EFFECTS OF THINNING ON STAND-STRUCTURE DYNAMICS AND GROWTH IN PURE AND MIXED DOUGLAS-FIR AND WESTERN HEMLOCK STANDS IN COASTAL BRITISH COLUMBIA

by

Grace Carsky

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The following individuals certify that they have read, and recommend to the Faculty of Graduate and Postdoctoral Studies for acceptance, a thesis/dissertation entitled:

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Examining Committee:

Bianca Eskelson, Forest Resources Management
Supervisor

Bruce Larson, Forest Resources Management
Supervisory Committee Member

Ian Cameron, Azura Formetrics Ltd.
Supervisory Committee Member

Suzanne Simard, Forest and Conservation Sciences
Additional Examiner

Additional Supervisory Committee Members:

Supervisory Committee Member

Supervisory Committee Member

Abstract

Thinning treatments are an important management tool, as they help reduce competition and promote tree growth by increasing available resources in a stand (e.g., light, water, etc.). Thinning leads to differences in stand composition and structure, and this variation has been linked to forest productivity. Previous research has found that tree growth can be improved in some mixed species stands, if trees do not directly compete for the same resources. Reduced competition and improved productivity has been found in mixed species stands of Douglas-fir and western hemlock. Many studies on thinning effects have found that thinning improves average tree size and growth, but this does not provide insight into whether small or large trees benefit most from thinning. Using data from 22 pure and mixed Douglas-fir and western hemlock stands that were part of long-term thinning experiments, I analyzed how thinning (0%, 20% and 35% basal area removed) affects stand-structure dynamics and basal area growth in pure and mixed species stands over time. To understand how thinning affects size inequality—expressed by the Gini coefficient—and growth dominance over time, a linear mixed effects models was fit that included thinning and years since thinning as explanatory variables. Results found that size-inequality did not change over time and growth dominance was reduced in mixed species stands, indicating that mixed species stands may be more productive and all trees have improved growth efficiency. An individual tree analysis was performed to understand thinning and competition effects on tree basal area growth. The results indicate that basal area growth was highest in the largest trees. Results also show that inter-specific competition increases basal area growth of western hemlock trees. Both analyses found that mixed species stands resulted in improved basal area growth, likely through reduced competition. Forest managers may look to planting mixed species stands to improve forest productivity.

Lay Summary

Thinning is an important silviculture treatment, as it reduces competition and promotes tree growth in a forest stand. Previous research has found that tree growth may be improved in mixed species stands, if tree species do not directly compete for resources. Douglas-fir and western hemlock have been shown to grow more efficiently when growing together. This research analyzes the effects of thinning and competition on basal area growth in pure and mixed Douglas-fir and western hemlock stands. Results from the thesis show that mixed species stands can increase growth efficiency in small and large trees. Results also indicate that mixed species stands can increase basal area growth of dominant trees. Overall, this thesis illustrates that mixed species stands can improve tree growth over time.

Preface

The experimental data (EP703) used for this thesis was provided by the British Columbia Ministry of Forests, Lands, Natural Resource Operations, and Rural Development, Resource Practices Branch (BC FLNRORD). Data compilation was done by S.A.Y. Omule (Kasetsart University, Bangkok, Thailand). All data organization, exploration, and calculations were performed by myself, with the assistance of Dr. Bianca Eskelson, Ian Cameron, and Dr. Louise de Montigny.

The objectives for Chapter 3 (*Effects of thinning on stand-structure dynamics in pure and mixed Douglas-fir and western hemlock stands*) were presented by myself and modified with the help of Dr. Bianca Eskelson. All analyses, figures, tables, and writing were my own work, with the assistance of Dr. Bianca Eskelson. The objectives for Chapter 4 (*Effects of thinning and competition on growth in pure and mixed Douglas-fir and western hemlock stands*) were formed by Dr. Bianca Eskelson, Dr. Louise de Montigny, Ian Cameron, and myself. Analyses were performed by me, with the assistance of Ian Cameron and Dr. Bianca Eskelson. Figures, tables, and writing were my own work, with assistance from Dr. Bianca Eskelson.

The thesis is the original, unpublished work of the author, Grace Carsky. All figures, tables, and writing are my own work. Text and figure/table reviews were provided by Dr. Bianca Eskelson, Dr. Bruce Larson, Dr. Louise de Montigny, and Ian Cameron. Chapter 3 will be submitted for publication upon acceptance of the thesis. Dr. Bianca Eskelson will be included as co-author.

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List of Abbreviations

BA – basal area

BAL – basal area in larger trees

BA PAI – basal area periodic annual increment

cm - centimeters

EP703 – Experimental Project 703 (Thinning and Fertilization treatments in mixed coastal Douglas-fir and western hemlock forests)

FD – Douglas-fir

GC – Gini coefficient

GD – growth dominance

HW – western hemlock

m^2 – squared meters

m^2/year – meters squared per year

MIX – mixed Fd/Hw stands

SDI – stand density index

SDIL – stand density index in larger trees

SI – site index

T0 – control treatment (0% BA removed)

T1 – thinning treatment 1 (20% BA removed)

T2 – thinning treatment 2 (35% BA removed)

YST – years since thinning treatment

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First, I would like to thank my supervisor, Dr. Bianca Eskelson. Working with you for the last three years has been one of my most rewarding experiences at UBC. You have pushed me to work harder than I have before and have taught me so much. Your kindness and compassion for your students has not gone unnoticed, and I am so grateful to have had you as a mentor.

Thanks to my supervising committee, Dr. Bruce Larson and Ian Cameron, as well as to Dr. Louise de Montigny, for your guidance and advice throughout the completion of my thesis. Thank you to the British Columbia Ministry of Forests, Lands, Natural Resource Operations, and Rural Development for providing the data and funding the research. And thanks to everyone in the Biometrics Lab for being available to help out when I needed it.

Finally, thank you to my friends and family for the continued support and encouragement. To my friends, Jill, Kate, and Marie-Eve, who have been my biggest support system throughout graduate school; I could not have gotten through graduate school without you all. To my parents, thank you for the financial support and emotional support, even though you are both still confused by what I actually do.

Dedication

To my father, Jack Carsky. Here is your return on investment.

Chapter 1: Introduction

Tree growth is determined by the available growing space, defined as the combination of aboveground (i.e., light, physical space) and belowground (i.e., soil water, nutrients) resources. Trees in a stand compete for these resources, which can result in differentiation and stratification, repression, or mortality of trees (BCMOF 1999, Weiskittel et al. 2011). Variation in tree growth results in differences in tree height, tree diameter, and crown size. In low density stands, individual trees are larger and competition occurs later, while in high density stands, stand volume is greater, but competition between trees occurs earlier (BCMOF 1999, Harrington et al. 2009). Forest managers must find a balance between high stand volume and high individual tree volume when managing forests (Forrester et al. 2013).

Thinning is one option in managing stand density, and as a result, individual tree growth and total stand yield. Thinning experiments provide information on how removing trees from a stand affects neighbouring trees, the health and resilience of the surrounding forest stand, and the wildlife that live there (Tappeiner et al. 2007). Thinning increases growing space and reallocates resources in a forest stand, affecting individual tree growth, stand structure, and species composition. In a thinned stand, neighbouring trees can expand their crown size (Curtis and Reukema 1970), increase their average diameter (Cochran and Barrett 1993), and increase height growth of certain species in dense stands (e.g., Holmes and Tackle 1962, Curtis and Reukema 1970, Barrett and Roth 1985). Availability of resources such as light, water (Aussenac and Granier 1988), and soil nutrients (Thibodeau et al. 2000) are also increased when a stand is thinned, allowing understory trees and plants to establish and grow (Tappeiner et al. 2007). This can lead to a change in the species composition of the forest, especially if shade-intolerant species are established in the understory (Bailey and Tappeiner 1998).

Some mixed species stands are better able to utilize available growing space and stratify in a way that results in greater stand production (Smith et al. 1997). Complementary species, defined as species with different growth characteristics, are able to utilize growing space in different ways and reduce competition in the stand. Species that have the same resource needs will compete more, resulting in repression or mortality (Smith et al. 1997). Coastal Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco) and western hemlock (*Tsuga heterophylla* (Raf.) Sarg.), two commonly found commercial species in British Columbia, are considered complementary species. Both species grow well in moist soils with medium nutrient regimes, but Douglas-fir is faster growing and grows best in open light, while western hemlock is slower growing and shade tolerant. Research has shown that these two species grow well in the same stand without individual diameter, height, and volume growth being significantly reduced (Amoroso and Turnblom 2006, de Montigny and Nigh 2007, Nigh 2013).

Variability in stand structure has been linked to forest productivity (Soares et al. 2017). Metrics such as the Gini coefficient (Gini 1912, Weiner and Solbrig 1984) and growth dominance (Binkley 2004, Binkley et al. 2006) have been used to quantify stand structure. The Gini coefficient quantifies the size-inequality in a forest stand. Previous studies have shown that size-inequality increases over time (Sun et al. 2018) and is higher in mixed species stands than in pure stands (Pretzsch and Schütze 2014). Growth dominance provides insight into whether small or large trees make up the majority of stand growth. The theory of growth dominance has been studied for many species, mostly in unthinned stands (Binkley 2004, Binkley et al. 2006, McGown et al. 2016, Pothier 2017). Growth dominance studies in thinned stands have produced varying results though (Bradford et al. 2010, Keyser 2012, Soares et al. 2017). Bradford et al. (2010) concluded that the effects of thinning on growth dominance might depend on the type of thinning done in the stand.

Extensive research on the effects of thinning at the stand level have found that thinning increases mean size and growth (Oliver and Larson 1996, Diaconu et al. 2015), but individual tree growth can provide better insights to stand growth and development (Pretzsch 2009). While individual tree analyses have been conducted, there are few that have focused on Douglas-fir (e.g., Monserud 1984) and western hemlock (e.g., Canham et al. 2003), and even fewer that have been conducted on mixed species stands of the two species (e.g., Erickson et al. 2009). Furthermore, researchers have only recently started to analyze how these individual changes in size and growth modify forest structure over time (e.g., McGown et al. 2016, Pretzsch and Schütze 2014).

1.1 Research goals

The main objective of this thesis is to understand the effects of thinning at the stand and individual tree level in pure and mixed species stands. One issue with stand-level analyses is that they assume a stand is mostly uniform in appearance and behaviour (Pretzsch 2009). On the other hand, individual tree models provide a better understanding of stand development by allowing differences in tree size and growth rates to be modelled (Pretzsch 2009).

In Chapter 3, Gini coefficient and growth dominance were calculated at the stand level to understand how thinning alters size inequality and growth dominance over time. The main questions were: a) How do different thinning treatments affect size inequality in pure and mixed Douglas-fir and western hemlock stands over time? and b) How do thinning treatments affect growth dominance in pure and mixed Douglas-fir and western hemlock stands over time?

In Chapter 4, individual tree models were built to understand how individual trees respond after thinning treatments are applied. The main questions were: a) How does thinning affect tree growth over time across different sizes, sites, and ages? and b) How does competition influence tree growth? Do inter- and intra-specific competition have the same effect on tree growth?

Chapter 2: EP703 – Thinning and fertilization trials in Coastal British Columbia

2.1 Study area and measurements

The British Columbia Ministry of Forests, Lands, Natural Resource Operations, and Rural Development (BC FLNRORD) established a designed experiment (EP703) from 1971-1975 to observe the effects of thinning and fertilization in pure and mixed immature coastal Douglas-fir and western hemlock (Darling and Omule 1989, Stone, 1994). Thinning and fertilization treatments were applied over 940 0.05- to 0.10-ha permanent yield plots in 85 installations located in the Vancouver Forest Region in the Coastal Western Hemlock (CWH) Biogeoclimatic Ecosystem Classification (BEC) Zone. The installations were established in both natural and planted stands, and include a variety of stand ages (10-79 years), site indices (16-38 m at 50 years of total age; Wiley 1978, Bruce 1981), soil types, and environmental characteristics (e.g., slope, elevation, aspect) (Darling and Omule 1989). Species composition varied by installation, ranging from pure (>80% basal area) Douglas-fir to pure western hemlock. EP703 was initially set up as a randomized complete block design with three levels of thinning (0, 20, and 35% basal area [BA] removed) and three levels of fertilization (0, 225, 450 kg N/ha). Each treatment combination was replicated twice, resulting in 18 plots per installation. The design expanded later to include higher levels of thinning (50% BA removed) and fertilization (900 kg N/ha), but not all installations include the new treatments (Stone 1994).

Each plot was surrounded by a buffer that was equal in area to the plot size (Darling and Omule 1989). In each plot, species, diameter at breast height (DBH, cm), and pathological indicators were recorded for each tree while height (HT, m) measurements were recorded for a subsample of trees. Preliminary measurements were taken before treatments were applied, and included tree class code, crown class, pathological conditions, and dbh for all trees that had a diameter of 5.0 cm or greater. Subsequent dbh, height, and qualitative measurements were taken every three years for the first 15 years after treatments were applied, and then every six years thereafter.

2.2 Data compilation

The expansion of EP703 altered the randomized complete block design, so the dataset was modified with the intention to recover the initial design. Only installations 1-72 (806 plots) were considered for this analysis. Installations 73-79 (98 plots) were thinned chemically as opposed to manually and installations 80-85 (36 plots) were juvenile stands (trees aged <15 years). Plots that had fertilization treatments were removed from the working dataset as it was not a focus of this analysis. Plots with a stand age of less than 25 years were dropped so analyses could focus on commercial thinning rather than juvenile thinning. Then, plots that had less than 80% basal area of Douglas-fir and western hemlock combined were removed. This was to reduce the number of plots that had species other than Douglas-fir and western hemlock, as they were not a focus of this thesis. Installations were checked to verify that there were at least two plots per thinning treatment (T0 – 0% BA removed; T1 – 20% BA removed; T2 – 35% BA removed) to maintain a randomized complete block design. Installations that did not meet this criterion were dropped. This resulted in 22 installations, with 44 plots each for treatments T0-T2 (Figure 2-1, Table 2-1).

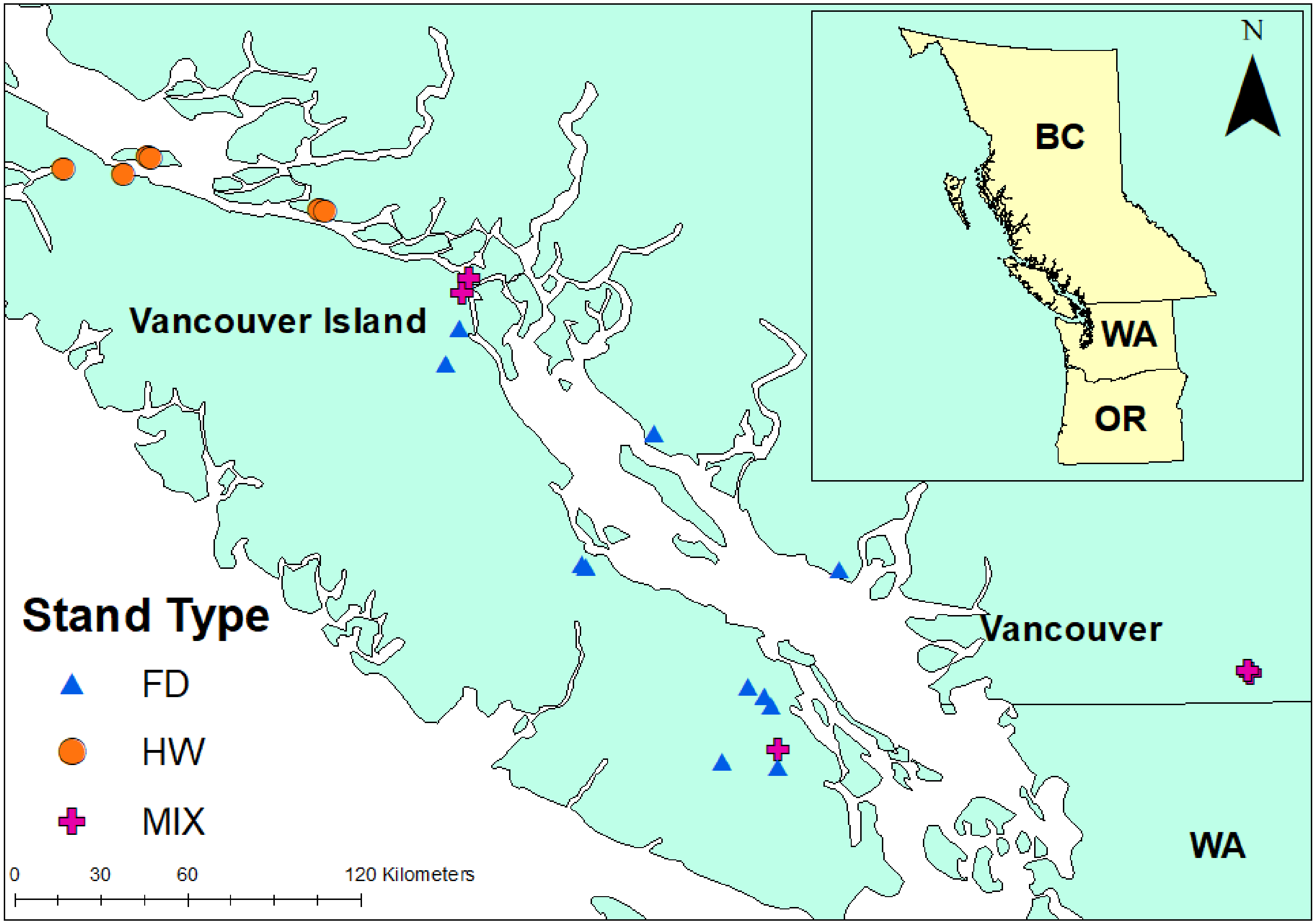

Figure 2-1. EP703 installations in coastal British Columbia. FD – Douglas-fir; HW – western hemlock; MIX – mixed FD/Hw stands; BC – British Columbia; WA – Washington; OR – Oregon.

Table 2-1. EP703 Installations and stand characteristics.

Install.[a]	Year Est.[b]	Species Composition[c]			Site Index[d]	# Meas.[e]	Last Meas.	Years Since[f]
		Fd	Hw	O				
1	1972	89	6	5	33	11	2014	42
2	1972	79	21	1	23	10	2010	38
3	1972	89	6	5	30	9	2006	34
4	1972	94	4	2	28	12	2016	44
5	1972	83	14	3	32	11	2014	42
7	1972	96	0	4	25	10	2014	42
10	1972	84	11	6	30	10	2009	37
19	1973	93	7	0	34	8	1996	23
22	1973	67	32	2	30	10	2014	41
28	1973	0	100	0	31	11	2015	42
30	1973	0	95	5	28	11	2007	34
31	1973	0	97	3	27	8	1996	23
33	1973	5	95	5	31	10	2014	41
35	1973	2	96	4	28	10	2014	41
38	1974	62	41	1	33	9	2008	34
43	1974	71	19	10	31	10	2013	39
44	1974	67	20	13	33	10	2010	36
46	1974	89	6	5	30	9	2007	33
47	1974	99	0	1	28	10	2015	41
56	1974	0	92	8	34	9	2009	35
71	1971	99	1	4	33	11	2009	37
72	1971	91	5	8	41	11	2014	43

a – Installation; b – Year of plot establishment; c - Species composition by %BA (Fd – Douglas-fir; Hw – western hemlock; O – other species). Percentages are averages of all plots in an installation; d - Site index value calculated from dominant species in the stand; e – Number of measurements; f – Years since thinning treatment.

Chapter 3: Effects of thinning on stand-structure dynamics in pure and mixed Douglas-fir and western hemlock stands

3.1 Introduction

Stand structure variability has been found to influence forest productivity (Soares et al. 2017). Variability in stand structure comes from differences in individual tree growth, driven by the amount of available resources, the proportion of resources trees obtain, and how efficient trees are at using those resources (Binkley et al. 2004). Thinning changes stand structure by removing trees in a stand to promote growth of residual trees. Though the effects of thinning on individual trees are known, researchers have only recently started to analyze how these individual changes in size and growth modify forest structure over time (e.g., Pretzsch and Schütze 2014, McGown et al. 2016).

Forest stand structure can be quantified using the Gini coefficient, first used to quantify income inequality (Gini 1912) and later adapted for plant size inequality (Weiner and Solbrig 1984). The Gini coefficient quantifies the size inequality between trees in a stand, i.e., whether tree sizes are relatively similar or different from each other. Size inequality has mostly been quantified in single-species stands (McGown et al. 2016, Soares et. al 2017), but also in some mixed-species stands (Pretzsch and Schütze 2014). Size inequality has been found to increase over time, especially in older, denser, and more productive stands (Sun et al. 2018). Pretzsch and Schütze (2014) found that size inequality is larger in mixed species stands than in pure stands. While the Gini coefficient can provide insight to the size inequality of the stand, it cannot provide information on where the individual tree growth is concentrated that results in these changes in inequality.

One way to analyze how individual trees contribute to stand growth is by calculating growth dominance (Binkley 2004, Binkley et al. 2006). Growth dominance indicates whether smaller or larger trees contribute more to stand growth. Binkley et al. (2006) found that growth dominance changes in forest stands depending on the current phase of stand development based on stem mass and growth. Younger stands tend to have positive growth dominance, where larger trees are contributing more to stand growth, while very old stands show negative growth dominance, where smaller trees are contributing more to stand growth. The theory of growth dominance has been studied on a variety of species in unthinned monocultures, such as ponderosa pine (Binkley et al. 2006, McGown et al. 2016), aspen (Binkley et al. 2006), and lodgepole pine (Binkley et al. 2006). Growth dominance has also been studied in mixed species stands of Douglas-fir, western hemlock, western redcedar, Sitka spruce, and red alder (Binkley 2004), Englemann spruce and subalpine fir (Binkley et al. 2006), and trembling aspen, Jack pine, white birch, black spruce, and balsam fir in eastern Canada (Pothier 2017). Some research has been done on thinned monocultures, but results have been inconsistent. Bradford et al. (2010) found that the type of thinning affects growth dominance trends over time. While some studies found increases in growth dominance after thinning from above (Bradford et al. 2010, Keyser 2012), others have found decreases or no changes after thinning, specifically in stands that were thinned from below (Bradford et al. 2010, Soares et al. 2017).

This study describes post-thinning size inequality and growth dominance trajectories in pure and mixed Douglas-fir and western hemlock stands. Specifically, the following questions were answered: 1) How does thinning affect changes in diameter distributions over time in pure and mixed Douglas-fir and western hemlock stands?, 2) How do thinning treatments affect size inequality in pure and mixed Douglas-fir and western hemlock stands?, and 3) How do thinning treatments affect growth dominance over time in pure and mixed Douglas-fir and western hemlock stands? Because thinning trees can result in a net loss of stand volume, forest managers need to take caution and not remove a large portion of the growing stock in a stand (Johnstone and van Thienen 2006). This analysis can provide insight into where individual tree growth is concentrated in pure and mixed Douglas-fir and western hemlock stands after thinning, and thus help with prescribing future thinning treatments.

