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Long-term effects of vegetation management on biomass stock of four coniferous species in the Pacific Northwest United States

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ABSTRACT

Silvicultural treatments applied during the early stages of stand development can have long-lasting impacts on forest ecosystem structure. Forest vegetation management (VM) is an important component of many reforestation programs and although several studies have demonstrated the benefits of VM on planted conifer growth and survival, few reports have been published on the long-term effects of VM treatments on total ecosystem biomass accumulation. In this study we assessed the effects of two contrasting VM treatments on total tree and ecosystem biomass stock for Douglas-fir, western hemlock, western redcedar, and grand fir growing in Oregon's central Coast Range (CR) and Douglas-fir and western redcedar growing in Oregon's Cascade foothills (CF). The assessments were made at age 16 years, 11 years after treatment application ended. The study contained two vegetation management treatments: control (C) and vegetation management (VM). Both the C and VM plots received a pre-planting herbicide site preparation treatment. The VM plots had, additionally, sustained vegetation control using herbicides during the first 5 years after planting. At age 16 years, at the CR site, the VM treatment increased the biomass stock of crop trees by 26.5, 91.2, 44.7, and 96.1 Mg ha^{-1} for Douglas-fir, western hemlock, western redcedar, and grand fir, respectively. At the same age, at the CF site, the VM treatment increased crop tree biomass stock by 48.1 Mg ha^{-1} for Douglas-fir and 42.2 Mg ha^{-1} for western redcedar. When other ecosystem components were considered, however, total ecosystem biomass did not differ between C and VM treated plots for western hemlock, western redcedar and grand fir at the CR site largely due to the development of an abundant hardwood midstory. On the other hand, VM treatments increased the ecosystem biomass stock of Douglas-fir and western redcedar at the site with a low abundance of hardwood midstory (CF site). Midstory biomass of C plots at the CR site averaged 52.9, 64.7, and 36.0 Mg ha^{-1}, for western hemlock, western redcedar, and grand fir, respectively. At the CF site, midstory biomass of C plots averaged 1.2 and 5.9 Mg ha^{-1}, for Douglas-fir and western redcedar, respectively. The results of this study demonstrate that sustained VM treatments during the first 5 years of stand establishment increases the biomass stock of crop trees, directing site resources towards planted crop trees.

1. Introduction

Silviculturists can influence the trajectory and rate of forest development using several different management techniques. The use of artificial regeneration (planted seedlings) and forest vegetation management treatments are two important management strategies used in the United States Pacific Northwest (PNW) to successfully establish healthy and highly productive conifer plantations. When establishing a new stand, forest managers must select a crop tree species and make vegetation management decisions that may have long-term impacts on stand condition and growth. Understanding how these decisions impact forest ecosystems can help silviculturists to develop management strategies for diverse objectives such as timber production, forest restoration, or carbon sequestration.

Forest vegetation management (VM) is an integral part of reforestation in the PNW. After a harvest, site resources become readily available and early seral species quickly use these resources to occupy the site. This can create intense competition with crop trees, especially during the dry summers typical to the region (Dinger and Rose, 2009). Research has shown that controlling competing vegetation increases the growth of planted conifer species in the PNW (Newton and Preest, 1988, Rose et al., 2006; Maguire et al., 2009). The most effective VM method in the PNW, and in other parts of the world, has been herbicide use due to its low cost, high efficacy, and associated improvements in seedling growth and survival (Ketchum et al., 1999, Rose et al., 2006, Maguire et al., 2009).

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VM studies in the PNW have often focused on the short-term effects of VM (Clark et al., 2009) and in other regions only a few studies have monitored long-term effects [Nilsson and Allen (2003) (SE USA), Albaugh et al. (2015) (Chile), Vargas et al. (2017) (Chile)]. Many of these studies focused on stand attributes, such as stem volume, basal area, mean diameter at breast height, and dominant height, as they are of most popular interest to forest managers. However, other stand attributes such as forest biomass stock, net primary productivity, and leaf area are equally important. These stand attributes, separate or in combination, are useful indices of productivity, light use efficiency, maturity and stability of forest ecosystems (Gholz, 1982).

Forests in the PNW are highly productive, dominated by long-lived species, and are known for their large accumulation of biomass (Waring and Franklin, 1979, Franklin et al., 2017). Common conifer species in the region include Douglas-fir (*Pseudotsuga menziesii* (Mirbel) Franco), western hemlock (*Tsuga heteophylla* (Raf.) Sarg.), western redcedar (*Thuja plicata* Donn ex D. Don), and grand fir (*Abies grandis* (Dougl. ex D. Don) Lindl.). Of these, Douglas-fir is the most adaptable species and can thrive on a diversity of sites while western hemlock prefers mesic conditions and is most commonly found in the temperate rainforests of the northwest coast (Burns and Honkala, 1990). Western redcedar is found in many forest swamps, however, it is also more drought tolerant than western hemlock. Grand fir is most commonly found in stream bottoms, valleys, and mountain slopes. In Oregon, Douglas-fir accounted for 70% of timber volume harvest between 2013 and 2014 followed by western hemlock (11%), true firs (abies) (8%), and western redcedar (2%) (Simmons et al., 2016).

In the past, forests in the PNW have accounted for 39% of the 57.8 billion tons of carbon stored in U.S. forests (Birdsey, 1992). While mature forests have high biomass storage, young forests accumulate biomass at a higher rate (Gray et al., 2016) which has led to some debate as to whether planted forests are better suited for sequestering carbon than mature forests (Harmon, 2001). Silvicultural practices that increase stand productivity, such as VM, could also increase forest carbon sequestration and storage (Martin and Jokela, 2004; Wagner et al., 2006).

A large fraction of the carbon stored in forest ecosystems is found in overstory trees. Forest stands, however, are not only composed of planted overstory trees and other ecosystem components must also be accounted for to estimate forest biomass. These include midstory vegetation, understory vegetation, forest floor, and soil organic matter. While allometric functions exist for many tree species, other ecosystem components must be determined by direct field samplings. In this study we analyzed the long-term effects of contrasting vegetation management treatments on total and component tree biomass and total and component ecosystem biomass stock for four coniferous species at age 16 years growing on two sites in western central Oregon. The specific objectives were: (1) determine the effect of crop species, VM treatment, and site on stand biomass stock, (2) determine the effect of crop species, VM treatment, and site on understory, midstory, and forest floor biomass and soil organic matter content, and (3) determine the effect of crop species, VM treatment, and site on total ecosystem biomass. Even though the species used in this study have a long life-span, intensive forest management is reducing harvest age to 35–50 years (Briggs, 2007; Curtis et al., 2007), our estimations at age 16 years represent about 1/3 to 1/2 of the rotation length.

2. Materials and methods

2.1. Description of sites

This study contained two sites, one located in the central Coast Range (CR) near Summit, OR, and the other in the Cascade foothills (CF) near Sweet Home, OR. The CR site was planted in January of 2000 and is located approximately 40 km from the coast, 44.62°N, 123.57°W. The mean annual temperature is 11.1 °C, and the mean annual rainfall is 1,707 mm. The site is characterized by fine loamy soil. The CF site was planted in February of 2001 and is located approximately 110 km from the coast, 44.48°N, 122.73°W. The mean annual temperature is 12.4 °C and the mean annual rainfall is 1179 mm. The site is characterized by silty clay loam soil. At both sites most of the annual rainfall occurs between October to April.

