Evaluating the efficacy of structural complexity enhancements to achieve old-growth conditions in Pacific Northwest coastal forests

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ABSTRACT

After nearly two centuries of logging, only a small percentage of original old-growth forests in the Pacific Northwest (PNW) remains. Old-growth forests are characterized by heterogeneous forest structures with large and mature trees, multi-story canopies, and complex understories composed of snags, logs, and downed woody material. To jumpstart succession processes and restore old-growth forests, structural complexity enhancements (SCE), including prescribed burning and variable-density thinning, have been developed and used more frequently in forest management. Compared to traditional thinning methods (thin from below), SCE have been documented to provide greater ecosystem-wide benefits (Harmon et al. 1990, Gunn et al. 2014).

To test the effectiveness of SCE techniques in the PNW, the long-term effects of different management methods—prescribed burning, variable-density thinning, and traditional thinning—on previously logged coastal forests of the South Slough National Estuarine Research Reserve (NERR) located in Charleston, Oregon were investigated. Using the Forest Vegetation Simulator (FVS), 11 forest stands of different age classes were simulated from 2015-2125 under four management scenarios: no action (control), traditional thin from below, variable-density thin, and prescribed burn. The main variables of interest were structural complexity and carbon sequestration. Forest structure complexity (large trees, large snags, downed wood) was quantified using the Old Growth Habitat Index. Results showed that there were no significant differences in carbon sequestration among treatments except for the control. Thinning and variable-density thinning were similar across all structural elements and were most effective at accelerating large tree growth. The control treatment created the most downed wood and large snags. Among treatments excluding the control, prescribed burns created the most snags and downed wood. Findings suggest that multiple variable-density thin treatments or a combination of treatments may need to be implemented in order to effectively promote structural complexity.

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1. Introduction

Prior to large-scale timber harvesting, the Pacific Northwest (PNW) contained vast amounts of old-growth forests. Old-growth forests are structurally complex and highly biodiverse systems that take centuries to develop and mature. These complex forests harbor ecologically valuable species, such as the threatened Northern spotted owl, which depend on old-growth structures for habitat (Swanson and Hanson 1992). Following the 1848 gold rush, logging grew exponentially in the PNW, developing into the present-day multi-billion-dollar timber industry (Puettmann et al. 2016). The legacy of logging in old-growth forests, followed by replantings of Douglas fir monocultures for over a century, has produced many regenerating forests across the PNW. As a result, forest composition has shifted from primarily diverse old-growth forests to young, dense, and homogenous forests.

Forests that have undergone decades of timber harvesting and replanting are characteristically very different from the original standing old-growth forest. Regenerated forests have lower biodiversity and less structural complexity, resulting in a less resilient forest (e.g., higher vulnerability to insect outbreaks, wildfires, invasive species) that supports fewer wildlife species (Puettmann et al. 2016). Due to the influence of timber production objectives on early forest management, traditional silvicultural techniques or traditional thinning from below sustained simple forests (O'Hara et al. 1994). Traditional forest management employed one-dimensional objectives such as increasing timber yield, minimizing insects and disease, and reducing wildfire risk (O'Hara et al. 1994). However, in recent decades, management interest has shifted towards holistic ecosystem-wide approaches to promote diverse and stable environments (O'Hara et al. 1994; Swanson & Hanson 1992).

To achieve landscape-wide benefits of forest management, structural complexity enhancements (SCE) have been developed to obtain more multi-faceted objectives. Notable benefits of SCE, compared to traditional even-aged and uneven-aged thinning treatments, include greater forest structural complexity and higher levels of carbon sequestration (Harmon et al. 1990; Gunn et al. 2014). However, often the most desired objective achieved by SCE is its ability to promote forest succession and ultimately achieve old-growth forest conditions.

In general, old-growth conditions are characteristic of high aboveground and belowground carbon sequestration as well as structural complexity at both the understory and canopy level. Complexity in the understory is created by snags, logs, and downed wood. Complexity in the forest canopy is created by multi-layered canopies of shade tolerant and intolerant trees. Two SCE techniques that will be investigated in this research are prescribed burns and variable-density thinning. These techniques differ from traditional, even-aged thinning by providing more lateral and vertical heterogeneity in forest structure. Prescribed burns are particularly effective at creating complexity among fuels including downed wood and snags. Prescribed burns have also been shown to promote structural diversity among trees but to a lesser extent than variable-density thinning (Knapp et al. 2017).

Prescribed burning began as a Native practice to maintain forests, mimicking naturally occurring forest fires (Ryan et al. 2013). While the most prominent benefit of prescribed burns is fuel reductions, there is discourse about the ability of prescribed burning to create heterogeneous forest structures. For example, Holland et al. (2017) examined the effects of prescribed burning on forest structures using a landscape approach, focusing on changes in woody structures such as snags and logs. Findings showed that changes in forest heterogeneity post-burn depended on pre-burn forest structure. Homogeneous forests experienced an increase in heterogeneity following prescribed burns, whereas heterogeneous forests became more homogenous post-burn. The burns performed in the study also resulted in a loss of 31% of hollow trees and logs, causing a decrease in available habitat for wildlife species such as the yellow-footed antechinus. While overall forest heterogeneity (overstory and understory) may increase following a homogenous forest burn, important structural components and the species that utilize them may also be lost.

Variable-density thinning is a recently developed management technique with a primary goal of jumpstarting the succession process and achieving old-growth forest conditions. This technique utilizes thinning to mimic skips (unthinned areas) and gaps (thinned patches), which are naturally found in forests. Puettmann et al. (2016) investigated the effects of variable-density thinning using growth responses such as tree mortality and crown control. While most responses were expected (decrease in canopy cover, increase in understory vegetation), results were spatially variable, with different components of stand structures responding differently to treatments.

Objective

To test the effectiveness of SCE techniques in the PNW, this research will analyze the long-term effects of different management methods on different aged forest stands of the South Slough National Estuarine Research Reserve (NERR) located in Charleston, Oregon. The primary goal of this research is to evaluate the ability of management techniques to promote old-growth forest structures beginning with different aged forests, and to answer the following research questions:

- What management techniques are the most effective at achieving old-growth conditions from different aged forest stands using the following Old Growth Habitat Index (OGHI) parameters:

- Density of large trees
- Density of large snags
- Volume of coarse woody debris
- Diameter Diversity Index
- Stand age

- How does carbon sequestration differ among management methods and different aged forest stands?

Respective drawbacks and benefits will be investigated, focusing on carbon sequestration and structural complexity. This research will provide quantitative insights on structural complexity enhancement techniques (prescribed burning and variable-density thinning) for future management, and how they can best be utilized in logged forests at different regrowth stages to achieve desired management outcomes. Furthermore, this research will help inform the effects of these techniques on a longer timescale than existing field studies.

