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Research Article

Variable-density Retention Promotes Spatial Heterogeneity and Structural Complexity in a Douglas-fir/Tanoak Stand

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Abstract

After harvesting the merchantable conifers decades ago, many secondary forests in northern California regenerated naturally and are now fully stocked with low value hardwoods intermingled with conifers. Partial harvesting to reduce hardwood densities and release conifers is expected to enhance tree vigor and reduce risk of stand-replacing wildfire. Planting a new cohort of merchantable conifers in the understory would enhance structural complexity and future value. A flexible new forest restoration treatment called variable-density retention (VDR) was designed to achieve these objectives. Desirable trees can be kept regardless of their location while the new cohort of conifers is planted among existing trees or in gaps created by removal of patches of undesirable trees. At our study site in northern California, 20×20 m (0.04 ha) squares each received one of five treatments (gap, low-/medium-/high-density retention, and no cut). This created a mosaic of different densities. Planted conifer seedlings exhibited variable growth rates. Different stand variables were associated with growth of seedlings of the native coast Douglas-fir (*Pseudotsuga menziesii* var.*menziesii*) versus coast redwood (*Sequoia sempervirens*) planted outside its natural range. We found no correlation between point counts of overstory basal area and either leaf area index or understory light at each seedling. The VDR system promoted heterogeneity in the spatial pattern of tree locations, restored conifer dominance, and enhanced structural complexity by introducing a new cohort of trees growing at different rates.

Keywords: Forest Restoration; *Notholithocarpus densiflorus*; *Pseudotsuga menziesii*; Redwood; *Sequoia sempervirens*; Variable-Density Thinning; Variable Retention

Introduction

Fully stocked secondary forests dominated by low-value hardwoods are common throughout northern California. Many of these forests were left to regenerate naturally after the merchantable conifers were removed decades ago [1]. Hardwoods such as tanoak (*Notholithocarpus densiflorus*) were sometimes left standing, or they re-sprouted quickly after broadcast burning or from cut stumps, giving them a competitive advantage over coast Douglas-fir (*Pseudotsuga menziesii* var.*menziesii*) seedlings [2,3].Therefore many secondary forests throughout the region have a lower proportion of commercial conifer stocking and more hardwood than the typical primary forest where conifers dominated above a hardwood subcanopy [4]. There is interest in restoring conifer dominance for socioeconomic reasons [5], and because stands dominated by large conifers mirror a pre-settlement condition and are expected to be more resistant to wildfire; an important disturbance agent in the western US [6,7]. There are several approaches to restoration of conifer dominance. Thinning is an intermediate treatment that can preferentially remove hardwoods to release residual conifers. Clearcutting offers an alternate solution by efficiently removing the hardwood-dominated stand which is then replanted with conifers. Enhancing resilience by creating heterogeneous and structurally complex conifer-dominated multiaged stands is another popular management objective among private and public land managers [8,9]. Managers seeking to transform stands to multiaged management can implement selection methods, shelter wood with reserves, or variable retention silvicultural systems [10].

Variable-density thinning (VDT) is an intermediate treatment that enhances complexity within stands by varying the spatial patterns of retention at small scales [11]. One approach is to treat small patches differently, such that some patches are skipped (no treatment) while others are thinned to different densities or completely cut to create gaps throughout the stand. This creates a mosaic of different densities and gaps throughout the stand, enhancing variability in tree growth rates [12-14]. Thinning response can be short-lived in areas of lighter thinning [15]. VDT on the north coast of California shifted species composition in favor of redwood (*Sequoia sempervirens*), however the enhanced residual tree growth encouraged bears to damage redwood and Douglas-fir [16-18]. Harrington et al. [12] reported an enhancement in cover and diversity of understory plants after VDT. Kuehne and Puettmann [19] noted that while understory vegetation cover was more variable after VDT, it was lower overall than after clearcutting. Ares et al. [20] reported greater cover of understory plants after VDT than more uniform thinning treatments. Investigators have also noted varying densities and patterns of natural tree seedling regeneration and understory vegetation after VDT [21].