A randomized complete-block experiment with eight VM treatments was implemented at both sites. All plots at both sites received a broadcast fall site preparation treatment of sulfometuron (0.15 L/ha), metsulfuron (0.04 L/ha), and glyphosate (4.68 L/ha) prior to seedling planting. The eight different VM treatments consisted of spring release applications that differed in the number and timing of herbicide treatments applied during the first 5 years after planting. For this study, only the control (C; pre-planting vegetation control) and the 5 consecutive years of spring release vegetation management treatment (VM) were used. Atrazine (4.5–4.9 kg/ha) and clopyralid (0.58–0.73 L/ha) were applied for the spring release treatments. If competing vegetation cover of treated plots exceeded a 25% threshold during the growing season, glyphosate (1.5–2.0%) was applied during the summer. Percent cover by species was visually determined in late summer of growing seasons 1 through 5 using six 1-m radius vegetation survey subplots per plot. The VM treatments created significant differences in competing vegetation cover during the first 5 years of stand establishment. During the fifth growing season, across species and sites, the summed cover of competing vegetation in VM treated plots, ranged between 4 and 11%, while in C plots it ranged between 124 and 151% (Table 1). Further details on treatment design can be found in Maguire et al. (2009).

Plots were planted with Styro-15 seedlings in eight tree by eight tree rows at 3 m (10-ft) spacing. Stand inventories were conducted on the internal 6 rows of 6 trees allowing for a one tree buffer on all sides. This resulted in a measurement plot size of about 0.06 ha. At the CR site, four coniferous species were planted: Douglas-fir (*Pseudotsuga menziesii* (Mirbel) Franco), western hemlock (*Tsuga heterophylla* (Raf.) Sarg.), western redcedar (*Thuja plicata* Donn ex D. Don), and grand fir (*Abies grandis* (Dougl. ex D. Don) Lindl.). There are four blocks of Douglas-fir and western hemlock, and three blocks for western redcedar and grand fir. The CF site was planted with only Douglas-fir and western redcedar, each with four blocks. Prior to the start of this study, the last stand inventories were conducted at age 12 years, corresponding to 2011 for the CR site and 2012 for the CF site. At both sites, Douglas-fir VM and C plots were thinned from below to reduce stocking by 25% at this age.

Table 1
Cover of competing vegetation during the fifth growing season for Douglas-fir, western hemlock, western redcedar, and grand fir trees growing under contrasting treatments of vegetation management on sites located in the central Coast Range (CR) and the Cascade foothills (CF) of western Oregon. C: no post-planting vegetation control, VM: sustained vegetation control for first 5 years post planting. Understory cover represented the summed cover of each individual species of competing vegetation.

Site	Species	Treatment	Vegetation Cover (%)
CR	Douglas-fir	C	124
		VM	5
	Western hemlock	C	139
		VM	4
	Western redcedar	C	139
		VM	6
	Grand fir	C	130
		VM	6
CF	Douglas-fir	C	151
		VM	9
	Western redcedar	C	140
		VM	11

2.2. Crop tree biomass, leaf area, and stem volume

In March of 2016 (CR) and 2017 (CF), when the stands were 16 year-old, treatment plots at both study sites were inventoried. The diameter at 1.37 m height (DBH, cm) and height (m) of all living measurement trees were measured with metric diameter tapes (mm) and Haglof Vertex IVs (cm), respectively. The stem wood biomass (W, kg), stem bark biomass (B, kg), foliage biomass (F, kg), living branch biomass (LB, kg), dead branch biomass (DB, kg), projected leaf area (LA, m^2), stem volume over-bark (VOB, m^3) and stem volume inside bark (VIB, m^3) were then calculated for each measurement tree using the species-specific models reported in Gonzalez-Benecke et al. (2018). Crop tree biomass was calculated as the sum of W, B, F, LB, and DB. Projected leaf area index (LAI, $m^2\ m^{-2}$) was calculated using the LA equations in Gonzalez-Benecke et al. (2018) and the inventory data collected at age 16 at both sites.

2.3. Thinning residues biomass

At both sites, all Douglas-fir plots were pre-commercially thinned at age 12 years (CR site in 2011, CF in 2012) and all cut trees were left on site. The DBH and height of all trees were recorded prior to thinning allowing for the stem volume of each tree to be calculated from the volume equations reported in Gonzalez-Benecke et al. (2018). The current biomass of thinned stems (currently on the ground) was calculated by determining the stem wood density of the stem residues left on the ground for 5 or 6 years. To accomplish this, in May of 2017, 10 stem samples were randomly collected from the thinned Douglas-fir stems at each site. Samples were cut to 50 cm in length and were taken from different positions along the stem. Back in the lab, stem samples were placed in a Moore-Kiln REI TT drying oven set to 74 °C for at least 72 h. Each sample was then weighed using an OHAUS NV4101 scale (g) and the diameter and length of each sample was measured with a meter stick (mm) in four directions by turning the sample 45° clockwise. From the four diameter and length measurements taken from each stem sample, an average diameter and length was calculated and the volume was determined as a cylinder (cm^3). The density of thinning residues 5 or 6 years after thinning was determined by dividing stem mass by stem volume. The biomass of thinning residues was then calculated by multiplying the volume of cut stems at the time of thinning and the current density of thinning residues.

2.4. Midstory biomass

Within the 0.06 ha measurement plot, all non-crop trees that were > 10 cm in DBH, were considered volunteer trees and accounted for as midstory. The DBH of all these trees was measured and the species was recorded. Additionally, six 4 m^2 subplots were randomly placed inside each 0.06 ha measurement plot to sample midstory trees with DBHs less than 10 cm. Subplots were sampled in June of 2016 (CR) and 2017 (CF). All non-planted trees within the subplot that were greater than 1.37 m in height were measured and the species was recorded. Generalized biomass functions from Chojnacky et al. (2014), Ohmann et al. (1976), and Ter-Mikaelian and Korzukhin (1997) were applied to estimate the aboveground biomass for all hardwood species found at the sites except for cascara buckthorn (*Rhanmus purshiana* (D.C.) Cooper) (Appendix A). For conifer volunteers, the species-specific biomass equations reported in Gonzalez-Benecke et al. (2018) were used.

A species-specific biomass function was developed for cascara buckthorn as we did not find species-specific equations in the literature. In July of 2017, seven trees were selected at the CR site for destructive sampling. The DBH of sampled trees encompassed the range of DBH's measured in the subplots (Table 2). The trees were cut at ground level, and total height and DBH were measured. Branches were cut from the stem and placed in bags along with the foliage. The stem was cut into smaller sections to facilitate transportation. In the lab, branches were separated from foliage, placed in aluminum trays, put in the drying oven at 74 °C for at least 72 h, and then weighed using the OHAUS NV4101 scale. An equation was created using DBH as the main predictor (Appendix A). Biomass equations of hardwood species were then applied to the age 16 years midstory and volunteer inventory. Biomass was summed per plot and expressed in Mg ha^{-1}.

Table 2
List of hardwood species and range of diameter at breast height (DBH, cm) measured in the year 2016.