3.2 Data and analysis

3.2.1 Calculations

All live trees are included in this analysis to see how forest stand dynamics change over time. This includes trees that arrived later in measurements due to ingrowth, ongrowth, or regeneration, as well as trees that died midway through measurements. Darling and Omule (1989) stated that ingrowth was not removed from plots, but its growth and abundance in younger stands was substantial. The presence of ingrowth can have an effect on growth in younger stands (Busse et al. 1996). Therefore, I chose to analyze stand size inequality and growth dominance in installations with substantial ingrowth and installations with little or no ingrowth to observe if any differences in trends could be found.

The number of trees per hectare labeled "ingrowth" (i.e., trees that met the 5cm dbh threshold) were summed over all measurements in each plot for each installation. The range of number of "ingrowth" trees per hectare per plot in each installation was evaluated to identify installations that had more ingrowth than others. Installations were considered to have a substantial amount of ingrowth if at least 75% of plots included 1,000 or more "ingrowth" trees per hectare over all measurements. This resulted in five out of the 22 installations being defined as “ingrowth” installations, four pure Douglas-fir installations and one mixed Douglas-fir/western hemlock installation.

3.2.1.1 Gini coefficient

To consider size inequality in pure and mixed species stands, the Gini coefficient (GC) (Pretzsch and Schütze 2014) was calculated per plot for each measurement:

$$GC = \frac{\sum_{i,j=1}^{n} |x_i - x_j|}{2n(n-1) * \bar{x}} \tag{3.1}$$

where $x_{i,j}$ is the individual tree basal area (m^2), n is the number of trees in a plot, and $\bar{x}$ is the mean plot basal area (m^2). The GC quantifies relative distribution of tree size (i.e., tree basal area). A GC = 0 indicates all trees are of equal size, while a theoretical GC = 1 indicates that all trees except for one have a value of zero (Weiner and Solbrig 1984). Values closer to one indicate higher inequality in size between trees.

3.2.1.2 Growth dominance

While the GC is an effective way to analyze the inequality of size distributions, it does not provide information on where the inequality is present (Weiner and Solbrig 1984). Growth dominance (GD) can be used to determine whether small trees or large trees produce the majority of total stand growth (West 2014). Using the equation from West (2014), GD is calculated as:

$$GD = 1 - \sum_{i=1}^{n} (\boldsymbol{s}_i - \boldsymbol{s}_{i-1})(\boldsymbol{d}_i + \boldsymbol{d}_{i-1}) \tag{3.2}$$

where **s** and **d** are vectors of individual tree (i) basal area (m^2) and basal area growth (basal area periodic annual increment [BA PAI], m^2/yr) expressed as the cumulative proportions they make of total stand size and growth, respectively. In other words, the GD is the proportion of stand growth by individual trees relative to the proportion of individual tree size to total stand size.

Values of GD range from -1 to 1, where GD = -1 indicates smaller trees contribute more to stand growth and GD = 1 indicates larger trees contribute more to stand growth. GD was calculated per plot for each growth period post-thinning.

3.2.2 Statistical analyses

A linear mixed-effects model was fit using PROC MIXED in SAS (SAS Institute Inc.) to analyze how thinning affects stand inequality and growth dominance over time, in both mixed and pure stands. Dependent variables included GC and GD. Independent variables included the thinning treatment factor (T0, T1, and T2), years since thinning (YST), defined as the number of years after the initial thinning treatment, a squared YST term (YST^2), and interactions between thinning, YST, and YST^2. YST^2 was included in the model to account for nonlinear trends of GC and GD over time. A random plot-in-installation effect was included in the model to account for the repeated measures over time. Assumptions of equal variance and normality were checked using residual plots, histograms, and QQ-plots. A full model was fit for each stand type—pure Douglas-fir, pure western hemlock, and mixed species stands—as well as for plots including substantial ingrowth and for those that did not within stand types. Beginning with the highest order interactions, terms that were not significant at $\alpha = 0.05$ were dropped until all terms were significant. Terms that were part of a significant interaction were retained in the model even if the term itself was not significant.

3.3 Results

3.3.1 DBH distributions

In all thinning treatments and stand types, the variation in DBH of trees was small at the first post-thinning measurement, with most trees concentrated in the smaller diameter classes (< 20cm). Over time, differences in size distributions could be seen across the different stand types. In all stands, the variation in tree size increased over time. The frequency of minor species, mostly shade intolerant, decreased over time (Appendix A.1). These minor species appeared in the smaller diameter classes in the first several years post-thinning, but tended to decrease in frequency or disappear altogether over time (Appendix A.2). In pure Douglas-fir stands, the size distribution was typically unimodal across all treatments, but some bimodal distributions were seen in T1 and T2 treatments over time (Figure 3-1). Douglas-fir trees were typically the largest trees, whereas western hemlock, western redcedar, and all other species were concentrated in the smaller diameter classes. In pure western hemlock stands, size distributions were symmetrically unimodal across all treatments at the final measurements (Figure 3-2). Other minor species in pure western hemlock stands typically appeared in the smaller diameter classes as suppressed trees. In mixed Douglas-fir and western hemlock stands, there were clear bimodal distributions (Figure 3-3). The distributions were usually unimodal by species. Douglas-fir trees were mostly concentrated in the larger diameter classes, whereas western hemlock, western redcedar, and other minor species occurred in the smaller diameter classes.

There were some exceptions to these trends. In some pure Douglas-fir and mixed species stands, western hemlock trees appeared in larger diameter classes as co-dominant trees, creating a bimodal distribution for western hemlock trees. Occasionally, a large western redcedar became a co-dominant tree over time, rather than surviving in the understory as an intermediate or suppressed tree. Some pure western hemlock stands had a few large, co-dominant Sitka spruce trees, rather than intermediate or suppressed trees. In one case, a pure Douglas-fir installation with substantial ingrowth started out with very few minor species in all treatments, but over time, western hemlock and western redcedar appeared in the smaller diameter classes, resulting in a bimodal DBH distribution.

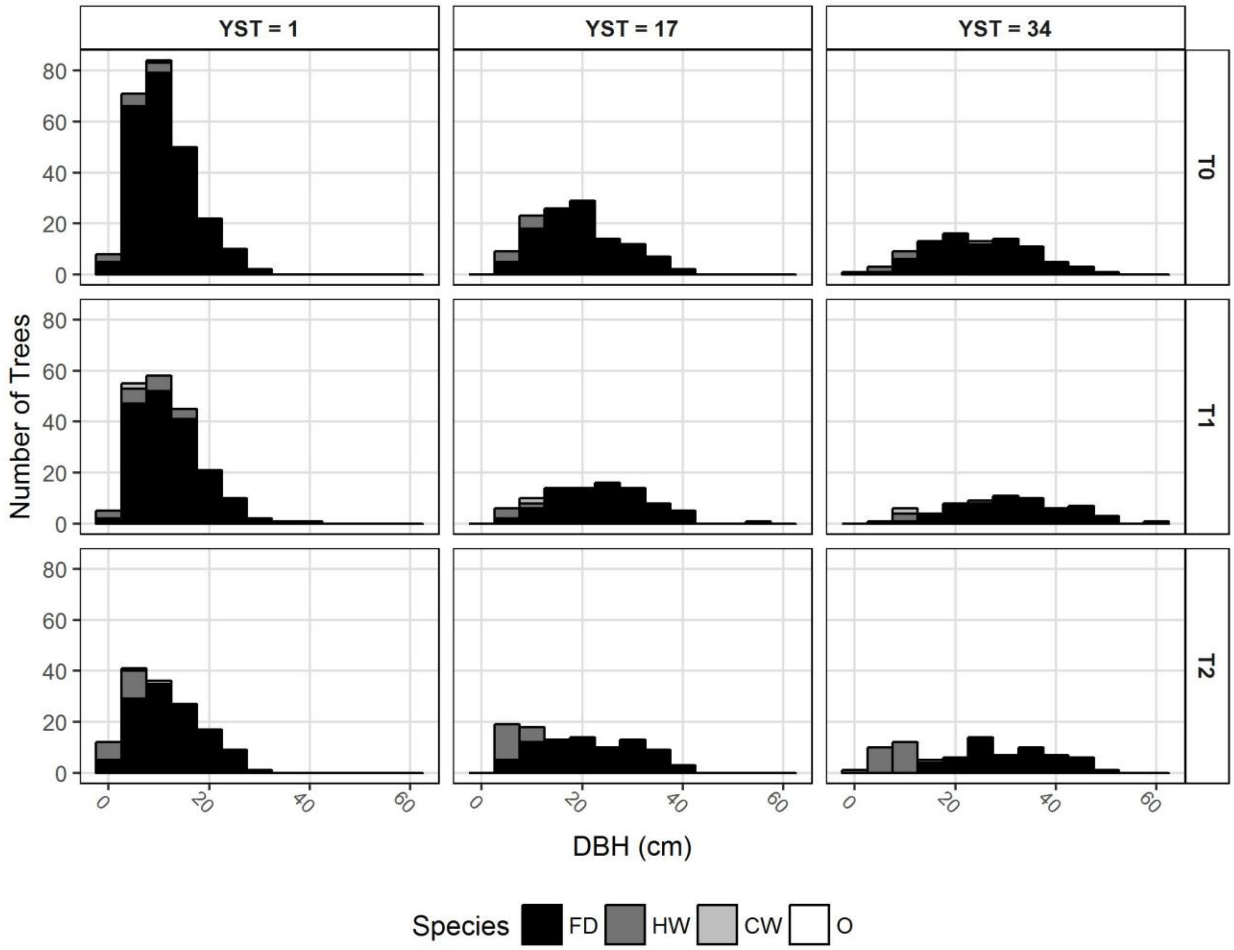

Figure 3-1. Histograms of tree diameter (cm) in Installation 4 (94% FD, 4% HW, 2% O; Site Index – 28) for measurements taken at 1, 17, and 34 years since treatment. YST – years since thinning; T0 – control plots (0% BA removed); T1 – 20% BA removed; T2 – 35% BA removed; FD – Douglas-fir; HW – western hemlock; CW – western redcedar; O – other.

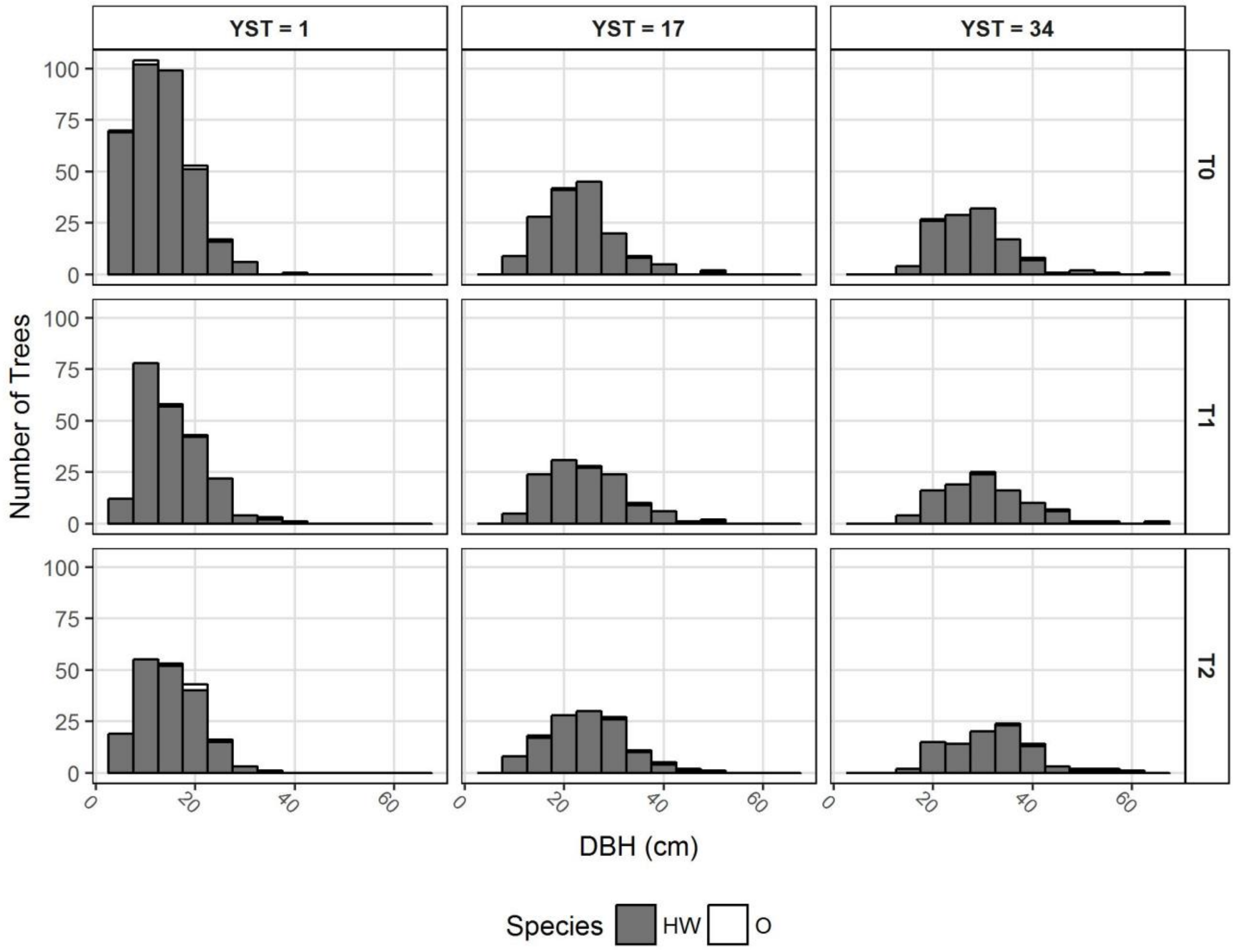

Figure 3-2. Histograms of tree diameter (cm) in Installation 30 (95% HW, 5% O; Site Index – 28) for measurements taken at 1, 17, and 34 years since treatment. YST – years since thinning; T0 – control plots (0% BA removed); T1 – 20% BA removed; T2 – 35% BA removed; HW – western hemlock; O – other.

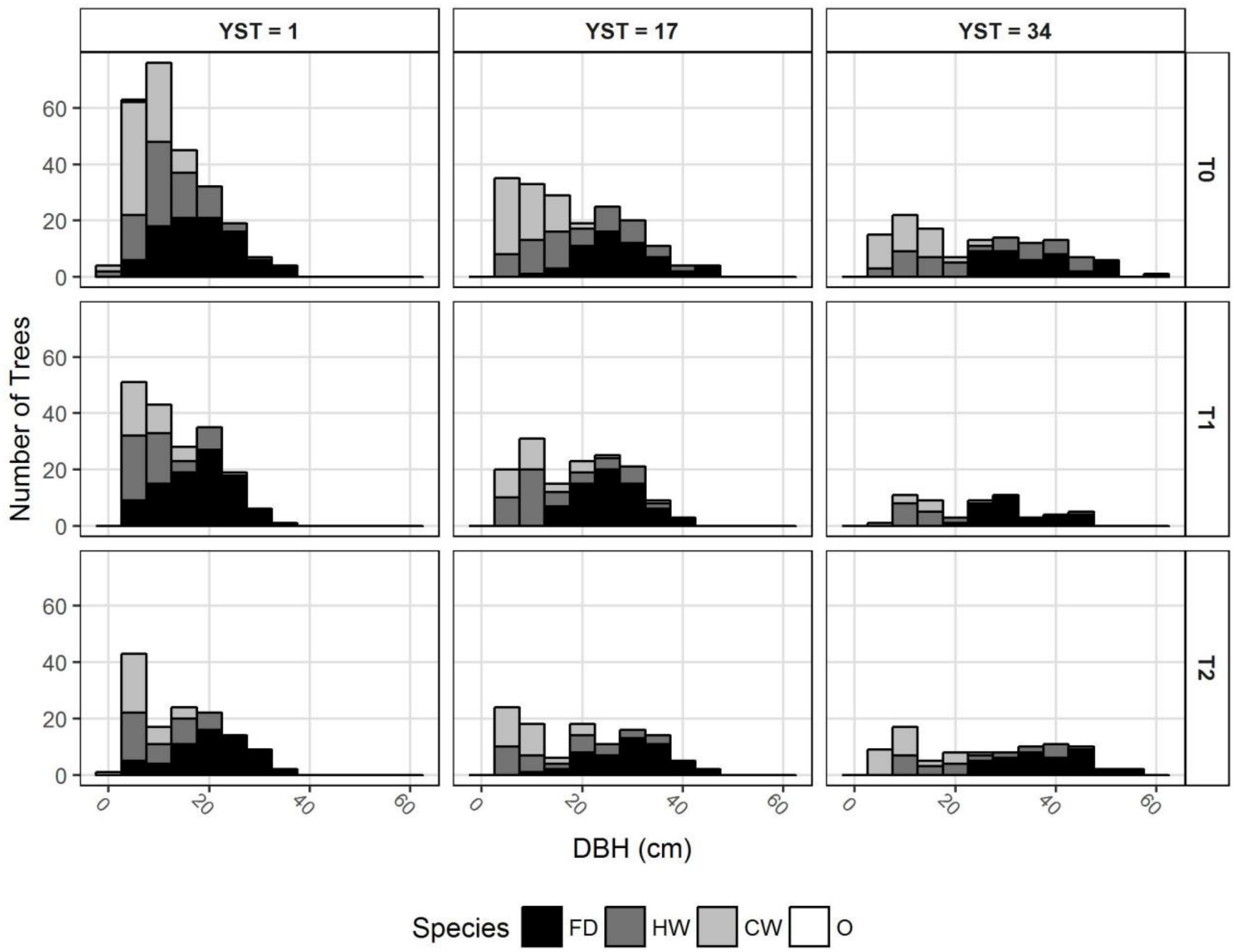

Figure 3-3. Histograms of tree diameter (cm) in Installation 43 (71% FD, 19% HW, 10% O; Site Index – 31) for measurements taken at 1, 17, and 34 years since treatment. YST – years since thinning; T0 – control plots (0% BA removed); T1 – 20% BA removed; T2 – 35% BA removed; FD – Douglas-fir; HW – western hemlock; CW – western redcedar; O – other.

3.3.2 Gini coefficient

There were no significant differences in GC model intercepts among thinning treatments in Douglas-fir or mixed species stands. However, there were significant differences in model intercepts in pure western hemlock stands. GC in T0 and T2 stands were significantly different from each other (p = 0.0170) while there was suggestive but inconclusive evidence of differences between T0 and T1 stands (p = 0.0527). GC in T1 and T2 stands was not significantly different (p = 0.6481).

GC decreased across all treatments in pure Douglas-fir and western hemlock stands without substantial ingrowth (Figure 3-4). In Douglas-fir stands, this decrease was constant for T0 and T1 stands, but non-constant in T2 stands (Table 3-1). In western hemlock stands, GC decreased at a constant rate in T1 and T2 stands, but at a non-constant rate in T0 stands (Table 3-1). In mixed species stands without ingrowth, a different trend was observed in each treatment (Figure 3-4). GC did not change over time in T0 stands, decreased in T1 stands, and increased in T2 stands (Figure 3-4, Table 3-1).

GC increased across all treatments in pure Douglas-fir stands with substantial ingrowth (Figure 3-4). In mixed species stands with substantial ingrowth, however, GC only increased significantly in T2 stands while no change was observed in T0 and T1 stands (Figure 3-4, Table 3-1).

Table 3-1. Parameter estimates of years since treatment by stand type, thinning treatment, and ingrowth vs. non-ingrowth plots for Gini coefficient models.

Stand Type[1]	Ingrowth Plots (Y/N)	Thinning Treatment[2]	Intercept	Linear coefficient (YST)	Quadratic coefficient (YST^2)
FD	N	T0	0.4269***	0.000006	-0.00004***
	N	T1	0.4395***	0.000383	-0.00004***
	N	T2	0.4238***	0.001427**	-0.00004***
	Y	T0	0.4035***	0.002180ǂ	0.000073*
	Y	T1	0.4149***	0.001348	0.000073*
	Y	T2	0.3762***	0.003730**	0.000073*
HW	N	T0	0.4074***	-0.00662***	0.000095***
	N	T1	0.3754***	-0.00288**	0.000025
	N	T2	0.3679***	-0.00302**	0.000024
MIX	N	T0	0.4359***	-0.00003	
	N	T1	0.4315***	-0.00102***	
	N	T2	0.3953***	0.000886**	
	Y	T0	0.4638***	0.001117	
	Y	T1	0.5053***	0.000705	
	Y	T2	0.4868***	0.003337***	

1 FD – pure Douglas-fir; HW – pure western hemlock; MIX – mixed Douglas-fir/western hemlock
2 T0 – control (0% BA removed); T1 – 20% BA removed; T2 – 35% BA removed
***p-value < 0.001; **p-value < 0.01; *p-value < 0.05; ǂ p-value < 0.10

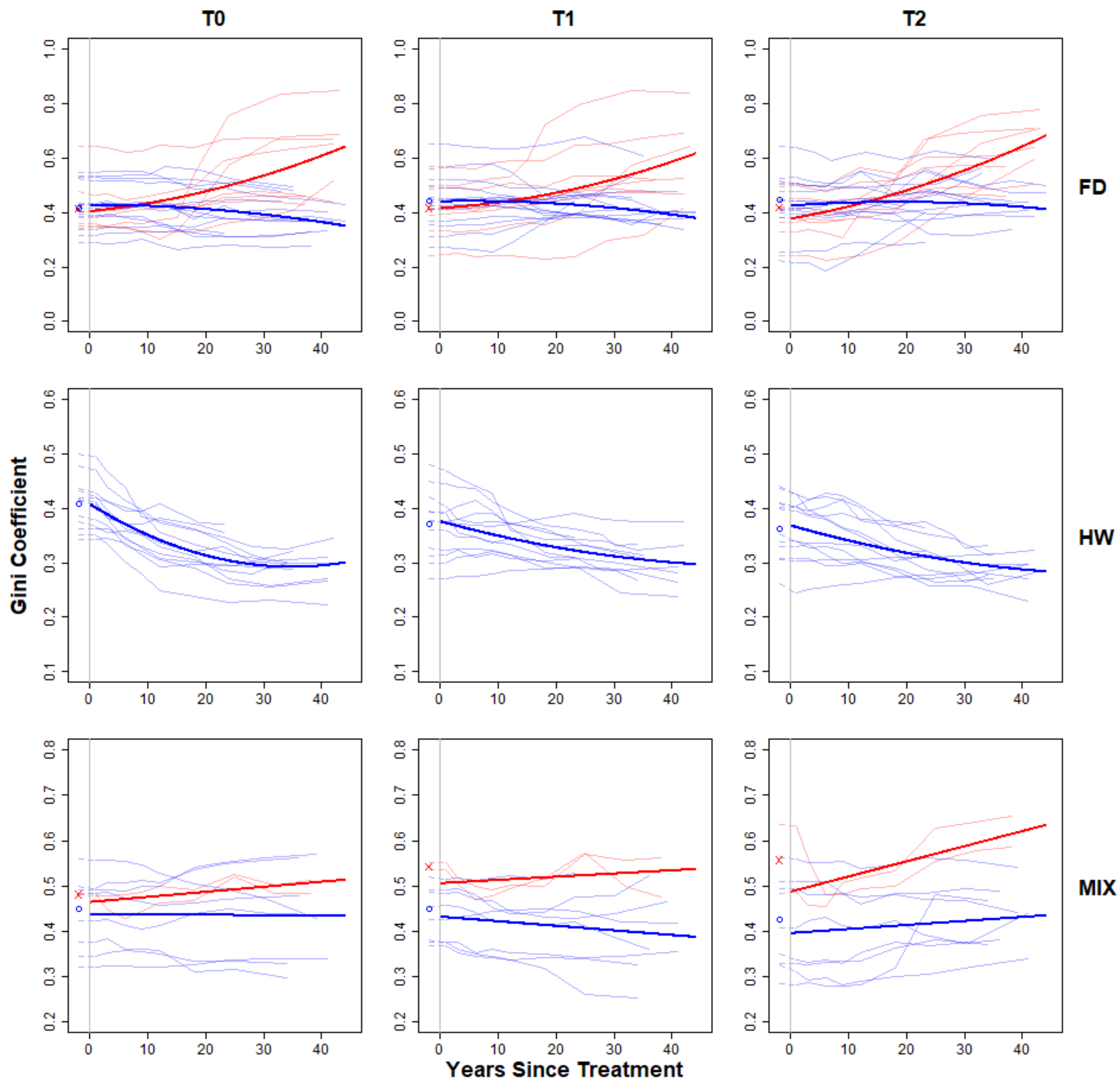

Figure 3-4. Gini coefficient vs. years since treatment across stand type and thinning treatment. Ingrowth models are shown in bold red and non-ingrowth models are shown in bold blue. T0 – control plots (0% BA removed); T1 – 20% BA removed; T2 – 35% BA removed; FD – Douglas-fir; HW – western hemlock; MIX – mixed Douglas-fir and western hemlock.

