Potential climate change impacts on management outcomes for western Oregon BLM forestlands simulated using Climate-FVS

Report to Bureau of Land Management

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Key Findings

This study offers the largest spatial extent to which Climate-FVS has been applied to date to simulate forest growth-and-yield outcomes under projected climate change. At this scale, growth-and-yield outcomes show trends driven by both the underlying projections of future climates as well as how Climate-FVS models the response of forests to those climatic changes. This study offers a broad illustration of Climate-FVS model behavior and the influence of several assumptions that justify further evaluation before integrating this model directly into management planning. In particular, we suggest additional research and development, comparison with other models, and—where possible—validation with field observations to improve confidence in the modeling of the adaptive responses of trees and forests under shifting environmental conditions and climate change. Despite several important caveats and sources of uncertainty, we nevertheless suggest this analysis provides what Pearson and Dawson (2003) refer to as "a useful first approximation as to the potentially dramatic impacts of climate change" and encourage the interpretation of outputs from Climate-FVS in this context.

- The simulations presented here show forest growth and mortality governed solely by gradual shifts in climatic suitability along with active forest management. These model runs do not incorporate any natural disturbances such as wildfire, pest, or pathogen events which are generally expected to play an even stronger role in shaping our forests under climate change.

- Current global emissions of greenhouse gases, energy usage, and a variety of other metrics of economic development and carbon pollution are consistent with the projections of the high emissions scenario. The low emissions scenario evaluated here would require substantial reductions in the rate at which humans are producing greenhouse gases. The high emissions scenario evaluated in this study consistently showed much greater impacts on forest growth, mortality, increases in fire hazards, shifts in forest composition and losses of forest carbon storage. Under both the low- and high emissions scenarios, forest growth-and-yield outcomes were clearly distinct from what would otherwise be expected in the absence of climate change.

- In general, the ability to clearly distinguish between low and high emissions scenarios in terms of projected impacts on forest dynamics emerged in the latter half of the century. In comparison to simulations without climate change, climate change impacts simulated in all BLM Districts in western Oregon using Climate-FVS showed substantial declines in growth rates under every emissions scenario and circulation model considered. Changes in annual mortality rates were more variable than growth rates, showing both increases and decreases relative to simulations without climate impacts.
    - Under the low emissions scenario, growth rate declines in Salem, Eugene, and Coos Bay Districts correspond to a decrease in average productivity from Site Class II to Site Class III by mid-century, and a further decline to low Site Class III for Eugene and Salem and Site Class IV for Coos Bay by 2100. In the high emissions scenario, growth rate declines in these Districts follow a similar trajectory as the low emissions scenario through mid-century, but then rapidly fall to Site Class V by end-of-century.

- In Medford and Lakeview, growth rates under climate change were always lower than the '*No Climate Change*' scenario, but were observed to increase or stay approximately level through the century under the low emissions scenario. Under the high emissions scenario, both Medford and Roseburg showed substantial declines in growth rates, corresponding to the decline from Site Class IV-/V+ to VI over the century for Medford, and from Site Class III to IV by mid-century, and VI by end-of-century for Roseburg.

➢ Forest composition under the low emissions scenario was relatively consistent with the '*No Climate Change*' scenario, although individual forest type groups such as Hemlock-Sitka spruce showed noticeable declines in areal extent. Under the high emissions scenarios, large shifts in forest composition begin mid-century, as shifts in climatic suitability increasingly favor northward migration of key commercial species, including western hemlock, western redcedar, and Douglas-fir, which appears to be replaced towards the end of the century along the southern edge of its range by hardwood forest type groups more commonly found in northern California.

➢ Under nearly all emissions scenario and circulation models, the harvest scheduling model was able to maintain a 500 mmbf/yr timber harvest across the western Oregon BLM lands through the end of the century, but increasing tradeoffs of timber yields with standing timber volume carbon storage were apparent under both low- and high emissions scenarios. Under the *'No Climate Change'* scenario, a 500 mmbf/yr yield was sustained while simultaneously increasing both the standing volume of timber and forest carbon storage. Under the low emissions scenario, this level of removals allowed little or no timber volume or carbon storage accumulation over the century, and in the high emissions scenario, harvest removals and mortality began to collectively outpace growth by 2050-2060, and led to a reduction in standing inventory timber volume compared to 2014 levels by 2080-2090.

➢ To maintain the annual harvest target across all BLM lands in western Oregon as growth rates declined under climate change scenarios, larger areas of unrestricted BLM lands were subject to more intensive harvests (i.e., shifting from thinning-only or grow-only scenarios to regeneration harvests) and to decreasing even-age rotation lengths. The simulated increases in harvest intensity and shortening of even-age rotation lengths were more pronounced under high emissions than low emissions scenarios.

Scope and objectives of this report

This report has been prepared for the Bureau of Land Management (BLM) to evaluate the potential impacts and the associated variability of projected climate changes on a variety of forest management outcomes for BLM lands in western Oregon. This evaluation is conducted using the Climate extension of the Forest Vegetation Simulator (Climate-FVS), an empirical/statistical growth-and-yield model developed and maintained by the US Forest Service. This report follows an earlier review of bioclimate envelope model projections covering the same study area, which are used as inputs for growth-and-yield simulations in Climate-FVS (Diaz *et al.* 2014).

Growth-and-yield modeling has typically historically been performed without consideration of future climatic conditions. The increasing awareness that climate change is in fact expected to have significant effects on forests in our region and throughout the world suggests that relying on modeling without regard to future climatic conditions will be increasingly problematic and unreliable, especially if projections used to inform management planning extend more than a couple decades into the future.

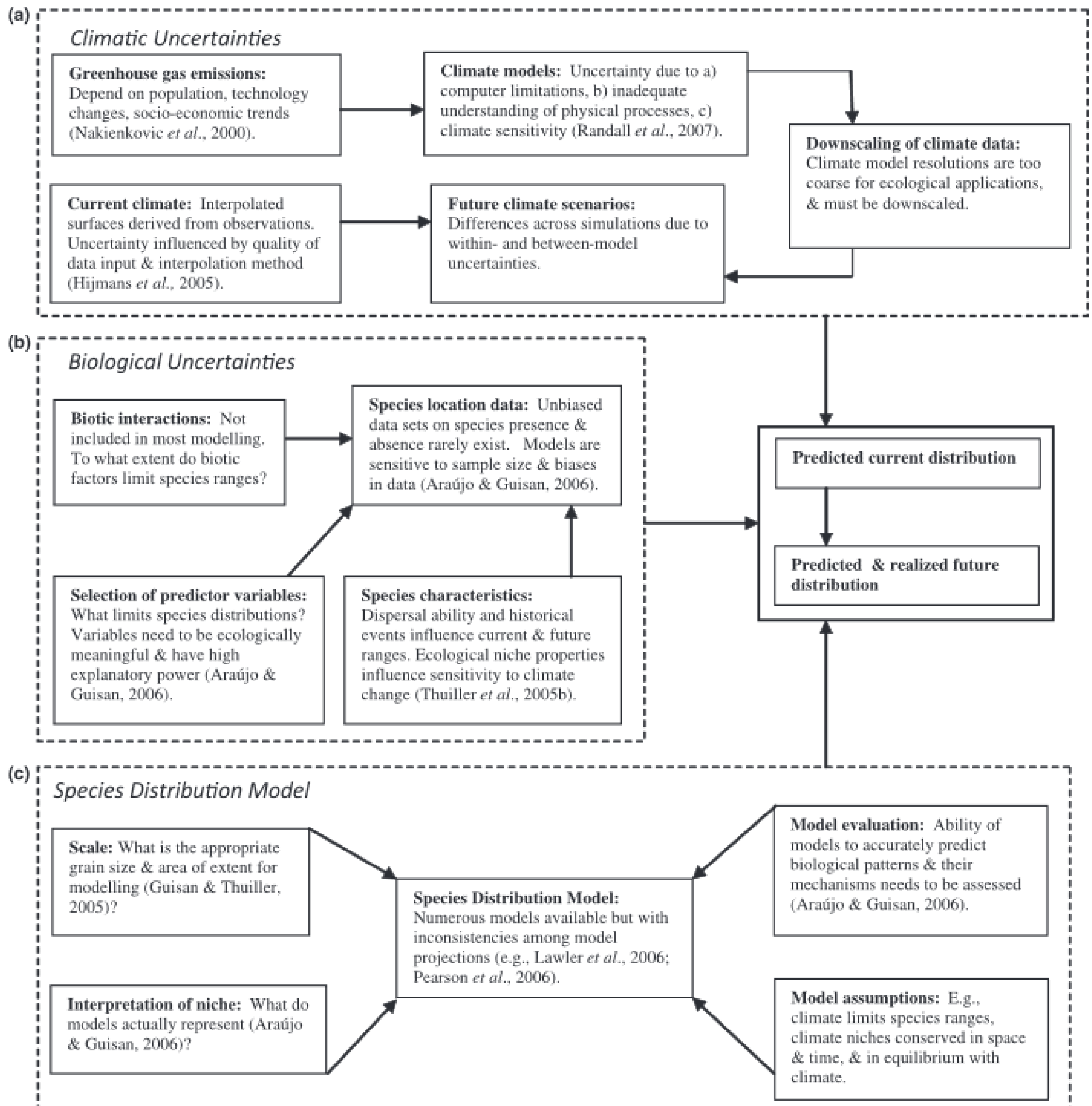
The primary goal of this study is to present a new modeling approach applied at a large scale to offer a general sense of the variability and uncertainty that projected changes in climate may present for the forestlands managed by BLM in western Oregon. The intent here is not to offer management advice regarding specific climate adaptation strategies or management practices, but rather to review the general model behavior of Climate-FVS and the trends that it produces under a spectrum of climate scenarios using forest management practices and timber targets defined in consultation with BLM staff. Our hope is that this analysis provides “a useful first approximation as to the potentially dramatic impacts of climate change” (Pearson & Dawson 2003) as modeled by Climate-FVS.

It is important to note that the land use categories, management prescriptions, and harvest targets used in this study are not the same as those being evaluated in BLM’s current planning effort in western Oregon. In this study, these inputs were defined in consultation with BLM staff, but are intended to explore the interaction of management practices and climate change in a more general context. In particular, this Climate-FVS study was originally conceived to identify how much uncertainty or variability was introduced by climate change for BLM’s ability to sustain previously defined Allowable Sale Quantities, or annual timber sale targets, across the western Oregon BLM Districts. The harvest targets used in this study are drawn from the 2008 Western Oregon Plan Revision—even though that decision was withdrawn—to provide a clear set of inputs for the current modeling effort.

Primary sources of uncertainty in climate and forest-climate modeling

In our earlier report on bioclimate envelopes, we highlighted and discussed in greater detail the primary sources of uncertainty involved in estimating the suitability of future climates for individual species or communities. These are illustrated in Figure 1, below.

Figure 1: Major sources of uncertainty in bioclimate envelope modeling as described by Beaumont et al. (2008)



In general, there are three major groupings of sources of uncertainty identified by Beaumont et al. (2008): of future climate; of biological responses to climate and other environmental factors; and model parameterization and statistical uncertainty within the species distribution projections themselves.

Wiens et al. (2009) further describe sources of model uncertainty including structural model uncertainty, the translation of niche associations into distributional probabilities by model algorithms, and the quantity and quality of training data including spatial and temporal extents, scales, and mismatches between datasets. Although model uncertainty within species distribution models is commonly reported in terms of how well the models reflect current species distributions, the uncertainty related to future climate projections and biological responses to climatic variables are often unquantifiable and rarely reported.

In the context of this study, the sources of uncertainty highlighted by Wiens et al. (2009) and Beaumont et al. (2008) correspond, for example, to the structural uncertainty of FVS in modeling forest growth-and-yield in the absence of climate change, the additional uncertainty of modeling biological responses to projected climate conditions added with Climate-FVS, measurement and sampling uncertainty in BLM site conditions, as well as potential error and uncertainty involving the use of forest inventory data derived from remote sensing.

The combination of multiple data sources, for which uncertainty is often unquantified or unquantifiable, makes it effectively impossible to quantify the accuracy or uncertainty of the simulations of climate change impacts on forests presented in this study. Throughout this report, we identify several sources of uncertainty that appear to biased or to exert significant control over model behavior, and where appropriate, describe mitigating measures to parameterize or constrain model behavior to achieve more conservative projections of future impacts on forest growth-and-yield due to climate change.

In this study, we offer a visual approach to illustrate this uncertainty and variability in climate changes and impacts on forest growth-and-yield using the ranges of outcomes projected by three emissions scenarios and four general circulation models. These results are portrayed using multi-model means as well as clouds displaying the range of values across the circulation models available in each emissions scenario. In general, we encourage readers to interpret these results as relative indications of potential climate change impacts for the purpose of illuminating the primary influences and drivers of forest impacts under climate change in western Oregon as simulated by Climate-FVS. This study may be interpreted as an exploratory analysis of the models and model inputs used as much as it is an analysis of the outcomes these models project.

Projected climatic changes for BLM lands in western Oregon

By the end of the twentieth century, the climate across the Pacific Northwest (PNW) is on course to be substantially shifted from the conditions under which our region's forests and other ecosystems have developed. Dalton and Mote (2013 chap. 2) report the latest round of climate modeling as projecting an increase in annual average temperatures of 2.0-8.5°F by mid-century. This warming is consistently projected to be more intense in summers, which are also more commonly expected to become drier, as precipitation is frequently modeled to shift earlier in the season while summertime temperatures are projected to increase. The climate models are unanimous in projection of increases in heat and precipitation extremes and decreases in cold extremes.

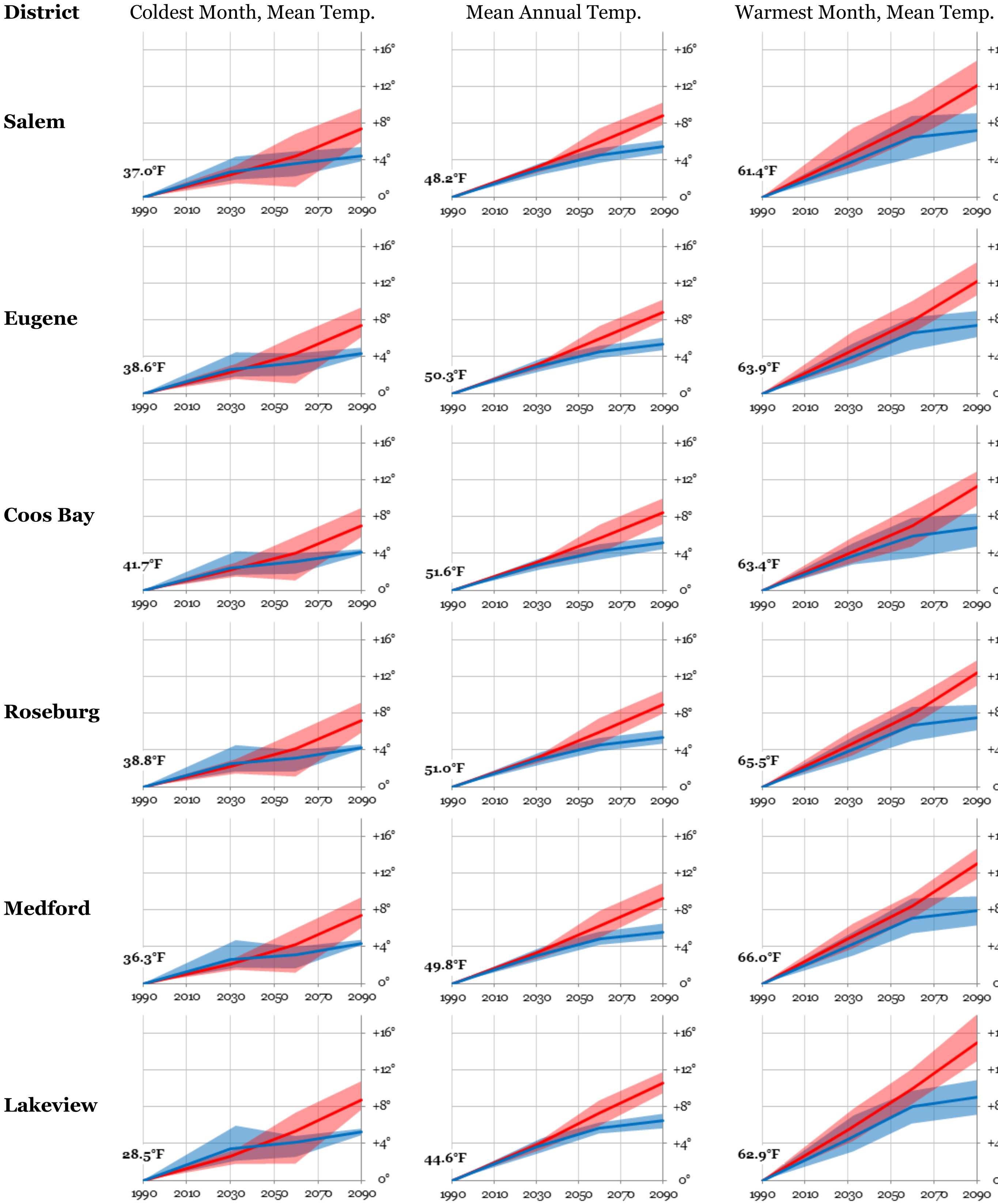
Emissions scenarios applied by the Coupled Model Intercomparison Project leading up to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change are now referred to as Representative Concentration Pathways (RCPs), and identified by the radiative forcing value associated with a particular emissions schedule in terms of watts per square meter by 2100 (Vuuren *et al.* 2011).