Code	Species	DBH Range
COCO	beaked hazelnut (*Corylus cornuta*)	0.8–2.9
ACMA	bigleaf maple (*Acer macrophyllum*)	1.5–20.0
PREM	bitter cherry (*Prunus emarginata*)	0.5–12
RHPU	cascara buckthorn (*Rhanmus purshiana*)	0.7–7.8
CHCH	golden chinquapin (*Chrysolepis chrysophylla*)	13.5
ALRH	red alder (*Alnus rubra*)	0.5–19.0
ACCI	vine maple (*Acer circinatum*)	1.0–4.0
ALRH	white alder (*Alnus rhombifolia*)	0.1–2.8

2.5. Understory and forest floor biomass

Understory and forest floor biomass was sampled in each of the six subplots per measurement plot where the midstory was measured. Samples were collected in the summer of 2016 (CR) and 2017 (CF) using a 0.6 × 0.6 m frame that was placed over the center of the 4 m^2 midstory subplots. Before biomass collection, the percent cover of the understory was estimated visually by life form (ferns, forbs, graminoids, moss, shrubs) in each 0.36 m^2 subplot. All vegetation inside the subplot was then clipped at ground level and placed into bags. Vegetation that came over the top of the frame and belonged to a plant that was less than 1.37 m in height was also clipped. Once the vegetation was sampled, the forest floor was raked, collected down to bare mineral soil and placed in a labelled bag. In the case of the Douglas-fir plots that were thinned, stem residues were left on site. Within each 0.36 m^2 subplot, forest floor, that included fine woody debris consisting mainly of branches, was collected for dry mass determination. All litter, duff, and coarse wood debris were considered as forest floor.

In the laboratory, understory and forest floor samples were placed in the drying oven in aluminum bins and dried at 74 °C for at least 72 h. After that time, understory samples were separated by life form and weighed. Forest floor was also weighed using the OHAUS NV4101 scale. Understory and forest floor was then summed per plot and expressed in Mg ha^{-1}.

2.6. Fine root biomass and soil organic matter

In summer 2016 (CR) and 2017 (CF), at the same time as forest floor measurement, a soil core was extracted at the center of each of the six subplots. The soil cores were extracted using pvc tubes of 5.1 cm in diameter and 20 cm in length. All six cores from each treatment plot were placed into one bag, providing one composite sample per plot. In the laboratory, the soil samples were sieved with a 2 mm sieve and fine roots were removed. Soil and fine root samples were placed in aluminum trays and put in the drying oven at 74 °C for at least 72 h. After that time, dry weight of fine roots and soil was determined using the OHAUS NV4101 scale. The dry weight of fine roots in each plot was then estimated as the quotient of the dry weight and the area of the six soil cores and then expressed in Mg ha^{-1}. The amount of fine roots assigned to crop trees and vegetation (midstory + understory) was assumed to be proportional to the mass of foliage of each of these pools on each plot. Soil bulk density (g cm^{-3}) was estimated using the dry weight of the soil and the volume of the soil core. Two grams of each soil sample were stored in a glass vial for soil organic matter determination. It is important to note that in this study, coarse root biomass was not accounted for.

In the Forest Soils Lab at Oregon State University, a ceramic crucible was weighed for every two grams of soil that were stored in glass vials. The weight of the crucible with the soil sample was also recorded. Samples were then dried in a muffle furnace set at 288 °C for 24 h. After that time, samples were reweighed and soil organic matter percentage (SOM%) was calculated as the quotient between sample weight before and after drying. Soil organic matter content per ha (SOMC, Mg ha^{-1}) was then estimated as the product of SOM%, bulk density, and the soil depth that the soil cores were extracted from (20 cm).

2.7. Total ecosystem biomass

Ecosystem biomass (Mg ha^{-1}) was calculated as the sum of crop tree, midstory, understory, and forest floor biomass. As the amount of biomass in soil organic matter largely exceed the amount of biomass in vegetation, soil organic matter content was analyzed separately.

2.8. Statistical analysis

The Statistical Analysis Software version 9.4 (SAS Institute Inc. Cary, NC) was used for all statistical analysis. Analysis of variance, including Tukey multiple comparisons tests, was used to test the effects of treatments on tree and ecosystem biomass components of all species (PROC MIXED; SAS Institute Inc., Cary, NC, USA), where block, block within site and block within combinations of treatment and species were considered as random effects. As only Douglas-fir and western redcedar were planted on both sites, site × species, site × treatment and site × species × treatment effects were tested using a reduced dataset containing only those species. For each site, species × treatment effect was tested separately using all species present on each site. SigmaPlot version 13.0 (Systat Software, Inc. San Jose, CA) was used to create all figures.

3. Results

3.1. Stand inventory

Tables 3 and 4 provides the results of the ANOVA tests discussed in this section and Table 5 summarizes stand characteristics at age 16 years (CR site, March of 2016; CF site, March of 2017). There was a significant site × species × treatment interaction for stand stocking (TPHA, $P = 0.002$), mean height ($P < 0.0001$), and quadratic mean diameter (QMD, $P < 0.0001$) suggesting that the species (Douglas-fir and western redcedar) responded to the VM treatments differently across sites. The stocking of Douglas-fir was not affected by treatment and averaged 707 and 704 trees per ha, for the CR and CF sites, respectively ($P > 0.390$). This result is not surprising as the Douglas-fir plots were thinned to the same stocking level in 2012. It is worth noting, however, that there were no differences in tree survival between the treatments prior to the thinning operation ($P = 0.998$, data not shown) and tree survival averaged 80%. The stocking of VM treated western redcedar was similar across sites, however there was a strong effect of site on the stocking of western redcedar C plots which averaged 778 and 351 trees per ha at the CR and CF sites, respectively (Table 5).

The mean height and QMD of VM treated plots was higher than C plots for both species as both sites. The mean height of VM treated Douglas-fir was similar across sites averaging 15.2 m, however the mean height of Douglas-fir in the C plots was 1.2 m greater at the CR site than the CF site (14.0 vs 12.8 m). A similar pattern was observed for Douglas-fir QMD. The mean height of VM treated western redcedar also didn't differ between sites, however the mean height of C plots was 2.7 m greater at the CF site than the CR site (7.4 vs 4.7 m). A similar pattern for western redcedar QMD was observed.

There was a significant species × treatment interaction for stand stocking ($P = 0.002$), mean height ($P = 0.035$), and QMD ($P < 0.001$) at the CR site. The VM treatment increased the mean height and QMD of all species at this site. Douglas-fir was the tallest species followed by western hemlock, grand fir, and western redcedar, respectively. The stocking of VM treated western hemlock was greater than in C plots while the stocking of grand fir was not affected.

3.2. Leaf area index

There was a significant species × treatment interaction for LAI ($P < 0.001$) and site did not have a significant effect ($P = 0.345$) (Fig. 1). The LAI of VM treated plots was higher than C plots for all species at both sites. LAI of VM treated western hemlock was greater than the other species and the LAI of C western redcedar was the lowest of all species. Within each treatment, there were no differences in LAI between Douglas-fir and western redcedar growing at CR and CF sites ($P > 0.46$).