2. Methods

2.1 Site description

South Slough NERR is located in Charleston, Oregon, and includes ~8,000 acres of coastal forested uplands. Prior to Reserve management, all South Slough forests had undergone commercial timber harvesting and currently exist at various regrowth stages or age classes (Figure 1). Forests primarily consist of mixed conifers, dominated by Sitka spruce (*Picea sitchensis*), Douglas fir (*Pseudotsuga menziesii*), Port-Orford-cedar (*Chamaecyparis lawsoniana*), and western hemlock (*Tsuga heterophylla*). Other forest types include red alder (*Alnus rubra*) hardwood forests and Sitka spruce tidal swamps. As a result of logging, each forest age class maintains certain characteristics that suggest the need for management. Young age class forests have been recently harvested and are in a stand establishment stage, characteristic of high density of trees per acre and dense understories (Figure 2a). Middle age class forests are in a competitive exclusion phase with dense canopies and limited understory growth (Figure 2b). Mature age class forests are the most similar to old-growth forests, with multi-story canopies and a variety of shade tolerant and shade intolerant species (Figure 2c). However, they differ from old-growth forests due to fewer large snags and a lower density of large trees as a result of younger stand age (earlier successional stage).

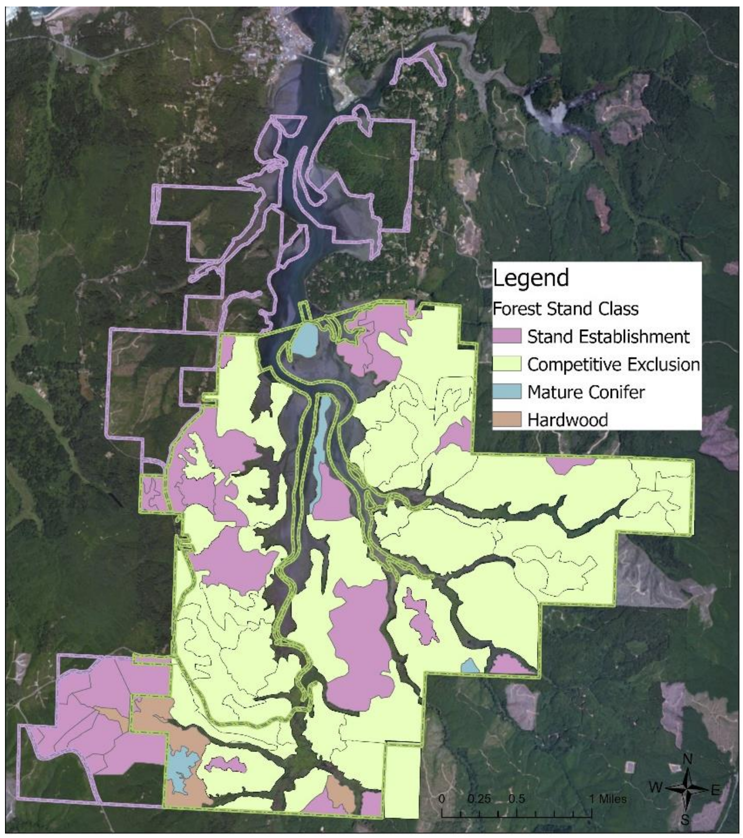

Figure 1. Study site of South Slough NERR. Different forest stand classes are shown, with stand establishment describing young age stands, competitive exclusion describing middle age stands, and mature conifer encompassing mature age stands.

a) Young stand establishment forest | b) Middle-aged competitive exclusion forest stand | c) Mature conifer forest

Figure 2. Different aged forest stands and classes showing their various characteristics in South Slough NERR in 2021.

2.2 Data

The data used for this project were obtained from South Slough NERR located in Charleston, Oregon, containing tree data from 2015 for 11 forest stands. All forest stands had been logged and exist in various regrowth stages. Younger stands are typically denser and have higher management priority compared to older stands. The forest stands in the dataset were categorized by age class and priority. They were grouped as follows:

1. Young (15-30 years) / High priority
2. Middle (40-80 years) / Mid-high priority
3. Mature (80-150 years) / Low priority

Raw data from multiple Forest Inventory Analysis (FIA) plots were combined to represent a respective forest stand. For this project, data from FIA plots at the stand level were input for forest simulation projections (Figure A1). Each plot was composed of four subplots (7.315 m radius), with each subplot surrounded by a macroplot (17.95 m radius) (see Figure A1). Three forest stands from Group 1 (young) and four forest stands from Groups 2 and 3 (middle and mature) (11 stands total) were chosen for each simulation run.

Input variables are as follows:

- **Stand location** – geographic region and GPS coordinates.
- **Diameter at breast height (DBH)** – sampled in centimeters from trees in subplot (trees with DBH >= 12.7 cm) and macroplot (trees with DBH >= 61 cm).
- **Tree species** – sampled from subplot (trees with DBH >= 12.7 cm) and macroplot (trees with DBH >= 61 cm).
- **Tree height** – sampled in meters from subplot (trees with DBH >= 12.7 cm) and macroplot (trees with DBH >= 61 cm).
- **Crown ratio** – percentage of tree height occupied by its crown sampled from subplot (trees with DBH >= 12.7 cm) and macroplot (trees with DBH >= 61 cm) (Figure A2).

2.3 Modelling with the Forest Vegetation Simulator

The Forest Vegetation Simulator (FVS) was the primary method used to model and predict management outcomes. FVS is an individual-tree, distant-independent model that predicts forest growth and yield in U.S. regions (Dixon 2002). FVS simulates changes in vegetation in response to succession, disturbance, and management action. The main functional relationships used to calculate tree growth are height-diameter, bark ratio, crown ratio, and crown width. FVS contains multiple variants that are geographic versions of the simulation to which tree growth and mortality models are specifically calibrated (Figure A3). FVS utilizes variant-specific component models to produce outputs. The Pacific Northwest Coast (PN) variant, which was used in this project, consists of the following component models: large tree growth, small tree growth (Gould and Harrington 2013), mortality (Hann et al. 2003; Hann and Hanus 2001), crown-ratio change, regeneration (partial establishment model), live wood volume, and downed wood volume.

To predict tree growth, FVS uses different strategies for large and small trees. For large trees, the diameter increment is predicted followed by height growth, which is predicted as a function of diameter (Crookston and Dixon 2005). For small trees, height growth is predicted first, followed by the diameter increment, which is predicted as a function of height growth. Other variables driving growth included in the growth model are site-specific, including species, slope, aspect, elevation (Crookston and Dixon 2005). Crown dynamics are also used to predict growth, namely crown ratio, crown width relationship, and crown competition factor. Crown competition factor is a relative measurement of stand density based on tree diameters and estimates crown cover percentage in a stand.

Morality is predicted using individual tree mortality equations for all species in the PN variant (Hann et al. 2003; Hann and Hanus 2001). Annual mortality rate estimates are based on tree size, stand density, basal area, and crown ratio (Dixon et al. 2008). For stands with small trees and high density, mortality rates are relatively high. However, large tree mortality is unaffected by density. Instead, basal area growth drives mortality for large trees as well as small trees. Seedlings are automatically added following a harvest or burning (Dixon et al. 2008). Regeneration parameters for sprouting species (minimum bud width, minimum tree height, maximum tree height) are specific to tree species found in the PN variant.

For data input, tree species and diameter at breast height variables are required, but other variables such as crown ratio will enhance the results. After data are input, desired management actions (parameters) may be selected, such as thinning to a specified trees per acre. Results from the simulation include data tables, 3D renderings of stands, graphs/plots, and maps.