3.3.3 Growth dominance

GD model intercepts were significantly different from zero in pure Douglas-fir stands, pure western hemlock stands, and mixed species stands without substantial ingrowth, but not in mixed species stands with substantial ingrowth (Table 3-2). Positive GD values indicate that larger trees are contributing more to stand growth than smaller trees, whereas a GD value of zero indicates neutral dominance, i.e., all trees are growing respective to their size (Binkley et al. 2006).

GD model intercepts significantly differed between treatments in all stand types except mixed species stands with substantial ingrowth. In these cases, GD was significantly larger in control plots than in plots with the highest thinning intensity (35% BA removed). Significant differences between the GD model intercept in T0 and T1 stands were seen in pure Douglas-fir stands without substantial ingrowth ($p < 0.0001$), pure western hemlock stands ($p = 0.0215$), and in mixed species stands without substantial ingrowth ($p < 0.0001$).

GD increased or did not change over time in any of the stand types or any of the treatments (Table 3-2). GD stayed positive over time in pure Douglas-fir and western hemlock stands, as well as in mixed species stands without substantial ingrowth (Figure 3-5). In mixed species stands with substantial ingrowth, GD increased over time, except in stands with highest thinning intensity (Figure 3-5).

Table 3-2. Parameter estimates of years since treatment by stand type, thinning treatment, and ingrowth vs. non-ingrowth plots for growth dominance models.

Stand Type[1]	Ingrowth Plots (Y/N)	Thinning Treatment[2]	Intercept	Linear coefficient (YST)	Quadratic coefficient (YST^2)
FD	N	T0	0.1606***	0.001147***	
	N	T1	0.08706***	0.001147***	
	N	T2	0.05850***	0.001147***	
	Y	T0	0.1445***		
	Y	T1	0.1216***		
	Y	T2	0.07754***		
HW	N	T0	0.2242***	-0.00042	0.000041*
	N	T1	0.1811***	-0.00042	0.000041*
	N	T2	0.1275***	-0.00042	0.000041*
MIX	N	T0	0.1648***	0.003694**	-0.00007**
	N	T1	0.07480***	0.004765***	-0.00007**
	N	T2	0.04826**	0.005351***	-0.00007**
	Y	T0	0.03114	0.002403**	
	Y	T1	-0.03143	0.003939***	
	Y	T2	0.01284	0.000638	

1 FD – pure Douglas-fir; HW – pure western hemlock; MIX – mixed Douglas-fir/western hemlock
2 T0 – control (0% BA removed); T1 – 20% BA removed; T2 – 35% BA removed
***p-value < 0.001; **p-value < 0.01; *p-value < 0.05; ǂp-value < 0.10

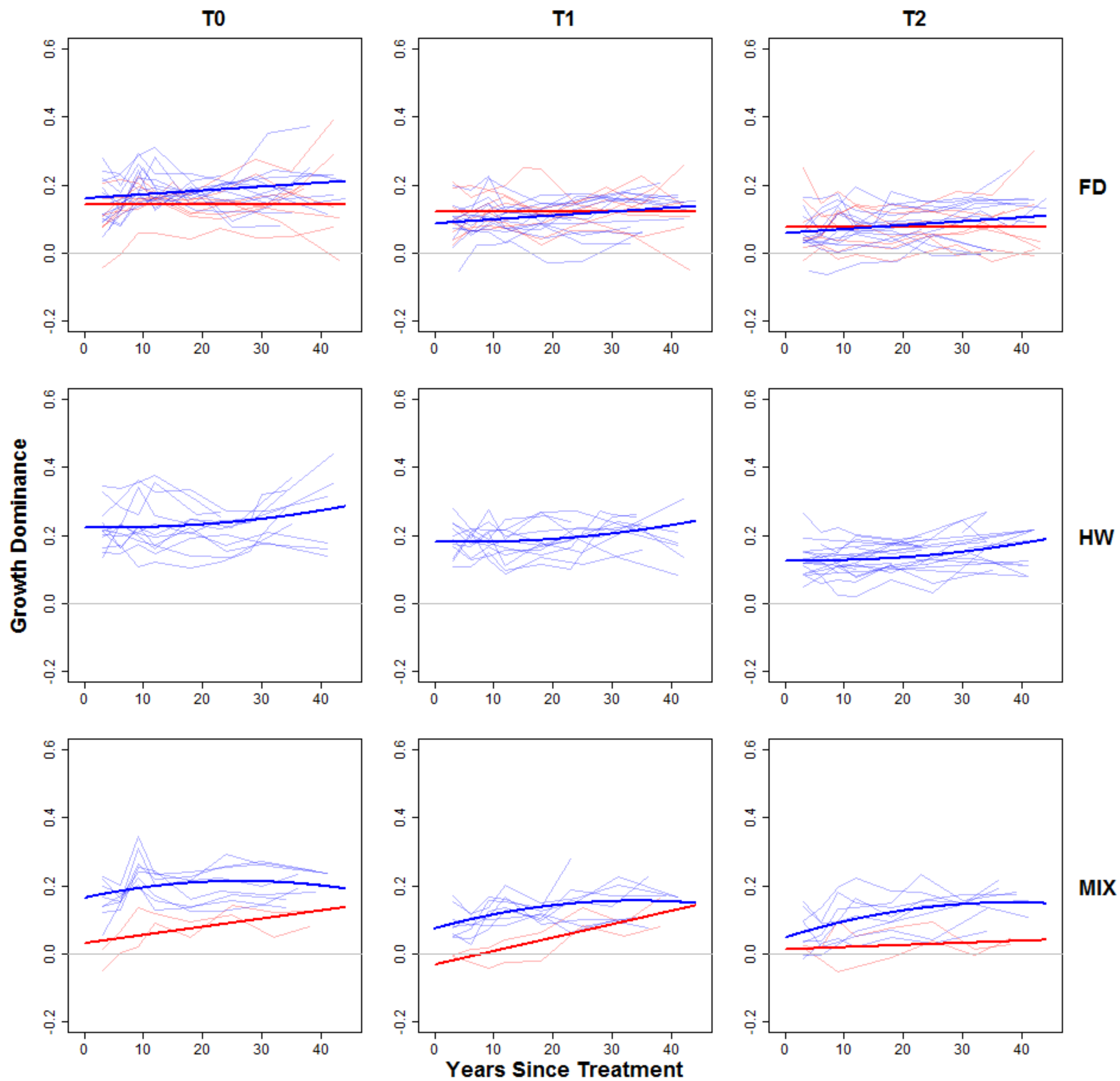

Figure 3-5. Growth dominance vs. years since treatment across stand type and thinning treatment. Ingrowth models are shown in bold red and non-ingrowth models are shown in bold blue. T0 – control plots (0% BA removed); T1 – 20% BA removed; T2 – 35% BA removed; FD – Douglas-fir; HW – western hemlock; MIX – mixed Douglas-fir and western hemlock.

3.4 Discussion

3.4.1 Changes in DBH distributions

Diameter distributions in pure, single-cohort stands tend to be narrow and right-skewed, becoming more symmetric and normally distributed over time (Prodan 1951). Results from pure Douglas-fir and western hemlock stands follow this pattern as well, with some bimodal distributions in thinned Douglas-fir stands. Ford and Newbould (1970) found that diameter distributions in monocultures might result in bimodal distributions because of differences in growth rates between smaller and larger trees. In thinned stands where resource allocation is increased, larger trees can take up more resources than smaller trees (Tappeiner et al. 2007). Mixed stands of species with differences in growth rates would have similar results. In this study, mixed Douglas-fir and western hemlock stands had bimodal diameter distributions over time. Douglas-fir is a faster growing, shade intolerant species, whereas hemlock is slower growing and shade tolerant (Klinka 2000), which is why the Douglas-fir trees are almost always the dominant species in the mixed species stands.

3.4.2 Gini coefficient

Increases and decreases in size variability have been linked to size-asymmetric and size-symmetric competition, respectively (Weiner and Thomas 1986). Studies in unmanaged, even-aged stands have typically found increases in GC (Weiner and Thomas 1986, Sun et al. 2018), whereas studies in thinned stands have typically found declining or stable GC values over time (Knox et al 1989, McGown et al. 2016, Soares et al. 2017). In this study, size inequality decreased in pure and mixed species stands without substantial ingrowth and were stable in mixed species stands with substantial ingrowth, though these changes over time were minor (Figure 4). However, decreases in GC in pure western hemlock appeared larger and may be attributed to thinning and mortality. In unthinned western hemlock stands, substantial mortality of smaller trees reduced GC in the stand over time. In thinned stands, competition is reduced by reallocating resources to other trees in the stand, allowing smaller trees to grow. This results in smaller size variation of the stand (Tappeiner et al. 2007).

The presence of substantial ingrowth produced different trends in size inequality in pure Douglas-fir and mixed species stands, where GC increased over time in all treatments. Ingrowth is defined as a level at which smaller trees enter the smallest measureable size class in a stand (Husch et al. 2002). Because GC calculates the size inequality in a stand, GC is expected to be higher in stands with ingrowth than in stands without. Shifley et al. (1993) found that the number of ingrowth trees decreased as the ingrowth threshold diameter was increased, so future research may look into how results in size-inequality changes over time if the threshold diameter for ingrowth was increased.

3.4.3 Growth dominance

GD has been reported to decrease right after thinning in *Pinus* and *Eucalyptus* stands, with smaller GD values in more intensely thinned stands (Bradford et al. 2010, Soares et al. 2017). The results from this study, which found significantly larger GD values in control stands than in heavily thinned stands (T2), concur with these earlier study results. This may be explained by smaller trees being able to better grow in proportion to their size (Binkley et al. 2006) due to thinning reducing competition among trees and thus reducing GD during the first growth period post thinning.

Binkley (2004) and Binkley et al. (2006) linked growth dominance with phases of stand development, where younger stands have positive GD and shift to negative GD as the stand ages. Though GD has been linked to stand development, values and trends over time may be species specific (Fernández et al. 2011). High, positive GD values have been seen in 20 year old *Eucalyptus* stands (Binkley et al. 2003), whereas low positive or neutral values have been seen in young *Pinus* species (Bradford et al. 2010, McGown et al. 2016) and aspen (Binkley et al. 2006). Negative values have been found in old-growth stands of ponderosa and lodgepole pine species (Binkley et al. 2006), as well as in old, mixed spruce and fir stands (Binkley et al. 2006). Positive GD values in pure Douglas-fir and western hemlock stands with and without substantial ingrowth were consistent with previous studies, given the age range of the stands. Pure Douglas-fir and western hemlock stands were relatively young, averaging 37 (26-63) and 39 (31-66) years, respectively, at thinning, and are still growing, therefore positive GD values were expected. Growth rates in Douglas-fir stands remain constant up to about 100 years (Tappeiner et al. 2007) and trees can survive up to 600 years (Hermann and Lavender 1990), whereas western hemlock growth rates are constant for roughly 70 years (Meyer 1937) and trees survive up to 400 years (Packee 1990). Therefore, negative GD values would not be expected in these stands.

Mixed species stands may have higher growth efficiency (del Río et al. 2016), resulting in GD values close to zero. Katholnig (2012) found that even-aged mixed species stands had smaller GD values than pure stands. Binkley (2004) found a near-zero GD in mixed species stands of Douglas-fir, western hemlock, and western redcedar, which increased over time with increasing age up to 80 years. GD values in this study followed a similar pattern, where GD was low in mixed species stands without substantial ingrowth, negative in mixed species stands with substantial ingrowth, and increased over time in both stand types. There were only two plots per thinning treatment that were considered to have substantial ingrowth in mixed species stands, so results need to be interpreted with caution due to the small sample size. Positive GD values are expected in stands with size-asymmetric competition, whereas stands with neutral dominance typically experience size-symmetric competition (Fernández-Tschieder and Binkley 2018). Studies have shown that mixed stands of certain species often experience less competition (Kelty 2006), therefore trees are better able to grow proportional to their size (Binkley et al. 2006). Douglas-fir and western hemlock are two complementary species, i.e., they have similar growth characteristics but do not have completely overlapping niches. Douglas-fir is a shade intolerant species, whereas western hemlock is shade tolerant (Hermann and Lavender 1990, Packee 1990, Klinka 2000). While Douglas-fir grows faster and takes up more space in the canopy, western hemlock benefits from the partial shade, allowing it to grow without being affected by the surrounding Douglas-fir trees. The complementarity between Douglas-fir and western hemlock reduces competition so all trees grow proportional to size, resulting in lower GD values. The results in mixed species stands without substantial ingrowth were similar to those in pure Douglas-fir stands. This is most likely because mixed species stands still had Douglas-fir as dominant species and were not a true 50:50 mixture of the two species.

3.5 Conclusion

I sought out to find if thinning had any effects on size distributions, size inequality, and growth dominance in pure and mixed Douglas-fir and western hemlock stands. Size inequality decreased in pure stands after thinning, but remained relatively consistent in mixed species stands. Growth dominance was positive in pure stands across all treatments over time, but mixed species stands showed neutral dominance right after thinning. The addition of ingrowth resulted in increased size-inequality, but did not alter GD trends. One issue with thinning treatments is the risk of removing too many trees because total stand yield is not replaced by the increased growth from residual trees. Pretzsch and Schütze (2016) suggest that mixed species stands may be similar to thinning from below by replacing slow growing trees with species that are resource efficient and shade tolerant. In mixed species stands with lower thinning intensities, size-inequality did not increase over time and trees grew in relative proportion to their size. This could indicate that mixed species stands may lead to higher productivity over time.

Chapter 4: Effects of thinning and competition on basal area growth in western hemlock stands

4.1 Introduction

Tree growth is determined by the resources available in a stand, including light, water, nutrients, and physical space (BCMOF 1999). As long as trees have the required resources, they will continue to grow, but competition between trees increases as trees increase in size (Harrington et al. 2009). Thinning is a common way to control the density of forest stands (Tappeiner et al. 2007), and thus manage competition between trees. By removing a percentage of trees in an area, resources are made available to trees left behind (Oliver and Larson 1996, Tappeiner et al. 2007).

Our understanding of the effects of thinning at the stand level is extensive. At the stand level, thinning generally increases mean size and growth (Oliver and Larson 1996, Diaconu et al. 2015) and reduces competition (Boncina et al. 2007). However, this does not provide insight into the effects of thinning on individual trees. Individual trees grow at different rates, depending on their initial size and competitive status in a stand (Canham et al. 2004, Collet et al. 2014). Previous research has found that larger trees in pure stands may acquire more resources and suppress smaller trees post-thinning (Diaconu et al. 2015, Bose et al. 2018). The response to thinning can also vary depending on the pre-and post-thinning stand and site conditions, but many studies do not have pre-thinning data available (Bose et al. 2018).

This study aims to analyze the effects of thinning on basal area growth of individual western hemlock trees in pure stands across a range of stand ages and site indices using long term pre- and post-thinning data (23-43 years), as well as understand how inter- and intra-specific competition varies across three thinning treatments. The main questions are: 1) How does basal area growth change with initial size and stand characteristics (i.e., site and age)? and 2) How does inter- and intra-specific competition affect basal area growth over time?

For this analysis, the focus is on trees that were measured in all measurement periods, hereby known as "survivor trees." This eliminates any trees that died at any point in the measurement periods, as well as any ingrowth or ongrowth in the stand. Including trees that arrived or died midway through the measurement period brings up topics of mortality, regeneration, and understory competition, none of which are a focus in this study.

4.2 Data and methods

4.2.1 Study area

This analysis focuses on pure western hemlock stands. Therefore, the six pure western hemlock installations (>80% basal area) were analyzed (Table 4-1). Minor components of western redcedar, Sitka spruce, and red alder were present in the plots.

Table 4-1. Number of plots per treatment with age and site index (SI) range in pure western hemlock stands.

	T0	**T1**	**T2**
# of plots	12	12	12
Age range	31-63	33-63	32-66
SI range (m)	22-33	24-34	24-35

4.2.2 Data compilation

The periodic annual increment of basal area (BA PAI, m^2/year) was used as the dependent variable to represent individual tree growth:

$$BA\,PAI_t = \frac{BA_t - BA_{t-1}}{age_t - age_{t-1}} \qquad (4.1)$$

where *BA* is the tree basal area at time *t* and *age* is the age of the stand at time *t*. To analyze how BA PAI changed over time, years since thinning (YST) was calculated and included in the model.

Individual tree growth is assumed to be a function of tree size, site characteristics, and competition (Wykoff 1990). A variety of covariates were calculated to represent size, site and competition (Table 4-2). Tree size was represented using individual tree DBH or BA before thinning treatments were applied. Site characteristics were described by stand age before thinning and site index.

Several competition indices were derived (Table 4-2) using all live trees in the stand at the time of each measurement, including ingrowth, ongrowth, and trees that died at any point throughout the measurement periods. Distance-independent competition indices were computed by plot for the model: basal area in larger trees (BAL, Wykoff 1990) and stand density index in larger trees (SDIL, Pretzsch and Biber 2010). BAL is the sum of basal area of trees larger than the subject tree. SDIL is calculated as:

$$SDIL = N_l \left(\frac{25}{QMD_l}\right)^E \qquad (4.2)$$

where N_l is the number of stems per hectare larger (*l*) than the subject tree, QMD_l is the quadratic mean diameter of all trees larger (*l*) than the subject tree, and *E* = -1.605 (Reineke 1933).

Two trees may have the same BAL, but different competitive effects. For example, a small tree will have less of a competitive effect than a larger tree of the same BAL. Relative BAL and relative SDIL were also calculated as a way to model the relative size effect as it varies with tree size (Wykoff 1986):

$$BAL_{rel_i} = \frac{BAL_i}{BAL_{max}} \quad (4.3)$$

$$SDIL_{rel_i} = \frac{SDIL_i}{SDIL_{max}} \quad (4.4)$$

where BAL_{rel_i} and $SDIL_{rel_i}$ are the individual tree relative BAL and SDIL, respectively, BAL_i and $SDIL_i$ are the individual tree BAL and SDIL, respectively, and BAL_{max} and $SDIL_{max}$ are the maximum BAL and SDIL values per measurement-in-plot-in-installation.

One disadvantage to calculating competition indices (e.g., BAL and SDIL) across all trees in a stand (i.e., “total” competition indices) is the underlying assumption that all trees of a given size have equal competitive influence, regardless of species (Weiskittel et al. 2011). Weighting trees by their competitive ability, such as separating BAL or SDIL by species, has shown to be an effective way of analyzing competition in stands with a mixture of species (Pukkala et al. 2009). BAL, SDIL, and their respective relative indices were also computed separately by species (i.e., western hemlock and “other” species) for each measurement in each plot within an installation (Table 4-2).

Table 4-2. Model covariates.

Covariate Type	Variable	Units
Treatment	Thinning treatment T0 – T2	% BA removed
	T0 – 0% BA removed	
	T1 – 20% BA removed	
	T2 – 35% BA removed	
	Years since treatment (YST)	years
Size	Pre-thinning basal area (BA)	m^2
	Pre-thinning diameter at breast height (DBH)	cm
Competition	Basal area in larger trees (BAL)	m^2/ha
	Stand density index in larger trees (SDIL)	stems per hectare
	Relative BAL (BAL_{rel})	%
	Relative SDIL ($SDIL_{rel}$)	%
	BAL by species (BAL_{hw}, BAL_{other})	m^2/ha
	SDIL by species ($SDIL_{hw}$, $SDIL_{other}$)	stems per hectare
	Relative BAL by species (BAL_{rel_hw}, BAL_{rel_other})	%
	Relative SDIL by species ($SDIL_{rel\_hw}$, $SDIL_{rel\_other}$)	%
Site	Site index (Wiley 1978)	Height at age 50 years
	Stand age	years

4.2.3 Model development

To quantify the effects of thinning on individual tree basal area growth, a longitudinal model was fit using the mixed model procedure in SAS 9.4 (SAS Institute Inc.):

$$\boldsymbol{y}_{ijkl} = \boldsymbol{X}_{ijkl}\boldsymbol{\beta} + \boldsymbol{Z}_{ijkl}\boldsymbol{b}_i + \boldsymbol{\varepsilon}_{ijkl} \quad (4.5)$$

where $\mathbf{y}_{ijkl}$ is the vector of the response variable BA PAI for the *i*th tree at the *j*th measurement post-thinning in the *k*th plot within the *l*th installation. $\boldsymbol{X}_{ijkl}$ is the fixed effects design matrix of predictor variables (Table 1) for the *i*th tree at the *j*th measurement in the *k*th plot in the *l*th installation and $\boldsymbol{\beta}$ is the vector of fixed effect parameters. Because trees (*i*) were measured multiple times (*j*) within a plot (*k*), and there are multiple plots within an installation (*l*), random effects were included to account for lack of independence between individual trees-in-plots-in-installations and to account for the repeated measurements over time on individual trees. $\boldsymbol{Z}_{ijkl}$ represents the random effects design matrix on intercept and slope for each individual tree within a plot within an installation and $\boldsymbol{b}_i$ represents the random effect parameters for each individual tree.