3.3. Biomass stock

Similar to stem volume and LAI, using the equations in Gonzalez-Benecke et al. (2018) and plot inventory data measured at age 16 on both sites, aboveground stand biomass was calculated for each plot (Fig. 2). The estimates of each component of stand-level crop tree biomass (fine roots, foliage, branch, stem, and bark) are provided in Table 5 and ANOVA results for each crop tree biomass component are provided in Tables 3 and 4. Stand level crop tree biomass was significantly different across crop species ($P < 0.001$) and affected by VM treatments ($P < 0.001$) at both sites and site was not a significant factor ($P = 0.192$) for Douglas-fir and western redcedar. At the CR site, there was a significant species × treatment interaction ($P = 0.0005$). Stand-level tree biomass was greatly increased under sustained VM treatments ($P < 0.001$) and the magnitude of this response differed by species. At the CR site, average biomass gain was 26.5, 91.2, 44.7, and 96.1 Mg ha^{-1} for Douglas-fir, western hemlock, western redcedar, and grand fir, respectively. At the CF site, the average biomass gain was 48.1 Mg ha^{-1} for Douglas-fir and 42.2 Mg ha^{-1} for western redcedar. Differences in stand-level biomass allocation among the species were observed. Western redcedar allocated more biomass to foliage and live branches than the other species ($P < 0.003$) which allocated more biomass to stemwood and bark. Fine roots biomass differed between species ($P = 0.002$) and VM treatment ($P < 0.001$). It ranged between 1.9 Mg ha^{-1} for Douglas-fir in C plots at the CF site, to 9.2 Mg ha^{-1} for western hemlock in VM plots at the CR site. Differences in biomass allocation were not observed between sites for Douglas-fir and western redcedar.

When the biomass of the midstory, understory, forest floor and thinning residues were taken into account, the pattern of treatment responses were different than if only the crop trees were considered (Fig. 3, Table 6). There was a significant species × treatment interaction of total ecosystem biomass ($P = 0.002$). Total ecosystem biomass, which includes the biomass of crop trees, midstory, understory, forest floor and thinning residues, was higher in VM treated plots for Douglas-fir at both sites ($P < 0.003$) and western redcedar ($P = 0.016$) at the CF site. The increase in total ecosystem biomass in VM treated plots was 32.5, 56.9 and 34.3 Mg ha^{-1} for Douglas-fir at the CR site, Douglas-fir at the CF site, and western redcedar at the CF site, respectively. There were no significant effects of treatment on the total ecosystem biomass of western hemlock, wester redcedar, and grand fir at the CR site ($P > 0.129$) despite large differences in crop tree biomass. At the CR site, the lack of differences between treatments for these species was largely due to an abundant hardwood midstory developing in control plots.

There was a significant site × species × treatment interaction for understory biomass ($P = 0.026$). The understory biomass of VM treated Douglas-fir was minimal at both sites ranging from 0.2 Mg ha^{-1} at the

Table 3
Results of ANOVA test for Douglas-fir and western redcedar (species) growing under contrasting treatments of vegetation management (Treatment) on sites located in the central Coast Range and the Cascade foothills (Site) of western Oregon. (1) Stand characteristics: stand trees per hectare (TPHA), mean height, quadratic mean diameter (QMD), basal area (BA) and leaf area index (LAI), (2) Biomass pool of crop trees (fine roots, foliage, branch, stemwood and bark), midstory, understory, forest floor and entire ecosystem, and (3) Soil characteristics: bulk density, percent organic matter, and organic matter content (upper 25 cm).

Stand Characteristics	Site	Species	Treatment	Site × Species	Site × Treatment	Species × Treatment	Site × Species × Treatment
TPHA	0.2084	0.0345	0.0012	0.2996	0.0018	0.002	0.0022
Height	0.0892	< 0.0001	< 0.0001	0.0017	0.0608	0.035	< 0.0001
QMD	0.0038	< 0.0001	< 0.0001	0.9105	< 0.0001	0.0006	< 0.0001
BA	0.2889	< 0.0001	< 0.0001	0.5037	0.39	0.0038	0.0631
LAI	0.345	< 0.0001	< 0.0001	0.6291	0.4179	0.0005	0.1132
Biomass Pool	**Site**	**Species**	**Treatment**	**Site × Species**	**Site × Treatment**	**Species × Treatment**	**Site × Species × Treatment**
Tree	0.1919	< 0.0001	< 0.0001	0.384	0.1378	0.3196	0.0698
Fine Roots	0.4392	0.001	0.0012	0.9062	0.088	0.0409	0.1787
Foliage	0.4029	0.0005	< 0.0001	0.7266	0.5216	< 0.0001	0.1502
Branch	0.4029	0.0005	< 0.0001	0.7266	0.5216	< 0.0001	0.1502
Stemwood	0.1314	< 0.0001	< 0.0001	0.2199	0.0879	0.1857	0.0178
Bark	0.1008	< 0.0001	< 0.0001	0.2943	0.384	0.881	0.0081
Midstory	0.0166	0.0047	0.0036	0.0124	0.0169	0.0048	0.0126
Understory	0.8545	0.0067	0.0025	0.1909	0.1286	0.4641	0.0256
Forest Floor	0.9951	< 0.0001	0.1293	0.4176	0.1365	0.1845	0.5907
Ecosystem	0.0026	< 0.0001	0.0004	0.2105	0.0013	0.002	0.1099
Soil Characteristics	**Site**	**Species**	**Treatment**	**Site × Species**	**Site × Treatment**	**Species × Treatment**	**Site × Species × Treatment**
Bulk Density	0.721	0.7243	0.0876	0.0495	0.788	0.589	0.4614
OM%	0.2646	0.7187	0.1237	0.1779	0.1552	0.2291	0.4247
OMC	0.1551	0.4613	0.9781	0.9852	0.3182	0.4862	0.8611

OM%: Soil organic Matter percent; OMC" Soil organic matter content.

CF site to 0.4 Mg ha^{-1} at the CR site. The understory biomass of C Douglas-fir was great at the CR site than the CF site (3.5 vs 2.7 Mg ha^{-1}). The opposite was true for western redcedar and understory biomass of C plots for this species ranged from 7.5 Mg ha^{-1} to 5.5 Mg ha^{-1} at the CF and CR sites, respectively. At the CR site, understory biomass of control plots was greater than VM treated plots for all species. Forest floor biomass did not differ between treatments for any species at either site but was significantly affected by crop tree species ($P < 0.0001$, Table 3). Douglas-fir had the largest amount of biomass in forest floor averaging 16.4 Mg ha^{-1}, followed by grand fir

Table 4
Results of ANOVA test for Douglas-fir, western hemlock, western redcedar and grand fir (Species) growing under contrasting treatments of vegetation management (Treatment) on sites located in the central Coast Range (CR) and the Cascade foothills (CF) of western Oregon. (1) Stand characteristics: stand trees per hectare (TPHA), mean height, quadratic mean diameter (QMD), basal area (BA) and leaf area index (LAI), (2) Biomass pool of crop trees (fine roots, foliage, branch, stemwood and bark), midstory, understory, forest floor and entire ecosystem, and (3) Soil characteristics: bulk density, percent organic matter, and organic matter content (upper 25 cm).

