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Idaho forest growth response to post-thinning energy biomass removal and complementary soil amendments

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Abstract

Utilization of woody biomass for biofuel can help meet the need for renewable energy production. However, there is a concern biomass removal will deplete soil nutrients, having short- and long-term effects on tree growth. This study aimed to develop short-term indicators to assess the impacts of the first three years after small-diameter woody biomass removal on forest productivity to establish optimal biomass retention levels for mixed-conifer forests in the Inland Northwest region, and to evaluate the ability of soil amendments to compensate for potential adverse effects from biomass removal. We examined impacts of four biomass retention-level treatments at two study locations: full biomass removal (0x), full biomass retention (1x), double biomass retention (2x), and unthinned control. We combined biomass retention with four soil amendment treatments: biochar (B), fertilizer (F), fertilizer and biochar combined (FB), and an untreated control (C). We considered treatment effects on basal area and total stem volume growth for all trees per plot (plot trees) and for the six largest trees per plot (crop trees). Biomass removal had no effect on plot ($P > 0.40$) or crop tree growth ($P > 0.65$) compared to normal biomass retention. High biomass retention (2x) decreased plot tree growth as compared to normal biomass retention (1x) levels ($P < 0.05$) after three years. This growth difference was not explained by soil moisture, temperature, or nutrient uptake. While there were strong tree growth differences between study locations, patterns of biomass and amendment treatment responses did not differ. Fertilizer increased basal area growth and total volume growth ($P < 0.10$) as expected, because nitrogen is limiting in the region. Biochar had no effect on tree growth ($P > 0.47$). Initial findings after three years suggest removing small-diameter biomass for biofuel feedstocks is feasible in the Inland Northwest without negative impacts on tree growth.

Keywords: biochar, bioenergy feedstock, biomass, Douglas fir, mixed-conifer, nitrogen fertilizer, ponderosa pine, slash loading

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Introduction

There has been a global demand to reduce reliance on fossil fuels and a growing interest in using woody biomass for energy production. The Energy Independence and Security Act (2007) requires the United States to replace 36 billion gallons a year of fossil fuels with biofuels including 16 billion gallons coming from cellulosic feedstocks (Schnepf & Yacobucci, 2015). Small-diameter woody biomass thinning operations produce abundant forest residues which can be used for bioenergy. There are many benefits to using forest biomass for biofuel, as it can reduce the risk of wildfire and disease (Schroeder, 2008; Evans & Finkral, 2009) and provides a source of income as a secondary commercial product. However, little is known of the impacts removal operations will have on soil properties and short- and long-term forest productivity.

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Forest harvest impact research has focused on comparing whole-tree to bole-only harvest removal. Studies have found whole-tree harvests can reduce soil nutrient availability (Johnson & Todd, 1998; Saarsalmi *et al.*, 2010), but others found no impact on nitrogen (N) or site productivity (Voldseth *et al.*, 2011; Slesak *et al.*, 2017). Powers *et al.* (2005) found that biomass removals during clear-cut harvesting result in declines in soil carbon, but not in forest growth through 10 years. The impacts of nutrient removal from whole-tree harvesting are site specific and depend on such factors as nutrient capital, soil type, parent material, climate and moisture regime, forest type, and harvest technique (Slesak *et al.*, 2017). The impacts of small-diameter biomass removal from forest sites during precommercial thinning operations are not as well understood as harvest removal impacts, because few studies examine the removal of biomass from thinning operations. Helmisaari *et al.* (2011) found lower 10- and 20-year volume growth increments from whole-tree harvesting after thinning compared to conventional harvesting after thinning, finding a negative correlation between amount of residue harvested and volume growth. However, these stands were thinned at 44 years. Precommercial thinning typically fells biomass when stands are relatively young, about 10–15 years for Douglas-fir stands (Reukema, 1975). Precommercial thinning is used to reduce tree competition for resources such as light, water, and soil nutrients and usually results in higher nutrient and water availability (Brockley, 2005; Chase *et al*., 2016). While it is difficult to make generalizations that can be applied in every forest type, biomass harvesting from nutrient limited sites will have a proportionally greater impact than harvesting from nutrient abundant sites (Thiffault *et al*., 2011). Small-diameter biomass removal will likely impact site conditions less than whole-tree harvesting (Kabrick *et al*., 2013; Klockow *et al*., 2014) as smaller quantities of biomass will be removed, but soil impacts will depend on the harvest method (e.g., skidder, forwarder), how much slash remains after harvesting, soil conditions, and climatic regime (Page-Dumroese *et al*., 2010).

Thinning activities in the western United States are estimated to generate 155 Mt of woody biomass that can be used for bioenergy (Rummer *et al*., 2005). Often during harvesting, whole trees are moved to a central logging deck where they are delimbed and detopped (Polagye *et al*., 2007). However, depending on the age of the stand, trees can be left where they are felled or piled and burned for wildfire mitigation (Kalabokidis & Omi, 1998). An alternative to burning woody biomass after thinning is to use the residues for bioenergy production (U.S. Department of Energy, 2011). Removing biomass from forests and using it as a biofuel source provides a secondary source of income that also reduces the risk of wildfire and disease (Schroeder, 2008; Evans & Finkral, 2009).

Thinning is a common silvicultural treatment in many areas of the world and can be accompanied by the addition of fertilizer (Crane, 1982; Donald, 1987; Valinger, 1992). Nitrogen is considered to be the main limiting nutrient in western forest soils (Edmonds *et al*., 1989; Coleman *et al*., 2014) and biomass removal can decrease nitrogen pools (Elliot *et al*., 1998). Fertilizing thinned stands has the potential to increase tree production (Footen *et al*., 2009), and may compensate for loss of nutrients from biomass removal (Helmisaari *et al*., 2011). In the northwestern United States, Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco) forests typically respond to nitrogen fertilization for up to ten years (Coleman *et al*., 2014) and one study found nitrogen fertilization of Douglas-fir plantations increased site productivity for 15–22 years in low-quality sites (Footen *et al*., 2009). But growth benefits of fertilization may not be initially detectable.

In addition to fertilizer increasing post-thinned stand productivity, the application of biochar may also mitigate the effects of biomass removal. Depending on the feedstock and pyrolysis method, biochar can be fine-grained and highly porous with high water-holding capacity and nutrient retention (Laird, 2008; Page-Dumroese *et al*., 2017). On forest sites, biochar can increase ground cover after disturbance, increase soil moisture, and decrease soil compaction associated with harvesting (Page-Dumroese *et al*., 2017). Biochar can also decrease greenhouse gas emissions (Laird, 2008). The carbon in biochar is resistant to decomposition when added as a soil amendment (Amonette *et al*., 2009), so the benefits are likely long term.

In order to understand the impacts of small-diameter biomass removal on residual forest growth, there is a need for regional, site-specific studies (Smith *et al*., 2000). Our goal was to evaluate the impacts of various levels of biomass removal on forests in the Inland Northwest while maintaining or enhancing site productivity. The objectives were to develop short-term indicators of the impact on forest productivity of small-diameter woody biomass removal, establish ideal biomass retention levels for the region, and evaluate the ability of soil amendments to compensate for potential adverse effects from biomass removal, such as decreased growth. We hypothesized tree growth would be higher on plots with retained biomass compared to complete biomass removal. Any differences in growth in sites with biomass removal would be mitigated by fertilizer and biochar amendments, as fertilizer would replace nitrogen lost, and biochar would replace carbon lost and increase water availability during dry summers.

Materials and methods

Site characteristics

Two northern Idaho study locations, Pitwood (46.983104, −116.483943) and the University of Idaho Experimental Forest (UIEF) (46.849512, −116.845068), were chosen in different forest types (Fig. 1). The 1981–2010 mean annual temperature at Pitwood was 6.6 °C, while at UIEF it was 7.8 °C. Mean annual precipitation at Pitwood was 106 cm, while at UIEF it was 74 cm (PRISM Climate Group). Both sites were regenerated mixed-conifer forests and had predominately silt loam soils that contain volcanic ash. The Pitwood site was mostly Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco var. *glauca* (Beissn.) Franco), grand fir (*Abies grandis* (Douglas ex D. Don) Lindl.), and western redcedar (*Thuja plicata* Donn ex D. Don) on land owned by Potlatch Corporation and adjacent to the St. Joe River region of the Idaho Panhandle National Forest. Understory vegetation includes Rocky Mountain maple (*Acer glabrum* Torr.), Scouler's willow (*Salix scouleriana* Barratt ex Hook), menziesia (*Menziesia ferruginea* Sm.), thimbleberry (*Rubus parviflorus Nutt.*), twisted stalk (*Streptopus amplexifolius* (L.) DC), nightshade (*Circaea alpina* L.), oakfern (*Gymnocarpium*

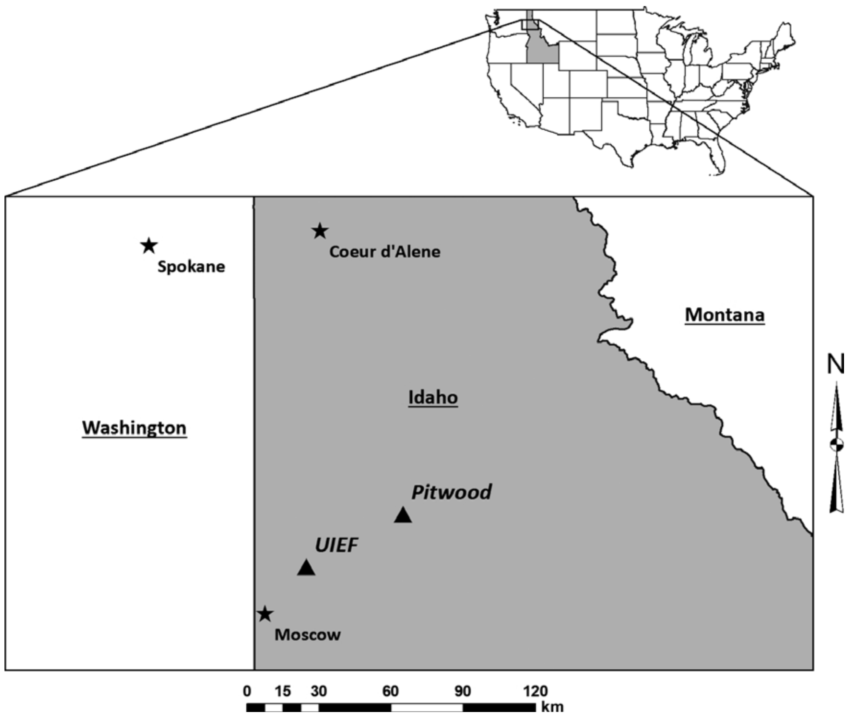

Fig. 1 Site locations. Triangles indicate Pitwood and University of Idaho Experimental Forest (UIEF) sites.

disjunctum (Rupr.) Ching), and ladyfern (*Athyrium filix-femina* (L.) Roth). Its elevation ranges from approximately 990 to 1060 meters above sea level. The site area has a slope of 20–60% with a northern aspect. The soil is deep, well drained, and formed from material weathered from fine-grained quartzite with a thick mantle of volcanic ash. It is classified as ashy over loamy, amorphic over isotic, frigid Typic Udivetrand (Flewsie soil series; National Cooperative Soil Survey 2013). Pitwood has been managed as a commercial forest with a rotation period of approximately 40 years, with the last harvest occurring in 1992. It was broadcast burned in 1993 and planted in 1994 with Douglas-fir. There is considerable natural regeneration of associated species (Table 1).