RCP 4.5 corresponds to a “low emissions” scenario, while RCP 8.5 corresponds to a “high emissions” scenario that reflects the world’s current emissions trajectory under the continuation of business-as-usual. In this study, RCPs are generally presented in contrast to a “*No Climate Change*” scenario reflecting no change from current conditions.

A sampling of several climate variables, including temperature, frost-free periods, and seasonal precipitation are presented in Figures 2, 3, and 4 under two RCPs and across four general circulation models (GCMs). The climate projections graphed below were prepared using ‘Climate-FVS Ready Data’, which can be generated by uploading a list of stands with latitude, longitude, and elevation details through a website managed by the USFS Moscow Forestry Sciences Laboratory[1]. The four GCMs used are described in more detail under the Methodology section on Bioclimate Envelopes below.

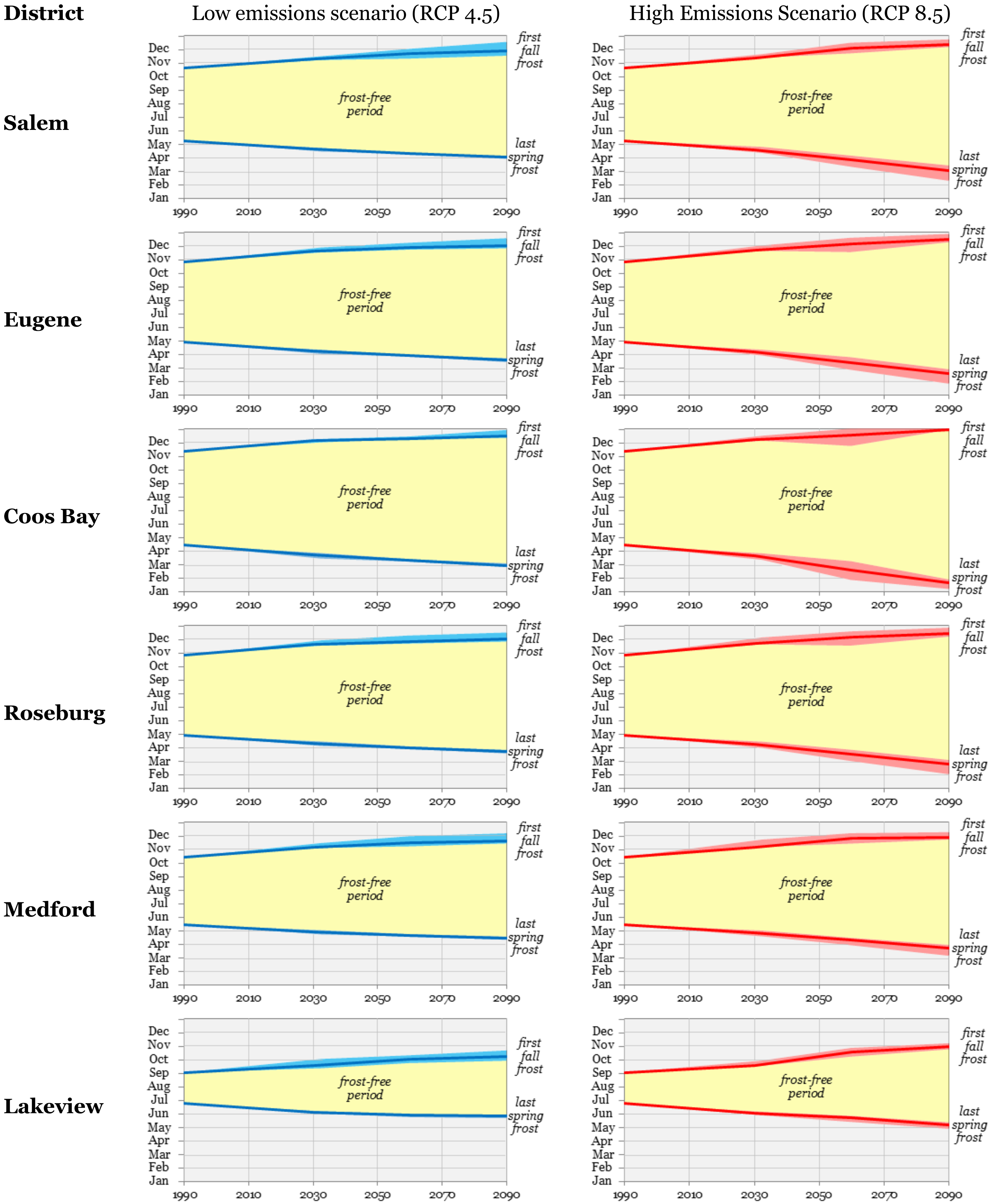
[1] http://forest.moscowfsl.wsu.edu/climate/customData/fvs_data.php

Figure 2: Projected changes in temperature with climate change



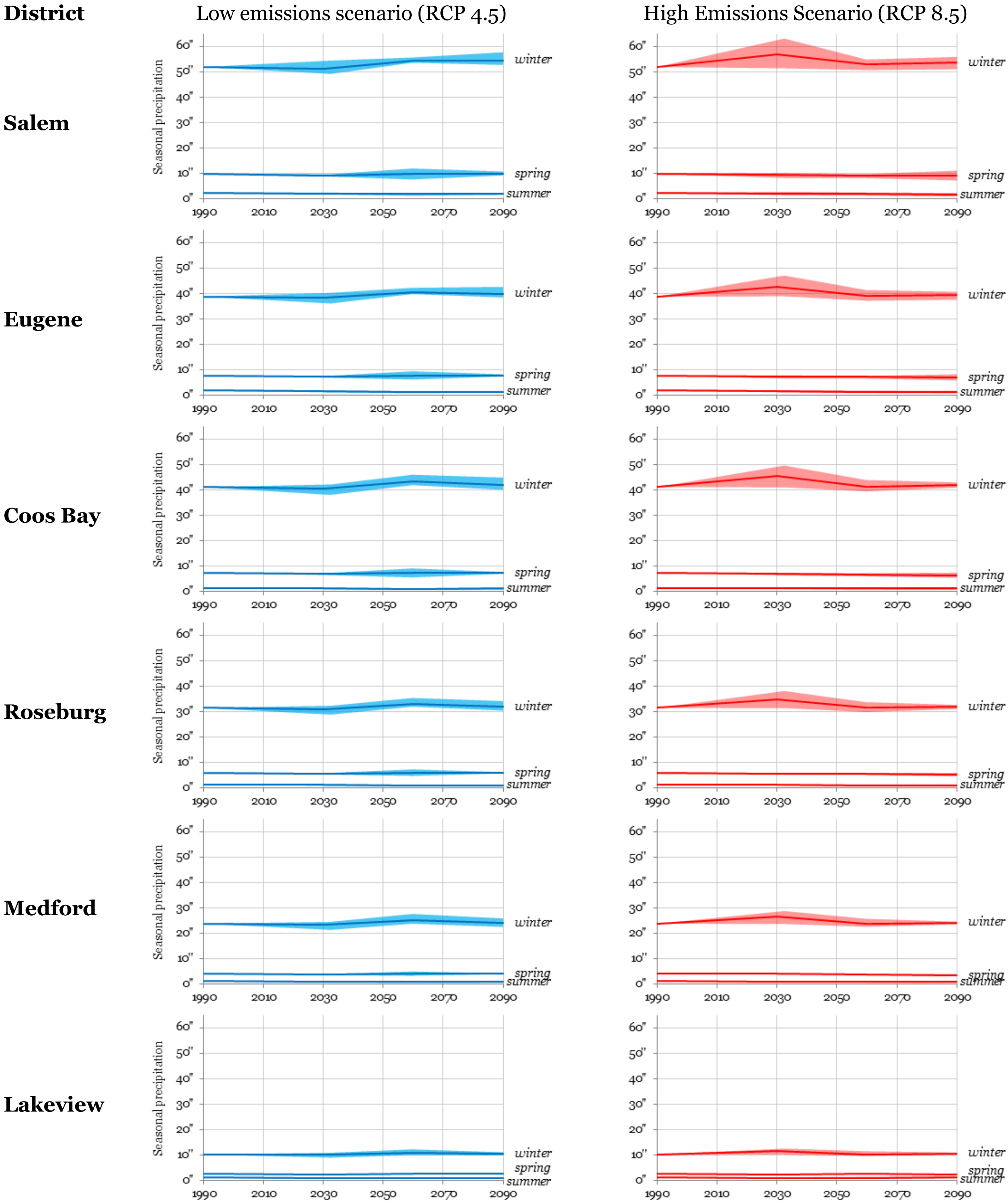
Note: These graphs show the projected temperature changes for the forested areas within the 5% sample of Western Oregon BLM lands that were simulated using Climate-FVS in each BLM District. The ranges of projections among four general circulation models (GCMs) are shown as clouds for low (RCP 4.5, blue cloud) and high (RCP 8.5, red cloud) emissions scenarios with multi-model means indicated by a solid line within each cloud.

Figure 3: Projected expansion of frost-free periods under climate change



Notes: The ranges of first and last frost dates across four GCMs are shown as color clouds; multi-model means shown as lines within each cloud.

Figure 4: Projected seasonal precipitation under climate change



Notes: The ranges of seasonal precipitation across four GCMs are shown as color clouds; multi-model means are shown as lines within each cloud.

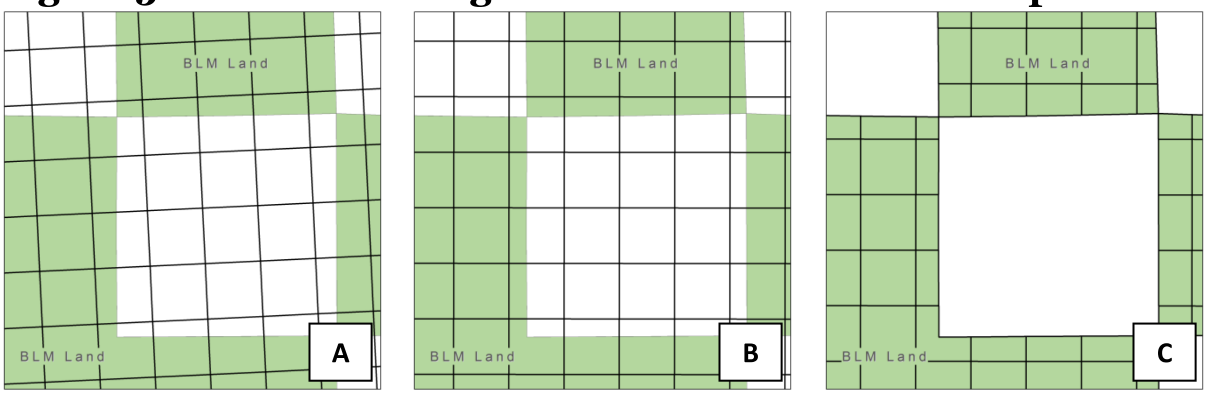
Methods for modeling forest management under climate change

The area considered in this study is comprised of all BLM lands in Western Oregon, including those lands in the Eugene, Salem, Coos Bay, Roseburg, and Medford Districts, as well as the Klamath Falls Resource Area in the Lakeview District.

Stand delineation and land classification

In order to assess the outcomes of different forestry prescriptions across the study area, we delineated management units (used interchangeably in this report with 'stands') across the landscape and summarized a variety of data relevant to the modeling process to each stand. This process is illustrated in Figure 5.

Figure 5: Illustration of grid-based stand delineation process

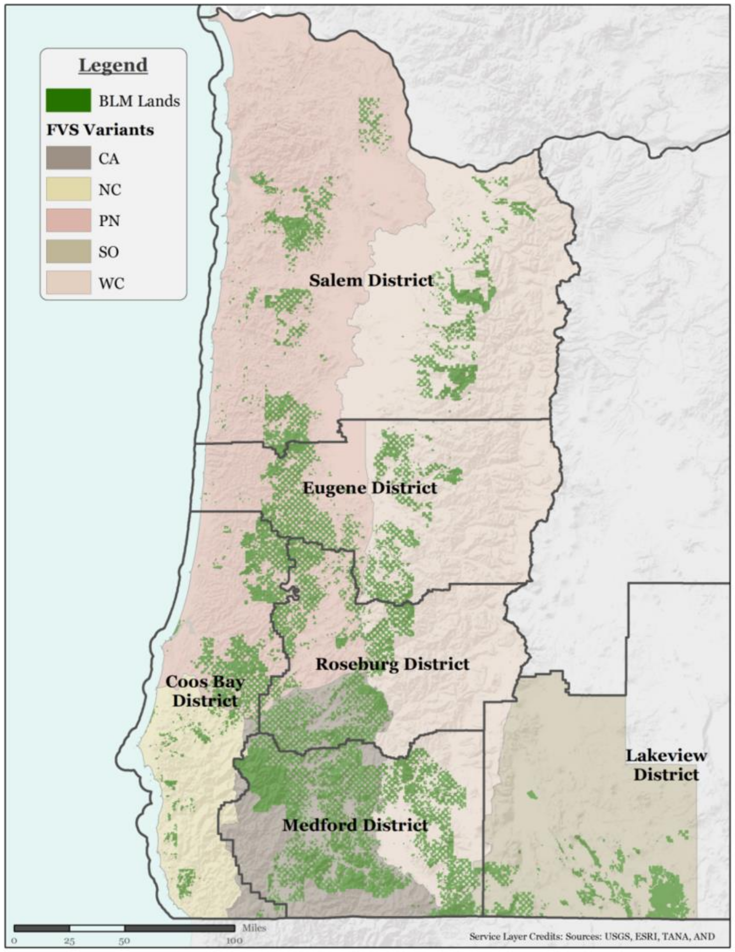


To create management units, a grid of 40-acre square cells was generated covering all of western Oregon using ArcGIS geoprocessing tools (A). The north-south axis of the grid was adjusted to more closely parallel the majority angle of BLM lands on the landscape in order to minimize small, irregularly-shaped polygons (B) and then constrained the grid to include only BLM lands (data source: Conservation Biology Institute 2010) in the study area (C). The resulting dataset was simplified by identifying small (<5 acres) remnant polygons from the clipping process, and deleting or merging them with adjacent cells.

Identifying Districts and FVS variants

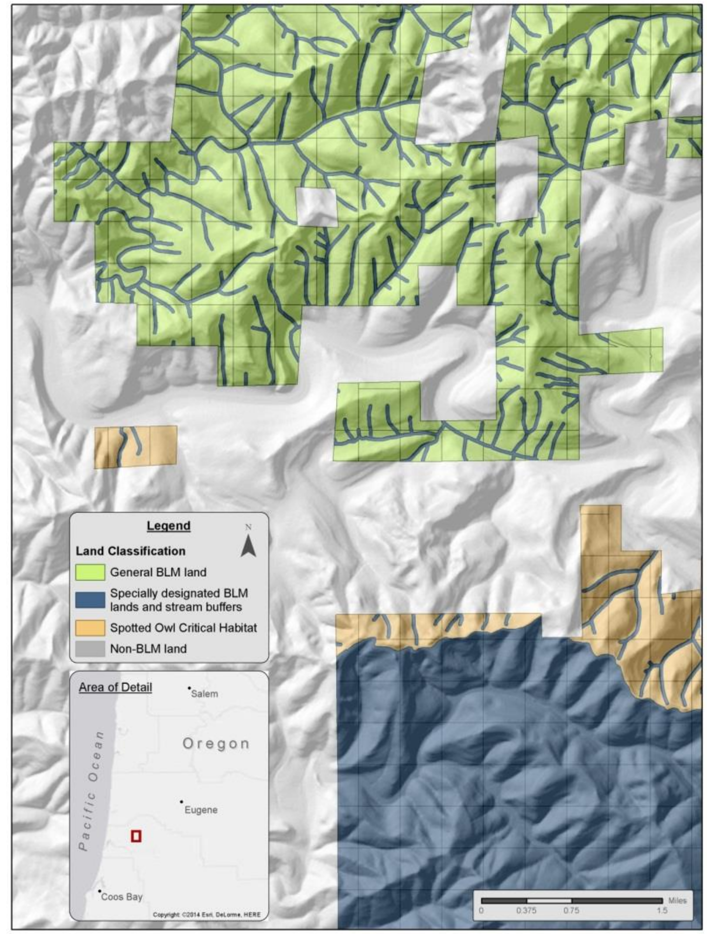
Each polygon in the grid was identified by its respective BLM District (BLM 2008a) and assigned to a Forest Vegetation Simulator (FVS) regional variant (Bovack & Van Dyck 2010). When assigning FVS variants to stands, the geographic extent of each variant was modified slightly to more closely follow EPA ecoregion boundaries (EPA, Western Ecology Division 2003) and locations of BLM land. These adjustments were made to reduce the treatment of adjacent lands within a particular BLM District or Resource Area under substantially different FVS modeling environments (based on default FVS variant maps). FVS Location Codes indicating the nearest USFS National Forest to each stand were also identified for each stand. Map 1 shows the distribution of FVS Regional Variants, as modified, applied to the study area.