CR Site				CF Site			
Stand Characteristics	**Species**	**Treatment**	**Species × Treatment**	**Stand Characteristics**	**Species**	**Treatment**	**Species × Treatment**
TPHA	< 0.0001	0.3303	0.9574	TPHA	0.4820	0.0023	0.0030
Height	< 0.0001	< 0.0001	0.0095	Height	< 0.0001	< 0.0001	0.0016
QMD	< 0.0001	< 0.0001	0.0002	QMD	< 0.0001	< 0.0001	< 0.0001
BA	< 0.0001	< 0.0001	0.0004	BA	0.0007	< 0.0001	0.2882
LAI	< 0.0001	< 0.0001	0.0004	LAI	0.0019	< 0.0001	0.0740
Biomass Pool	**Species**	**Treatment**	**Species × Treatment**	**Biomass Pool**	**Species**	**Treatment**	**Species × Treatment**
Tree	< 0.0001	< 0.0001	0.0005	Tree	< 0.0001	< 0.0001	0.4486
Fine Roots	0.1294	0.0243	0.0745	Fine Roots	0.0137	0.0006	0.0051
Foliage	0.0073	< 0.0001	0.0005	Foliage	0.0363	< 0.0001	0.0265
Branch	0.0073	< 0.0001	0.0005	Branch	0.0363	< 0.0001	0.0265
Stemwood	< 0.0001	< 0.0001	< 0.0001	Stemwood	< 0.0001	< 0.0001	0.0104
Bark	< 0.0001	< 0.0001	0.0003	Bark	< 0.0001	< 0.0001	0.0306
Midstory	0.1135	0.0019	0.1146	Midstory	0.1674	0.0452	0.1674
Understory	0.1234	0.0234	0.0578	Understory	0.0014	0.0008	0.1721
Forest Floor	0.0019	0.8342	0.5976	Forest Floor	0.0008	0.0197	0.4913
Ecosystem	0.0488	0.0242	0.0134	Ecosystem	< 0.0001	0.0001	0.0770
Soil Characteristics	**Species**	**Treatment**	**Species × Treatment**	**Soil Characteristics**	**Species**	**Treatment**	**Species × Treatment**
Bulk Density	0.1604	0.192	0.6592	Bulk Density	0.3185	0.3391	0.8948
OM%	0.8906	0.2124	0.6012	OM%	0.149	0.8916	0.6695
OMC	0.8959	0.4887	0.8200	OMC	0.5911	0.4983	0.5680

OM%: Soil organic Matter percent; OMC" Soil organic matter content.
At the CR site: 4 species (Douglas-fir, western hemlock, western redcedar and grand fir).
At the CF site: 2 species (Douglas-fir and western redcedar).

Table 5
Average trees per ha (TPHA, ha^{-1}), mean height (height, m), quadratic mean diameter (QMD, cm), and basal area (BA, $m^2\ ha^{-1}$), for 16-year-old Douglas-fir, western hemlock, western redcedar, and grand fir trees growing under contrasting treatments of vegetation management on sites located in the central Coast Range (CR) and the Cascade foothills (CF) of western Oregon. C: no post-planting vegetation control, VM: sustained vegetation control for first 5 years post planting.

Site	Species	Treatment	TPHA (ha^{-1})	Height (m)	QMD (cm)	BA ($m^2\ ha^{-1}$)
CR	Douglas-fir	C	688	14.0	18.5	18.4
		VM	703	15.1	20.7	23.6
	Western hemlock	C	860	10.8	14.2	13.7
		VM	1025	14.1	20.2	33.0
	Western redcedar	C	778	4.7	8.6	4.7
		VM	967	8.3	15.4	17.9
	Grand fir	C	927	8.7	12.3	11.1
		VM	997	12.1	20.1	31.8
CF	Douglas-fir	C	696	12.8	16.5	14.8
		VM	710	15.2	20.8	24.2
	Western redcedar	C	351	7.4	13.8	5.2
		VM	935	8.6	15.1	16.8

(9.9 $Mg\ ha^{-1}$), western hemlock (8.1 $Mg\ ha^{-1}$) and western redcedar (7.1 $Mg\ ha^{-1}$).

The average stemwood density of living Douglas-fir was 411 and 471 $kg\ m^3$, at the CR and CF sites, respectively while the average density of stemwood thinning residues at the time of sampling was 316 and 350 $kg\ m^3$, at the CR and CF sites, respectively (Gonzalez-Benecke et al., 2018). There was no difference in wood density of thinning residues between sites ($P = 0.35$) and, on average, wood density of thinning residues was 23% lower than the density of standing stemwood ($P = 0.02$). When the time since cut was taken into account, the average decay rate for stemwood was 6.3% per year. The bark of thinning residues was not accounted for. We used the average density of stemwood thinning residues to estimate thinning residues biomass shown in Fig. 3 and Table 6. The biomass of thinning residues was higher in VM treated Douglas-fir plots at both the CR (10.6 vs 16.6 $Mg\ ha^{-1}$, $P = 0.011$) and CF sites (4.9 vs 11.2 $Mg\ ha^{-1}$, $P = 0.021$). The average biomass of thinning residues was also higher at the CR site than the CF site ($P = 0.018$).

The models and parameter estimates used to estimate biomass for all midstory species are shown in Appendix A. There was a significant site × species × treatment interaction for midstory biomass ($P = 0.0126$, Table 3), indicating that the amount of midstory biomass differed on Douglas-fir and western redcedar plots in response to VM treatments across sites. The midstory represented a large component of total ecosystem biomass in the C plots of western hemlock, western redcedar, and grand fir at the CR site (Fig. 4). Bitter cherry was the most abundant midstory species with an average biomass ranging between 26 and 41 $Mg\ ha^{-1}$ (Fig. 4). The diversity of midstory species was highest in the western redcedar plots. Negligible midstory biomass was observed in the Douglas-fir plots as all midstory trees were removed at the time of thinning. At the CF site, midstory biomass was a minor component of total ecosystem biomass, even in unthinned western redcedar plots.

3.4. Soil bulk density and organic matter content

There was a trend of increased soil bulk density, decreased organic matter concentration, and decreased organic matter content of top soil on VM treated plots, however, these differences were not significant between treatments and sites (Table 7). There was a marginally significant site × species interaction for soil bulk density ($P = 0.049$, Table 3), a response maybe associated to varying amounts of vegetation (understory and midstory) root biomass on Douglas-fir or western redcedar plots in response to VM treatments across sites. Average soil bulk density ranged between 0.64 $g\ cm^{-3}$ (C plots, western redcedar) and 0.76 $g\ cm^{-3}$ (VM plots, Douglas-fir). The average soil organic matter concentration (OM%) ranged between 16.7% (VM plots, western redcedar, CF site) and 22.2% (C plots, western redcedar, CR site), and the soil organic matter content (OMC) ranged between 246 and 282 $Mg\ ha^{-1}$ in C plots at the CR and CF sites, respectively (Table 7).

4. Discussion

This study represents one of the few attempts to quantify how VM treatments impact the long-term ecosystem biomass accumulation of conifer plantations in the PNW. The results demonstrate that sustained vegetation management during the first five years of stand establishment direct site resources to crop trees and indicates that the benefits of VM persist long after the treatments are applied. The biomass stock of crop trees was greater in plots with sustained vegetation control for all tested species and sites. The results from this study demonstrate the remarkable productivity of artificially regenerated stands growing without interspecific competition.