The second location at UIEF near Princeton, ID, was a naturally regenerated mixed-conifer stand of ponderosa pine (*Pinus ponderosa* Douglas ex P. Lawson & C. Lawson), Douglas-fir, grand fir, lodgepole pine (*Pinus contorta* Douglas ex Loudon), and western larch (*Larix occidentalis* Nutt.). The understory species included mallow ninebark (*Physocarpus malvaceus* (Greene) Kuntze), common snowberry (*Symphoricarpos albus* (L.) S.F. Blake), roses (*Rosa* L spp.), ocean spray (*Holodiscus discolor* (Pursh) Maxim.), Idaho fescue (*Festuca idahoensis* Elmer), Columbia brome (*Bromus vulgaris* (Hook.) Shear), pinegrass (*Calamagrostis rubescens* Buckley), bluebunch wheatgrass (*Pseudoroegneria spicata* (Pursh) A. Love), yellow avalanche lily (*Erythronium grandiflorum* Pursh), and strawberry (*Fragaria* L. spp.). The site elevation ranges from 830 to 890 meters above sea level with a 0–15% slope and south-facing aspect. The soils are moderately well drained and underlain with a fragipan, classified as coarse-silty, mixed, superactive, frigid Vitrandic Fragixeralf (Santa series; National Cooperative Soil Survey 2016). These soils are deep loess with a small amount of volcanic ash in the surface. The parent material is granite bedrock. The UIEF was used for grazing cattle, recreation, and research, and managed for commercial forestry. This stand was harvested in the late 1980s as a seed-tree harvest, leaving ponderosa pine for forest regeneration, with a harvest rotation period of 45–50 years. Seed trees were harvested in 2012. Pretreatment site characteristics including stand composition are noted in Table 1.

Biomass treatments

Two replicate stands, each approximately 6–10 ha in size, were selected at each location. To install the study plots, each stand was divided into four biomass treatment whole plots, including three thinned treatments with varying biomass retention levels and one unthinned control. The three biomass retention plots at each stand were thinned in spring 2013. Plots were thinned to approximately 5 m spacing and ~400 trees per hectare (Table 1). Stands were thinned from below, removing the smaller and less desirable trees. Douglas-fir was retained at Pitwood, with primarily western redcedar being removed. Ponderosa pine was retained at the UIEF upper stand after the thinning, while a mix of species was retained in the lower stand (Table 1). The thinned treatment whole plots were divided into three biomass retention levels: full biomass removal (0x), full biomass retention (1x), and double biomass retention (2x). In the 2x treatment, all thinning residues were retained and all the residues from 0x plots were added. The four whole-plot treatments are represented in Fig. 2.

Table 1 Pre- and post-treatment site characteristics of stands at two experimental locations. Pretreatment characteristics were measured in 2012, and post-treatment characteristics were based on plots that were thinned and measured in 2013

	TPH (trees ha^{-1})	QMD (cm)	BA (m^2 ha^{-1})	SDI (trees ha^{-1})	RD (Curtis)	Species distribution (% BA)						
						DF	GF	WH	RC	LP	PP	WL
Pretreatment site characteristics												
Pitwood												
North	3181	8	16	498	39	49	24	21	4	1	0	0
South	2068	10	18	463	40	35	5	12	48	0	0	0
Mean	2625	9	17	481	40	42	15	17	26	1	0	0
UIEF												
Lower	1613	12	17	484	34	12	27	0	0	28	15	18
Upper	1513	11	15	395	31	8	0	0	0	1	91	0
Mean	1563	12	16	440	33	10	14	0	0	14	53	9
Post-treatment site characteristics (thinned plots)												
Pitwood												
North	440	15	8	189	14	64	11	18	5	<1	0	1
South	494	18	12	284	20	54	4	10	31	0	0	0
Mean	467	17	10	237	17	59	8	14	18	<1	0	1
UIEF												
Lower	371	13	5	127	10	17	27	0	0	26	21	9
Upper	375	14	6	144	11	9	0	0	0	2	90	0
Mean	373	14	6	136	11	13	13	0	0	14	55	5

TPA, trees per acre; QMD, quadratic mean diameter; BA, basal area; SDI, standard density index (Reineke, 1933); RD, Curtis's relative density (Curtis, 1982); DF, Douglas-fir; GF, grand fir; WH, western hemlock; RC, western redcedar; LP, lodgepole pine; PP, ponderosa pine; WL, western larch.

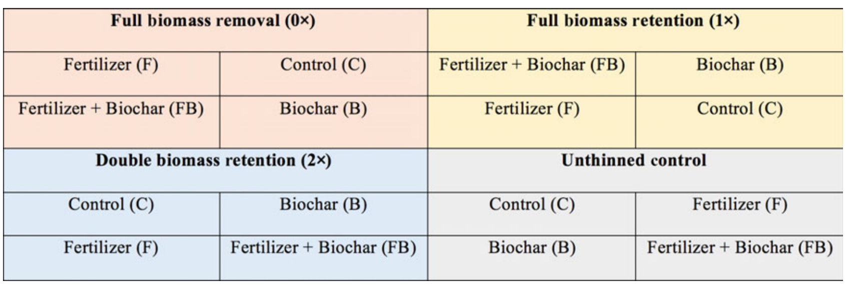

Fig. 2 Representation of the biomass treatment whole plots within a stand, and the soil amendment split-plot treatments within each whole plot. The study included two replicates at each location for a total of four replicate stands, 16 whole plots, and 64 split plots.

Soil amendments

Soil amendment treatments were randomly assigned within each whole plot to one of four 40 × 40 m split plots (Fig. 2). As a result, there were a total of 64 study plots (2 locations × 2 replicate stands × 4 thinning treatments × 4 amendments). A 20 × 20 m measurement plot was assigned in the middle of each plot, leaving a 10-m treatment buffer surrounding each plot. The amendment treatments were fertilizer (F), biochar (B), fertilizer and biochar (FB), and a control with no amendments (C). Biochar was obtained from Evergreen Forest Products (Tamarack, ID, USA) and was produced from mixed-conifer mill residue at 890 °C. Biochar was applied to the top of the O horizons and added in the amount of 2.5 Mg ha^{-1} to each B and FB plot. It was hydraulically sprayed on UIEF plots in the upper stand in October 2013 and the lower stand in April 2014. It was applied manually at Pitwood in May 2014. Nitrogen fertilizer (urea) was applied at a rate of approximately 630 kg ha^{-1} to the F and FB plots in November 2013 at UIEF and May 2014 at Pitwood.

Biomass retention

To quantify the amount of woody debris left in the biomass retention treatments, total aboveground standing biomass was calculated from tree diameters using an allometric equation specific to each species group (Jenkins *et al.*, 2003) for the pretreatment and post-treatment stands (Table 2). The difference between post-treatment aboveground total biomass and pretreatment standing biomass was an estimate of the amount cut in tons per hectare in each plot, and the amount deposited

Table 2 Average downed wood estimates and estimated nitrogen content in DWD

	Pitwood		UIEF	
	1x	2x	1x	2x
Estimated				
DWD (t ha^{-1})	76 (9)	158 (12)	27 (2)	72 (4)
Nitrogen content (kg ha^{-1})	44 (4)	258 (5)	44 (1)	118 (2)

Numbers in parentheses are standard error of the mean.

for each of the 1x plots. To estimate the debris left in the 2x plots, we added the amount cut to the average amount cut in the 0x plots within the same replicate stand. The 0x plots were assumed to have 0 tons per hectare of biomass added, as the cut debris was manually moved to the 2x plots.

We estimated the amount of nitrogen in the DWD. The approximate proportions of foliage, branches, bole wood, and bark of the cut trees were estimated from whole-tree ratios (Ares *et al.*, 2007). The biomass of each component was multiplied by their respective nitrogen concentration (Ares *et al.*, 2007) and summed to calculate the DWD nitrogen content in each plot. Nitrogen content in each plot was averaged for each biomass treatment at each location (Table 2).

Tree growth

We measured trees in three to six randomly selected 20 × 20 m plots within each replicate stand at the end of 2012 growing season. Residual trees within all 20 × 20 m plots were measured in the fall of 2013 through fall 2016. Diameter at breast height (DBH) for all trees greater than 2.5 cm DBH was measured with a D-tape, and species were identified and tagged with a unique tree ID at all UIEF plots and at all thinned plots at Pitwood. In the unthinned plots at Pitwood, which contained high stem densities, all trees with a DBH of 13 cm or larger were measured in the 20 × 20 m plot and all trees with a diameter of 2.5 cm or larger were measured within a 5 × 5 m subplot. Tree heights were measured annually at UIEF with TruPulse laser rangefinder (Laser Technology Inc, Centennial, CO, USA). Tree heights at Pitwood were measured at least once in each plot. In any one year, tree heights were measured in an average of two plots in each of the four biomass treatments. Missing tree heights for volume calculations were estimated using allometric equations specific to tree species (Wykoff *et al.*, 1982) and validated against measured tree heights.

