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Northern mixedwood composition and productivity 50 years after whole-tree and stem-only harvesting with and without post-harvest prescribed burning

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ABSTRACT

Whole-tree harvesting (WTH) is increasingly used to extract forest biomass for energy and commercial wood products. Slash burning, which is used for fuels reduction and site preparation, also reduces aboveground biomass. Yet effects of incremental biomass reduction, from either WTH or slash burning, on long-term forest productivity and composition are poorly understood. This research uses data from a 50-year-old study in northern mixedwood (*Picea* – *Abies* – hardwood) stands on the Penobscot Experimental Forest in Maine, U.S.A., to address these concerns. Clearcutting was conducted in 1964–65 with WTH, stem-only harvesting (SOH), and SOH with post-harvest prescribed burning of logging residues (SOHB). Growing stock, composition, and soil properties (O horizon thickness and soil drainage) were measured 50 years after treatment. Hardwood composition (percent of total basal area) increased from pre-treatment levels in all treatments but was greater in SOHB than SOH and WTH. Eastern white pine (*Pinus strobus*), though a minor species, was significantly more abundant in WTH than SOH or SOHB. Results indicated no other significant differences in species composition, or in stand structure or productivity (total basal area, stem density, dominant height, quadratic mean diameter, and total above-ground carbon stock) among treatments. Independent of treatment, we observed relationships between soil properties and stem density and quadratic mean diameter (qmd), such that lower stem density and greater qmd were observed on sites with greater O horizon thickness. These findings suggest that relative to SOH, WTH and SOHB do not degrade northern mixedwood stand productivity as expressed by stand structure and stocking 50 years after a single treatment, even on a site with low to moderate production potential. Nevertheless, species shifts associated with clearcutting (i.e., shade-tolerant conifer to intolerant hardwood composition) and prescribed burning in this forest type should be considered in light of the potential application of either for intensive silviculture treatments.

1. Introduction

Forest woody biomass is increasingly used as an alternative source of energy (Janowiak and Webster, 2010; Lattimore et al., 2009; Perlack et al., 2005; Perlack and Stokes, 2011). A common method of extracting woody biomass during forest management is whole-tree harvesting (WTH), wherein both the bole and woody residues from the canopy and branches are extracted for various wood products including fuel stock for the production of heat and electricity (Janowiak and Webster, 2010; Kellomäki et al., 2013). In the northeastern U.S., WTH is a common practice, accounting for approximately 50 to 80 percent of timber production depending on state (Leon and Benjamin, 2012). However, there are concerns about the long-term impacts of incremental stem-only to whole-tree removal of biomass on, but not limited to, nutrient availability (Cleavitt et al., 2018; Kimmins, 1976; Mann et al., 1988; Smith Jr. et al., 1986), carbon storage (Fahey et al., 2010; Kellomäki et al., 2013; Lackner, 2003), and post-harvest structure and composition (Lattimore et al., 2009).

Results appear to vary by site condition, with a predominant concern of negative productivity impacts following WTH on poorly drained, less fertile, and conifer-dominated sites (Thiffault et al., 2011). However, effects of harvest on productivity may be further confounded

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by ecological factors such as stand structure and composition, and site condition (Fahey et al., 2010). In stands of hardwoods and softwoods in mixture, resources are utilized differently by each species depending on their functional traits, with implications for differences in stand structure and dynamics (Hendrickson et al., 1987; Kelty et al., 1992). The literature highlights the complexities associated with quantifying outcomes of WTH and SOH, e.g., interactions between pre-treatment stand condition, harvest method, and site on residual stand attributes such as regeneration composition and density (Waters et al., 2004), carbon stocks (Puhlick et al., 2016a, 2016b) and standing dead and down woody material (Briedis et al., 2011). In addition, there is a need to better understand long-term outcomes, particularly in mixedwood stands. Yet few studies of northern mixedwood stands following WTH are currently available (e.g, Hendrickson, 1988; McInnis and Roberts, 1994). Furthermore, most studies measuring aboveground stand productivity following WTH have not extended past 20 years post-harvest (Thiffault et al., 2011). Implications of biomass removal within one to two decades of treatment may not be adequate for evaluating multi-decadal long-term effects.

The inception of long temporal scale WTH studies is a function, in part, of the timing of the emergence of WTH in Europe, the U.S., and Canada, all of which host some of the longest post-harvest observations of stand productivity. The shift from conventional SOH to WTH methods became most prominent in the 1970s (McInnis and Roberts, 1994), with some of the earliest studies on stand productivity beginning in the mid-late 1980s (Thiffault et al., 2011). Furthermore, long-term comparisons between North America and Europe are limited in applicability at a global scale given differences in species mixtures (i.e. multi-species compared to monocultures) and number of stand rotations (i.e., single-rotation compared to multiple rotations; Thiffault et al., 2011). However, most studies of long temporal scale, globally, have encouraged a focus on both species-specific responses and other confounding factors such as site condition, in addition to investigating treatment effects on stand productivity following harvest.

In addition to biomass removal through harvest, site preparation and fuels reduction treatments such as prescribed burning have the potential to not only reduce biomass in the short term (Chiang et al., 2008; Stephens et al. 2009), but also affect residual stand attributes such as species composition, structure, and productivity over the long term (Jang et al., 2015; Clyatt et al., 2017). Currently, few studies have compared the long-term stand productivity effects of biomass removal through prescribed burning relative to mechanical whole-tree removal (e.g., Parker et al., 2001; Thiffault et al., 2007). The effects of slash burning on long-term stand development as either a fuels reduction or site preparation technique are poorly understood (Clyatt et al., 2017; Stephens et al., 2009), particularly in northern mixedwood stands where burning is less prevalent than in other forest types.

The goal of our study was to determine the effects of incremental biomass removal via WTH and SOH with post-harvest prescribed burning (SOHB), relative to conventional SOH, on long-term stand composition and productivity in mixedwood (*Picea* – *Abies* – hardwood) stands. This study repurposes an existing slash disposal experiment (Bjorkbom and Frank, 1968; Czapowskyj, 1979; Czapowskyj et al., 1977, 1976; Frank and Safford, 1970; Rinaldi, 1970) to address contemporary concerns regarding biomass harvesting. Our objectives were to evaluate the influence of site, treatment, and their potential interaction on: (1) stand structure (e.g. stem density, basal area, dominant height, and quadratic mean diameter); (2) species composition; and (3) total aboveground carbon stock (Mg ha^{-1}). We hypothesized that site factors such as drainage class and O horizon thickness would have a greater influence on the examined attributes than the type of biomass removal treatments 50 years after harvest.

