Simulating Forest Dynamics, Disturbance, and Management in the Elliott State Research Forest, Oregon: A Comparative Study of Land Sharing, Land Sparing, and Triad Management

by

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THESIS ABSTRACT

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Title: Simulating Forest Dynamics, Disturbance, and Management in the Elliott State Research Forest, Oregon: A Comparative Study of Land Sharing, Land Sparing, and Triad Management

Forests serve as critical reservoirs for carbon, provide habitat for a significant proportion of terrestrial species, and provision renewable building materials in the form of timber. However, forests are increasingly at risk due to increased demand for forest products and forested land, necessitating new forest management strategies that lessen the impacts of resource production on carbon storage and biodiversity. The recent management plan for the Elliott State Research Forest (ESRF) outlines the experimental comparison three strategies: land sparing (separates timber production from conservation), land sharing (integrates timber production with conservation), and Triad management (divides forests into intensive, extensive, and reserve areas). However, the long-term results from implementing these strategies will not emerge for decades. Therefore, we used LANDIS-II to simulate the proposed management plan under natural disturbances (i.e. windthrow and wildfire) and climate change. Results indicate that while all management strategies ensured sustainable timber production, land sharing promoted the highest diversity of trees and shrubs, whereas Triad management maximized carbon storage. However, under extreme climate change projections, carbon storage was compromised and there was a further shift towards Douglas-fir. Managers must therefore evaluate tradeoffs and choose the strategy best suited to management objectives. This study represents the first modelled comparison of land sharing, land sparing, and Triad management under climate change and natural disturbance and highlights the potential use of LANDIS-II in adaptive forest management.

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CHAPTER I

INTRODUCTION

Forests represent important reservoirs for carbon and biodiversity, storing 861 gigatons (Gt) of above and belowground carbon globally (361 Gt live biomass and 498 Gt necromass) (Pan et al. 2013) and providing habitat for 80 percent of amphibians, 75 percent of birds, and 68 percent of mammal species (Vié et al. 2009). Furthermore, the forestry sector produces renewable building materials that are important to the global economy, producing 3.9 billion cubic meters of round wood in 2019 (FAO 2021) and employing more than 33 million people (Lippe et al. 2022). The global demand for roundwood has increased by nearly 60% since 1960 and is expected to increase by as much as 30% by 2050 (Beck-O'Brien et al. 2022). This rising demand for timber products, coupled with land use change, shifting agriculture, natural disturbance, and climate change is causing a decline in global forest cover (Curtis et al. 2018). Global tree cover has declined by roughly 10% since 1990, with an annual loss in tree cover of 14 Mha (FAO 2020). This loss and degradation of forests is causing a rapid decline in biodiversity and carbon storage (Lapola et al. 2023), necessitating the development of new strategies for producing timber while conserving carbon storage and biodiversity.

Two approaches to land conservation, land sharing (integration of production with conservation) and land sparing (separation of production and conservation), arose from the agricultural sciences to meet the rising demand for crops and meat products (Green et al. 2005). Under a land sharing approach, low-intensity resource production is integrated across a large portion of the landscape to reduce the impact of production on any given location. Conversely, a land sparing approach concentrates management over a small area, often using industrial management practices, to maximize the amount of land set aside for conservation elsewhere. While a common finding of empirical studies has been that land sparing is superior for conserving most species (Phalan 2018), a caveat for the success of this approach is that it is paired with strong regulations to protect the 'spared' land and that this land is not already heavily modified (Edwards et al. 2014). Few studies have compared these two approaches beyond biodiversity, necessitating research that considers additional ecosystem services such as economic values and carbon storage (Sidemo-Holm et al. 2021).

Foresters have traditionally met the demand for timber products through intensive, high input clearcut plantations that maximize yield at a stand scale (Puettmann et al. 2008). This strategy lends itself to a land-sparing framework if paired with strong protections for unmanaged land. However, there is an increasing push to develop alternative management designs that promote both timber and non-timber forest values due to the low biodiversity within intensely managed stands(Puettmann et al. 2015). Extensive, or ecological forestry, aims to increase the conservation value within managed stands while replicating the historical disturbance regimes within a region (Franklin et al. 2007). Ecological forestry falls within the land sharing framework, with techniques including thinning and variable retention harvesting, which aim to increase species diversity, structural complexity, and ecosystem resilience, while still producing timber. The applications of land sparing and sharing both have merit in forestry, with the implementation of either approach resulting in benefits for different species. Empirical and modeling studies suggest that land sharing promotes generalist species, while land sparing protects specialists impacted by even minor forest loss or degradation (Matthews et al. 2014; Valente et al. 2022). Recent modeling work indicates that the increased reserves resulting from land sparing may result in an increase in carbon storage at a landscape level relative to land sharing (Harris and Betts 2023). Whether land sharing or sparing is preferable largely depends on management objectives and landscape. Furthermore, these two approaches are not mutually exclusive and an approach that combines land sparing and sharing may be best suited for promoting biodiversity and carbon storage while meeting the demand for natural resources (Kremen 2015).

First proposed in 1991, Triad management partitions a forest landscape into the three categories of management described above: reserve (no management), intensive management (clear-cut plantations), and extensive (ecological) management (Seymour and Hunter 1992). This approach aims to create heterogeneous forest conditions that benefit a wider range of species while providing for multiple management objectives. This management approach has been empirically evaluated in Eastern Canada (Messier et al. 2009; Himes et al. 2022) and through forest modeling (Côté et al. 2010; Ward and Erdle 2015; Carpentier et al. 2016; Harris and Betts 2023; Blattert et al. 2023). However, to date, there has yet to be an analysis of Triad management that assesses climate resilience. Furthermore, few studies have compared Triad management with land sharing and land sparing, which represent promising alternative to balancing economic and ecological forest values.

This experimental evaluation was the rationale behind the management design for the recently proposed Elliott State Research Forest (ESRF), located in the south-central Coast Range of Oregon (Oregon State University College of Forestry, 2023). The ESRF presents a unique opportunity to conduct long-term ecological research on the impacts of land sharing, land sparing, and Triad management strategies on ecosystem services, including carbon storage, biodiversity, and timber production. The proposed management design follows a nested spatial hierarchy (Figure 1). Managers plan to compare four management strategies within a section of the forest designated as the Management Research Watershed (MRW). These management strategies represent different spatial configurations of harvesting, implemented by varying the proportion of land included within extensive, intensive, and reserve management. These strategies include land sharing (100% extensive treatments), land sparing (50:50 split between intensive and reserve), Triad-share (60:20:20 split between extensive, intensive, and reserve), and Triad-spare (20:40:40 split between extensive, intensive, and reserve). In addition to these four management areas, 41% of the forest will be designated as part of the Conservation Research Watershed (CRW) and will represent a conservation strategy, with stands under 65 years old receiving an initial thin to help with old growth structural development. This area will serve as a control for how the forest would grow without management. Buffers have also been designated around rivers within the forest and will receive reserve status to improve water quality, protect riparian habitat, and reduce erosion. Including the CRW, RCA, reserve areas within the MRW, 63% of the forest would fall under protected status.

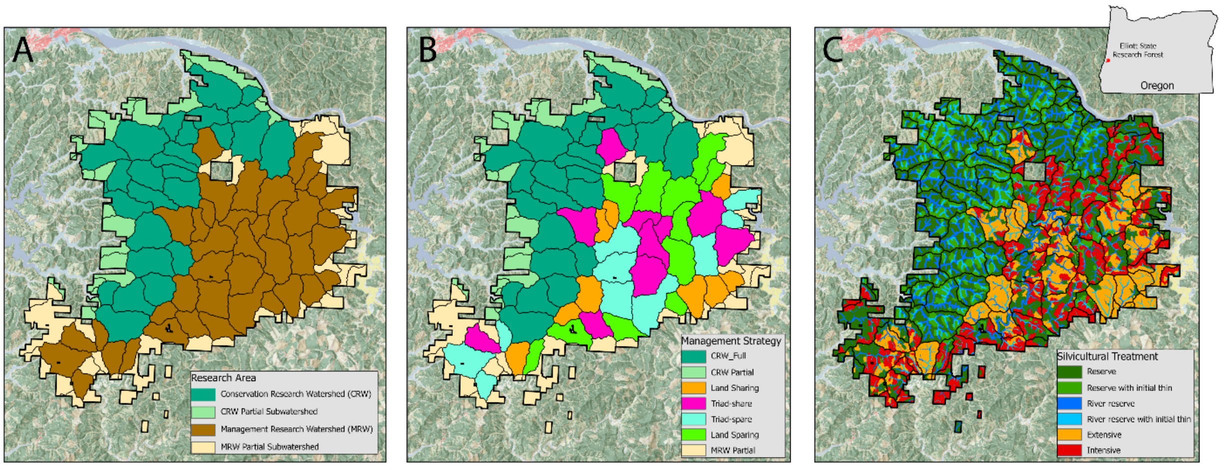


Figure 1. Elliott State Research Forest management Design showing: ***A)*** *the Conservation Research Watershed (CRW), Management Research Watershed (MRW), and periphery partial subwatersheds,* ***B)*** the experimental management framework, and **C)** the stand-scale silvicultural treatments that define each experimental management approach.

To compare the effectiveness of each management strategy in promoting non-timber values, each strategy will have equal timber outputs per unit area. However, there remains uncertainty over how this proposed management design may interact with natural disturbance under a wide range of potential future climatic conditions. Furthermore, the long-term impacts of these management strategies will not emerge for decades. This has prompted several modeling efforts to help refine the preliminary forest management strategy and produce model-driven comparisons between the four proposed strategies (Harris and Betts 2023, Lucash, et al., 2023). This research contributes to these efforts, using LANDIS-II, a forest landscape model, to simulate the proposed strategies, windthrow, and wildfire under a four-corner approach to climate modeling that captures a range of potential future climates in the Coast Range of Oregon. Model outputs were then compared to determine how implementing land sharing, land sparing, and Triad strategies may influence both the diversity of trees and shrubs and the storage of carbon in the Elliott State Research Forest throughout the 21st century.

CHAPTER II

METHODS

2.1 Study Area

The ESRF covers 33,500 hectares of coastal montane forest in the south-central Coast Range of Oregon. Wet mild winters, warm dry summers, and the long life spans of native tree species make the Coast Range of Oregon one of the most productive systems in the world (Waring and Franklin 1979). The Coast Range also boasts the highest carbon density in the Pacific Northwest, storing an average of 1127 Mg C/ha (Smithwick et al. 2002). Established as Oregon's first state forest in 1930 as part of Oregon's Common School Fund, the ESRF historically generated profits from the sale of timber to subsidize public education. Active management of the forest began in 1955 and continued for 47 years until, in 2012, a lawsuit concerning habitat protection for the endangered marbled murrelet led to the cancelation of several timber sales and a halt to timber production. The cost of forest maintenance subsequently outpaced timber revenues, and the forest began to cost the Common School Fund rather than contribute. This cost resulted in a discussion over whether the Elliott should remain publicly owned or be sold to private timber companies to recoup the loss in profits. In 2017, the State Land Board decided to keep the forest public, directing the Department of State Lands to work with Oregon State University to create a plan for converting the forest into a publicly owned research forest. The long history of timber production created a mosaic of young to early mature forests in the ESRF, with a median stand age of 90 years and standard deviation of 55.5 years. Pockets of forest on steep, hard-to-reach terrain have remained unharvested and are much older (350+ years old). These stands hold high conservation value for the Marbled Murrelet and Northern spotted owl. The forest also serves as potential habitat for the coastal marten and Pacific fisher, although none have yet to be found within the forest.

Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco var. menziesii) and western hemlock (*Tsuga heterophylla* (Raf.) Sarg.) dominated the landscape. Vine maple (*Acer circinatum* Pursh), Pacific rhododendron (*Rhododendron macrophyllum* Pursh), salal (*Gaultheria shallon* Pursh), Cascara buckthorn (*Frangula purshiana* (DC.) A. Gray ex J.G. Cooper), evergreen huckleberry (*Vaccinium ovatum* Pursh), ocean spray (*Holodiscus discolor* (Pursh) Maxim), and Oregon grape (*Mahonia nervosa* Pursh) are common understory species found in these stands. On wetter slopes and riparian areas, Western redcedar (*Thuja plicata* Donn ex D. Don), bigleaf maple (*Acer macrophyllum* Pursh), and red alder (*Alnus rubra* Bong.) are common within the canopy, with Oregon Myrtle (*Umbellularia californica* (Hook. & Arn.) Nutt.), salmonberry (*Rubus spectabilis* Pursh), and beaked hazelnut (*Corylus cornuta* Marshall) in the understory. Less common tree species found within the study area include Sitka spruce (*Picea sitchensis* (Bong.) Carr.), Port Orford cedar (*Chamaecyparis lawsoniana* (A. Murray bis) Parl.), golden chinquapin (*Chrysolepis chrysophylla* (Douglas ex Hook.) Hjelmq.), Pacific madrone (*Arbutus menziesii* Pursh), and bitter cherry (*Prunus emarginata* (Dougl. ex Hook.) Eaton).

Windthrow has been the predominant natural disturbance in the Coast Range of Oregon for the last several decades. Influenced by climatic, biotic, and topographic interactions, higher windthrow susceptibility occurs on steep slopes with poorly developed soils and in old stands (>500-year-old canopy) located along forest edges (Sinton et al. 2000). The steep sloped coastal forests of the ESRF are therefore highly susceptible to windthrow, especially along clear cuts. However, windthrow is not the only disturbance in the region. Fires and landslides are also common disturbances. Few studies have attempted to develop a fire history for the southcentral Oregon Coast Range landscape around the ESRF. What research does exist suggests that the region experiences a moderate to low-frequency, moderate to high-severity fire regime, but likely with distinct longitudinal variability from the east (drier, more frequent, lower-severity fires) to the west (wetter, less frequent, higher severity fires) (Impara 1997). Much higher frequencies of low-severity fire may have occurred in the past, as detected in the slightly drier forests of the Oregon Cascades at similar latitudes (Merschel 2021). Native burning practices pre-Euro-American settlement would undoubtedly influence such fires (Zybach 2004). There is also historical records of a large, high-severity fire which occurred in 1868 (Phillips 1997) and is responsible for the bimodal age-class distribution in the ESRF. The fire ignited just northeast of the Elliott near Scottsburg, north of the Umpqua River. However, due to fire suppression and improved wildfire safety regulations, the ESRF has experienced 0.65 fires on average per year between 1992 and 2020, all under 5 acres in size (Short 2022).

2.2 Model Description

Long-term forest and carbon dynamics were modeled using LANDIS-II, a spatially interactive, raster-based forest landscape model that represents forested landscapes as species-aged cohorts (Scheller et al. 2007). LANDIS-II allows for multiple ecological processes (e.g., growth, mortality, regeneration, and disturbances) to overlap in space and time and has been widely adopted for use in climate change research in the U.S. (e.g., Loudermilk et al. 2014; Duveneck and Scheller 2015), including within the Pacific Northwest (e.g., Creutzburg et al. 2017; Cassell et al. 2019). LANDIS-II uses a process-based approach to forecasting the interactive effects of climate, succession, and disturbances and simulates species-level succession as an emergent property of these processes and species' life history strategies (Table 1). LANDIS-II's modular design allows users to use the succession and disturbance extensions best-suited for their research objectives.

Table 1. Species included within the model and key life history traits, including longevity, sexual maturity, probability of vegetative reproduction (resprouting) following fire, and effective seed dispersal distance (distance at which a seed has the highest probability of traveling).

Common name	Scientific name	Plant functional type	Longevity (years)	Sexual Maturity (years)	Prob. of veg. rep.	Effective disp. (m)
Douglas-fir	*Pseudotsuga menziesii*	Conifer	1000	15	0	140
Western hemlock	*Tsuga heterophylla*	Conifer	450	25	0	320
Port Orford-cedar	*Chamaecyparis lawsoniana*	Conifer	1200	7	0	180
Western redcedar	*Thuja plicata*	Conifer	1200	20	0	130
Sitka spruce	*Picea sitchensis*	Conifer	700	30	0	90
Oregon myrtle	*Umbellularia californica*	Evergreen broadleaf	250	5	0.8	400
Golden chinquapin	*Chrysolepis chrysophylla*	Evergreen broadleaf	450	40	0.8	100
Pacific madrone	*Arbutus menziesii*	Evergreen broadleaf	450	5	0.8	400
Cherry	*Prunus emarginata*	Deciduous broadleaf	100	5	0.6	400
Bigleaf maple	*Acer macrophyllum*	Deciduous broadleaf	300	10	0.8	50
Red alder	*Alnus rubra*	Deciduous broadleaf	125	4	0.4	400
Salmonberry	*Rubus spectabilis*	Evergreen shrub	100	5	0.9	400
Oregon grape	*Mahonia nervosa*	Evergreen shrub	250	5	0.8	400
Salal	*Gaultheria shallon*	Evergreen shrub	200	4	1	400
Rhododendron	*Rhododendron macrophyllum*	Deciduous shrub	60	5	0.8	100
Beaked hazelnut	*Corylus cornuta*	Deciduous shrub	250	2	0.6	400
Ocean spray	*Holodiscus discolor*	Deciduous shrub	30	5	0.8	100
Cascara buckthorn	*Frangula purshiana*	Deciduous shrub	250	5	0.6	400
Vine maple	*Acer circinatum*	Deciduous shrub	250	7	0.9	50
Evergreen huckleberry	*Vaccinium ovatum*	Deciduous shrub	250	5	0.5	400

Species succession was modelled using the Net Ecosystem Carbon and Nitrogen (NECN) succession extension. This extension simulates the growth, mortality, reproduction, dispersal, and regeneration of trees, shrubs, and grasses as a function of climate, soil, and life history strategies (Scheller et al. 2011). NECN simulates monthly changes in individual species growth as dictated by life history attributes (e.g., serotiny, vegetation regeneration, seed dispersal distance), biogeochemistry (e.g., C:N ratios of wood, leaves, and roots), and resource availability (e.g., light, nutrients). It tracks C and N in multiple pools of live biomass and detritus (leaves, wood, fine roots, coarse roots), and soil (Parton et al. 1988; Parton 1996). NECN also simulates hydrologic processes (e.g. precipitation, snow accumulation and melt, evaporation, transpiration) and simulates feedbacks between soil water availability and plant growth. NECN simulates many facets of climate change, both direct (e.g., temperature, precipitation) and indirect (e.g. changes in growing season length, soil temperature, soil moisture, available N), and simulates the impacts these facets have on growth, mortality, and regeneration. This comprehensive tracking of species composition, hydrology, and biogeochemical processes was the reason this extension was selected to explore different management scenarios under a changing climate.