Variable retention (VR) is a silvicultural system with dual objectives of regenerating a new cohort of trees and retaining chosen residual trees in either aggregated or dispersed spatial arrangements [22,23]. In contrast to VDT which creates small-scale spatial variations in density, stands undergoing VR typically have large areas with similar levels of retention (i.e, residual stand density or stocking). Combinations of aggregated and dispersed VR may be prescribed throughout the same stand. For example, uncut aggregates retained to protect sensitive areas can be surrounded by areas of dispersed retention created by partial harvesting. Similarly, VR can be implemented to mimic a mixed-severity fire regime by removing smaller trees in some areas and creating open areas between patches of trees [24]. The pattern and level of retention affects growth of planted seedlings [25-29]. Higher retention leaves less growing space available for the new cohort [30,31].

We designed and tested a new silvicultural system, variable-density retention (VDR), a variant of VR that incorporates key elements of VDT. The objectives of management were to enhance productivity by restoring conifer dominance in a mixed hardwood-conifer stand dominated by tanoak, and enhance structural complexity in the stand by establishing a new cohort of commercial conifers. Given the spatial variations in hardwood and conifer stocking characteristic of this Douglas-fir/tanoak forest type, we sought to test partial harvesting to varying densities in small contiguous patches. We deliberately liberated enough growing space for a new cohort of conifers to become established in harvested patches, with different levels of retention enhancing variability and allowing for study of understory responses. This paper introduces the study design and presents early results of analyses of planted seedling growth throughout the study area. We hypothesized that early growth of Douglas-fir and redwood seedlings would be greater in areas of lower residual stand density in the vicinity of each seedling, lower canopy cover or leaf area index, higher understory light, concave microsite topography, greater soil moisture, and less competition from understory vegetation and re-sprouting hardwood stumps.

Materials and Methods

Study Area

The L.W. Schatz Demonstration Tree Farm (N 40° 46’ 30.306’’, W 123° 51’ 58.036’’) is 14 km southeast of Korbel, California in Humboldt County, north coastal California. Elevation is 160 meters above sea level and average annual rainfall is 1450 mm. Precipitation is uncommon during the hot and dry summer and autumn months in this Mediterranean climate. The property is located outside the Pacific coast’s fog belt and the natural range of coast redwood. Soils derived from colluvium and residuum from sandstone and mudstone make up the Moon creek-Tossup-Noisy complex. These soils are well-drained gravelly clay loams, very gravelly loam, or loams that form on mountain slopes, and have an average depth of 2 m [32].

The study area faces north and was once dominated by Douglas-fir. After the primary forest was removed around 1960, a dense second-growth conifer-hardwood forest regenerated and re-occupied the site. The conifers on site were mostly Douglas-fir and some grand fir (*Abies grandis*), and the hardwoods were mostly tanoak and California bay (*Umbellularia californica*), with an occasional Pacific madrone (*Arbutus menziesii*). The understory was dominated by western sword fern (*Polystichum munitum*), redwood sorrel (*Oxalis oregana*), and evergreen huckleberry (*Vaccinium ovatum*). Poison oak (*Toxicodendron diversilobum*) vines encircled and climbed many trees. Other plants present included salmonberry (*Rubus spectabilis*), salal (*Gaultheria shallon*), western walnut (*Corylu scornuta* var.*californica*), blue blossom (*Ceanothus thyrsiflorus*), red huckleberry (*Vaccinium parvifolium*), gooseberry (*Ribes uva-crispa*), and California blackberry (*Rubus ursinus*).