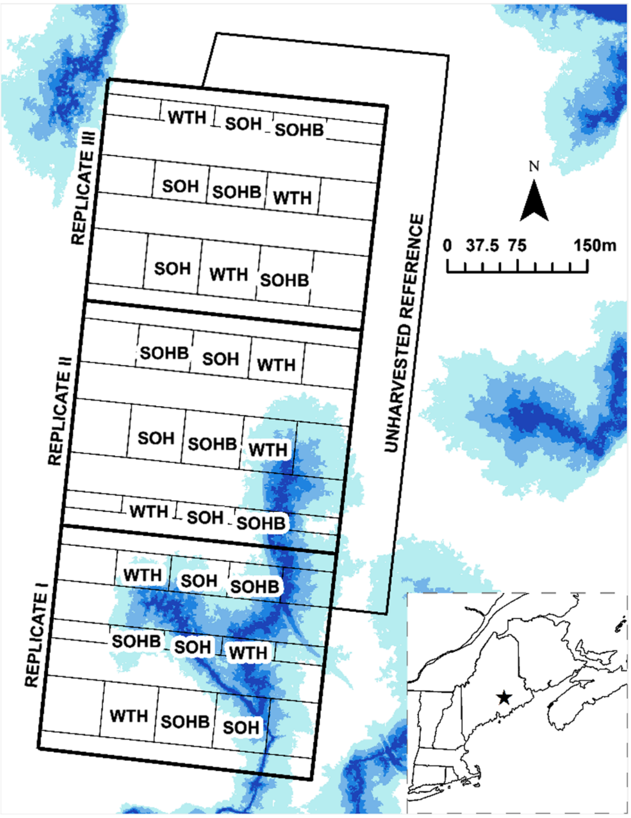

Fig. 1. Compartment 33 experimental design. Darker shading in background indicative of higher water table depth and poor soil drainage. Treatments are as follows: SOH = stem-only harvest; SOHB = stem-only harvest with burn; WTH = whole-tree harvest.

2. Materials and methods

2.1. Study site

The 26-ha manipulative experiment repurposed for the present study is in compartment (management unit) 33 (C33; Fig. 1) on the Penobscot Experimental Forest (PEF) in Bradley, Maine, U.S. (44°51′56.754″N, 68°38′12.1812″W). The PEF falls within a transition zone between boreal and broadleaf forest types in the Acadian Forest region (Bailey, 2009; McMahon, 1990), thus contributing to its mixed species (mixedwood) nature (Barton et al., 2012). Natural regeneration is prolific in the region, with composition and density a function of site and overstory conditions (Brissette, 1996). Topography is relatively flat on the PEF. From 1995 to 2015 the forest received on average 107 cm of annual precipitation, with a mean annual temperature of 7.2 °C (National Weather Service, NOAA). Soils in C33 are derived primarily from glacial-till and marine sediments. Typic Haplorthods (Danforth series) dominate the northern portion of the study, and an association of Typic Epiaquepts, Aeric Epiaquepts, and Aquic Haplorthods (Scantic-Lamoine-Colonel series) dominate the southern portion (Natural Resources Conservation Service, 2017). Soil drainage varied throughout the site and is evident in cartographic depth-to-water tables estimated from light detection and ranging data (LiDAR), as seen in Fig. 1 (Murphy et al., 2011; UNB Forest Watershed Research Center, 2014). This variation in soil drainage and in other soil properties contributes to within-site variation in species composition.

At the start of the experiment in 1964, overstory species composition of C33 was characterized as spruce-fir (*Picea* – *Abies*) (Czapowskyj et al., 1977). All areas of the site contained red maple (*Acer rubrum*), balsam fir (*A. balsamea*), and *Picea* spp. Eastern hemlock (*Tsuga canadensis*) and eastern white pine (*Pinus strobus*) were more prevalent on well-drained soils, northern white-cedar (*Thuja occidentalis*) and black ash (*Fraxinus nigra*) were more prevalent on poorly drained soils, and mesic sites supported red spruce (*P. rubens*), black spruce (*P. mariana*), white spruce (*P. glauca*), and balsam fir (Rinaldi, 1970). *Betula* and *Populus* spp. were found in small numbers throughout the study area (Rinaldi, 1970). Prior to treatment application, the stand density for trees ≥ 8.9 cm diameter at breast height (dbh) was 1216 trees ha^{-1}. Dominant tree species ranged from 70 to 80 years of age with heights of 11–17 m (Bjorkbom and Frank, 1968; Czapowskyj et al., 1977; Frank and Safford, 1970). For trees ≥ 11.4 cm dbh, total volume was 130 m^3 ha^{-1} (Czapowskyj et al., 1977). Spruce-fir made up 50 percent of this total followed by 25 percent hardwood composition, 10 percent eastern white pine and eastern hemlock, and 5 percent northern white-cedar. Average diameter of merchantable growing stock was 18 cm (Czapowskyj et al., 1977). At the time of our sampling in 2014–15, C33 had a northern mixedwood composition (Supplement 1). Dominant tree species included balsam fir, quaking aspen (*Populus tremuloides*), bigtooth aspen (*P. grandidentata*), red maple, red and black spruce, and eastern white pine. Other species present in minor proportions included: northern white-cedar, gray birch (*B. populifolia*), paper birch (*B. papyrifera*), eastern hemlock, red oak (*Quercus rubra*), white spruce, and white ash (*F. americana*).

2.2. Experimental design and treatments

The experimental design of the study was randomized complete block replicated three times across the site (Fig. 1). Within each block, three strips were oriented east–west and randomly assigned one of three strip widths: 20.1 m, 40.2 m, and 60.4 m, each separated by a 40.2-m wide buffer. A 60.4-m long buffer was also designated at the end of each strip. Though not explicitly stated in the original study plan, variation in strip width was likely included to evaluate effects of distance from edge and incident radiation on post-harvest regeneration (Marquis, 1965; Rinaldi, 1970); subsequent assessments suggested few differences in composition and structure related to the strip-width variable (Czapowskyj et al., 1976). Each strip was divided into three experimental units (EUs; 60.4 m long), and randomly assigned one of three treatments: clearcutting with whole-tree skidding; clearcutting with slash left in place; or clearcutting with slash left in place and burned. These treatments are comparable to whole-tree harvesting (WTH), stem-only harvesting (SOH), and SOH with post-harvest prescribed burning (SOHB). All trees ≥ 1.3 m in height, regardless of quality, were felled with a chainsaw in each EU (Czapowskyj et al., 1977; Rinaldi, 1970).

Harvesting occurred from November 1964 – April 1965 (Bjorkbom and Frank, 1968). Skidding was done with a John Deere Model 420 crawler-type tractor. To avoid skidding across treatment boundaries, sawlogs and pulpwood were hauled from the EU to a skid trail on the northern side of each strip (Bjorkbom and Frank, 1968). An average volume of 127.9 m^3 ha^{-1} in wood products was harvested. Burning treatments were performed in August 1965 during low wind speeds (Bjorkbom and Frank, 1968). Immediate edges of the strips were excluded from the burn (Czapowskyj et al., 1976). Treatment descriptions are further detailed in Table 1. Minimal disturbance (either abiotic or biotic) has occurred since treatment (Supplement 2).

2.3. Data collection

In 2014–15, 0.08-ha permanent sample plots were installed in each EU within the 40.2-m and 60.4-m wide strips (the 20.1-m wide strips were excluded because they were too narrow to accommodate the 0.08-ha permanent sample plots). Each permanent sample plot contained 3 nested sub-plots, laid out in concentric circles around plot center: 0.008, 0.02, and 0.08 ha (Fig. 2; Waskiewicz et al., 2015). Small saplings, ≥1.3 cm but < 6.4 cm dbh, were sampled within the 0.008-ha nested plot. Large saplings, ≥6.4 cm, but < 11.4 cm dbh, were sampled within the 0.02-ha nested plot. Overstory live trees and standing snags ≥ 11.4 cm dbh were measured within the 0.08-ha nested plot. To balance site conditions assessed, one 0.02-ha plot was installed in a 20.1-m wide strip, but was later excluded from the analysis due to its influence of high variability on subsequent mixed-effects models (described in the following section; Iles, 2003). One plot of the remaining 18 was very poorly drained and poorly stocked (i.e., basal area of 24 m^2 ha^{-1}, about half the average found in other permanent sample plots; Table 2). This plot was determined to represent forested wetland conditions and was excluded from analysis.