Mean total and component tree biomass was found to be significantly different between species, but no differences were observed between sites for Douglas-fir and western redcedar stands. At the CR site, VM treated western hemlock and grand fir had larger crop tree biomass than Douglas-fir and wester redcedar. The lower tree biomass

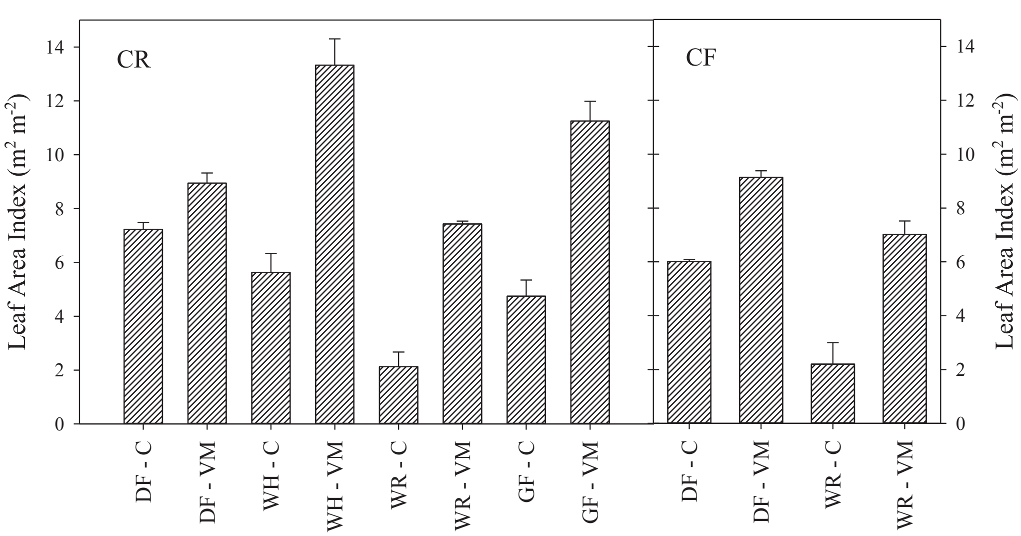

Fig. 1. Projected leaf area index (LAI, $m^2\ m^{-2}$) for 16-year-old Douglas-fir (DF), western hemlock (WH), western redcedar (WR), and grand fir (GF) stands growing under contrasting treatments of vegetation control on sites located in the Coast Range (CR, left panel) and in the Cascade foothills (CF, right panel). C: no post-planting vegetation control, VM: sustained vegetation control for first 5 years post planting. Error bars represents standard error.

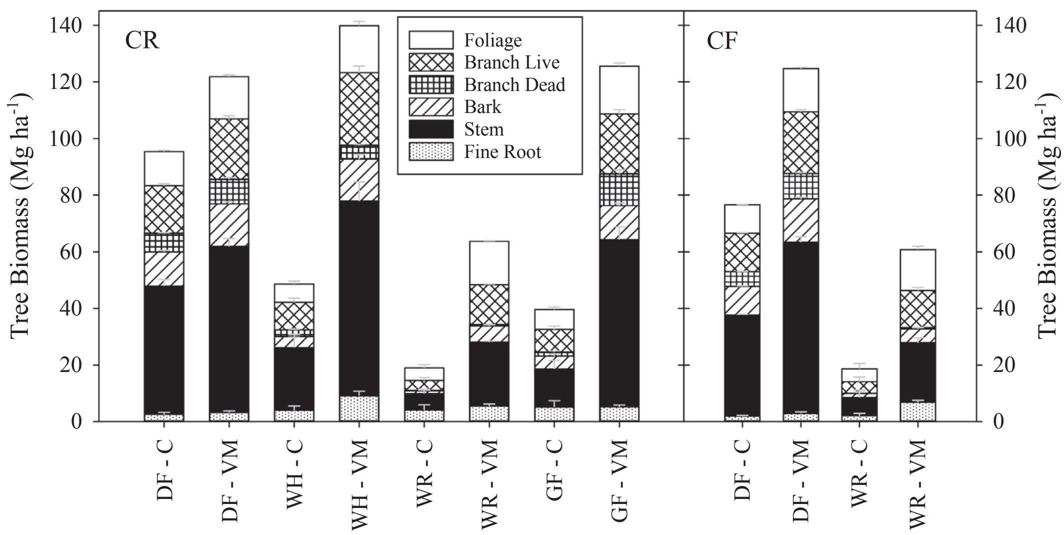

Fig. 2. Biomass stock (Mg ha^{-1}) of tree components for 16-year-old Douglas-fir (DF), western hemlock (WH), western redcedar (WR), and grand fir (GF) stands growing under contrasting treatments of vegetation control on sites located in the Coast Range (CR, left panel) and in the Cascade foothills (CF, right panel). C: no post-planting vegetation control, VM: sustained vegetation control for first 5 years post planting. Error bars represents standard error.

observed for VM treated Douglas-fir compared to these species is assumed to be due to a pre-commercial thinning at age 12 reducing stand stocking. Despite this, the tree biomass of VM treated Douglas-fir was still higher than the unthinned VM western redcedar plots at both sites. A significant interaction in total tree biomass among species and treatments was also observed at the CR site, suggesting that some species were more susceptible to competition than others at that site. Douglas-fir appears to be the most tolerant species and western redcedar appears to be the most sensitive species to competition.

The midstory accounted for a large fraction of above ground ecosystem biomass for western hemlock, western redcedar, and grand fir plots that did not receive post planting vegetation control at the CR site. We expect that the midstory of control Douglas-fir would have been a factor had it not been cut in the pre-commercial thinning. The midstory of control western redcedar plots at the CR site accounted for 68% of total ecosystem biomass. Mortality of western redcedar crop trees was high in these plots allowing competing species, particularly bitter cherry, to occupy the site. The understory was not as big of a factor as the midstory in these plots. Turner and Long (1975) reported that understory biomass ranged between 1.1 and 7.6 Mg ha^{-1}, for stands with basal areas ranging between 32 and 57 m^2 ha^{-1}. In our study, understory biomass ranged between 1.8 and 3.6 Mg ha^{-1} for stands with BA ranging between 4.2 and 33.1 m^2 ha^{-1}.

When understory, midstory, and forest floor were accounted for, no differences in total ecosystem aboveground biomass were found between VM and C plots of western hemlock, western redcedar, and grand fir at the CR site largely due to the development of a robust midstory. In C plots, crop tree biomass accounted for about 75, 47, 19, and 43% of total ecosystem aboveground biomass, for Douglas-fir, western hemlock, western redcedar, and grand fir stands, respectively. Turner and Long (1975) reported a value of 82% for 22-year-old Douglas-fir stands. VM treatments increased the total ecosystem biomass of Douglas-fir at both sites and western redcedar at the CF site. The CF site had a less abundant hardwood midstory in control plots and this suggest that the long-term impact of VM treatments on ecosystem biomass may be site specific and depend on the amount of hardwoods that become established in the midstory.

