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Thinning Intensity and Ease-of-Access Increase Probability of Bear Damage in a Young Coast Redwood Forest

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Abstract

Precommercial thinning is an integral part of coast redwood (*Sequoia sempervirens* (D Don) Endl.) forest management but is often followed by bear damage in northern parts of redwood's natural range. We counted incidences of black bear (*Ursus americanus* Pallas) damage along transects oriented perpendicular to forest roads in thinned and unthinned stands. Damage decreased slightly at greater distances from roads, suggesting that bears were traveling along forest roads and damaging nearby trees that were easier to access. Frequency of damage was higher among larger trees in these conifer-dominated mixed even-aged stands. Redwood was more likely to be damaged than coast Douglas-fir (*Pseudotsuga menziesii var. menziesii* (Mirb.) Franco). Precommercial thinning (PCT) incited damage to redwood, and PCT to lower residual densities incited more damage in Douglas-fir. Unthinned control stands were least damaged. Increment cores collected from pairs of damaged and undamaged redwood trees confirmed that damage occurred after thinning and revealed that – at the time of bear damage – trees sustaining damage had been growing faster than undamaged trees of similar size. Our findings support mitigation strategies such as lighter thinning, leaving higher densities of redwood in anticipation of higher damage rates, and leaving unthinned buffers adjacent to roads and other paths traveled by bears.

Keywords

Black bear; Even-aged management; Logistic mixed-effects regression; Precommercial thinning; *Ursus americanus*

Introduction

Forest thinning is an integral part of forest management for timber production and for old-growth restoration in north coastal California. The evergreen mixed conifer forests near the coast are dominated by coast redwood (*Sequoia sempervirens* (D Don) Endl.), coast Douglas-fir (*Pseudotsuga menziesii var. menziesii* (Mirb.) Franco), and tanoak (*Notholithocarpus densiflorus* (Hook and Arn) Manos et al.). After even-aged harvesting in these productive coastal forests, abundant natural regeneration of conifer and hardwood develops quickly and becomes crowded. Thinning relieves crowding and improves tree growth and vigor and can be used to favor merchantable or desired species and alter spatial patterns of tree locations [1-3].

Rapid growth of merchantable conifers supports management of these forests for timber production and carbon sequestration [4,5]. Coast redwood is highly sought after for its attractive decay-resistant heartwood. Douglas-fir is common in these forests and is valued for structural lumber. A variety of even-aged and uneven-aged silvicultural practices are applied on different ownerships [6,7]. A history of clearcutting throughout the region has left millions of acres of redwood forests in an even-aged condition. Industrial owners will usually thin crowded young stands, regardless of whether the long-term goal is even-aged management or transformation to multiaged management.

For public land agencies in California, restoration of old-growth redwood forest characteristics has become a management priority across vast acreages of younger forests within park boundaries and new land acquisitions. Characteristics of old-growth forest structure have been well documented [2,8-11]. Common features of old-growth forest structure include basal stem cavities, stems with forks and multiple leaders, large snags, and tall widely-spaced overstory trees (i.e., 48-61 stems ha^{-1} on hillslopes [2]; 45-74 stems ha^{-1} on alluvial flats [10]). These features, however, take decades or centuries to develop naturally. Contemporary restoration efforts include reducing stand density to accelerate tree-size development [12,13]. This is accomplished through thinning to direct the development of young stands towards old-growth forest structures [2,3].

One drawback of thinning operations is the manifestation of black bears (*Ursus americanus* Pallas) damaging conifers. This has been well documented throughout many parts of California, Oregon and Washington, particularly for Douglas-fir forests [14-17]. Seasonal food availability typically determines black bear diets, and a higher rate of conifer damage tends to occur in early spring when plants that make up the bears' regular food sources are beginning to grow but are still limited [18]. Black bears feed on the sugar-rich phloem of conifers by stripping off large pieces of bark and scraping the sugar-rich vascular tissue with their incisors [14,19]. The bears damage all or part of a stem's circumference. Damage is often concentrated within the first few meters above ground, but can extend to great heights on some trees where bears have climbed and stripped the bark along the length of the stem. Radial growth ceases in those exposed areas. Kimball et al. [20] found that total sugar concentrations were higher in low-density stands, and that foraging bears were attracted to changes in terpene and enhanced sugar concentrations in thinned stands.