The six largest live trees in each plot were designated as crop trees in 2016. Tree growth was calculated as basal area growth (m^2 ha^{-1}) and total volume growth (m^3 ha^{-1}) for each of the 64 plots each year from 2013 to 2016 at the plot level and for crop trees. Plot and crop tree total volume was calculated from tree diameters and heights using species-specific allometric equations (Browne, 1962).

Foliar nutrient analysis

Three branches were collected from one to three trees of the dominant species in each plot. For each branch, 20 ponderosa pine needles and 100 Douglas-fir needles were removed for analysis. Needles were weighed and analyzed for nitrogen concentration using Kjeldahl digestion analysis at Harris Lab (Lincoln, NE, USA). Relative concentrations and content were calculated using the unthinned and unamended control plots as the baseline for each species.

Soil moisture and temperature

Soil moisture and temperature were measured seasonally at the 15 cm soil depth with a soil moisture probe (HydroSense II, Campbell Scientific, Logan, UT, USA) and a soil temperature probe (6000-09TC Soil Probe Thermocouple, Li-Cor, Lincoln, NE, USA) in three random locations in each split plot every nonwinter season from spring 2014 through fall 2016, typically in April, July, and October. Additionally, one or more Em5b data loggers (Decagon Devices, Pullman, WA, USA) were installed in biomass treatment blocks. Soil moisture and temperature readings were recorded continuously at 4-h intervals throughout each day at 15 cm using MAS-14-20 moisture and RT-1 temperature sensors (Decagon Devices). Soil temperature and moisture averages were calculated from spot measurements, and were checked for accuracy using the data logger measurements.

Statistical analysis

An analysis of covariance (ANCOVA) was performed for both the plot level and crop tree basal area growth and total stem volume growth as the response variables. Each growth year increment and the three-year periodic annual increment (PAI) for basal area growth were analyzed separately as response variables. Initial basal area as measured in 2013 was used as covariate using the 'aov' function in the 'stats' package in R (R Development Core Team 2015). Each model included three factors with varying levels including location ($n = 2$), biomass retention/thinning treatment ($n = 4$), and soil amendment ($n = 4$), as well as interactions between factors. If interactions were not significant, they were eliminated from the model. The same model was used for the needle nitrogen concentration, without a covariate.

A mixed-effects linear model with an initial BA covariate and a random factor of split plot within whole plot for each stand was completed using the 'lme' function in the 'nlme' package (Pinheiro *et al.*, 2014) to evaluate differences within factors and had comparable results of significance to the ANCOVA. The random factor did not improve the model, so we used the ANCOVA for the final analysis. Growth means were calculated using the least squared estimates derived in the 'lsmeans' package (Lenth, 2016).

A regression analysis was used to calculate growth response associated with the amount of residual downed woody debris. We used a quadratic equation $y = x + x^2 + \text{error}$, where y is basal area growth and x is downed woody debris in tons per hectare. This was completed using the 'lm' function in the 'stats' package (R Development Core Team 2015).

Tukey's 'honestly significant difference' *post hoc* test was used to test each pairwise comparisons between biomass retention/thinning treatments and soil amendment treatments using the 'TukeyHSD' function in the 'stats' package (R Development Core Team 2015). Differences within factors were assumed to be significant at $\alpha = 0.1$.

Seasonal soil moisture and soil temperature differences between whole-plot biomass treatments and split-plot soil amendment treatments were analyzed using an analysis of variance via the 'aov' function in the 'stats' package (R Development Core Team 2015) with moisture or temperature as the response variable and location ($n = 2$), biomass treatment ($n = 4$), soil amendment treatment ($n = 4$), and season ($n = 3$) as factors, as well as interactions.

Results

Downed wood estimates and stand growth

The amount of biomass felled during thinning operations differed between locations and in turn affected residual tree growth. Pitwood had 181% more downed woody debris in the 1x plots and approximately 119% more downed debris in the 2x plots (Table 2) compared to UIEF. We used the downed woody debris estimates to calculate the quadratic growth relationship between downed woody debris and basal area growth at the plot level and crop tree level in the thinned treatments (Figs S1 and S2). The regression results were not significant ($P > 0.1$), but stand growth was affected by biomass treatment as a categorical variable in the ANCOVA (Table 3). Basal area and volume growth were also sensitive to study location, soil amendment, and initial basal area at both the plot level and crop tree level (Table 3). However, stand growth response to biomass treatments did not vary between locations and were consistent at all levels of amendment treatments (i.e., no two- or three-way interactions).

Stand growth response to location

Pitwood basal area growth was greater than UIEF at the plot level and at the crop tree level for all growth increments (Table 4). The plot-level basal area periodic annual increment (PAI) at Pitwood was 107% greater than at UIEF. Crop tree PAI basal area growth at Pitwood was 44% greater than UIEF (Table 4). Three-year PAI plot-level growth response to initial basal area depended on location (I × L interaction) and was associated with a steeper response to initial basal area at Pitwood than at UIEF because larger Pitwood trees had greater basal area growth compared to smaller trees at Pitwood, while the growth rate of UIEF of smaller trees and larger trees was more consistent (Fig. 3).

The plot-level PAI volume growth at Pitwood was 119% greater than UIEF and Pitwood crop tree PAI volume growth was 68% greater than UIEF (Table 5). As with basal area, three-year volume PAI response to initial basal area depended on location (I × L interaction) at the plot level (Table 3) due to a steeper response to initial basal area at Pitwood than at UIEF.

Basal area response to biomass treatment

Response of basal area to biomass treatments depends on mortality as well as tree growth. Significant mortality did not occur in the thinned plots, but did occur in the unthinned plots, especially during the 2016 growing season, where the unthinned plot basal area showed a decrease in growth rate (Fig. 4a). The basal area of the six largest living trees in each plot represents the crop tree basal area in each year (Fig. 4b). The slope of the lines between each year shows relative growth among treatments was higher in thinned plots (Fig. 4).

Plot tree growth was affected by biomass treatment starting at the second year of growth (Table 3). The basal area PAI in 1x was 30% greater than 2x, and 44% greater than unthinned plots (Fig. 5d). Growth in the 1x was not significantly greater than 0x in any year increment (Fig. 5a–c), or for the PAI growth (Fig. 5d). A regression analysis for tree growth by coarse woody residue loads as a continuous variable did not find any significant correlations (Figs S1 and S2).

Biomass treatments contributed to significant changes in crop tree growth each year after thinning (Table 3; Fig. 6a–c). Most of the differences were due to diminished growth in unthinned plots. Basal area PAI in 1x was 50% greater than in unthinned (Fig. 6d), while 0x growth was 44% greater than unthinned (Fig. 6d).

Volume growth response to biomass treatment

Plot-level tree volume was affected by biomass treatment starting the first year after thinning (Table 3). The PAI volume growth in the 1x treatments was 45% greater than the 2x treatment growth, and 52% greater than the unthinned plots (Fig. 7d). Volume growth in the 1x plots was not significantly greater than the 0x treatment plots in any year (Fig. 7a–c).

Crop tree volume growth was affected by biomass treatment beginning the first year after thinning (Table 3; Fig. 8a–c). In the third year, crop tree volume growth in the 1x treatments was 32% greater than the 2x treatment growth, and 63% greater than the unthinned plots (Fig. 8c).

Basal area response to soil amendments

Soil amendments did not affect plot basal area growth during the first two years post-thin (Table 3; Fig. 9a, b),

Table 3 Analysis of covariance results for plot basal area and volume growth. Results include *F*-statistic (*F*) and *P*-values (*P*) for first three years after thinning and the periodic annual increment (PAI) at the plot level and for crop trees. Initial basal area (basal area in 2013) was used as a covariate. Three-year PAI is the difference in basal area for the three years from 2013 to 2016. Only significant interactions were included in the final models for each growth variable

	Total plot								Crop trees							
	1st year		2nd year		3rd year		PAI		1st year		2nd year		3rd year		PAI	
	F	*P*	*F*	*P*	*F*	*P*	*F*	*P*	*F*	*P*	*F*	*P*	*F*	*P*	*F*	*P*
Basal area ANCOVAS																
Location (L)	50.46	**<0.01***	40.37	**<0.01***	40.72	**<0.01***	81.73	**<0.01***	50.51	**<0.01***	41.57	**<0.01***	13.88	**<0.01***	42.37	**<0.01***
Biomass (B)	0.92	0.44	3.17	**0.03***	2.95	**0.04***	4.04	**0.01***	3.15	**0.03***	5.79	**<0.01***	5.03	**<0.01***	6.11	**<0.01***
Amendment (A)	1.32	0.28	1.93	0.13	2.45	**0.07**	3.19	**0.03***	1.20	0.32	3.53	**0.02***	4.37	**0.01***	3.58	**0.02***
Initial BA (I)	77.38	**<0.01***	39.19	**<0.01***	0.82	0.37	32.67	**<0.01***	10.92	**<0.01***	21.89	**<0.01***	4.01	**0.05**	14.11	**<0.01***
I × L	7.10	**0.01***			5.18	**0.03***	5.07	**0.03***								
Volume ANCOVAS																
Location (L)	52.38	**<0.01***	39.65	**<0.01***	42.60	**<0.01***	72.54	**<0.01***	52.28	**<0.01***	54.14	**<0.01***	24.66	**<0.01***	50.39	**<0.01***
Biomass (B)	2.93	**0.04***	5.53	**<0.01***	4.50	**<0.01***	7.06	**<0.01***	2.99	**0.04***	7.00	**<0.01***	5.42	**<0.01***	6.14	**<0.01***
Amendment (A)	1.98	0.13	3.74	**0.02***	3.53	**0.02***	4.67	**<0.01***	1.25	0.30	4.02	**0.01***	3.42	**0.02***	2.96	**0.04***
Initial BA (I)	54.20	**<0.01***	26.45	**<0.01***	1.06	0.31	22.44	**<0.01***	28.71	**<0.01***	57.62	**<0.01***	12.75	**<0.01***	35.17	**<0.01***
I × L			4.58	**<0.01***			3.69	**0.02**								

Asterisk (*) indicates significance within factor at $\alpha = 0.05$, and bold text indicates significance within factor at $\alpha = 0.1$.