Both natural and human disturbances were modeled using LANDIS-II extensions. Forest management activities, modeled using the Biomass Harvest extension, emulate the type and spatial distribution of planned silviculture across the ESRF (Gustafson et al. 2000). Windstorms, simulated using the Base Wind extension, create spatially explicit stochastic wind events that affect cohorts based on life-span defined susceptibility class whereby the oldest cohorts are most vulnerable to wind-induced mortality (Mladenoff and He 1999). While fire has had little impact on the ESRF over the last three decades, large historical fires indicate the importance of capturing the relationships between climate, fuel, topography, and fire. Therefore, the ignition, spread, and impact of natural and human-ignited fire were modeled using the Social-Climate Related Pyrogenic Processes and their Landscape Effects (SCRPPLE) extension of LANDIS-II. This extension allows for the simulation of both natural and anthropogenic fire and captures the spatial and temporal pattern of fires as driven by topography, fuels, climate, and human activity (Scheller et al. 2019). Fire in SCRPPLE is separated into natural, human accidental, and prescribed fire and is modeled based on four algorithms: ignition, spread, intensity, and severity. Only natural and human accidental fires were modeled based on the available management plans for the ESRF.

2.3 Climate Scenarios

Climate data was obtained for each climate region from the USGS Geo Data Portal (Blodgett et al. 2011). The Multivariate Adaptive Constructed Analogs (MACA) method of downscaling datasets, comprising general circulation models (GCMs) in the CMIP5 archive, created the data in this repository (Thrasher et al. 2013). Climate models and RCPs for inclusion in this analysis were selected using the four-corners approach often applied in evaluations of climate change effects (Lutz et al.

2016). Under this approach, model scenarios representing relatively "warm-wet," "warm-dry," "hot-wet," and "hot-dry" conditions are selected. The mean maximum daily temperature and mean total annual precipitation were calculated for each decade of GCM data obtained for contemporary climate (2010-2019) and future late-century climate (2090-2099). The projected change in these variables was then calculated as late-century climate minus contemporary climate. These changes were plotted (Figure 2), and models representing the "four corners" were identified visually after first ruling out potential outliers. In addition to these four climate scenarios, a historical climate scenario was selected. This historical climate scenario, obtained from downscaled gridMET data from 1979 to 2021 (Abatzoglou 2013), acts as a baseline for comparing future conditions. Climate inputs in LANDIS-II are grouped into homogenous climate regions, which have important implications for the model's ability to facilitate spatial variation in plant growth and wind susceptibility. Climate regions were created using K-means and CLARA cluster algorithms based on historic total precipitation, mean daily maximum temperature, and mean wind speed during the growing season. Climate region maps were assessed using a combination of their quantitative silhouette scores and visual interpretation of the output cluster analysis maps, and trends in the mean daily temperature and total annual precipitation were graphed (Supplementals 1 & 2).

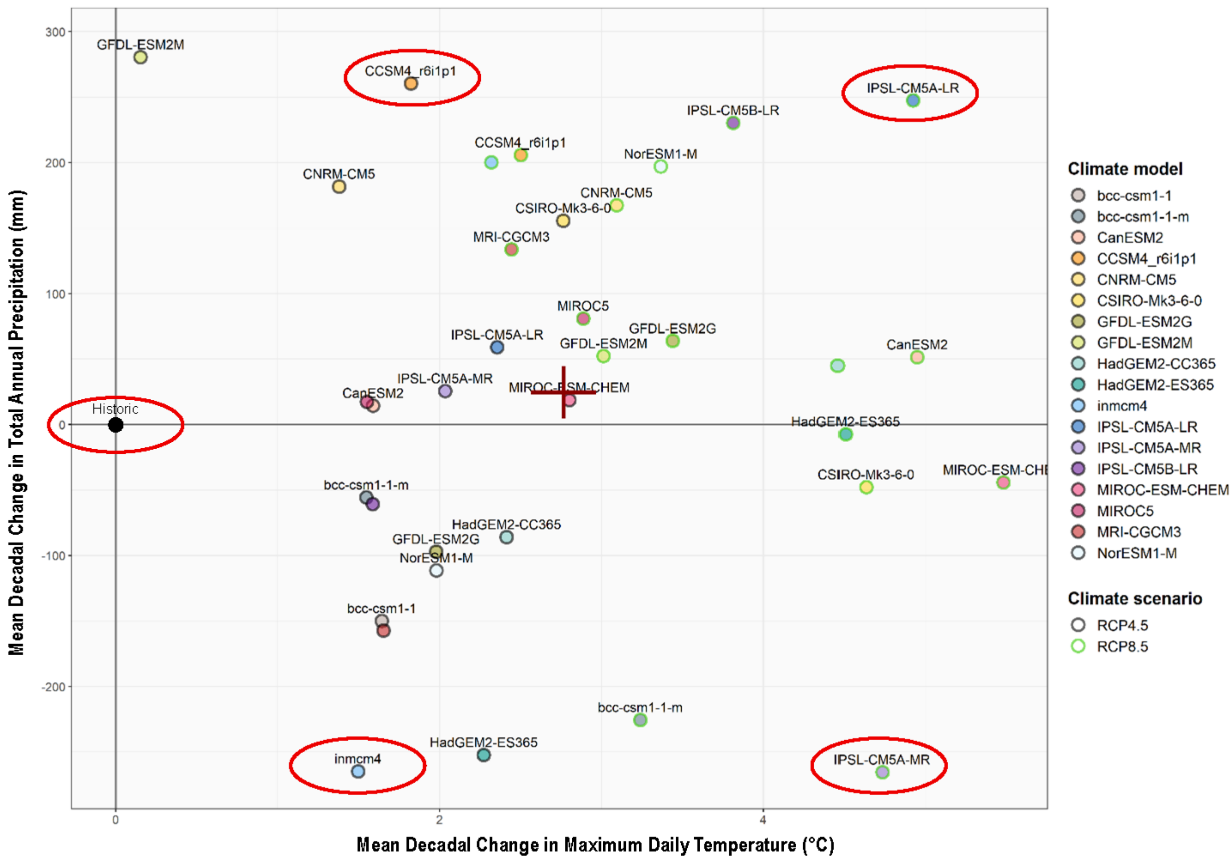


Figure 2 Climate models and RCPs for inclusion in analysis were selected using the "four corners" approach often applied in evaluations of climate change effects.

2.4 Parameterization and Calibration

2.4.1 Model landscape and Initial Vegetation

LANDIS-II requires an initial community map that defines the vegetation on the landscape by identifying the age and biomass of each species within every cell. Given the precedent set by the 5000-ha fire in the ESRF in 1868, future projections may include large wildfires. So, our model includes a buffer extending along the forest's eastern edge and up the Umpqua River to Elkton to allow for the spread of fire into the Elliott from the east (Figure 3). The basis of this decision was the likelihood that large fires would be driven by sustained east wind events. Our buffer captures potential fire spread into the ESRF while retaining a feasible simulation landscape. To develop a list of species for inclusion in our model, data from a 2016 ODF stand inventory of the ESRF and FIA data from plots located (approximately) within the boundaries of the ESRF landscape were assessed. Tree species were included if they were found in 5% of FIA plots and/or 2% of ESRF inventory plots. Shrub species, which were not surveyed, were selected for inclusion in the model if they were present in 30% or more of FIA plots. Based on these thresholds, nine tree species and eleven shrub species were selected for inclusion in the model (Table 1). Preliminary species lists developed before querying these data sources were also reviewed for reasonableness by experts previously stewarding the ESRF.

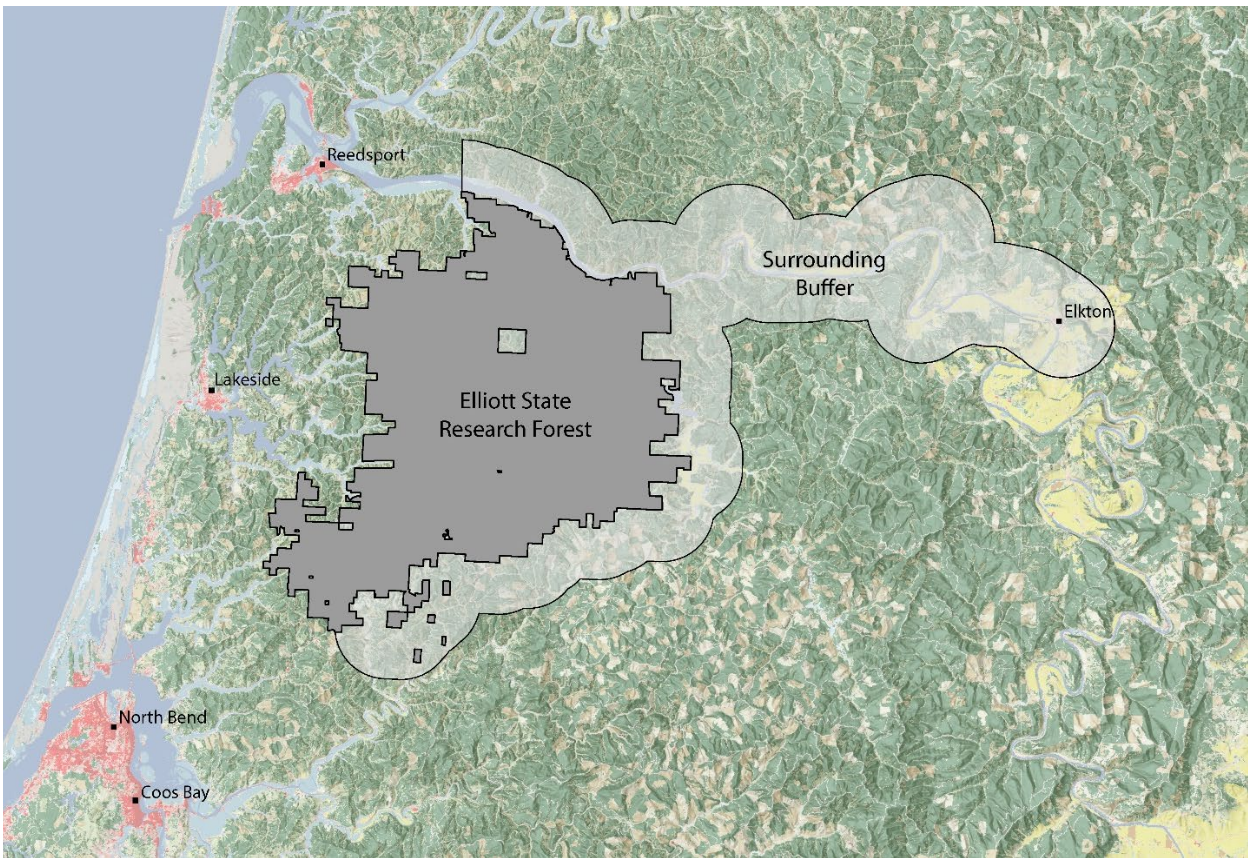


Figure 3. Map displaying the LANDIS-II landscape, composed of the Elliott State Research Forest and a surrounding buffer to allow fires to spread into the forest from the East and along the Umpqua River.

The development of the IC map was separated into two processes to incorporate data from the ESRF and FIA inventories. First, an interpolation-based approach fused FIA plot data with gridded LEMMA products to create an IC map for the buffer region. The second process made use of the most recent inventories of the ESRF and FIA data to define vegetation within the ESRF. To calculate the age of tree species within inventory plots, species presence and age were pulled directly from the ESRF inventory, which used visual assessments to estimate stand age. Age estimates for tall trees in the ESRF were sometimes toward the upper end of each species' longevity (Table 1). This created a step function in the relationship between height and age. Large clusters of trees at this age are unrealistic, particularly in the ESRF, which has been largely affected by both stand-replacing fire in 1868 and subsequent logging. Therefore, to account for residual old trees within the ESRF while introducing a more realistic variability in the ages of tall trees, the age of tall trees with clear overestimation were randomized to produce a more natural relationship between height and age (Supplemental 3). The age of shrubs cohorts was quantified in FIA based on cover percentage.

Separate approaches were used to compute cohort biomass for trees and shrubs using FIA data. The biomass of trees in the ESRF inventory computed by the Oregon Department of Forestry was significantly lower than expected for the region. Therefore, cells in the ESRF were assigned biomass from FIA data using a hierarchical matching approach (Supplemental 4). Shrub biomass was calculated using allometric equations relating cover to biomass. An important caveat is that most shrub biomass equations use basal diameter and/or width as the independent variable, whereas FIA data only includes cover data. Furthermore, FIA shrub age was equivalent to the age assigned to the FIA plot rather than actual age of the shrub layer. Hence, the development of allometric equations was affected by this constraint, and for most species, the accuracy of these equations was likely to be lower than that of alternative equations using basal diameter (Chojnacky and Milton 2008).

2.4.2 Succession

Species-specific life history traits responsible for growth and mortality were derived from literature review and previous LANDIS-II models in western Oregon. Data obtained from the EPA Community Multiscale Air Quality Modeling System (CMAQ) data set for 2002-2017, employed by (Geiser et al. 2021), helped parameterize the NECN inputs controlling the deposition of wet and dry nitrogen. Previous Pacific Northwest LANDIS-II models and plant databases such as BIEN, FRED, PLANTS, and TRY formed the basis to parameterize species-level parameters controlling various species attributes, such as annual net primary productivity (ANPP), maximum biomass, drought tolerance, and minimum temperature tolerance. Functional group-level parameters controlling broader attributes, such as soil temperature response, woody decay rate, and fraction of fine to coarse roots were also parameterized. Data for conifers and deciduous broadleaved trees came from flux-tower data from the Ameriflux network, while data for evergreen broadleaved trees, deciduous shrubs, and evergreen shrubs came from LANDIS-II parameters from the Klamath Mountains (Serra-Diaz et al. 2018). The accumulation of biomass over time due to growth was calibrated by running simulations under historical climate conditions and comparing the age-biomass relationship at the end of the simulation with FIA data (Supplemental 5).

2.4.3 Wind

Empirical data on the mean, minimum, and maximum wind event size was obtained from a study in the Bull Run basin of northwestern Oregon (Sinton et al. 2000). Input data on wind severity was obtained from a study in the Cascade Head Experimental Forest (Harmon and Pabst 2019). Wind event size and severity were calibrated through repeated simulation and adjustment of parameters until the wind regime matched that of the two empirical studies. Our simulations had a mean wind event size of 6.7 ha and a max wind event size of 96.6 ha. This range of wind event sizes matched literature values of 7.5 and 157 ha. The mean biomass mortality rate (2.24%) also matched the literature value of 2.21%. The mean wind rotation period in our simulations was 58 years.

2.4.4 Fire

Fire has been a minor disturbance within the ESRF in recent years. However, the ESRF has historically experienced widespread fire events and fire likely played a pivotal role in forest development prior to contemporary management. The SCRPPLE extension was selected to allow for future modeling of extreme fire events. However, for this study, the decision was made to model the contemporary fire regime. The fire extension was parameterized to match empirical data on fires observed within our study area over the past three decades. The probability of natural and accidental ignitions was fit to a Poisson distribution. The relationship between FWI and ignitions was parameterized using historical ignition data within our landscape from 1992 to 2020 (Short 2022) in conjunction with daily fire weather index (FWI) data computed by the climate library in NECN. SCRPPLE calculates the probability of fire spread based on FWI, fine fuels, and effective wind speed, which combines downscaled wind speed and direction within a cell. Empirical data on daily fire spread was extremely limited within the modeled landscape and, more broadly, in the Oregon Coast Range due to the small average size of recent fires within this region. Therefore, fire spread parameters for these three variables (FWI, fine fuels, and effective wind speed) were derived from a model created for the nearby Siskiyou Mountains (Deak et al. 2024). Parameters were adjusted to match empirical data, with a frequency of 3.49 fires/year (3.83 empirical), mean fire size of 1.2 ha (0.77 empirical) and a maximum size of 13.7 ha (17.8 empirical). SCRPPLE calculates fire intensity based on the mass of fine fuels, ladder fuels, and the intensity of fires in adjacent cells. This intensity, combined with the age and species of a cohort, determines the percent mortality of a cohort. Parameters were also obtained from the Siskiyou Mountains study and adjusted so that cohort mortality matched the recent low-severity fire regime found on the landscape with a 21% cohort mortality of trees and shrubs.

2.4.5 Management

The ESRF's management plan and the Biomass Harvest extension both have a hierarchical design. Using the management plan's framework, the forest was divided into a conservation research watershed and a management research watershed. The management research watershed was further divided into subwatersheds, which were each assigned one of the four timber producing management strategies described above (land sharing, Triad-share, Triad-spare, and land sparing). Finally, each subwatershed was then further divided into management areas defined using a combination of sub-watershed-scale experimental treatments, stand-scale silvicultural treatments, and stand-age (Table 2). The three stand-scale silvicultural treatments were intensive, extensive, and reserve. Management areas based on intensive treatments were treated with precommercial thinning followed by clearcutting and the replanting of Douglas-fir. Management areas based on extensive treatments were treated with four variants of variable density thinning followed by five variants of variable retention harvesting, with three levels of retention and two different spatial configurations (aggregate & dispersed). Replanting following variable retention harvesting focused on supporting the following key minor tree species identified by the management plan: pacific madrone and golden chinquapin (selected for their drought resistance), western redcedar (selected for its disease resistance and cultural importance to indigenous communities), and Port Orford cedar (selected for its endemic nature). Finally, treatments were excluded from reserve-based management areas with stand age greater than 65 years old and limited to an initial thinning in stands less than 65 years old. Although initially assigned to no active silvicultural treatments, the River Conservation Area was separated into stands greater than and less than 65 years old to allow for complexity enhancement treatments (if desired at a later stage). Stand maps were derived from Oregon Department of Forestry (ODF) stand maps, with stands adjacent to rivers separated into riparian and non-riparian portions of the stand.