Black bears have become more abundant throughout the northern parts of the redwood region. Emanuel Fritz [21] observed bear damage among regenerating redwood stump sprouts up to 75 cm dbh, with damage extending from ground line up the stem as far as bears would climb (i.e., up to stem diameters of approx. 10 cm). Damage to redwood typically occurs in spring and is widespread in the northern part of redwood range [21-23]. Industrial timberland managers have also noticed an increase in bear damage following pre-commercial thinning (PCT). This led many to abandon this silvicultural technique [3]. Bear damage is frequently noted and thought to be concentrated along logging roads, skid trails, or other openings in the forest [22]. Like humans, wildlife often utilizes forest roads to more efficiently travel across the landscape. In particular, roadways allow large animals to move freely along the forest edge rather than expending energy to

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maneuver through trees, shrubs and slash. It follows that bears might strip trees near the forest edge more frequently due to ease of access. To our knowledge the relationship between stand access and bear damage has not been proven and quantified. It has also been observed that one of two trees in close proximity and of similar size may be damaged while the other remains untouched. This suggests there might be differences other than tree size, such as recent growth rate or thickness of the phloem at breast height at the time damage occurred.

We studied bear damage in thinned and unthinned coast redwood stands, seeking to identify factors correlated with incidences of damage. Our goal was to better understand relationships between bear damage, management, and stand characteristics. We hypothesized that probability of bear damage to conifers - after accounting for expected differences between tree species and silvicultural treatment - was related to ease of access in terms of distance from road. We also hypothesized that recent growth rate (annual ring width) was positively correlated with probability of a tree sustaining bear damage.

Methods

Study area

Our study was conducted at Mill Creek in Del Norte Coast Redwoods State Park, approximately 6 km south of Crescent City, in Del Norte County, California. Prior to its acquisition by California State Parks (CSP) in 2002, the 10,000 ha Mill Creek property had been managed for timber production for >100 years. Even-aged management was practiced throughout the 1970s, 80s, and 90s resulting in a mosaic of young regenerating stands [24]. At the time of study, the majority of stands within the Mill Creek Watershed were less than 30 years old, dominated by second- or third-growth coast redwood and Douglas-fir. Naturally-regenerating hardwoods included tanoak, red alder (*Alnus rubrus* Bong.) and Pacific madrone (*Arbutus menziesii* Pursh), and a minor component of other conifers, such as Sitka spruce (*Picea sitchensis* (Bong.) Carr.) and grand fir (*Abies grandis* (Dougl. ex D. Don) Lindl.) were occasionally found. Rapid tree growth in this fertile, productive watershed with mild climate caused these young stands with >1,250 stems ha^{-1} to quickly become crowded [3]. Crescent City and the surrounding area experience a humid Mediterranean climate with cool, rainy winters and moderately warm summers. December is the coldest month with an average high and low temperature of 11°C and 5°C, respectively. The warmest month is August with an average high and low of 16°C and 11°C, respectively. Summer temperatures higher than 19°C and winter temperatures lower than 0°C are rare (www.weatherspark.com) because of a strong coastal influence that moderates seasonal and diurnal temperature fluctuation. Nearly 1700 mm of precipitation falls annually, almost entirely as rain, with the majority occurring in the winter months (www.weather.com).

In 2003, CSP began actively managing within the Mill Creek Watershed for old-forest structures by designating areas of highest priority and testing a variety of silvicultural treatments within those areas. For each high-priority stand, a thinning treatment was randomly assigned, creating a mosaic of stands with different treatments spread across the property (L. Leonard, pers. comm.). Treatment designations were based on the number of trees remaining per hectare after thinning and consisted of a low-density thin (LDT), high-density thin (HDT), or control in which no thinning was done. Target residual tree spacing were 6.4 m × 6.4 m after LDT and 4.9 m × 4.9 m after HDT, giving stand densities of 185-270 stems ha^{-1} after LDT and 370-420 stems ha^{-1} after HDT. A range of tree spacing and densities resulted because prescriptions called for retention of redwood stems in sprout clumps [5]. We randomly selected three stands that had received each treatment type for sampling.