Table 4 Average basal area growth (m^2 ha^{-1} yr^{-1}) by location in each year

	1st year		2nd year		3rd year		PAI	
Plot								
Pitwood	1.27 (0.13)	a	1.61 (0.16)	a	1.53 (0.29)	a	1.47 (0.14)	a
UIEF	0.67 (0.13)	b	1.03 (0.16)	b	0.42 (0.3)	b	0.71 (0.14)	b
Crop tree								
Pitwood	0.55 (0.05)	a	0.73 (0.05)	a	0.67 (0.06)	a	0.65 (0.04)	a
UIEF	0.32 (0.05)	b	0.51 (0.05)	b	0.51 (0.06)	b	0.45 (0.04)	b

Standard errors are shown in parentheses. Same letters within each time period and measurement indicate no differences between locations at α = 0.1.

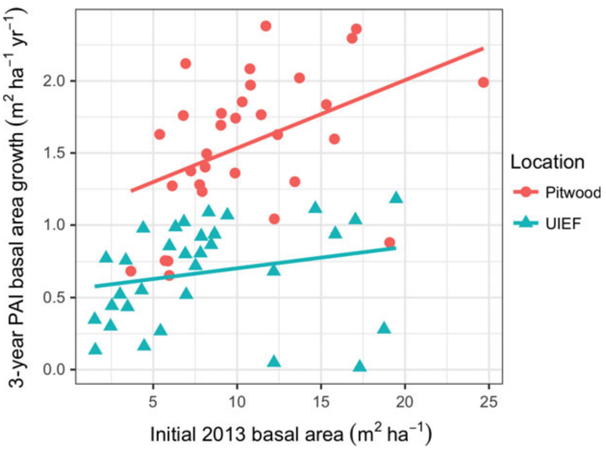

Fig. 3 Average plot-level basal area growth over the three years after thinning by initial basal area and location. Location and initial basal area interaction is significant (*P* = 0.03).

but showed a fertilizer effect after the third year (Fig. 9c). Fertilizer-only (F) plots had 39% higher basal area PAI compared to unamended control (C) plots (Fig. 9d). Biochar did not affect basal area growth within the plots in any year.

Table 5 Mean periodic annual volume increment (m^3 ha^{-1} yr^{-1}) from 2013 to 2016 by location

	Plot level		Crop tree	
Plot				
Pitwood	12.66 (1.30)	a	6.79 (0.55)	a
UIEF	5.78 (1.30)	b	4.04 (0.55)	b

Standard errors are shown in parentheses. Same letters with each measurement indicate no differences between treatment levels at α = 0.1.

Soil amendments did not affect crop tree basal area in the first year (Table 3). After three years, crop trees in F plots had 23% greater PAI basal area growth compared to the unamended plots, and trees in FB increased basal area growth 27% as compared to the control (Fig. 10d). Biochar did not diminish or improve residual tree growth in any year increment compared to the unamended control plots.

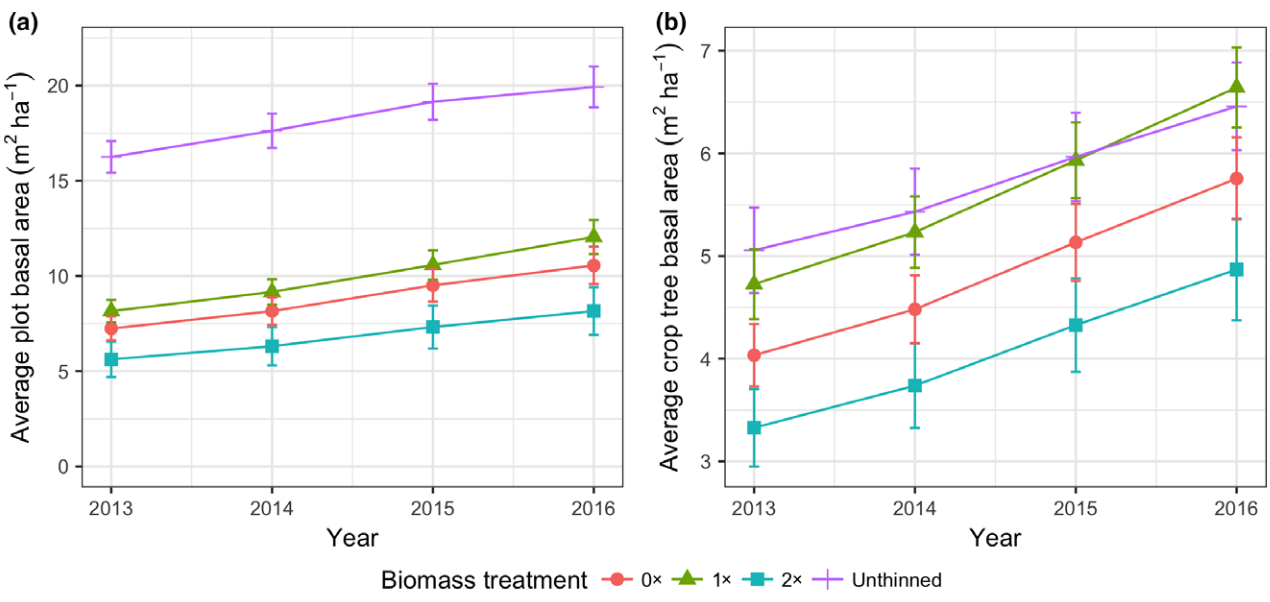

Fig. 4 Average basal area of plots (a) and crop trees (b) in each study year by biomass treatment.

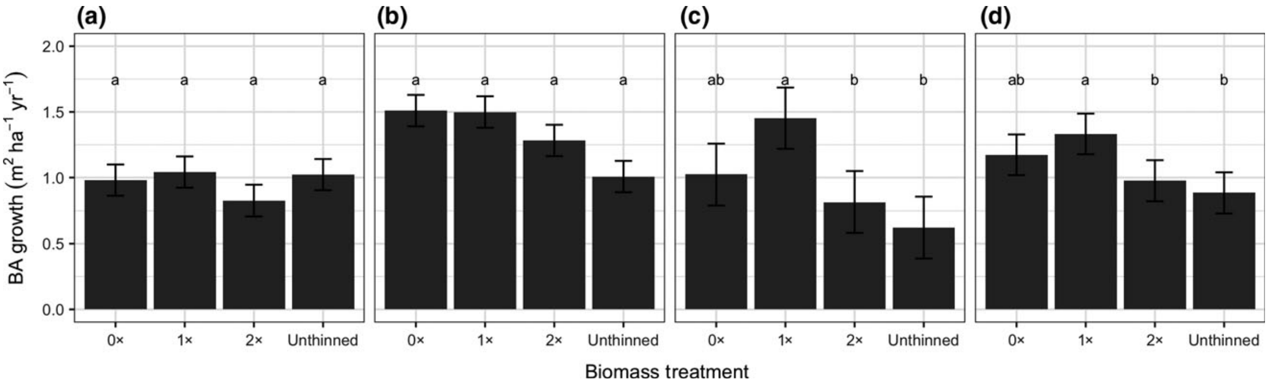

Fig. 5 Average plot basal area growth from 2013 to 2016 by biomass treatment. (a) 1st year, (b) 2nd year, (c) 3rd year (d) PAI. Same letters over bars indicate no differences between treatment levels at $\alpha = 0.1$.

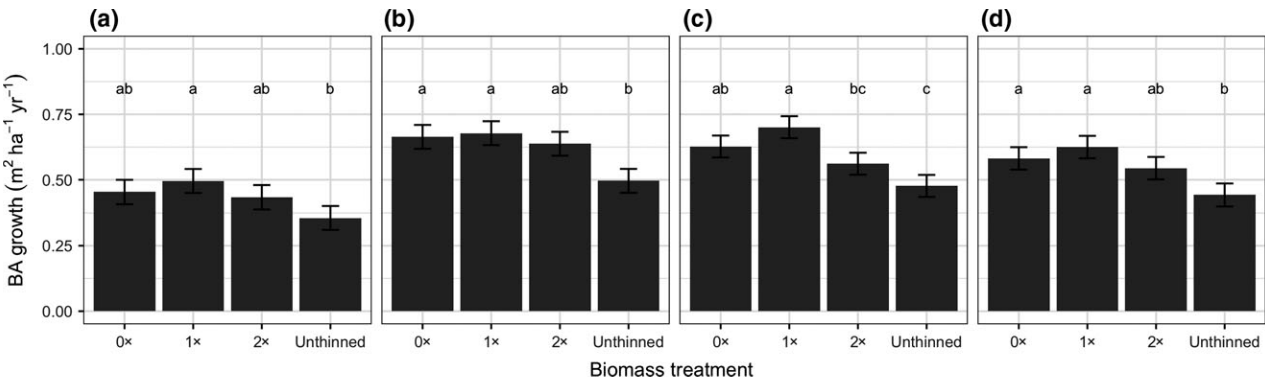

Fig. 6 Average crop tree basal area growth from 2013 to 2016 by biomass treatment. (a) 1st year, (b) 2nd year, (c) 3rd year (d) PAI. Same letters over bars indicate no differences between treatment levels at $\alpha = 0.1$.

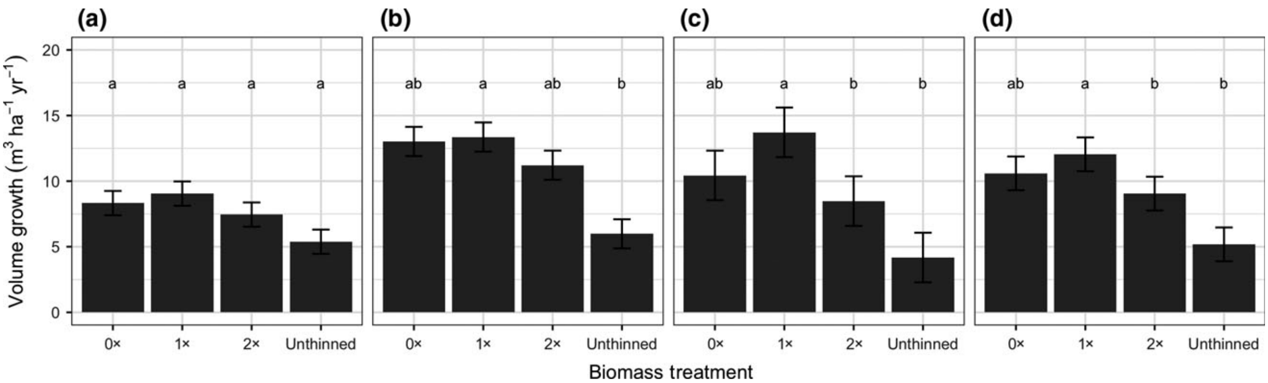

Fig. 7 Average plot volume growth from 2013 to 2016 by biomass treatment. (a) 1st year, (b) 2nd year, (c) 3rd year (d) PAI. Same letters over bars indicate no differences between treatment levels at $\alpha = 0.1$.