Models were built in steps for pure western hemlock stands, adding covariates from Table 1 one at a time. Models were compared using Akaike's information criterion (AIC, Akaike 1974) to determine the best fitting model. Residual plots and histograms were assessed to ensure that model assumptions of homogeneity and normality were met.

4.2.3.1 Individual tree growth over time

First, a longitudinal model was built to understand how individual tree basal area growth changed over time:

$$BA\ PAI_{ijkl} = (\beta_0 + b_0) + (\beta_1 + b_1) \times YST_{ijkl} + \varepsilon_{ijkl} \quad (4.6)$$

where *YST* is the years since the thinning treatment was applied for the *i*th tree at the *j*th measurement in the *k*th plot within the *l*th installation, β_0 is the intercept, β_1 is the fixed effects parameter for *YST*, b_0 and b_1 are the random effects on the intercept and slope, respectively, and e_{ijkl} is the error term. Random effects on intercept and slope were included for each tree to account for the nested structure of the data, as well as to account for the repeated measurements over time. This model was fit for each thinning treatment. The relationship between basal area growth and time was linear, so no transformation of YST was needed. Weights were calculated for each observation using the reciprocal of initial tree basal area to account for heteroscedasticity.

4.2.3.2 Size and site effects

Next, pre-thinning individual tree basal area was included in the model to represent the size effect:

$$BA\ PAI_{ijkl} = (\beta_0 + b_0) + (\beta_1 + b_1) \times YST_{ijkl} + \beta_2 \times BA_{ijkl} + \varepsilon_{ijkl} \quad (4.7)$$

where β_2 is the fixed effects parameter for *BA* and all other coefficients are the same as in Equation 4.6.

Because the installations ranged in age and site productivity (Table 4-1), terms needed to be added to the model to take these differences into account. Initial stand age (*AGE*) was included to take into account the range of ages between installations and site index (*SI*) was used to represent the differences in site productivity:

$$BA\ PAI_{ijkl} = (\beta_0 + b_0) + (\beta_1 + b_1) \times YST_{ijkl} + \beta_2 \times BA_{ijkl} + \beta_3 \times AGE_{kl} + \beta_4 \times SI_{kl} + \varepsilon_{ijkl} \quad (4.8)$$

where β_3 is the fixed effects parameter for *AGE*, β_4 is the fixed effects parameter for *SI*, and all other coefficients are the same as in Equations 4.6 and 4.7. The random effect on intercept and slope tree-in-plot-in-installation was included to account for the nested structure of the data as well as the repeated measures. Weights, calculated from the inverse of initial basal area, were included to account for heteroscedasticity.

4.2.3.3 Competition effects

Competition terms were added next to observe how competition affects basal area growth:

$$BA\ PAI_{ijkl} = (\beta_0 + b_0) + (\beta_1 + b_1) \times YST_{ijkl} + \beta_2 \times BA_{ijkl} + \beta_3 \times AGE_{kl} + \beta_4 \times SI_{kl} + \beta_5 \times COMP_{ijkl} + \varepsilon_{ijkl} \quad (4.9)$$

where β_5 is the fixed effects parameter for the competition term *COMP*, and all other coefficients are the same as in Equations 4.6, 4.7, and 4.8. Total competition indices (BAL and SDIL) and competition indices by species (BAL_{hw}, BAL_{other}, $SDIL_{hw}$, $SDIL_{other}$) were included in the models and compared for the best fit using AIC. If the inclusion of the competition indices by species gives a better model fit than the total competition indices, it may indicate which tree species have more of a competitive effect (Pukkala et al. 2009).

4.2.3.4 Thinning effects

To quantify the effects of thinning on individual tree basal area growth, the thinning term was added to the model last:

$$BA\ PAI_{ijkl} = (\beta_0 + b_0) + (\beta_1 + b_1) \times YST_{ijkl} + \beta_2 \times BA_{ijkl} + \beta_3 \times AGE_{kl} \quad (4.10)$$

$$+ \beta_4 \times SI_{kl} + \beta_5 \times COMP_{ijkl} + \beta_6 \times THIN_{kl} + \varepsilon_{ijkl}$$

where β_6 is the fixed effects parameter for the thinning term *THIN*, and all other coefficients are the same as in equations 4.6, 4.7, 4.8, and 4.9.

4.3 Results

4.3.1 Differences in site and size

Including both site (SI, AGE) and size (initial BA) terms in the model resulted in the best fitting model (i.e., smallest AIC) for all treatments (Table 4-3). All terms were significant in the model for T1 plots, but the site index term was not significant in the control and T2 models. In T1 plots, individual basal area growth increased with increasing site index and initial basal area, but decreased as the initial age of the stand increased. In other words, basal area growth was larger in larger trees on more productive sites, but basal area growth was reduced in older stands. In control and T2 plots, individual basal area growth increased with initial basal area (i.e., basal area growth was larger in larger trees), but basal area growth was smaller if the age of the stand before thinning was older (Table 4-3).

Table 4-3. Estimated coefficient and p-values with the inclusion of site and size effects for models by thinning. AGE – age of the stand before thinning; SI – site index; T0 – control plots (0% BA removed); T1 – 20% BA removed; T2 – 35% BA removed.

		T0		T1		T2	
Variable	**Parameter**	**Estimate**	**p-value**	**Estimate**	**p-value**	**Estimate**	**p-value**
Intercept	β_0	0.001128	<0.0001	0.001597	<0.0001	0.001723	<0.0001
YST	β_1	$-2.96*10^{-6}$	0.0070	-0.00001	<0.0001	-0.00001	<0.0001
AIC		-62129.3		-50601.8.5		-46415.0	
Intercept	β_0	-0.00086	<0.0001	0.000703	0.0851	0.000213	0.5955
YST	β_1	$-2.65*10^{-6}$	0.0166	-0.00001	<0.0001	-0.00001	<0.0001
Age	β_2	-0.00002	<0.0001	$-5.125*10^{-6}$	0.3021	$-5.22*10^{-6}$	0.3760
SI	β_3	0.000114	<0.0001	0.000025	0.1320	0.000064	0.0003
AIC		-62181.5		-50564.7		-46385.7	
Intercept	β_0	0.002081	<0.0001	0.004418	<0.0001	0.003610	<0.0001
YST	β_1	$-3.94*10^{-6}$	0.0006	-0.00001	<0.0001	-0.00001	<0.0001
Age	β_2	-0.00005	<0.0001	-0.00005	<0.0001	-0.00007	<0.0001
SI	β_3	$3.475*10^{-6}$	0.6554	-0.00008	<0.0001	-0.00002	0.1516
Initial basal area	β_4	0.02442	<0.0001	0.03103	<0.0001	0.03201	<0.0001
AIC		-62723.6		-50989.0		-46765.9	

4.3.2 Inter- and intra-specific competition

The inclusion of relative BAL resulted in a better model fit (i.e., model AIC decreased) than relative SDIL, so results presented are based on relative BAL only. Including the relative BAL terms by species resulted in a decrease in AIC compared to including the total relative BAL. The species-specific relative BAL for western hemlock was significant in all models, but the relative BAL for other species was only significant in the unthinned models (Table 4-4).

All terms were significant in the unthinned model (Table 4-4). Basal area growth increased over time and with increasing site productivity, and growth was larger in larger trees than in smaller trees. Basal area growth was reduced if the stands were older at the time of thinning. The relative BAL terms by species showed that basal area growth decreased as competition from hemlock trees increased, but basal area growth increased as relative BAL of other species increased (Table 4-4).

Not all terms were significant in the T1 and T2 models (Table 4-4). In the T1 models, including the relative BAL terms by species resulted in AGE no longer being significant in the model, while there was suggestive evidence that basal area growth increased with increased BA pre-thinning (p=0.0871). Relative BAL of other species was also not significant in the model. In T1 plots, basal area growth increased over time, and with site productivity, but decreased with increasing competition from hemlock trees. In T2 models, only relative BAL of hemlock species was significant, indicating that basal area growth decreased with increasing competition from hemlock trees. There was suggestive but inconclusive evidence that YST was significant in the model (p=0.0848). In other words, it is not certain that basal area growth was changing over time (Table 4-4).

Table 4-4. Parameter estimates of variables in models with the inclusion of competition effects.

		T0		T1		T2	
Variable	**Parameter**	**Estimate**	**p-value**	**Estimate**	**p-value**	**Estimate**	**p-value**
Intercept	β_0	0.001221	<0.0001	0.001912	<0.0001	0.002699	<0.0001
YST	β_1	$6.533*10^{-6}$	<0.0001	$5.157*10^{-6}$	<0.0001	$2.678*10^{-6}$	0.0848
Age	β_2	-0.00003	<0.0001	$-1.18*10^{-6}$	0.7235	$6.686*10^{-6}$	0.2681
Site Index	β_3	0.00005	<0.0001	0.000043	<0.0001	0.000011	0.1173
Initial basal area	β_4	0.01082	<0.0001	0.002221	0.0871	0.001869	0.2089
Relative BAL_{hw}	β_5	-0.00161	<0.0001	-0.00321	<0.0001	-0.00307	<0.0001
Relative BAL_{other}	β_6	0.000105	0.0026	0.000012	0.7718	$8.936*10^{-6}$	0.9984
AIC		-62927.1		-51587.2		-47095.0	

4.3.3 Full model

Basal area growth was larger in larger trees, and growth rates increased over time, and with higher site productivity (Table 4-5). Basal area growth decreased as competition from hemlock increased, but was not affected by increasing competition from other trees. Basal area growth was lower in stands that were thinned at older ages.

Significant differences in basal area growth after thinning were found between the treatments ($p < 0.0001$). Specifically, the more a stand was thinned, the larger the average individual-tree basal area growth was after thinning.

Table 4-5. Model coefficients and p-values for full model

Variable	Parameter	Estimate	p-value
Intercept	β_0	0.001892	<0.0001
Treatment T1	β_0	0.000294	<0.0001
Treatment T2	β_0	0.000537	<0.0001
YST	β_1	$6.016*10^{-6}$	<0.0001
Age	β_2	$-5.73*10^{-6}$	0.0049
Site Index	β_3	0.000021	<0.0001
Initial basal area	β_4	0.005748	<0.0001
Relative BAL_{hw}	β_5	-0.00259	<0.0001
Relative BAL_{other}	β_6	0.000041	0.0702
AIC		-161254	

4.4 Discussion

Using long-term data, this study aimed to describe 1) how basal area growth of individual western hemlock trees varies across different tree size and stand and site characteristics, and 2) how inter- and intra-specific competition affects basal area growth of western hemlock trees. Results showed that basal area growth of western hemlock trees in pure stands increases with tree size and varies with stand age and site conditions. Results also showed that inter- vs intra-specific competition had different effects on basal area growth.

4.4.1 Effects of initial basal area on tree growth

One limitation to analyzing average basal area growth is the assumption that all trees are growing at the same rate (Pretzsch 2009). The full model indicated that average basal area growth increased with heavier thinning treatments, but the significant initial basal area term indicated that basal area growth differed across tree sizes. In this study, a modified commercial thinning was applied at moderate intensities, with a focus on keeping the size distribution of the stands identical to their pre-thinning conditions, though dominant and co-dominant trees were usually preferred as residual trees in the stand (Darling and Omule 1989). Removing smaller trees from the stands will instantly increase the average basal area, thus leading to an apparent increase in basal area growth. This artificial increase in basal area growth is known as the "false effect" or "chainsaw effect" (BC MoF 1999). Other studies have found similar results. In a long-term growing stock experiment in coastal Oregon, Washington, and British Columbia, Marshall and Curtis (2002) found that thinning did not improve basal area growth in Douglas-fir stands when the diameter distribution was kept similar before and after thinning. These results are comparable to my findings in western hemlock stands. Marshall and Curtis (2002) state that thinning treatments would not normally be applied to maintain diameter distributions. The benefits of thinning include the production of larger trees and the salvaging of mortality and enhanced tree vigor (Marshall and Curtis 2002). Thinning treatments would then remove the smallest, least vigorous trees in favour of larger trees. By incorporating individual tree basal area pre-thinning in the model, I observed that individual tree basal area growth is differs across tree sizes, and that the increased average basal area growth is likely due to the "false effect".

4.4.2 Effects of stand characteristics on tree growth

Individual tree growth changes over time, where young trees have higher rates of growth and old trees have slower growth (Oliver and Larson 1996). Stand and species characteristics will also have an effect on the growth efficiency of a tree (Binkley et al. 2004). In general, previous research has found that tree growth is affected by site in both pure and mixed species stands to some degree (Monserud and Sterba 1996, Diaconu et al. 2015, Mina et al. 2017). While this study used site index to represent site quality, a number of variables can be used, such as habitat type, slope, aspect, elevation, or climate variables (Weiskittel et al. 2011). Diaconu et al. (2015) used aspect to represent site in European beech forests, and found that tree basal area growth differed between southwest and northeast aspects. Mina et al. (2017) found that slope and soil pH had a negative effect on basal area growth of Norway spruce, silver fir, European beech, maple, and ash trees, though the strength of this effect differed among species. Results of this study found that basal area growth increased with higher site quality. The years since thinning term was significant and positive in the full model, indicating that basal area growth was still increasing over time. The western hemlock stands were still relatively young, with a median age of 39 years (31-66 years) at the time of thinning, so positive growth rates are expected, as western hemlock trees have been shown to have constant growth rates up to around age 70 (Meyer 1937). However, individual tree basal area growth was negatively related to stand age.

This is expected, as tree growth is reduced in older stands (Oliver and Larson 1996), so basal area growth in younger western hemlock stands will be higher than in the older stands in this study.

4.4.3 Effects of inter- vs intra-specific competition on tree growth

Previous research has shown that the inclusion of a competition term is necessary for explaining tree growth over time (Forrester et al. 2017). Our results showed that including competition terms by species improved the basal area growth model. Though the focus of this study was on “pure” western hemlock stands, there was still a minor component (<10% basal area) of other species, so some level of inter-specific competition was present. Results of this study showed that intra-specific competition had a greater effect than inter-specific competition. Many studies of mixed species stands have found that intra-specific competition has a greater effect on tree growth than inter-specific competition, regardless of the species and mixture types (Canham et al. 2004, del Río et al. 2014). However, this effect can be positive or negative, depending on the species characteristics and site conditions, such as shade tolerance (Dietze et al. 2008), wood density (Forrester et al. 2017), stand density, and stand development (Mina et al. 2017).

Previous research has also found that the strength of inter-specific competition varies with species. Canham et al. (2004) looked at inter-specific competition in mixed western hemlock and western redcedar, where western hemlock dominated the stand, and found that western redcedar had little effect on western hemlock trees, similar to our results. However, western hemlock had a strong competitive effect on western redcedar trees, which Canham et al. (2004) concluded was partially due to the increased presence of western hemlock trees. The weak inter-specific competition in our stands can be explained by the small presence of other species present in these plots. Inter-specific competition was only significant in control plots, where there was a greater proportion of other species compared to the thinned plots. Where other species were established in the plots, they were normally intermediate or suppressed trees. Therefore, they do not have much of an effect on the growth of co-dominant or dominant hemlock trees.

4.5 Conclusion

This study analyzed the effects of thinning and competition on the basal area growth of western hemlock trees in pure western hemlock stands across a variety of stand and site characteristics. Many stand-level thinning studies find that basal area growth increases with heavier thinning treatments, but my tree-level analysis showed that basal area growth does not increase with thinning. Results also showed that inter- and intra-specific competition have different effects on western hemlock trees. Specifically, the low inter-specific competition may indicate that mixing species results in improved basal area growth of western hemlock trees. Forest managers may look to move from monocultures to mixed species stands to improve individual tree basal area growth.

Chapter 5: Conclusions

5.1 Overall conclusions

This thesis contributes to the understanding of thinning effects at the stand and tree level in pure and mixed Douglas-fir and western hemlock stands. At the stand level, I found that size inequality decreased over time in pure stands, but stayed the same over time in mixed species stands, regardless of thinning treatment. Results also indicated that thinning treatments increased growth efficiency in smaller trees, and that growth efficiency of all trees was better in mixed species stands then in pure stands. At the tree-level, I found that larger trees responded better to thinning treatments than small trees did. I also found that an increase in intra-specific competition negatively affected basal area growth of western hemlock trees, while an increase in competition from other species may benefit basal area growth in western hemlock trees. Overall, the two thesis chapters display that mixed species stands have the potential to reduce competition between trees and increase growth efficiency in both small and large trees.

This thesis largely focused on complementarity of aboveground resources (e.g., light, growing space) to reduce competition, but research suggests that facilitative interactions (i.e., one species benefits another) in mixed species stands may increase stand productivity (Kelty 2006). Future research may look into species mixtures where one species facilitates the growth of the other, through soil nutrients or ectomycorrhizal connections (Simard et al. 1997).

5.2 Pure vs mixed species stands

One limitation to this study is that the “pure” stands included tree species other than Douglas-fir and western hemlock. In the stand-level chapter, size inequality and growth dominance over time in pure Douglas-fir and mixed species stands had similar trends, largely because the pure Douglas-fir stands were anywhere from 83-99% of Douglas-fir basal area and mixed species stands were dominated by Douglas-fir (e.g., 60:40 percent basal area Douglas-fir/western hemlock). In the tree-level chapter, the addition of other species provided insight into how the presence of minor species (i.e., inter- vs intra-specific competition) affects basal area growth of dominant species in a stand.

5.2.1 Effects of thinning and competition on growth in pure and mixed species stands

Thinning treatments are typically applied to remove small, growth inefficient trees and promote growth in larger trees (Oliver and Larson 1996). Forest managers must find a balance of removing enough trees to increase growth in residual trees, but not removing so much that there is a net decrease in stand volume (Johnstone and van Thienen 200, Forrester et al. 2013). Pretzsch and Schütze (2016) suggest that mixed species stands could replace heavy thinning treatments by planting growth efficient mixtures rather than removing suppressed trees. Previous research has shown that mixed species stands may be more productive than pure stands through complementary resource use (Chen et al. 2003, Kelty 2006). Trees of the same species will directly compete with each other for the same site resources (Pretzsch and Schütze 2016), but species with differences in characteristics (e.g., shade tolerance, growth rates, root morphology, etc.) are able to use site resources in a more efficient manner (Kelty 2006). Douglas-fir and western hemlock are considered complementary species, as Douglas-fir is a fast growing, shade intolerant species, whereas western hemlock is a slower growing, shade tolerant species (Oliver and Larson 1996). Other studies have found that mixtures of these two species have resulted in increased productivity (Reukema and Smith, 1987, Amoroso and Turnblom 2006), and our results agreed. In the stand-structure dynamics analysis, I found that stand productivity and growth efficiency of small and large trees was highest in mixed species stands. Amoroso and Turnblom (2006) suggest that increased productivity is a result of the stratification of Douglas-fir and western hemlock trees, which leads to better site resource use and decreased competition. In the tree-level basal area growth analysis, results suggested that increased intra-specific competition improves the basal area growth of western hemlock trees. Forest managers may look to manage stands of complementary species, such as Douglas-fir and western hemlock, in order to increase individual tree growth and stand volume simultaneously.

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Appendices

Appendix A Chapter 3 Additional Figures and Tables

A.1 Tables of average DBH and trees per hectare by thinning treatment, measurement, species, and stand type

Table A-1. Average DBH (cm) and standard deviation (in parentheses) by species, measurements, and stand type.

Stand Type	Species	Thin	YST		
			1	17	34
FD	FD	T0	18.82 (7.26)	21.08 (7.80)	26.44 (8.91)
		T1	19.86 (6.99)	22.32 (7.26)	27.73 (7.69)
		T2	21.14 (7.81)	23.77 (8.24)	28.72 (9.12)
	HW	T0	9.36 (6.70)	11.02 (6.27)	10.41 (4.18)
		T1	12.41 (9.51)	14.61 (9.28)	13.56 (10.02)
		T2	7.71 (7.32)	10.92 (7.89)	10.89 (6.18)
	CW	T0	7.79 (3.16)	9.15 (2.53)	10.17 (2.48)
		T1	9.77 (6.12)	11.54 (6.04)	13.56 (6.34)
		T2	7.11 (4.36)	9.48 (4.16)	11.27 (5.38)
	O	T0	13.19 (8.57)	14.06 (9.56)	15.86 (10.88)
		T1	14.59 (10.05)	15.48 (10.49)	17.22 (10.83)
		T2	8.60 (7.74)	7.98 (3.31)	5.77 (0.24)
HW	FD	T0	20.80 (--)	21.80 (--)	22.30 (--)
		T1	--	--	--
		T2	--	--	--
	HW	T0	17.89 (7.45)	20.83 (7.20)	25.95 (7.18)
		T1	19.72 (7.31)	21.97 (7.21)	27.27 (6.27)

		T2	20.71 (8.26)	23.19 (8.11)	28.68 (6.96)
	CW	T0	19.58 (4.60)	21.64 (5.14)	29.41 (7.54)
		T1	14.64 (4.32)	14.98 (5.79)	15.36 (6.83)
		T2	15.04 (4.11)	15.32 (4.28)	17.51 (2.88)
	O	T0	15.10 (8.42)	20.98 (14.53)	30.95 (17.83)
		T1	23.10 (12.67)	27.62 (13.82)	32.72 (14.21)
		T2	22.71 (10.67)	25.20 (10.96)	32.69 (10.23)
MIX	FD	T0	20.27 (8.62)	23.48 (9.09)	28.70 (10.70)
		T1	22.46 (10.82)	25.54 (11.55)	31.21 (13.02)
		T2	22.85 (9.98)	25.78 (10.06)	30.80 (10.901)
	HW	T0	14.75 (8.30)	16.69 (8.38)	19.99 (10.00)
		T1	16.06 (10.80)	18.86 (11.20)	22.42 (12.44)
		T2	19.32 (15.74)	22.30 (16.19)	24.32 (13.38)
	CW	T0	8.54 (1.45)	9.14 (1.00)	10.10 (1.58)
		T1	10.06 (4.20)	11.03 (4.25)	12.11 (4.32)
		T2	10.33 (12.37)	13.08 (12.77)	15.17 (15.89)
	O	T0	5.55 (0.49)	7.00 (--)	7.50 (--)
		T1	9.50 (--)	12.40 (--)	17.40 (--)
		T2	16.80 (--)	--	--

Table A-2. Trees per hectare (TPH) by species, measurement, and stand type.