Harvest prescriptions were then applied to the landscape by specifying the annual harvest area percentages for each prescription (Supplemental 6). The objective of these annual harvest area percentages was to ensure that management strategies with greater proportions of extensive treatments had a larger annual spatial footprint than strategies more reliant on intensive treatments, but that all strategies produce equivalent timber densities. Our initial harvest area percentages were adjusted through repeated simulation and analysis of annual harvest area and harvested biomass until each management strategy in the MRW produced similar harvest biomass densities and a higher proportional harvest area occurred in subwatersheds with higher allocations of extensive stand-level treatments (i.e., the land sharing and Triad-share subwatersheds). Further calibration ensured that harvesting levels approximated management goals of 15 MMBF harvested across an extent of 240 ha annually (14.4 and 170 respectively).

Table 2. Management areas (MAs) used in the LANDIS-II model to replicate the silvicultural activities defined in the Oregon State University management plan.

MAs	Type	Description	Silvicultural analog and intended effect
MA 1	Reserve	Stands in the CRW aged ≥ 65 years	These stands will never be actively managed within the Harvest configuration. No prescriptions.
MA 2	Reserve	Stands in the CRW aged < 65 years.	These stands will be managed using a single-entry variable density thinning, with gaps and thinning of the matrix for the first 21 years of the simulation, after which they will be placed in passive reserve-based management. Stands may be assigned one of three alternative gap sizes.
MA 3	Reserve	Stands aged ≥ 65 years in the MRW that have been assigned to reserve-based silvicultural treatments.	These stands will never be actively managed within the Harvest configuration. No prescriptions.
MA 4	Reserve	Stands aged < 65 years in the MRW that have been assigned to reserve-based silvicultural treatments.	These stands will be managed using a single-entry variable density thinning, with gaps and thinning of the matrix for the first 21 years of the simulation, after which they will be placed in passive reserve-based management. Stands may be assigned one of three alternative gap sizes.
MA 5	Reserve	Stands aged ≥ 65 years located in the RCA of either the CRW or the MRW.	Initially, these stands have been assigned to passive reserve-based silvicultural treatments. No prescriptions
MA 6	Reserve	Stands aged < 65 years located in the RCA of either the CRW or the MRW.	Initially, these stands have been assigned to passive reserve-based silvicultural treatments. No prescriptions
MA 7	Intensive	Stands of any age in the Partial MRW sub-watersheds that have been assigned to intensive stand-scale silvicultural treatments.	Thin stands to reduce density, promote growth of residual trees and obtain intermediate revenues, followed by clearcutting at age ~ 60 and replanting with PSME.
MA 8	Extensive	Stands of any age in the Partial MRW sub-watersheds that have been assigned to extensive stand-scale silvicultural treatments.	Variable density thinning, followed by one of five variants of a variable retention harvest. Variants of the retention harvest include three levels of retention and two alternative spatial configurations of retention. Planting of minor species of interest following harvest.
MA 9	Intensive	Stands of any age located in sub-watersheds of the MRW to which land sparing, Triad-spare or Triad-share experimental treatments have been assigned, and which will be managed using intensive silvicultural treatments.	Thin stands to reduce density, promote growth of residual trees and obtain intermediate revenues, followed by clearcutting at age ~ 60 and replanting with PSME.
MA 10	Extensive	Stands of any age located in sub-watersheds of the MRW to which land sharing, Triad-share or Triad-spare experimental treatments have been assigned, and which will be managed using extensive silvicultural treatments.	Variable density thinning, followed by one of five variants of a variable retention harvest. Variants of the retention harvest include three levels of retention and two alternative spatial configurations of retention. Planting of minor species of interest following harvest.

2.5 Experimental Framework and Analysis

To assess the impact caused by the five management strategies under a range of feasible climate scenarios, the proposed management plan was simulated under five climate scenarios, windthrow, and wildfire. Model outputs were assessed spatially using R v4.4.0 (R Core Team 2013) in RStudio 2024.04.1 (RStudio, 2022). The terra package v1.7-3 was used to compare changes in forest condition under each strategy (Hijmans, et. al., 2022). To capture a range of potential outcomes produced by the stochastic nature of the model, 10 replicates of each climate scenario were run. The model was run through the end of the 21st century, allowing for the differences in management strategies to sufficiently impact forest characteristics. The annual area disturbed by windthrow, wildfire, and management was calculated to compare their relative spatial footprints over time. Timber production was compared at the landscape, management strategy, and silvicultural treatment-level by summarizing annual biomass removal map. To compare the relative impacts of management strategies on the diversity of trees and shrubs, species richness and Shannon diversity index (SDI) were calculated for the first and last year of simulation (2016 and 2100), and annual percent site occupancy for each species. SDI was calculated based on species biomass. Diversity metrics were calculated for a single replicate randomly selected from each climate scenario, as the landscape-scale variation between replicates was low and averaging between replicates reduced the spread of data due to the spatial variation of species richness and SDI between replicates (Supplemental 7). Finally, carbon storage was calculated at the species-level, age-level, and in terms of different carbon pools (aboveground woody, soil organic, and total).

CHAPTER III

RESULTS

3.1 Disturbance

Natural disturbances play a major role in shaping forest development within the ESRF and throughout the Coast Range of Oregon. Wind was the most prevalent disturbance within the ESRF, followed by harvesting, and then fire, which experienced the most annual variability (Figure 4). Following the start of management in 2026, there was a 16.6% increase in the extent of wind damage. This mirrors the expected increase that would result from increased forest edge density; however, the base wind extension does not consider edges when modelling windthrow and this increase was likely due to changes in mortality probability as defined by the wind severity table (Supplemental 8). There was a 37.3% decline in the extent of harvesting in the year 2047, which coincided with the end of thinning within reserve stands less than 65 years of age for the purpose of promoting structural complexity. The average area harvested increased back to pre-2047 extents by 2065. This rebound was likely due to increases in the extent of stands available for harvest within areas assigned to intensive and extensive treatments. Under climate change, disturbance extents remained relatively consistent with the historical scenario, except for an increase in large fire years, with years in the 95th percentile of area burned under a historic climate being 2.5 times more frequent under climate change.

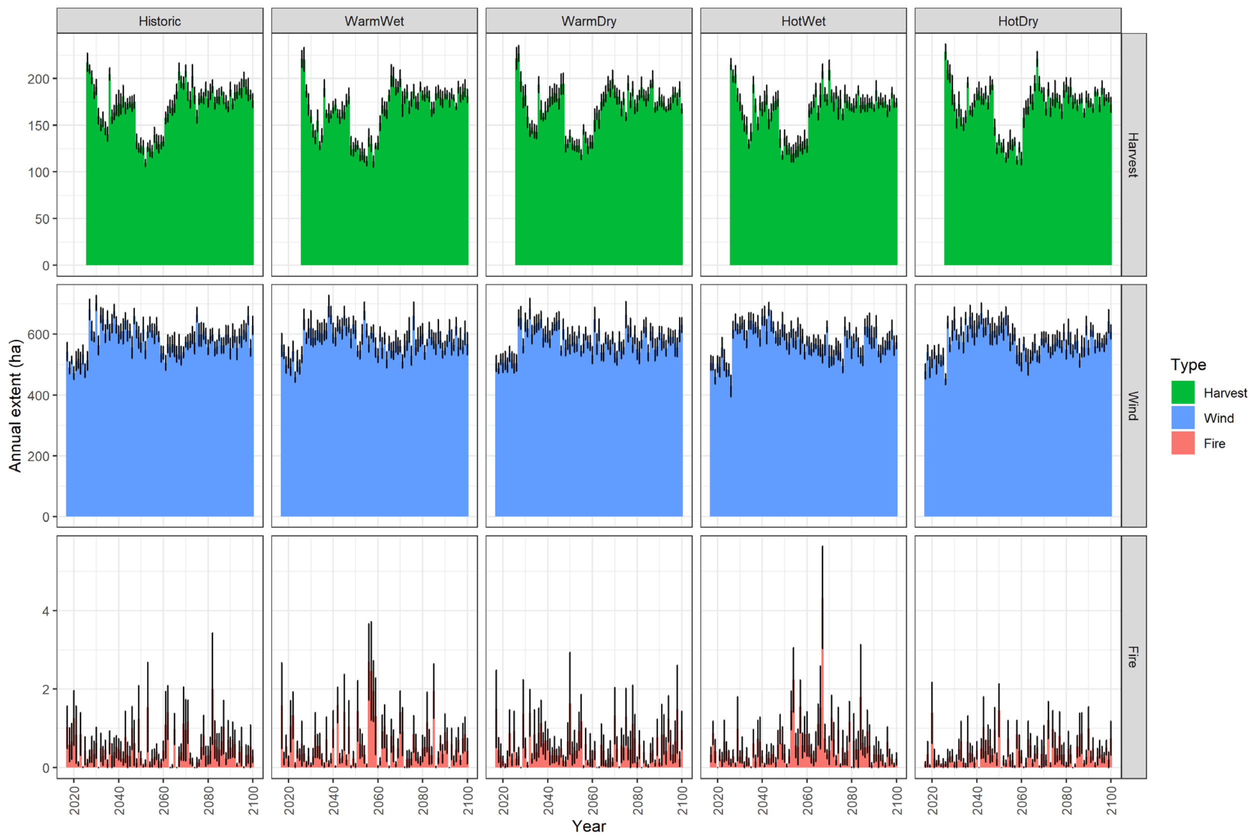


Figure 4 Annual disturbance trends for timber production, wind, and fire. Results show the annual average and standard deviation across replicates.

3.2 Timber Production

The ESRF management plan set an annual timber production goal of 15 MMBF and a harvesting limit of 19.6 MMBF. Our results indicate that while management was initially able to meet this 15 MMBF target, timber output drops after the first decade to an average of 13 MMBF before returning to the desired range in the year 2060 and then largely remaining within this range through the end of century under the historic and warm wet scenarios (Figure 6). Timber production was slightly lower during the last 20 years of the simulation under the warm dry and the two hot scenarios. This could be due to lower aboveground biomass within harvested sites caused by a decrease in growth rates under the more xeric conditions produced by these climate projections.

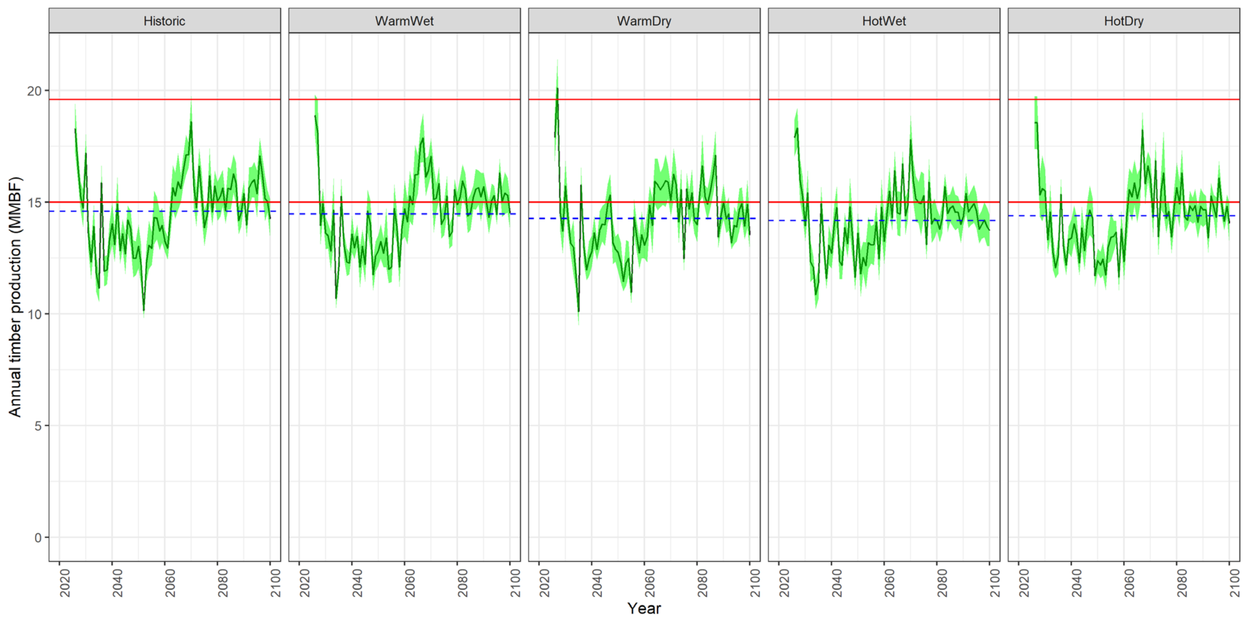


Figure 5. Total timber production in millions of board feet (MMBF) within the ESRF under different climate scenarios. Red lines indicate the desired range of timber production set by the management plan and the dashed blue line indicates the average annual timber produced over the simulation.

All management strategies produced roughly equivalent timber output per unit area, but with different harvesting annual harvest extents, arranged by proportion of extensive silvicultural treatments (land sharing = 0.94% of management area, Triad-share = 0.69%, and Triad-spare = 0.6%, land sparing = 0.63%). Strategies that incorporated extensive treatments (land sharing, Triad-share, and Triad-spare) also tended to have more variability in their annual biomass production (Figure 7). This variability was responsible for the large inter quartile range seen in figure 4, as opposed to any trend in timber production over time (supplemental 9). Despite minor increases in annual variability, the average biomass harvested under each management strategy remained consistent under all climate change scenarios, indicating that timber production in the ESRF is likely sustainable through the end of the 21st century.

Figure 6. Modeled timber production in the ESRF between 2026 and 2100. Red boxplots indicate the annual biomass removed due to timber production in megagrams per meter squared and the blue box plots indicate the annual percent of management area needed to be treated to meet that level of timber production.

By the end of the 21st century, the spatial segregation of stand-scale silvicultural treatments assigned to extensive, intensive, and reserve resulted in predictable spatial distribution of biomass removal within management areas (Figure 8). Land sharing subwatersheds experienced low-level, homogenous biomass removal, while land sparing subwatersheds experienced high biomass removals over half of the area and no removals over the other half. The Triad approaches experienced a mix of high, low, and no biomass removal, with the Triad-spare subwatersheds having higher concentrations of high and no biomass removal. Finally, reserve subwatersheds experienced small clusters of low biomass removal due to single-entry variable density thinning during the first 21 years of management, within stands less than 65 years of age for the purpose of promoting structural complexity.

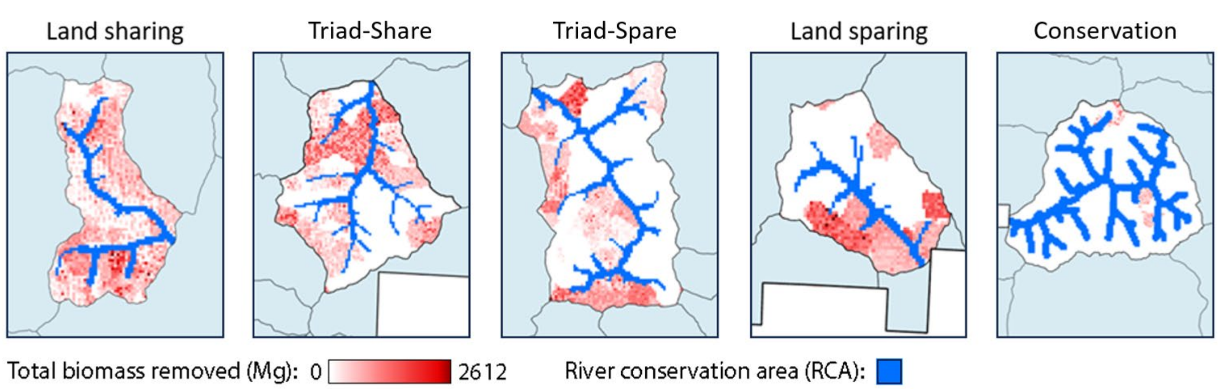


Figure 7. Example subwatersheds from each management approach depicting the different spatial patterns of cumulative biomass removal from 74 years of timber production under a historic climate.

3.3 Tree and Shrub Diversity

Differences in the spatial arrangement of treatments, intensity of timber production, and the type of replanting following harvest had large impacts on tree and shrub diversity (Figure 9). When comparing the relative impacts of sharing, sparing and Triad management on tree and shrub diversity, management strategies that incorporate more extensive treatments (sharing and Triad-share) tended to have slightly higher species richness (averaging 1 to 2 species more in a site). However, mean species richness was more sensitive to climate than management strategy, as evidenced by the hot scenarios exhibiting only half the species richness compared to the historic scenario. Despite the general comparability of species richness between management areas, the mean SDI under the land sharing approach was far greater than under the other approaches (nearly double on average). This indicates that while there were on average a similar number of species in any given cell, minor tree species accounted for a much larger portion of the biomass under land sharing. This was likely due to variable density thinning and retention harvesting in extensive treatments, which favored non-Douglas-fir species via selective removal, creation of canopy gaps, and planting of minor tree species. The Gini-Simpson Diversity Index was also calculated, and results largely aligned with SDI, further indicating the dominance of Douglas-fir under strategies utilizing intensive and reserve treatments (Supplemental 10). The end-of-century SDI was also heavily impacted by climate change, with SDI in the historic scenario being 2.5 times greater than in the hot scenarios on average. The low average SDI value found within the reserve portion of the forest was likely due to the dominance of young Douglas-fir, which limited the growth of younger shade-tolerant tree species over the course of the simulation in the absence of management.