Map 1: FVS Variants applied to BLM Districts



FVS Variant Codes: CA = Inland California and Southern Cascades; NC = Klamath Mountains; PN = Pacific Northwest Coast; SO = South Central Oregon and Northeast California; WC = Westside Cascades.

Map 2: Example of stand delineation and land classification



Identifying prescription zones

Several land type designations of BLM lands correspond to constraints in the types of management practices that may be applied. To identify these areas, we gathered spatial data on a variety of land classifications. These areas include federally-designated Northern spotted owl Critical Habitat (USFWS 2012) and six specially-designated protected areas on BLM lands: Wilderness Areas, Wilderness Study Areas, Areas of Critical Environmental Concern, National Monuments, Research Natural Areas, and Wild, Scenic and Recreation Rivers (Conservation Biology Institute 2010). Additionally, we used BLM-identified stream data to demarcate riparian areas (OR/WA Hydgrography Framework Partnership, USGS and BLM). From this dataset's NHD_FLOW field, which describes the periodicity of a stream or river, we identified perennial streams and buffered them by 100 feet. All other flow types (ephemeral, intermittent/seasonal, and unknown/unclassified) were buffered by 50 feet.

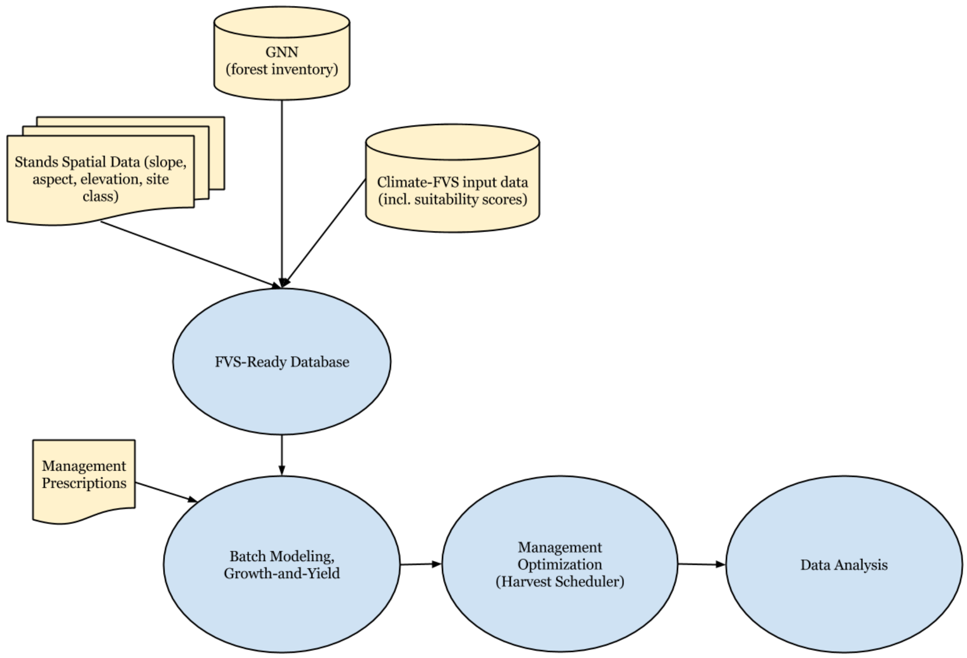
These three land-use categories were integrated with the BLM-lands grid (see Map 2). Stream buffers and specially-designated BLM lands were treated as a single class for applying forest management prescriptions. Where spotted owl Critical Habitat overlapped these areas, stream buffers and special designations took priority because forestry prescriptions applied to those areas would be more restrictive. So if, for example, spotted owl Critical Habitat occurs within a Wilderness Area, in our dataset the area is identified as Wilderness Area only. As described further below, protected and riparian areas are not subject to any active forest management in growth-and-yield simulations; the only active management allowed in Critical Habitat is complex thinning or patch cuts. The breakdown of BLM lands in each District by land classification is provided in Table 1.

Table 1: Land classification and stand delineation

	Unrestricted		**Exclusion Areas & Stream Buffers**		**Critical Habitat**		**TOTAL**	
	Acres	*# Stands*	*Acres*	*# Stands*	*Acres*	*# Stands*	*Acres*	*# Stands*
North/Moist Region								
Salem	215,342	8,847	69,306	5,244	121,650	4,501	406,298	18,592
Eugene	131,372	5,320	34,313	3,042	149,507	5,522	315,192	13,884
Coos Bay	131,766	5,362	54,515	4,471	139,526	5,152	325,807	14,985
Total	*478,480*	*19,529*	*158,134*	*12,757*	*410,683*	*15,175*	*1,047,297*	*47,461*
South/DryRegion								
Roseburg	130,875	5,539	61,135	4,933	234,993	8,962	427,002	19,434
Medford	308,151	12,396	199,226	13,257	361,824	13,688	869,202	39,341
Lakeview	182,370	5,988	18,050	944	19,929	676	220,349	7,608
Total	*621,396*	*23,923*	*278,411*	*19,134*	*616,746*	*23,326*	*1,516,553*	*66,383*
GRAND TOTAL	**1,099,876**	**43,452**	**436,544**	**31,891**	**1,027,429**	**38,501**	**2,563,850**	**113,844**

Figure 6 illustrates the datasets and processes used to prepare input data, complete growth-and-yield modeling, schedule management practices to optimize multiple objectives, and analyze the forest management outcomes. A brief overview of these processes is provided here, followed by a more detailed description further below.

Figure 6: Diagram of forest modeling workflow



In brief, remotely estimated stand-level forest inventory data were imputed to grid-cells delineating stands within BLM Districts in western Oregon. These stands were assigned geographic and productivity attributes. Stand locations and geographic attributes were also used to generate Climate-FVS input datasets, which describe the climatic suitability of each species into the future under several climate change scenarios. These combinations of stand-level data (forest inventory, geography, productivity, climatic suitability) were formatted into an FVS-ready database.

All forest management prescriptions, defined in consultation with BLM Staff, were then simulated on all eligible stands through a batch modeling process, producing a database containing all eligible combinations of management activities for each stand. A harvest scheduling model is then used to identify the combination and timing of management practices across the landscape that achieves a near-optimal outcome across several metrics including even-flow timber yield targets, carbon sequestration, fire hazard minimization, etc. The practices identified in these near-optimal scenarios were then pulled out of the database for display and analysis in the graphs and tables in this report.

Input datasets

Three general sources were used for data inputs into this modeling study: forest inventory data; stand-level attributes; and bioclimate envelope/climatic suitability data.

Inventory data and non-spatial site attributes

In this study, we utilized forest inventory data for live trees and snags prepared through the Gradient Nearest Neighbor (GNN) process by the Landscape Ecology, Modeling, Mapping, and Analysis (LEMMA) Team from Oregon State University. GNN inventory data and grid-based stand delineations were used rather than BLM's own forest inventory data and stand boundaries at the request of BLM staff, and to avoid conflation of forest inventory and growth-and-yield predictions provided in this study with those being prepared in support of the Western Oregon Resource Management Plan by Mason, Bruce and Girard. That is, the primary intent of this study was to present and characterize the range and variability of climate change impacts simulated using Climate-FVS at a regional or District-level rather than providing site-specific quantitative analysis of forest management outcomes.

The GNN process imputes publicly-available forest inventory plots across the landscape using several spatial predictors describing soil type, climate, etc. (Ohmann *et al.* 2011). A database of these inventory plots was provided by the LEMMA team (data source: Ohmann, Gregory & May 2010) and queried to create tree list files (including live and dead trees) formatted for FVS.

Overlaying the BLM stands with the GNN raster of imputed forest inventory plots, we assigned the treelist of the GNN plot that was most common within each BLM stand. Each BLM stand is represented by the treelist from one GNN plot.

For the 8% of GNN plots that did not have a stand age in the original dataset, we utilized a step-wise linear regression based on the 92% (or 3,994 out of 4,355 GNN plots) that did have a stand age to assign a non-zero stand age to remaining stands. The predictive variables determined to offer the best fit (R^2=0.85) were Stand Density Index, quadratic mean diameter of dominant trees, height to crown base, and old growth structure index.

Calculating maximum Stand Density Index

Apart from Site Class/Site Index, the FVS growth-and-yield model is also sensitive to the user-defined maximum density for each stand, which is used to drive density-related changes in growth and mortality. If no maximum Stand Density Index (SDI) is provided, FVS will assign a default value for each regional variant based on a single Plant Association Code. In some cases, the default Plant Association Code chosen for a FVS variant has a very high stand density (e.g., FVS Coast Range or PN variant) which would likely overestimate the density that many stands in BLM ownership could sustain. Although FVS can automatically assign a maximum Stand Density Index to each stand if a Plant Association Code is provided, we were unable to identify a map of Plant Association Codes covering the study area.

To generate an estimate of the maximum SDI in each FVS variant, we utilized reported SDI values in the GNN database. Using the GNN Stand Summary Table (considering only the plots within the geographic extent of each FVS variant), we queried the database to identify the distribution of SDI values for each dominant species. The 95th percentile of observed SDI values from these plots was assumed to correspond to full stocking for that species; this query was repeated for each geographic variant. In FVS, full stocking is represented as 55% of the theoretical maximum Stand Density Index (i.e., the point at which density-related mortality is triggered). For each regional FVS variant, we thus divided the observed 95th percentile SDI by 55% to estimate the maximum SDI value for that species. These maximum SDI values were then applied in each FVS regional variant. Table 2 shows the maximum SDI values used:

Table 2: Maximum Stand Density Index values used in FVS

	FVS Variant				
Species	Pacific Northwest Coast (PN)	Westside Cascades (WC)	Inland California and Southern Cascades (CA)	Klamath Mountains (NC)	South Central Oregon and Northeast California (SO)
Douglas-fir	582 (320)	622 (342)	647 (356)	643 (354)	545 (300)
Grand fir/ White fir	--	545 (300)	580 (319)	--	577 (317)
Lodgepole pine	--	679 (373)	--	--	687 (378)
Mountain hemlock	--	796 (438)	--	--	708 (389)
Noble fir	--	655 (360)	--	--	--
Pacific madrone	--	619 (340)	633 (348)	--	--
Pacific silver fir	881 (485)	823 (453)	--	--	--
Ponderosa pine	--	446 (245)	456 (251)	--	422 (232)
Red alder	476 (262)	510 (281)	--	--	--
Red fir	--	--	--	--	633 (348)
Tanoak	--	--	880 (484)	861 (474)	--
Western hemlock	743 (409)	769 (423)	--	--	--
Western juniper	--	--	--	--	169 (93)
White oak	--	345 (190)	351 (193)	--	--
All others	640 (352)	657 (361)	642 (353)	655 (360)	560 (308)

Note: If a species-specific maximum SDI value is not listed for a particular FVS variant in this table, that species and any others without values specified here were assigned the maximum SDI value shown in the last row for "All others." For context, values in parenthesis show the implied SDI for "full stocking," which equates to the number of trees per acre in a stand with a 10" average DBH (quadratic mean) that can be sustained before density-related mortality will begin. FVS considers all tree species in a stand to calculate a composite maximum SDI for each stand.

Spatial assignment of stand attributes: Site Class, slope, aspect, elevation

We summarized basic terrain values for each stand from a 10-meter raster dataset of elevation (USGS 2009), assigning each stand the average elevation in meters. Using the same elevation dataset, we used standard ArcGIS geoprocessing tools to derive values of slope and aspect over the landscape, and calculated the average of each.

We used Oregon BLM Site Index spatial data (Oregon BLM 2013) to assign a Site Class value to each polygon in the grid dataset. The input data was converted to a 30m x 30m (.22 acres) raster dataset, where each cell's value was determined by the Site Class value with the largest total area. Each polygon then received the Site Class value that occurred most often within its boundaries.

Management Prescriptions

In consultation with BLM staff, six different management prescriptions were developed for simulation. The specific activities included with each of these prescriptions are described in Table 3. All FVS code used for these prescriptions is published online at https://github.com/Ecotrust/growth-yield-batch/tree/master/projects/BLMClimate/rx. The 'grow only' scenario is simulated for all land classifications. Lands classified as exclusion areas or stream buffers are not subject to any active forest management. Active management in Critical Habitat is limited to complex thinning or patch cuts.

Table 3: Management prescriptions used in Climate-FVS simulations

General Description	Included practices
Grow only	- No active management
80-year rotation	- Regeneration harvest at age 80, retaining 15 trees per acre (TPA) in WC and PN variants, 7 TPA all others - Pre-commercial thin (PCT) at age 15-20 (WC and PN variants) or 25-30 (all other variants); PCT retains 150 TPA for pine stands, 225 TPA for all others - Commercial thin at age 30-35 (PN and WC variants) and 50-55 (all variants) to 35% of maximum SDI - Several species were given higher priority for retention and removal in CA, NC, and SO variants, including: - Retain Douglas-fir, Ponderosa pine, Incense cedar, and Sugar pine; remove true firs (NC variant) - Retain Douglas-fir, Ponderosa pine, and Western larch; remove true firs and Western juniper (CA and SO variants) - All slash piled and burned following thins and regeneration harvests (all variants) - Replant with 450 TPA apportioned based on abundance of commercial timber species present prior to harvest (CA, NC and SO variants), otherwise or if no commercial species present, using: - Douglas-fir, Incense cedar, Ponderosa pine, and Sugar pine, 25% each (CA and NC variant) - Ponderosa pine plantation (SO variant) - 25% Douglas-fir, 55% Western hemlock, 10% Western redcedar, and 10% Sitka spruce (PN variant) - 65% Douglas-fir, 20% Western hemlock, 10% Western redcedar, and 5% to Grand fir, Silver fir, or Noble fir based on site elevation (WC variant)
100(+)-year rotations	- Regeneration harvest at age 100, 120, 140, or 160 for Site Classes 1-2, 3, 4, and 5, respectively, retaining 15 TPA in WC and PN variants, 7 TPA all others - Pre-commercial thin (PCT) at age 15-20 (all variants) retaining 150 TPA for pine stands, 225 TPA for all others - Commercial thin to 35% of maximum SDI at ages 40 & 70, 50 & 80, 50 & 90, or 50 & no second commercial thin for Site Classes 1-2, 3, 4, and 5, respectively - Species priorities for retention and removal and replanting same as for 80-yr rotation - All slash piled and burned following thins and regeneration harvests (all variants)
Thin every 20-25 years	- Thin throughout diameter distribution every 20 years (WC and PN variants) or 25 years (all other FVS variants) down to 35% of maximum SDI, beginning at age 30 - Species priorities for retention and removal same as for 80-yr rotation - All slash piled and burned following thins (all variants)
Complex structure thinning	- Thin triggered every 25 years to 50% of maximum SDI, targets uneven-aged structure with J-shaped diameter distribution (5" diameter classes, q-value=1.3) - No slash treatment following thinning
Patch cut	- Remove 1/8 of stand every 25 years (≤ a 5-acre patch cut). FVS does not implement this as a patch cut, but rather removes 1/8 of trees throughout the stand, comparable to a commercial thinning, although modifications were made to increase height growth and decrease mortality slightly for naturally regenerating trees (no tree planting following harvest) - All slash piled and burned following harvest (all variants)

For each prescription, we also created a series of 'offsets', which effectively delay the implementation of the first activity in the management scenario by 5, 10, or 15 years. These offsets offer choices to the optimization model to schedule the initiation of activities to best achieve multiple objectives.