Stand Type	Species	Thin	YST		
			1	17	34
FD	FD	T0	35,023	32,937	24,397
		T1	25,046	23,209	18,751
		T2	19,760	19,109	16,834
	HW	T0	5,157	4,963	4,817
		T1	3,549	3,369	3,949
		T2	3,486	3,203	4,054
	CW	T0	2,102	2,102	2,286
		T1	1,474	1,474	1,649
		T2	943	929	1,191
	O	T0	1,080	871	469
		T1	474	394	234
		T2	274	254	100
HW	FD	T0	20	20	20
		T1	0	0	0
		T2	0	0	0
	HW	T0	37,231	26,383	17,340
		T1	23,294	20,311	14,457
		T2	18,069	15,926	12,237
	CW	T0	489	389	234
		T1	137	103	89
		T2	154	154	140
	O	T0	589	394	194
		T1	397	363	283

		T2	243	243	203
MIX	FD	T0	10,770	9,630	7,960
		T1	7,760	7,370	6,480
		T2	6,270	6,080	5,580
	HW	T0	7,520	7,030	4,970
		T1	4,150	3,870	3,660
		T2	3,140	3,070	2,630
	CW	T0	2,750	2,610	2,290
		T1	1,260	1,280	1,240
		T2	1,320	1,340	2,060
	O	T0	40	20	20
		T1	20	20	20
		T2	20	0	0

A.2 DBH distribution for EP703

The following figures show the DBH distributions for the 22 installations from this study. Each bar represents a 5cm DBH class. Each histogram includes the DBH distribution before the thinning treatment (PRE) and the DBH distribution for each measurement post-thinning. Histograms are divided by thinning treatment (T0 – T2) and each species (Douglas-fir, western hemlock, western redcedar, and others) are represented by different colours.

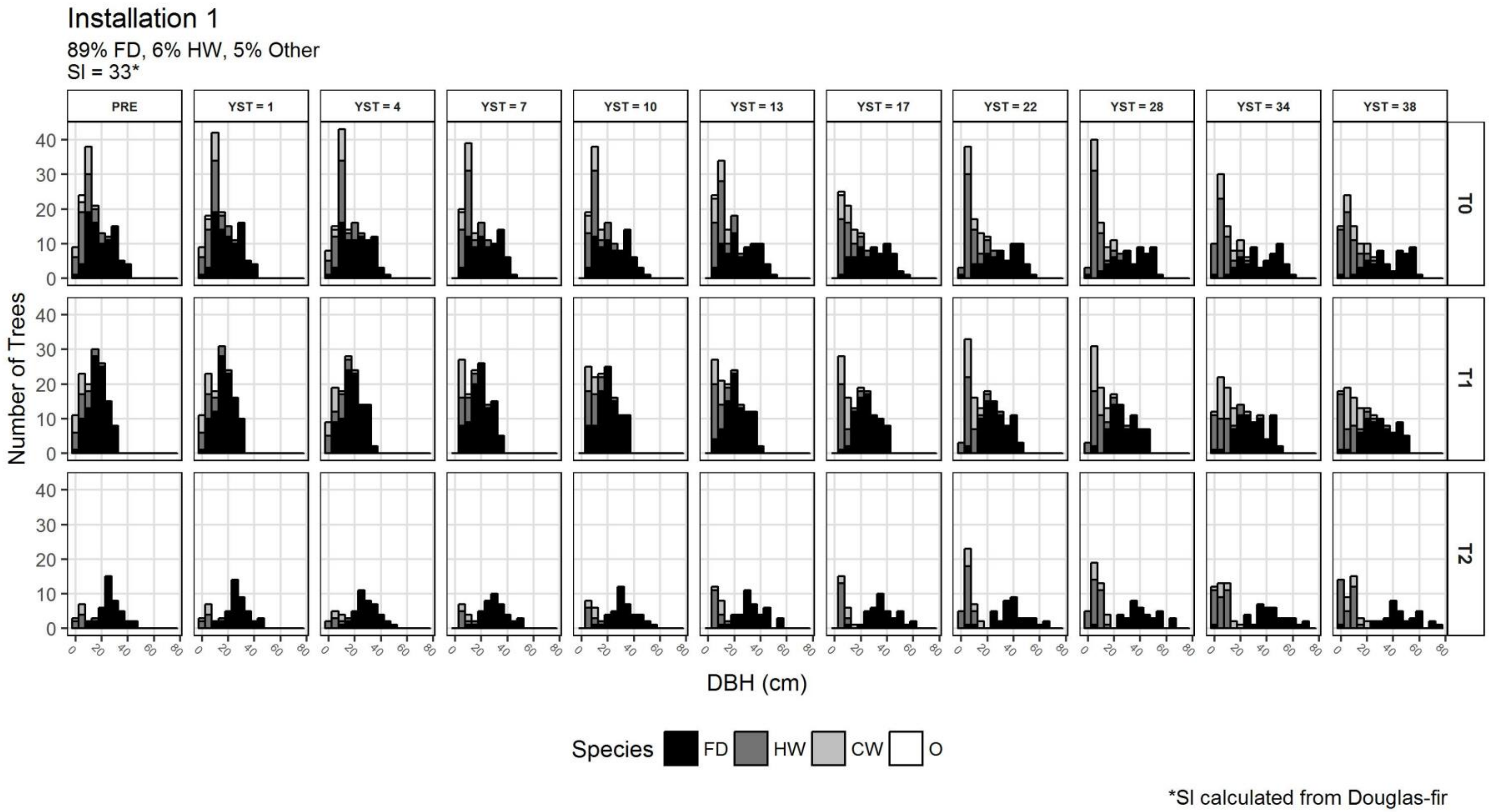

Figure A-1. DBH distributions over time and across treatments. PRE: pre-thinning measurement period; YST: years since treatment; T0: control, 0% BA removed; T1: 20% BA removed; T2: 35% BA removed; SI: site index; FD: Douglas-fir; HW: western hemlock; CW: western redcedar; O: other species.

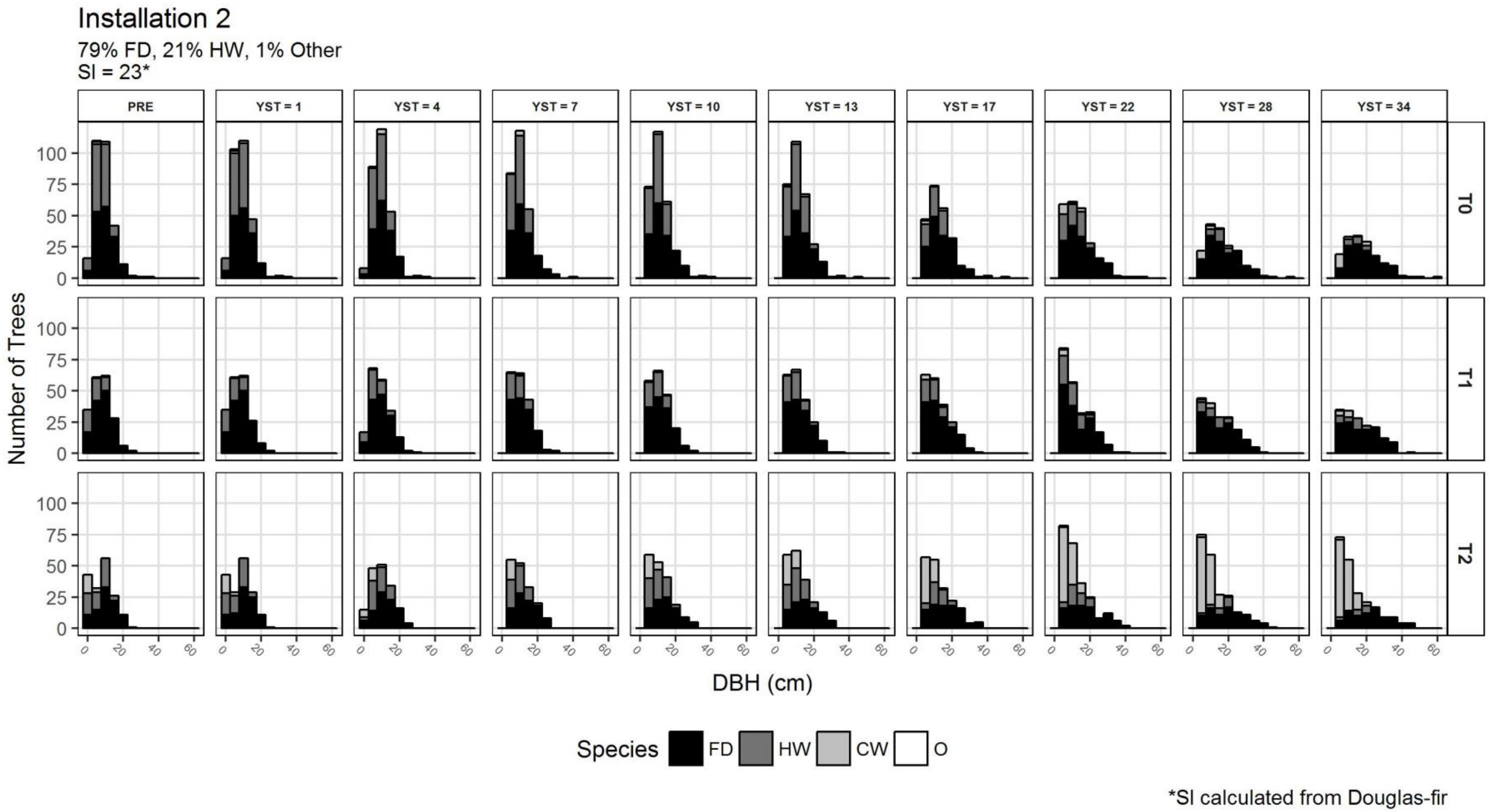

Figure A-2. DBH distributions over time and across treatments. PRE: pre-thinning measurement period; YST: years since treatment; T0: control, 0% BA removed; T1: 20% BA removed; T2: 35% BA removed; SI: site index; FD: Douglas-fir; HW: western hemlock; CW: western redcedar; O: other species.

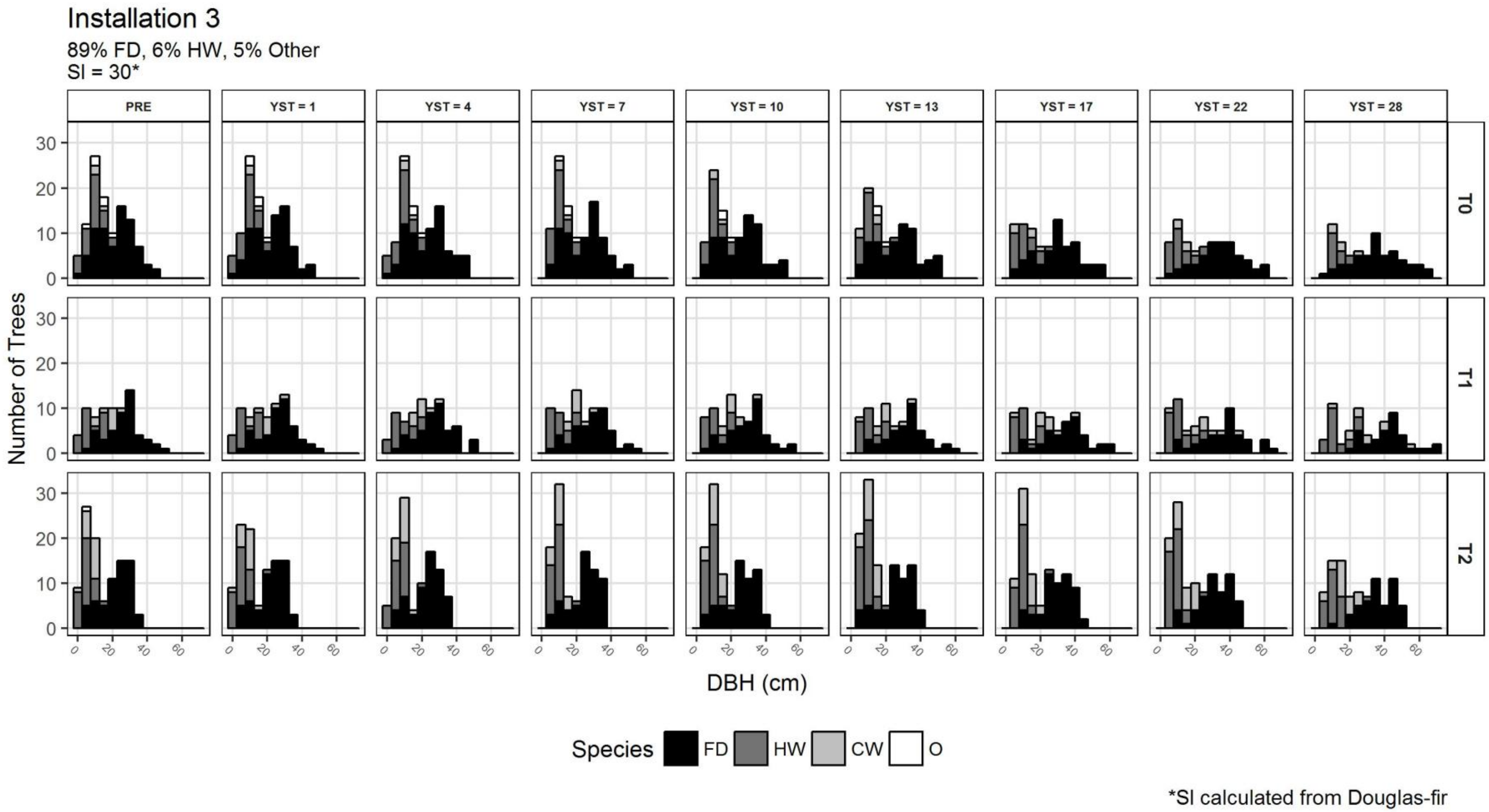

Figure A-3. DBH distributions over time and across treatments. PRE: pre-thinning measurement period; YST: years since treatment; T0: control, 0% BA removed; T1: 20% BA removed; T2: 35% BA removed; SI: site index; FD: Douglas-fir; HW: western hemlock; CW: western redcedar; O: other species.

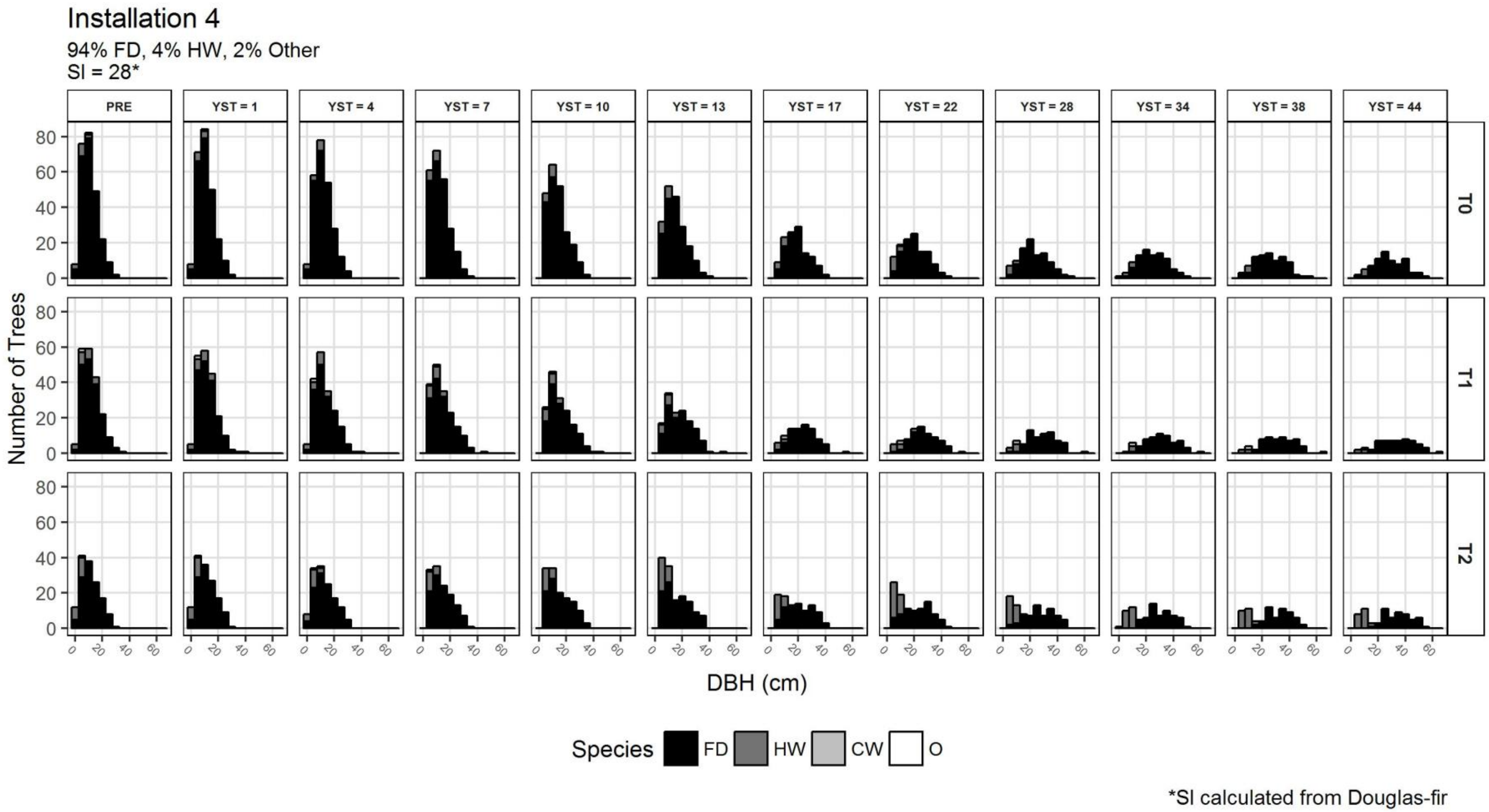

Figure A-4. DBH distributions over time and across treatments. PRE: pre-thinning measurement period; YST: years since treatment; T0: control, 0% BA removed; T1: 20% BA removed; T2: 35% BA removed; SI: site index; FD: Douglas-fir; HW: western hemlock; CW: western redcedar; O: other species.

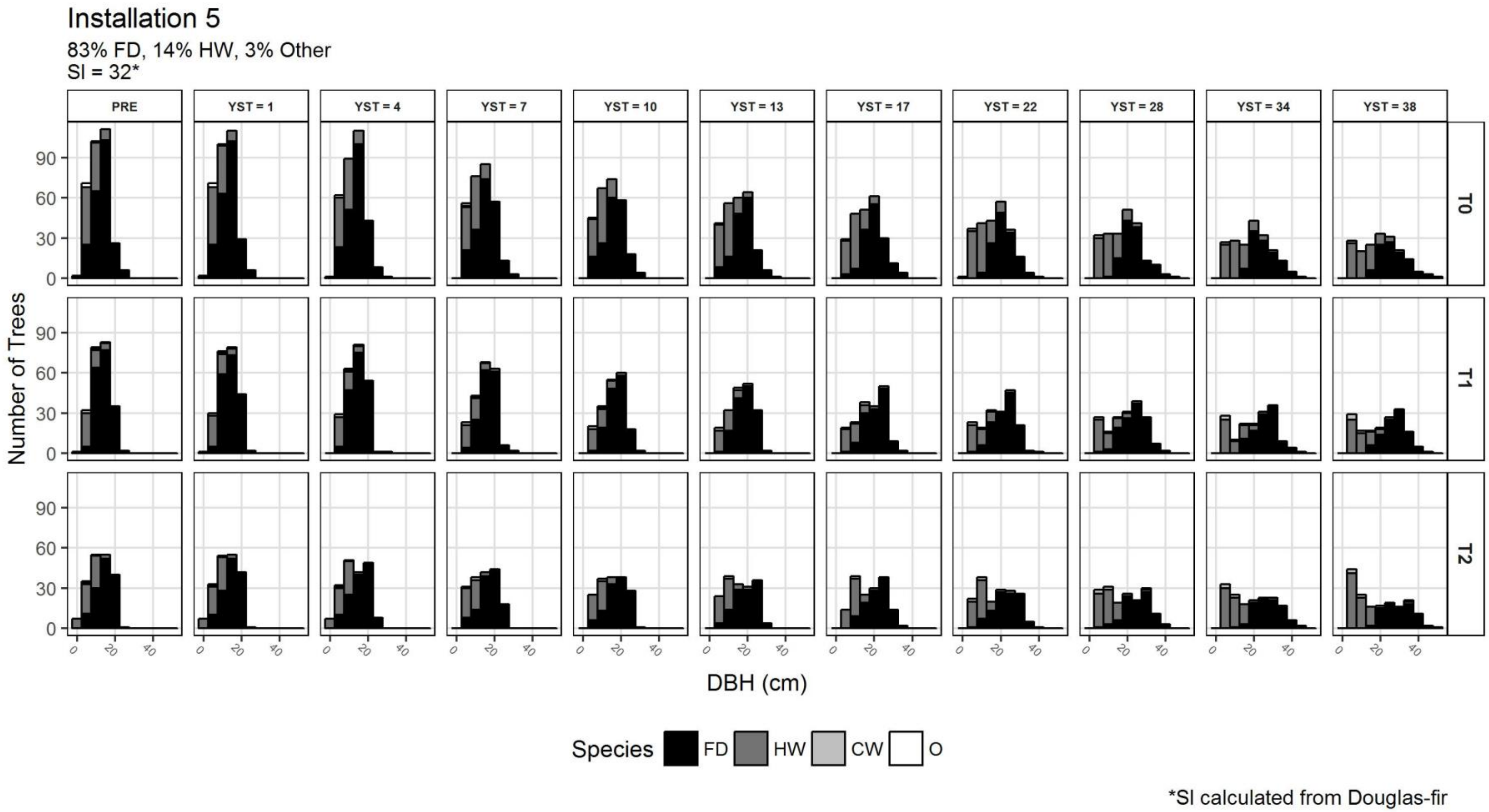

Figure A-5. DBH distributions over time and across treatments. PRE: pre-thinning measurement period; YST: years since treatment; T0: control, 0% BA removed; T1: 20% BA removed; T2: 35% BA removed; SI: site index; FD: Douglas-fir; HW: western hemlock; CW: western redcedar; O: other species.