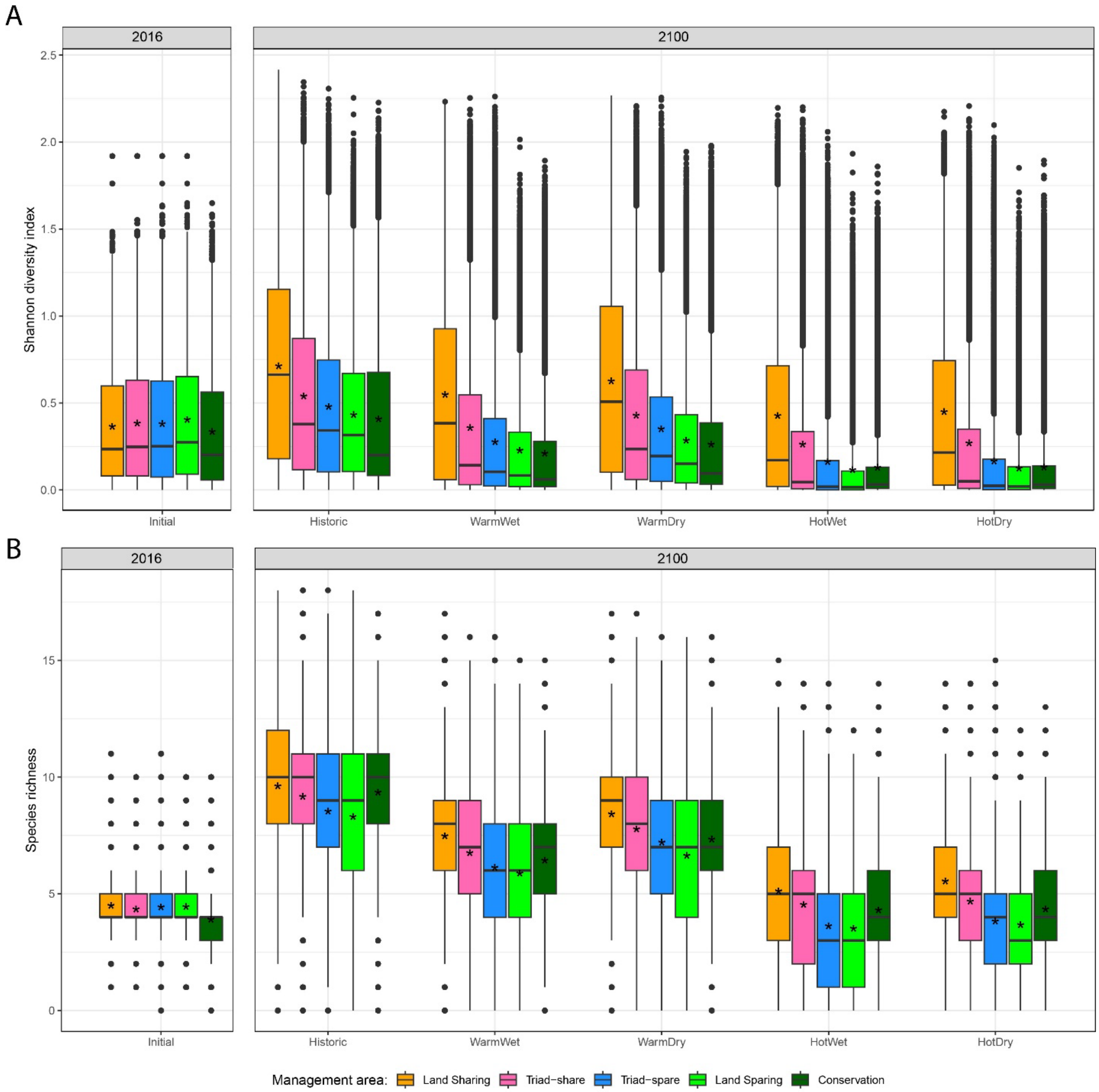


Figure 8 Landscape-scale tree and shrub species richness (A) and Shannon diversity index of biomass (B) under each management strategy in 2016 and at the end of century for each climate scenario.

The diversity of trees and shrubs was also assessed by calculating the percent site occupancy of individual species over time. Results indicate a significant expansion in the distribution of minor tree species under historical climate conditions, with the distribution of western hemlock and Port Orford cedar nearing, or in some cases, even surpassing that of Douglas fir, particularly in instances of land sharing (Figure 9). The four key species identified from the management plan, western redcedar, Port Orford cedar, Pacific madrone, and golden chinquapin, all benefitted from strategies with high proportions of extensive treatments (land sharing, Triad-share), especially golden chinquapin which occupied roughly 25% of sites under the land sharing strategy, while failing to persist under the land sparing and conservation strategies. However, some species benefited under the increased proportions of reserve treatments within the land sparing and conservation strategies. For instance, Oregon myrtle maintained a broader spatial distribution under these strategies relative to land sharing, particularly under climate change. Despite the improved relative success of Oregon myrtle compared to other species, all minor tree species were less successful under climate change. This was primarily driven by increased temperatures as there was little difference in percent occupancy between the two warm and the two hot scenarios. Despite the difficulty for other tree species to establish under climate change, the extent of Douglas-fir was largely unaffected by climate. However, it was sensitive to management, with the extent of Douglas-fir decreasing relative to the proportion of extensive treatments in each management strategy. The presence of shrubs on the landscape was far less sensitive to changes in management with the end of century percent occupancy rates of shrubs being similar across management strategies. Shrub presence was also less sensitive to changes in climate, except for cascara buckthorn and rhododendron, which were both heavily impacted by the hotter climate scenarios. The presence of cascara buckthorn was halved under the hot scenarios compared to historic, while the presence of rhododendron decreased from 50% of sites to 0% by midcentury (Figure 10).

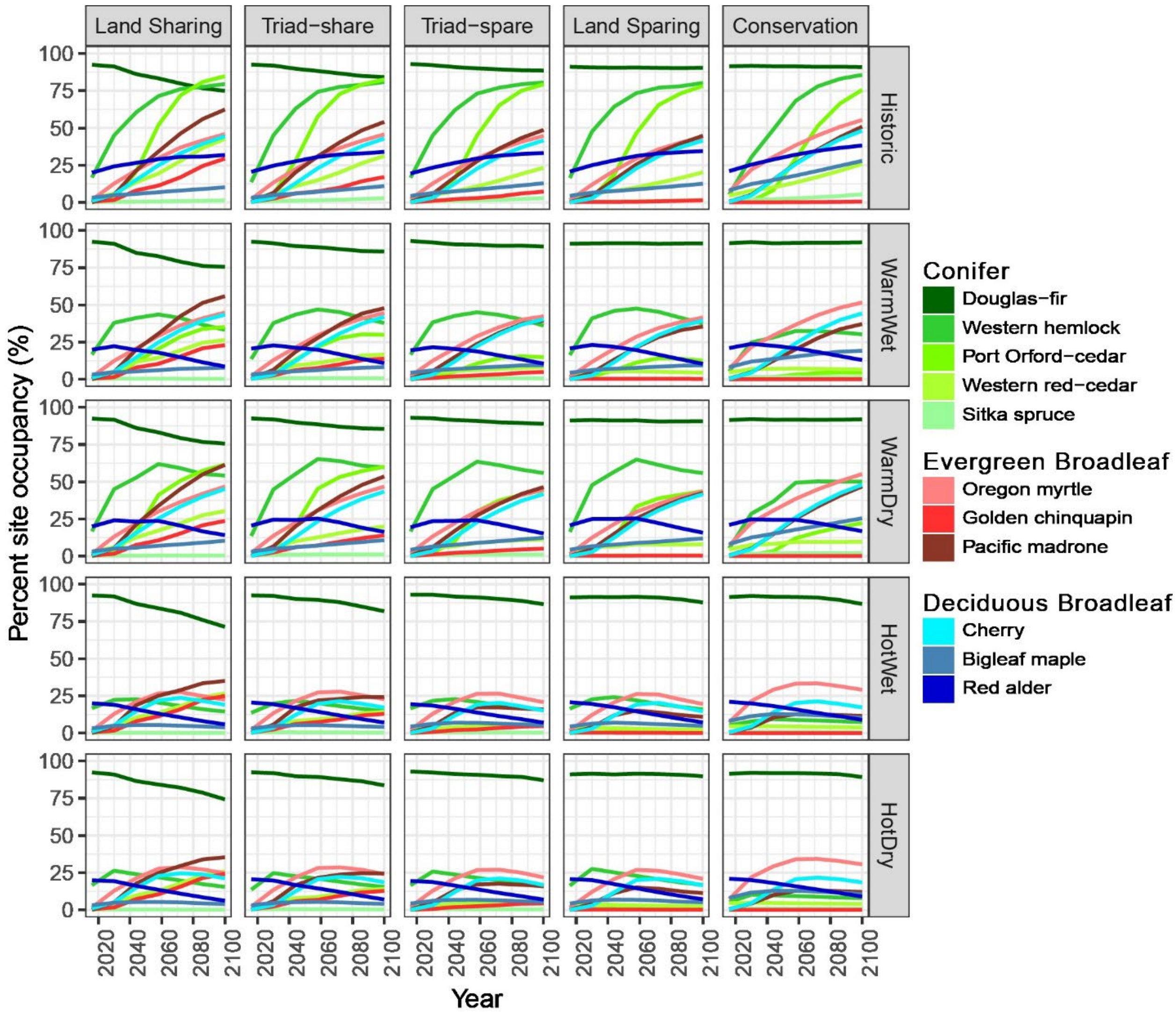


Figure 9 Trends in the percent of cells occupied by tree species over the course of the 21st century under each management strategy and the five climate scenarios.

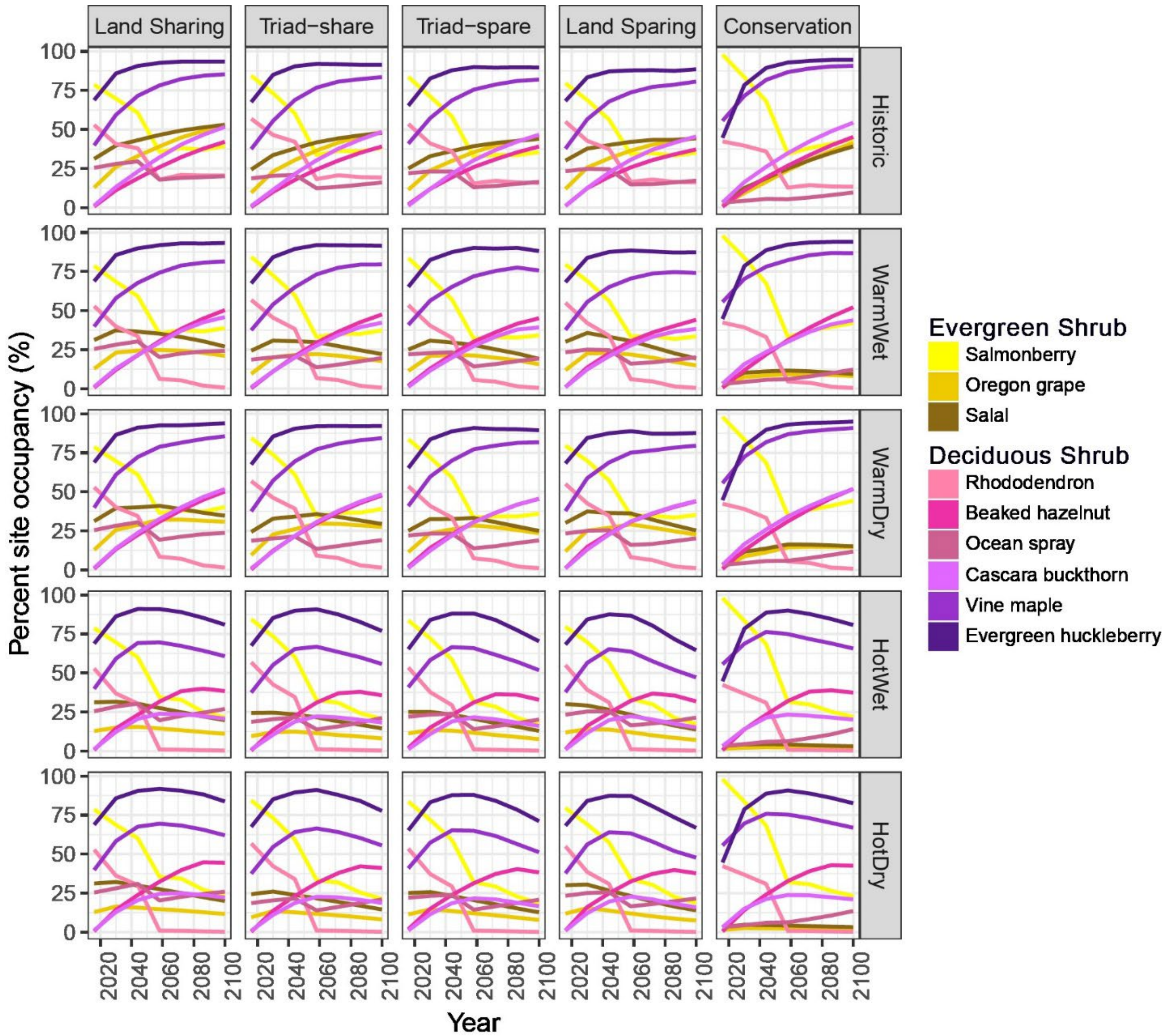


Figure 10 Trends in the percent of cells occupied by shrub species over the course of the 21st century under each management strategy and the five climate scenarios.

3.4 Carbon

The different approaches to forest management also impacted carbon storage. Unsurprisingly, Douglas-fir dominated the aboveground live carbon (AGC) pool under all management strategies and climate scenarios (Figure 12). This pool increased by 33.5% under the conservation strategy and, but only 9% under the land sharing strategy. The lower total AGC under land sharing was likely due to the increase in carbon stored within species other than Douglas-fir, particularly Western hemlock and Port

Orford cedar, slow growing species which out-competed Douglas-fir. Land sharing was also the only management strategy to experience increases in carbon associated with shrubs, with the largest increases occurring in Evergreen huckleberry and Cascara buckthorn (Figure 13). This may have also increased the competition faced by young tree species, reducing their ability to grow into adulthood, despite their success in establishing. Minor tree species were more sensitive to climate change than Douglas-fir and carbon associated with these species decreased under climate change. Despite this decrease, the overall AGC stayed fairly consistent under climate change due to increases in Douglas-fir. Shrub carbon under the land sharing strategy increased with climate change, but remained consistent under the other management strategies, indicating that shrubs in the other management strategies are not limited by climate but by competition with the overstory.

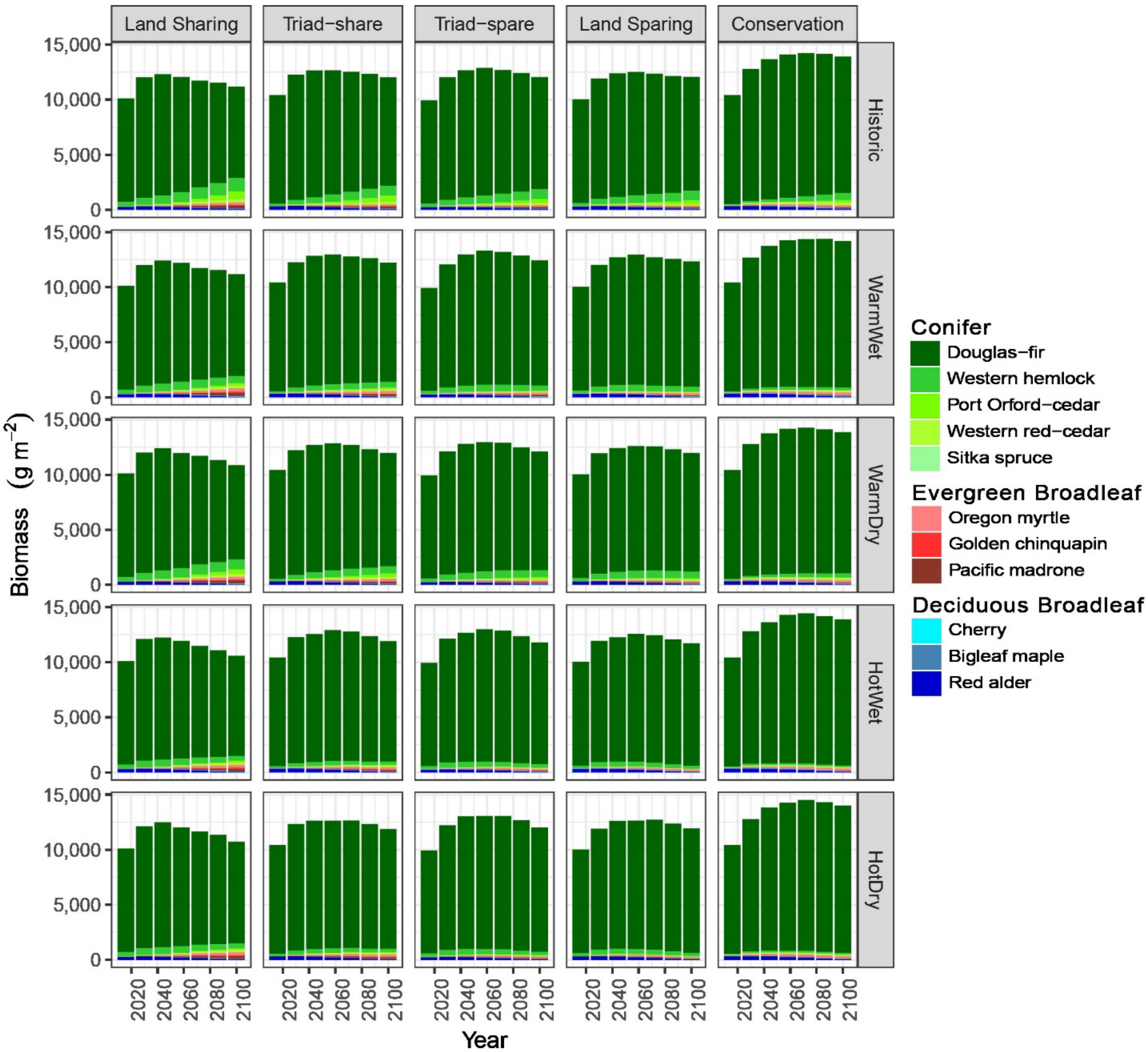


Figure 11. Trends in species specific aboveground live tree carbon under each management strategy and climate scenario.