On the 17 plots remaining, a random 6.4 percent sub-sample of trees ≥ 1.3 cm dbh, stratified by species and diameter distribution, were measured for height using a Haglöf Vertex III (Haglöf, 2002). A 10 percent sample was desired, but only 6.4 percent was achieved which covered a full range of species and diameters required for accurate imputation. Thickness of the O horizon (cm) and drainage class were quantified 3.1 m from plot extent at true north (−17° declination). O_i was excluded from these measurements, focusing on partially and well decomposed organic horizons, O_e and O_a. Soil drainage class was predetermined using an existing soils map (Natural Resources Conservation Service, 2017) and confirmed in the field through visual inspection of defining properties, such as soil texture and water movement. Down woody material ≥ 10 cm was measured using calipers along three 10-m transects, at azimuths of 0, 120, and 240° (Brown, 1974, 1971; Harmon et al., 2008; Van Wagner, 1968). Stumps and fine woody material were excluded from down woody material measurements.

Stem density (trees ha^{-1}), total basal area (m^2 ha^{-1}), dominant height (m), quadratic mean diameter (qmd; cm), and hardwood basal area (percent of total basal area) were calculated for live-tree structure and composition. Missing heights were estimated using a species- and plot-specific mixed-effects linear regression equation similar to Robinson and Wykoff (2004). Heights were used in allometric regression equations to estimate carbon stock for aboveground live trees and snags.

For carbon stock (Mg ha^{-1}), estimated for total live-tree, total coarse woody material (snags + down woody material), and total aboveground (live-tree + snags + down woody material), biomass was first estimated and then converted to carbon stock estimates. Oven-dry, aboveground live-tree biomass was estimated using allometric regression equations (Chapman and Gower, 1991; Lambert et al., 2005; Young et al., 1980). Equations were selected based on diameter range covered as well as proximity to the PEF. Live-tree carbon stock was then estimated using species-specific coefficients for carbon content (Lamlom and Savidge, 2003).

Aboveground volume was estimated prior to calculating snag biomass using a modified variable exponent taper equation (Li et al., 2012). Snag biomass was then estimated by multiplying snag volume estimates by species-specific, absolute density by decay class factors (Harmon et al. 2011). To estimate down woody material biomass, volume of each piece measured was estimated using Van Wagner's (1968) volume per unit area equation. To convert to biomass, down woody material volume estimates were multiplied by species-specific, absolute density by decay class factors (Harmon et al., 2008). Snag and down woody material carbon stock was then estimated using biomass to carbon conversion factors by decay class (Harmon et al., 2008). Both snag and down woody material carbon stock were summed together to estimate total coarse woody material carbon stock. Live-tree, snag, and down woody material carbon stock were summed to estimate total aboveground carbon stock.

2.4. Statistical analyses

To determine the effects of treatment and site condition on stand structure, composition, and carbon stock at the stand level, linear mixed-effects models were constructed in R version 3.5.2 (R Core Team,

Table 1
Previous findings pre- and post-treatment on Compartment 33.

Treatment	General Description[1,2]	Pre-Treatment Conditions[3*]	1–3-Year Results[1]	4-Year Results[4*]	10-Year Results[3**]	
					0–3 *m*	≥ 6 *m*
Stem-Only Harvest (SOH)	Branches removed and left on-site as cut; only merchantable trees removed off-site	Spruce – 247 Balsam fir – 8649 Other Softwoods – 741 Hardwoods – 1730	Mostly intact forest floor, slash covered 69 percent of treated area (observed)	Spruce – 504 Balsam fir – 13,912 Other Softwoods – 1192 Hardwoods – 44,160	Spruce – 3707 Balsam fir – 30,147 Other Softwoods – 5189 Hardwoods – 13,097	Spruce – 1483 Balsam fir – 22,487 Other Softwoods – 1730 Hardwoods – 20,757
Stem-Only Harvest with Burn (SOHB)	Branches removed, left on-site and broadcast burned; only merchantable trees removed off-site	Spruce – 1483 Balsam fir – 13,097 Other Softwoods – 1236 Hardwoods – 4695	Only 50 percent of area treated was identified as scorched or partially charred (observed)	Spruce – 0 Balsam fir – 0 Other Softwoods – 0 Hardwoods – 84,243	Spruce – 0 Balsam fir – 0 Other Softwoods – 0 Hardwoods – 0	Spruce – 4201 Balsam fir – 7413 Other Softwoods – 2224 Hardwoods – 52,880
Whole-Tree Harvest (WTH)	Branches left attached, all trees skidded off-site whole	Spruce – 494 Balsam fir – 12,108 Other Softwoods – 741 Hardwoods – 3954	3 percent area harvested exposed mineral soil; more mineral soil exposed than burned sites (observed)	Spruce – 549 Balsam fir – 6452 Other Softwoods – 365 Hardwoods – 71,198	Spruce – 9390 Balsam fir – 43,243 Other Softwoods – 11,367 Hardwoods – 33,606	Spruce – 3212 Balsam fir – 13,097 Other Softwoods – 988 Hardwoods – 34,595

NOTE: dbh = diameter at breast height.

[1] Bjorkbom and Frank (1968).

[2] Czapowskyj et al. (1977).

[3] Czapowskyj et al. (1976).

[4] Rinaldi (1970).

* Stems $ha^{-1} > 0.15$ m in height to 8.9 cm dbh by species.

** Stems $ha^{-1} > 0.15$ m in height to 8.9 cm dbh by species, 0–3 m and ≥6 m from south edge of a strip.

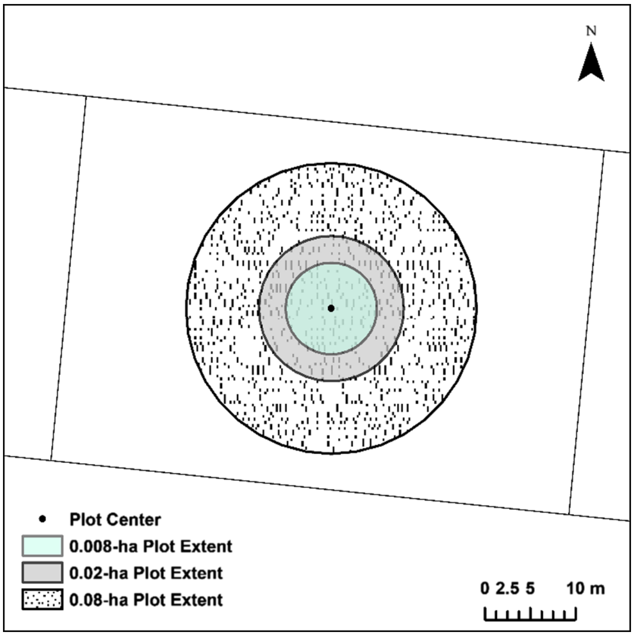

Fig. 2. Nested-plot design within an experimental unit of a 40.2-m strip width. Starting from plot center, overstory live trees and standing snags were measured within an 0.08-ha plot extent, large saplings within a 0.02-ha plot extent, and small saplings within an 0.008-ha plot extent.