Volume growth response to soil amendments

Volume growth responded to fertilizer at the plot level and crop tree level. None of the soil amendments affected tree growth during the first growing season after thinning (Table 3). At the plot level, fertilized plots had 19% (F) and 25% (FB) greater PAI volume growth than the control plots after three years (Fig. 11d). Crop trees in FB plots had 28% greater PAI growth compared to unamended control plots (Fig. 12d). Biochar-only plots did not diminish or improve plot or crop tree basal area growth compared to the unamended control plots.

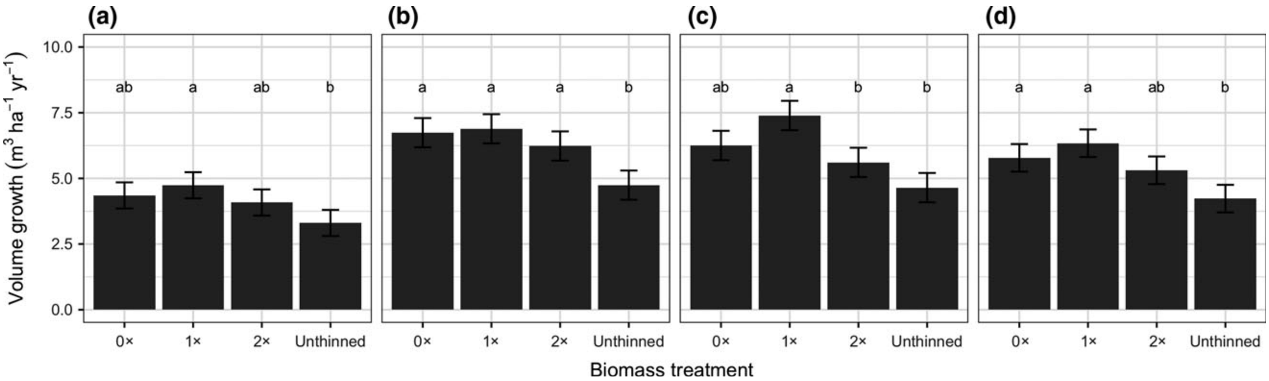

Fig. 8 Average crop tree volume growth from 2013 to 2016 by biomass treatment. (a) 1st year, (b) 2nd year, (c) 3rd year (d) PAI. Same letters over bars indicate no differences between treatment levels at $\alpha = 0.1$.

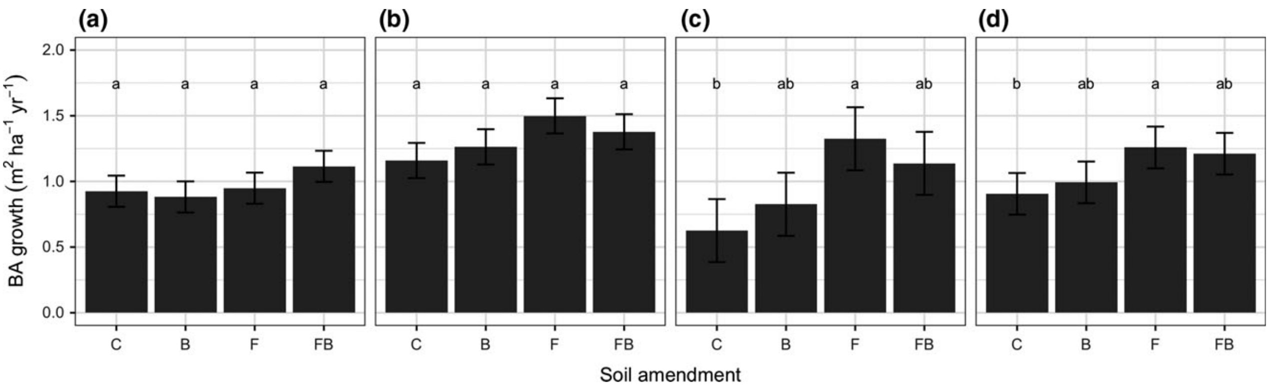

Fig. 9 Average plot basal area growth from 2013 to 2016 by soil amendment. (a) 1st year, (b) 2nd year, (c) 3rd year (d) PAI. Same letters over bars indicate no differences between treatment levels at $\alpha = 0.1$.

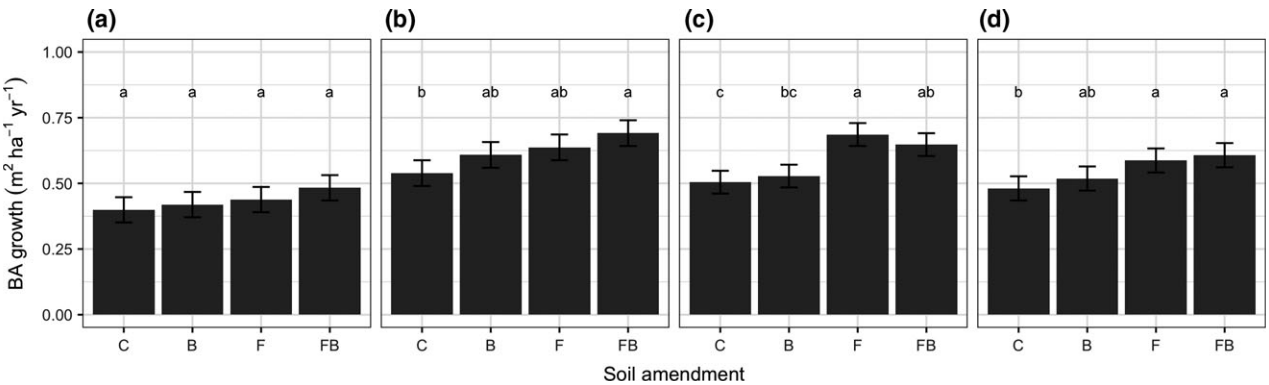

Fig. 10 Average crop tree basal area growth from 2013 to 2016 by soil amendment. (a) 1st year, (b) 2nd year, (c) 3rd year (d) PAI. Same letters over bars indicate no differences between treatment levels at $\alpha = 0.1$.

Foliar nitrogen

Relative foliar nitrogen concentrations increased after nitrogen fertilization, but the response was not consistent between locations (Fig. 13). The F and FB plots had equal foliar nitrogen concentrations at Pitwood, but FB plots had higher concentrations than F plots at UIEF. There were no differences in foliar nitrogen between biomass treatments, or any interactions ($P > 0.05$).

Soil moisture and temperature

Neither the level of biomass nor soil amendment affected soil moisture or temperature at the 15 cm

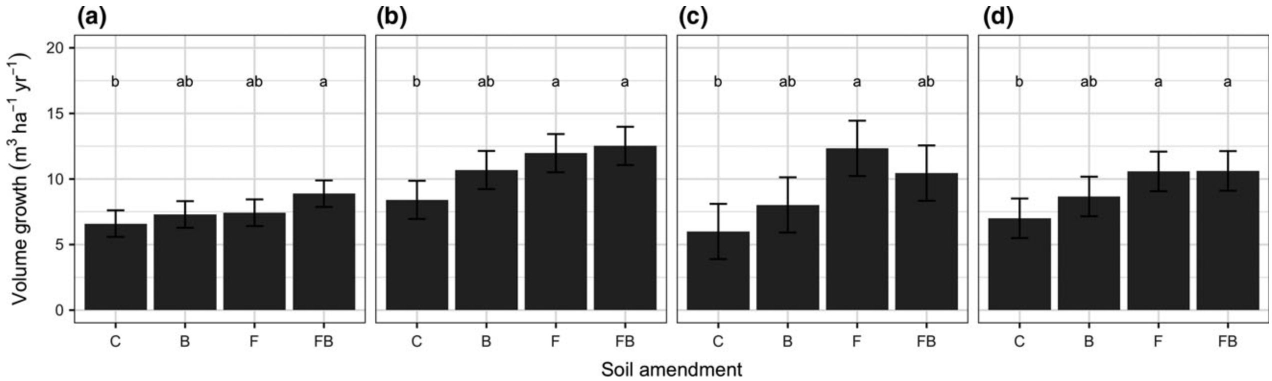

Fig. 11 Average plot volume growth from 2013 to 2016 by soil amendment. (a) 1st year, (b) 2nd year, (c) 3rd year (d) PAI. Same letters over bars indicate no differences between treatment levels at α = 0.1.

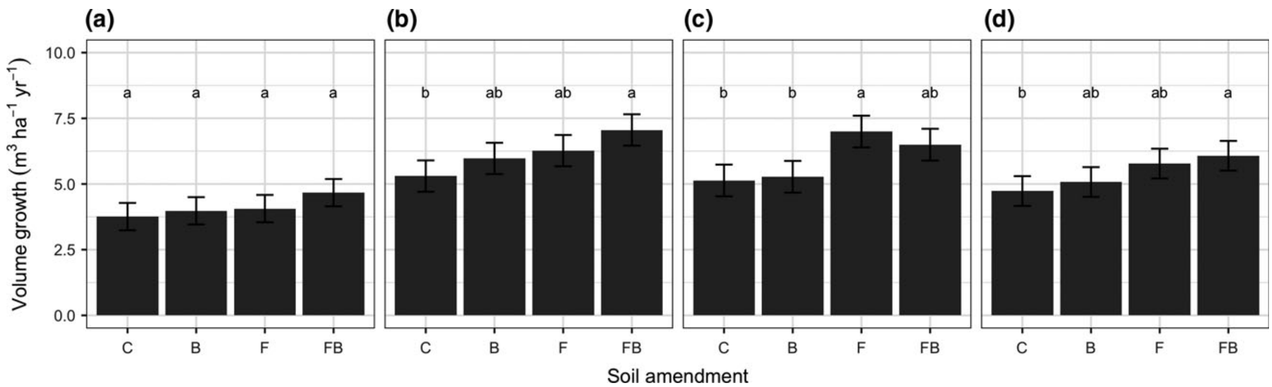

Fig. 12 Average crop tree volume growth from 2013 to 2016 by soil amendment. (a) 1st year, (b) 2nd year, (c) 3rd year (d) PAI. Same letters over bars indicate no differences between treatment levels at α = 0.1.