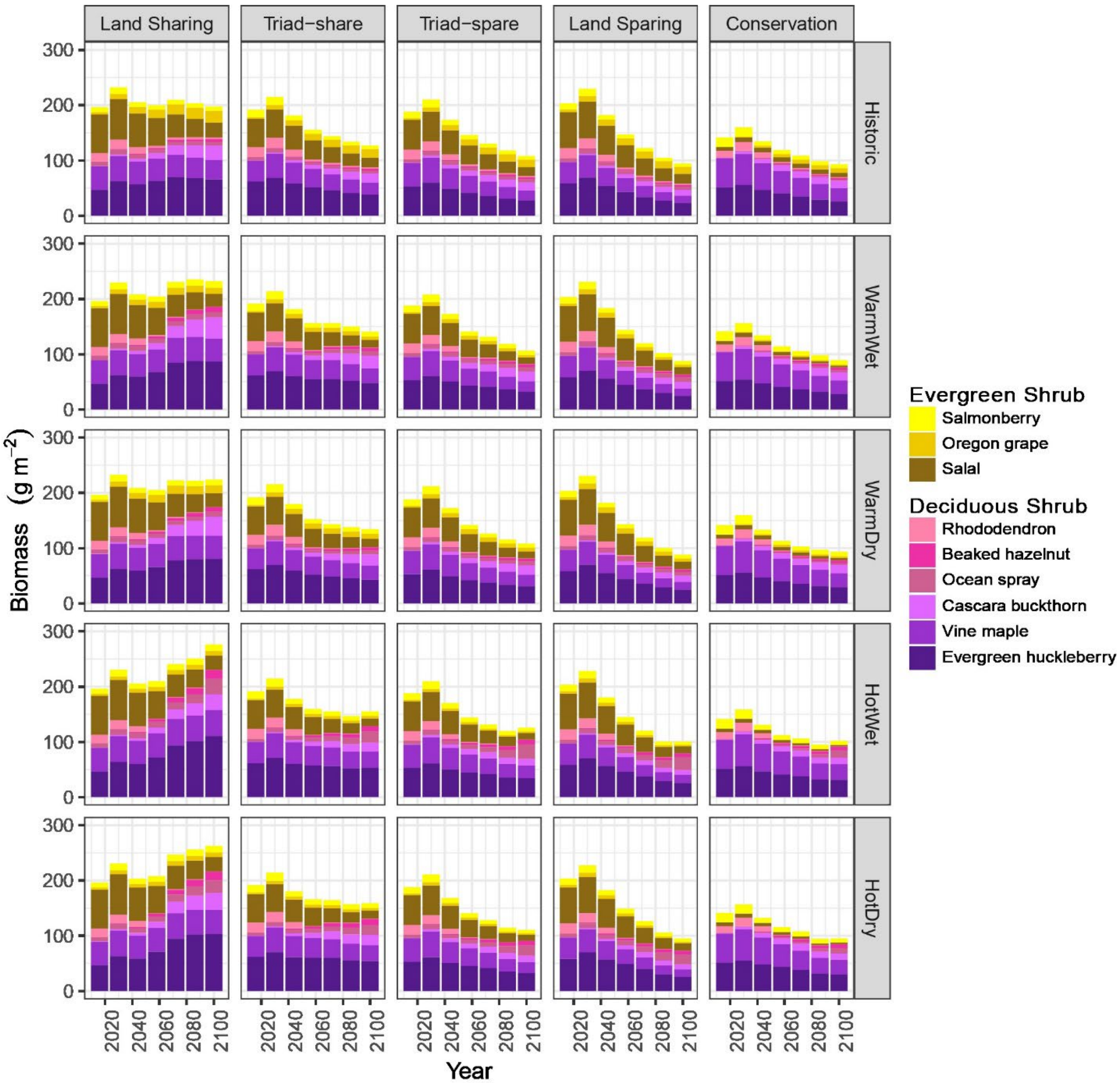


Figure 12. Trends in species specific aboveground live shrub carbon under each management strategy and climate scenario.

The distribution of carbon density by age at the end of our simulation was highly dependent on initial conditions. The ESRF initially had a bimodal age class distribution, with modes at 35 and 110 years of age, although this 110-year-old mode had a very minor presence in areas assigned to the land sharing management strategy (Figure 14). The importance of the 35-year-old mode decreased over time under all management strategies. However, the relative proportion of carbon stored within the

110-year-old mode increased under strategies with large reserve components (Triad-spare, land sparing, and reserve). Cohorts under 84 years old accounted for a small percentage of carbon at the end of the simulation, indicating that the trees which dominated the forest at the start of the simulation were largely able to outcompete new arrivals. Climate change had little impact on the age of cohorts in which carbon was stored under all strategies. However, these last two findings are due in part to the large influence of Douglas-fir on this distribution. Differences in the importance of minor tree species and shrubs between strategies and the influence of climate change in altering the distribution of carbon are masked by the prevalence of the largely climate resistant Douglas-fir (Supplemental 11).

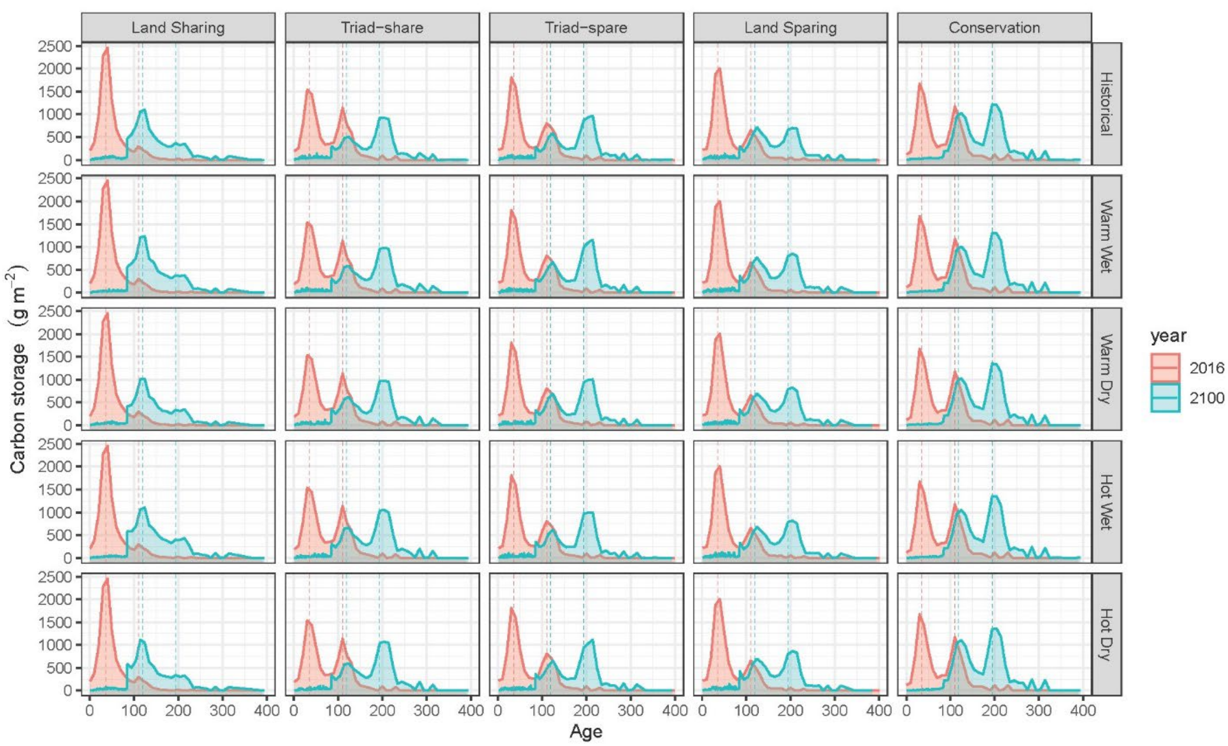


Figure 13 Distribution of carbon density by cohort age at the beginning of simulation (2016) and end of simulation (2100) for each management strategy and climate scenario. The two red dashed lines indicate the two modes (35 and 110 years old) at the start of simulation and the two blue dashed lines indicate these same modes at the end of simulation.

Finally, trends in AGC, soil organic carbon (SOC), and total carbon were assessed by management strategy and climate scenario (Figure 15). While all management strategies began with similar levels of AGC, these levels greatly change over the 21st century depending on the strategy. Results indicated the importance of reserve treatments in increasing AGC in young coastal temperate forests, with end of century AGC arranged based on the proportional allocation of stand-scale reserve treatments (i.e., reserve > land sparing > Triad-spare > Triad-share > and land sharing). The Triad-share and conservation strategies experience minor increases in AGC under climate change (0.37% & 0.84% respectively), while the Triad-spare and land sparing strategies experienced minor decreases in AGC under climate change (-0.38% and -0.67% respectively). AGC under the land sharing strategy was more sensitive to climate change and decreased by an average of 3.95%. All management strategies saw a decrease in AGC under hot climates, except for the conservation strategy which experienced a 1.08% increase in AGC under the hot dry scenario.

Unlike AGC, initial SOC was 18.5% higher in areas assigned to the conservation strategy than in areas assigned to the other four strategies. The initial SOC within these other four was similar, with a range of only 427 g/m^2 (sharing to Triad-share). In each climate scenario, SOC decreased under the conservation strategy while increasing under the sharing, sparing and Triad strategies. Land sharing saw the largest percent increase in SOC, followed by Triad-spare, Triad-share, land sparing, and finally the conservation strategy. SOC was also reduced by climate change, especially under the conservation strategy which had 3.8% less SOC at the end of century in the hot dry scenario compared to the historic scenario.

Total carbon storage increased under all management strategies and climate scenarios, with total carbon plateauing and beginning to decrease by the end of the century under the two hot scenarios. Larger increases in AGC and higher starting conditions in SOC contributed to the conservation strategy having the highest end of century total carbon storage, but not the largest percent increase. Of the four timber-focused management strategies, Triad-spare produced the highest total carbon stocks followed by Triad-share, land sparing, and finally land sharing. The largest increase in carbon storage occurred under the Triad-spare strategy (24.6%), followed by land sparing (22.9%), conservation (21.8%), Triad-share (21%), and finally land sharing (18.3%). While the difference in timber production between land sharing and the other management strategies was slight, the replanting of minor tree species with lower carbon accumulation rates led to lower AGC and consequently total carbon. This was partially offset by their higher SOC accumulation, but not enough to catch up with the other management strategies by the end of the 21st century. Therefore, while land sharing produced the highest metrics for the diversity of tree and shrub species, it resulted in the lowest carbon stocks by the end of the century.

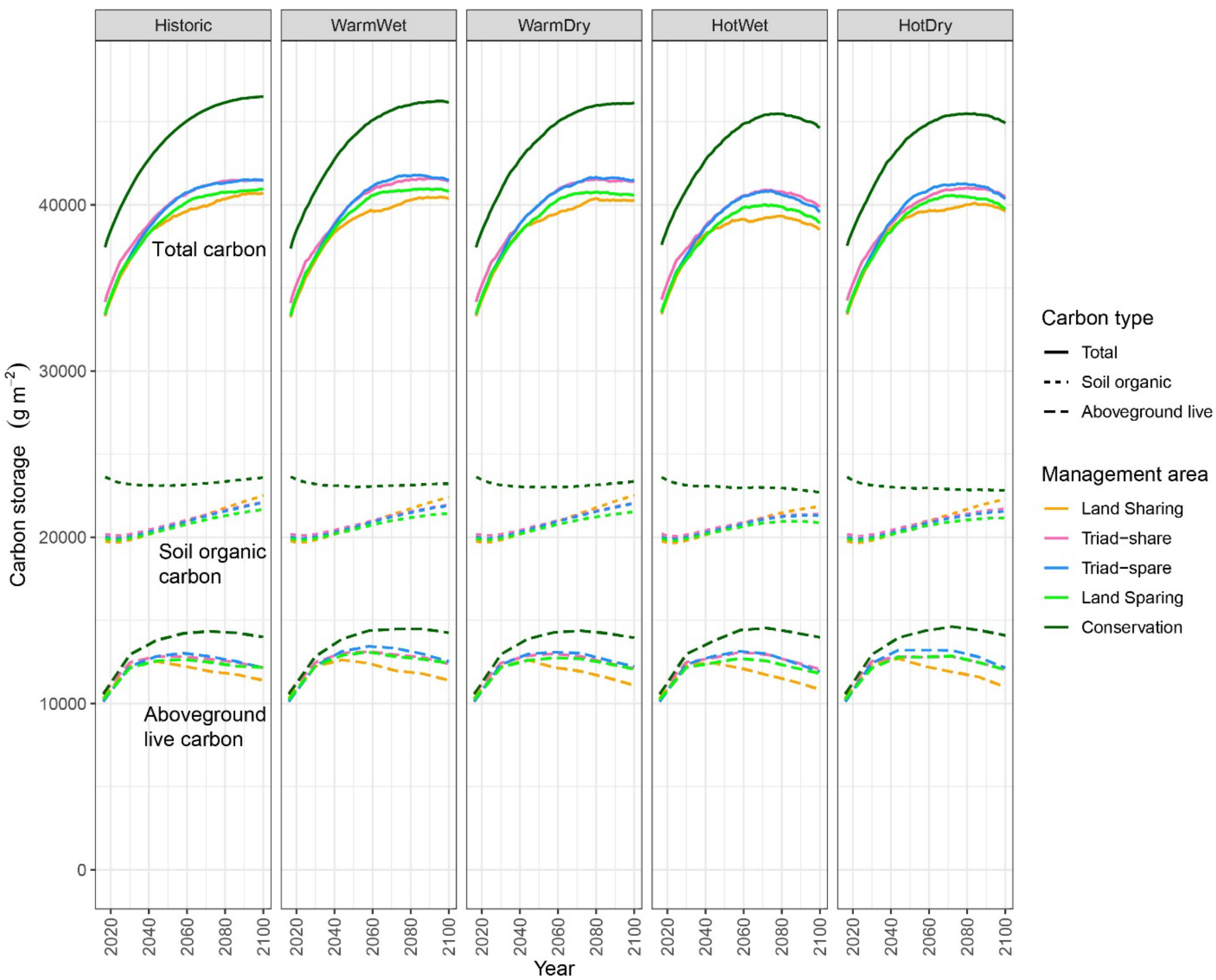


Figure 14 Trends in aboveground live, soil organic, and total carbon storage within each management areas and under the five climate scenarios.

CHAPTER IV

DISCUSSION

4.1 Research outcomes

The ESRF management plan was designed to promote multiple forest benefits, including recreation, education, research, ecosystem health, timber production, and climate mitigation, while keeping the forest publicly owned. Our results indicate: 1) that timber production is sustainable under all management strategies and climate scenarios, 2) that management strategies with high proportions of extensive treatments promote higher diversity of trees and shrubs, 3) a shift towards further Douglas-fir dominance under climate change and under conservation, 4) that management strategies with high proportions of reserve treatments promote higher carbon storage, and 5) the inability of the ESRF to increasingly store carbon under climate change scenarios with extreme increases in temperature.

The goal of promoting sustainable timber production under climate change, without sacrificing non-timber values is shared to different degrees across all managed forests in Oregon. Sustained yield has been a key management objective in all national forests since the Multiple-Use Sustained-Yield Act of 1960. Sustainable yield has also been a focus within state forests in Oregon since the establishment of the Oregon Board of Forestry in 1911 and within privately owned forests in Oregon since the Oregon Forest Practices Act of 1971. While the ESRF's timber quotas were less than those in private timber forests (15-20 MMBF vs 40 MMBF), our management results demonstrate the effectiveness of sharing, sparing, and Triad management in meeting a reduced demand for timber production under climate change. However, our results also indicate emergent tradeoffs between tree and shrub diversity and carbon storage based on management strategy (Figure 16).

Diversity metrics increased with the proportional allocation of extensive treatments. Therefore, land sharing was the best approach for promoting the diversity of trees and shrubs in our study area. The relative difference in diversity metrics based solely on species presence between management strategies was minor. However, metrics that accounted for biomass were much more sensitive to the differences in management strategy. Therefore, while land sharing had little impact on the presence of minor tree and shrub species compared to land sparing, it played a significant role in determining the success of these species relative to Douglas-fir. Under climate change, minor tree species and shrubs in areas not managed using land sharing were less able to compete with Douglas-fir, causing the forest composition in these areas to become more homogenous. This homogenization under the other management strategies was primarily driven by large decreases in tree diversity under climate change, with shrubs diversity remaining constant. Overall diversity of trees and shrubs decreased under all management strategies in the two hot scenarios.

No management strategy maximized all carbon storage metrics. However, the conservation strategy produced the highest total end of century carbon storage and strategies that incorporated reserve treatments resulted in larger increases in total carbon storage than the land sharing strategy. This indicates the importance of reserve treatments in promoting carbon storage in our study area. Carbon storage was more susceptible to changes in management than climate, especially AGC, which increased with the proportion of reserve treatments within management strategies. SOC had less variation between management strategies but was influenced by the proportion of extensive treatments within management strategies. This could be due to the increased litter inputs resulting from thinning. While total carbon storage was largely resilient to moderate increases in temperature, it plateaued in 2070 under the two hot scenarios before beginning to decline towards the end of the 21^{st} century. This indicates that the ESRF has the capacity to increase carbon storage annually over the long term under moderate increases in temperature, but not under extreme ones.

*Table 3. Heatmap of management outcomes for the four timber producing management strategies over the course of the simulation. Key species were identified from the final management plan and are represented by western redcedar, Port Orford cedar, Pacific madrone, and golden chinquapin. Dark green = best outcome, light green = second best, yellow = second worst, red = worst. A * indicates that this strategy outperformed the conservation strategy.*

		Land sharing	Triad-share	Triad-spare	Land sparing
Tree/shrub Diversity	SR	7.25*	6.60*	5.87	5.62
	SDI	0.55*	0.37*	0.29*	0.24*
	Key species extent	37.3*	28.1*	18.8*	15.1
	%Δ SR	61	51	32	26
	%Δ SDI	49*	-3*	-24*	-40*
	%Δ key sp. extent	4044*	3749*	2665*	1473*
Carbon	SOC	22,313	21,841	21,775	21,328
	AGC	11,147	12,151	12,159	12,102
	Total C	39,898	40,936	40,872	40,204
	%Δ SOC	13.0*	8.3*	8.9*	7.2*
	%Δ AGC	8.1	14.4	20.2	18.3
	%Δ Total C	19.71	19.73	22.3*	20.2*

4.2 Comparison with previous studies

Previous studies comparing the impacts of sharing, sparing and Triad management on biodiversity have primarily focused on animal diversity for specific taxa and have found that different taxa benefit from different management strategies (Betts et al. 2021). A recent study on the ESRF found that bird species which rely on late successional and early successional forest habitat benefit from land sparing, while birds that rely on mid successional forest habitat benefit from land sharing (Harris and Betts 2023). Our results did not find the same importance of reserve treatments for promoting tree and shrub diversity. The young homogenous Douglas-fir forest that covers the ESRF experienced a decrease in tree and shrub diversity under natural disturbance (conservation) and only minor increases under land sparing. However, management strategies that incorporate extensive treatments experienced increased diversity of both minor trees and shrubs. Had the initial conditions in the ESRF held higher conservation value, with old stands of western hemlock and Douglas-fir, then strategies that utilize reserve treatments may have been more effective.