2018), using function *lme* within package *nlme* (Pinheiro et al., 2016). Linear mixed-effects models were also used at the species level to further explore treatment effects. All models were evaluated with an analysis of variance (ANOVA). Final models were the highest ranking as determined using Akaike's "An Information Criterion". This was performed using the *AIC* function within the R base *stats* package (R Core Team, 2018). When testing at the species level, species were grouped into six classes based on most dominant species present in the stand (Table 3). *Other Species* includes those present in smaller numbers throughout the stand. EU nested within block were specified as the random effects. To meet the equal variance assumption, variables were either log- or logit transformed (for proportion data). For log-transformed values, a consistent value of 0.1 was added to the observed data. Proportion values were logit transformed to produce conservative estimates (Warton and Hui, 2011). Applying Tukey's adjustment for multiple comparisons, least-squares means were estimated using the function *lsmeans* within package *emmeans* (Lenth, 2019). Function *CLD*, within the *multcompView* package (Graves et al., 2015), was used to determine whether least-squares means were significantly different at $\alpha = 0.05$. In the case where the response was transformed (i.e. log or logit), significance tests were performed on the transformed scale. Back-transformed least-squares means and standard errors (SE) are presented. For significant terms, 95 percent confidence bands (hereafter referred to as '95 CI') were computed and plotted for comparison.

For site condition, soil drainage and O horizon thickness were considered as covariates. Due to unequal sample size in soil drainage type, soil drainage classes identified as well drained or moderately well drained were grouped as "well drained". Similarly, soil drainage classes identified as either poorly drained or somewhat poorly drained were grouped as "poorly drained". A correlation analysis was performed to determine the relationship between the variables. We found that mean O horizon thickness within each drainage group had a positive multiple correlation coefficient (R) of 0.28 with observed O horizon thickness (RMSE = 5.19). Because O horizon thickness was a more direct measure of site condition, we used it as a covariate in our models. For the purpose of multiple comparisons, structure, composition, and carbon stock estimates were tested at the 25th, 50th, and 75th percentiles of O horizon thickness.

A total of 17 plots were analyzed for effects of clearcutting with either WTH or SOHB on aboveground stand productivity, relative to clearcutting with conventional SOH (Table 2). Nine plots were established on poorly drained sites and eight were on well-drained sites. Five plots received SOH, and six plots received SOHB and WTH. Overall mean O horizon thickness was 3.7, 4.8, and 12.3 cm at the 25th, 50th, and 75th percentiles, respectively.

3. Results

3.1. Stand-level comparisons

At 50 years of age and for stems ≥ 12.7 cm, average relative density was 0.43 ± 0.08 (SD; standard deviation) and qmd ranged from 15.9 to 20.8 cm (Supplement 3; Miles and Smith, 2009; Woodall et al., 2005). For stems ≥ 1.3 cm dbh, stem density ($p = 0.01$) and qmd ($p = 0.02$) of live trees were found to be significantly related to O horizon thickness, such that stem density decreased and qmd increased as O horizon thickness increased (Table 4, Fig. 3). Other stand structural attributes investigated (i.e. basal area and dominant height) did not differ significantly across treatments, site conditions, or their interaction ($p > 0.05$).

Percent hardwood basal area differed significantly among treatments ($p < 0.01$) and by O horizon thickness ($p = 0.01$) separately, but lower AIC indicated that treatment alone was the superior model. Multiple comparisons of least-squares means further indicated a

Table 2
Mean (standard deviation) and range values of the observed data at stand-level, by treatment. Stand structure, composition (% basal area), live-tree and snag carbon stock data, with the exception of dominant height (m), are for stems ≥1.3 cm dbh. Down woody material carbon stock are for stems ≥10 cm.

	Stem-Only Harvest		Stem-Only Harvest with Burn		Whole-Tree Harvest		Overall	
Poorly-Drained Plots	2		5		2		9	
Well-Drained Plots	3		1		4		8	
Total Number of Plots	**5**		**6**		**6**		**17**	
Variable	Mean (SD)	Range	Mean (SD)	Range	Mean (SD)	Range	Mean (SD)	Range
O Horizon Thickness (cm)	4(1.4)	1.9–5.7	10.8(6.4)	2.1–19.5	5.8(5.4)	0–12.6	7(5.6)	0–19.5
Stem Density (trees ha^{-1})	6743(898)	5325–7561	6491(1868)	3534–8154	6779(1853)	4436–9452	6667(1544)	3534–9452
Total Basal Area (m^2 ha^{-1})	42.6(5.6)	35.5–49.6	41(3.9)	34.2–45	42(4.4)	36.2–48.8	41.8(4.4)	34.2–49.6
Average Height (m)	12(2.1)	9.4–15.1	12.2(1.3)	11.2–14.6	11.4(1.2)	9.8–12.9	11.9(1.5)	9.4–15.1
Dominant Height (m)	19.3(3)	16–24.2	19.4(0.9)	18.2–20.8	18.5(1.9)	16–20.9	19(2)	16–24.2
Quadratic Mean Diameter (cm)	9(1.1)	7.9–10.6	9.2(1.1)	8.2–11.1	9.1(1)	8.1–10.8	9.1(1)	7.9–11.1
% Live-Tree Hardwood Basal Area	58.4(11.4)	47–74.9	70.7(14)	54.2–87.3	51.7(12.3)	36.6–65.7	60.4(14.5)	36.6–87.3
Total Live-Tree Carbon Stock (Mg ha^{-1})	80.4(15)	62.5–100.5	82.1(5)	74.9–87.3	77.1(8.7)	66.9–89.6	79.9(9.6)	62.5–100.5
Total Snag Carbon Stock (Mg ha^{-1})	1.4(0.6)	0.8–2.3	1.9(0.9)	1–3.5	0.9(1.3)	0–2.8	1.4(1)	0–3.5
Total Down Woody Material Carbon Stock (Mg ha^{-1})	0.8(0.6)	0–1.6	2.3(2.4)	0.4–7	1.2(1.1)	0–2.6	1.5(1.7)	0–7
Total Aboveground Carbon Stock (Mg ha^{-1})	82.6(15.7)	63.7–103.1	86.3(7.4)	76.5–97.8	79.2(10.6)	67.8–94	82.7(11.1)	63.7–103.1

Table 3
Species-groups based on dominance in C33. Mean (standard deviation) and range of percent live-tree basal area derived from the observed data, for stems ≥ 1.3 cm dbh are presented by treatment.