The 6,000 m^2 (0.6 ha) study area was divided into three rectangular blocks oriented east-west: the upslope block, mid-slope block, and lower-slope block. Each block was further divided into five contiguous 20×20 m (0.04 ha) square “patches”. Within each block, one of five treatments was assigned randomly to each patch: gap, low-/medium-/high-density retention, and no cut treatment. Gaps were created by cutting 100% of trees in a patch. Conifers were favored over hardwoods for retention in partial harvest treatment patches. Target stand density index (SDI) for the residual stand in each partially-harvested patch was 225, 450, and 675 metric SDI for the low-, medium-, and high-density patches, respectively. These levels of retention are equivalent to 15, 30, and 45% of the upper limit for Douglas-fir SDI (metric SDI 1500); [33]. The no-cut "control" patches had inherent variations in density (1000, 1050, and 1600 SDI) and composition (comprising 58, 67, and 90% conifer in terms of SDI). Therefore, a total of 15 square "patches" created a mosaic of gaps and patches of different densities across the study site (Figure 1).

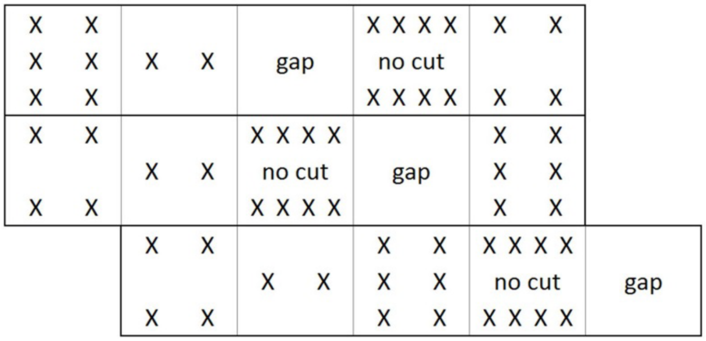

Figure 1: Schematic representation of variable-density retention study area showing five treatments (gap, low-/medium-/high-density retention, no cut) randomly assigned within each rectangular block, for a total of 15 treatment squares (20×20 m; 0.04 ha).

In autumn 2014, the trees marked for cutting in each patch were felled, limbed, bucked, and removed for use as firewood. Hardwood limbs and tops and some of the larger conifer logs (one or two per block) were left on site as down wood (coarse woody debris). One-year-old styro-15 containerized Douglas-fir and redwood seedlings from a local nursery were hand planted in early spring 2015 with individuals planted approximately 3 m apart. The goal was to plant 35 seedlings in each of the 12 patches where harvesting had occurred. Tree planters were allowed to deviate from the prescribed spacing to choose the best available microsites and avoid hardwood stumps where possible.

Field Data

Seedlings were mapped and measured for height at the time of planting, and re-measured two and three years after planting. Basal stem diameter (caliper) was measured three years after planting, near ground level above any swelling. Instances of animal browse damage to the leader were recorded at each measurement.

Three years after planting, at the end of the dry summer season before any winter rains (October 2017), the relative water content (RWC) of soil was measured adjacent to each seedling. Two readings were taken within a 20 cm radius of each seedling at a depth of approximately 20 cm, and then averaged. RWC was measured using a Field Scout TDR 300 meter equipped with 20.23 cm probes. The meter was calibrated to measure RWC using the Field Scout software and a silt loam sample from the study site as the standard, where field capacity and permanent wilting points were 35 and 18% volumetric water content, respectively.

Microsite topography in a 1 m radius from each seedling was categorized on a scale of 0-4 as follows: slope concavity was assessed across the slope (along the contour) and again downslope, with each direction scoring zero for convex, one for flat slope, and two for concave slope. The two concavity scores were summed for each seedling. For example, terrain that was convex in both directions scored a zero, while a score of four was assigned to areas that were concave across and down the slope.

