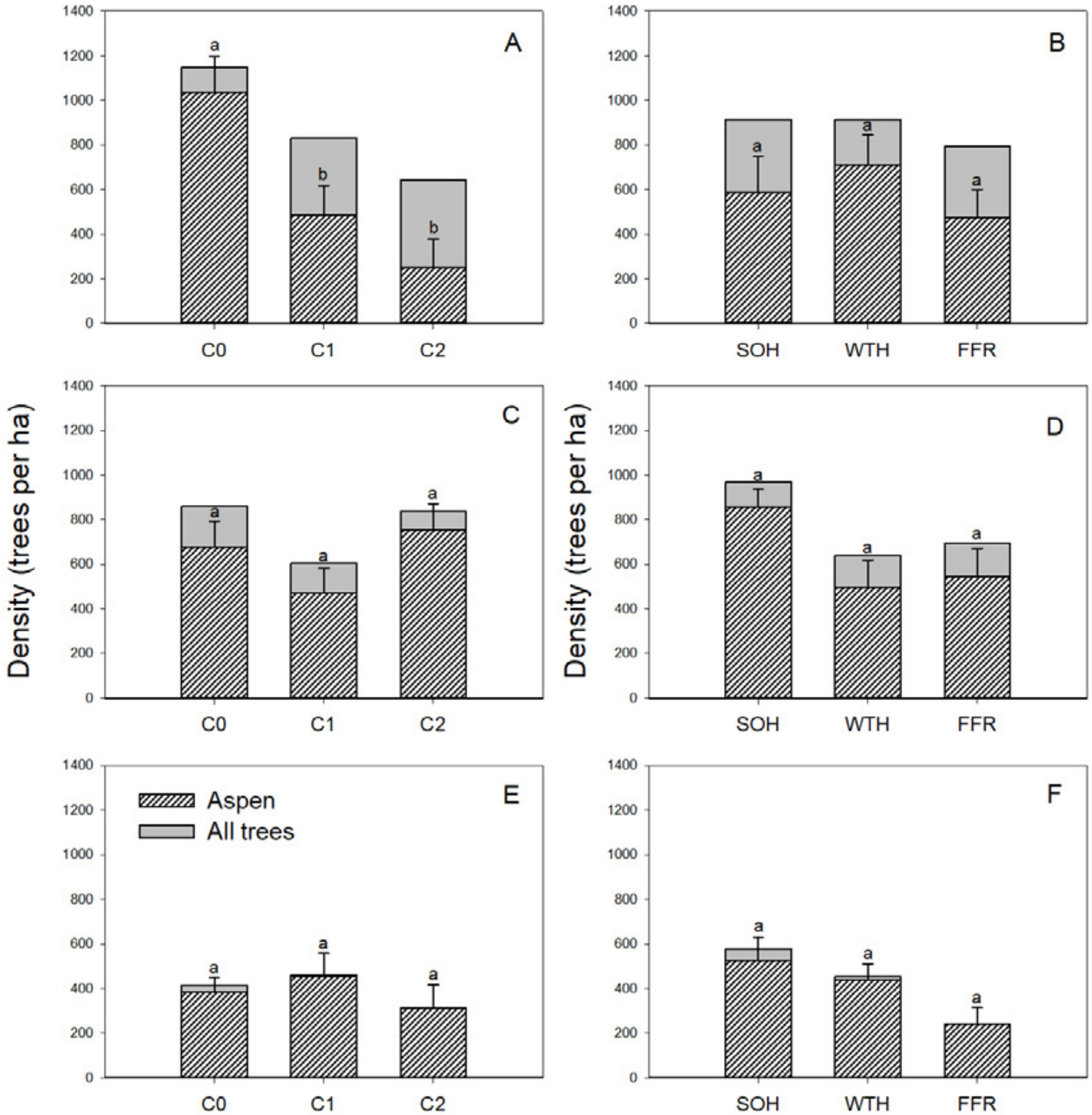

Figure 1.— Stem density for trees (d.b.h. >10 cm) in response to compaction (panels A, C, and E) and organic matter removal (B, D, F) 25 years post-harvest at Chippewa NF (A, B), Huron NF (C, D), and Ottawa NF (E, F). Grey bars show density for all tree species combined while the hashed portion of each bar indicates aspen (*P. tremuloides* and *P. grandidentata*, combined). Lowercase letters indicate significant differences in aspen density between factor levels ($p<0.05$). At Huron NF, mean stem density for all species also differed significantly between OMR factors (SOH > WTH, FFR; $p<0.05$). Abbreviations are as follows: CO, minimal compaction; C1, moderate compaction; C2, heavy compaction; SOH, stem-only harvest; WTH, whole-tree harvest; and FFR, forest floor removal.