Few studies have compared carbon outcomes of sharing, sparing, and Triad management and none under climate change. However, studies that have modelled carbon storage under Triad management have largely agreed on the importance of reserve treatments (Carpentier et al. 2016; Harris and Betts 2023; Blattert et al. 2023). Our results agree on this, with the largest end of century carbon storage under the conservation strategy, but with the largest increase in carbon under the Triad-spare strategy. Of these studies, only Blattert et al. (2023) considered soil carbon, which they found also benefited most from reserve treatments. While our model showed the largest total SOC under the conservation strategy, this was primarily due to the higher starting SOC found within the CRW. Extensive treatments were more important in promoting SOC in our model, with SOC decreasing under the conservation strategy and experiencing the largest increase under the land sharing approach.

4.3 Limitations

While the long legacy of timber management resulted in largely homogenous initial conditions across the ESRF, there was spatial variability in terms of SOC and age structure. Because our model replicates the proposed management plan for the ESRF (instead of taking a scenario-based approach to management), this spatial variability resulted in difference in the initial conditions within areas assigned to different management strategies. The higher initial SOC in areas assigned to the conservation strategy significantly contributed to this strategy's higher total end of century carbon storage. The 110-year-old Douglas-fir cohort was less prevalent in areas assigned to land sharing at the start of simulation. This may have improved the ability for other species to compete with Douglas-fir under this strategy, increasing tree and shrub diversity over time relative to the other strategies.

Another limitation of this study was the choice of species to include in the model. The model only considers tree and shrub diversity and includes the most common species by site occurrence (all trees and shrubs found in >5% of ESRF survey plots). Therefore, the model did not include endangered species or specialists found in less than five percent of plots. These species tend to be sensitive to minor perturbations and would have likely benefited from management strategies with reserve treatments. This decision favors generalists that benefit from a sharing approach and may have biased our diversity results against the land sparing and conservation strategies, as the value gained from allowing some patches of forest to age is not fully captured.

Natural disturbance regimes in our landscape posed several problems to parameterization and calibration. Our model landscape included a buffer to facilitate large, catastrophic fires spreading from the east, as occurred in 1868. However, the decision was made to replicate the fire regime of the last 30 years, characterized by small, semi-frequent fire events. Past catastrophic fire events were the result of prolonged periods of drought, sustained east wind events, and fuel build-up from improper post-harvest management. While it is possible that the ESRF may experience such an event during the 21st century, it is unclear to what degree fuel buildup from improper post-harvest fuel management accounted for these catastrophic fires. The inclusion of such large catastrophic fires would also strongly impact our results in a near stochastic manner, making comparison between management approaches difficult. The behavior of small fires was also hard to fully capture, as empirical daily fire perimeters were not available until they were greater than 10 acres and the average size of fires in our landscape over the last 30 years was 2 acres. There were similar difficulties in accounting for small wind events, as virtually all records of wind disturbance are for large windthrow events.

4.3 Further Considerations

This research demonstrates the applicability of LANDIS-II in management planning and the final model serves as a powerful tool for adaptive management. This model allows forest planners at OSU to change the allocation of management units or alter harvesting requirements to predict how these decisions may interact with natural disturbances and forest succession under climate change. As part of this project, and to demonstrate the use of LANDIS-II in adaptive management, a reduction of stand age requirements for regeneration harvesting was simulated and showed that reducing the minimum stand age from 100 to 70 years old increased timber output over the first decade but failed to increase the average timber output over the course of the 21st century (Supplemental 12). Shorter rotation lengths have been associated with reduced stand age, lower carbon storage, loss of ground water and soil, and reduced biodiversity (Başkent and Kašpar 2023).Therefore, lowering the stand age requirement for regeneration harvesting in the ESRF is undesirable as it fails to increase long term timber production while potentially producing negative ecological impacts due to reduced average stand age.

Triad management seeks to not only balance timber value with biodiversity and carbon values, but also with social, recreational, and spiritual values. While this research has focused on the ecological impacts of management, other studies have demonstrated the potential for Triad management to produce greater social benefit through its multi-use framework (Messier et al. 2009). By strategically setting aside areas of high value to stakeholder groups, Triad management can increase the social acceptability of timber plantations (Tittler and Messier 2009). While some of our metrics may be correlated with such values, they do not fully represent them, and these broader societal values and the interests of all stakeholders should be considered when deciding how to manage forests. The relative weights of competing values are case dependent and further stakeholder research needs to be conducted to estimate which framework best meets the needs of those living near the ESRF.

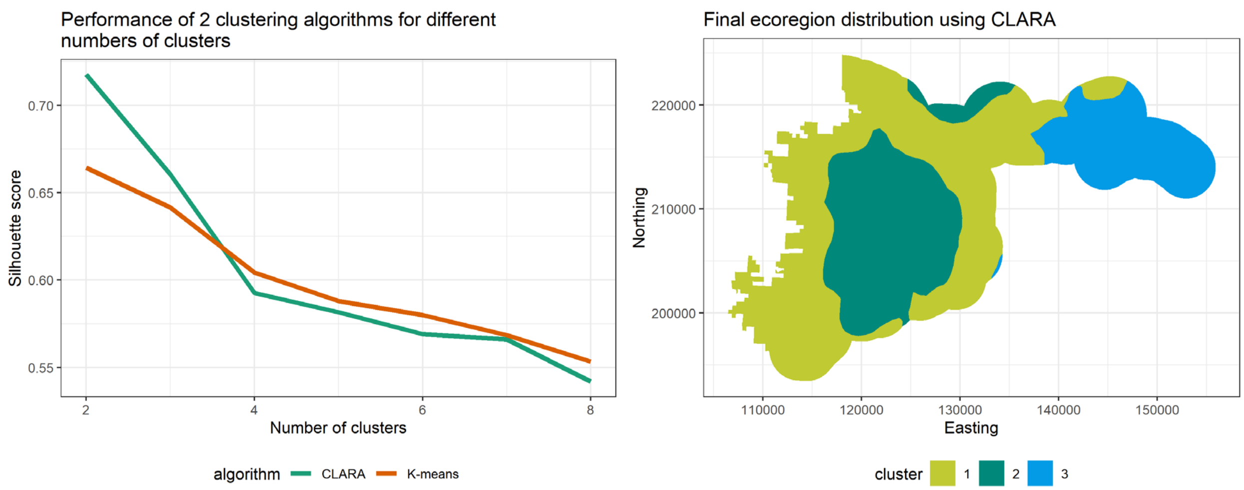
CHAPTER V

CONCLUSION

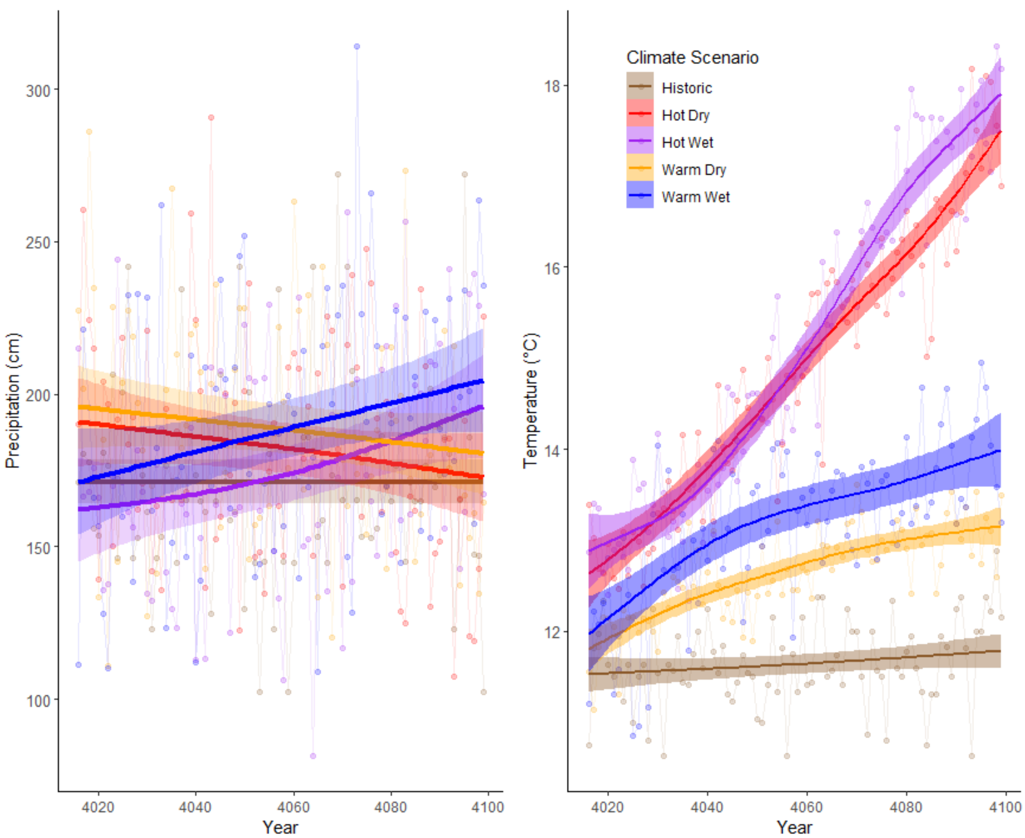
As the demand for forest products and forest land increases globally, managers must develop new and innovative ways of managing forests that account for ecological health and the ability of forests to mitigate climate change. Three potential frameworks to forest management (land sharing, land sparing, and Triad) aim to balance these conflicting forest values but have not been rigorously compared under climate change. In this study, the potential outcomes of land sharing, land sparing, and Triad management in the Elliott State Research Forest were modeled using LANDIS-II. Our results indicate that timber production is sustainable at 15 MMBF/year and that these management strategies may be successful in promoting both tree and shrub diversity and carbon storage under moderate changes in climate. However, there are notable tradeoffs between carbon storage and biodiversity. Management strategies with high proportions of extensive treatments (land sharing and Triad-share) promote higher levels of tree and shrub diversity, while management strategies with high proportions of reserve treatments (Triad-spare and land sparing) are more effective at promoting carbon storage. Moreover, regardless of management strategy, extreme changes in climate reduced the ability of the ESRF to conserve tree and shrub diversity and promote carbon storage over the 21st century. If managers seek a middle ground between biodiversity and carbon storage trade-offs, then a Triad approach holds merit. These results are applicable to forest managers interested in promoting non-timber values and highlight the ability of Triad management to occupy a niche between land sharing and land sparing. However, modeling studies provide only a partial view, and long-term empirical testing is necessary to fully grasp the implications of land sharing, land sparing, and Triad management in forestry.

APPENDIX A

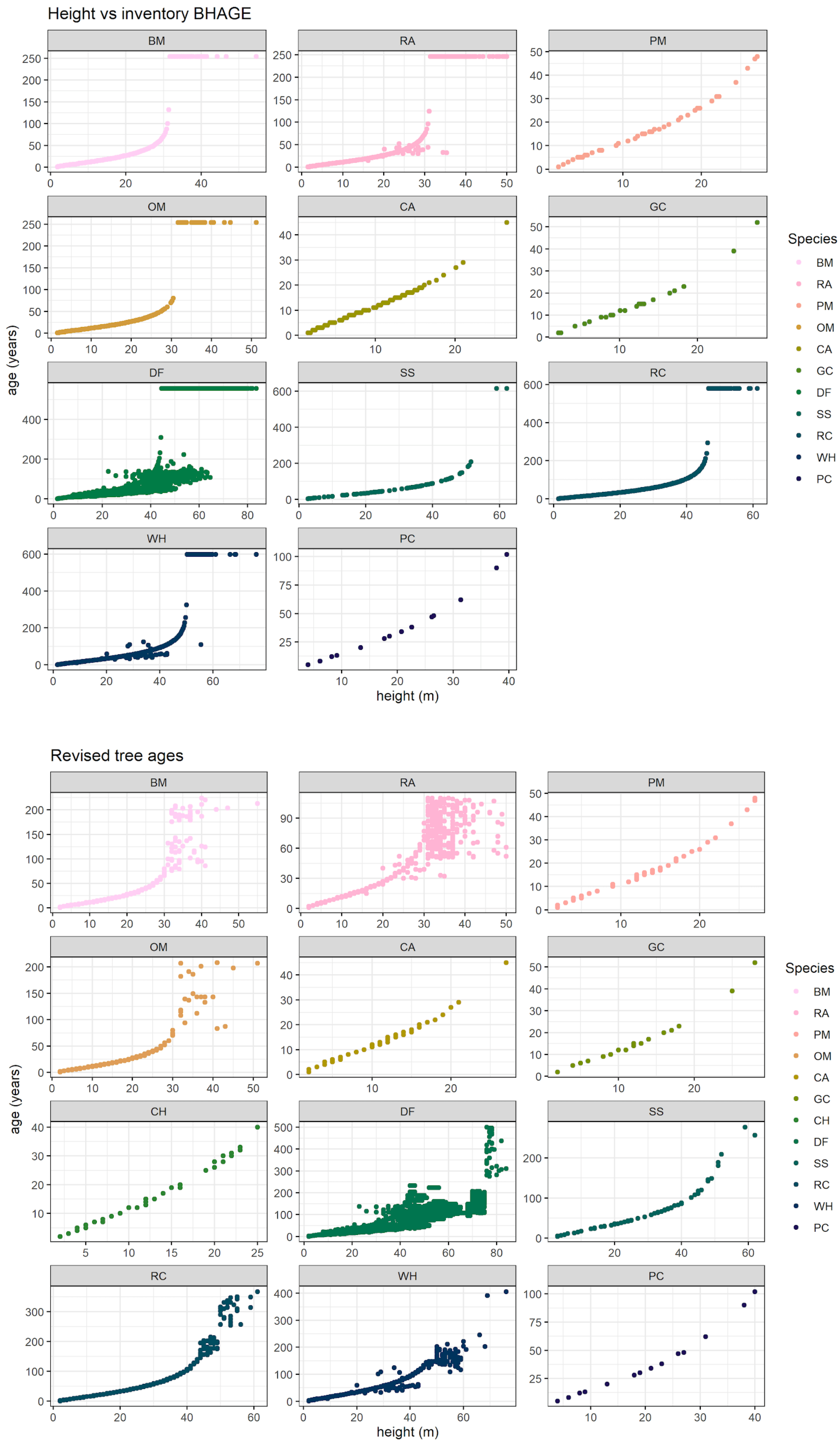
SUPPLEMENTAL FIGURES



Supplemental 1. Evaluation of alternative ecoregion numbers (left) using the K-means and CLARA algorithms. The optimal cluster solution based on quantitative and visual evaluation was the CLARA three-cluster solution (right).



Supplemental 2. Trends in total annual precipitation and maximum daily temperature from 2016 to 2100 under each climate scenario.



Supplemental 3. Tree height-age relationship before and after randomization process.

Algorithm:

For a given ESRF plot,

1. Find the distribution of species cohorts, e.g. 3 cohorts for spp A, 2 cohorts for B, and 4 cohorts for C. Likewise, find the species distributions for each FIA plot.
2. Evaluate each FIA plot for "all species cohort match". Define $AllSppCohortDelta$ as the sum of the differences in cohort counts between the ESRF and FIA plots across all species in the ESRF and FIA plots combined. For example, the $AllSppCohortDelta$ below is 7.

Spp	ESRF cohorts	FIA cohorts	Delta
A	2		3
B	1	1	1
C	3	3	0
D		3	3
	AllSppMatchDelta =		**7**

3. For each target species in the ESRF plot, e.g. spp A with 3 cohorts:
   a. Find the FIA plots that have at least 1 cohort of the target species.
   b. Of these, find the best match for cohort ages for the target species. For each cohort age in the target species, find the difference in age to the closest age point in the FIA plot cohorts. Sum these age deltas and find the FIA plots with the minimum delta. Call this $SppAgeDelta$. For example, if the target ESRF plot has ages {34, 48, 80} for spp A, the FIA plot with ages {20, 50, 60, 80, 100} is a better fit than the FIA plot with ages {10, 20, 30}. There may be more than one best FIA plot, especially if there is only one cohort.
   c. Of these, find the FIA plots that have the nearest number of target species cohorts as found in the ESRF plot. Call this $SppCohortDelta$. For example, if there are 3 cohorts of species A in the ESRF plot, find the FIA plots whose number of species A cohorts is closest to 3.
   d. Of these, find the FIA plots with the best match to the range of ages in the ESRF cohorts. For example, if the ESRF plot has ages {15, 30}, FIA plot 1 with {10, 20, 80} and FIA plot 2 with {10, 20, 40} have the same $SppAgeDelta$ (=15) and $SppMatchDelta$ (=0), but plot 2 is a better match to the range of ages, 10-40 is a better match to 15-30 than is 10-80. Define $SppAgeRangeDelta$ as the abs delta between the minimum ESRF age and the minimum FIA age, plus the abs delta between the maximum ESRF age and the maximum FIA age. In this case, FIA plot 1 would have $SppAgeRangeDelta = 55$, while plot 2 has $SppAgeRangeDelta = 15$.
   e. Of these, find the FIA plots with the minimum age extrapolation. Define $SppAgeExtrapolation$ as the sum of $FiaAgeMin - EsrfAge_i$ for all ESRF ages less than the minimum age in the FIA plot, plus the sum of $EsrfAge_i - FiaAgeMax$ for all ESRF ages greater than the maximum age in the FIA plot. For example, if the ESRF plot has a single cohort at age 60, FIA plot 1 with {10, 20, 80} and FIA plot 2 with {10, 20, 40} have the same $SppAgeRangeDelta$, but FIA plot 1 would be chosen because age 60 is within the range of the FIA ages.

f. Of these, find the FIA plots that have the minimum $AllSppCohortDelta$, e.g. if the minimum $AllSppCohortDelta$ is 0, find all FIA plots that have $AllSppCohortDelta = 0$.

g. Define 'MatchingFiaPlotCount' as the number of FIA plots after step f.

h. If the ESRF plot has lat/lon data, find the closest remaining FIA plot. The distance in miles between an ESRF plot and an FIA plot is given by