Sample stands within the Mill Creek Watershed were all located within a maximum of 10 km of each other and ranged from 2.8 ha up to almost 70 ha in size (Table 1). A range of site conditions were sampled. The stands named Childs Hill were located on relatively flat ground with occasional small streams running the length of the stand. Stands NEE-N, NEE-E, and NEF were located on slopes which fell or rose directly from the roads, while SEX, SEW, and SETS were located on still steeper slopes. The elevations of sample stands ranged from 92 m to 670 m above sea level. The Control stands had closed canopies and very little understory vegetation. LDT and HDT stands had a deep layer of slash. Generally, slash consisted of felled whole trees and smaller branches laid down in subsequent layers and forming discontinuous platforms suspended 0.6 m to 2.1 m above the ground. In riparian zones, on steeper hillsides, and in some clearings, lower slash heights were observed.

Transect sampling

In order to evaluate the relationship between distance from the road and bear damage, we established transects perpendicular to the road prism extending 120 m into each stand (Figure 1). The first transect began at the vegetation edge where the rocked road transitioned to grass and/or shrubs. We collected data along the transect over a distance of 20 m within a buffer extending 3.66 m on either side of the transect line which created a 0.147 ha rectangular sample 'section'. We recorded distance from road as the section's midpoint distance along each transect.

While following a transect line, we recorded four variables for each tree >10 cm dbh: 1) species, 2) diameter at breast height (dbh), 3) presence/absence of bear damage, and 4) section number. Since hardwoods were rare within our stands, we focused sampling primarily on conifers—although hardwood presence was noted. Instances of bear damage, which are easily recognized and distinctive, were recorded when the removal of bark by bears had exposed sapwood and resulted in visible damage to the vascular tissue.

After the first transect was completed, we moved to the next transect line located 20 m away and sampled along this parallel transect line back to the road. We repeated this process based on the length of the sample stand adjacent to the road. A minimum of two transects were completed within each stand, with most stands being able to accommodate at least four transects.

We sought to identify factors associated with bear damage by constructing generalized logistic mixed-effects regressions predicting probability of bear damage (yes/no, binary response variable) as a

Table 1: Sample stand area and number of transects per stand.

Stand name	Treatment	Stand area (ha)	No. of transects
Childs Hill Low	Low Density Thin	2.8	6
SEX	Low Density Thin	14.4	4
NEE-N	Low Density Thin	34.1	6
SETS	High Density Thin	29.1	4
Childs Hill High	High Density Thin	6.1	2
NEF	High Density Thin	69.2	8
NEE-E	Control	11.4	4
Childs Hill Control	Control	4.2	4
SEW	Control	8.5	4

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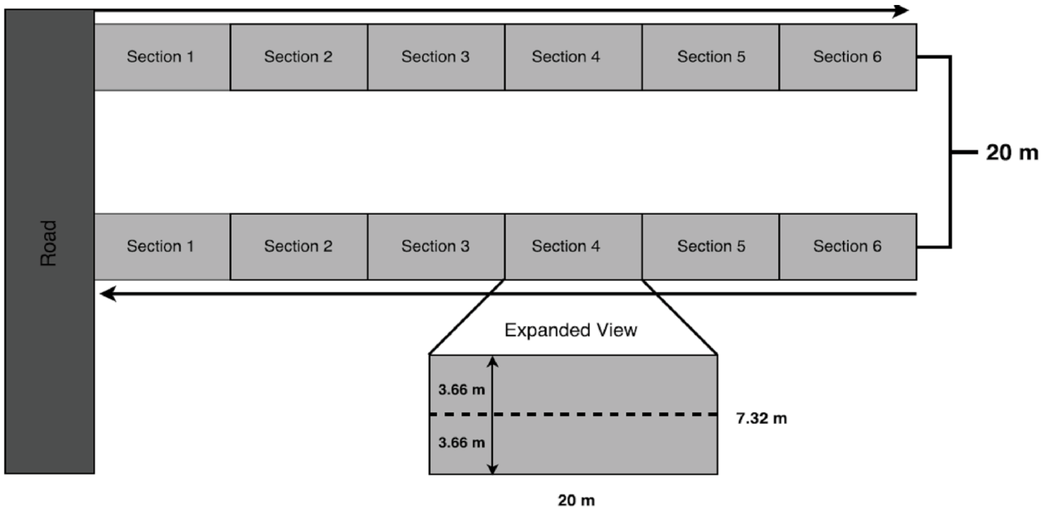