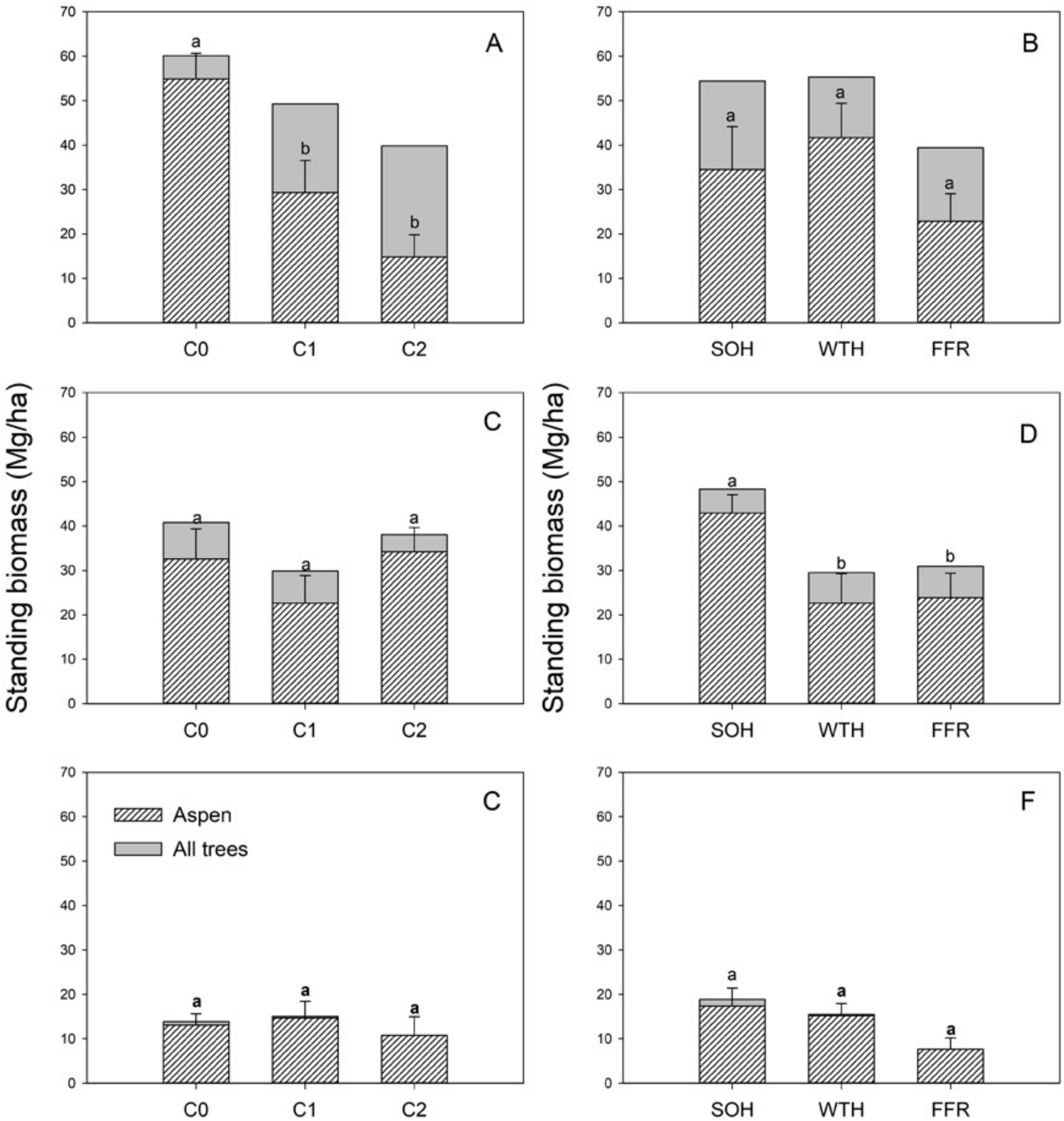

Figure 2.—Live standing biomass for trees (d.b.h. >10 cm) in response to compaction (panels A, C, and E) and organic matter removal (B, D, F) 25 years post-harvest at Chippewa NF (A, B), Huron NF (C, D), and Ottawa NF (E, F). Grey bars show density for all tree species combined while the hashed portion of each bar indicates aspen (*P. tremuloides* and *P. grandidentata*, combined). Lowercase letters indicate significant differences between factor levels for aspen biomass (p<0.05). Standing biomass for all tree species combined did not differ significantly among factors at any of the sites (see Table 1). Abbreviations are as follows: CO, minimal compaction; C1, moderate compaction; C2, heavy compaction; SOH, stem-only harvest; WTH, whole-tree harvest; and FFR, forest floor removal.