2.4 Applying Treatments Using FVS

FVS was used to produce four runs with different management actions for each of the 11 selected stands and the PN variant from years 2015-2125 in 10-year time steps.

- **Run 1: No action (control).** No management applied.
- **Run 2: Traditional thin.** Thinning and pruning applied with a thin from below (starting with small DBH trees) to 371 trees per hectare scheduled for 2022. Trees thinned from 371 trees per hectare to 173 trees per hectare over 20 years following the initial thin.
- **Run 3: Variable-density thin.** Stands were thinned in 2022 to a proportion of skips (no thin), gaps (clearcut), and thinned areas: 88% thinned to 371 trees per hectare, 6% clearcut, and 6% skipped. Trees thinned to 173 trees per hectare over 20 years following the initial treatment.
- **Run 4: Prescribed burn.** A prescribed burn was scheduled for fall 2022 with the following parameters based on average seasonal conditions in Charleston, Oregon:
    - Wind speed: 8 km/h
    - Fuel condition: Moist
    - Temperature: 15.6 degrees C
    - Percentage burned: 70%

Outputs from each run were used to calculate the following variables:

- **Large tree presence** – large tree density (trees per hectare)
- **Large snag presence (standing dead trees)** – snag density (snags per hectare)
- **Fuels (woody debris and snags)** – coarse woody debris (CWD) volume (Mg/ha)
- **Carbon** – total stand carbon (Mg/ha)
- **Stand age** (years)

2.5 Statistical Analysis

2.5.1 Carbon

Analyses of variance (ANOVA) were conducted using R to evaluate the significance of stand age and management method on total stand carbon (Mg/ha) at the following time steps: 2025 (3 years after initial treatment), 2075 (50 years after initial treatment), 2125 (100 years after initial treatment). Post hoc Tukey HSD tests were performed on significant ANOVA results to further examine which relationships accounted for the differences in means.

2.5.2 Old Growth Habitat Index

The old-growth habitat index (OGHI) developed by Franklin et al. (2005) for the PNW Coast Range was used to compare widely accepted characteristics of old-growth forests in the PNW. The indices integrate the following old-growth elements:

- Large tree density (trees per hectare > 100 cm DBH)
- Large snag density (snags per hectare > 50 cm DBH and > 15 m tall)
- Woody debris volume (cubic meters per hectare)
- Diameter Diversity Index (DDI)
    - DDI is a proxy for tree height diversity and is calculated using a slope-corrected value of tpha for four different DBH size classes: (1) 5.0 - 24.9 cm, (2) 25.0 - 49.9 cm, (3) 50.0 - 99.9 cm, (4) > 100 cm (Franklin et al. 2005).
- Stand age (years)

The OGHI used in this project was based on stand data from the Washington Cascades collected by Spies and Franklin (1991). These elements were chosen because the strongest distinguishing characteristics of old-growth stands are large tree density, tree size diversity, and stand age. While there are other old-growth characteristics not included in the index, such as broken-topped crowns, shade-tolerant species, and spatial heterogeneity, these variables are generally correlated with OGHI elements (Franklin et al. 2005). Each element was scored on a scale from 0 to 100, with higher scores indicating greater affinity to old-growth forests for each respective element/characteristic.

To score each element, multi-segmented lines were created connecting distributional points in the data (Figure A4). For example, to score large tree density, the 25th percentile value of trees per hectare from the reference dataset corresponded to a score of 50; the median corresponded to a score of 75; and the maximum corresponded to a score of 100. For snag density and downed wood volume, the dataset minimum was the corresponding distributional point for a score of 50 instead of the 25th percentile. Median values from simulation results were used to score each element using the appropriate regression equation. Standard OGHI was calculated by averaging all elements. The cutoff score for an old-growth forest is 60, which was subjectively determined by Franklin et al. 2005. To examine structural characteristics, a modified OGHI may be used which excludes the age element.

3. Results

The effect of each respective treatment on basal area and tree density is described in Table 1. Initially, the young age stands had the greatest density of trees, followed by the middle and mature age stands (Table 1). Following the first round of treatments in 2023, the thin treatments had the lowest tree density in all age groups. The control groups had the greatest tree density, followed by the variable-density thin and prescribed burn treatments across all age groups. However, there was a greater range of densities between treatments in the young and middle age stands. Following the second treatments in 2043, the thin and variable-density thin groups had much lower tree density compared to the control and prescribed burn groups (Table

1). Across all age groups, the variable-density thin maintained the lowest tree density and basal area after the second treatments were applied (Table 1).

Table 1. Average basal area (m^2/ha) and mean tree density (tpha) for young, mid, and mature age stands at the initial stage (2015), after first treatments (2023), and after second treatments for thinning (2043). Note that the (2) notation in the management column indicates the second thin treatment, which was a thin from below to 173 tpha applied to both thin *and* variable-density thin runs.

Age group	**Management**	**Year**	**Status**	**Basal area (m^2/ha)**	**Density (tpha)**
Young	-	2015	Untreated	18.8	2103.1
Mid	-	2015	Untreated	39.4	1608.2
Mature	-	2015	Untreated	57.7	484.1
Young	Control	2023	No treatment	43.3	1914.6
Young	Thin	2023	Treated once	19.8	515.3
Young	Variable density	2023	Treated once	38.7	1557.3
Young	Prescribed burn	2023	Treated once	18.8	917.4
Young	Control	2043	No treatment	99.3	1316.8
Young	Thin (2)	2043	Treated twice	39.0	313.9
Young	Variable density (2)	2043	Treated twice	36.4	276.2
Young	Prescribed burn	2043	Treated once	60.8	791.9
Mid	Control	2023	No treatment	55.2	1381.4
Mid	Thin	2023	Treated once	31.3	392.6
Mid	Variable density	2023	Treated once	54.7	1374.2
Mid	Prescribed burn	2023	Treated once	38.2	847.2
Mid	Control	2043	No treatment	89.3	973.7
Mid	Thin (2)	2043	Treated twice	42.0	234.4
Mid	Variable density (2)	2043	Treated twice	38.6	212.6
Mid	Prescribed burn	2043	Treated once	69.9	685.3
Mature	Control	2023	No treatment	64.9	439.1
Mature	Thin	2023	Treated once	62.4	317.7
Mature	Variable density	2023	Treated once	64.5	433.7
Mature	Prescribed burn	2023	Treated once	53.7	325.3
Mature	Control	2043	No treatment	81.6	363.9
Mature	Thin (2)	2043	Treated twice	68.1	194.5
Mature	Variable density (2)	2043	Treated twice	67.8	193.9
Mature	Prescribed burn	2043	Treated once	69.4	281.6

3.1 Carbon

Initially in 2015, mature age group stands sequestered the greatest amount of carbon, followed by the mid age group, and the young age group stands. Over the course of the simulation, the control and prescribed burn treatments in the young and middle age groups surpass the control and prescribed burn treatments in the mature age group (Figures 3 and 4). Across all age groups, the thin and variable-density thin treatments sequestered similar amounts of carbon following the second thin treatment in 2042 (Figure 4). Prior to the second thin, the variable-density thin treatment had total stand carbon values closer to the control and prescribed burn treatments but decreased following the second thin.