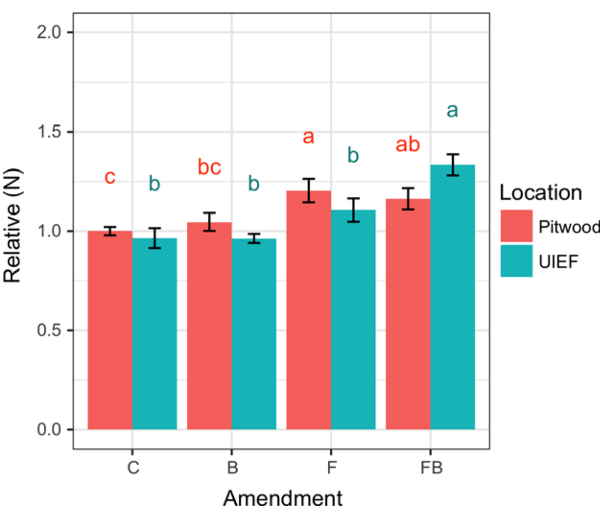

Fig. 13 Relative foliar nitrogen concentration in 2014 by soil amendment and location. Same letters over bars within location indicate no differences between treatment levels at α = 0.1.

depth. There were highly significant seasonal and locational effects on soil moisture and soil temperature. UIEF was warmer in the spring and summer and cooler in the fall compared to Pitwood. Generally, in spring soil temperature was mild (10.8 ± 0.3 °C) with high moisture (22.9 ± 0.4), summer was hot (15.3 ± 0.4 °C) and dry (4.4 ± 0.2 %VMC), while fall was cool (9.1 ± 0.11 °C) with moderate moisture (14.7 ± 0.3). No seasonal differences in soil moisture or temperature were found between biomass treatments or soil amendment treatments (Figs S3–S6).

Discussion

Response to biomass retention level and thinning

The biomass treatments provided an opportunity to compare different woody debris retention levels with the goal of determining best management practices for leaving enough woody biomass to sustain site productivity. During the three years following thinning, removing all of the thinned biomass from the forest did not significantly affect basal area or total volume growth compared to the slash retention plots at both the plot level and the crop tree level. This indicates that over the relatively short study period, these two sites may be resilient to biomass removal during precommercial thinning, and the results support the use of small-diameter biomass for biofuel feedstocks. In contrast, some long-term studies have shown negative effects of biomass removal that were not apparent during the first five years (Voldseth *et al.*, 2011), or not measured during the first 5 years (Helmisaari *et al.*, 2011) so it is possible that long-term impacts may be different than our three-year results indicate. Other long-term studies also show few or no impacts of whole-tree removal (Slesak *et al.*, 2017), which removes greater amounts of carbon and nutrients than precommercial thinning, so it is likely that smaller diameter biomass removal will not impact forest growth on these sites. The impacts of biomass removal during thinning in combination with an intensive whole-tree harvest remain an open question.

Previous harvests occurred at both locations in the late 1980s and early 1990s, but quantities of residual biomass retained are unknown. Site preparation practices during this time often involved broadcast burning. Remnants of decaying, charred logs were visible at both locations. Inputs of dead wood from these harvest operations undoubtedly contribute nutrients to soil (Chen & Xu, 2005; Klockow *et al.*, 2013). The lack of impact of biomass removal on growth might not be replicated on a site that had been whole-tree harvested prior to planting or naturally regenerated (Johnson & Todd, 1998; Saarsalmi *et al.*, 2010).

We expected to see an increase of tree growth with increased slash loading. The reduced basal area and volume growth in the 2x plots compared to other thinned plots with less biomass retention was unexpected. Decreased tree growth associated with greater slash loadings has not been widely shown, but possible explanations include an increased risk of pests and disease, slash influencing soil moisture and temperature, and nutrient immobilization. Greater slash retention increases the risk of pests and disease (Fettig *et al.*, 2007; Schroeder, 2008). While it is possible insect damage or disease occurred, significant mortality was not observed in thinned plots. Greater biomass loads have been shown to increase soil moisture and decrease summer soil temperature following a clear-cut harvest (Devine & Harrington, 2007; Harrington *et al.*, 2013), which could affect residual tree growth, and has actually been shown to increase Douglas-fir growth in young stands (Harrington *et al.*, 2013), yet our study did not show significant moisture and temperature differences between the biomass treatments at either site (Figs S3–S6). Although we may have seen a different moisture and temperature response had we measured vertical spatial variation within treatments, we chose to focus the limited number of ports per data loggers on horizontal variation at a consistent depth within measured plots. Nutrient immobilization is another possible explanation for the decrease in growth in 2x plots. Wood decay fungi may have decreased nutrients available to tree roots by translocating and accumulating soil nitrogen in the woody debris. The presence of woody residue has been shown to decrease nitrogen and phosphorus leaching in some soils (Carlyle *et al.*, 1998). However, other studies showed increased logging debris retention increased nutrient leaching (Strahm *et al.*, 2005; Wall, 2008) and also increased total soil N, but not foliar N in Douglas-fir stands (Slesak *et al.*, 2010). Our study did not find significant biomass impacts on foliar nitrogen.

We estimated from calculations of nitrogen concentrations in tree components (Ares *et al.*, 2007) that an average of 44 kg ha^{-1} of nitrogen was present in the logging residue of the 1x treatments, and 188 kg ha^{-1} of N was present in the 2x treatments at the time of harvest and residue deposit. Nitrogen demand is expected to increase with tree growth throughout the stand development. However, our study only looked at the first three years postharvest, during that time the proportion of nitrogen released from the woody debris may be relatively small compared to long-term decomposition effects. In Douglas-fir forests, woody debris has been shown to both immobilize and release nitrogen in the first two years postharvest depending on factors such as soil temperature and residue mass (Piatek, 2007). The increased mass of debris in the 2x plots may have contributed to a decrease in nitrogen mineralization during our study period. If we had reduced the size of the woody debris in the slashed treatments, we may have seen a faster response. Mulched residue can increase nitrogen availability by 32% after three to five years, and provide added benefit of fuel reduction (Rhoades *et al.*, 2012).

We could not find studies where slash was doubled to evaluate aboveground responses, or studies with slash loading greater than 70 tons per hectare to compare with our 2x treatment. Slash levels at Pitwood averaged 158 tons per hectare. Decreased growth may be due to the excessive slash level, which was due to the overstocked pretreatment conditions and the unique 2x slash treatment. Average 2x slash levels at UIEF were around 72 tons per hectare, which is high compared with other reports. Decreased growth response in 2x plots was consistent between locations, which makes the underperforming 2x growth of greater interest, as Pitwood 2x plots had 119% more slash retention in tons per hectare than UIEF 2x plots.

The results of this study suggest large amounts of slash can decrease tree growth at these two sites. In addition, removing all thinning biomass residue on the soil surface did not change tree growth as compared to retaining it. Assessing an ideal biomass retention level for this region was an objective of this study. There was a peak slash level of ~30 tons per hectare of slash at UIEF and ~60 tons per hectare at Pitwood for growth response using a second-order polynomial. Unfortunately, the regression results were not significant, possibly due to wide variation in slash levels, the accuracy of our method of quantifying downed debris, and limited replicates. The trend of our regression model suggests that an ideal biomass retention level is between zero and more than the full biomass retention level. This indicates best management practices in Inland Northwest forests may include full biomass removal or retention as convenient during thinning operations and, where necessary, at a level that limits a fuel source for wildfire. It should be noted our study sites had very productive soils, and therefore, our results may not transfer to low-productivity sites.

There are advantages to using thinned forest stands to study biomass removal impacts. Empirical field trials with small-diameter thinned stands give results sooner than clear-cut studies that monitor subsequent seedling growth. Significant growth deficiencies in seedlings established after timber harvesting may take decades to detect in the western United States, while thinned stands can show responses within one to five growing seasons. Retained trees in thinned stands quickly occupy available growing space, and respond sensitively to changes in site resource availability (Binkley & Reid, 1984; Grady & Hart, 2006; Roberts & Harrington, 2008). Our study used this time advantage to quickly obtain information on the growth responses to biomass retention, which is most relevant to forest bioenergy production systems.

Response to soil amendments

This study supports previous studies that found fertilizing forest soil increases forest productivity, especially in N-limited environments. Because N is limited in most forest soils in the Inland Northwest, fertilization was expected to increase tree growth compared to the control (Coleman *et al.*, 2014). Fertilized plots showed increased plot and crop tree growth compared to the unfertilized control during the study. While biomass removal did not result in decreased growth in the first three years of the study, it is reasonable to assume fertilizer would be beneficial to Inland Northwest forest productivity if longer-term research finds biomass removal impacts forest growth later in the rotation cycle. Fertilizer has been shown to mitigated impacts of biomass removal in other regions (Powers *et al.*, 2005).