Figure 1: Schematic diagram depicting sampling design within each stand, with 0.0147-ha sample sections (20 m × 7.32 m) placed contiguously along transects of 120 m total length separated by 20 m.

function of candidate explanatory variables: tree species (Douglas-fir, redwood), tree size (dbh), thinning treatment (LDT, HDT, or Control), and distance from road, and their interactions. We included a random effect for the class variable 'transect', which accounted for the nesting of, transects within each stand. We transformed data by taking the square-root or natural logarithm when this corrected curvature in residuals and improved model fit. We fitted models using PROC GLIMMIX in SAS [25]. Model selection was based on Akaike's Information Criterion AIC; [26] after ensuring that residuals from candidate models did not show deviations from normality when plotting residuals against fitted values and covariates. We also compared BIC, which penalizes model complexity more heavily, among candidate models. We created graphs of bear damage rates (proportion of trees damaged) according to treatment, tree species, and dbh size class, and graphed logistic model predictions depicting modeled relationships between predictor variables and probability of bear damage using Sigma Plot 12.0 (Systat Software Inc.).

Increment core sampling

We sampled pairs of damaged and undamaged redwood trees with the goal of comparing their growth in the years prior to bear damage. We collected breast height increment cores in eight sample stands: three controls, three LDTs, and two HDT stands. In each stand, core samples were taken from three damaged trees and three undamaged neighboring trees of similar diameter and height. In order to ensure damaged tree and neighboring tree experienced similar site and stand conditions, we arbitrarily restricted our selection of the neighboring tree to trees of similar size located <3.66 m away from the damaged tree. The damaged trees were cored twice, once through the damaged portion (where the damage had exposed sapwood and caused radial growth to cease) and a second time on the back side of the tree where no damage occurred and radial growth continued. The neighboring tree was cored only once. Data collected for each tree were dbh, total height, and live crown ratio.

At the lab, all core samples were dried at 40°C for 24 hours then glued to medium density fiber board. The samples were then sanded down sequentially starting with coarse sandpaper and ending with an extra fine 1600 grit. The samples were scanned and imported into WinDENDRO (Regent Instruments Inc.). Thickness measurements were collected for the last (most recent) annual growth ring and the last five years of radial growth immediately preceding the year of damage.

With two cores from each damaged tree, one taken in the damaged portion, and one on the backside where bark was still attached and growth had continued, we were able to cross date the rings in order to determine what year damage occurred. We also used the increment cores to reconstruct approximate dbh at the time of damage, by measuring radial growth since the time of damage and predicting bark thickness (BT) at that time using a bark thickness equation for young redwood:

BT (cm)=(0.183 $dbh^{0.761}$) (J-P. Berrill, unpublished data)

We constructed paired t-tests to assess differences in tree size at the time of damage, crown ratio, and radial growth between damaged and undamaged trees.

Results

Incidence of bear damage along transects

Tree sizes within our sample ranged from a minimum of 10 cm to a maximum of 66 cm dbh, and were similar between sample stands (Table 2). Of 2,434 trees sampled, 378 instances of bear damage were recorded, resulting in 15.5% of trees damaged on average across the entire sample area. Douglas-fir were more numerous (n=1565) than redwood (n=869) in our sample. Bears had damaged 11% of Douglas-fir and 30.7% of redwoods in our sample. In transect sections nearest the road (within 0-20 m from road), 44% of redwood sustained damage from bears. Incidences of damage to redwoods decreased steadily, falling to 35% in the second transect sections (20-40 m from road), and between 21-29% damage in the third, fourth, fifth, and sixth sections (40-120 m from road). Damage to Douglas-fir remained approximately constant along the transects, averaging 11% (range 9-14%).