Bioclimate envelopes

To run Climate-FVS, an input file containing the climatic suitability scores for each stand under the various emissions scenarios and General Circulation Models (GCMs) is required. These 'Climate-FVS Ready Data' can be generated by uploading a list of stands with latitude, longitude, and elevation details through a website managed by the USFS Moscow Forestry Sciences Laboratory[2]. Following the delineation of stands across the study area, we used the latitude and longitude coordinates of the centroid of each stand as well as the median elevation calculated for each stand using the 10m-resolution USGS Digital Elevation Model.

The resulting input files include the parameters needed to run Climate-FVS simulations under RCPs 4.5, 6.0, and 8.5 and three individual GCMs (CCSM4: The Community Earth System Model, GFDLCM3: Geophysical Fluid Dynamics Laboratory, and HadGEM2ES: Met Office (UK)) as well as an Ensemble climate projection based on the combination of 17 different GCMs[3,4]. These files contain the climate suitability scores (and some climatic data) for all tree species in 1990, 2030, 2060, 2090, as well as several other climatic variables that drive additional Climate-FVS growth and mortality factors described above.

We also created a "*No Climate*" scenario in these Climate-FVS input files so that our scenario without climate change impacts was directly comparable to those with climate change impacts (i.e., rather than modeling climate change using Climate-FVS and *No Climate* using the Base FVS model). The parameters for the *No Climate* scenario were created in these input files by copying the values from 1990 to all other years (i.e., climatic suitability scores do not change over time).

Several examples of projected climatic suitability (or bioclimate envelopes) are shown in Map 3. These maps and the methods, uncertainty, and implications are discussed in detail in our earlier report on bioclimate envelopes (Diaz *et al.* 2014). Climate-FVS utilizes the climatic suitability scores visualized in these maps to provide both species-specific growth and mortality effects, as well as stand-level changes in growth potential (i.e., Site Index). The projected shifts in the distribution of Site Classes within each BLM District over time are visualized in Figure 7. In all Districts, both low and high emissions scenarios produce a downward shift in site potential. This effect becomes increasingly pronounced under the high emissions scenario in the second half of the century.

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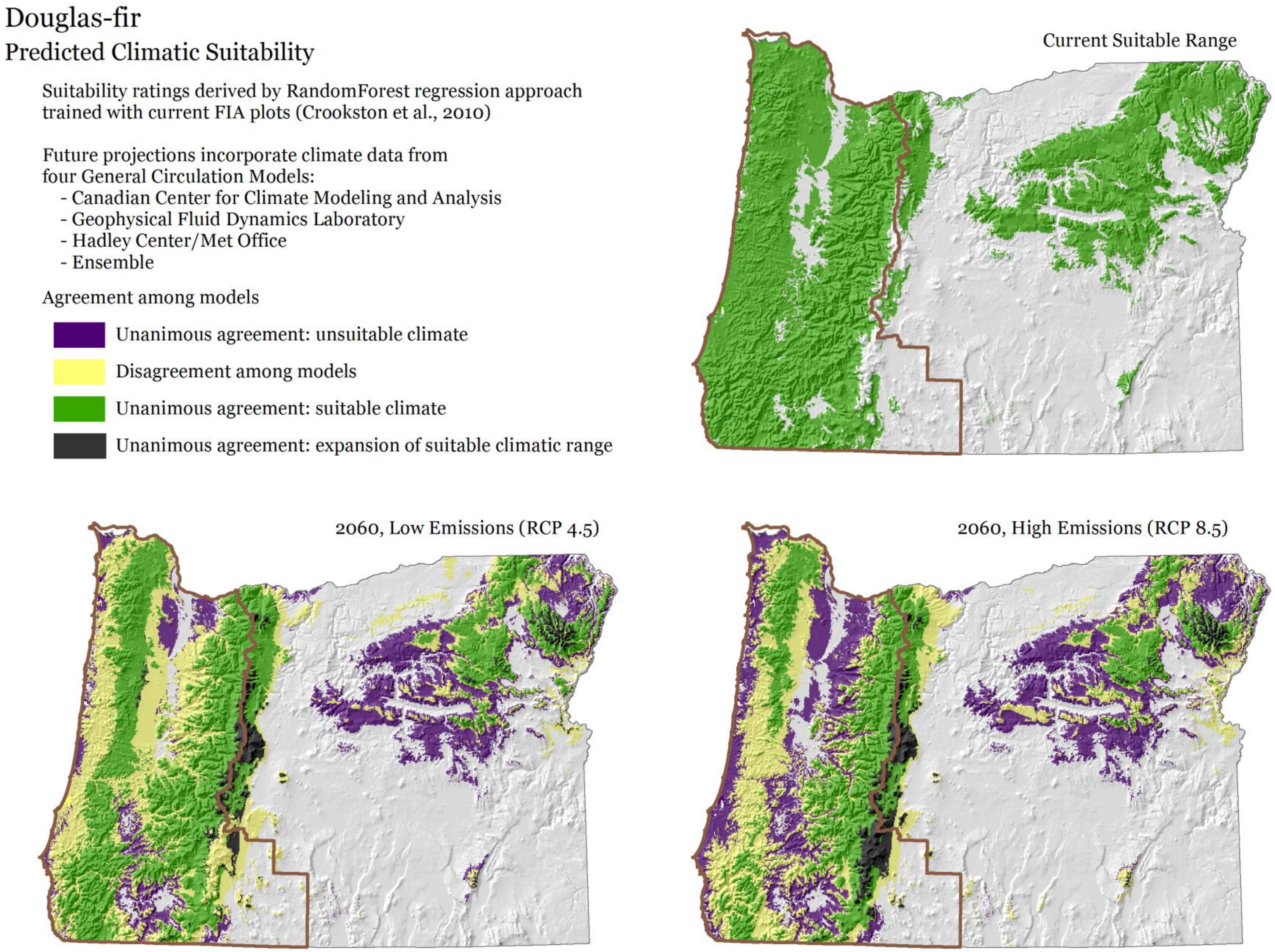
[2] http://forest.moscowfsl.wsu.edu/climate/customData/fvs_data.php

[3] The 17 GCMs included in the Ensemble are: BCC-CSM1-1; CCSM4; CESM1-CAM5; CSIRO-Mk3-6-0; FIO-ESM; GFDL-CM3; GFDL-ESM2G; GFDL-ESM2M; GISS-E2-R; HadGEM2-AO; HadGEM2-ES; IPSL-CM5A-LR; MIROC5; MIROC-ESM-CHEM; MIROC-ESM; MRI-CGCM3; NorESM1-M. More information about the modeling approach of Crookston et al. (2010) is available online at http://forest.moscowfsl.wsu.edu/climate/future/details.php.

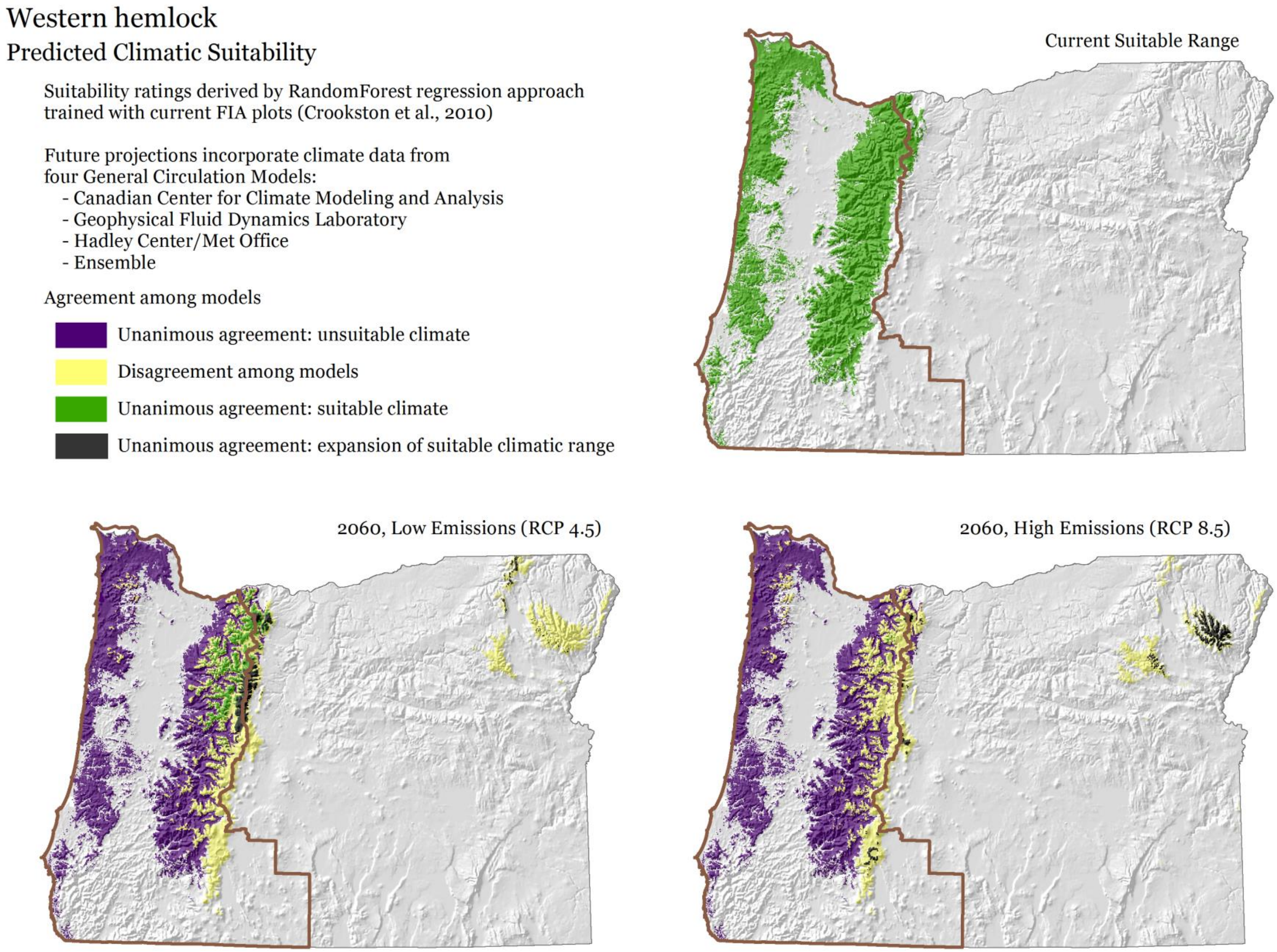
[4] Readers are encouraged to consult Rupp et al. (2013), which ranks 41 CMIP5 GCMs for performance hindcasting observed PNW climate. For the GCMs incorporated into this study –by virtue of their development for Climate-FVS by Crookston et al. (2010)—CCSM4 and HadGEM2ES were in the top 10, GFDLCM3 was in the bottom 10, and of the 17 GCM models included in the Ensemble, 4 were in the top 10, 6 in the bottom 10, and 7 in-between.

Map 3: Future bioclimate envelopes for several tree species



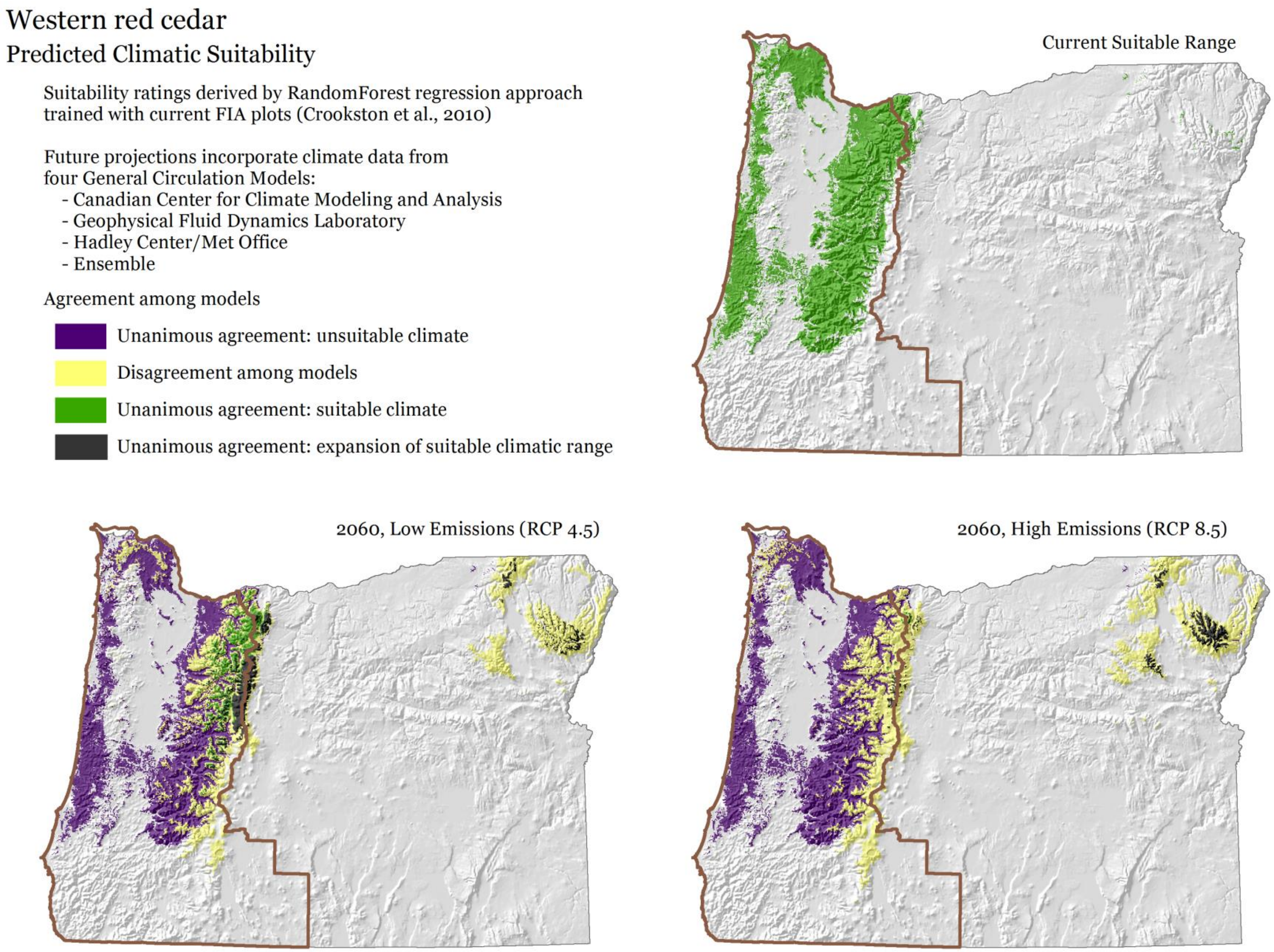
Note: These maps do not represent predicted future species distributions. *These maps show future climatic suitability, which is one of several factors that affect species distributions. These maps help answer the question: "How similar are future climatic conditions in each location to the places where a species currently grows?" Changes in climatic suitability should be expected to affect the growth and/or mortality of species over time by interacting with many other important environmental and physiological factors not represented here.*

Map 3 (continued)