DISCUSSION

Following enactment of the National Forest Management Act (NFMA) of 1976, a series of discussions led to the definition of productivity (for the purposes of monitoring and enforcing compliance with the NFMA) as maintaining the carrying capacity of a given site for vegetative growth. Departures from baseline productivity exceeding 15 percent were deemed substantive (Powers 2006). The combination of stem-only harvest and no additional compaction (SOH/C0) in this study serves as an operational control for comparison with other treatments. Using those numbers as a baseline, our results demonstrate that excessive compaction on silt loam soils at the Chippewa NF undoubtedly decreased carrying capacity for the dominant species, quaking aspen. Reductions in mean standing biomass for all species combined also exceeded the 15 percent threshold, but results were not considered statistically significant ($p = 0.06$, Table 3). The removal of harvest residues with whole-tree harvest at the Huron NF, relevant to ongoing conversations about bioenergy feedstocks, also reduced productivity quantified in terms of standing biomass based on 25-year results.

Early results from the Chippewa, Ottawa, and Huron National Forests reported 4–5 years post-harvest suggested that a greater degree of disturbance impacted vegetation response relative to conventional practices, though many responses were not statistically significant. Initial observations indicated compaction at the Huron NF might have had a positive effect on mean aspen sapling height and biomass. These trends, reported following the fourth (Stone et al. 1999) and fifth growing seasons (Stone 2001), have diminished over time and are no longer apparent when analyzing only the 25-year data. Early observations from the fifth growing season at the Ottawa NF showed increased aspen sucker density in response to FFR compared to SOH as did greater levels of compaction (C1, C2 > C0) (Stone 2001), but neither factor continued to impact stem densities after 25 years. On the other hand, initial observations of reduced stem densities in response to greater compaction observed at the Chippewa NF (C0 > C1 > C2; Stone 2001) persisted to 25 years post-harvest (C0 > C1, C2; Fig. 1), and initial, non-significant observations of potentially reduced sapling biomass at the Huron NF (Stone et al. 1999) have become more pronounced (Fig. 2).

Analyses of data collected in earlier sampling periods also suggest changes occurring to the composition and diversity of regenerating forests across all three sites. Results based on 15-year data suggest that shrub biomass is greater in those plots at the Chippewa NF treated with heavy compaction, particularly when combined with forest floor removal, but that shrub species took time to occupy the sites rather than dominating immediately after disturbance (Curzon et al. 2014). Responses assessed 15 years post-harvest also indicate that severity of disturbance created by combining forest floor removal and heavy compaction reduced recovery of woody community composition (all shrub and tree species) relative to conventional harvest (Curzon et al. 2016). Whole-tree harvest has been shown to influence species composition and diversity in other forest types as well, suggesting this is an important factor to consider even if overall productivity is maintained (Muñoz Delgado et al. 2019).

Overall, our results indicate precautions should be taken to protect finer-textured soils (such as those at the Chippewa NF) and support other studies that discourage whole-tree harvesting on sandy soils that are less nutrient rich and have lower water-holding capacity (Flinn et al. 1980, Janowiak and Webster 2010, Thiffault et al. 2011, Vangansbeke et al. 2015). The LTSP research program was designed to follow forest stands through an entire rotation, so comparing responses to standing biomass prior to harvest at these sites will not be possible for some time. Even after 25 years, our results might still be considered preliminary, and while they are relevant to current management, they also highlight the value of designing experiments for the purpose of collecting long-term data.

Table 3.—Median (IQR) d.b.h. (cm) for each tree species by treatment at the Chippewa, Huron-Manistee, and Ottawa National Forests. Abbreviations are as follows: ABBA, *Abies balsamea*; ACRU, *Acer rubrum*; ACSA, *Acer saccharum*; BEPA, *Betula alleghaniensis*; FRPE, *Franxinus pennsylvanica*; POBA, *Populus balsmifera*; POGR, *P. grandidentata*; POTR, *P. tremuloides*; PIRE, *Pinus resinosa*; PIST, *Pinus strobus*; PRPE, *Prunus pensylvanica*; PRSE, *Prunus serotina*; QUAL, *Quercus alba*; QUMA, *Q. macrocarpa*; QURU, *Q. rubra*.