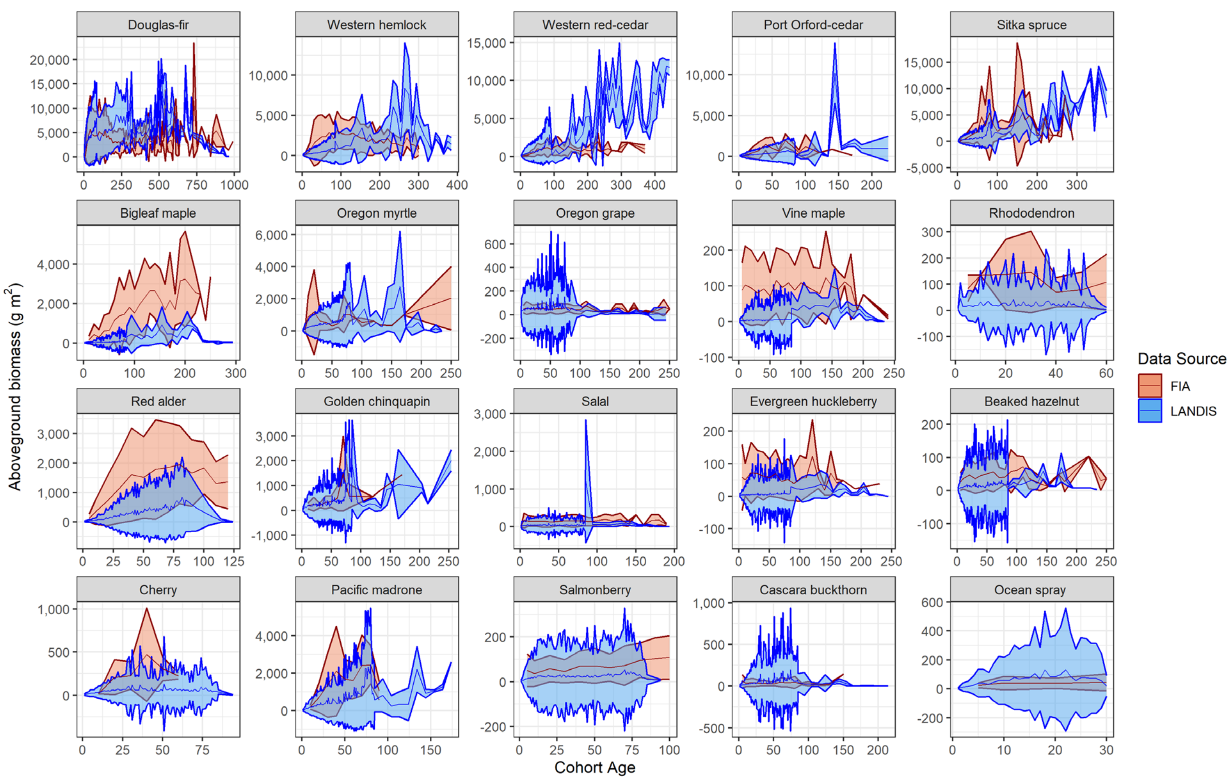
$$d = \sqrt{(milesPerLatDegree \cdot (FIA.Lat - ESRF.Lat))^2 + (milesPerLonDegree \cdot (FIA.l}$$

, where $milesPerLatDegree$ is set to 69.0, while $milesPerLonDegree = milesPerLatDegree \cdot \sin(45°)$ since all plots are at approximately 45 degree N latitude.

i. If the ESRF plot does not have lat/lon data, then randomly choose a FIA plot among the FIA plots remaining after step d.

j. Given the best-match FIA plot, find the FIA biomass for each cohort age in the ESRF plot. If the ESRF age is outside the range of the FIA plot ages, use the FIA biomass of the lowest or highest age point. Otherwise, linearly interpolate the FIA biomass between FIA points whose ages bracket the ESRF age. Define this as the 'FiaEstBiomass'.

Supplemental 4: Algorithm for assigning FIA plot data to sites within the ESRF.

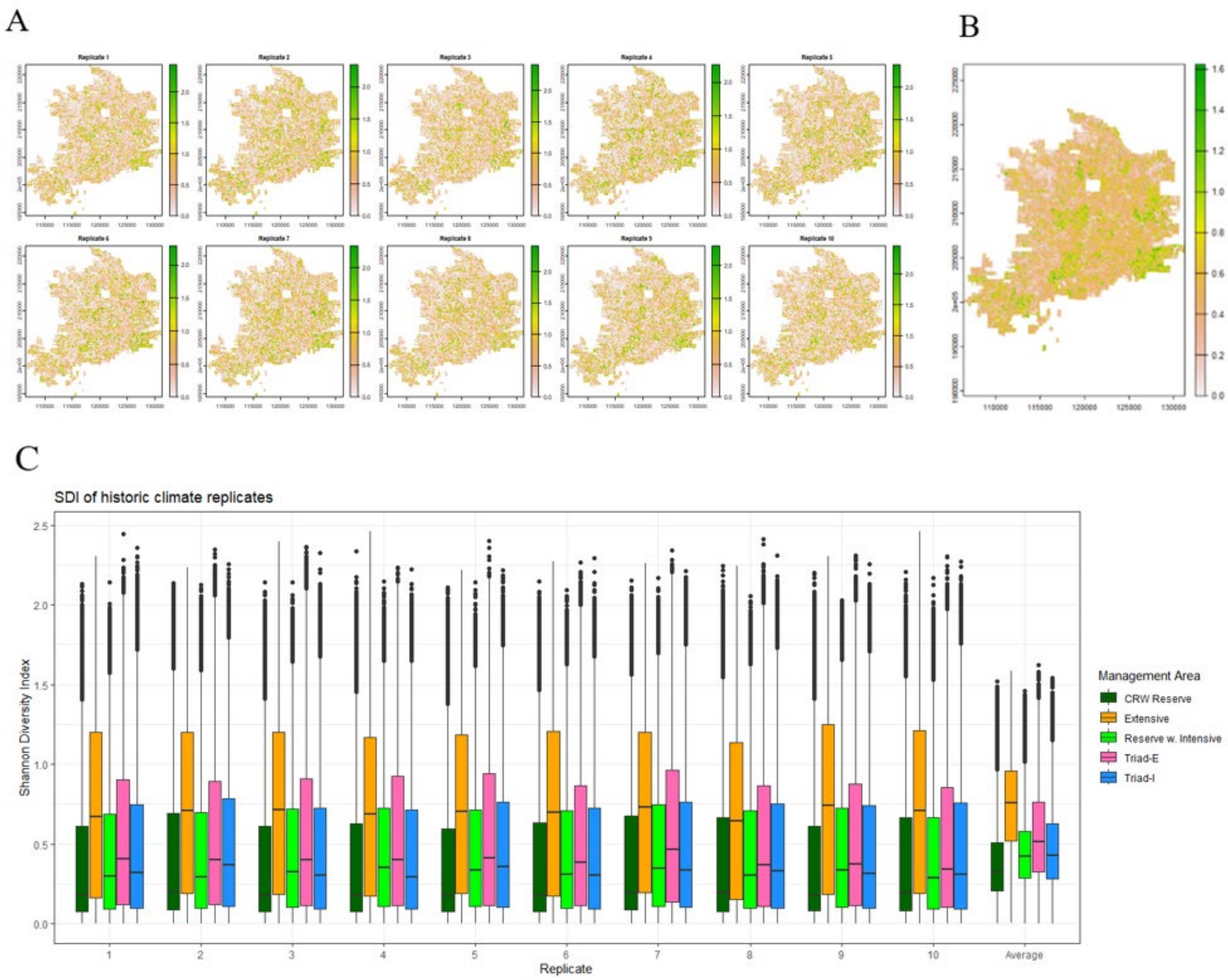


Supplemental 5. End of simulation age biomass relationship for the 9 shrub and 11 tree species included within the model compared to FIA.

Harvest Implementations

Mgmt Area	Prescription	Harvest Area	BeginTime	EndTime
2	Extensive_young_stand_thin_agg_small	0.96%	10	31
2	Extensive_young_stand_thin_agg_mid	0.96%	10	31
2	Extensive_young_stand_thin_agg_large	0.96%	10	31
2	Extensive_young_stand_thin_disp	0.96%	10	31
4	Extensive_young_stand_thin_agg_small	0.96%	10	31
4	Extensive_young_stand_thin_agg_mid	0.96%	10	31
4	Extensive_young_stand_thin_agg_large	0.96%	10	31
4	Extensive_young_stand_thin_disp	0.96%	10	31
7	Intensive_thinning	0.64%	10	
7	Intensive_clearcut	0.64%	10	
8	Extensive_young_stand_thin_agg_small	0.04%	10	
8	Extensive_young_stand_thin_agg_mid	0.04%	10	
8	Extensive_young_stand_thin_agg_large	0.04%	10	
8	Extensive_young_stand_thin_disp	0.04%	10	
8	Extensive_regen_harv_high_rtn_agg	0.016%	10	
8	Extensive_regen_harv_mid_rtn_agg	0.016%	10	
8	Extensive_regen_harv_mid_rtn_disp	0.016%	10	
8	Extensive_regen_harv_low_rtn_agg	0.016%	10	
8	Extensive_regen_harv_low_rtn_disp	0.016%	10	
9	Intensive_thinning	0.64%	10	10
9	Intensive_clearcut	0.64%	10	10
10	Extensive_young_stand_thin_agg_small	0.005%	10	20
10	Extensive_young_stand_thin_agg_mid	0.005%	10	20
10	Extensive_young_stand_thin_agg_large	0.005%	10	20
10	Extensive_young_stand_thin_disp	0.005%	10	20
10	Extensive_regen_harv_high_rtn_agg	0.018%	10	20
10	Extensive_regen_harv_mid_rtn_agg	0.004%	10	20
10	Extensive_regen_harv_mid_rtn_disp	0.004%	10	20
10	Extensive_regen_harv_low_rtn_agg	0.004%	10	20
10	Extensive_regen_harv_low_rtn_disp	0.004%	10	20
10	Extensive_young_stand_thin_agg_small	0.044%	20	
10	Extensive_young_stand_thin_agg_mid	0.04%	20	
10	Extensive_young_stand_thin_agg_large	0.04%	20	
10	Extensive_young_stand_thin_disp	0.04%	20	
10	Extensive_regen_harv_high_rtn_agg	0.144%	20	
10	Extensive_regen_harv_mid_rtn_agg	0.032%	20	
10	Extensive_regen_harv_mid_rtn_disp	0.032%	20	
10	Extensive_regen_harv_low_rtn_agg	0.032%	20	
10	Extensive_regen_harv_low_rtn_disp	0.032%	20	

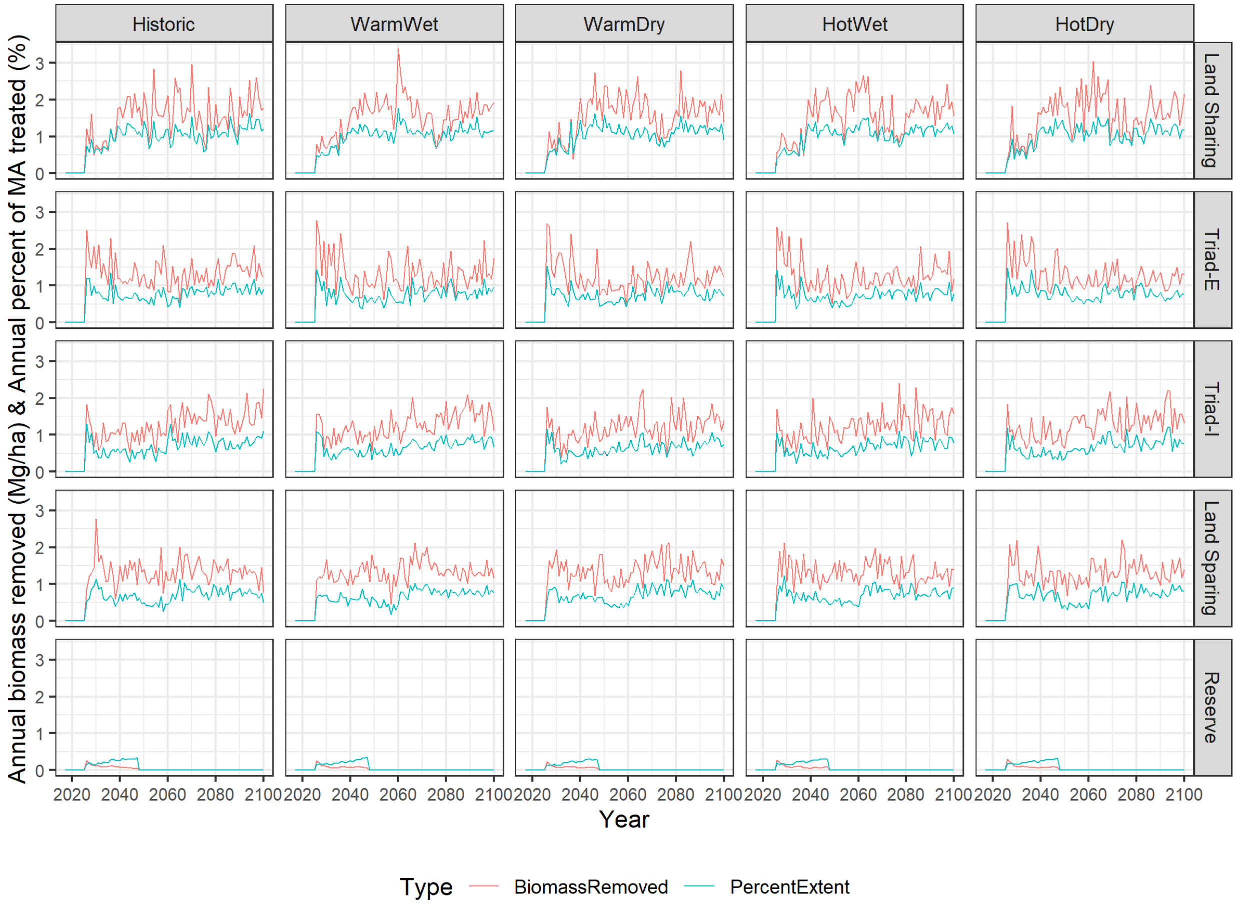
Supplemental 6. Harvest implementation table allocation the percent extant of treatments at different times within different management areas.



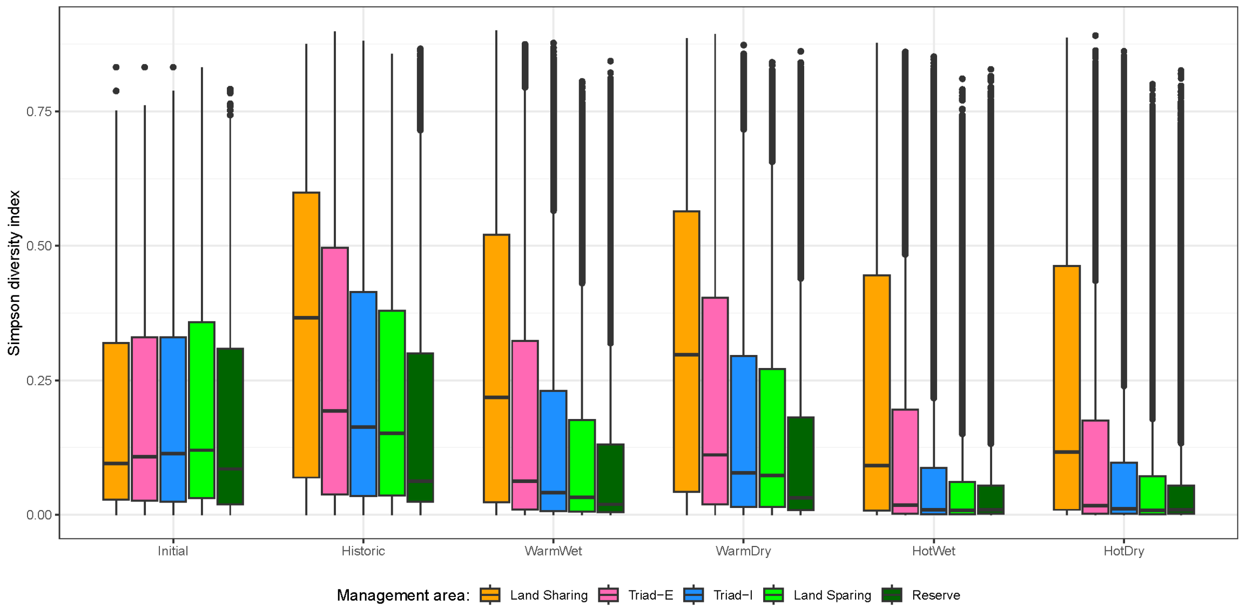
Supplemental 7. Shannen diversity index (SDI) of all modeled vegetation for 10 historical climate replicates grouped by management strategy. Note the high spatial variation in SDI between replicates (A), compared to the decreased range in SDI in any given cell when replicates are averaged together (C). Also note the low overall variation in SDI within each management strategies between replicates as compared with the averaged SDIs (C).

Supplemental 8. Wind severity table from the Base Wind input text file.