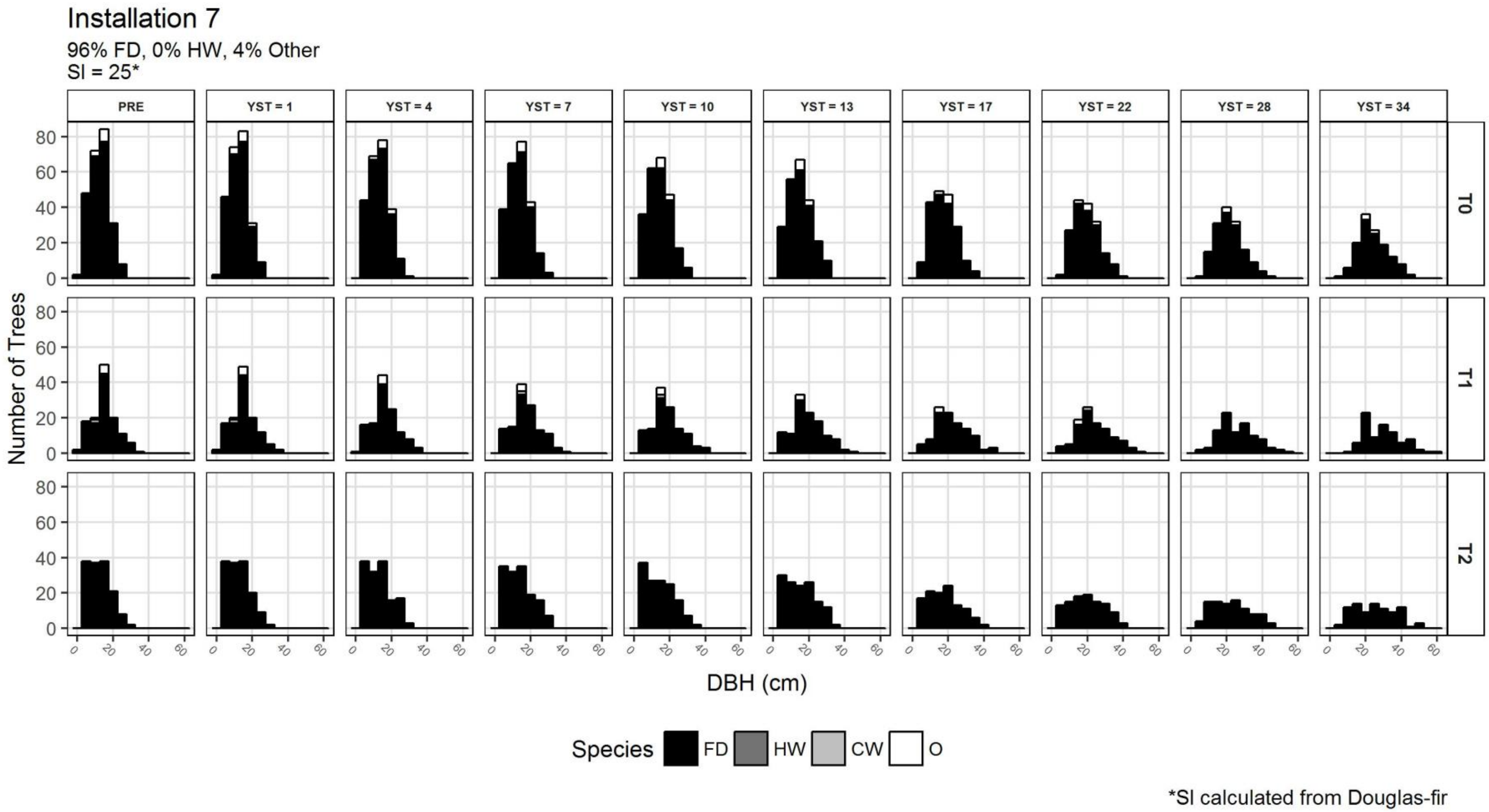

Figure A-6. DBH distributions over time and across treatments. PRE: pre-thinning measurement period; YST: years since treatment; T0: control, 0% BA removed; T1: 20% BA removed; T2: 35% BA removed; SI: site index; FD: Douglas-fir; HW: western hemlock; CW: western redcedar; O: other species.

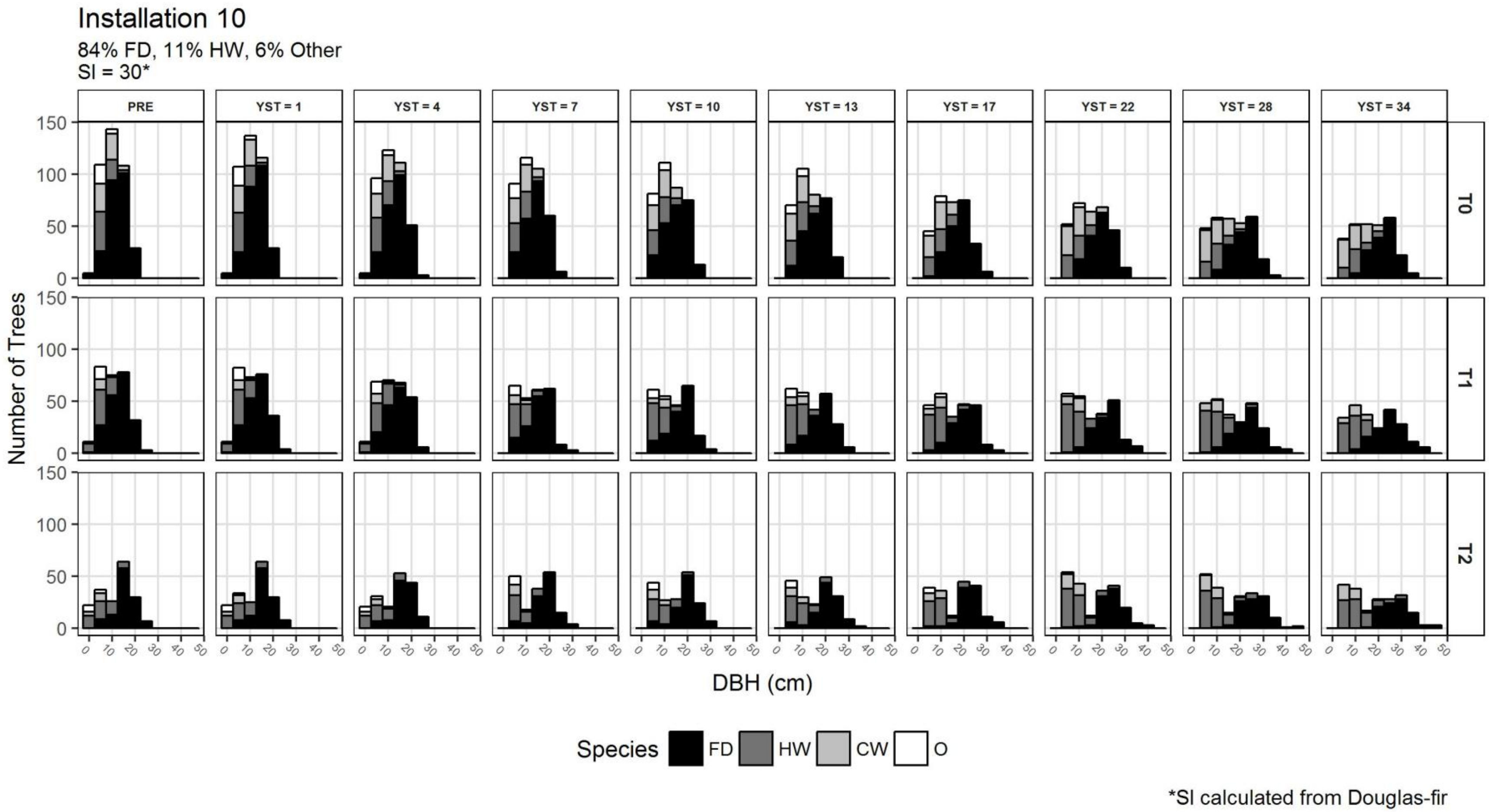

Figure A-7. DBH distributions over time and across treatments. PRE: pre-thinning measurement period; YST: years since treatment; T0: control, 0% BA removed; T1: 20% BA removed; T2: 35% BA removed; SI: site index; FD: Douglas-fir; HW: western hemlock; CW: western redcedar; O: other species.

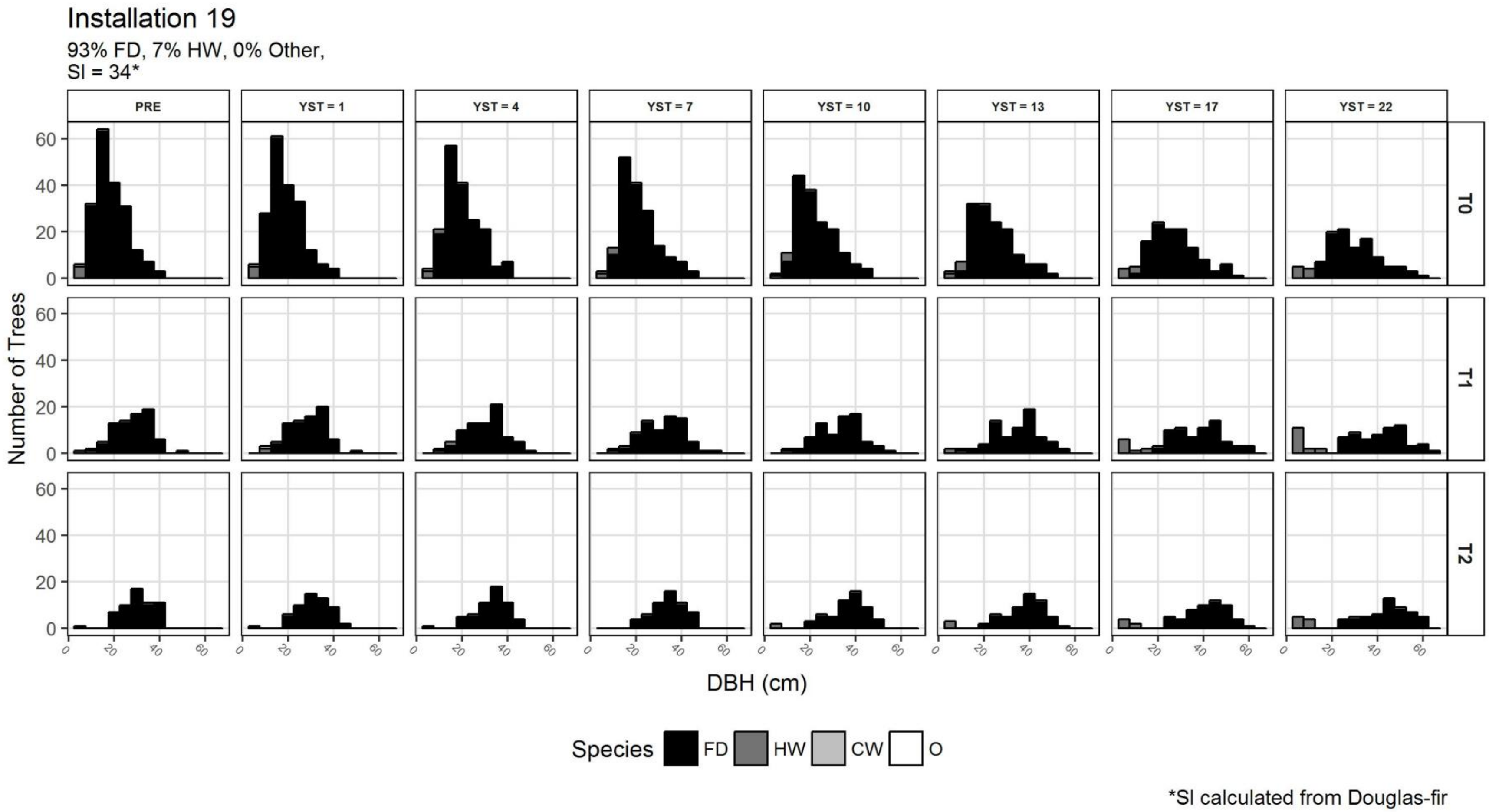

Figure A-8. DBH distributions over time and across treatments. PRE: pre-thinning measurement period; YST: years since treatment; T0: control, 0% BA removed; T1: 20% BA removed; T2: 35% BA removed; SI: site index; FD: Douglas-fir; HW: western hemlock; CW: western redcedar; O: other species.

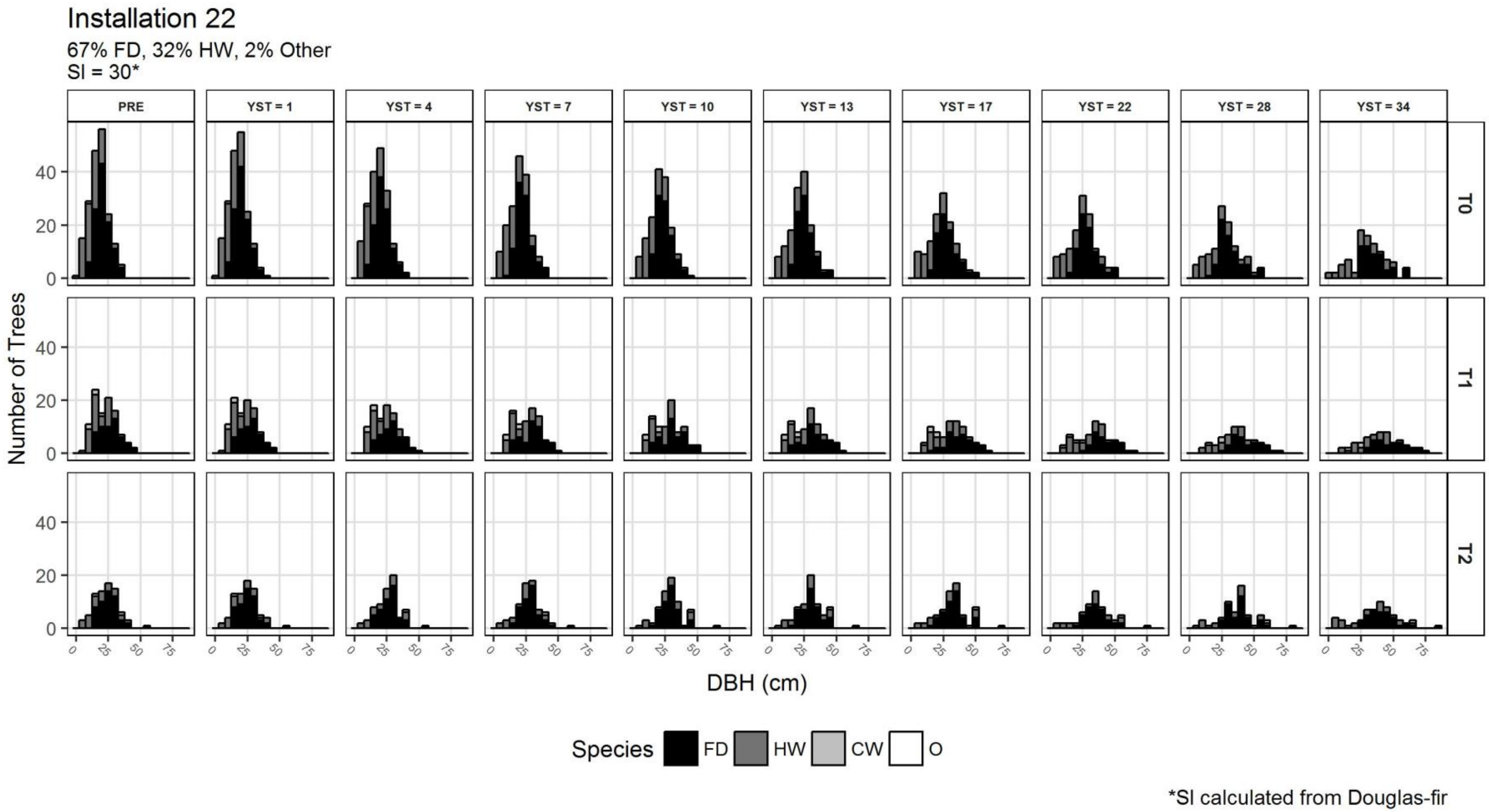

Figure A-9. DBH distributions over time and across treatments. PRE: pre-thinning measurement period; YST: years since treatment; T0: control, 0% BA removed; T1: 20% BA removed; T2: 35% BA removed; SI: site index; FD: Douglas-fir; HW: western hemlock; CW: western redcedar; O: other species.

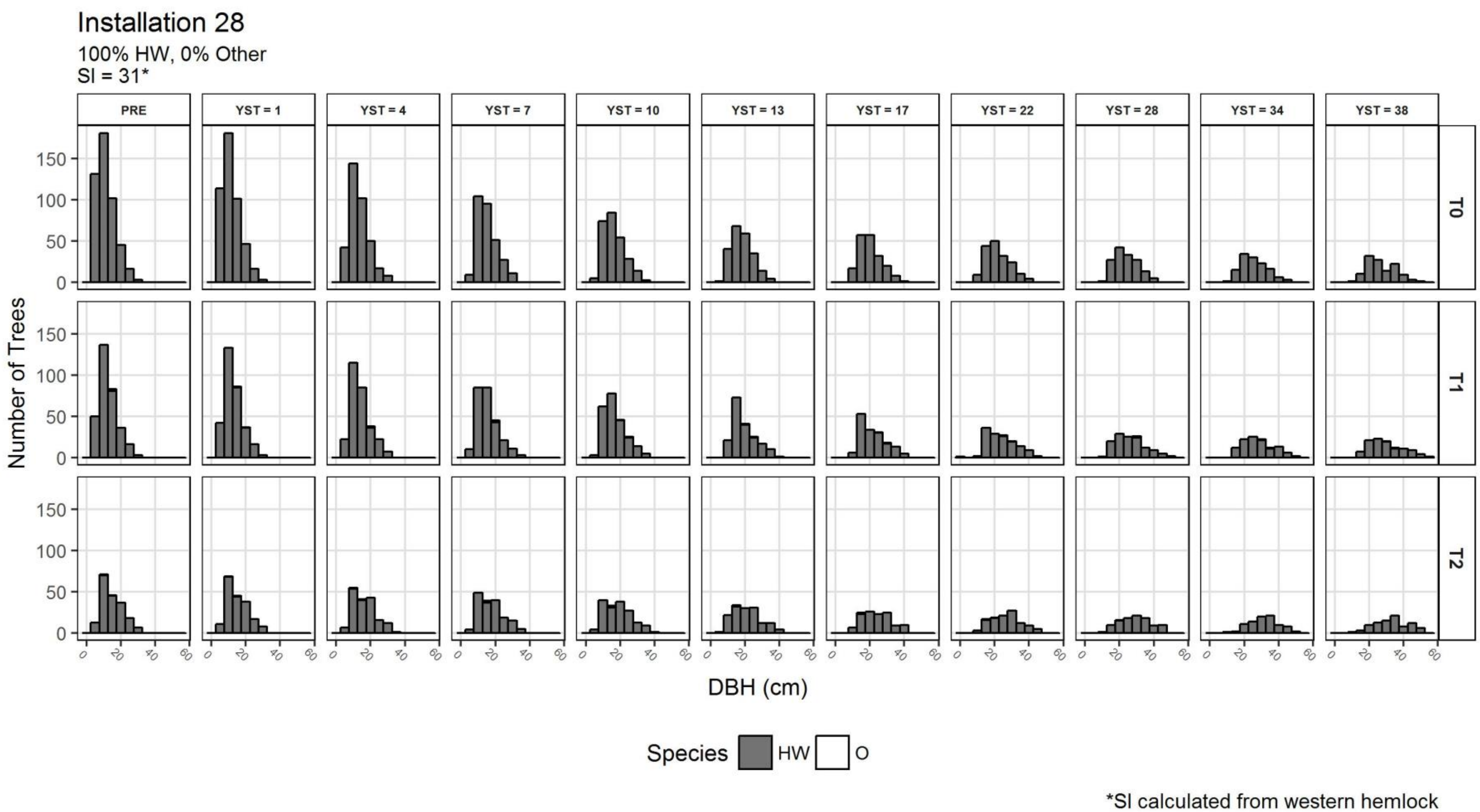

Figure A-10. DBH distributions over time and across treatments. PRE: pre-thinning measurement period; YST: years since treatment; T0: control, 0% BA removed; T1: 20% BA removed; T2: 35% BA removed; SI: site index; HW: western hemlock; O: other species.

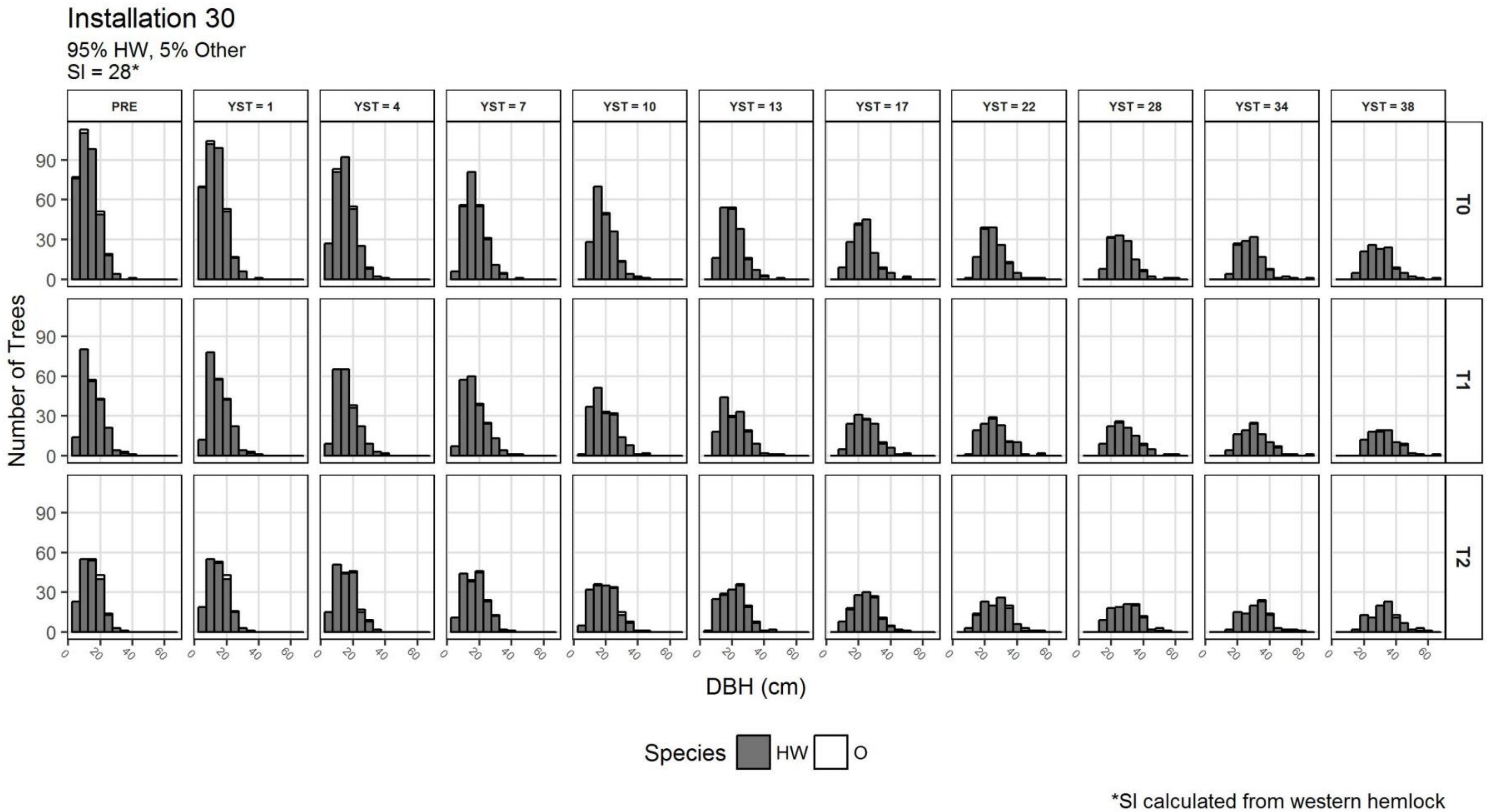

Figure A-11. DBH distributions over time and across treatments. PRE: pre-thinning measurement period; YST: years since treatment; T0: control, 0% BA removed; T1: 20% BA removed; T2: 35% BA removed; SI: site index; HW: western hemlock; O: other species.