Average total stand carbon was greatest for the control group across all age classes for the majority of the 100-year simulation period (Figure 3). Prescribed burning sequestered the second greatest amount of carbon compared to the other management actions, surpassing variable-density thinning following its second round of thinning in 2042 (Figure 3).

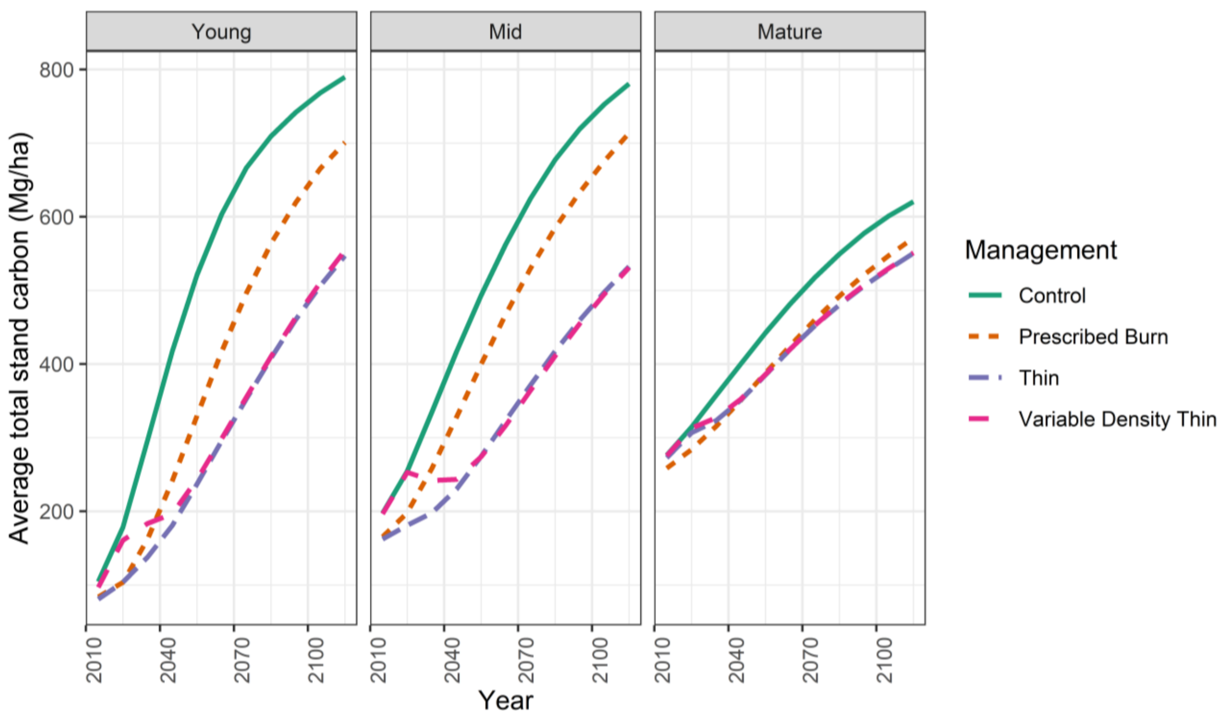

Figure 3. Projected average total stand carbon (Mg/ha) from 2015 to 2115 for age groups and management actions.

In 2075, fifty years after initial treatments, the control treatment in the young age group stands had significantly greater average total stand carbon compared to the thin and variable-density thin treatments ($p<0.001$) (Figure 4). Mature age group stands responded with a smaller range of total stand carbon values than the young and middle age stands, but there were no statistically significant differences among age groups. Average total stand carbon at the end of the simulation in 2125, 100 years after initial treatments, showed similar results to fifty years prior. Relative carbon sequestration among age groups and management treatments were consistent with 2075 values (Figure 4-5). However, in 2125, the young and middle age control treatments had significantly greater average total stand carbon than the middle and mature age variable-density thin treatments (Figure 5).

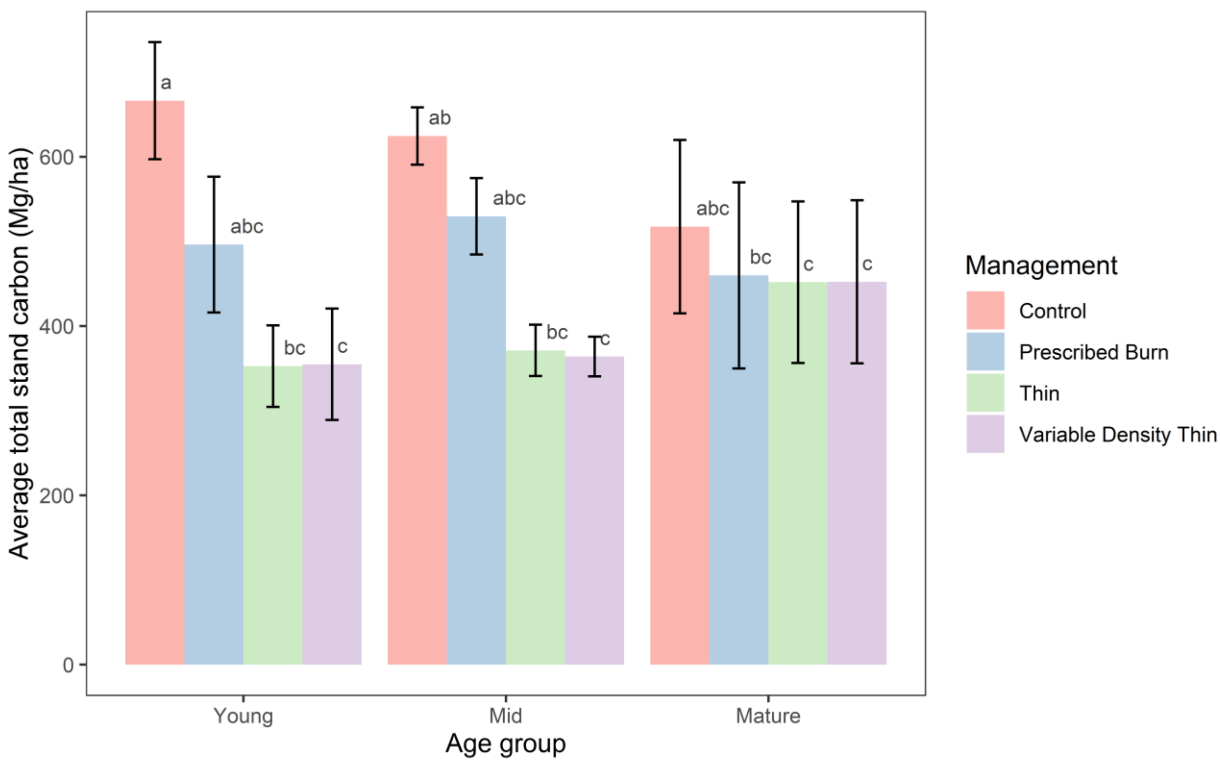

Figure 4. Average total stand carbon (Mg/ha) in 2075 fifty years after initial treatment for different age groups and management actions. Standard error bars included. Letters a-c indicate significance based on a two-way ANOVA and post hoc Tukey HSD test (p-value<0.05).