Biochar had no negative impacts on tree growth, indicating it can be used for carbon sequestration without negatively affecting aboveground processes. Biochar is highly variable and agricultural studies often find different growth responses (Spokas *et al.*, 2011) ranging from increased growth (Graber *et al.*, 2010; Hossain *et al.*, 2010; Carter *et al.*, 2013), diminished growth (Asai *et al.*, 2009; Hammond *et al.*, 2013), or no response (Schulz *et al.*, 2014). The lack of biochar affect may be due to the existing volcanic ash content in the soils. Andisols and andic property soils found on both study sites produce highly productive forests when compared to other mineral soil orders (Meurisse *et al.*, 1991). The porous quality of volcanic ash-influenced soil increases water-holding capacity which can increase tree and understory productivity (Meurisse *et al.*, 1991). The increased water-holding capacity in ash-influenced soils is an important factor for forest productivity in the Inland Northwest as the region experiences warm, dry summers with a prolonged summer drought (McDaniel *et al.*, 2005). Biochar amended soil may not increase tree growth because without biochar, these soils already support a high level of biomass production associated with adequate soil moisture retention during dry seasons. We expected biochar to alter soil water-holding capacity and result in higher seasonal soil moisture (Page-Dumroese *et al.*, 2017), but we could not detect any differences in soil moisture (Figs S5 and S6). This may be due to the low quantity of biochar added, the nature of the soil, or other factors not yet identified. Studies have examined various levels of biochar applications in forestry, ranging from 2 Mg ha^{-1} to 47 Mg ha^{-1} (Thomas & Gale, 2015; Page-Dumroese *et al.*, 2017). This study applied 2.5 Mg ha^{-1} of biochar to plots, while other biochar field studies with significant findings applied 7.8 Mg ha^{-1} (Ma *et al.*, 2016), 10 Mg ha^{-1} (Brantley *et al.*, 2015), and 47–105 Mg ha^{-1} (Ippolito *et al.*, 2015). It is possible that increasing the rate of biochar would have resulted in increased impacts, yet application at higher rates, which were done in agricultural contexts, may be impractical in forestry practices using current technology.

Management implications

Forest management objectives aim to provide commercial products along with other ecosystem services including biodiversity, fire reduction, pest control, wildlife habitat, clean water, and climate change mitigation (Thompson *et al.*, 2011). The finding that removing all of the thinning residues did not impact forest growth in the first three years after thinning indicates that the studied soils and forest types may be resilient to this type of harvesting and could be a source of bioenergy feedstocks without impacting forest productivity. Full biomass removal for biofuel production from precommercial thinning would provide a secondary monetary crop and will decrease fossil fuel consumption, potentially aiding in climate change mitigation. Another benefit of biomass removal for this fire-prone region is decreased wildfire risk. Alternatively, while leaving thinned residue did not provide growth benefits within the first three years, there may be longer-term impacts because woody debris decomposition can provide a slow release of nutrients or add to the organic matter pool (Fahey *et al*., 1991). Leaving some woody debris decreases erosion and protects seedlings from exposure, thereby increasing survival rates (Jurgensen *et al*., 1997). It also increases biodiversity by providing structure and forage for wildlife and fungi (Franklin *et al*., 2002; Berch *et al*., 2011). Forest managers will need to evaluate the benefits and detriments of biomass removal when managing for cellulose biofuel production. We found that adding nitrogen fertilizer to these nitrogen-limiting forests increased forest growth. If long-term impacts of biomass removal are shown later, fertilization may be an important practice when managing forests for biomass fuel. A follow-up study is recommended for these measurement plots to assess the long-term impacts of small-diameter biomass removal, as well as similar studies in other soil and forest types to more fully understand impacts of biomass removal and the global capacity for cellulose biofuel systems.

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References

Amonette J, Amonette J, Joseph S (2009) *Biochar for Environmental Management: Science and Technology*. Earthscan, London.

Ares A, Terry TA, Piatek KB *et al.* (2007) *The Fall River Long-Term Site Productivity Study in Coastal Washington: Site Characteristics, Experimental Design, and Biomass, Carbon and Nitrogen Stores Before and After Harvest*. USDA Forest Service General Technical Report PNW-GTR-691, Portland, OR, USA.

Asai H, Samson BK, Stephan HM *et al.* (2009) Biochar amendment techniques for upland rice production in Northern Laos: 1. Soil physical properties, leaf SPAD and grain yield. *Field Crops Research*, **111**, 81–84.

Berch SM, Morris D, Malcolm J (2011) Intensive forest biomass harvesting and biodiversity in Canada: a summary of relevant issues. *Forestry Chronicle*, **87**, 478–487.

Binkley D, Reid P (1984) Long-term responses of stem growth and leaf-area to thinning and fertilization in a Douglas-fir plantation. *Canadian Journal of forest Research*, **14**, 656–660.

Brantley KE, Savin MC, Brye KR, Longer DE (2015) Pine woodchip biochar impact on soil nutrient concentrations and corn yield in a silt loam in the Mid-Southern US. *Agriculture*, **5**, 30–47.

Brockley RP (2005) Effects of post-thinning density and repeated fertilization on the growth and development of young lodgepole pine. *Canadian Journal of Forest Research*, **35**, 1952–1964.

Browne JE (1962) *Standard Cubic-Foot Volume Tables for the Commercial Tree Species of British Columbia*. British Columbia Forest Service, Victoria, BC.

Carlyle JC, Bligh MW, Nambiar ES (1998) Woody residue management to reduce nitrogen and phosphorus leaching from sandy soil after clear-felling *Pinus radiata* plantations. *Canadian Journal of Forest Research*, **28**, 1222–1232.

Carter S, Shackley S, Sohi S, Suy T, Haefele S (2013) The impact of biochar application on soil properties and plant growth of pot grown lettuce (*Lactuca sativa*) and cabbage (*Brassica chinensis*). *Agronomy*, **3**, 404–418.

Chase CW, Kimsey MJ, Shaw TM, Coleman MD (2016) The response of light, water, and nutrient availability to pre-commercial thinning in dry inland Douglas-fir forests. *Forest Ecology and Management*, **363**, 98–109.

Chen CR, Xu ZH (2005) Soil carbon and nitrogen pools and microbial properties in a 6-year-old slash pine plantation of subtropical Australia: impacts of harvest residue management. *Forest Ecology and Management*, **206**, 237–247.

Coleman MD, Shaw TM, Kimsey MJ, Moore JA (2014) Nutrition of Douglas-fir in the inland northwest. *Soil Science Society of America Journal*, **78** (S1), S11–S22.

Crane WJB (1982) Fertilizer treatment of *Pinus radiata* at establishment and at thinning—an evaluation of its potential in Australia. *New Zealand Journal of Forestry Science*, **12**, 293–307.

Curtis RO (1982) A simple index of stand density for Douglas-fir. *Forest Science*, **28**, 92–94.

Devine WD, Harrington CA (2007) Influence of harvest residues and vegetation on microsite soil and air temperatures in a young conifer plantation. *Agricultural and Forest Meteorology*, **145**, 125–138.

Donald DGM (1987) The application of fertiliser to pines following second thinning. *South African Forestry Journal*, **142**, 13–16.

Edmonds RL, Binkley D, Feller MC, Sollins P, Abee A, Myrold DD (1989) Nutrient cycling: effects on productivity of northwest forests. In: *Maintaining the Long-Term Productivity of Pacific Northwest Forest Ecosystems* (eds Perry DA *et al.*), pp. 17–35. Timber Press, Portland, OR.

Elliot WJ, Page-Dumroese D, Robichaud PR (1998) The effects of forest management on erosion and soil productivity. In: *Soil Quality and Erosion*, (ed Lal R), pp. 195–209. St. Lucie Press, Boca Raton, FL.

Evans AM, Finkral AJ (2009) From renewable energy to fire risk reduction: a synthesis of biomass harvesting and utilization case studies in US forests. *GCB Bioenergy*, **1**, 211–219.

Fahey TJ, Stevens PA, Hornung M, Rowland P (1991) Decomposition and nutrient release from logging residue following conventional harvest of Sitka spruce in North Wales. *Forestry: An International Journal of Forest Research*, **64**, 289–301.

Fettig CJ, Klepzig KD, Billings RF, Munson AS, Nebeker TE, Negrón JF, Nowak JT (2007) The effectiveness of vegetation management practices for prevention and control of bark beetle infestations in coniferous forests of the western and southern United States. *Forest Ecology and Management*, **238**, 24–53.

Footen PW, Harrison RB, Strahm BD (2009) Long-term effects of nitrogen fertilization on the productivity of subsequent stands of Douglas-fir in the Pacific Northwest. *Forest Ecology and Management*, **258**, 2194–2198.

Franklin JF, Spies TA, Van Pelt R *et al.* (2002) Disturbances and structural development of natural forest ecosystems with silvicultural implications, using Douglas-fir forests as an example. *Forest Ecology and Management*, **155**, 399–423.

Graber ER, Meller Harel Y, Kolton M *et al.* (2010) Biochar impact on development and productivity of pepper and tomato grown in fertigated soilless media. *Plant and Soil*, **337**, 481–496.

Grady KC, Hart SC (2006) Influences of thinning, prescribed burning, and wildfire on soil processes and properties in southwestern ponderosa pine forests: a retrospective study. *Forest Ecology and Management*, **234**, 123–135.

Hammond J, Shackley S, Prendergast-Miller M, Cook J, Buckingham S, Pappa VA (2013) Biochar field testing in the UK: outcomes and implications for use. *Carbon Management*, **4**, 159–170.

Harrington TB, Slesak RA, Schoenholtz SH (2013) Variation in logging debris cover influences competitor abundance, resource availability, and early growth of planted Douglas-fir. *Forest Ecology and Management*, **296**, 41–52.

Helmisaari HS, Hanssen KH, Jacobson S *et al.* (2011) Logging residue removal after thinning in Nordic boreal forests: long-term impact on tree growth. *Forest Ecology and Management*, **261**, 1919–1927.

Hossain MK, Strezov V, Yin Chan K, Nelson PF (2010) Agronomic properties of wastewater sludge biochar and bioavailability of metals in production of cherry tomato (*Lycopersicon esculentum*). *Chemosphere*, **78**, 1167–1171.

Ippolito JA, Donnelly A, Grob J (2015) Anatomy of a field trial - wood-based biochar and compost influences a Pacific Northwest Soil. *The Biochar Journal (TBJ)*, 1–44.

Jenkins JC, Chojnacky DC, Heath LS, Birdsey RA (2003) National-scale biomass estimators for United States tree species. *Forest Science*, **49**, 12–35.

Johnson DW, Todd DE Jr (1998) Harvesting effects on long-term changes in nutrient pools of mixed oak forest. *Soil Science Society of America Journal*, **62**, 1725–1735.