		Stem-Only Harvest		Stem-Only Harvest with Burn		Whole-Tree Harvest		Overall	
Poorly-Drained Plots		2		5		2		9	
Well-Drained Plots		3		1		4		8	
Total Number of Plots		**5**		**6**		**6**		**17**	
Species Group	Species Represented	Mean (SD)	Range	Mean (SD)	Range	Mean (SD)	Range	Mean (SD)	Range
Balsam fir	balsam fir	36.5(7.4)	25.1–43.4	24.8(11.1)	11.3–38.8	35.8(5)	30.6–44.3	32.1(9.6)	11.3–44.3
Red Maple	red maple	20(8.6)	10.5–31.1	24.6(3.5)	20.4–29	18.6(6.7)	6.9–25.1	21.1(6.6)	6.9–31.1
Aspen	quaking aspen, bigtooth aspen	30.4(21.6)	5.3–58.8	43.3(11.5)	30.6–57.2	28.8(19.5)	4.3–57.9	34.4(18)	4.3–58.8
Spruce	red or black spruce, white spruce	1.5(1.8)	0–4.4	2.8(4.9)	0–12.7	7.5(8.5)	0–23.5	4.1(6.1)	0–23.5
Eastern White Pine	eastern white pine	0.9(1.5)	0–3.6	1.7(3.3)	0–8.3	4.7(3.5)	1.3–10.8	2.5(3.3)	0–10.8
Other Species	eastern hemlock, northern white-cedar, paper birch, gray birch, white ash, red oak	10.7(7.5)	2.4–19	2.8(1.7)	0.6–5.1	4.6(3.5)	0.8–8.7	5.8(5.5)	0.6–19

significantly ($p < 0.05$) greater percent of hardwood basal area in the SOHB treatment (72.6 percent ± 6.4 SE) than either SOH or WTH (Fig. 4). No difference was found in percent hardwood basal area between SOH (57.0 ± 8.1 SE) and WTH (51.8 ± 8.0 SE).

Least-squares means of live-tree carbon stock for WTH, SOH, and SOHB were 76.8 ± 3.9 SE, 79.4 ± 4.5 SE, and 82.1 ± 4.2 SE Mg ha^{-1}, respectively. For total coarse woody material (i.e. snag + down woody material), least-square means were 1.2 ± 0.5 SE, 2.0 ± 0.9 SE, and 3.6 ± 1.5 SE Mg ha^{-1}, for WTH, SOH, and SOHB. When these pools were combined, total aboveground carbon stock least-squares means were 78.7 ± 4.4 SE, 81.5 ± 5.0 SE, and 86.2 ± 4.9 SE Mg ha^{-1}, for WTH, SOH, and SOHB. Treatment, site condition, and their interaction were not significant in our models of live-tree, total coarse woody material, or total aboveground carbon stock ($p > 0.05$) (Table 4).

3.2. Species-level comparisons

A species by treatment interaction was found for both percent basal area ($p = 0.01$) and percent live-tree carbon stock ($p < 0.01$) (Table 5). For both percent basal area and live-tree carbon stock, multiple comparisons of least-squares means found eastern white pine to be significantly ($p < 0.05$) greater on WTH sites, relative to either SOH or SOHB (Figs. 5 and 6). Basal area of eastern white pine was 4.0 ± 1.6 SE percent on WTH sites, compared to 0.7 ± 0.3 SE percent on the SOH, and 0.8 ± 0.3 SE percent on the SOHB sites. By comparison, the percent live-tree carbon stock of eastern white pine was 3.6 ± 1.5 SE percent on WTH sites, compared to 0.5 ± 0.2 SE percent on SOH and 0.6 ± 0.2 SE percent on the SOHB sites. No other species groups were found to differ among treatments or O horizon thickness (as determined by multiple comparisons), and there were no three-way

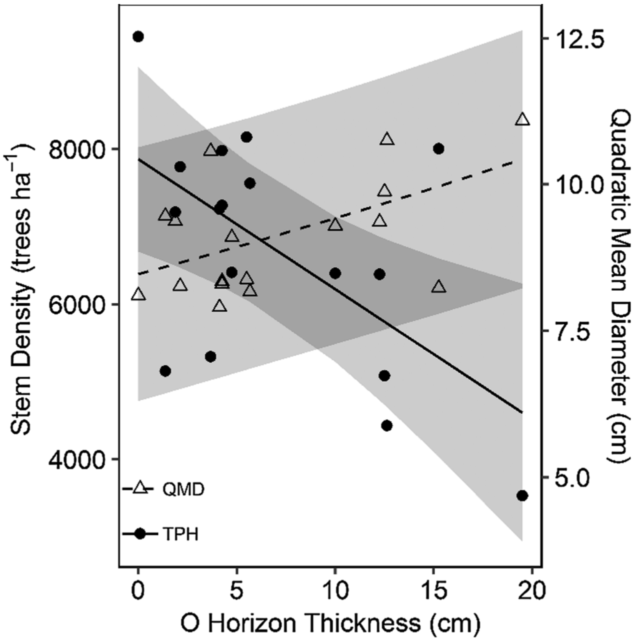

Fig. 3. Stem density (trees ha^{-1}) and quadratic mean diameter (cm) by O horizon thickness (cm) for trees ≥ 1.3 cm dbh. Black dots (filled) and empty triangles represent observed data. Complete (trees per hectare) and dashed (quadratic mean diameter) lines represent predicted data. Gray shading represents 95 percent confidence bands. QMD = quadratic mean diameter; TPH = trees per hectare.

Table 4
ANOVA p-values (α = 0.05) from linear mixed-effects models at the stand-level. Significant p-values italicized and bolded.

		Treatment * O Horizon Thickness				Treatment				O Horizon Thickness			
Variable		*p*	*R²M*	*R²C*	*RMSE*	*p*	*R²M*	*R²C*	*RMSE*	*p*	*R²M*	*R²C*	*RMSE*
Structure	Basal Area (m^2 ha^{-1})	0.23	0.275	1.000	2.79	0.83	0.022	1.000	3.43	0.13	0.143	1.000	3.20
	Stem Density (trees ha^{-1})	0.82	0.340	0.931	907.60	0.95	0.007	1.000	1218.30	***0.01***	0.320	0.928	978.14
	log(Dominant Height (m) + 0.1)	0.76	0.069	0.907	0.07	0.64	0.040	0.905	0.07	0.42	0.029	0.910	0.07
	log(Quadratic Mean Diameter (cm) + 0.1)	0.20	0.401	0.943	0.06	0.96	0.005	1.000	0.08	***0.02***	0.272	0.922	0.07
Composition	logit(Hardwood Basal Area (% of total basal area))	0.88	0.299	0.956	0.36	***0.007***	0.295	0.950	0.37	***0.01***	0.178	0.944	0.44
Carbon Stock	log(Total Live-Tree Carbon Stock (Mg ha^{-1}) + 0.1)	0.27	0.203	0.919	0.08	0.67	0.050	1.000	0.09	0.83	0.003	1.000	0.10
	log(Total Coarse Woody Material Carbon Stock (Mg ha^{-1}) + 0.1)	0.91	0.206	0.916	0.62	0.11	0.211	0.917	0.62	0.71	0.008	0.894	0.73
	log(Total Aboveground Carbon Stock (Mg ha^{-1}) + 0.1)	0.41	0.183	1.000	0.09	0.54	0.076	1.000	0.10	0.98	0.000	1.000	0.11

NOTE: R^2M = Marginal R^2; R^2C = Conditional R^2; RMSE = Root Mean Square Error.