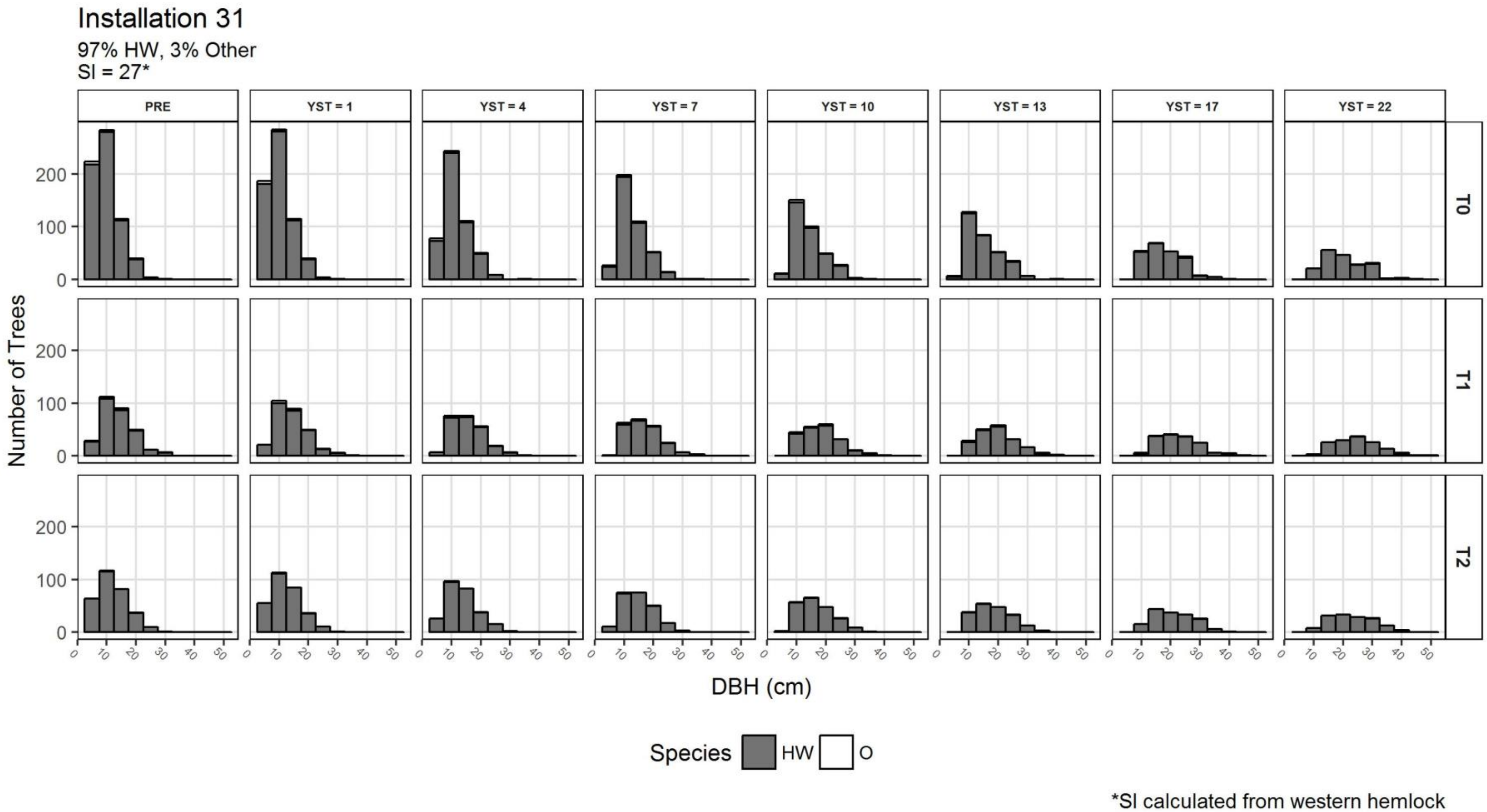

Figure A-12. DBH distributions over time and across treatments. PRE: pre-thinning measurement period; YST: years since treatment; T0: control, 0% BA removed; T1: 20% BA removed; T2: 35% BA removed; SI: site index; HW: western hemlock; O: other species.

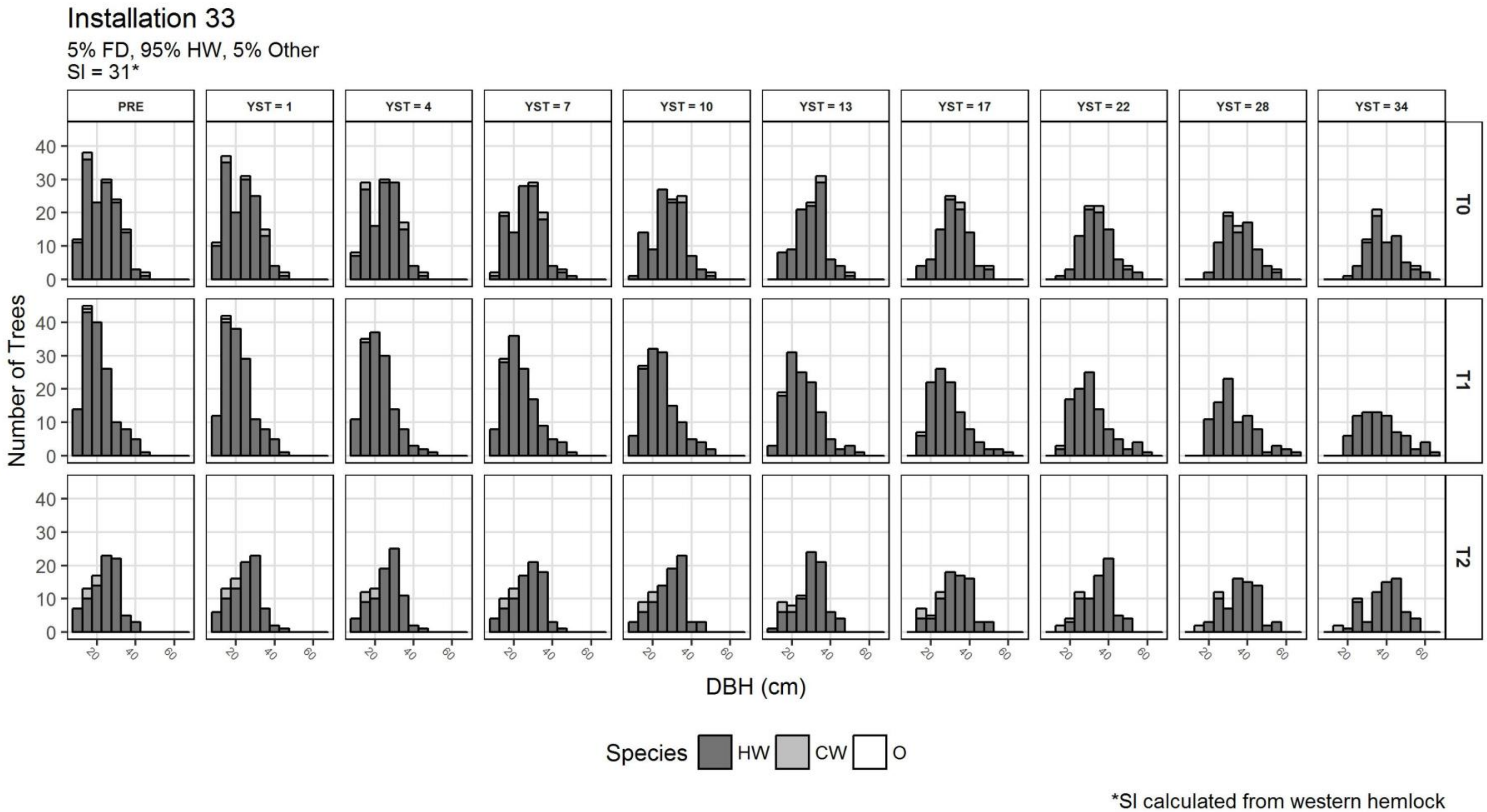

Figure A-13. DBH distributions over time and across treatments. PRE: pre-thinning measurement period; YST: years since treatment; T0: control, 0% BA removed; T1: 20% BA removed; T2: 35% BA removed; SI: site index; HW: western hemlock; CW: western redcedar; O: other species.

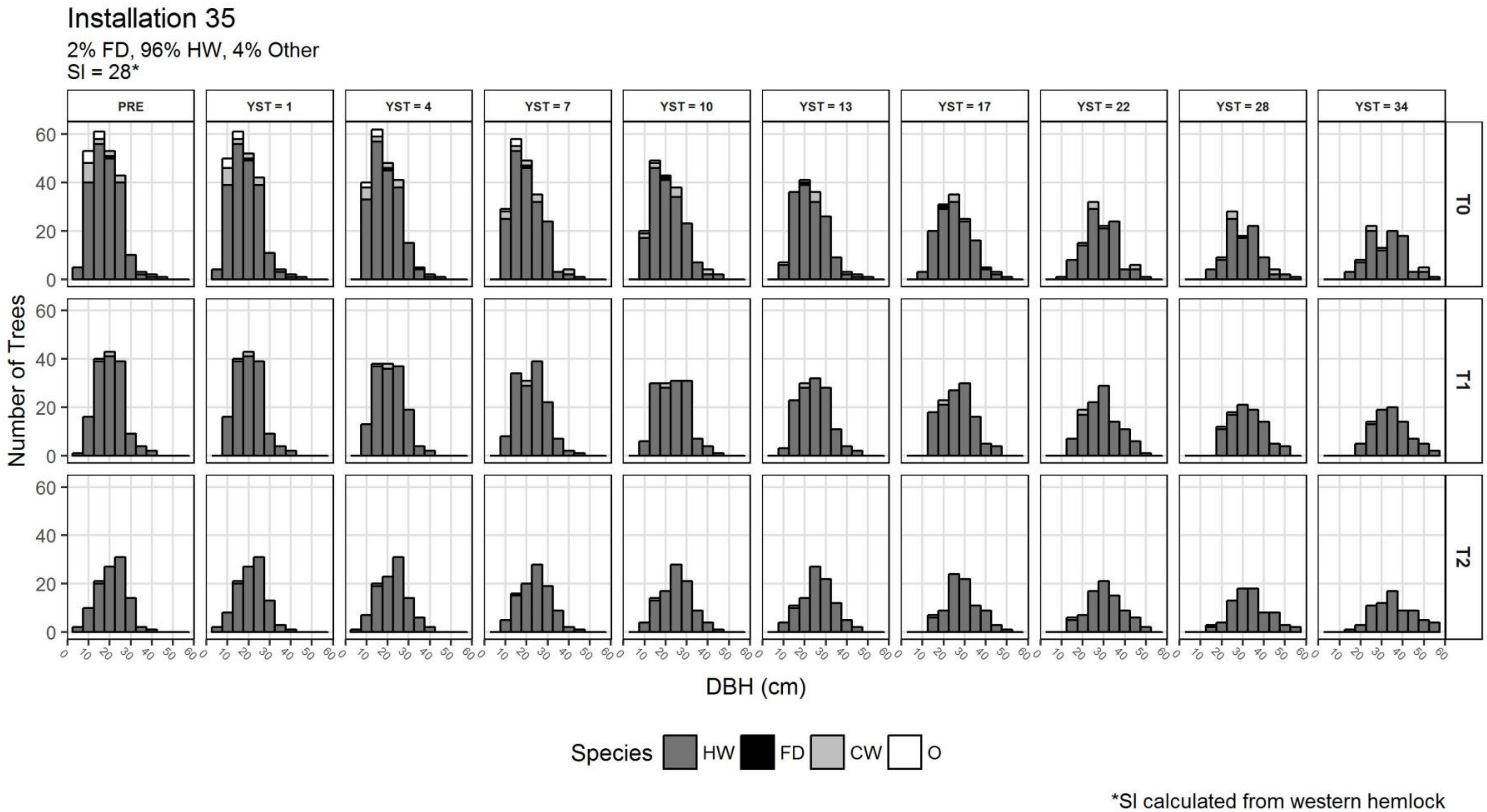

Figure A-14. DBH distributions over time and across treatments. PRE: pre-thinning measurement period; YST: years since treatment; T0: control, 0% BA removed; T1: 20% BA removed; T2: 35% BA removed; SI: site index; HW: western hemlock; FD: Douglas-fir; CW: western redcedar; O: other species.

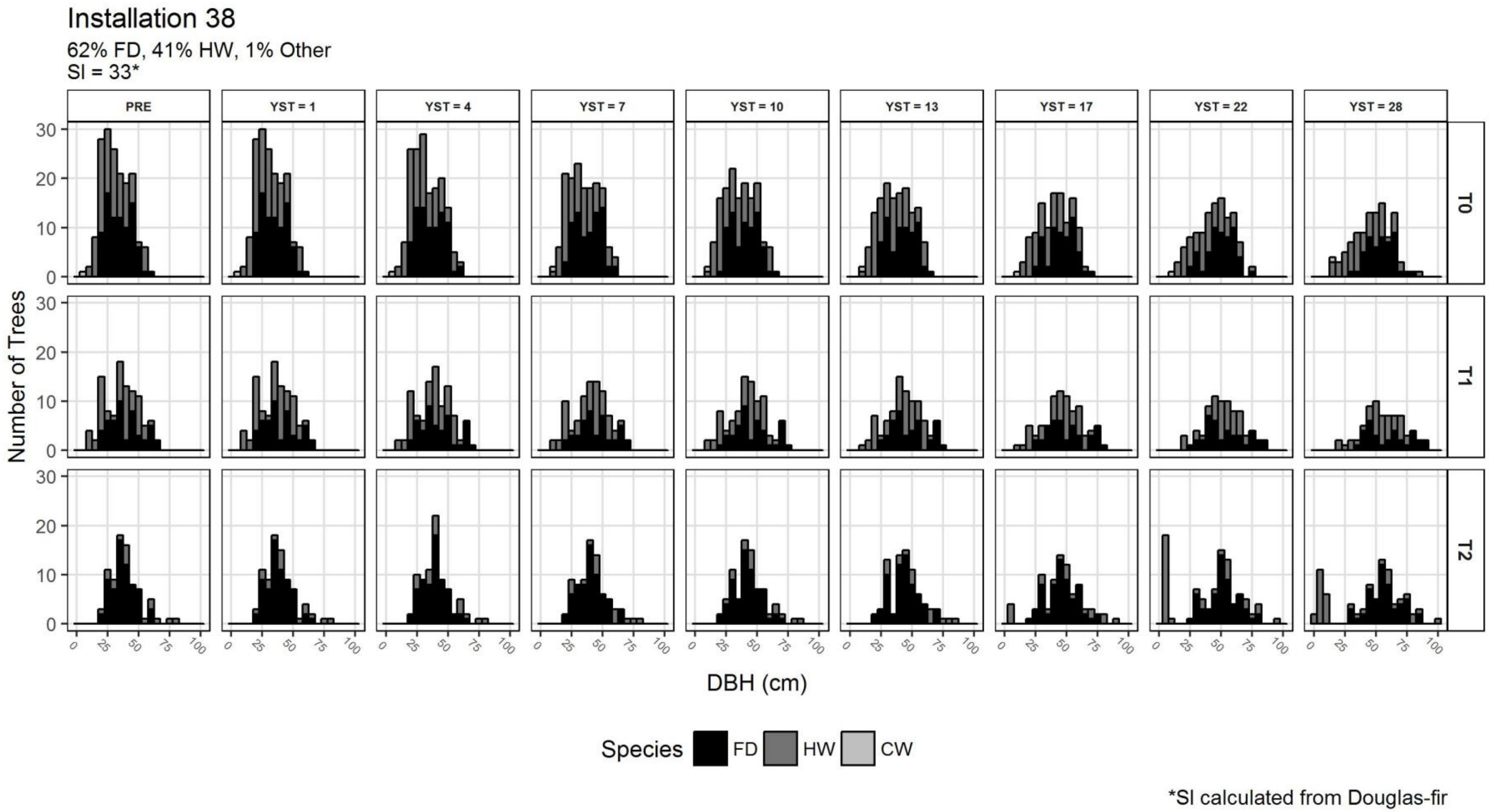

Figure A-15. DBH distributions over time and across treatments. PRE: pre-thinning measurement period; YST: years since treatment; T0: control, 0% BA removed; T1: 20% BA removed; T2: 35% BA removed; SI: site index; FD: Douglas-fir; HW: western hemlock; CW: western redcedar.

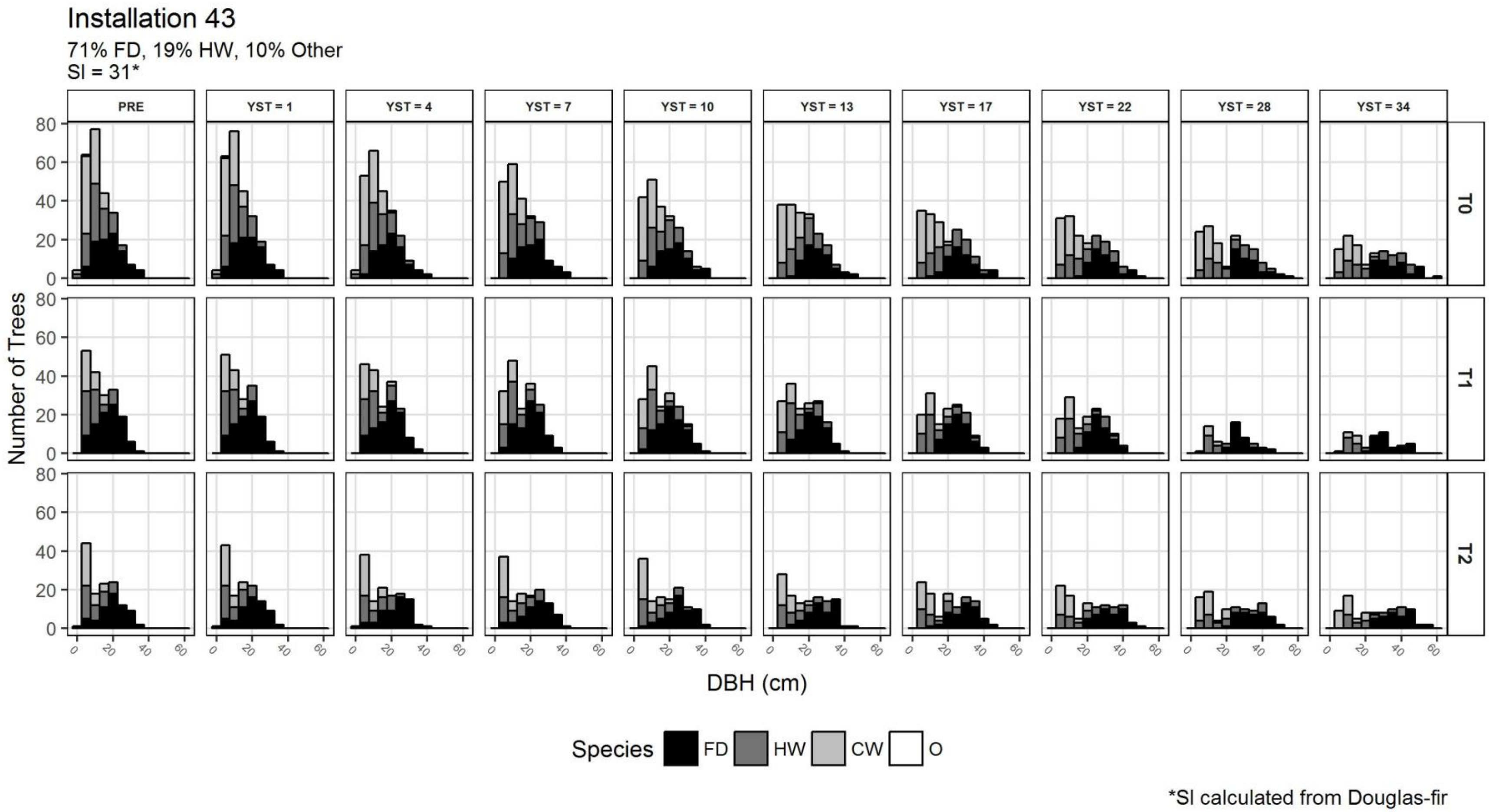

Figure A-16. DBH distributions over time and across treatments. PRE: pre-thinning measurement period; YST: years since treatment; T0: control, 0% BA removed; T1: 20% BA removed; T2: 35% BA removed; SI: site index; FD: Douglas-fir; HW: western hemlock; CW: western redcedar; O: other species.