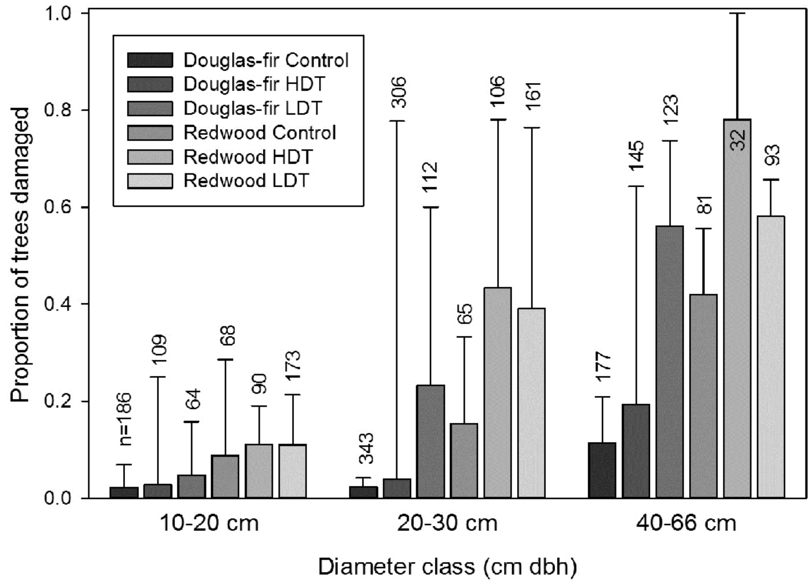

Figure 2: Influence of dbh size class, species, and thinning treatment on proportion of sample trees damaged by bears. Shaded bars depict mean damage for each species and size class in three sample stands receiving each treatment (Control=no thin; HDT=high-density thin; LDT=low-density thin), and error bars depict maximum damage rate (i.e., for that species-size-treatment combination in worst-affected of those three stands). Sample sizes (number of trees) for each species-size-treatment combination sum to 2434 trees sampled in nine stands at Mill Creek, Del Norte County, California, USA.

Table 2: Summary data for tree size in terms of diameter at breast height (dbh; cm), and damage as a percentage of all conifers sampled, according to treatment type (LDT=low-density thin, HDT=high-density thin, Control=no thin).

Variable	Treatment	n trees	Mean	St.dev.	Min.	Max.
Dbh (cm)	LDT	726	23.3	10.5	10.2	66.0
	HDT	788	22.8	7.4	10.2	50.8
	Control	920	23.8	9.3	10.2	66.0
Damage	LDT	726	32.2	46.8	-	-
(% of trees)	HDT	788	15.7	36.4	-	-
	Control	920	8.9	28.5	-	-

On average, damage was more frequent among larger trees (Figure 2). Low density treatments had the highest occurrence of damage overall, including one stand (Childs Hill Low) where 46% of all trees suffered an injury. Incidences of bear damage occurred more frequently in redwood than in Douglas-fir. Medium and large-sized redwood in HDT and LDT stands were damaged in the greatest proportions. Damage to Douglas-fir increased according to thinning intensity and tree size. A greater proportion of redwoods were damaged in thinned stands versus unthinned control stands (Figure 2).

The logistic regression analysis revealed that bear damage incidence varied between treatment type, and according to species composition, tree size (dbh), and, for redwood only, distance from the road (Table 3). Incorporating the predictor variable 'distance-from-road' in a logistic model of bear damage probability improved goodness of fit. The best model also included an interaction between species and distance-from-road, indicating that redwood (and not Douglas-fir) suffered more damage closer to the road (Table 4). This model represented an improvement of 34.5 AIC points and 21.3 BIC points over the next best model. Due to poorer AIC score, we rejected an alternate model with a weak positive interaction between distance-from-road and tree size which indicated that bears focused their damage on larger trees further from roads, but were more inclined to damage any size of tree closer to roads. Modeled relationships between probability of bear damage and tree species, tree size, treatment, and distance-from-road are depicted by way of logistic model predictions (Figure 3).

Table 3 Comparing goodness of fit among bear damage probability models, where p_i= probability of bear damage, TRT=treatment (low-density thin, high-density thin, control), SP=species (Douglas-fir, redwood), DBH=diameter at breast height (cm), and *ln*DIST=the natural log of distance from road (m). Model fitted to data for 2434 trees sampled in nine stands at Mill Creek, Del Norte County, California, USA. Smaller AIC is better.