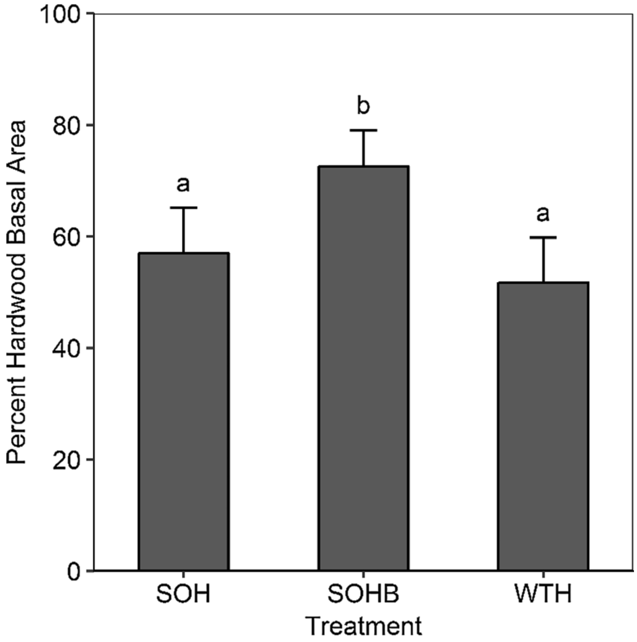

Fig. 4. Hardwood basal area (% of total basal area) least-squares means and standard errors by treatment, for trees ≥ 1.3 cm dbh. Treatments are as follows: SOH = stem-only harvest; SOHB = stem-only harvest with burn; WTH = whole-tree harvest. Different lower-case letters indicate significant differences.

interactions found among these variables.

4. Discussion

Our goal for this study was to determine the effect of incremental biomass removal on stand productivity through a comparison of whole-tree harvesting (WTH) and stem-only harvesting with and without post-harvest prescribed burning (SOHB and SOH, respectively). There were no clear or strong differences in productivity, as measured by stand structure or carbon stock, among WTH, SOHB, and SOH treatments after accounting for site conditions. These findings are consistent with other long-term studies (e.g., Jang et al., 2015; Johnson et al., 2016; Roxby and Howard, 2013). Many studies indicate that there is not a consistent productivity response following biomass removal (Thiffault et al., 2011). It has been suggested that the variable responses reported are likely due to differences in site conditions rather than harvesting method (Lattimore et al., 2009; Thiffault et al., 2011).

Independent of treatment, we observed a relationship between O horizon thickness and some measures of stand composition and structure. It was a significant covariate in the analyses that was positively related to qmd and negatively related to stem density. O horizon thickness also was positively related to the percent hardwood basal area (data not shown). There may be an influence of overstory composition on O horizon thickness. Previous research in Canada revealed increasingly slower rates of decomposition of aspen litter during a five-year incubation period (Prescott et al., 2000b). In addition, Prescott et al. (2000a) did not find any difference in rates of decomposition in aspen leaves between forested areas and adjacent clearcuts after four years in Canada. No effect of mixing needle and broadleaf litter types together was found on decomposition rate during a five-year incubation period (Prescott et al., 2000b). This is similar to the findings of Delaney et al. (1996), who reported no significant differences in percent mass remaining between single species and mixed litter following a six-month incubation period in Maine. Nevertheless, it is possible that self-thinning mortality of hardwood sprouts and/or suckers resulted in greater inputs of organic matter, a conjecture supported by the lower stem densities and larger qmds observed on these plots. Coupled with slow decomposition on poorly drained, seasonally flooded sites, there may be an influence of hardwood composition on O horizon thickness in C33. Additional research, including evaluation of fine woody material biomass, litterfall, and decomposition rates relative to drainage and composition, is needed to better understand O-horizon thickness, soil drainage, tree species composition, and stand structure relationships in C33.

Given no differences by treatment or site condition, low abundances of total coarse woody material carbon stock may be more reflective of stand developmental patterns (Franklin et al., 2002; Nyland et al., 2016) than harvesting method or site condition. With an average relative density of 0.43 ± 0.08 SD (for stems ≥ 12.7 cm) across the 17 plots, measured stands within C33 are considered to be roughly at the lower limit of full site occupancy (Woodall et al., 2005). These stands have not yet reached the developmental stage at which coarse woody material would be recruited through gap formation or other dynamics associated with the understory reinitiation stage of stand development.

One of the challenges to managing forests for woody biomass production for fossil fuel replacement is that biomass harvesting reduces short-term C storage in the form of on-site deadwood C stocks (Fahey et al., 2010; Mika and Keeton, 2015). Of greater concern is the possibility that intensive biomass removals, such as those associated with WTH and SOHB, will negatively impact forest productivity such that the future forest will store less C above- and below-ground (Hume et al., 2018; Puhlick et al., 2016b; Stephens et al., 2009). For aboveground living and dead biomass, we did not observe this effect in our study; aboveground C stocks 50 years after harvest did not differ between sites where tree tops and branches had been left on site, extracted, or burned. These findings suggest that, over the long term, extracting woody biomass will not negatively impact aboveground C storage in the future stand. Additional research is needed to understand belowground C dynamics, as well as the implications of C released through burning and on-site decomposition (Fahey et al., 2010; Puhlick et al., 2016a; Stephens et al., 2009).

Following intensive silvicultural treatments such as clearcutting, shifts in species composition are common in northern mixedwood stands (Westveld, 1928). Though a lack of historical observed data precluded statistical analysis of longitudinal change, there is convincing evidence that the hardwood component in C33 has increased in proportion relative to pre-harvest composition. According to Czapowskyj et al. (1977), only 25 percent of the stand was hardwood prior to harvest. At the time of our study, 60.4 ± 14.5 SD percent of total basal area was hardwood, regardless of treatment. Of the hardwood composition in 2014–15, 29 ± 17.8 SD percent was quaking aspen and

Table 5
ANOVA p-values (α = 0.05) from linear mixed-effects models at the species-level. Significant p-values italicized and bolded.

	Species * Treatment * O Horizon Thickness				Species * Treatment				Species * O Horizon Thickness			
Variable	*p*	*R^2M*	*R^2C*	*RMSE*	*p*	*R^2M*	*R^2C*	*RMSE*	*p*	*R^2M*	*R^2C*	*RMSE*
logit(Species Basal Area (% of total basal area))	0.79	0.717	0.727	0.79	***0.01***	0.719	0.728	0.86	0.45	0.661	0.672	0.98
logit(Species Live-Tree Carbon Stock (% of total live-tree carbon stock))	0.79	0.723	0.742	0.83	***0.007***	0.726	0.741	0.91	0.56	0.660	0.678	1.05

NOTE: R^2M = Marginal R^2; R^2C = Conditional R^2; RMSE = Root Mean Square Error.