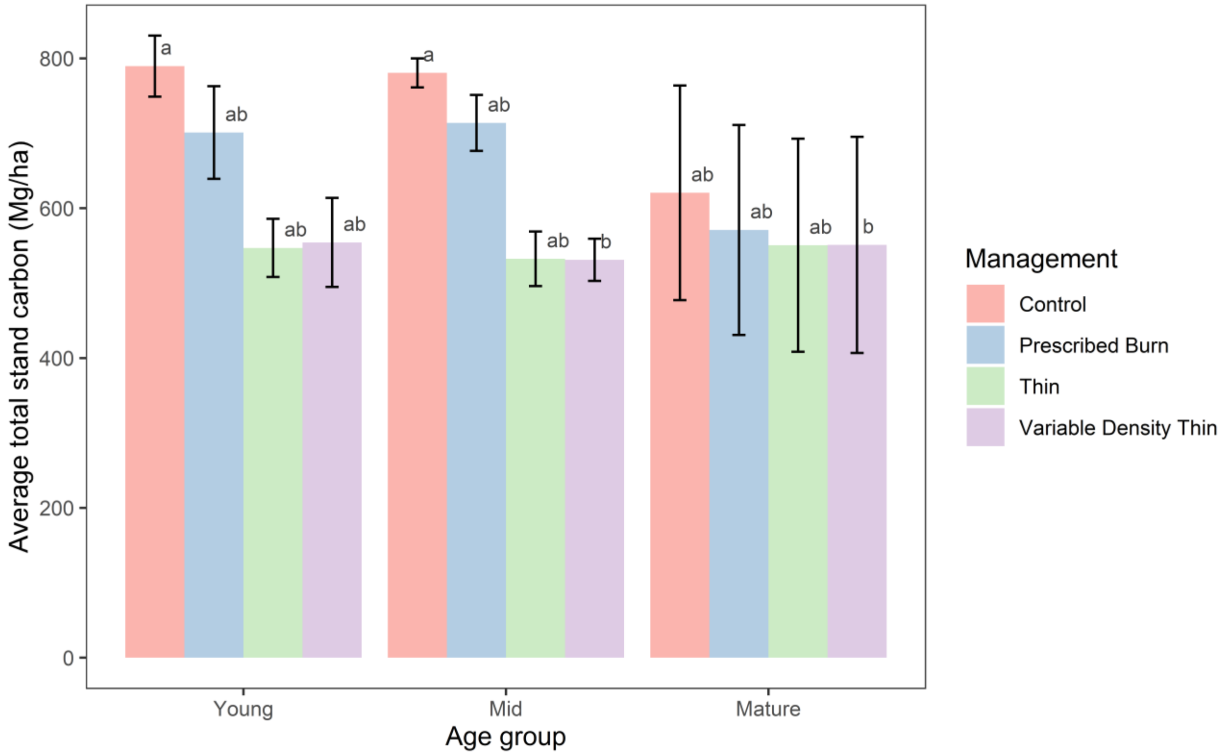

Figure 5. Average total stand carbon (Mg/ha) in 2125, 100 years after initial treatment for different age groups and management actions. Standard error bars included. Letters a and b indicate significance based on a two-way ANOVA and post hoc Tukey HSD test (p-value<0.05).

3.2 Old Growth Habitat Index

Across age groups, the mature age stands scored highest for the standard OGHI and was the only age treatment to meet the old-growth cutoff (standard OGHI = 75.61 > 60) (Table 2). The middle age stands scored higher than the young age stands for the thin, variable-density thin, and prescribed burn treatments, but not for the control treatment (Table 2). Among management methods across all age groups, the control treatments scored highest. The prescribed burn treatments scored the second highest, and the other treatments (thin, variable-density thin) scored similarly. The control treatment maintained the highest standard OGHI score due to its high downed wood volume element score (Table 2).

Table 2. Standard OGHI index scores and individual element scores for age groups and management methods. Elements included were stand age, large tree density, large snag density, downed wood volume, and DDI. Scores were calculated using regression equations from the OGHI element curves (Figure A4).

		Element scores					
Age group	**Management**	**Age**	**Large trees/ha**	**Large snags/ha**	**Downed wood volume**	**DDI**	**Standard OGHI**
Young	Control	46	88.87	0.00	72.56	71.86	55.86
Young	Thin	46	100.00	0.00	36.68	71.14	50.76
Young	Variable density	46	100.00	0.31	36.78	70.36	50.69
Young	Prescribed burn	46	74.09	0.00	57.16	76.18	50.69
Mid	Control	52	62.30	0.12	70.08	82.19	53.34
Mid	Thin	52	95.36	0.02	43.04	70.77	52.24
Mid	Variable density	52	89.95	0.02	43.45	70.73	51.23
Mid	Prescribed burn	52	64.73	14.79	57.39	78.95	53.57
Mature	Control	77.6	90.64	85.54	48.96	75.30	75.61
Mature	Thin	77.6	97.36	6.39	31.39	70.00	56.55
Mature	Variable density	77.6	97.24	6.51	31.60	70.00	56.59
Mature	Prescribed burn	77.6	93.75	6.30	35.38	75.71	57.75

Most treatments across all age groups had low large snag scores (Table 2). Across age groups, the mature stands had the highest scores for large snags, with the control treatment receiving a substantially larger score of 85.54 (Table 2). The prescribed burn treatment in the middle age stands received the second highest score across all runs, with a large snag score of 14.79 (Table 2). Excluding the control, the prescribed burn treatments received the highest DDI score in all age groups and created the most downed wood volume among treatments (Table 2). Overall, the control and prescribed burn treatments scored highest for DDI (Table 2).

For large tree element scores, the young age stands that were treated with a thin and variable-density thin were the only groups to receive a score of 100 (Table 2). The mature age group treatments received similar large tree element scores, all scoring over 90 (Table 2). Control and prescribed burn treatments in middle age stand scored the lowest (62.30 and 64.73, respectively) (Table 2). Across all age groups, the thin and variable-density thin treatments created the greatest number of large trees. The prescribed burn treatment scored higher than the control for the middle and mature age stands, but the control treatment scored higher than the prescribed burn for the young age stands.

3.3 Stand Visualization

3D visualizations show the difference in initial structure at the beginning of the simulation (2015). Young stands contained a high density of small trees (Figure 6). Middle age stands had taller trees but were still relatively dense with little spatial heterogeneity (Figure 6). Mature stands began with the most structural complexity, with an array of shade tolerant species as well as gaps in the structure (Figure 6). The control had more downed wood compared to the other treatments, which is consistent with OGHI results (Figure 6) (Table 2). Among treated stands, prescribed burning was the most effective at generating downed wood, also consistent with OGHI results (Figure 6) (Table 2).

In terms of spatial heterogeneity, mature stands exhibited the most complexity in the form of skips and gaps (Figure 6). Additionally, mature stands had the most variation in tree height at the end of the simulation compared to other age classes. Between the thin and variable-density thin treatments, the only visual spatial difference was apparent in young stands, with variable-density thinning creating a larger gap in the forest (Figure 6).