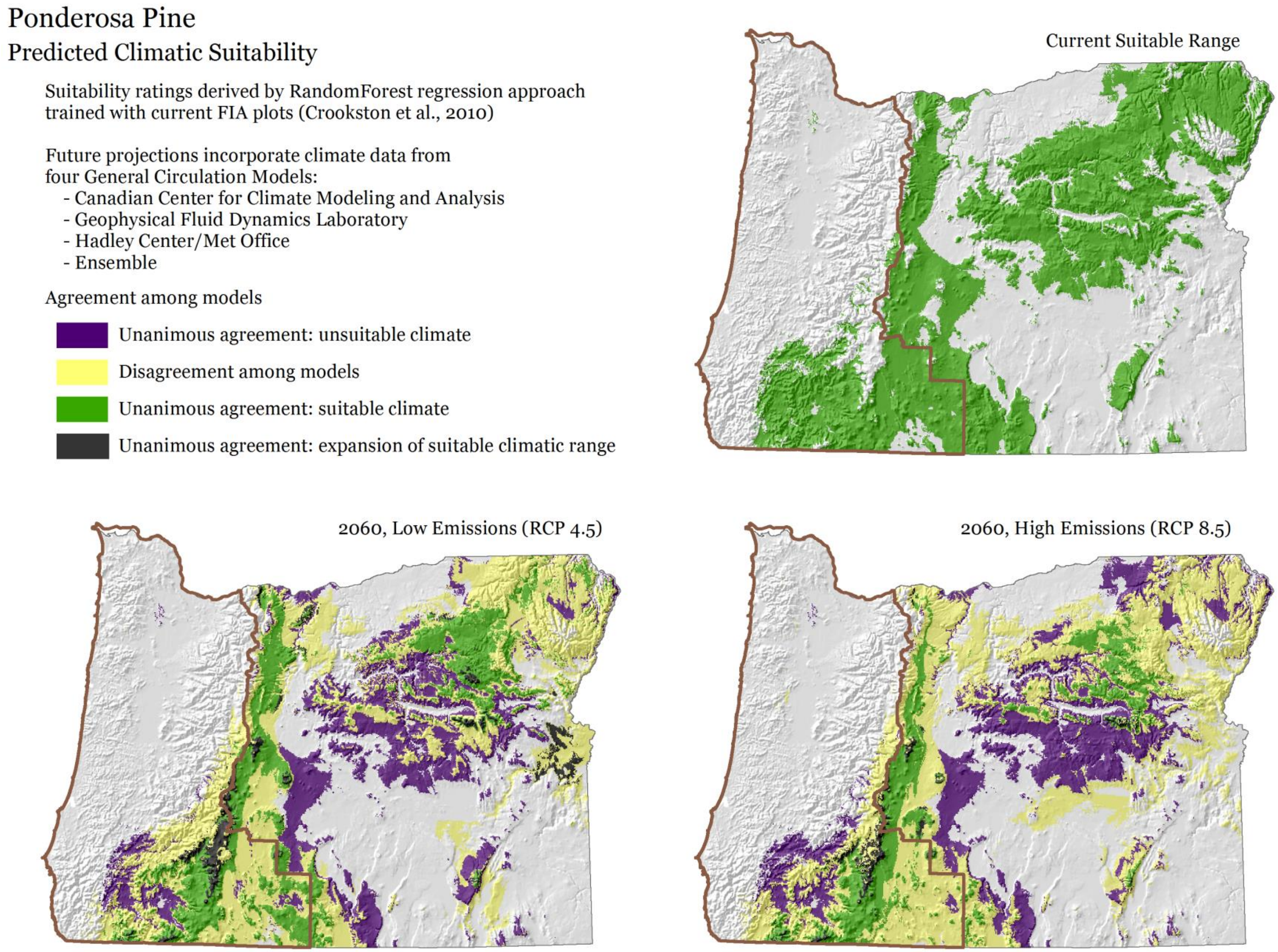
Note: These maps do not represent predicted future species distributions. *These maps show future climatic suitability, which is one of several factors that affect species distributions. These maps help answer the question: "How similar are future climatic conditions in each location to the places where a species currently grows?" Changes in climatic suitability should be expected to affect the growth and/or mortality of species over time by interacting with many other important environmental and physiological factors not represented here.*

Map 3 (continued)



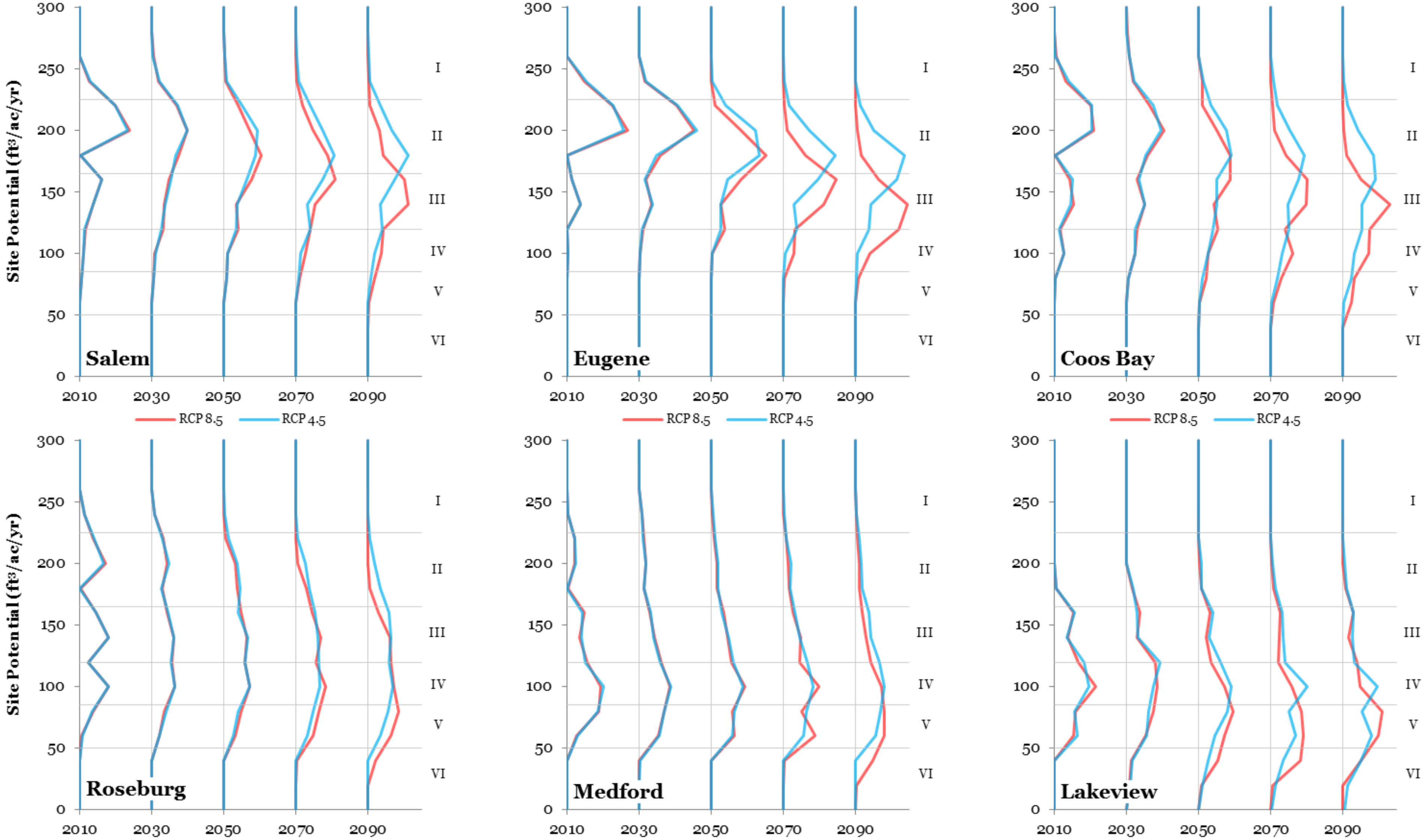
Note: These maps do not represent predicted future species distributions. *These maps show future climatic suitability, which is one of several factors that affect species distributions. These maps help answer the question: "How similar are future climatic conditions in each location to the places where a species currently grows?" Changes in climatic suitability should be expected to affect the growth and/or mortality of species over time by interacting with many other important environmental and physiological factors not represented here.*

Map 3 (continued)



Note: These maps do not represent predicted future species distributions. *These maps show future climatic suitability, which is one of several factors that affect species distributions. These maps help answer the question: "How similar are future climatic conditions in each location to the places where a species currently grows?" Changes in climatic suitability should be expected to affect the growth and/or mortality of species over time by interacting with many other important environmental and physiological factors not represented here.*

Figure 7: Projected shifts of potential site productivity due to climate change, Ensemble GCM



Notes: Climate-FVS modifies Site Index directly based on climatic signals in addition to altering species-specific growth rates.These graphs show the distribution of cubic volume site potential among simulated stands within each BLM District at 20 year intervals for low (RCP 4.5) and high (RCP 8.5) emissions scenarios under the Ensemble GCM. The area 'under' each line (i.e., between each colored line and the year represented) corresponds to 100% of all simulated stands. Roman numerals along the right side of each graph show growth potential categorized as Site Classes.

Batch Modeling

For this study, we created a batch modeling system to prepare all combinations of eligible management activities, execute them in parallel using Climate-FVS, and then parse the FVS output files to extract data on management outcomes of interest. We created FVS-ready keyfiles for all unique combinations of management prescriptions, offsets, emissions scenarios, and GCMs, which were then simulated using Climate-FVS with resulting output files parsed and data stored in a SQLite database. This provides a comprehensive set of management outcomes from all eligible management activities that can then be evaluated using the scheduler/optimization model. This growth-and-yield batch system is a distributed, fault-tolerant, and scalable system enabling parallel FVS operation; all code is published online at https://github.com/Ecotrust/growth-yield-batch/.

Climate-FVS runtime environment and customizations

Each regional variant of FVS was run on a 5-year timestep for a duration of 100 years beginning in 2013. The FVS Fire and Fuels Extension was used to calculate carbon storage and fire metrics. A fire hazard metric developed by Huggett et al. (2008) was incorporated into FVS code. Similar hazard metrics for pine beetle, spruce beetle, and other pests are also implemented in FVS code and useable for setting optimization targets, but have not been utilized to set objectives in the current study, and thus are not presented alongside the other metrics on forest conditions and outcomes considered below.

By default, Climate-FVS will naturally regenerate trees whenever stocking decreases beneath a set percentage of the maximum SDI, choosing species to introduce based on the 3-4 species with the highest climatic suitability scores at that time. Climate-FVS will introduce these species even if a seed source is not present in the stand. For this study, a custom logic was introduced into the FVS keyfiles to limit natural regeneration to those species present in the stand using a similar maximum SDI threshold, with the density of natural regeneration based on the proportion of SDI occupied by each species in the stand, and the default Climate-FVS natural regeneration process was turned off.[5]

Scheduling model

Ecotrust has developed a discrete optimization software library using a simulated annealing algorithm to find the (near) optimal combination of management practices on the landscape to satisfy multiple objectives. All code for the scheduling model is published online at https://github.com/Ecotrust/harvest-scheduler. The solution-space comprised of all possible combinations of prescriptions and timing for every BLM stand simulated is too large to complete an exhaustive search within a reasonable timeframe for the single global optimal combination of practices and timing. Simulated annealing is one approach for identifying a good approximation of the global optimum.

The scheduler considers four general approaches to quantifying how optimal a particular forest metric of interest is when searching the solution-space of forest management options to achieve multiple objectives:

[5] The replacement of the default Climate-FVS natural regeneration behavior with a custom logic limiting regeneration to species that are already present in the stand or introduced via planting should be expected to reduce the rate of change in forest composition that would have otherwise been simulated in Climate-FVS. That is, the default Climate-FVS natural regeneration logic would have allowed the more rapid introduction and growth of novel species into a stand where existing trees were no longer well-suited to future climatic conditions.

- **Maximize:** seeks to maximize the value of a metric (e.g., carbon storage) across the entire study area;
- **Minimize:** seeks to minimize the value of a metric (e.g., acres of high fire hazard, harvest costs, etc.) across the entire study area;
- **Evenflow:** seeks to minimize the standard deviation of a metric (e.g., timber yield) across the entire study area; and
- **Evenflow-Target:** seeks to minimize variation around a set target (e.g., timber yield) across the entire study area, which can be defined as single value or range of values, and can be varied over time.

Values for each specific management objective can be assigned weights to set relative levels of priority for achieving those individual objectives, potentially at the expense of other objectives.

For the active management scenarios evaluated in this report, we configured the scheduling model to optimize for the following objectives. Again, it is important to note that these objectives were developed in consultation with BLM staff, but are not drawn from the current BLM planning effort:

- Timber yield, using an evenflow-target approach, targeting a yield of 502 million boardfeet (mmbf) per year across all western Oregon BLM Districts. This value is based on the Allowable Sale Quantity from the 2008 BLM Proposed Resource Management Plan (BLM 2008b)
- Carbon storage: maximize
- Acres of high fire hazard: minimize
- Acres of forest structurally suited for Northern spotted owl habitat: maximize[6]
- Harvest and transportation cost proxy (boardfoot volume removed multiplied by slope): minimize

A 6x weight was set for the timber yield target, and all other weights were set at 1. This effectively means that the scheduling model will first and foremost attempt to achieve harvest targets and will try to minimize/maximize the other objectives within that constraint. All of these targets are specified at a global level. The scheduling model is thus free to vary the performance within any single District in the search for the global optimum. For example, the scheduling model will seek to hit the 502 mmbf timber target across the study area while also achieving the other objectives specified above. District-level timber yield targets are not enforced.[7]

Two studies using Climate-FVS

This report includes two fairly distinct lines of inquiry into the application of Climate-FVS for growth-and-yield modeling to estimate potential climate change impacts on forests. These studies are each described in turn.

[6] Although stand-level habitat suitability ratings for Northern spotted owl—based on nesting/roosting and foraging equations defined in Table Series C-10, C-12, C-14, and C-16 of the NSO Recovery Plan (USFWS 2011)—were calculated in the simulations in this study and incorporated into the scheduling model, the results of these habitat projections are not presented in this report. For reference, the code used for implementing these equations within FVS regional variant is available online at https://github.com/Ecotrust/growth-yield-batch/tree/master/projects/BLMClimate/rx/include.
[7] In practice, BLM does not determine sustained yields and define ASQs on the basis of the entire Western Oregon ownership, but rather by individual Sustained-Yield Units.

Study 1: Simulations to evaluate sensitivity to *dClim* mortality factor

The findings from our earlier report on bioclimate envelope projections (Diaz *et al.* 2014) confirmed that Random Forests more frequently predicts range contraction and climatic unsuitability compared to process models. These Random Forest-generated bioclimate envelope projections form the basis for Climate-FVS simulations (the process by which these scores are incorporated into Climate-FVS are described in Appendix I). This led us to the conclusion that, based solely on the climatic suitability scores that are used as inputs, Climate-FVS would likely be predisposed to project greater declines in growth and/or increases in mortality relative to process models.

In this study, we sought to identify the impacts of the addition of a new mortality factor, *dClim*, on overall model behavior. No evaluations have yet been published of Climate-FVS sensitivity to this factor. In particular, we conducted this study to identify the implications of using *dClim* with the default or 'out-of-the-box' Climate-FVS settings, and to determine the setting for *dClim* that would be used in our simulations of active forest management (described in Study 2 below).

For this study, we simulated growth without any active management on a 2% random sample of stands across BLM lands in western Oregon. These simulations applied three different levels of *dClim*:

- 1.0, which applies the default 'out-of-the-box' behavior;
- 0.5, which reduces the mortality induced by this factor in half; and
- 0.0, which effectively turns off *dClim* entirely. These simulations were performed using the Ensemble GCM and using RCPs 4.5, 6.0, and 8.5.

The results of this study were used to inform the value of *dClim* chosen for simulations using the full spectrum of management prescriptions, GCMs, and emissions scenarios.

Study 2: Simulations with active forest management under climate change

In this study, our primary focus was to complete an exploratory data analysis of forest growth-and-yield simulations of BLM lands in western Oregon using a range of management prescriptions, GCMs, and emissions scenarios. Our goals were to explore and communicate these data, to identify and characterize model behavior and trends, and to reveal potential implications for forest management strategies seeking to balance multiple competing uses and values under a changing climate. This study was not conceived with the purpose of statistical hypothesis testing of individual management actions or climate impacts.

In this study, we utilized a 5% stratified random sample of BLM stands for batch modeling of the full combination of eligible management prescriptions using multiple GCMs and the low (RCP 4.5) and high (RCP 8.0) emissions scenarios. A 5% sample was pulled from each combination of FVS variants, National Forest location codes, and land classifications. The breakdown of stands and acreages captured in this study are reported in Table 4. Based on the results of Study 1 regarding the significant mortality that *dClim* introduced at both its default 1.0 setting as well as at a setting of 0.5, we conducted these simulations with the *dClim* mortality factor turned off (i.e., set to 0).

Table 4: Stands modeled for climate change assessment

	Unrestricted		Exclusion Areas & Stream Buffers		Critical Habitat		TOTAL	
	Acres	*# Stands*	*Acres*	*# Stands*	*Acres*	*# Stands*	*Acres*	*# Stands*
North/Moist Region								
Salem	10,408	433	3,585	272	5,613	211	**19,606**	**916**
Eugene	6,276	248	1,516	135	7,361	272	**15,152**	**655**
Coos Bay	6,703	271	2,910	234	7,235	267	**16,848**	**772**
Total	*23,387*	*952*	*8,011*	*641*	*20,209*	*750*	***51,606***	***2,343***
South/Dry Region								
Roseburg	6,272	270	2,860	232	11,523	451	**20,655**	**953**
Medford	14,456	561	10,036	667	18,049	679	**42,541**	**1,907**
Lakeview	6,117	194	542	32	857	32	**7,517**	**258**
Total	*26,845*	*1,025*	*13,438*	*931*	*30,429*	*1,162*	***70,713***	***3,118***
GRAND TOTAL	**50,232**	**1,977**	**21,449**	**1,572**	**50,638**	**1,912**	**122,319**	**5,461**

Note: These values reflect the error-free FVS runs for all prescriptions, General Circulation Models (GCMs), and emissions scenarios drawn from the 5% subsample of all BLM stands used in "Study 2." This worked out to about 4.8% of total BLM lands by number of stands and 4.77% by area. The number of stands and acreage for the whole study area are provided above in Table 1.