		Treatment								
Site	**Species**	**SOH/C0**	**SOH/C1**	**SOH/C2**	**WTH/C0**	**WTH/C1**	**WTH/C2**	**FFR/C0**	**FFR/C1**	**FFR/C2**
Chippewa NF	ACRU	n/a	11.4 (11.4, 11.4)	n/a	n/a	13.7 (13.7, 13.7)	n/a	n/a	n/a	n/a
	ACSA	n/a	n/a	n/a	n/a	10.5 (10.5, 10.5)	10.5 (10.5, 10.5)	n/a	n/a	n/a
	BEPA	10.35 (10.2, 10.5)	11.9 (11.05, 16.05)	12.5 (10.7, 15.5)	10.5 (10.5, 10.5)	11.8 (11, 13.6)	15.7 (12.7, 18.5)	11.9 (11.3, 12.5)	11.5 (10.5, 12.7)	12.7 (11.1, 14.2)
	FRPE	12.6 (12.6, 12.6)	13 (13, 13)	13.2 (13.2, 13.2)	n/a	n/a	n/a	n/a	11.5 (11.5, 11.5)	n/a
	POGR	22.9 (19.4, 26.4)	n/a	n/a	n/a	17.4 (14.95, 20.3)	n/a	16 (15.6, 17.8)	n/a	n/a
	POTR	13.2 (11.7, 15.15)	13.5 (11.7, 16.2)	12.85 (11.05, 16.15)	13.4 (11.6, 15.8)	13.1 (11.7, 16.2)	14.65 (12.2, 16.5)	12.2 (11, 13.7)	13.2 (11.2, 14.6)	12.8 (11.8, 13.9)
	POBA	n/a	17.5 (17.5, 17.5)	21.7 (15.8, 27.6)	n/a	n/a	n/a	n/a	n/a	13.1 (12.7, 13.9)
	PRPE	n/a	14.2 (14.2, 14.2)	n/a	n/a	n/a	10.3 (10.1, 10.5)	n/a	n/a	11.3 (11.3, 11.3)
	QUMA	10.3 (10.3, 10.3)	10.8 (10.2, 12)	11.65 (10.8, 12.5)	n/a	n/a	11.4 (10.6, 13)	n/a	10.3 (10.3, 10.3)	10.6 (10.6, 10.6)
	QURU	n/a	12.4 (12.4, 12.4)	n/a	n/a	n/a	n/a	n/a	17.6 (14, 17.7)	n/a
	Salix spp.	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	10.7 (10.1, 11.3)
	TIAM	11.45 (11.2, 11.9)	10.85 (10.3, 12.4)	n/a	16.5 (12.5, 17.8)	12.7 (12.7, 12.7)	13.75 (11.3, 15.4)	11.05 (10.9, 11.8)	11 (10.9, 11.2)	11.2 (10.5, 11.7)
Huron-Manistee NF	ACRU	10.55 (10.3, 11.9)	12.6 (10.2, 12.7)	n/a	10.35 (10.15, 10.75)	11.2 (10.55, 14.7)	10.2 (10.2, 10.2)	11.35 (11.2, 11.5)	n/a	10.5 (10.3, 10.7)
	PIRE	n/a	n/a	n/a	13.3 (11.5, 15.1)	n/a	n/a	12.25 (11.05, 13.65)	n/a	n/a
	PIST	12 (11.4, 15.3)	n/a	n/a	11.7 (10.8, 12.7)	10.2 (10.2, 10.2)	n/a	12.8 (11.8, 14.8)	11.1 (11, 12.1)	n/a
	POGR	13.2 (12, 15.25)	13.05 (11.1, 15.5)	12.5 (11.2, 15.6)	14 (11.7, 15.6)	15.3 (14.2, 19.2)	13 (11.8, 16)	12.3 (11.5, 15)	12.7 (10.7, 14.7)	12.15 (10.85, 14.1)
	POTR	12.75 (11, 13.85)	11.1 (10.6, 11.3)	10.65 (10.2, 11.8)	11.3 (10.6, 12.6)	11 (10.5, 12)	11.1 (10.7, 12)	10.75 (10.5, 11)	10.85 (10.5, 12)	10.55 (10.15, 11.1)
	PRSE	11.8 (11.6, 12)	n/a	11.8 (11.5, 12.1)	10.5 (10.5, 10.5)	12.2 (12.2, 12.2)	11 (11, 11)	12.5 (12.5, 12.5)	13 (13, 13)	n/a
	QUAL	n/a	n/a	n/a	n/a	11.8 (11.8, 11.8)	n/a	n/a	11.4 (10.3, 11.6)	n/a
	QURU	12.6 (12.6, 12.6)	10.7 (10.5, 11.6)	10.7 (10.2, 12.5)	11.8 (11.4, 13.1)	12.6 (11, 14.3)	10.7 (10.2, 11.3)	10.95 (10.8, 11.1)	12.4 (11.9, 13.1)	10.8 (10.3, 14.1)
Ottawa NF	ABBA	10.75 (10.6, 10.8)	14.8 (14.8, 14.8)	11.15 (11, 11.3)	10.5 (10.3, 12.4)	10.4 (10.4, 10.4)	n/a	n/a	n/a	n/a
	PIST	n/a	n/a	10.4 (10.4, 10.4)	n/a	n/a	n/a	n/a	n/a	n/a
	POTR	11.1 (10.6, 12.2)	11.4 (10.5, 12.95)	n/a	11.3 (10.6, 12.9)	11.15 (10.5, 12.1)	12 (10.9, 13)	11.4 (10.5, 12.8)	11.25 (10.65, 11.6)	11.2 (10.7, 11.8)

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