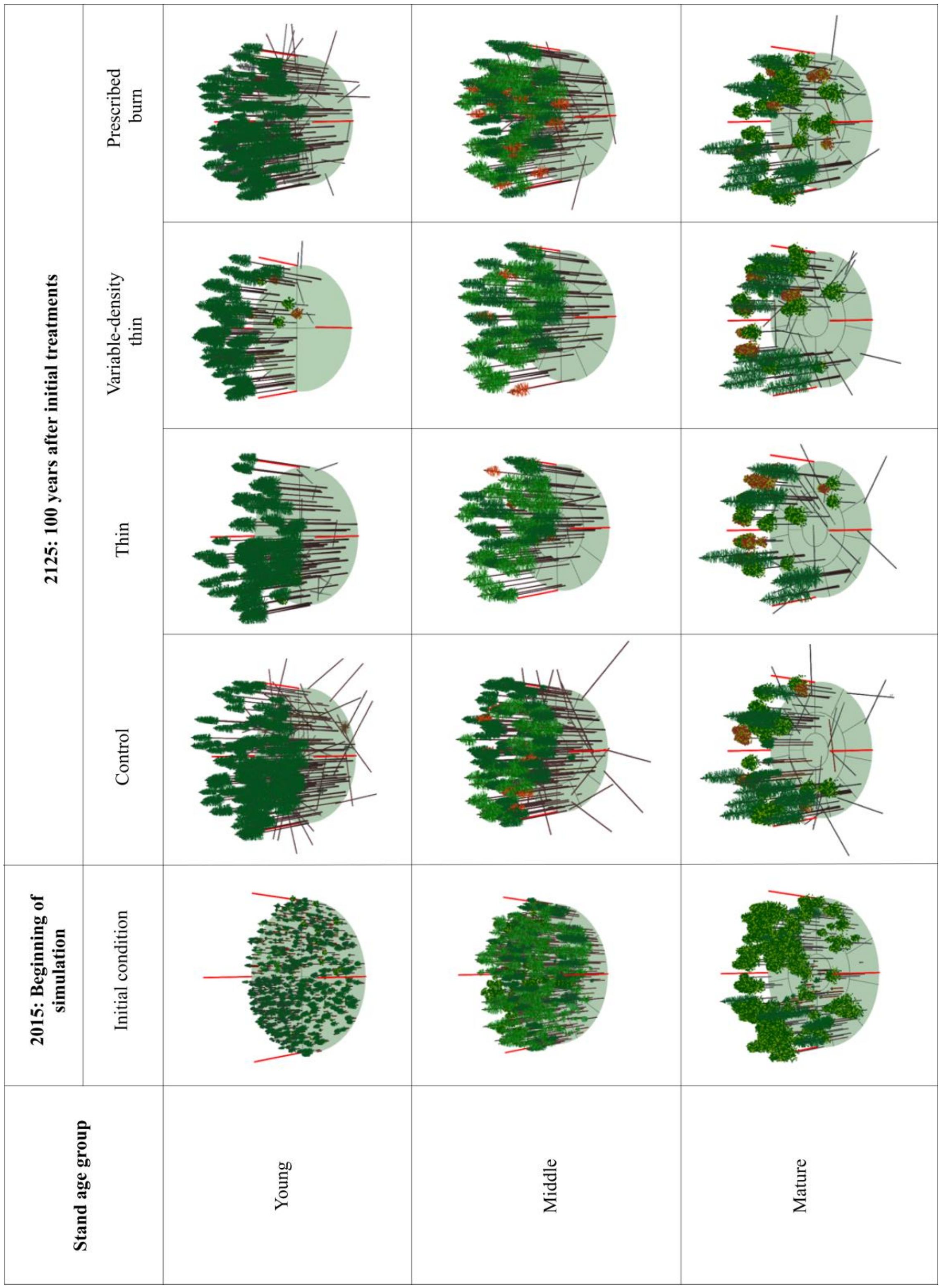

Figure 6. 3D visualizations of young, middle, and mature age group stands at the beginning of the simulation (2015) and 100 years post-treatment at the end of the simulation (2125) for each of the four management actions. Red vertical lines indicate 30.48 meters in height.

4. Discussion

4.1 Carbon

Although young age stands began with the least amount of carbon, they ended with values similar to middle and mature age stands, even surpassing them in some cases (control and prescribed burn) (Figure 3). Young and middle age stands likely had larger total stand carbon due to the difference in initial tree density. Young and middle age stands began with a much greater density of trees relative to the mature stands (Table 1). A higher turnover of trees resulted in a greater amount of carbon input in the form of downed wood and litter in response to tree removal and mortality. Similarly, differences in the density of trees removed caused the disparity between carbon in thinned treatments versus the control and prescribed burn. More trees (and biomass carbon) were removed in the thinning treatments, releasing a greater amount of carbon into the atmosphere. In all cases, as the downed woody material and litter decompose, a portion of carbon is released back into the atmosphere (Harmon et al. 2020).

Younger forests have been found to assimilate carbon at higher rates than older forests (Gray et al. 2016). As a result, the idea of using regrowth forest plantations (young stands in the stand exclusion phase) as a way to mitigate carbon at higher rates has become a point of interest in the carbon market (van Minnen et al. 2008). Regrowth plantations keep forests at young ages when carbon sequestration rates are highest. Once rates decline (~40-50 years), trees are harvested for timber products (sequestered carbon) and replanted. However, young plantations have little biological value beyond carbon sequestration. This shows that maximizing carbon sequestration does not necessarily align with sustaining healthy, resilient, and ecologically valuable forests.

4.2 Old Growth Habitat Index

4.2.1 Large trees

Thinning and variable-density thinning were the most effective treatments for creating large trees across all age groups (Table 2). The young stands achieved higher large tree scores than the middle and mature stands, suggesting that young age stands benefit most from thinning treatments for this element. Another important implication is that thinning treatments can accelerate large tree development in younger age stands to the point of surpassing older stands in density. Thinning creates spaces in the canopy, increasing the direct sunlight that reaches the forest floor (North and Zald 2007; Vernon et al. 2018). Thinning also decreases competition for resources (water, nitrogen, light) and creates space for standing trees to grow (North and Zald 2007; Roberts and Harrington 2008).

Large tree recruitment has been observed in response to variable-density thinning treatments even on significantly shorter time scales (Roberts and Harrington 2008; Willis et al. 2018). Large trees are a defining characteristic of old-growth forests. Results indicate that variable-density thinning and thinning from below effectively increase large tree density to a threshold equivalent to old-growth forests. This has major management implications, suggesting that variable-density thinning effectively encourages large tree growth, especially for young forests undergoing stand establishment.

4.2.2 Large snags

Large snags were only present in stands that were old enough to develop large trees. Mature age stands already had large trees developed from the beginning of the simulation, increasing the opportunity for large snag production. However, there is a critique that FVS underestimates tree mortality (Barker et al. 2019). This may also contribute to the low density of large snags observed at the end of the simulation. While snags are an important component for wildlife in forests, they are also fuel for wildfires and can spread fires in the vertical direction. These tradeoffs should be considered when defining management goals.