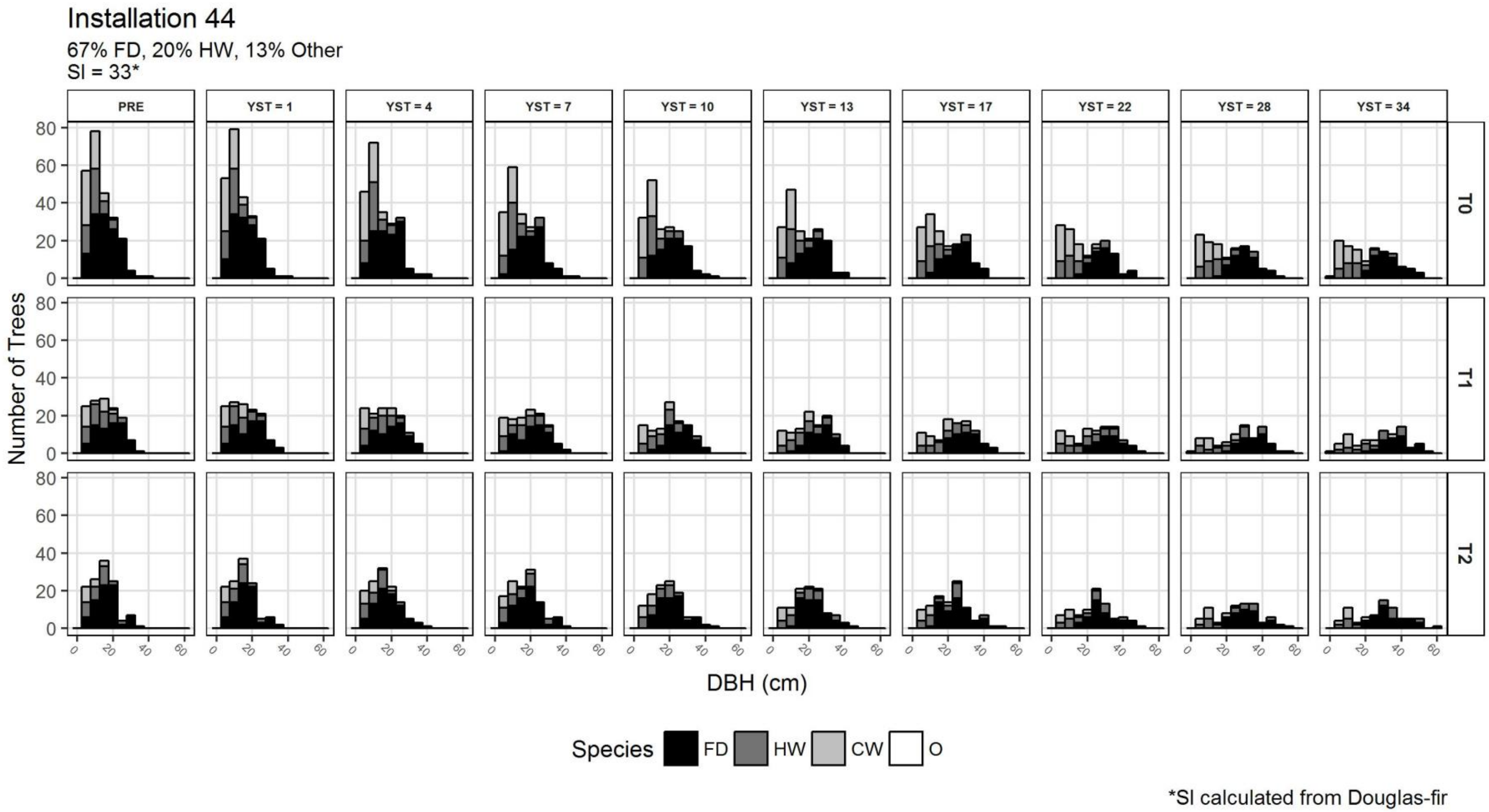

Figure A-17. DBH distributions over time and across treatments. PRE: pre-thinning measurement period; YST: years since treatment; T0: control, 0% BA removed; T1: 20% BA removed; T2: 35% BA removed; SI: site index; FD: Douglas-fir; HW: western hemlock; CW: western redcedar; O: other species.

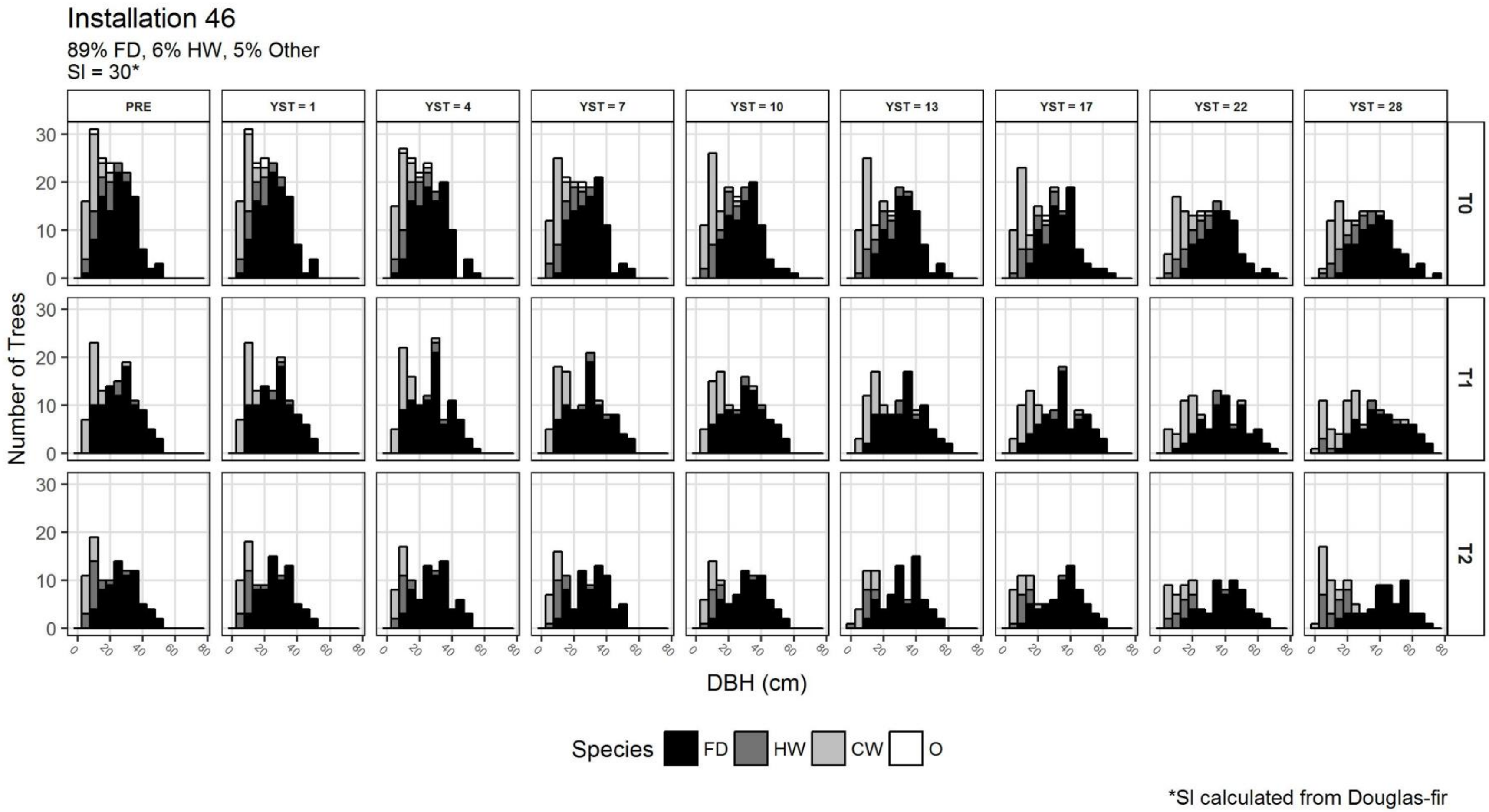

Figure A-18. DBH distributions over time and across treatments. PRE: pre-thinning measurement period; YST: years since treatment; T0: control, 0% BA removed; T1: 20% BA removed; T2: 35% BA removed; SI: site index; FD: Douglas-fir; HW: western hemlock; CW: western redcedar; O: other species.

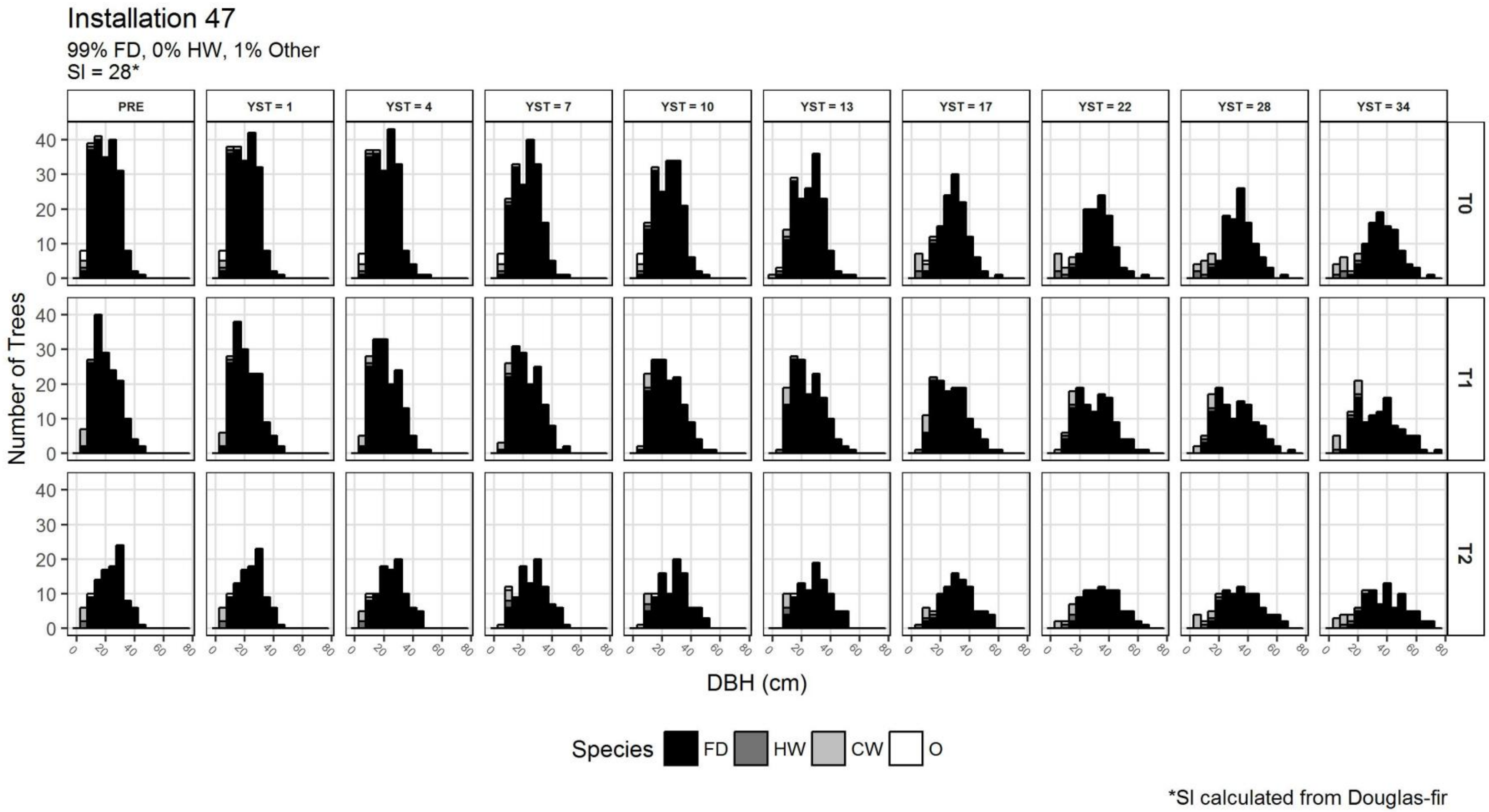

Figure A-19. DBH distributions over time and across treatments. PRE: pre-thinning measurement period; YST: years since treatment; T0: control, 0% BA removed; T1: 20% BA removed; T2: 35% BA removed; SI: site index; FD: Douglas-fir; HW: western hemlock; CW: western redcedar; O: other species.

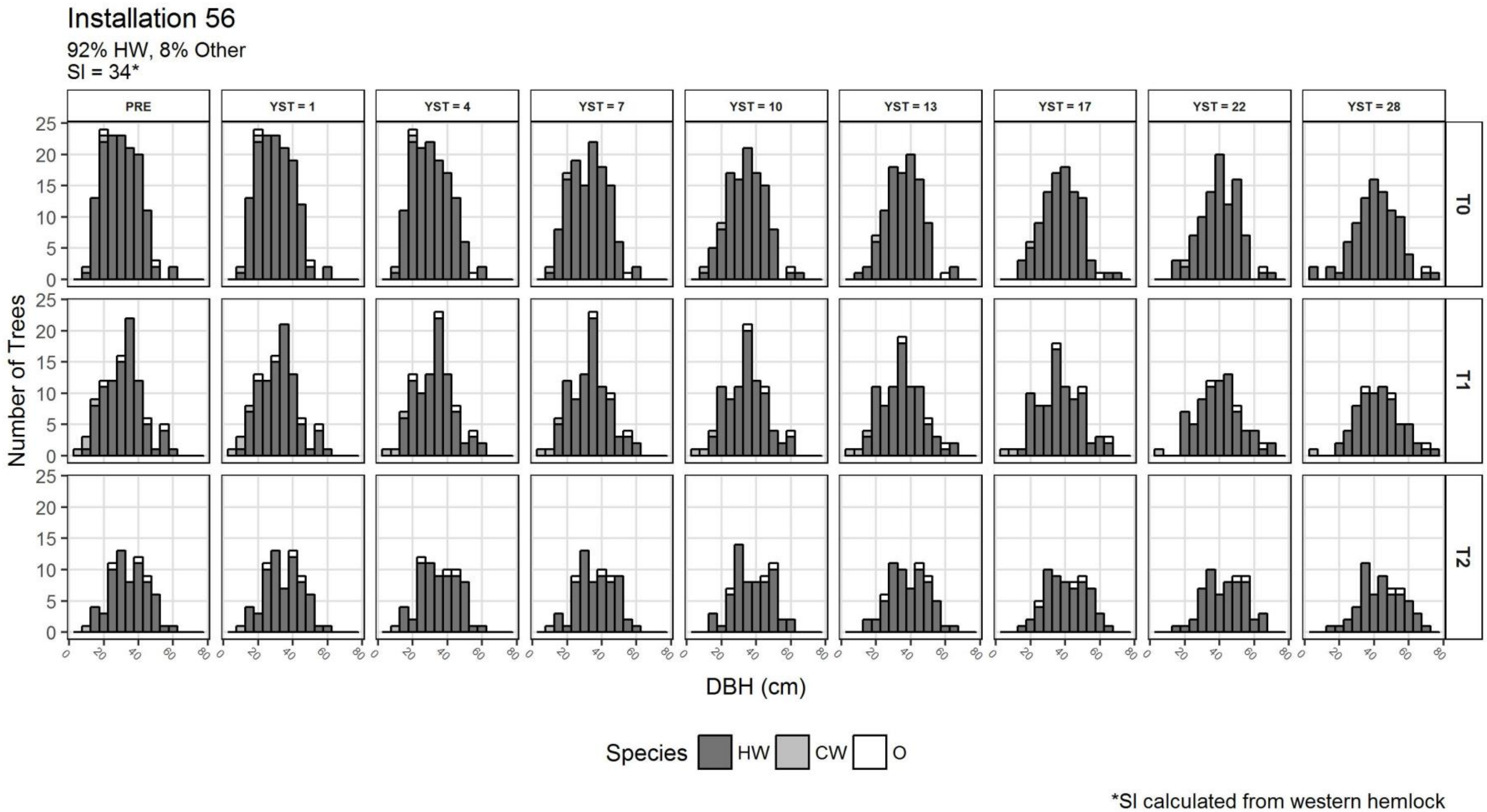

Figure A-20. DBH distributions over time and across treatments. PRE: pre-thinning measurement period; YST: years since treatment; T0: control, 0% BA removed; T1: 20% BA removed; T2: 35% BA removed; SI: site index; HW: western hemlock; CW: western redcedar; O: other species.

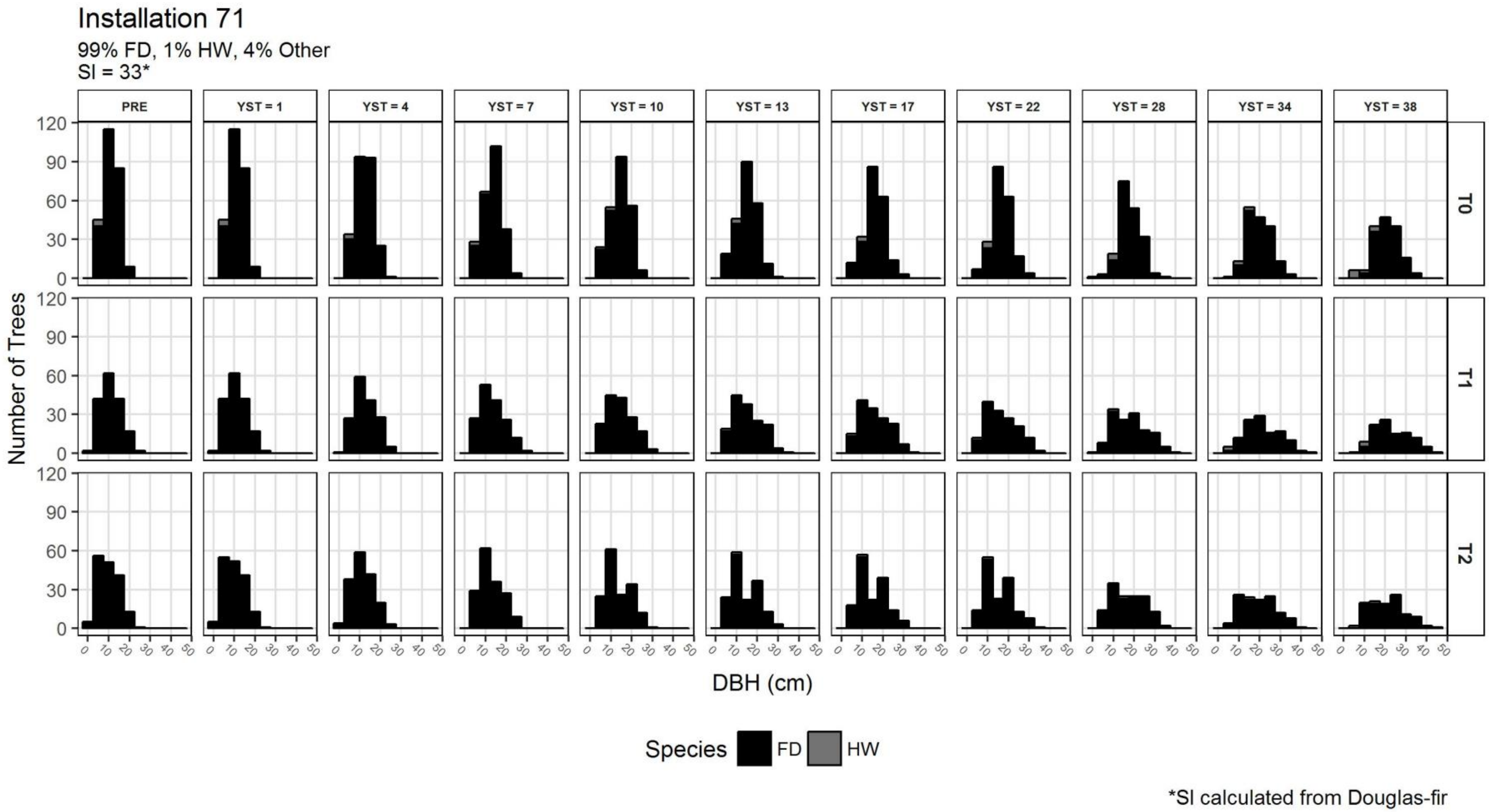

Figure A-21. DBH distributions over time and across treatments. PRE: pre-thinning measurement period; YST: years since treatment; T0: control, 0% BA removed; T1: 20% BA removed; T2: 35% BA removed; SI: site index; FD: Douglas-fir; HW: western hemlock; CW: western redcedar; O: other species.

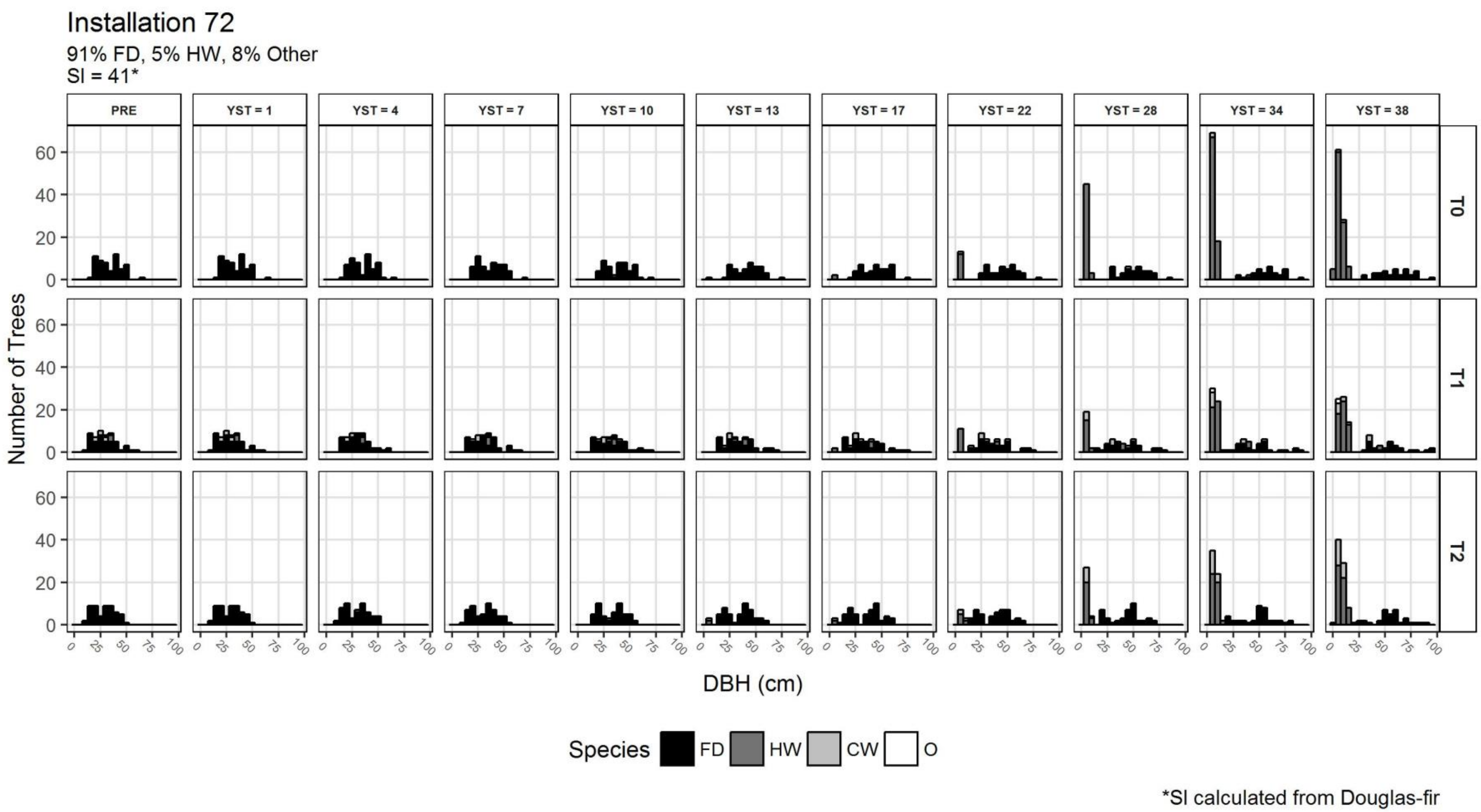

Figure A-22. DBH distributions over time and across treatments. PRE: pre-thinning measurement period; YST: years since treatment; T0: control, 0% BA removed; T1: 20% BA removed; T2: 35% BA removed; SI: site index; FD: Douglas-fir; HW: western hemlock; CW: western redcedar; O: other species.