Candidate models	AIC	ΔAIC
$p_i=1/(1+e\text{-}(\beta_0+\beta_1 TRT+\beta_2 SP+\beta_3 DBH^{0.5}+\beta_4 DBH))$	13478.7	-
$p_i=1/(1+e\text{-}(\beta_0+\beta_1 TRT+\beta_2 SP+\beta_3 DBH^{0.5}+\beta_4 DBH+\beta_5 lnDIST))$	13463.3	-15.4
$p_i=1/(1+e\text{-}(\beta_0+\beta_1 TRT+\beta_2 SP+\beta_3 DBH^{0.5}+\beta_4 DBH+\beta_5 lnDIST+\beta_6 SP \times lnDIST))$	13428.8	-34.5
$p_i=1/(1+e\text{-}(\beta_0+\beta_1 TRT+\beta_2 SP+\beta_3 DBH^{0.5}+\beta_4 DBH+\beta_5 lnDIST+\beta_6 DBH^{0.5} \times lnDIST))$	13621.0	192.3

Radial growth rate and bear damage

Trees selected for increment core sampling ranged from 15.7 cm to 47 cm dbh. On average, the damaged trees were 6.9 cm dbh larger (p=0.001) than undamaged neighbor trees in this paired sample designed to capture pairs of similar-sized trees. Radial growth in the year immediately prior to bear damage was significantly greater (p=0.0009) among damaged trees (5.3 mm yr^{-1}) vis-a-vis undamaged trees (3.1 mm yr^{-1}). Trees that sustained bear damage had been growing rapidly in thinned and unthinned stands (Figure 4). Radial growth over the five years preceding incidence of damage, which may have included some years of growth prior to PCT, was also significantly greater (p=0.0003) among damaged trees (6.8 mm yr^{-1}) vis-a-vis undamaged trees (3.5 mm yr^{-1}). Back-dating core samples

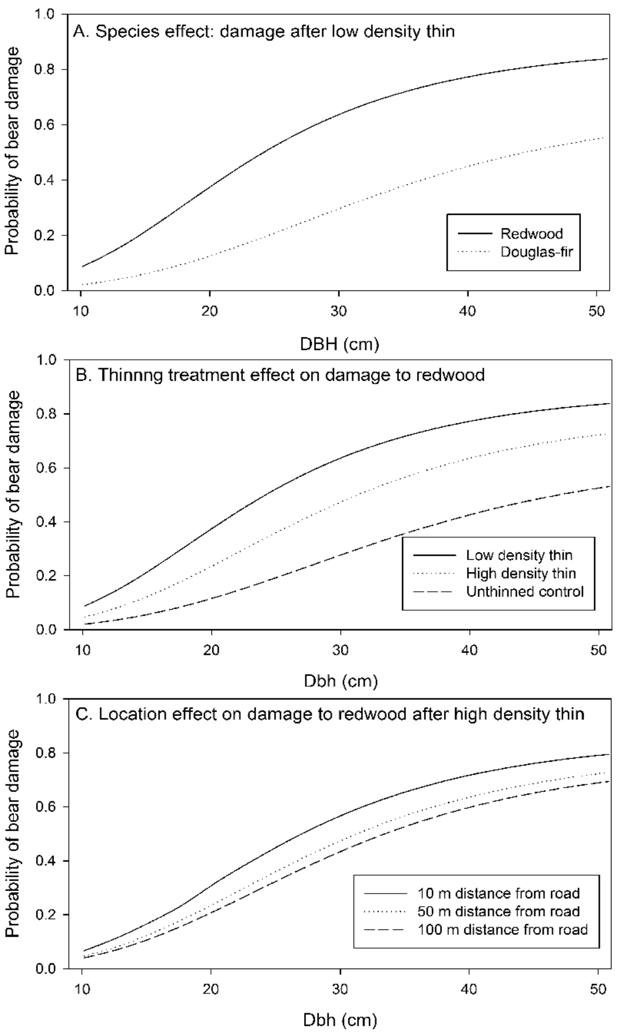

Figure 3: Logistic mixed-effects model predictions of probability of bear damage among (A) redwood and Douglas-fir trees after low-density thinning, and (B) redwood trees according to thinning treatment (Control=no thin; HDT=high-density thin; LDT=low-density thin) assuming 50 m distance-from-road, and (C) among redwood after HDT at different distances from forest road at Mill Creek, Del Norte County, California, USA.