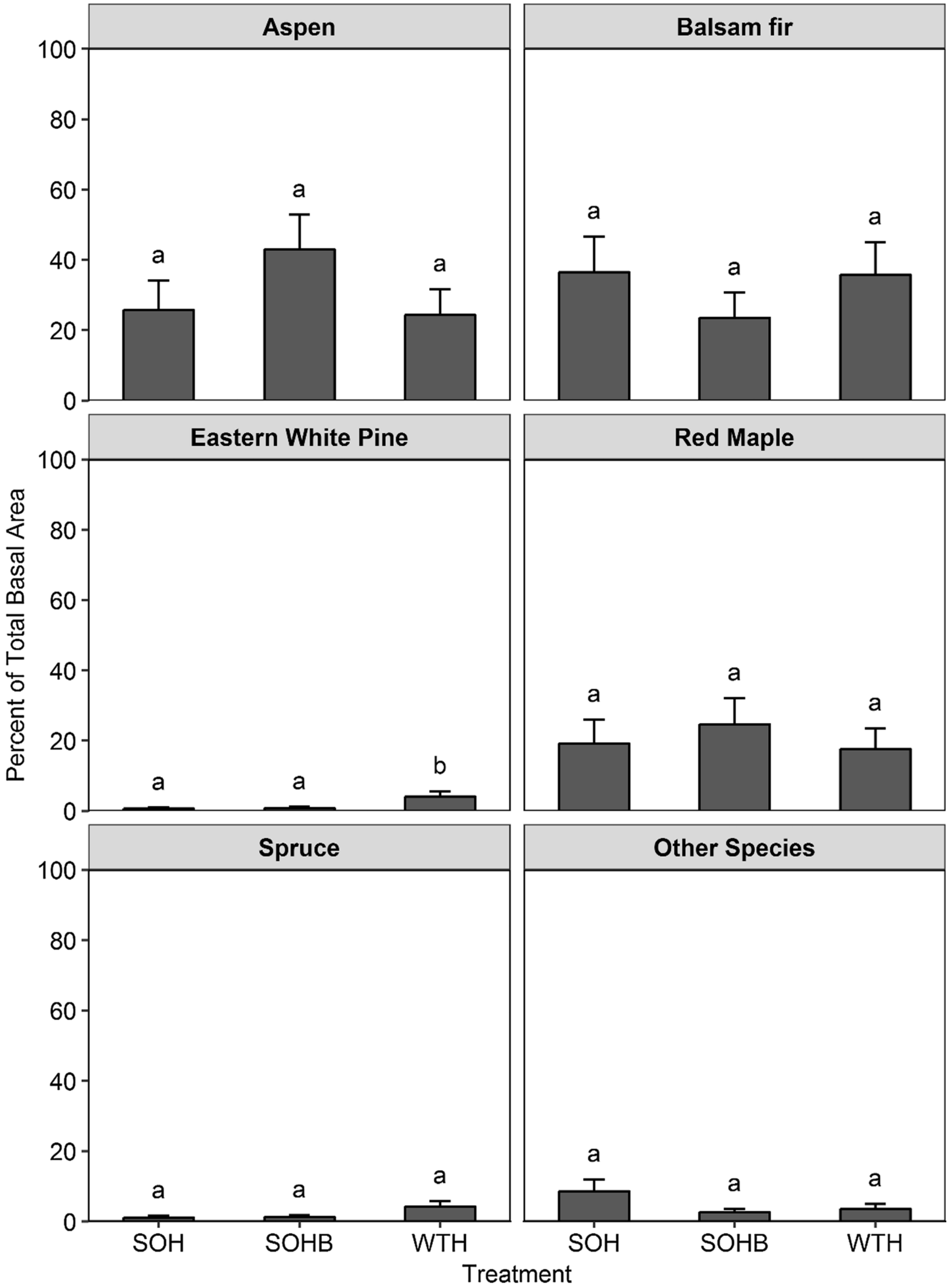

Fig. 5. Percent basal area (% of total basal area) by species least-squares means and standard errors by treatment, for trees ≥ 1.3 cm dbh. Treatments are as follows: SOH = stem-only harvest; SOHB = stem-only harvest with burn; WTH = whole-tree harvest. Different lower-case letters indicate significant differences.

21.1 ± 6.6 SD percent was red maple, together contributing to over half of all hardwood basal area (Supplement 1). Observed increases in hardwood composition were also found 40 and 60 years following commercial clearcutting in another study on the PEF (Rogers et al., 2017; Sendak et al., 2003).

Though present in small numbers overall in the current study, a greater proportion of eastern white pine was found on sites that were clearcut with WTH relative to SOH or SOHB. This is likely due to more exposed mineral soil following WTH than either SOH or SOHB in C33, as described by Bjorkbom and Frank (1968). Other studies have also found increases in eastern white pine establishment following exposure of the mineral soil after harvest (e.g., Elliott et al., 2002; Pitt et al., 2011; Raymond et al., 2003; Willis et al., 2016). While there is some concern that physical site impacts from WTH will negatively affect productivity, a study in north-central Maine of spruce – fir (*Picea* – *Abies*) productivity 32 years after clearcutting with WTH found no effect of mineral soil exposure or soil rutting on subsequent stand structure or growth (Lachance, 2016).

Late successional softwood species (e.g. *Picea* or *Abies*) are poor competitors to high-nutrient demanding pioneer or sprouting species