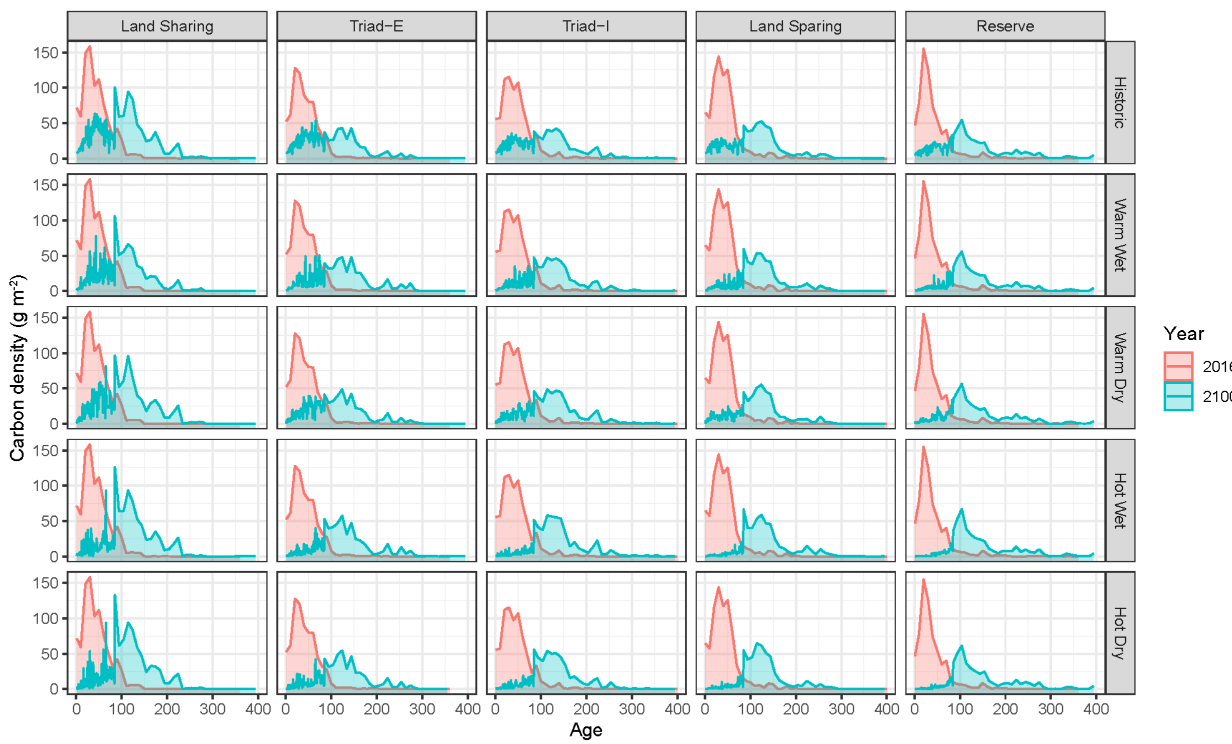
Severity	Cohort Age % of longevity	Mortality Probability
5	0% to 20%	0.01
4	20% to 40%	0.024
3	40% to 60%	0.034
2	60% to 80%	0.0485
1	80% to 100%	0.0691



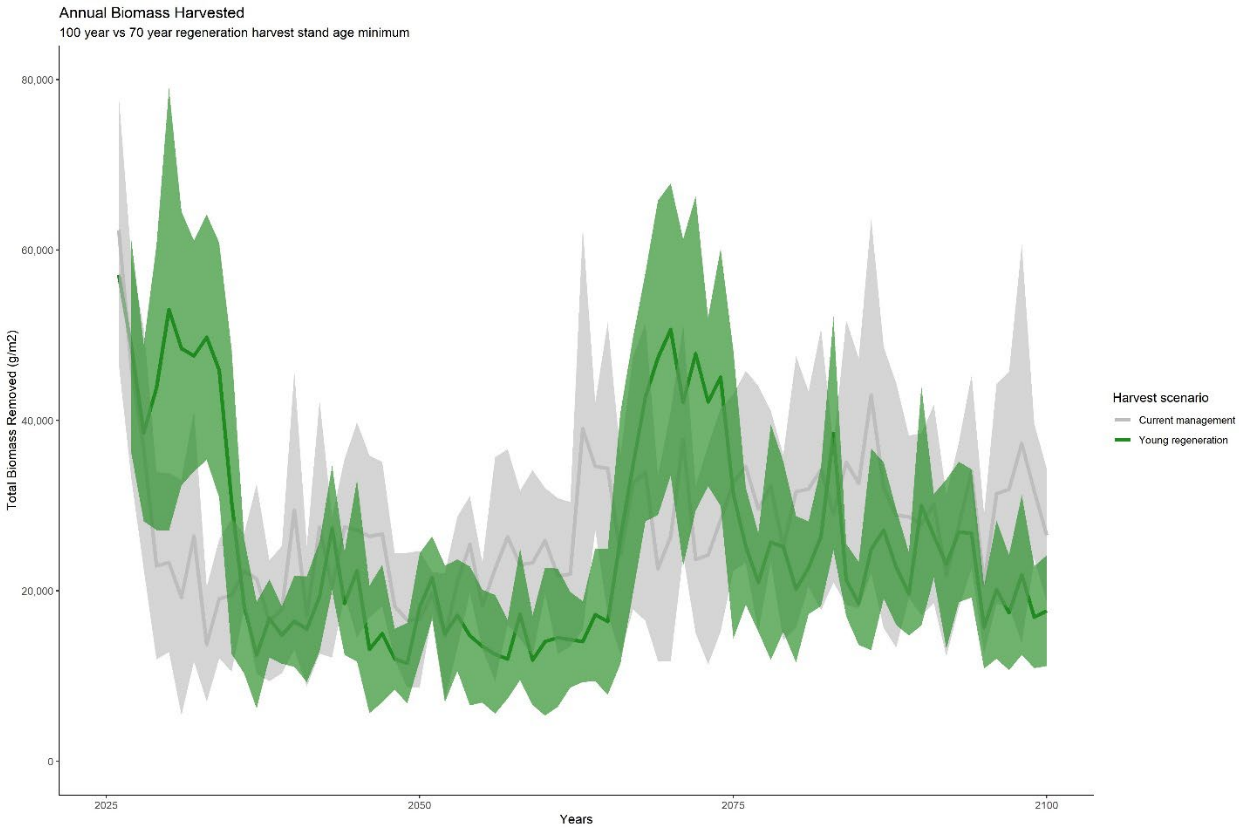
Supplemental 9. Trends in biomass removal density by timber production and percent extent of management area under each management strategy and climate scenario.



Supplemental 10. Gini-Simpson Diversity Index under each management strategy in 2016 and at the end of century for each climate scenario.



Supplemental 11. Carbon densities of minor tree and shrub species und each management strategy and climate scenario by age.



Supplemental 12. Reduced minimum stand age requirement for regeneration harvest.

REFERENCES

Abatzoglou JT (2013) Development of gridded surface meteorological data for ecological applications and modelling. International Journal of Climatology 33:121–131. https://doi.org/10.1002/joc.3413

Başkent EZ, Kašpar J (2023) Exploring the effects of various rotation lengths on the ecosystem services within a multiple-use management framework. Forest Ecology and Management 538:120974. https://doi.org/10.1016/j.foreco.2023.120974

Beck-O'Brien M, Egenolf V, Winter S, et al (2022) Everything from wood - The resource of the future or the next crisis? How footprints, benchmarks and targets can support a balanced bioeconomy transition.

Betts MG, Phalan BT, Wolf C, et al (2021) Producing wood at least cost to biodiversity: integrating Triad and sharing–sparing approaches to inform forest landscape management. Biological Reviews 96:1301–1317. https://doi.org/10.1111/brv.12703

Blattert C, Eyvindson K, Mönkkönen M, et al (2023) Enhancing multifunctionality in European boreal forests: The potential role of Triad landscape functional zoning. Journal of Environmental Management 348:119250. https://doi.org/10.1016/j.jenvman.2023.119250

Carpentier S, Filotas E, Handa I, Messier C (2016) Trade-offs between timber production, carbon stocking and habitat quality when managing woodlots for multiple ecosystem services. Environmental Conservation 44:1–10. https://doi.org/10.1017/S0376892916000357

Cassell BA, Scheller RM, Lucash MS, et al (2019) Widespread severe wildfires under climate change lead to increased forest homogeneity in dry mixed-conifer forests. Ecosphere 10:e02934. https://doi.org/10.1002/ecs2.2934

Chojnacky DC, Milton M (2008) Measuring Carbon in Shrubs. In: Hoover CM (ed) Field Measurements for Forest Carbon Monitoring: A Landscape-Scale Approach. Springer Netherlands, Dordrecht, pp 45–72

Côté P, Tittler R, Messier C, et al (2010) Comparing different forest zoning options for landscape-scale management of the boreal forest: Possible benefits of the TRIAD. Forest Ecology and Management 259:418–427. https://doi.org/10.1016/j.foreco.2009.10.038

Creutzburg MK, Scheller RM, Lucash MS, et al (2017) Forest management scenarios in a changing climate: trade-offs between carbon, timber, and old forest. Ecological Applications 27:503–518. https://doi.org/10.1002/eap.1460

Curtis PG, Slay CM, Harris NL, et al (2018) Classifying drivers of global forest loss. Science 361:1108–1111. https://doi.org/10.1126/science.aau3445

Deak AL, Lucash MS, Coughlan MR, et al (2024) Prescribed fire placement matters more than increasing frequency and extent in a simulated Pacific Northwest landscape. Ecosphere 15:e4827. https://doi.org/10.1002/ecs2.4827

Duveneck M, Scheller R (2015) Measuring and managing resistance and resilience under climate change in northern Great Lake forests (USA). Landscape Ecology 31:. https://doi.org/10.1007/s10980-015-0273-6

Edwards DP, Gilroy JJ, Woodcock P, et al (2014) Land-sharing versus land-sparing logging: reconciling timber extraction with biodiversity conservation. Global Change Biology 20:183–191. https://doi.org/10.1111/gcb.12353

FAO (2021) FAO Yearbook of Forest Products 2019. FAO, Rome, Italy

FAO (2020) Global Forest Resources Assessment 2020. FAO ;

Franklin JF, Mitchell RJ, Palik B (2007) Natural disturbance and stand development principles for ecological forestry

Geiser L, Root H, Smith R, et al (2021) Lichen-based critical loads for deposition of nitrogen and sulfur in US forests. Environmental Pollution 291:118187. https://doi.org/10.1016/j.envpol.2021.118187

Green RE, Cornell SJ, Scharlemann JPW, Balmford A (2005) Farming and the Fate of Wild Nature. Science 307:550–555. https://doi.org/10.1126/science.1106049

Gustafson E, Shifley S, Mladenoff D, et al (2000) Spatial simulation of forest succession and timber harvesting using LANDIS. Canadian Journal of Forest Research-revue Canadienne De Recherche Forestiere - CAN J FOREST RES 30:32–43. https://doi.org/10.1139/cjfr-30-1-32

Harmon ME, Pabst RJ (2019) The Long-Term Effects of Wind Disturbance on a Sitka Spruce-Western Hemlock Forest. Forests 10:119. https://doi.org/10.3390/f10020119

Harris SH, Betts MG (2023) Selecting among land sparing, sharing and Triad in a temperate rainforest depends on biodiversity and timber production targets. Journal of Applied Ecology 60:737–750. https://doi.org/10.1111/1365-2664.14385

Hijmans, R. J., Bivand, R., Forner, K., Ooms, J., Pebesma, E., & Sumner, M. D. (2022). Package 'terra'. Maintainer: Vienna, Austria.

Himes A, Betts M, Messier C, Seymour R (2022) Perspectives: Thirty years of triad forestry, a critical clarification of theory and recommendations for implementation and testing. Forest Ecology and Management 510:120103. https://doi.org/10.1016/j.foreco.2022.120103

Impara P (1997) Spatial and temporal patterns of fire in the forests of the central Oregon Coast Range

Kremen C (2015) Reframing the land-sparing/land-sharing debate for biodiversity conservation. Annals of the New York Academy of Sciences 1355:52–76. https://doi.org/10.1111/nyas.12845

Lapola DM, Pinho P, Barlow J, et al (2023) The drivers and impacts of Amazon forest degradation. Science 379:eabp8622. https://doi.org/10.1126/science.abp8622

Lippe RS, Schweinle J, Cui S, et al (2022) Contribution of the forest sector to total employment in national economies: Estimating the number of people employed in the forest sector. FAO, ILO, Rome, Italy

Loudermilk EL, Stanton A, Scheller RM, et al (2014) Effectiveness of fuel treatments for mitigating wildfire risk and sequestering forest carbon: A case study in the Lake Tahoe Basin. Forest Ecology and Management 323:114–125. https://doi.org/10.1016/j.foreco.2014.03.011

Lucash MS, Mast CN, Williams NG, Strimbu BM, West T (2023) Landscape level planning: a modeling approach. In: Oregon State University College of Forestry (ed) Elliott State Research Forest Forest Management Plan. Oregon State University, Corvallis, pp 99–119. https://www.forestry.oregonstate.edu/elliott-state-forest/forest-management-plan. Accessed 5 Jun 2024.

Lutz AF, ter Maat HW, Biemans H, et al (2016) Selecting representative climate models for climate change impact studies: an advanced envelope-based selection approach. International Journal of Climatology 36:3988–4005. https://doi.org/10.1002/joc.4608

Matthews TJ, Cottee-Jones HE, Whittaker RJ (2014) Habitat fragmentation and the species–area relationship: a focus on total species richness obscures the impact of habitat loss on habitat specialists. Diversity and Distributions 20:1136–1146. https://doi.org/10.1111/ddi.12227

Merschel AG (2021) Historical forest succession and disturbance dynamics in Coastal Douglas-fir forests in the southern western Cascades of Oregon

Messier C, Tittler R, Kneeshaw DD, et al (2009) TRIAD zoning in Quebec: Experiences and results after 5 years. The Forestry Chronicle 85:885–896. https://doi.org/10.5558/tfc85885-6

Mladenoff D, He H (1999) Design, behavior and applications of LANDIS, an object-oriented model of forest landscape disturbance and succession

Oregon State University College of Forestry (2023) Elliott State Research Forest Forest Management Plan. https://www.forestry.oregonstate.edu/elliott-state-forest/forest-management-plan. Accessed 5 Jun 2024. 630 pp.

Pan Y, Birdsey RA, Phillips OL, Jackson RB (2013) The Structure, Distribution, and Biomass of the World's Forests. Annu Rev Ecol Evol Syst 44:593–622. https://doi.org/10.1146/annurev-ecolsys-110512-135914

Parton WJ (1996) The CENTURY model. In: Powlson DS, Smith P, Smith JU (eds) Evaluation of Soil Organic Matter Models. Springer, Berlin, Heidelberg, pp 283–291

Parton WJ, Stewart JWB, Cole CV (1988) Dynamics of C, N, P and S in grassland soils: a model. Biogeochemistry 5:109–131. https://doi.org/10.1007/BF02180320

Phalan BT (2018) What have we learned from the land sparing-sharing model? Sustainability 10:1760

Phillips J (1997) Caulked Boots and Cheese Sandwiches: A Forester's History of Oregon's First State Forest, "The Elliott" (1912-1996). J. Phillips

Puettmann K, Coates D, Messier C (2008) Puettmann: A critique of silviculture: managing for... - Google Scholar. https://scholar.google.com/scholar_lookup?hl=en&publication_year=2008&pages=207&author=K.+J.+Puettmann&author=K.+D.+Coates&author=C.+C.+Messier&title=A+Critique+of+Silviculture%3A+Managing+for+Complexity. Accessed 29 Dec 2023

Puettmann KJ, Wilson SM, Baker SC, et al (2015) Silvicultural alternatives to conventional even-aged forest management - what limits global adoption? Forest Ecosystems 2:8. https://doi.org/10.1186/s40663-015-0031-x

R Core Team R (2013) R: A language and environment for statistical computing

RStudio Team. (2022). RStudio: Integrated Development Environment for R (2024.04.1). RStudio, PBC. http://www.rstudio.com/

Scheller R, Kretchun A, Hawbaker TJ, Henne PD (2019) A landscape model of variable social-ecological fire regimes. Ecological Modelling 401:85–93. https://doi.org/10.1016/j.ecolmodel.2019.03.022

Scheller RM, Domingo JB, Sturtevant BR, et al (2007) Design, development, and application of LANDIS-II, a spatial landscape simulation model with flexible temporal and spatial resolution. Ecological Modelling 201:409–419. https://doi.org/10.1016/j.ecolmodel.2006.10.009

Scheller RM, Hua D, Bolstad PV, et al (2011) The effects of forest harvest intensity in combination with wind disturbance on carbon dynamics in Lake States Mesic Forests. Ecological Modelling 222:144–153. https://doi.org/10.1016/j.ecolmodel.2010.09.009

Serra-Diaz JM, Maxwell C, Lucash MS, et al (2018) Disequilibrium of fire-prone forests sets the stage for a rapid decline in conifer dominance during the 21st century. Sci Rep 8:6749. https://doi.org/10.1038/s41598-018-24642-2

Seymour RS, Hunter ML (1992) New forestry in eastern spruce-fir forests: principles and applications to Maine. College of Forest Resources, University of Maine Orono, ME, USA

Short KC (2022) Spatial wildfire occurrence data for the United States, 1992-2020 [FPA_FOD_20221014]. 6th Edition.

Sidemo-Holm W, Ekroos J, Smith HG (2021) Land sharing versus land sparing—What outcomes are compared between which land uses? Conservation Science and Practice 3:e530. https://doi.org/10.1111/csp2.530

Sinton DS, Jones JA, Ohmann JL, Swanson FJ (2000) Windthrow Disturbance, Forest Composition, and Structure in the Bull Run Basin, Oregon. Ecology 81:2539–2556. https://doi.org/10.1890/0012-9658(2000)081[2539:WDFCAS]2.0.CO;2

Smithwick E, Harmon M, Remillard S, et al (2002) Potential Upper Bounds of Carbon Stores in Forests of the Pacific Northwest. Ecological Applications 12:1303–1317. https://doi.org/10.2307/3099973

Thrasher B, Xiong J, Wang W, et al (2013) Downscaled Climate Projections Suitable for Resource Management. Eos, Transactions American Geophysical Union 94:321–323. https://doi.org/10.1002/2013EO370002

Tittler R, Messier C (2009) The Mauricie TRIAD project: ecological, economic, and social considerations in forest management. Sustainable Forest Management Network Research Note

Valente JJ, Bennett RE, Gómez C, et al (2022) Land-sparing and land-sharing provide complementary benefits for conserving avian biodiversity in coffee-growing landscapes. Biological Conservation 270:109568. https://doi.org/10.1016/j.biocon.2022.109568

Vié J-C, Hilton-Taylor C, Stuart SN (2009) Wildlife in a changing world: an analysis of the 2008 IUCN Red List of threatened species. IUCN

Ward C, Erdle T (2015) Evaluation of forest management strategies based on Triad zoning. The Forestry Chronicle 91:40–51. https://doi.org/10.5558/tfc2015-009

Waring RH, Franklin JF (1979) Evergreen coniferous forests of the pacific northwest. Science 204:1380–1386. https://doi.org/10.1126/science.204.4400.1380

Zybach B (2004) The great fires : Indian burning and catastrophic forest fire patterns of the Oregon Coast Range, 1491-1951. Oregon State University