Table 5 presents several stand-level attributes to illustrate the representativeness of the 5% sample of stands used for simulations as compared to all stands delineated on BLM lands in Western Oregon. The spatial distribution of stand sampling is illustrated in Map 4, and the representativeness of the sampled stands in terms of site productivity is shown in Figure 8.

Table 5: Representativeness of sampled stands

	Quadratic Mean Diameter		Stand Density Index		Basal Area		Age	
District	*Sample*	*All Stands*	*Sample*	*All Stands*	*Sample*	*All Stands*	*Sample*	*All Stands*
Eugene	15.2 ± 9.6	15.6 ± 9.8	141 ± 63	140 ± 65	157 ± 89	161 ± 91	66 ± 54	67 ± 55
Salem	16.1 ± 9.6	16.0 ± 9.4	154 ± 73	153 ± 75	174 ± 96	174 ± 97	76 ± 72	74 ± 68
Coos Bay	17.7 ± 11.8	16.8 ± 12.0	163 ± 83	158 ± 84	182 ± 105	171 ± 103	79 ± 64	75 ± 65
Roseburg	17.1 ± 10.2	16.6 ± 10.4	164 ± 80	164 ± 83	162 ± 96	161 ± 98	90 ± 67	87 ± 69
Medford	13.6 ± 7.2	13.6 ± 7.2	183 ± 96	179 ± 99	149 ± 90	148 ± 91	88 ± 56	88 ± 58
Lakeview	14.4 ± 6.9	13.1 ± 6.3	56 ± 52	59 ± 59	54 ± 48	55 ± 49	98 ± 76	91 ± 70

Note: This table shows the mean and standard deviations for each of four variables for the 5% subsample of stands that were simulated using Climate-FVS compared to the full set of delineated BLM stands. All values in this table are calculated from GNN stand attributes (as opposed to BLM's own inventory data).

Map 4: Example of spatial distribution of sampled stands

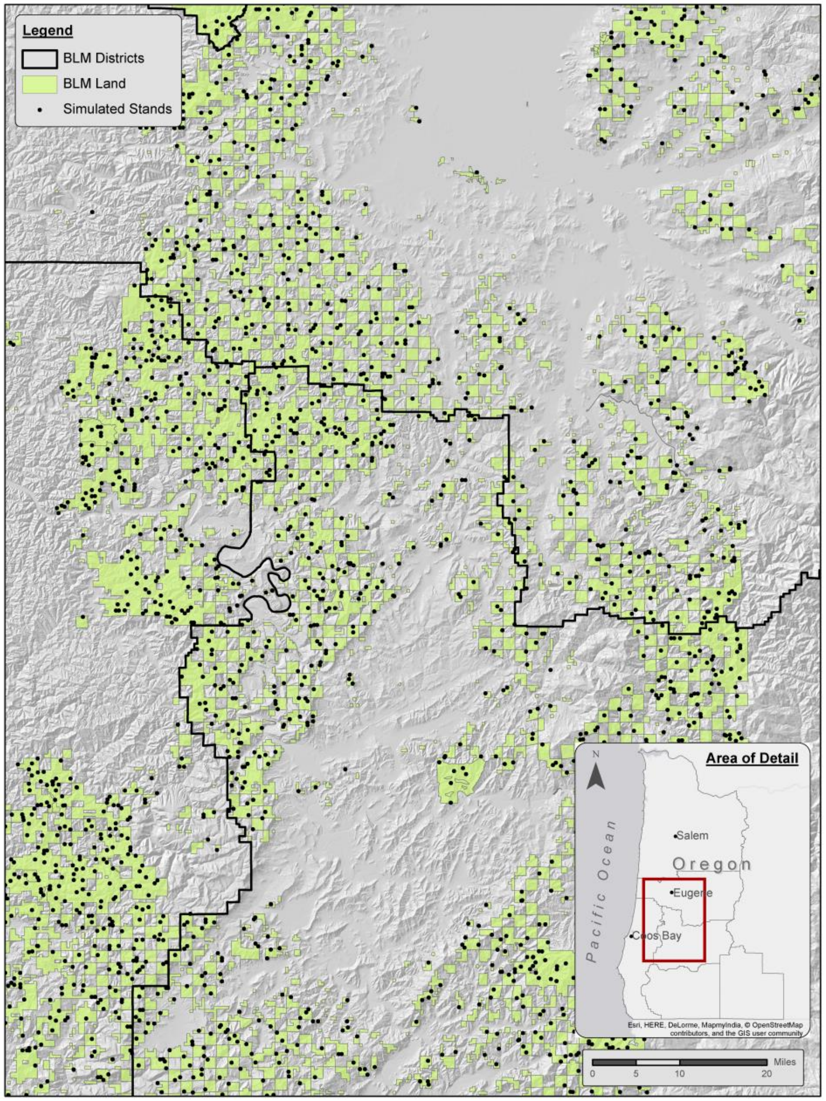
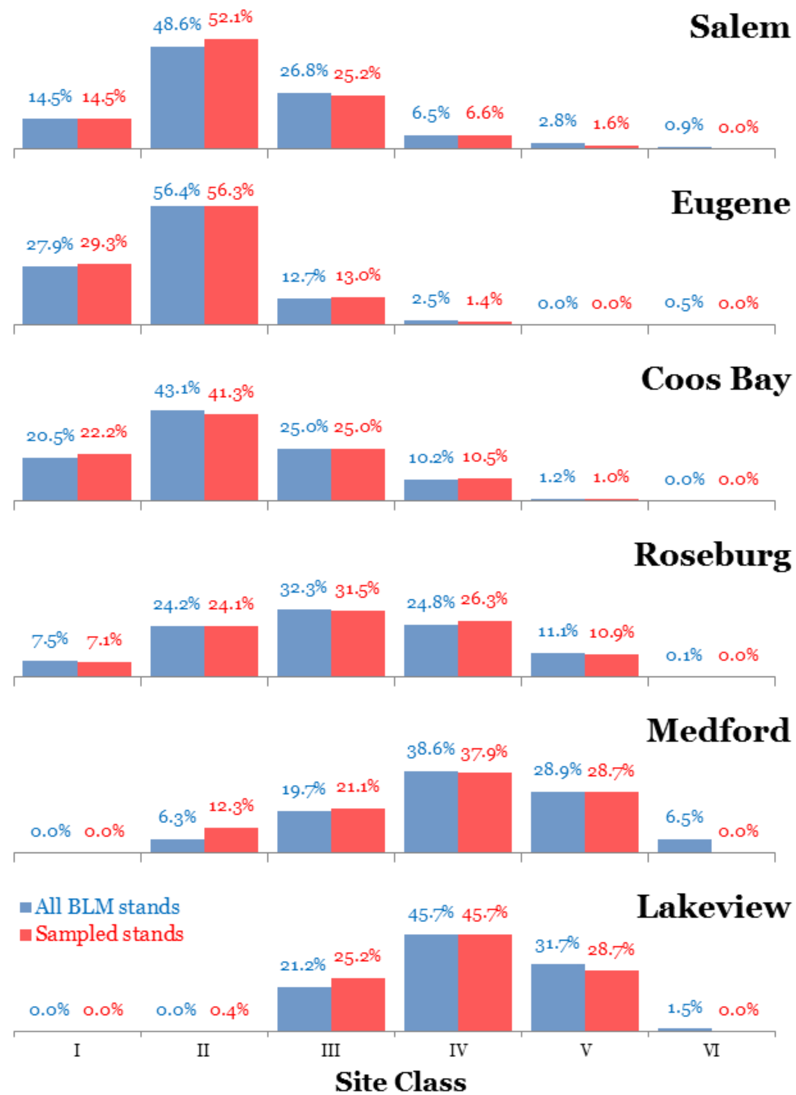


Figure 8: Representativeness of site productivity in sampled stands



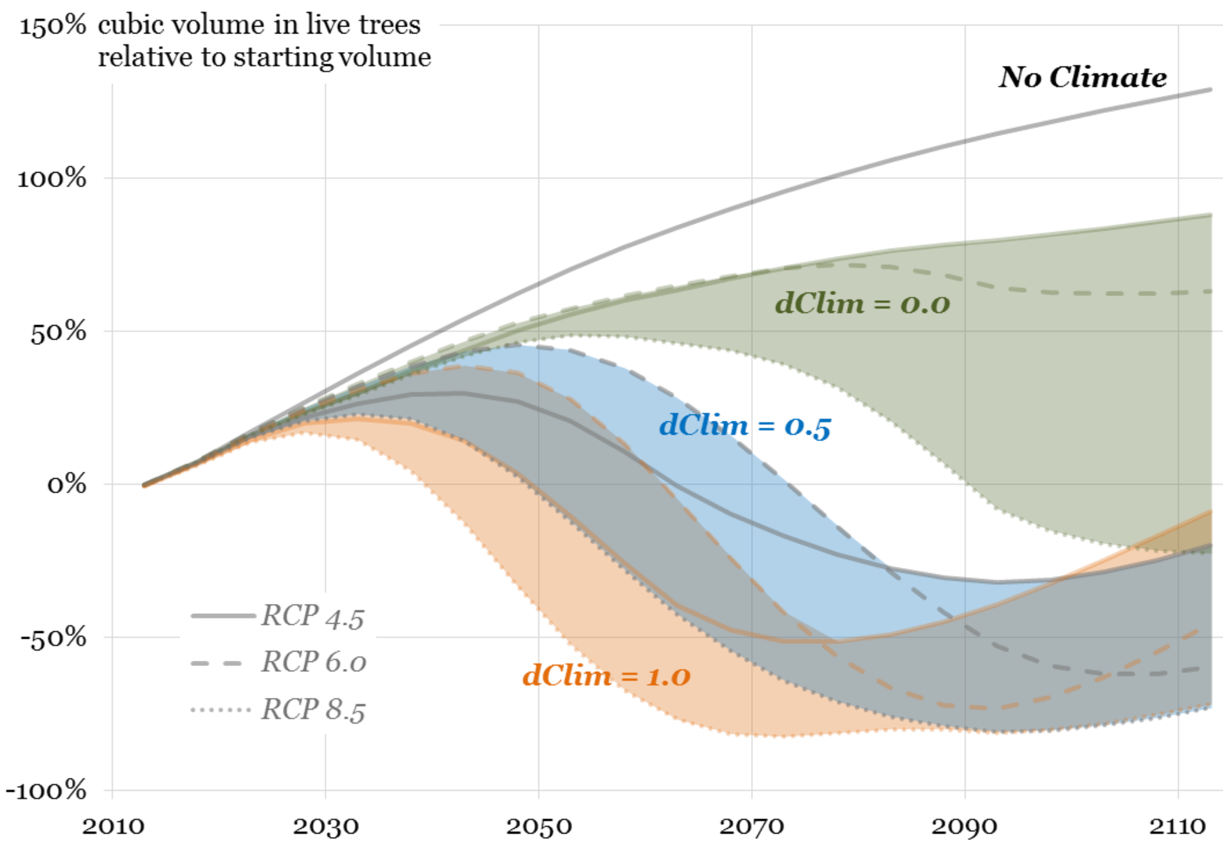
Note: These graphs show the present-day distribution of site classes among all stands compared to those selected in the 5% sample.

Considering all of these metrics, the 5% stratified sampling strategy was determined to provide a representative sample of the broader distribution of BLM lands from which these stands were selected.

Results: Study 1 (Effect of *dClim* settings on growth and mortality)

The *dClim* mortality factor evaluated in Study 1, which only considers the 'grow only' management prescription and the Ensemble GCM, produced very large changes in the growth and mortality dynamics simulated by Climate-FVS (see Figure 9).

Figure 9: Climate-FVS Sensitivity to *dClim* mortality multiplier



Notes: This graph shows the cubic volume in live trees for several different emissions scenarios and dClim settings using the Ensemble GCM without any active forest management. Cubic volume is quantified relative to the starting cubic volume of live trees. The color-shaded areas capture the range of values observed across emissions scenarios (RCPs) for each dClim setting. The solid line within each of these ranges reflects the low emissions scenario (RCP 4.5), the dashed line indicates the middle emissions scenario (RCP 6.0) and the dotted line indicates the high emissions scenario (RCP 8.0). Note that the minimum value of -100% in this graph would correspond the loss of all current live tree volume.

When climate impacts were turned off entirely (i.e., the *No Climate* scenario) and with no active forest management, cubic volume in live trees accumulated steadily, achieving a doubling of live tree volume across the study area by the 2070s. Under the default 'out-of-the-box' setting for Climate-FVS with the *dClim* mortality factor set to 1.0, live tree volume growth decreased sharply, returning to the starting volume across the study area within 30 years under the high emissions scenario (RCP 8.5) and within 40 years under the low emissions scenario (RCP 4.5).

Within 50 years (i.e., by 2063), the default setting for *dClim* led to a projected net loss of live tree volume ranging from 5% to 77%. Under the low emissions scenario, live tree volumes reached a nadir around 2070 at 49% of the starting volume, and showed modest recovery thereafter. Under the high emissions scenario with *dClim* set at 1.0, cubic volume crashed to 23% of starting volume within 50 years, reached its nadir within 60 years at 17% of starting volume, and failed to show any substantial regrowth.

When the default impact of the *dClim* mortality factor was halved (set to 0.5), the general trend seen under the 1.0 setting was replicated, albeit delayed by about 15-20 years, with gains in live tree volume reversed by mid-century and net volume loss observed by the latter half of the century. Under both the 0.5 and 1.0 *dClim* settings, there was a non-linear response between emissions scenarios and live tree volume; in both of these *dClim* settings, the moderate emissions scenario (RCP 6.0) showed better growth for 50-60 years than in either the low or high emissions scenarios, but eventually produced greater mortality and dove beneath the volumes observed in the low emissions scenario (RCP 4.5) in the latter half of the simulation period.

When the *dClim* mortality factor was turned off, the low and moderate emissions scenarios produced a relatively sustained growth trajectory, albeit substantially slower than the *No Climate* scenario. Under the high emissions scenario with *dClim* set to 0, gains in live tree volume began to be reversed mid-century, and net volume loss was observed by the late 2080s.

Discussion: Study 1 (Effect of *dClim* settings on growth and mortality)

The findings of the *dClim* parameter evaluation highlight the dramatic sensitivity of the Climate-FVS model to this newly introduced mortality factor. The motivation reported by Crookston (2013) is theoretically consistent with approaches taken by others to further constrain the adaptability of trees within seed zones or ecoregions rather than considering each tree to be more broadly adaptable to any climatic conditions experienced throughout the species' entire distribution (e.g., Wang *et al.* 2012). The inevitable effect of such an additional constraint on species adaptation capabilities is a greater projection of declines in climatic suitability, which Climate-FVS translates directly into decreased productivity and potentially increased mortality.

Nevertheless, it can be clearly observed that *dClim* produced dramatic dieoffs within the course of several decades, and that the settings of this parameter steered a very large range of uncertainty in the amount of mortality that would occur where local genetic variants became unsuited for their climatic environment. The justification for the values used in *dClim* are seemingly intuitive, based on the average elevation change distinguishing seed zones, but the application of this rule arbitrarily to all species appears to pose a particularly dramatic influence on Climate-FVS model behavior. Although a local genetic variant of a species may not necessarily demonstrate adaptability to all the climatic conditions experienced across the species' entire geographic range, it is not immediately clear whether the adaptability of these genetic variants should conversely be limited solely to the range of climatic conditions observed over relatively recent timeframes within a single seed zone.

It is also important to note that *dClim* is an additional mortality component that magnifies the changes in the underlying bioclimatic envelope projections. As described in our earlier report reviewing bioclimate envelope projections, the Random Forests statistical approach appeared predisposed to overpredict contractions in species ranges relative to process-based models. This is consistent with findings from other studies comparing statistical and process-based bioclimate envelope projections (Morin & Thuiller 2009; Rowland, Davison & Graumlich 2011; Cheaib *et al.* 2012). Although the premise of including a mortality effect such as *dClim* based on the limited adaptability of a particular genetic variant to climatic shifts is sensible, it is not immediately clear how this mortality factor should be quantified or whether doing so is appropriate in light of the magnitude of mortality already incorporated based solely on the underlying bioclimate envelope projections. Additional research from 'common garden' techniques or other longitudinal or transplant studies to identify climate-induced changes in mortality may provide further justification for the appropriate settings for a *dClim* factor within Climate-FVS.