Table 4: Coefficients and fit statistics for generalized logistic mixed-effects model predicting probability of bear damage as a function of treatment type (Control, HDT, LDT), species (Douglas-fir, redwood), diameter at breast height, dbh (cm), and the natural log of distance from road (m). Treatments were: Control (no thin), High-density Thin (HDT), and Low-density Thin (LDT). Model fitted to data for 2434 trees sampled in nine stands at Mill Creek, Del Norte County, California, USA.

Model Term	Treatment	Species	Coefficient	Std. Error	Pr. >|t|
Intercept	-	-	-8.1810	1.449	0.0008
Treatment	Control	-	-1.5208	0.158	<.0001
Treatment	HDT	-	-0.6663	0.143	<.0001
Treatment	LDT	-	0.0000	-	-
Species	-	Douglas-fir	-2.5541	0.594	<.0001
Species	-	Redwood	0.0000	-	-
$Dbh^{0.5}$	-	-	2.6092	0.549	<.0001
Dbh	-	-	-0.1548	0.052	0.0032
ln(Distance)	-	-	-0.2315	0.105	0.0268
Species×*ln*(Distance)	-	Douglas-fir	0.2884	0.150	0.0550
Species×*ln*(Distance)	-	Redwood	0.0000	-	-

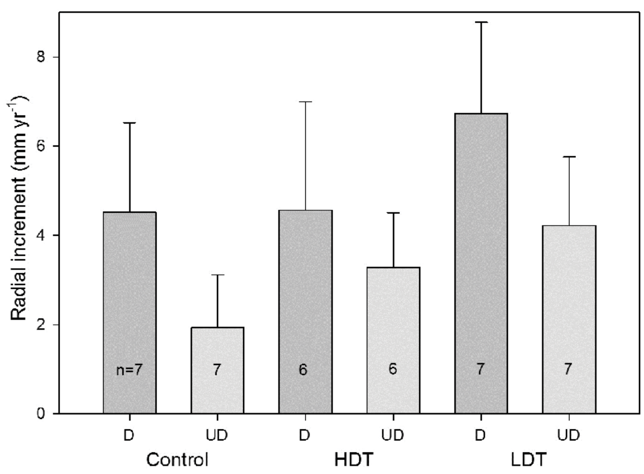

Figure 4: Average radial growth at breast height (1.37m above ground) in year immediately preceding bear damage in paired sample of damaged (D) and undamaged (UD trees in thinned and unthinned stands at Mill Creek. Control=no thin; HDT=high-density thin; LDT=low-density thin. Error bars denote one standard deviation.

to the year bear damage occurred indicated that damage to sample redwoods occurred exclusively after PCT treatments (Table 5).

Discussion

The analysis of transect data supported our hypothesis that probability of bear damage to conifers - after accounting for expected differences between tree species and silvicultural treatment - was related to ease of access in terms of distance from road. The analysis of increment core data supported our second hypothesis that recent radial growth was positively correlated with probability of a tree sustaining bear damage. Similar to findings of O'Hara et al. [3], the unthinned control stands had the lowest amount of damage overall. Control stands were much denser (>1250 stems ha^{-1}) than treated stands. Such crowding negatively affects tree growth [1], possibly making it less enticing for a bear to walk through these dense stands in search of the occasional large, more vigorous tree to feed on. Since PCT favored redwood by preferentially cutting its competitors, the proportion of redwoods was relatively higher in thinned stands (Control 19% redwood, HDT 24%, LDT 50%). On a per hectare basis, redwoods were more numerous in unthinned areas but may have been 'hidden' among other tree species such as Douglas-fir which outnumbered redwood >3× in our sample of dense unthinned control stands.

Bear damage occurred after treatment in thinned stands, which suggested that trees that were not released from competition, and thus had slower growth rates, were not as likely to be damaged. The low density thin had the most damage overall, which may be due to relatively large spacing between trees providing walking space unmatched by the other two treatments. Lower tree densities also enable shrub and understory growth that could impede bear movement but offer forage. The wide openings also open growing space within these stands, allowing for increased rate of growth for remaining trees [1]. Our increment cores indicated that rapid growth

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Table 5: Year of treatment and year of damage to sample redwood trees sustaining bear damage in thinned stands (n=13) at Mill Creek.