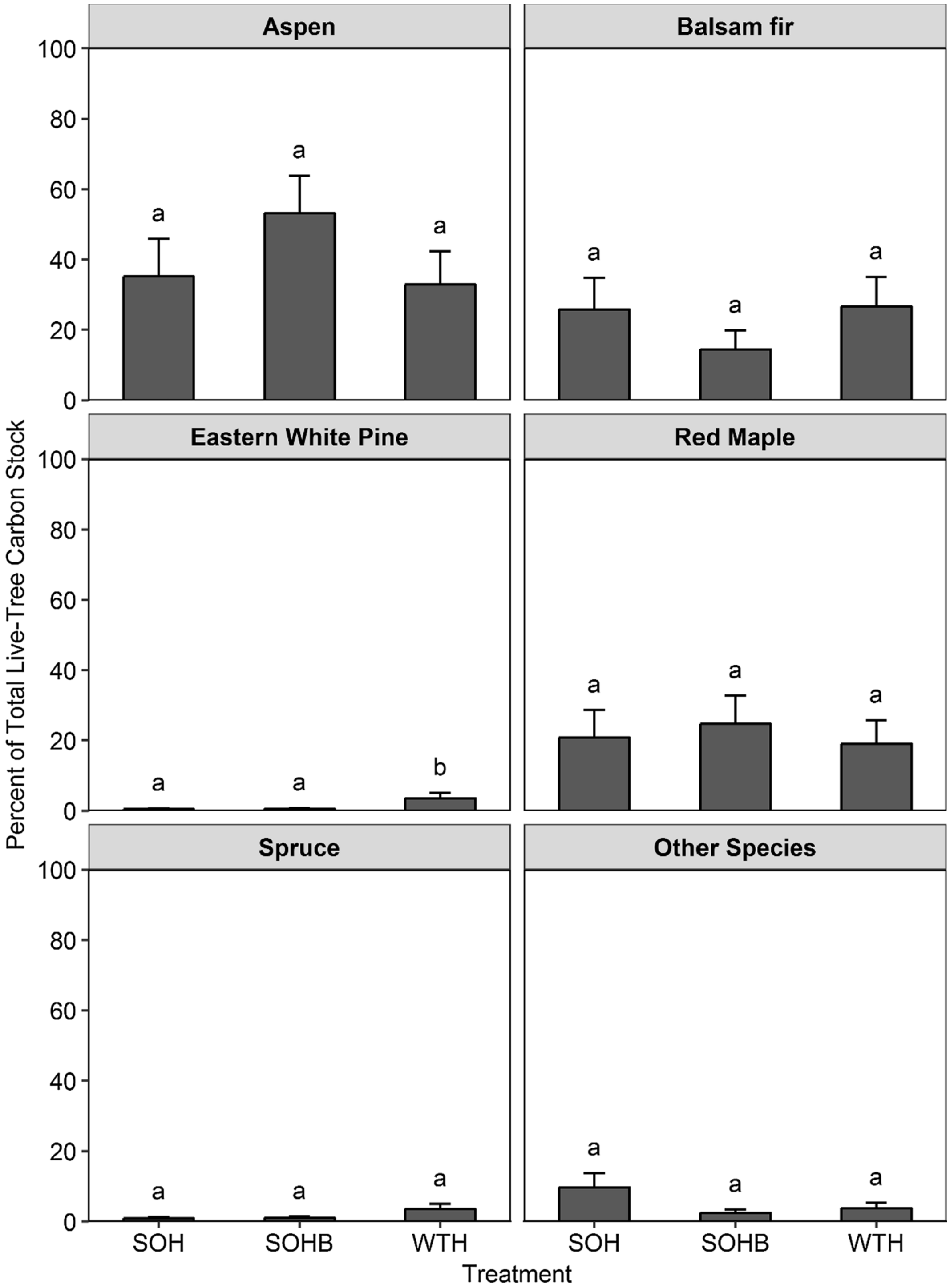

Fig. 6. Percent live-tree carbon stock (% of total live-tree carbon stock) by species least-squares means and standard errors by treatment, for trees ≥ 1.3 cm dbh. Treatments are as follows: SOH = stem-only harvest; SOHB = stem-only harvest with burn; WTH = whole-tree harvest. Different lower-case letters indicate significant differences.

(e.g., *Populus* and *Acer*) initially following stand-replacing disturbances in mixedwood stands (Kneeshaw and Bergeron, 1996). Suckering or sprouting was likely stimulated by increases in light and soil temperature following treatments on C33, allowing for these species to outcompete more late-successional and slower growing species common to mature mixedwood stands (Hendrickson, 1988; McInnis and Roberts, 1994). In addition, a treatment effect was observed on species composition, such that the proportion of hardwoods was greater in the burned (SOHB) than mechanical-only treatments (WTH or SOH). These findings are consistent with Rinaldi (1970), who observed a greater density of hardwood regeneration, and a lack of established softwood regeneration, in SOHB relative to SOH and WTH four years after harvesting and prescribed burning in C33. Though the mechanism for this difference was not determined, it is possible that post-harvest prescribed burning was disadvantageous to shade-tolerant softwoods due to their reliance on pre-established seedlings as a mechanism for post-harvest regeneration (Seymour, 1992; Westveld, 1953). Bjorkbom (1967) observed a similar outcome in a comparison of burned and unburned plots elsewhere on the PEF; he reported a greater density of shade-tolerant softwood seedlings (mostly advance regeneration) on unburned plots than on burned plots. The potential for these species to become newly established following removal of the canopy is greatly reduced due to short seeding distances and less than one year of seed viability in the forest floor (Frank and Safford, 1970).

Species composition of northern mixedwood stands following fire has often shifted to shade-intolerant hardwood dominance, relative to dominant shade-tolerant tree species otherwise common in these stands (Lorimer and White, 2003; Parker et al., 2001). On boreal mixedwood sites in southeastern Manitoba, for example, Kemball et al. (2005) found quaking aspen regeneration basal area to be significantly greater on burned relative to logged sites or sites previously affected by spruce budworm (*Choristoneura fumiferana*) 10–15 years following disturbance. This is a result of initial early successional (i.e. pioneer) species establishment characteristic of large-scale disturbance, with late-successional species growth increasing during later understory reinitiation (Seymour et al., 2002). Twenty-six years following a wildfire in central Maine, dominance by paper birch, quaking aspen, and bigtooth aspen was observed in the overstory of previously burned mixedwood stands, in addition to observed established conifer regeneration in the understory (Small, 2004). Temporary shifts in species composition on mixedwood sites following disturbance may also have implications for differences in belowground productivity, given production of nutrient-demanding pioneer species following fire (Bélanger et al., 2004; Brais et al., 1995; Parker et al., 2001).

Aboveground stand productivity has been observed to vary in mixedwood stands when comparing the effects of fire and logging. This variability following fire is likely a function of differing fuel loadings and fuel moistures characteristic of mixedwood stands (Vose and Swank, 1993; Wang, 2002), and reflects pre-disturbance stand condition. In addition to a greater presence of quaking aspen on burned sites, Kemball et al. (2005) found significantly greater stem densities and basal areas on burned plots relative to sites that had been selectively logged, 10–15 years following disturbance. Small (2004) found that burned sites alone in central Maine, U.S. had significantly higher standing snag densities and a greater volume of down logs relative to sites that were unburned. These trends were not seen in our data, but this might be more reflective of past stand history and the intensity of the burn.

In addition to its use as a site preparation treatment to expose mineral soil for seedbed purposes, post-harvest prescribed burning is used for fuel reduction (Agee and Skinner, 2005). With projected increases in summer temperatures in Maine's future climate (Fernandez et al., 2015; Jacobson et al., 2009) and a build-up of fuels over time, there is potential for an increase in intense, severe, and frequent fire events in the future. Fuel loads resulting from more common disturbances that occur in northern mixedwood stands, such as windthrow, eastern spruce budworm, or from slash left in harvests, have the potential to interact with the effects of fire (Small, 2004; Weed et al., 2013). Therefore, fuels reduction treatments may need to be applied. However, there is limited understanding of the effects of treatments such as post-harvest prescribed burning on stand productivity in northern mixedwood stands (Dibble et al., 2007; Dibble and Rees, 2005), or how these effects compare with SOH and WTH (e.g. Franklin et al., 2002, 2000). Though this study investigated post-harvest prescribed burning solely as a site-preparation treatment, it has implications for long-term stand productivity in the northern mixedwood forests following fuel reduction efforts (Northeast Regional Strategy Committee, 2015). The present study provides a unique opportunity to view long-term stand productivity following prescribed burning on sites with long fire-return intervals (Seymour et al., 2002).

Given concerns about climate change, long-term data are of particular importance for predicting the carbon storage capacity of our future forests, particularly under intensive forest management (Adams et al., 2010; Lugo, 2009). However, long-term datasets are limited in number, and financial means of establishing new studies are often not available. Our approach demonstrates the utility of using long-term silvicultural studies, including repurposing existing studies when possible, to address contemporary sustainability concerns related to forest management practices. Although our study was initially designed to compare spruce-fir regeneration under three slash disposal treatments following a clearcut, it has proven to be a valuable resource for understanding the long-term implications of biomass harvesting on stand productivity.

5. Conclusions

Though compositional differences were found across treatments, no evidence was found that either WTH or SOHB significantly reduced stand productivity relative to SOH, 50-years post-harvest in northern mixedwood stands. Differences in stand structure appear to be due to site rather than treatment. Overall, these outcomes suggest that a single application of WTH and SOHB can be used for biomass removal, fuels reduction, or site preparation in northern mixedwood stands of low to moderate production potential without negatively impacting long-term aboveground stand productivity as reflected by structure and carbon stock. Further work on soil and foliar nutrient availability will provide additional insight on the effects of biomass removal on stand productivity. Though this study is one of the longest, on-going evaluations of stand productivity following whole-tree harvesting on temperate forests, a spatiotemporal connection of long-term studies is needed further to support these findings and expand the scope of our results.

6. Declarations of interest

None.

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Appendix A. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.foreco.2019.03.032.

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