4.2.3 Downed wood

The control treatment produced more downed wood and snags compared to the other treatments (Table 2) (Figure 6). While large amounts of downed wood are characteristic of old-growth forests, it can also increase wildfire risk and surface fire spread. However, logs and coarse woody debris retain moisture, which can decrease risk of fires (Rose et al. 2001; Bunnell and Houde 2010). The role of woody debris as a fire hazard, habitat for wildlife, or source of moisture is largely dictated by climate and geography (Stokland et al. 2016). For South Slough NERR, large downed woody debris is mostly beneficial for moisture because of its coastal geography and low frequency of wildfires. However, based on historical fire patterns, woody debris can sustain the widespread, severe fires that infrequently occur at the site (Robinson 2009).

4.2.4 DDI

Middle aged control group stands exhibited the greatest diameter diversity due to their higher relative scores in the second size class (25.0-49.9 cm DBH). This is likely due to the competitive exclusion characteristic displayed initially in middle age stands (Figure 2). Due to the high density of trees initially in this size class and the lack of resources that would encourage size class advancement, many trees did not advance by the end of the simulation period. As a result, the middle age stands with no treatment (control) maintained more trees in this size class compared to middle age stands with treatments.

4.2.5 Standard OGHI

Mature age group stands received the highest standard OGHI scores, and the middle and young age stands scored similarly (Table 2). While the higher relative mature age group scores were expected given their initial age and forest class type, the similarity between the young and middle age stands suggest that treatments may be less beneficial for middle age stands, or that treatments to younger stands have the potential to accelerate conditions such that they catch up to middle age stands.

The standard OGHI score of the control groups in the young and mature age classes were greater than the management groups due to higher downed wood element scores (Table 2). However, the thin and variable-density thin treatments are more effective at creating large trees. It is important to note that site productivity and disturbance history heavily influence OGHI scores. Highly productive sites generally develop towards old-growth conditions faster than less productive sites. Therefore, it is possible for a young forest with high productivity to receive a OGHI score greater than 60, and it is also possible for an old-growth forest to receive a score below 60 (Franklin et al. 2005).

4.3 Limitations

FVS is a relatively old model, and several components should be updated to produce more accurate results. A popular critique of the FVS is that the mortality model does not kill off enough trees, which can lead to an overprediction in growth and survival (Barker et al. 2019). Additionally, senescence is not predicted well, also contributing to errors in growth and yield. One of the primary reasons for the development FVS is management for timber harvesting (Dixon 2002). As a result, there are some drawbacks in terms of ecological predictions. One main drawback is that FVS is not spatially explicit with regard to tree dynamics within a simulated stand (Dixon 2002). This limitation has been pointed out by previous studies and should be improved upon to generate more robust results (Christopher and Goodburn 2008).

OGHI also does not account for spatial heterogeneity. This may have resulted in the similarity between traditional thinning and variable-density thinning element scores. One of the primary benefits of variable-density thinning is the creation of skips and gaps to mimic spatial heterogeneity found in old-growth forests (Swanson and Franklin 1992). Without the ability to define or quantify the spatial element of treatments, spatial complexity was not fully captured by the index or by the simulation.

4.4 Conclusions and recommendations

SCE enhanced old-growth characteristics but in different ways. Variable-density thinning was effective for creating large trees, whereas prescribed burning created more downed wood volume (Table 2). Appropriate site conditions with existing large trees would likely also benefit from prescribed burns in terms of large snag density, as well as the creation of scorched trees which can house a suite of insects (Randall-Parker and Miller 2002). Lack of large snag density suggests that deliberate snag creation should be implemented in addition to thinning treatments to increase overall old-growth similarity for snag elements.

In terms of selecting among management options, treatments should be chosen based on site-specific goals. For example, if creating large trees is a priority, variable-density thinning should be implemented. Additionally, intentional creation of snags in addition to other treatments may be needed to increase snag presence. Both the variable-density thin and traditional thin treatments include a second thinning treatment from below to 173 tpha in the 20 years following the initial thin. The similarity between variable-density and traditional thinning across all measured characteristics (OGHI element scores, total stand carbon) suggests that one variable-density thin is not enough to promote old-growth heterogeneity and complexity, and a second variable-density thin may need to be implemented.

Especially in mature stands, applying no treatment was the most beneficial for development of old-growth characteristics. While thinning treatments encouraged large tree growth, the control treatment produced more large snags and downed wood in mature age stands (Table 2). Treatments are not universally beneficial, and the initial conditions of a stand should be evaluated before implementing management. Additionally, resources are more effectively allocated by prioritizing young, dense, and homogenous stands that will benefit the most from treatments.

While this project only examined the effects of individual treatments, a previous field study suggests that to achieve old-growth conditions, multiple site-specific techniques may need to be implemented (Puettman et al. 2016). Therefore, it may be favorable to implement prescribed burns and variable-density thinning to varying degrees, which has been shown to increase resiliency to more frequent fires and drought (Knapp et al. 2017). Utilizing this combination of techniques could prove especially useful as areas begin to experience higher fire frequency and drought due to climate change (Halofsky et al. 2020).

An important aspect of forest management as well as ecological function is tradeoffs. In an attempt to enhance one characteristic, a different characteristic may diminish. Similarly, there are tradeoffs between ecological health and resilience in forests. A forest with large standing snags is more ecologically valuable but may also be less resilient to wildfire disturbance. Managers should define explicit, measurable goals specific to a given site while acknowledging potential tradeoffs. FVS is a useful tool for evaluating the effects of different management methods and is more effectively used on shorter timescales due to more accurate predictions.

While the development of OGHI and growth models such as FVS are a major stride in characterizing forest structure, field observations are needed to fully capture characteristics, especially with regard to spatial heterogeneity. Observations can also help improve FVS and other models. Using a variety of methods may prove to be the best approach in evaluating variable-density thinning, structural complexity enhancements, and old-growth forest management.

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APPENDIX

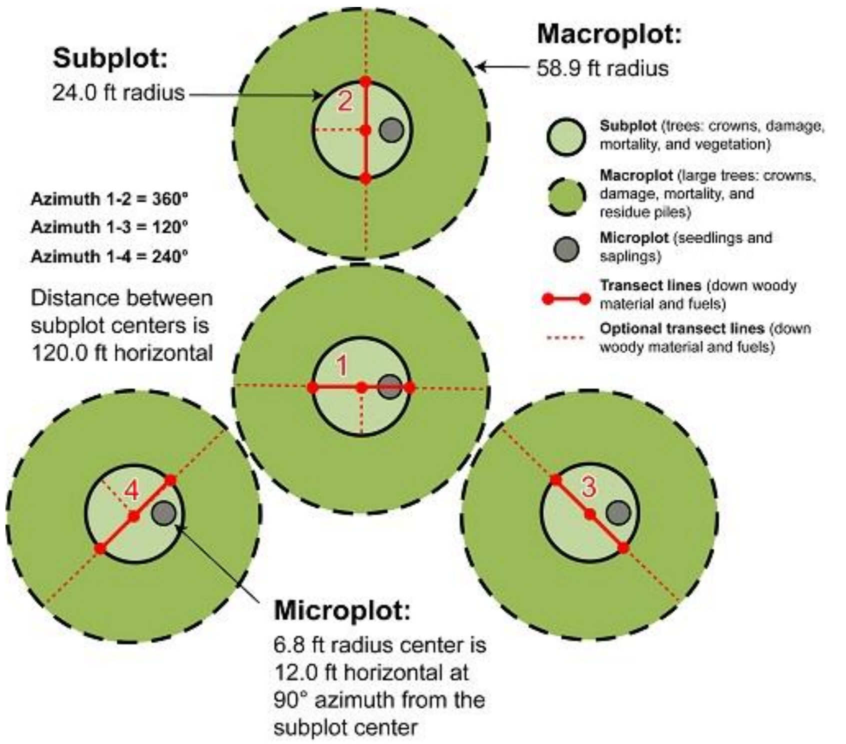

Figure A1. FIA plot diagram with subplot and macroplot components.