Vicinity basal area (BA) was estimated by tallying all trees >10 cm dbh within the critical radius of a 9.18 m^2 ha^{-1} basal area factor variable radius plot centered on the seedling being measured for size and growth. Re-sprouting hardwood competition was assessed by counting the number of re-sprouting stumps within 2.5 m radius of each planted seedling. Within 1 m^2 quadrats centered on each seedling we assessed percent cover of all understory vegetation (including ferns) and also assessed percent fern cover separately. Ferns were common and have a different growth habit (small root system, erect foliage) that we hypothesized may compete differently with planted seedlings than other types of understory vegetation.

Hemispherical images were taken immediately above each seedling on cloudy days. Images were processed using Gap Light Analyzer 2.0 software [34], assuming cloudiness index of 0.75, and growing season dates April 1st to September 30th, and using a topo mask developed using clinometer data giving inclination to the horizon at intervals of 10 degrees azimuth. Hemispherical image analysis gave an estimate of canopy openness (%), light transmitted to the understory (percent above canopy light; PACL, %), and 4-ring leaf area index (LAI) above each planted seedling.

Analysis

Seedlings with inexplicably poor needle retention and growth, or seedlings that had sustained major damage were excluded from analyses of growth. We transformed data to reduce skewness in data distributions. We used PROC REG in SAS software [35] to obtain coefficients and fit statistics for bivariate regressions among stand and site variables (density, canopy, light, vegetation, soil moisture) and multiple linear regressions of seedling growth. We used PROC GLM to test for influence of categorical variables: seedling species (Douglas-fir/redwood), presence/absence of ferns (yes/no) and re-sprouting hardwoods (yes/no). AIC was used for model selection [36].

Results

Stand Density, Canopy Cover and The Understory

The VDR harvest created heterogeneous canopy and understory light conditions. Canopy openness ranged from 20-43% and averaged 30% above planted seedlings (Table 1). Most of these seedlings were planted in areas of lower density outside the uncut patches. Therefore, our hemispherical image data do not represent areas where the canopy remained closed. Similarly, the summary data for BA, LAI, and understory light represent conditions experienced by planted seedlings, not conditions in uncut patches or across the entire site. Ferns made up over half of the understory vegetation cover surrounding each seedling. Basal area in the vicinity of each planted seedling varied widely (Table 1). At each seedling, there was almost no correlation between overstory BA and understory light (R^2=0.00), canopy cover (R^2=0.00), or LAI (R^2=0.01). Soil moisture was lowest in areas of high LAI with numerous re-sprouting hardwoods in the vicinity (R^2=0.11). In bivariate regressions predicting soil moisture, overstory BA or LAI were better predictors (R^2=0.08) than number of re-sprouting hardwoods in the vicinity (R^2=0.03). Understory light was not a useful predictor of soil moisture adjacent to each planted seedling (R^2=0.00).

Variable	Mean	s.d.	Min.	Max.
Basal area ($m^2 ha^{-1}$)	22.03	16.47	0	110.16
Canopy openness (%)	30.02	4.1	20.56	43.07
Leaf area index (LAI; 4-ring)	1.28	0.24	0.75	1.9
Percent above canopy light (PACL; %)	40.61	6.73	19.84	54.24
Relative water content of soil (%)	61.01	15.06	16	95
Number of hardwood stumps within 2.5 m	1.49	1.42	0	7
Understory vegetation cover (%)	30.29	27.82	0	100
Fern cover (%)	16.86	23.61	0	100

Table 1: Summary data for stand density, canopy cover, understory light, soil moisture, and vegetation in vicinity of each conifer seedling planted at variable-density retention site (n=243).

Performance of Planted Seedlings

Three years after planting, the Douglas-fir and redwood seedlings exhibited a wide range of sizes and growth (Table 2). The tallest seedling of each species had already surpassed breast height (1.37 m) in three years, double the average height for seedlings of each species. On average, Douglas-fir seedlings were not significantly larger in caliper (p=0.20) but were significantly taller than redwood (p<0.0001) after three years on site. Conversely, third-year height increment was significantly greater for redwood (p<0.0001). This indicated that redwood seedlings took longer to become established, but then quickly began catching up to the Douglas-fir seedlings. Approximately 12% of Douglas-fir and 13% of redwood seedlings exhibited signs of leader damage from browsing.