Based on these uncertainties, and the dramatic impacts of turning on *dClim* at all, we decided to turn this factor off when simulating active forest management. Although the premise of a *dClim* mortality factor has merit and is certainly worthy of further exploration and research, we were left without any intuitive strategy for choosing an appropriate setting for this parameter, and have assumed that the underlying sensitivity of the Random Forests species suitability scores to climatic shifts provides an adequately sensitive signal for changes in growth and mortality without necessitating further magnification using *dClim*.

Results: Study 2 (Simulations of active forest management)

General trends in growth, mortality, and sustainability of harvest levels

Compared to the *No Climate* scenario, all BLM Districts showed declines in growth rates under every circulation model and emissions scenario considered (see Figure 10). With the exception of Lakeview, all of the declines were often immediately distinguishable between the *No Climate* run and all GCMs under both low and high emissions scenarios, spreading further apart as the century progressed.

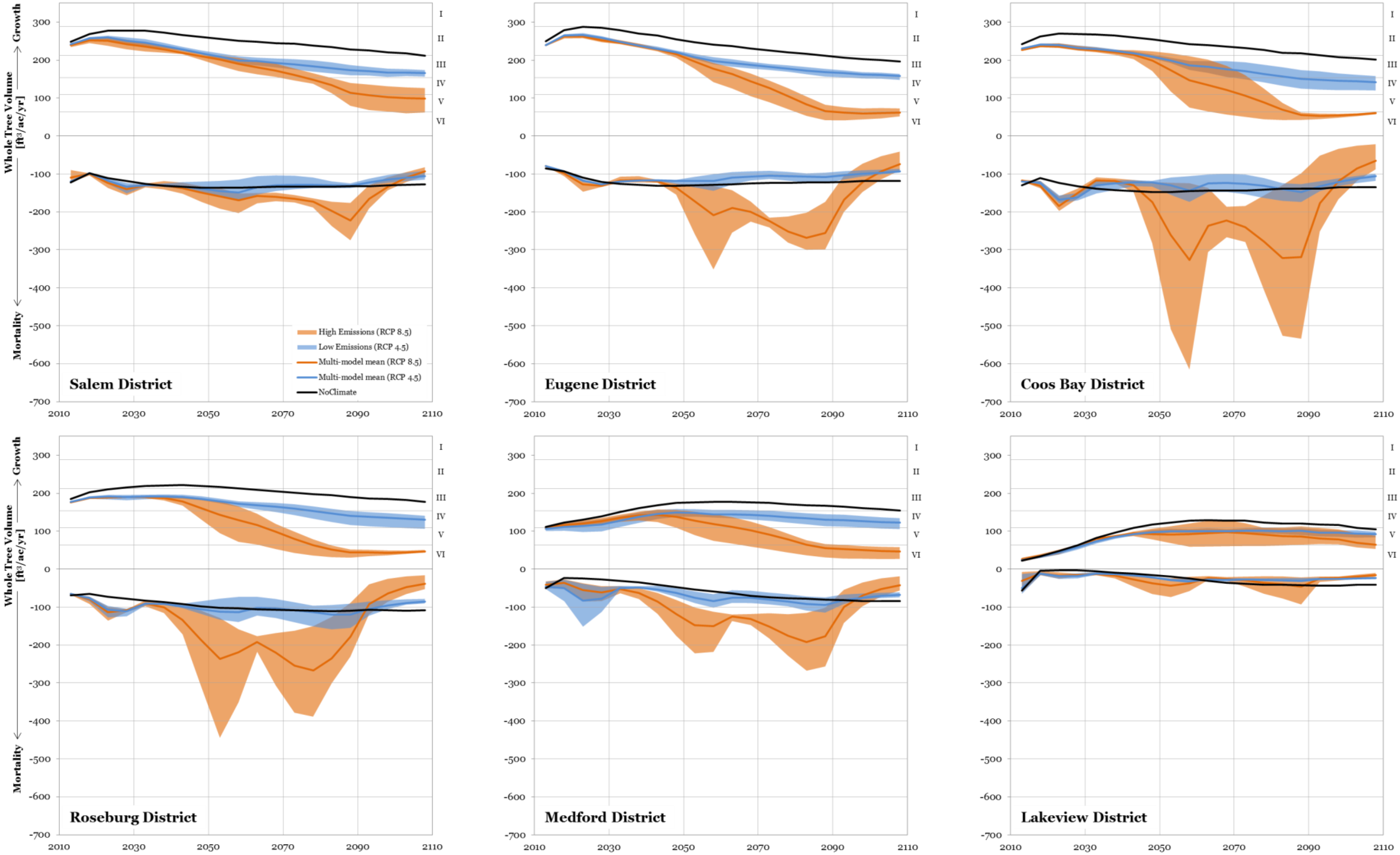
In the North/Moist Districts, growth rate declines in the low emissions scenario corresponded to a decline in average productivity from Site Class II to Site Class III by mid-century, and a further decline to Site Class III-/IV by 2100. In the high emissions scenario, growth rate declines in North/Moist Districts followed a similar trajectory as the low emissions scenario through mid-century, but then rapidly fell to Site Class V by end-of-century.

Medford and Roseburg both showed similar behavior to the North/Moist Districts in terms of both low- and high emissions scenarios showing greater declines in growth than the *No Climate* scenario, which worsened in the latter half of the century under the high emissions scenario. Lakeview was unique among Districts in that growth rates did not progressively decline over the course of the century in low or high emissions scenarios. Although Lakeview shows lower growth rates in both emissions scenarios compared to *No Climate*, the growth rates appeared to increase from the starting level of Site Class VI at a slower rate than *No Climate*, and to level-out around Site Class V within 20-30 years.

A pattern observed across all Districts reveals interesting model behavior where growth rates initially showed an increasing trend under all scenarios, including *No Climate*, RCP 4.5 and RCP 8.5. This model behavior may have been driven by replanting following regeneration harvest of 80 and 100+-year-old stands which may have lower annual growth rates than younger stands. This behavior could also originate from the conversion of under-stocked sparse stands with species such as Western juniper. It is not immediately clear whether these sites have soil or other growth conditions suitable for more productive growth of commercial tree species that were planted in these simulations.

In contrast to the graphs of growth rates, in which climate change impacts consistently decrease growth relative to the *No Climate* scenario, mortality rates under climate change are much more variable. The cloud of responses displayed for the range of GCMs in both low and high emissions scenarios wandered above and below the mortality rates observed in the *No Climate* scenario. Toward the end of the simulation period, both low and high emissions scenarios also showed reduced mortality rates (shown as upward swing in graphs which show mortality rates as negative values). This model behavior is consistent with the death of trees that are far outside their climatic suitability and their replacement with trees—via natural regeneration or tree planting—which are assumed in the model to be better adapted to the prevailing climatic conditions. Evidence of this behavior was also visible in the changes in forest composition discussed further below. It is important to note that the recovery of stands following significant mortality events relies upon a major assumption that the seedlings that are planted or which naturally regenerate are adapted to the contemporary climate in that location (regardless of provenance). This assumes a climate-adapted seed source is already present onsite, or is known by the forest manager and introduced via planting (e.g., assisted migration).

Figure 10: Simulated changes in annual growth and mortality



Notes: These graphs show changes in annual growth (above-zero) and mortality (below-zero) with and without climate change impacts simulated in Climate-FVS for each BLM District. Black lines show results observed without climate impacts. The range of values observed across 4 GCMs for the low (blue cloud) and high (red cloud) emissions scenarios are shown with multi-model means as a solid line within each cloud. Horizontal lines above zero represent Site Class boundaries, annotated in roman numerals and adjusted assuming merchantable volume is 78% of total tree volume (Zhou & Hemstrom 2009 p. 9). It is important to note that changes in growth and mortality may be influenced by simulated management activities, and not solely due to climate.

Under the low emissions scenario, each BLM District appeared capable of collectively sustaining a total timber yield target of 502 mmbf per year through the entire simulation period (see Figures 11 and 12). Under the high emissions scenario, however, more volume was being lost to harvest and mortality than growth, implying that these removals may exceed longer-term sustained yield levels. By 2080-2090, both the North/Moist and South/Dry regions were projected to have a reduction in standing timber inventory compared to current levels based on removals through harvest and mortality.

As shown in Figure 11.A, harvest levels in North/Moist Districts fairly consistently amounted to 20-30% of annual growth under the low emissions scenario. As time progressed through the simulation, mortality rates stayed relatively constant through the end of the century, but came to represent a larger proportion of annual growth as productivity progressively declined. This corresponded roughly to a decline in cubic volume accretion equivalent to a downward shift of one Site Class. In contrast, changes in cubic volume growth in South/Dry Districts appeared more muted in absolute terms, but moderate increases in mortality began to emerge by 2050.

Under the high emissions scenario, significant declines in productivity for both North/Moist and South/Dry regions were matched with increasing mortality. Together, these factors quickly reduced the sustained timber yield from both regions.

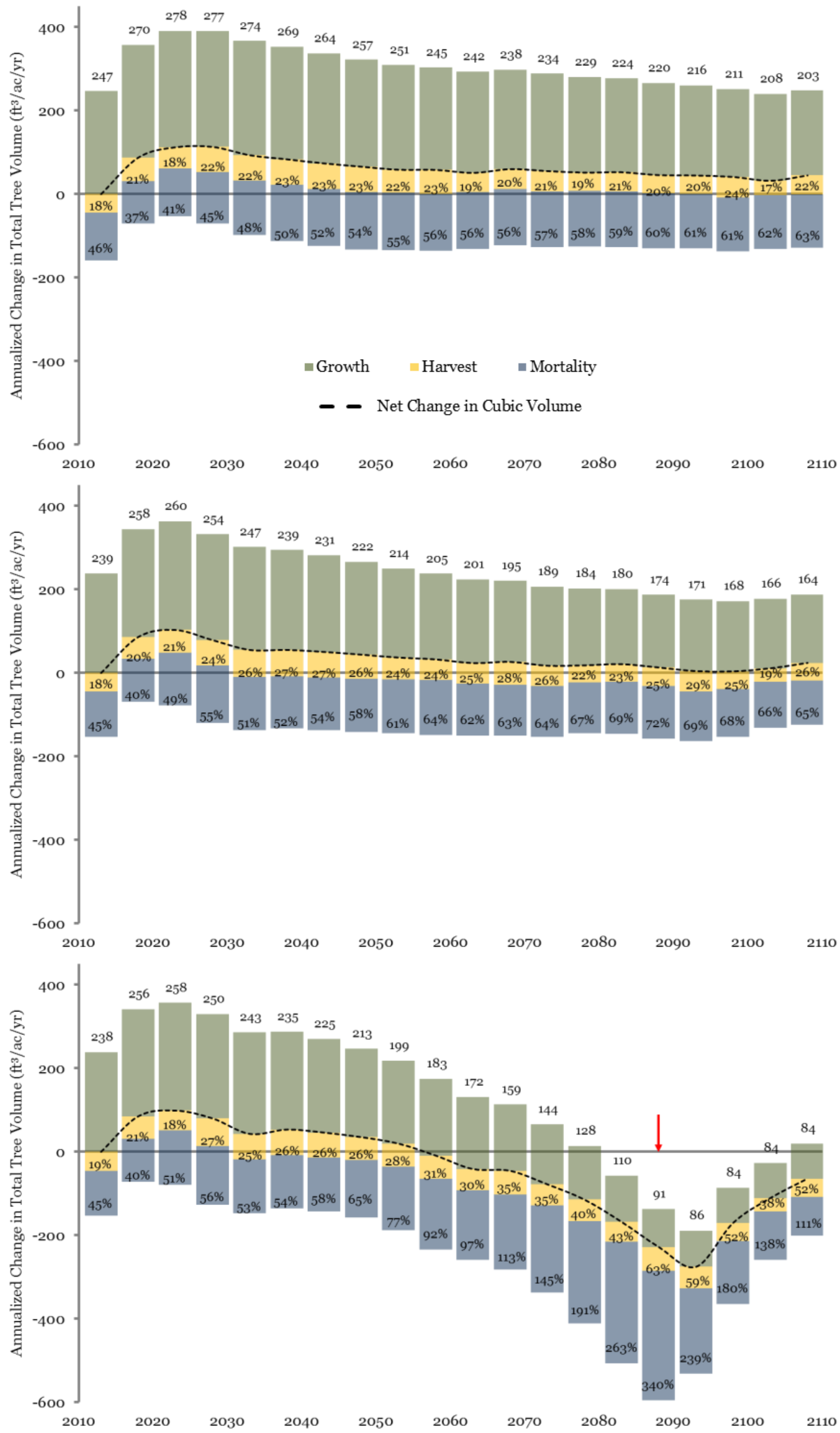
The view of individual District-level outcomes shown in Figure 12 offers insights into more localized climate impacts that may not be apparent at a regional level of aggregation. In the case of the Lakeview District, for example, both low and high emissions scenarios projected an increase in growth potential and sustainable yields compared to other Districts which all showed progressively worse conditions as emissions increased. Despite the fact that Lakeview showed increased growth potential under both the low and high emissions scenarios, the increases in growth were lower than those projected under the *No Climate* scenario where productivity gains were likely a result of converting less productive Western juniper forest types over to Ponderosa pine (see discussion of forest types further below). The largest increases in mortality rates were seen in Coos Bay followed by Eugene, and then Roseburg.

Figure 11.A: Projected volume growth, harvest, and mortality under climate change, North/Moist Region (Salem, Eugene, & Coos Bay)

No Climate Change

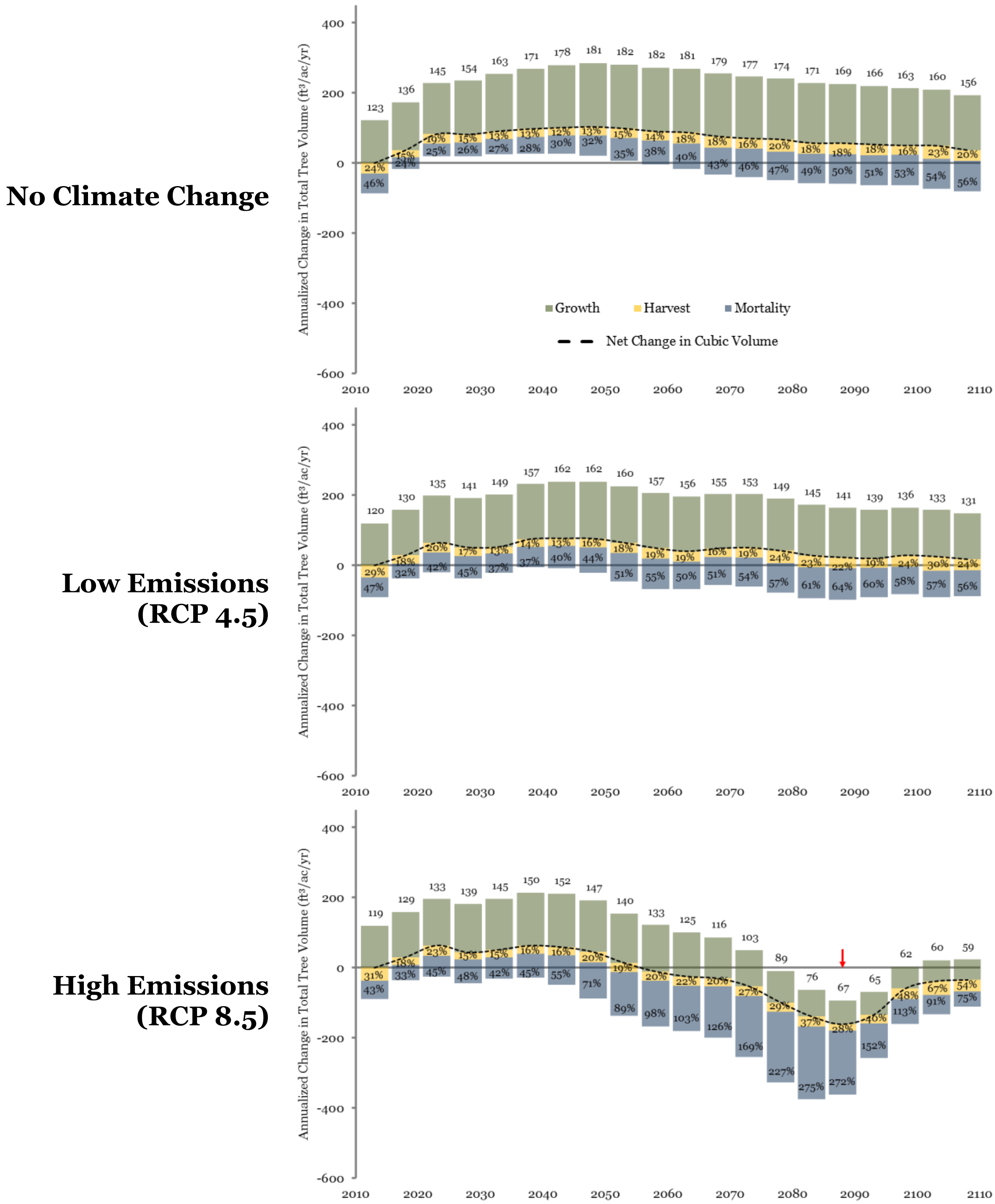
Low Emissions (RCP 4.5)