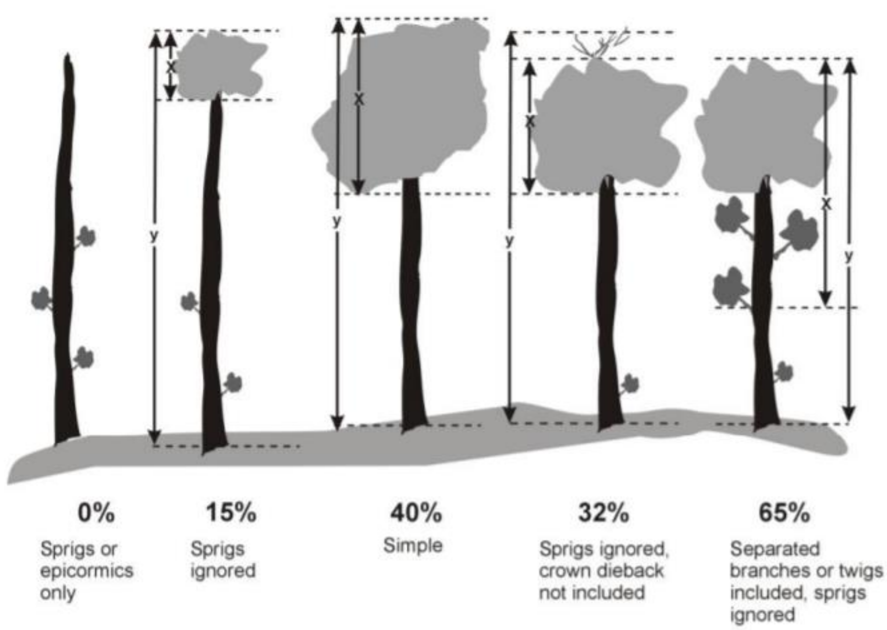

Figure A2. Tree crown ratio measurement examples.

Figure A3. Map of the Pacific Northwest coast variant.

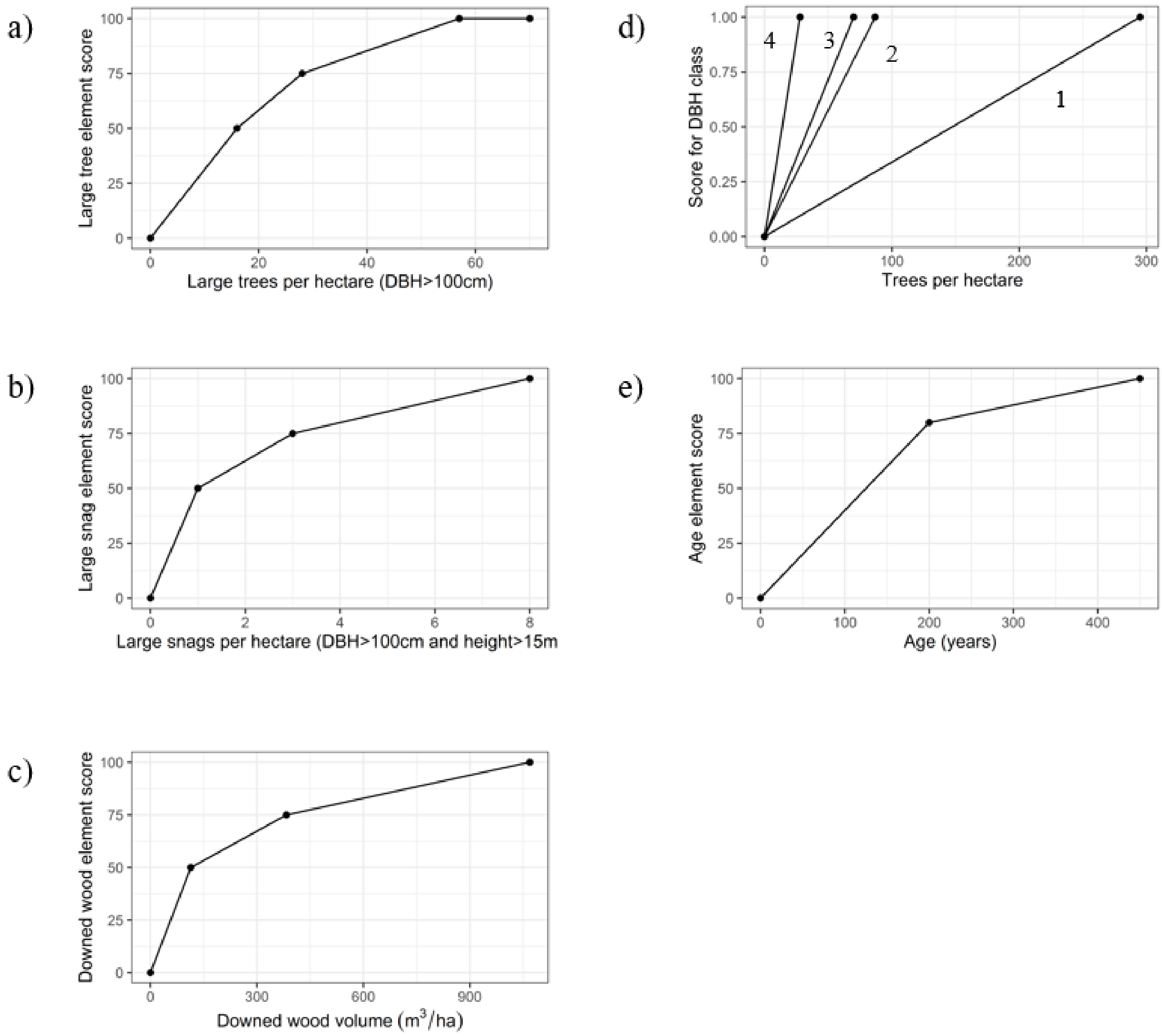

Figure A4. OGHI "curves" used to score elements. (a) large trees per hectare; (b) large snags per hectare; (c) downed wood volume (m^3/ha); (d) DDI element; (e) stand age element. DDI lines correspond to different DBH size classes: 1) 5.0 - 24.9 cm; 2) 25.0 - 49.9 cm; 3) 50.0 - 99.9 cm; 4) > 100 cm.