Variable	Species	n	Mean	s.d.	Min.	Max.
Seedling caliper (mm)	Douglas-fir	96	7.36	2.62	3.98	23.26
	Redwood	116	7.14	3.1	2.65	19.05
Seedling height (cm)	Douglas-fir	90	73.29	21.85	28	150
	Redwood	107	61.41	24.92	23	159
Seedling height increment (cm yr^{-1})	Douglas-fir	93	13.88	10.5	0	50
	Redwood	113	23.2	15.83	0	88

Table 2: Summary data for seedlings planted at the variable-density retention site: stem basal diameter (caliper) and height after three growing seasons, and height increment over third growing season.

The largest diameter seedlings had basal stem diameter (caliper) of approximately three times the average size (Table 2). Caliper of planted Douglas-fir seedlings was impacted more by overstory BA than the number of re-sprouting hardwoods or soil moisture. Redwood seedling caliper was lower in areas of higher LAI, and to a lesser extent lower in the presence of more re-sprouting hardwoods (Table 3).

After three growing seasons on site, Douglas-fir seedlings (showing no evidence of browsing) were taller in areas with lower overstory BA. In addition to the impact of overstory BA, re-sprouting hardwoods were having a modest impact on Douglas-fir height development. Canopy or understory light variables obtained from hemispherical photography did not correlate with Douglas-fir seedling heights. Redwood seedlings were taller in areas with more canopy openness and fewer re-sprouting hardwood stumps (Figure 2). Leaf area index was also a useful predictor of redwood seedling height, alone or in combination with number of re-sprouting hardwoods. Overstory BA was impacting redwood seedling height development, but was not as influential as LAI, canopy openness, or the number of re-sprouting hardwood stumps in the vicinity of redwood seedlings (Table 3).

Model	**R^2**	**$R^2_{adj.}$**	**AIC**	**ΔAIC**
Douglas-fir (n=96)				
LnCal=2.1367-0.06728Ln(BA+1)	**0.037**	**0.027**	**-227.33**	**-**
LnCal=2.2879-0.07368Ln(BA+1)-0.00200RWC	0.048	0.028	-226.39	0.93
LnCal=2.1675-0.06472Ln(BA+1)-0.05042Ln(HW+1)	0.044	0.023	-225.97	1.35
LnCal=1.9960-0.06897Ln(HW+1)	0.013	0.002	-224.91	2.41
LnCal=2.0348-0.00132RWC	0.005	-0.006	-224.13	3.19
Redwood (n=116)				
LnCal=2.7220-0.9259Ln(LAI+1)-0.1031Ln(HW+1)	0.082	0.065	-218.76	-
LnCal=2.5345-0.7998Ln(LAI+1)	**0.065**	**0.057**	**-218.7**	**0.06**
LnCal=1.9715-0.1151Ln(HW+1)	0.023	0.015	-213.61	5.15
Douglas-fir (n=90)				
$H^{0.5}=10.2917-0.5427Ln(BA+1)-0.3009Ln(HW+1)$	0.183	0.165	21.78	-
$H^{0.5}=10.0263-0.5408Ln(BA+1)$	**0.163**	**0.154**	**21.99**	**0.21**
$H^{0.5}=8.8321-0.4437Ln(HW+1)$	0.04	0.029	34.35	12.36
Redwood (n=107)				
$H^{0.5}=5.6028+0.08506CnpyOpen-0.6307Ln(HW+1)$	**0.107**	**0.09**	**82.26**	**-**
$H^{0.5}=10.8708-3.4105Ln(LAI+1)-0.5487Ln(HW+1)$	0.103	0.086	82.71	0.45
$H^{0.5}=10.9328-3.9589Ln(LAI+1)$	0.066	0.057	85.05	2.78
$H^{0.5}=8.9365-0.2764Ln(BA+1)-0.6615Ln(HW+1)$	0.098	0.081	86.09	3.83
$H^{0.5}=4.9701+0.09113CnpyOpen$	0.057	0.048	86.11	3.85
$H^{0.5}=8.1824-0.6769Ln(HW+1)$	0.057	0.048	89	6.74
$H^{0.5}=8.4395-0.2691Ln(BA+1)$	0.043	0.035	90.57	8.3
Douglas-fir (n=93)				
$(\Delta H+1)^{0.5}=5.1539-0.3487(BA+1)^{0.5}$	**0.142**	**0.133**	**51.23**	**-**
$(\Delta H+1)^{0.5}=5.2244-0.3270(BA+1)^{0.5}-0.2105Ln(HW+1)$	0.149	0.13	52.51	1.28
$(\Delta H+1)^{0.5}=3.9406-0.4580Ln(HW+1)$	0.034	0.024	62.25	11.01
Redwood (n=113)				
$(\Delta H+1)^{0.5}=6.0184-0.2104(BA+1)^{0.5}-0.5656Ln(HW+1)$	**0.096**	**0.08**	**105.97**	**-**
$(\Delta H+1)^{0.5}=5.5846-0.2090(BA+1)^{0.5}$	0.063	0.055	108.08	2.11
$(\Delta H+1)^{0.5}=5.1191-0.6281Ln(HW+1)$	0.042	0.033	110.62	4.65