Forest floor biomass accumulation was found to be different across

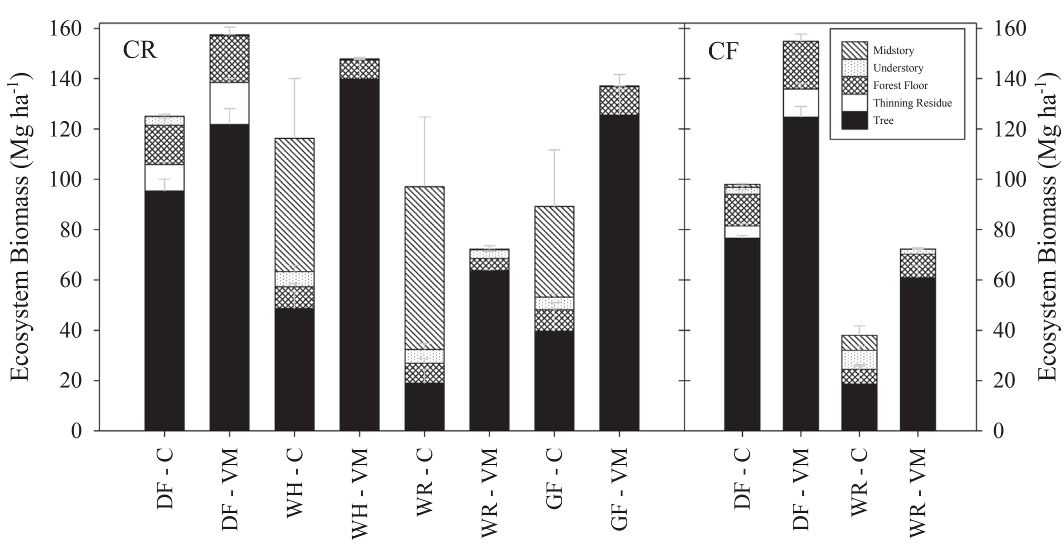

Fig. 3. Average biomass stock (Mg ha^{-1}) of ecosystem components for 16-year-old Douglas-fir (DF), western hemlock (WH), western redcedar (WRC), and grand fir (GF) stands growing under contrasting treatments of vegetation control on sites located in the Coast Range (CR, left panel) and in the Cascade foothills (CF, right panel). C: no post-planting vegetation control, VM: sustained vegetation control for first 5 years post planting. Error bars represents standard error.

Table 6
Biomass stock (Mg ha^{-1}) of tree and ecosystem components for 16-year-old Douglas-fir, western hemlock, western redcedar, and grand fir stands growing under contrasting treatments of vegetation control on sites located in the Coast Range (CR) and in the Cascade foothills (CF). SE is the standard error. The P-value shown, for each site, is in bold if the difference in biomass stock was significant at α = 0.05.

		CR					CF					
Species	Component	C	SE	VM	SE	P-Value	C	SE	VM	SE	P-Value	P-Value*
Douglas-fir	Tree	95.3	4.8	121.8	5.6	**0.006**	76.6	1.1	124.7	4.2	**< 0.0001**	0.478
	Fine Roots	2.6	0.7	3.2	0.6	0.483	1.9	0.3	2.9	0.5	0.074	0.343
	Foliage	12.0	0.5	14.9	0.7	**0.009**	10.0	0.1	15.2	0.5	**< 0.0001**	0.486
	Branch	23.3	0.9	30.0	1.7	**0.007**	18.8	0.4	30.7	1.1	**< 0.0001**	0.497
	Stemwood	45.2	2.3	58.7	2.8	**0.005**	35.7	0.3	60.5	1.9	**< 0.0001**	0.499
	Bark	12.1	0.5	15.0	0.7	**0.009**	10.1	0.1	15.3	0.5	**< 0.0001**	0.485
	Thinning Res	10.6	1.0	16.6	1.7	**0.011**	4.9	1.0	11.2	2.1	**0.021**	**0.018**
	Midstory	0.0	0.0	0.0	0.0	–	1.2	0.3	0.0	0.0	**–**	**–**
	Understory	3.5	0.9	0.4	0.2	**0.007**	2.7	0.8	0.2	0.1	**0.011**	0.587
	Forest Floor	15.5	2.6	18.6	3.5	0.450	12.6	1.8	18.8	2.9	0.083	0.621
	Total	124.9	2.3	157.4	7.5	**0.003**	98.0	1.8	154.9	5.0	**< 0.0001**	0.275
Western hemlock	Tree	48.6	8.6	139.8	11.8	**0.0004**						
	Fine Roots	4.0	1.5	9.2	1.6	**0.035**						
	Foliage	6.5	1.0	16.6	1.5	**0.001**						
	Branch	12.1	1.8	30.5	2.7	**0.001**						
	Stemwood	22.2	3.7	68.7	6.7	**0.0004**						
	Bark	3.9	0.8	14.8	1.7	**0.001**						
	Midstory	52.9	23.8	0.0	0.0	–						
	Understory	6.0	2.5	0.5	0.2	**0.042**						
	Forest Floor	8.7	1.2	7.5	1.1	0.420						
	Total	116.2	22.0	147.8	12.3	0.198						
Western redcedar	Tree	19.0	6.8	63.7	7.7	**0.001**	18.7	7.7	60.8	5.1	**0.002**	0.907
	Fine Roots	4.1	2.3	5.5	0.8	0.759	2.1	0.8	6.8	0.7	**0.002**	0.809
	Foliage	4.4	1.4	15.3	1.9	**0.001**	4.5	1.9	14.5	1.2	**0.002**	0.914
	Branch	3.7	1.3	14.6	1.7	**0.001**	4.2	1.7	13.6	1.1	**0.002**	0.929
	Stemwood	5.8	2.0	22.6	2.7	**0.001**	6.5	2.7	21.0	1.7	**0.002**	0.929
	Bark	1.0	0.4	5.7	0.5	**0.001**	1.4	0.5	4.9	0.4	**0.001**	0.878
	Midstory	64.7	33.8	0.2	0.3	0.102	5.9	3.7	0.0	0.0	–	0.086
	Understory	5.5	3.1	3.5	1.9	0.535	7.5	1.7	2.1	0.4	**0.011**	0.867
	Forest Floor	7.9	2.4	4.9	3.4	0.433	5.9	1.3	9.5	2.1	0.135	0.527
	Total	97.1	24.4	72.3	1.7	0.282	38.0	11.0	72.3	4.6	**0.016**	**0.043**
Grand fir	Tree	38.2	10.3	134.3	10.5	**0.002**						
	Fine Roots	5.1	2.8	5.2	0.8	0.976						
	Foliage	7.0	1.1	16.9	1.4	**0.002**						
	Branch	8.0	3.5	41.2	8.4	**0.011**						
	Stemwood	13.5	3.7	59.1	5.4	**0.001**						
	Bark	4.6	0.8	12.0	1.1	**0.002**						
	Midstory	36.0	27.5	0.0	0.0	–						
	Understory	5.0	1.7	0.3	0.1	**0.027**						
	Forest Floor	8.5	3.4	11.2	6.0	0.662						
	Total	89.2	26.0	137.0	16.4	0.129						

P-Value for treatment differences within sites. P-Value* for site differences.
C: no post-planting vegetation control, VM: sustained vegetation control for first 5 years post planting.