Plot Name	Treatment	Year Treated	Year Damaged
Childs Hill Low	LDT	2003	2004, 2009, 2013
NEE-W	LDT	2007	2012, 2013
SEX	LDT	2009	2012, 2013
Childs Hill High	HDT	2003	2011, 2013, 2013
SETS	HDT	2009	2009, 2012, 2013

rate post treatment invited bear damage in redwood. For Douglas-fir, the lighter thinning (HDT) appeared to provide the benefit of releasing trees from competition while limiting damage done by bears in comparison to the low density thin. Thinning more lightly may prevent Douglas-fir trees from reaching some growth threshold that attracts bears. More likely is that bears are attracted to any thinned stand [20] but also consider other factors such as ease-of-access [22] and presence (or high proportions) of redwood.

Tree size (dbh) was a significant predictor of the probability of bear damage among 2434 trees in our transect sample (Table 3). However, our increment core analysis revealed that bears favored fast-growing trees, suggesting that the tree size variable in our probability-of-damage model may be acting as a surrogate for radial growth rate. Therefore, while tree size may be a useful indicator of growth rate in our sample taken from young even-aged stands, the relationship is less likely to hold in thinned stands and multiaged stands. Studying relations between bear damage and tree growth requires model predictions or measurement of growth leading up to the time of injury. We recommend our method of coring twice using the injured and undamaged 'backside' of damaged trees to find year of damage and reveal annual rings giving growth rate leading up to the damage incident.

Our observation from the field was that bear damage appeared to be sporadic and without clear pattern. We therefore recommend further study of interactions between thinning treatment, ease-of-access, and tree variables such as tree size, growth rate, metrics of vigor such as crown ratio and crown position, and the sugar content and thickness of phloem. Bears strip tree bark to access the phloem layer where sugars are stored and transported. The phloem on our core samples was thicker on trees with larger dbh that in turn were more likely to sustain bear damage. Crown ratio (CR) could not be assessed retrospectively at the time of damage, but at the time of sampling CR did not differ (p=0.70) between damaged and undamaged trees (average CR: 46% and 45%, respectively). We frequently saw entire sprout clumps of redwood (of all sizes) sustaining damage, apparently independent of tree size and possibly just because it was convenient to feed on trees that were close together. Entire sprout clumps representing one genotype, or expanded clumps formed by repeated sprouting events after disturbances or cutting [27] may have physical or chemical characteristics attractive to bears [19]. Damage concentrated on any such 'attractive' genotypes or in areas of high basal area productivity [28] could explain variability in damage between stands receiving the same treatment (Figure 2). Ease-of access may explain why the highest damage rate was recorded greatest after heavy thinning (LDT) in the smallest sample stand (Childs Hill Low) with the highest edge-to-interior ratio among sample stands. Changes in bear populations, demographics, and food sources over time may also influence patterns and rates of damage [29,30].

Bear damage on a particular tree can range from small wounds that may heal within years, to wide (and sometimes tall) wound that partially or completely girdle and kill the tree. Mortality or severe damage resulting from bear damage can negate the advantages of low density thinning for timber production or forest restoration objectives if too few stems escape unacceptable damage [3]. Our logistic model supports design of adaptive, experimental silvicultural treatments that take into account probability of bear damage. We expect more redwoods to be damaged than Douglas-fir; therefore, relatively more redwoods could be retained at PCT to meet a target residual density. More redwoods could be retained near roads and areas that bears are known to frequent (e.g., bear trails along ridges, [14]), or PCT treatments could be 'hidden' behind unthinned buffers along roads and trails. In lieu of heavy thinning, more frequent lighter thinning treatments could also be adopted but would be less cost-efficient. Following up later with commercial thinning could expedite removal of badly damaged trees which would reallocate growing space to trees with less damage [16,17]. Future studies should sample stands with trees larger than those in our sample, in hopes of finding an upper size limit or size above which bear damage decreases, or a growth rate threshold below which damage is less likely.

With restoration of old-growth forest structure as a goal, damage to redwoods may be advantageous by promoting decadence and variability [3]. Redwoods that survive bark stripping near the ground may develop goose pens (basal cavities) after fire. Large snags (standing dead trees) are another distinctive feature associated with old-growth forest [11]. Tree mortality resulting from bear damage could also serve as a surrogate for restoration thinning treatments aimed at accelerating tree-size development, and eventually the snags would fall and become coarse woody debris which is abundant throughout old-growth redwood forests [11].

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