Table 3: Candidate models for planted seedling caliper (Cal; mm) and height (H; cm) after three years, and height increment (ΔH; cm yr^{-1}) over third growing season, at variable-density retention site as a function of vicinity basal area (BA; m^2 ha^{-1}), leaf area index (LAI), canopy openness (%), soil moisture (relative water content; RWC), and number of re-sprouting hardwood stumps (HW) within 2.5 m radius of seedlings. Best model shown in bold.

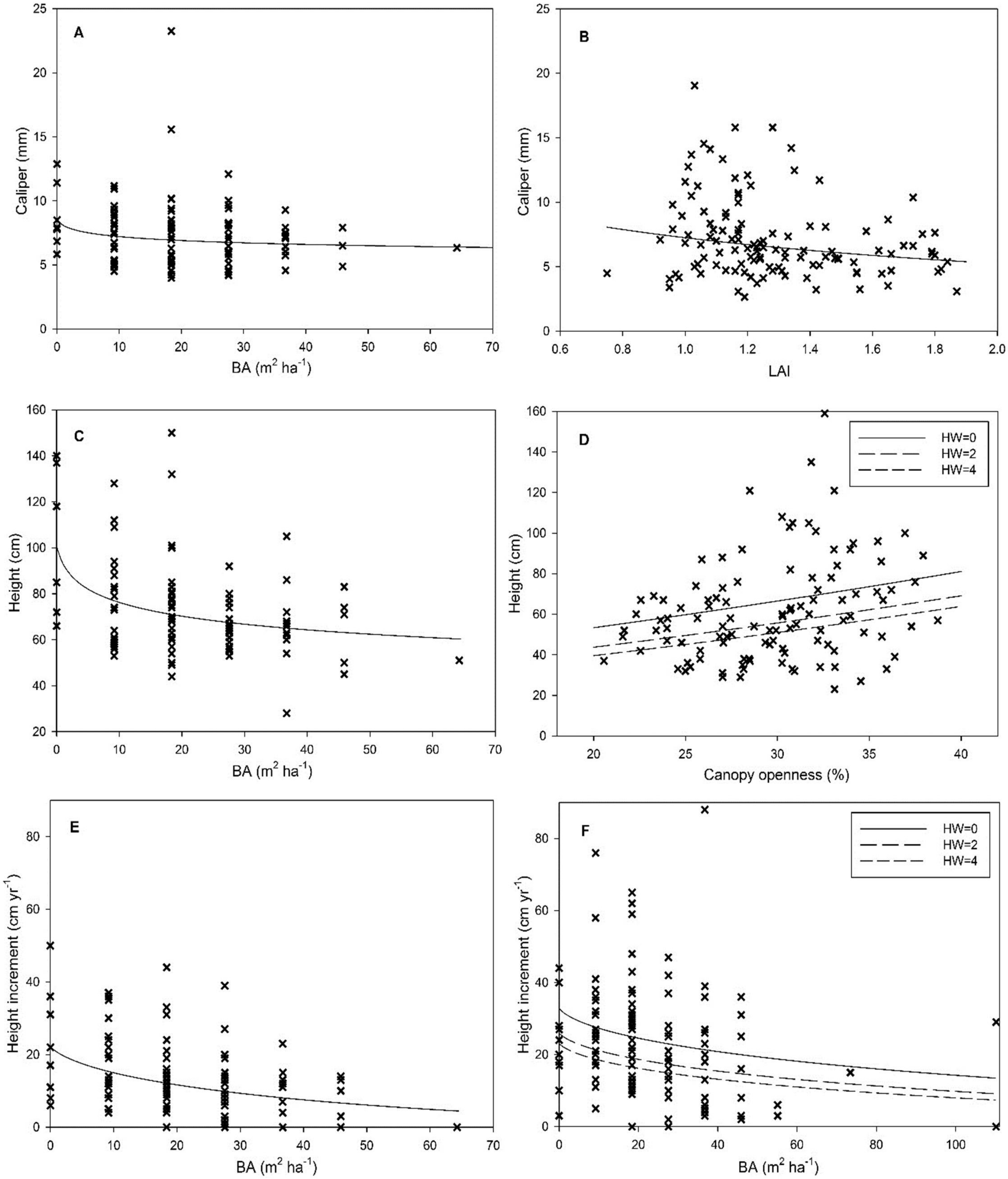

Figure 2: Data and models for third-year stem basal diameter (caliper), height, and height increment of planted Douglas-fir (A, C, E) and redwood (B, D, F) seedlings in variable-density retention study area, as function of best predictor variables: basal area (BA), leaf area index (LAI), canopy openness (%), and number of re-sprouting hardwood stumps (HW) within 2.5 m of planted seedlings.

Analysis of recent height growth (i.e., height increment over the third growing season) indicated that overstory BA in the vicinity was having the greatest negative impact on seedling height growth. Re-sprouting hardwoods were impacting the height growth of redwood seedlings more than Douglas-fir seedlings (Table 3; Figure 2). We did not detect any effects of understory vegetation cover or understory light on seedling performance.

Discussion

By combining the regeneration and retention objectives of VR with enhancements in spatial heterogeneity associated with VDT, the new VDR system is well suited to meeting multiple objectives in a variety of stand structures on all types and sizes of ownership. The system allows landowners to reserve a multitude of forest patches or corridors, while benefiting from the flexibility to cut heavily in other patches followed by planting of desired species to replace species that are less desirable or over-represented. With different levels and patterns of retention, many trees can be felled towards openings. Therefore, the VDR system should have low residual stand damage and allow for more efficient harvesting operations concentrated in gaps and areas where lower densities are retained.

At our study site, conifer dominance was achieved in the low-, medium-, and high-density retention patches by preferential removal of hardwoods. The partial harvest liberated growing space and allowed for seedling growth and development of understory vegetation, consistent with early results from VDT studies in the Pacific Northwest [12]. An average of 10 hardwood stumps (range 6-16) re-sprouted vigorously in each 20×20 m square treatment patch. We expected that proximity to hardwood stumps with established root systems would correlate with reduced growth of planted conifer seedlings, as was the case with a similar species mixture further north [37,38]. However, the analysis revealed that overstory tree variables, in particular vicinity BA, had a greater influence on young conifer seedling growth than understory variables. Our models showed improved seedling performance below 20 m^2 ha^{-1} BA which is consistent with Lam and Maguire [28] who reported adequate performance of planted Douglas-fir over a longer period (13 years) when retention did not exceed 18 m^2 ha^{-1} BA.