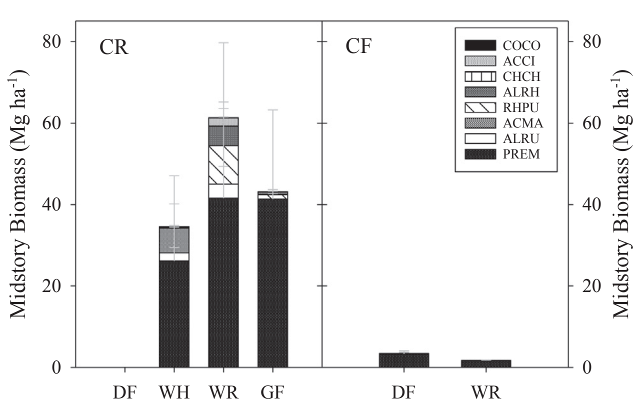

Fig. 4. Average midstory biomass stock (Mg ha^{-1}) for stands of 16-year-old Douglas-fir (DF), western hemlock (WH), western redcedar (WR), and grand fir (GF) growing under no vegetation control after planting (control treatment) on sites located in the Coast Range (CR, left panel) and in the Cascade foothills (CF, right panel). See Table 2 for species code descriptions.

species, accounting for between 5 and 16% of total ecosystem biomass. The largest forest floor biomass accumulation was observed in Douglas-fir stands (between 13 and 19 Mg ha^{-1}) and may be, in part, due to the accumulation of residues from the pre-commercial thinning and pruning carried out in the years of 2011 and 2012. Our observations are in agreement with Turner and Long (1975), who reported a forest floor biomass of 20.5 Mg ha^{-1} for a 22-year-old Douglas-fir stand.

The soil contained the largest amount of biomass. This study only sampled the first 20 cm of soil, but found that vegetation management had no effect on SOM. Johnson (1992) reported that a major disturbance such as clear-cut harvests had minimal impact on SOM. In our study, SOM% ranged between 18 and 22% at the CR site and between 17 and 19% at the CF site. These values were lower than what was reported by Griffiths and Swanson (2001), about 24%, for a 15-year-old Douglas-fir stand in the central Oregon Cascade mountains. There was a trend for SOM to be higher in the control plots suggesting future research on the effects of treatments on SOM at deeper soil profiles may be warranted.

LAI of Douglas-fir was within the range of reported values for young Douglas-fir stands growing in the Oregon Coast Range (Weiskittel and

Table 7
Soil bulk density, organic matter concentration (OM%), and organic matter content (OMC) of 0–20 cm depth of soils for Douglas-fir, western hemlock, western redcedar, and grand fir stands growing under contrasting vegetation control treatments in the Coast Range (CR) and Cascade foothills (CF). SE is the standard error. P-values are shown and there were no significant differences between the treatments at either site using a significance level of α = 0.05.

		CR					CF					
Species		C	SE	VM	SE	P-Value	C	SE	VM	SE	P-Value	P-Value*
Douglas-fir	BD	0.74	0.04	0.76	0.03	0.632	0.66	0.06	0.71	0.05	0.477	0.086
	OM%	19.2	0.02	18.3	0.01	0.684	18.9	0.01	19.2	0.01	0.855	0.795
	OMC	282.3	27.2	276.8	11.0	0.836	246.4	7.18	269.2	9.35	0.067	0.137
Western hemlock	BD	0.67	0.04	0.68	0.02	0.823						
	OM%	19.7	0.01	19.5	0.01	0.862						
	OMC	263.6	6.42	265.9	8.45	0.810						
Western redcedar	BD	0.64	0.05	0.73	0.05	0.168	0.71	0.05	0.75	0.04	0.542	0.255
	OM%	22.2	0.04	17.9	0.01	0.248	17.1	0.01	16.7	0.02	0.793	0.096
	OMC	277.5	28.9	259.5	11.4	0.518	246.3	31.8	248.3	23.3	0.955	0.355
Grand fir	BD	0.69	0.07	0.71	0.05	0.849						
	OM%	19.9	0.04	19.3	0.03	0.858						
	OMC	272.6	27.2	271.4	32.7	0.974						

BD is soil bulk density: g cm^{-3}; OM% is soil organic matter concentration (%); OMC is soil organic matter content (Mg ha^{-1}). C: no post-planting vegetation control, VM: sustained vegetation control for first 5 years post planting. P-Value for treatment differences within sites. P-Value* for site differences.

Maguire, 2007, Velazquez-Martinez et al., 1992). In most cases, LAI was observed to be higher in treated plots. This larger LAI in stands without competing vegetation reflects lower mortality and larger resource availability for surviving trees as LAI has been shown to be positively correlated with nutrient (Velazquez-Martinez et al., 1992) and water availability (Grier and Running, 1977). The higher LAI of treated plots eleven years after treatments had ended reflects the long-term benefit of VM during the early years of stand establishment. LAI of VM treated Douglas-fir and western redcedar did not differ across sites.

5. Conclusions

The results of this study demonstrate that sustained VM treatments during the first 5 years of stand establishment increased the crop tree biomass stock of Douglas-fir, western hemlock, western redcedar, and grand fir stands at age 16. This suggests that VM treatments can accelerate the long-term carbon sequestration rate of planted forests in the PNW. However, in analyzing other ecosystem components, there was no increase in total ecosystem biomass stock for western hemlock, western redcedar, and grand fir stands growing at the CR site at age 16, largely due to the development of a robust hardwood midstory. Even though sustained elimination of competing vegetation had no effect on ecosystem biomass stock for these species at this site, site resources were shifted towards crop trees, producing larger trees with higher commercial value. Total ecosystem biomass of Douglas-fir at both sites and western redcedar at the CF site was higher in VM treated plots than the control due to a large increase in crop tree biomass and minimal hardwood midstory. Western redcedar had the lowest biomass stock of all tested species and was also the most sensitive to interspecific competition. These results provide managers with options for VM, depending on management objectives and site conditions.

Acknowledgements

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Appendix A. Parameter and fit statistics of the models to estimate aboveground biomass of hardwood species.

Species	Component	Model	a	b	R^2	Source
ACCI	Total AG	$= a + b \cdot \ln(DBH)$	−2.047	2.3852	0.84	Chojnacky et al. (2014)
ACMA	Total AG	$= a + b \cdot \ln(DBH)$	−2.047	2.3852	0.84	Chojnacky et al. (2014)
ALRH	Total AG	$= a + b \cdot \ln(DBH)$	−2.5932	2.5349	0.81	Chojnacky et al. (2014)
ALRU	Total AG	$= a + b \cdot \ln(DBH)$	−2.5932	2.5349	0.81	Chojnacky et al. (2014)
CHCH	SW	$= a \cdot DBH^b$	0.024	2.658	0.98	Ter-Mikaelian and Korzukhin (1997)
	SB	$= a \cdot DBH^b$	0.0026	2.989	0.97	
	FL	$= a \cdot DBH^b$	0.0401	1.6930	0.81	
	BR	$= a \cdot DBH^b$	0.0092	2.5760	0.89	
COCO	Total AG	$= a \cdot DBH^b$	54.1	1.229	–	Ohmann et al. (1976)
PREM	Total AG	$= a + b \cdot \ln(DBH)$	−2.2118	2.4133	0.79	Chojnacky et al. (2014)
RHPU	FL	$= a \cdot DBH^b$	0.000003	6.788099	0.96	This study
	SW + BR	$= a \cdot DBH^b$	0.174466	2.161457	0.99	

Species code in Table 2. Total AG is aboveground biomass; SW is stemwood biomass; SB is bark biomass; FL is foliage biomass; BR is branch biomass; DBH is diameter at breast height (1.37 m). R^2 is coefficient of determination.

Appendix B. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.foreco.2018.09.033.

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