Jurgensen MF, Harvey AE, Graham RT, Page-Dumroese DS, Tonn JR, Larsen MJ, Jain TB (1997) Impacts of timber harvesting on soil organic matter, nitrogen, productivity, and health of Inland Northwest forests. *Forest Science*, **43**, 234–251.

Kabrick JM, Dwyer JP, Shifley SR, O'Neil BS (2013) Components and nutrient concentrations of small-diameter woody biomass for energy. *Northern Journal of Applied Forestry*, **30**, 137–142.

Kalabokidis KD, Omi PN (1998) Reduction of fire hazard through thinning/residue disposal in the urban interface. *International Journal of Wildland Fire*, **8**, 29–35.

Klockow PA, D'Amato AW, Bradford JB (2013) Impacts of post-harvest slash and live-tree retention on biomass and nutrient stocks in *Populus tremuloides* Michx.-dominated forests, northern Minnesota, USA. *Forest Ecology and Management*, **291**, 278–288.

Klockow PA, D'Amato AW, Bradford JB, Fraver S (2014) Nutrient concentrations in coarse and fine woody debris of *Populus tremuloides* Michx.-dominated forests, northern Minnesota, USA. *Silva Fennica*, **48**, 197–210.

Laird DA (2008) The charcoal vision: a win–win–win scenario for simultaneously producing bioenergy, permanently sequestering carbon, while improving soil and water quality. *Agronomy Journal*, **100**, 178.

Lenth Russel V (2016) Least-squares means: the R package lsmeans. *Journal of Statistical Software*, **69**, 1–33. https://doi.org/10.18637/jss.v069.i01.

Ma N, Zhang L, Zhang Y *et al.* (2016) Biochar improves soil aggregate stability and water availability in a mollisol after three years of field application. *PLoS ONE*, **11**, e0154091.

McDaniel PA, Wilson MA, Burt R, Lammers D, Thorson TD, McGrath CL, Peterson N (2005) Andic soils of the inland pacific northwest, USA: properties and ecological significance. *Soil Science*, **170**, 300–311.

Meurisse RT, Niehoff J, Ford G (1991) Dominant soil formation processes and properties in western-montane forest types and landscapes: some implications for productivity and management. In: *Proceedings – Management and Productivity of Western-Montane Forest Soils* (eds Harvey AE, Neunschwander LF), pp. 7–19. General technical report INT-180. U.S. Department of Agriculture, Forest Service, Intermountain Research Station, Ogden, UT.

National Cooperative Soil Survey (2013) Official series description – Flewsie Series. Available at: https://soilseries.sc.egov.usda.gov/OSD_Docs/F/FLEWSIE.html (accessed 30 October 2017).

National Cooperative Soil Survey (2016) Official series description – Santa Series. Available at: https://soilseries.sc.egov.usda.gov/OSD_Docs/S/SANTA.html (accessed 30 October 2017).

Page-Dumroese DS, Jurgensen M, Thomas T (2010) Maintaining soil productivity during forest or biomass-to-energy thinning harvests in the western United States. *Western Journal of Applied Forestry*, **25**, 5–11.

Page-Dumroese DS, Coleman MD, Thomas SC (2017) Opportunities and uses of biochar on forest sites in North America. In: *Biochar: A Regional Supply Chain Approach in View of Climate Change Mitigation* (eds Bruckman V, Varol Esin A, Uzun B, Liu J), pp. 315–335. Cambridge University Press, Cambridge.

Piatek K (2007) *Nitrogen Dynamics Post-Harvest: The Role of Woody Residues*. e-Gen. Tech. Rep. SRS 101. US Department of Agriculture, Forest Service, Southern Research Station, Asheville, NC, USA: 129–134.

Pinheiro J, Bates D, DebRoy S, Sarkar D, R Core Team (2014) _nlme: Linear and Nonlinear Mixed Effects Models_. R package version 3.1-131. https://CRAN.R-project.org/package=nlme (accessed 15 March 2016).

Polagye BL, Hodgson KT, Malte PC (2007) An economic analysis of bio-energy options using thinnings from overstocked forests. *Biomass and Bioenergy*, **31**, 105–125. https://doi.org/10.1016/j.biombioe.2006.02.005.

Powers RF, Andrew Scott D, Sanchez FG, Voldseth RA, Page-Dumroese D, Elioff JD, Stone DM (2005) The North American long-term soil productivity experiment: findings from the first decade of research. *Forest Ecology and Management*, **220**, 31–50.

PRISM Climate Group, Oregon State University, http://prism.oregonstate.edu, created 4 February 2004.

R Development Core Team (2015) *R: A Language and Environment for Statistical Computing*. R Foundation for Statistical Computing, Vienna. https://www.R-project.org/.

Reineke LH (1933) Perfecting a stand-density index for even-aged forests. *Journal of Agricultural Research*, **46**, 627–638.

Reukema DL (1975) *Guidelines for Precommercial Thinning of Douglas-fir*. General technical report, PNW-GTR-030. U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station, Portland, OR.

Rhoades CC, Battaglia MA, Rocca ME, Ryan MG (2012) Short-and medium-term effects of fuel reduction mulch treatments on soil nitrogen availability in Colorado conifer forests. *Forest Ecology and Management*, **276**, 231–238.

Roberts SD, Harrington CA (2008) Individual tree growth response to variable-density thinning in coastal Pacific Northwest forests. *Forest Ecology and Management*, **255**, 2771–2781.

Rummer B, Prestemon J, May D, *et al.* (2005) *A Strategic Assessment of Forest Biomass and Fuel Reduction in the Western States*. Technical Report RMRS-GTR-149. U.S. Department of Agriculture, U.S. Forest Service, Rocky Mountain Research Station, Fort Collins, CO.

Saarsalmi A, Tamminen P, Kukkola M, Hautajärvi R (2010) Whole-tree harvesting at clear-felling: impact on soil chemistry, needle nutrient concentrations and growth of Scots pine. *Scandinavian Journal of Forest Research*, **25**, 148–156.

Schnepf R, Yacobucci BD (2015) *Renewable Fuel Standard (RFS): Overview and Issues, Report No. R40155*. Congressional Research Service, Washington, D.C.

Schroeder LM (2008) Insect pests and forest biomass for energy. In: *Sustainable Use of Forest Biomass for Energy: A Synthesis with Focus on the Baltic and Nordic Region* (eds Röser D, Asikainen A, Raulund-Rasmussen K, Stupak I), pp. 109–128. Springer Netherlands, Dordrecht.

Schulz H, Dunst G, Glaser B (2014) No effect level of co-composted biochar on plant growth and soil properties in a greenhouse experiment. *Agronomy*, **4**, 34–51. https://doi.org/10.3390/agronomy4010034.

Slesak RA, Harrington TB, Schoenholtz SH (2010) Soil and Douglas-fir (*Pseudotsuga menziesii*) foliar nitrogen responses to variable logging-debris retention and competing vegetation control in the Pacific Northwest. *Canadian Journal of Forest Research*, **40**, 254–264.

Slesak RA, Palik BJ, D'amato AW, Kurth VJ (2017) Changes in soil physical and chemical properties following organic matter removal and compaction: 20-year response of the aspen lake-states long term soil productivity installations. *Forest Ecology and Management*, **392**, 68–77.

Smith CT, Lowe AT, Skinner MF, Beets PN, Schoenholtz SH, Fang S (2000) Response of radiata pine forests to residue management and fertilisation across a fertility gradient in New Zealand. *Forest Ecology and Management*, **138**, 203–223.

Spokas KA, Novak JM, Stewart CE, Cantrell KB, Uchimiya M, DuSaire MG, Ro KS (2011) Qualitative analysis of volatile organic compounds on biochar. *Chemosphere*, **85**, 869–882.

Strahm BD, Harrison RB, Terry TA, Flaming BL, Licata CW, Petersen KS (2005) Soil solution nitrogen concentrations and leaching rates as influenced by organic matter retention on a highly productive Douglas-fir site. *Forest Ecology and Management*, **218**, 74–88.

Thiffault E, Hannam KD, Paré D, Titus BD, Hazlett PW, Maynard DG, Brais S (2011) Effects of forest biomass harvesting on soil productivity in boreal and temperate forests—a review. *Environmental Reviews*, **19**, 278–309.

Thomas SC, Gale N (2015) Biochar and forest restoration: a review and meta-analysis of tree growth responses. *New Forests*, **46**, 931–946.

Thompson ID, Okabe K, Tylianakis JM *et al.* (2011) Forest biodiversity and the delivery of ecosystem goods and services: translating science into policy. *BioScience*, **61**, 972–981.

U.S. Department of Energy (2011) *U.S. Billion-Ton Update: Biomass Supply for a Bioenergy and Bioproducts Industry*. RD Perlack and BJ Stokes (Leads), ORNL/TM-2011/224. Oak Ridge National Laboratory, Oak Ridge, TN, 227 pp.

Valinger E (1992) Effects of thinning and nitrogen fertilization on stem growth and stem form of *Pinus sylvestris* trees. *Scandinavian Journal of Forest Research*, **7**, 219–228.

Voldseth R, Palik B, Elioff J (2011) *Ten-year Results from the Long-term Soil Productivity Study in Aspen Ecosystems of the Northern Great Lakes Region*. Res. Pap. NRS-17. U.S. Department of Agriculture, Forest Service, Northern Research Station, Newtown Square, PA.

Wall A (2008) Effect of removal of logging residue on nutrient leaching and nutrient pools in the soil after clearcutting in a Norway spruce stand. *Forest Ecology and Management*, **256**, 1372–1383.

Wykoff WR, Crookston NL, Stage AR (1982) *User's Guide to the Stand Prognosis Model*. US Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station, Ogden, UT, pp. 720–2600.

Supporting Information

Additional Supporting Information may be found online in the supporting information tab for this article:

Figure S1. PAI basal area growth response to downed woody debris by location with fitted quadratic curve.
Figure S2. PAI crop tree basal area growth response to downed woody debris by location with fitted quadratic curve.
Figure S3. Seasonal temperature differences by biomass treatment.
Figure S4. Seasonal temperature differences by soil amendment.
Figure S5. Seasonal moisture differences by biomass treatment.
Figure S6. Seasonal moisture differences by soil amendment.