The absence of correlation with understory light suggested that belowground competition as opposed to above-ground competition was limiting seedling growth at this study site. Additionally, the absence of correlation between understory light and stand density in the vicinity (variable radius plot) indicated that patchiness in forest structure at the scale of 20×20 m (400 m^2 patches) had led to spatial decoupling of above- and belowground competition (i.e., competition for light and water). This could lead to unexpected differences in performance among understory trees and plants and unusual spatial patterns of species dominance depending on whether above- and/or belowground resources were limiting or plentiful. To improve our understanding of the effects of VDR on the new cohort, we recommend trenching to isolate effects of above- and belowground competition [39,40].

Redwood seedlings kept pace with Douglas-fir seedlings planted at this hot dry location beyond the current eastern inland extent of coast redwood. Any silvicultural system that supports the expansion of redwood's range further inland has value to landowners and the regional economy. Redwood lumber typically commands higher prices than Douglas-fir lumber, and has different markets and uses. Redwood is also known to be relatively free from forest health problems and its heartwood resists decay [41]. Therefore, planting this mixture of merchantable species represents a potential value enhancement, product diversification, and risk mitigation strategy for landowners.

The risk of bear damage to fast-growing conifers throughout the region is another problem that may be mitigated by VDR. Bears feed on the inner bark of Douglas-fir and redwood [42,43]. After VDR harvesting, some of the planted seedlings may continue to grow slowly and be less attractive to bears [18,44], and the patchy spatial distribution may be a disincentive to bears that tend to damage more accessible trees [45]. Bear damage impacts the economics of timber production, but some bear damage may benefit restoration by creating large basal cavities which have been noted as reference conditions characteristic of old-growth forests in the region [46].

Variable-density retention shows promise as a flexible tool for restoration of hardwood-dominated stands. In our study, we cut hardwoods and they re-sprouted. Competition from re-sprouting hardwoods may increase over time as the fast-growing sprout clumps outsize planted seedlings. In future, we recommend experimentation with manual and herbicide control of re-sprouting hardwood stumps with the objective of enhancing planted seedling development [47]. An economical option for hardwood control is herbicide stem injection where the cull trees are left standing to break down gradually while planted seedlings replace them and residual conifer trees benefit from the reduction in competition [48] and expand their crowns into openings [49].

The rapid height growth of redwood seedlings in year three may reflect an inherent difference between Douglas-fir and redwood establishment patterns, or it could be related to the wetter years (2016, 2017) that came after a multiyear drought (through 2015). Establishing additional replicates in different years at the same site is planned, allowing for future studies of climate-growth relations and examination of the changes in resilience through density reductions [50] and enhanced heterogeneity and complexity [8]. We must also replicate the study at different locations, preferably in stands of different ages and stands located on different aspects and soil types where soil moisture may be more or less limiting [27]. Early results indicated that VDR had already met our goal of restoring conifer dominance by preferential retention of conifers over hardwoods while also regenerating a new cohort of conifers. The VDR system instantly enhanced structural complexity and spatial heterogeneity of tree locations by creating canopy gaps and patches of different densities where seedlings were planted. Three years after harvest, understory vegetation cover was variable, consistent with other studies [19], and did not have a detectable effect on planted seedling performance. Re-sprouting hardwoods impacted growth of redwood seedlings more than Douglas-fir seedlings. We expect differences in seedling growth and residual tree growth rates to persist over time [13,15,27] leading to further enhancement of variation in tree and crown sizes throughout the restored stand. Therefore, VDR appears to be an effective option for any owner or manager interested in concomitantly enhancing forest productivity and structural complexity.

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