High Emissions (RCP 8.5)



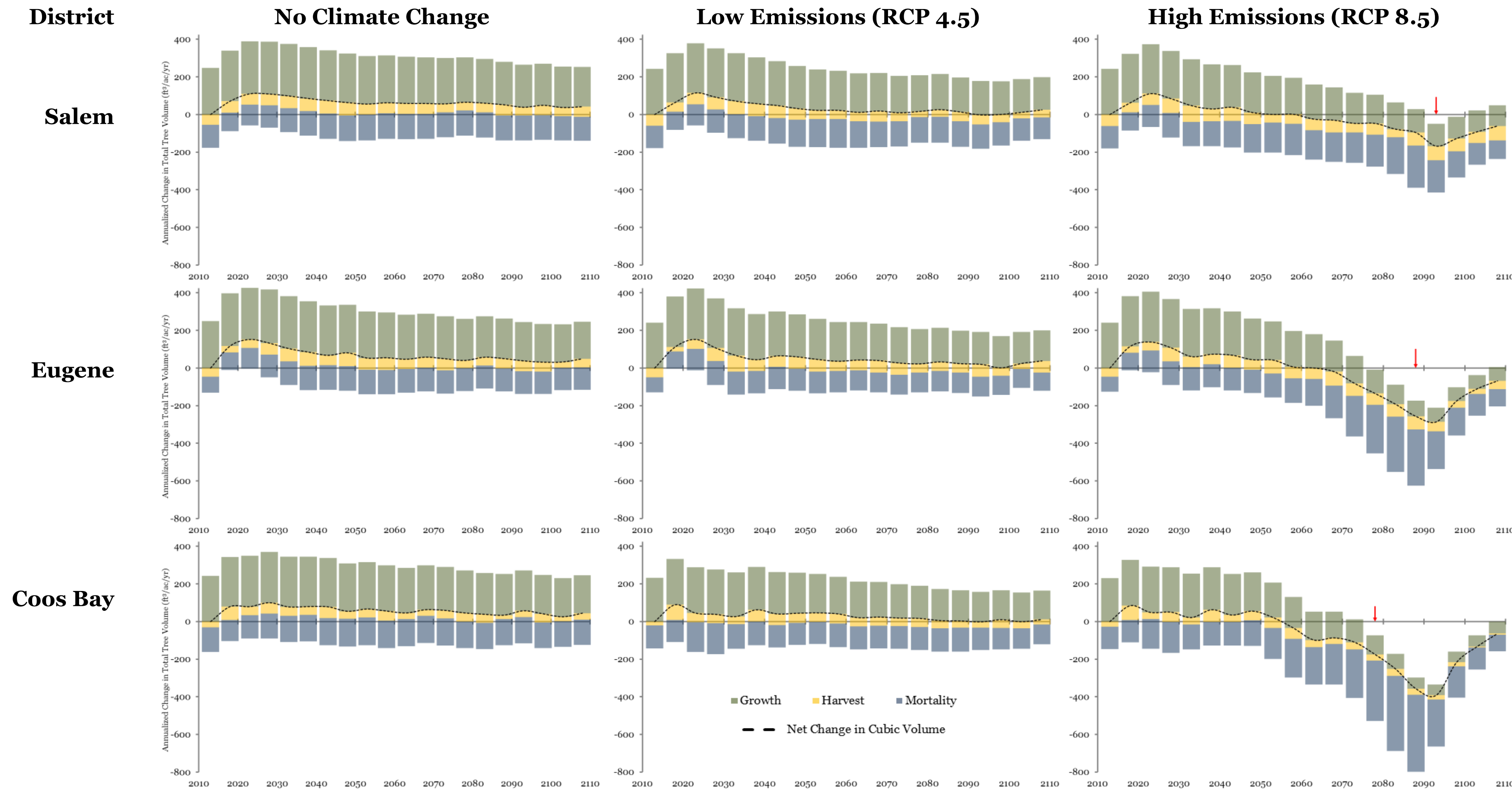
Notes: These graphs show the annualized change in whole-tree cubic volume per acre (including non-merchantable volume) for each five year period partitioned into growth, harvest, and mortality as simulated underthe Ensemble GCM. Data labels for growth show annualized accretion of cubic volume per acre; labels for harvest and mortality are shown as a percentage of growth during the same period. Where the dashed line drops below zero, harvest and mortality exceed growth (i.e., implies yield may not be sustainable). A red arrow along the x-axis indicates standing volume has been reduced by cumulative harvesting and mortality below starting volume (simulation begins 2013).

Figure 11.B: Projected volume growth, harvest, and mortality under climate change, South/Dry Region (Roseburg, Medford, & Lakeview)



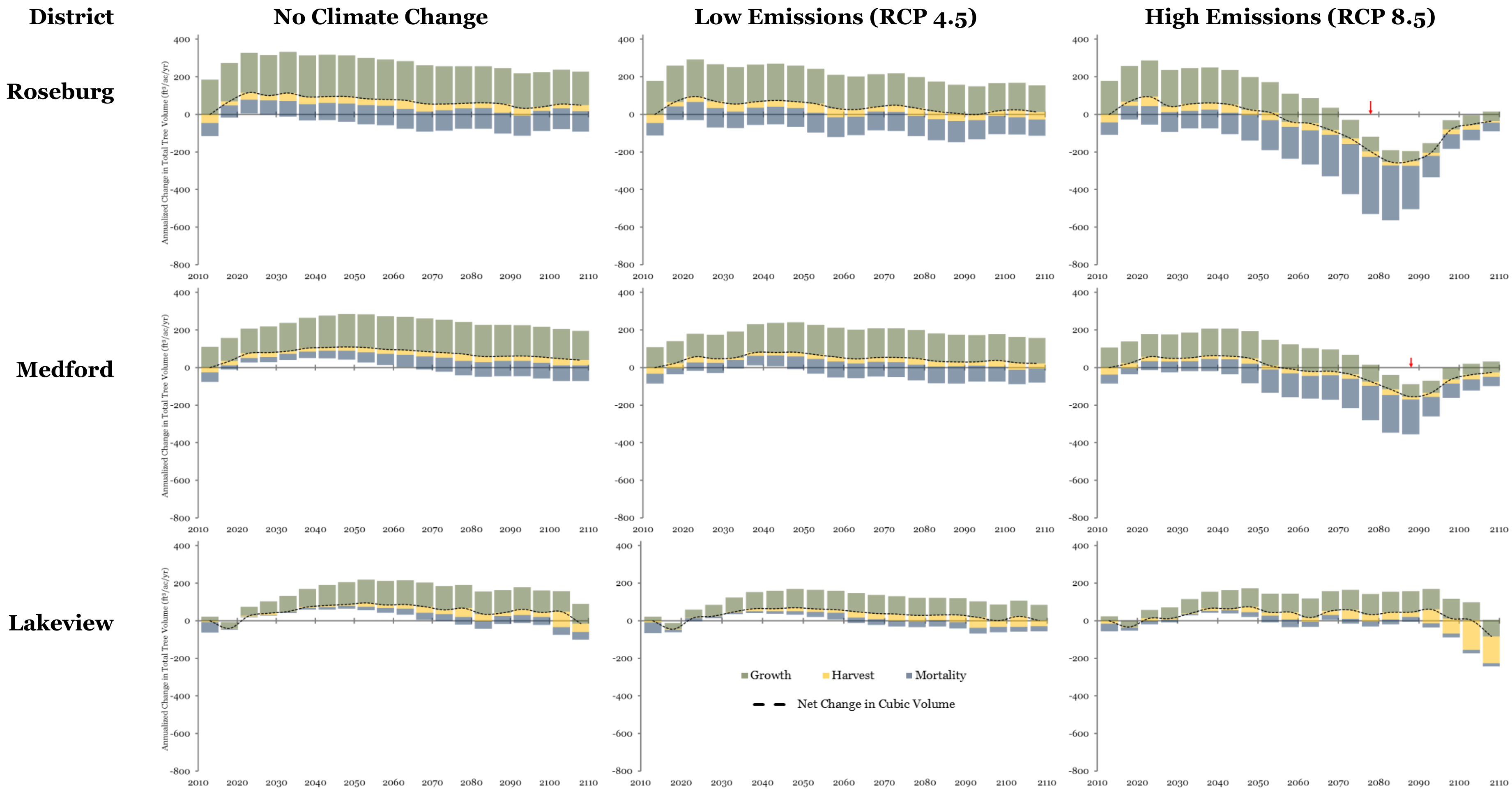
Notes: These graphs show the annualized change in whole-tree cubic volume per acre (including non-merchantable volume) for each five year period partitioned into growth, harvest, and mortality as simulated underthe Ensemble GCM. Data labels for growth show annualized accretion of cubic volume per acre; labels for harvest and mortality are shown as a percentage of growth during the same period. Where the dashed line drops below zero, harvest and mortality exceed growth (i.e., implies yield may not be sustainable). A red arrow along the x-axis indicates standing volume has been reduced by cumulative harvesting and mortality below starting volume (simulation begins 2013).

Figure 12.A: Projected volume growth, harvest, and mortality under climate change, by District for North/Moist Region



Note: These graphs show the annualized change in whole-tree cubic volume per acre (including non-merchantable volume) partitioned into growth, harvest, and mortality under the Ensemble GCM. Where the dashed line drops below zero, harvest and mortality exceed growth (i.e., implies yield may not be sustainable). A red arrow along the x-axis indicates standing volume has been reduced below the starting volume.

Figure 12.B: Projected volume growth, harvest, and mortality under climate change, by District for South/Dry Region



Note: These graphs show the annualized change in whole-tree cubic volume per acre (including non-merchantable volume) partitioned into growth, harvest, and mortality under the Ensemble GCM. Where the dashed line drops below zero, harvest and mortality exceed growth (i.e., implies yield may not be sustainable). A red arrow along the x-axis indicates standing volume has been reduced below the starting volume.

Changes in forest types across the landscape

At the scale of the entire study area, at a regional level, and at the District-level, changes in the distribution of forest types across the landscape were observed even in the *No Climate* scenario (see Figures 13-15). The results highlight the role that the simulated management actions would have in shaping the landscape of forest types even without the impacts of climatic shifts.

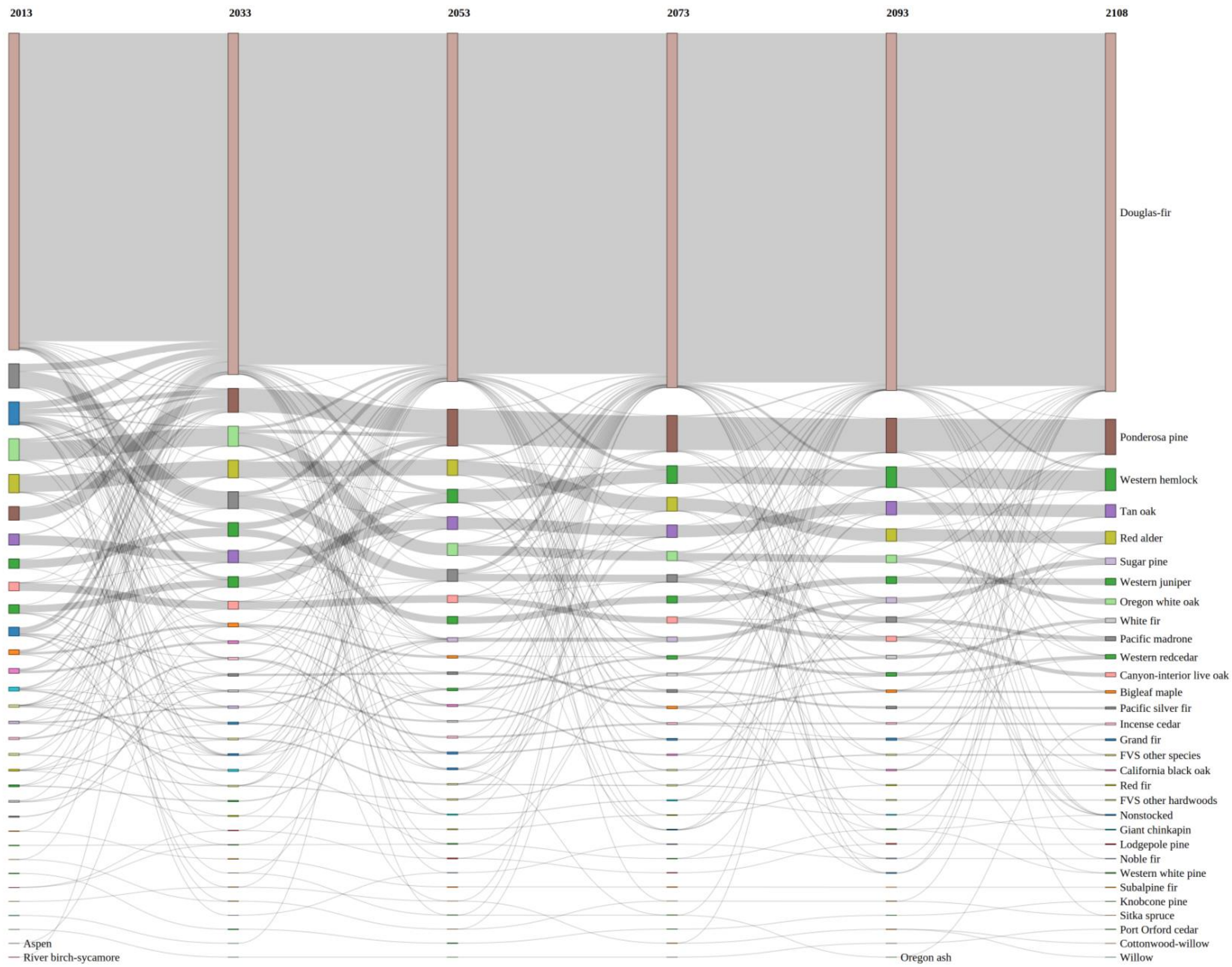
As shown in Figure 13, increasing emissions from *No Climate* to RCP 4.5 and 8.5 led to progressively 'noisier' illustrations of forest type composition and transitions across the entire study area, particularly in the second half of the century. As climate impacts progressively increased through these emissions scenarios, the conservation of forest types over time became increasingly less stable, as many more acres began to transition between forest types. Further, as emissions were elevated to RCP 4.5 and then 8.5, more forest types disappeared from the landscape. For example, under the low emissions scenario, Subalpine fir, Western white pine, and Lodgepole pine were simulated to be lost between 2013-2033. In the high emissions scenario, the Red fir forest type was also projected to be lost over the 2013-2033 time period, followed by Pacific silver fir and Port Orford cedar in the 2073-2093 period.

As shown in Figure 15, these shifts at the District level were most pronounced in the Lakeview District where Western juniper forest types are increasingly replaced with Ponderosa pine. In the Medford District, several oak and Pacific madrone forest types are increasingly replaced by Douglas-fir and Ponderosa pine. In the Salem District, Hemlock-Sitka spruce forests increase in area while modest declines are seen in Maple-Alder forest types and Douglas-fir as well. These changes in forest type cover help highlight the impact that the simulated forest management activities have on underlying tree species compositions, even in the absence of climate change. It is likely that both the selective retention of commercial conifer species and the priority for removal of species like Western juniper play a part in these shifts, although we were not able to isolate these effects from those induced by the act of tree planting focused on commercial timber species following regeneration harvests.

Under the low emissions scenario, shifts in forest types were comparable to those under the *No Climate* scenario, with a few minor exceptions. In the low emissions scenario, the decline of Western juniper in the Lakeview District was more rapid, coinciding with quicker replacement by Ponderosa pine forests. In all three North/Moist Districts, the progressive gains in Hemlock-Sitka spruce coverage seen under the *No Climate* scenario were virtually absent in the low emissions scenario; these changes appeared to be due to slight increases in coverage by Alder-Maple forest types compared to the *No Climate* scenario.

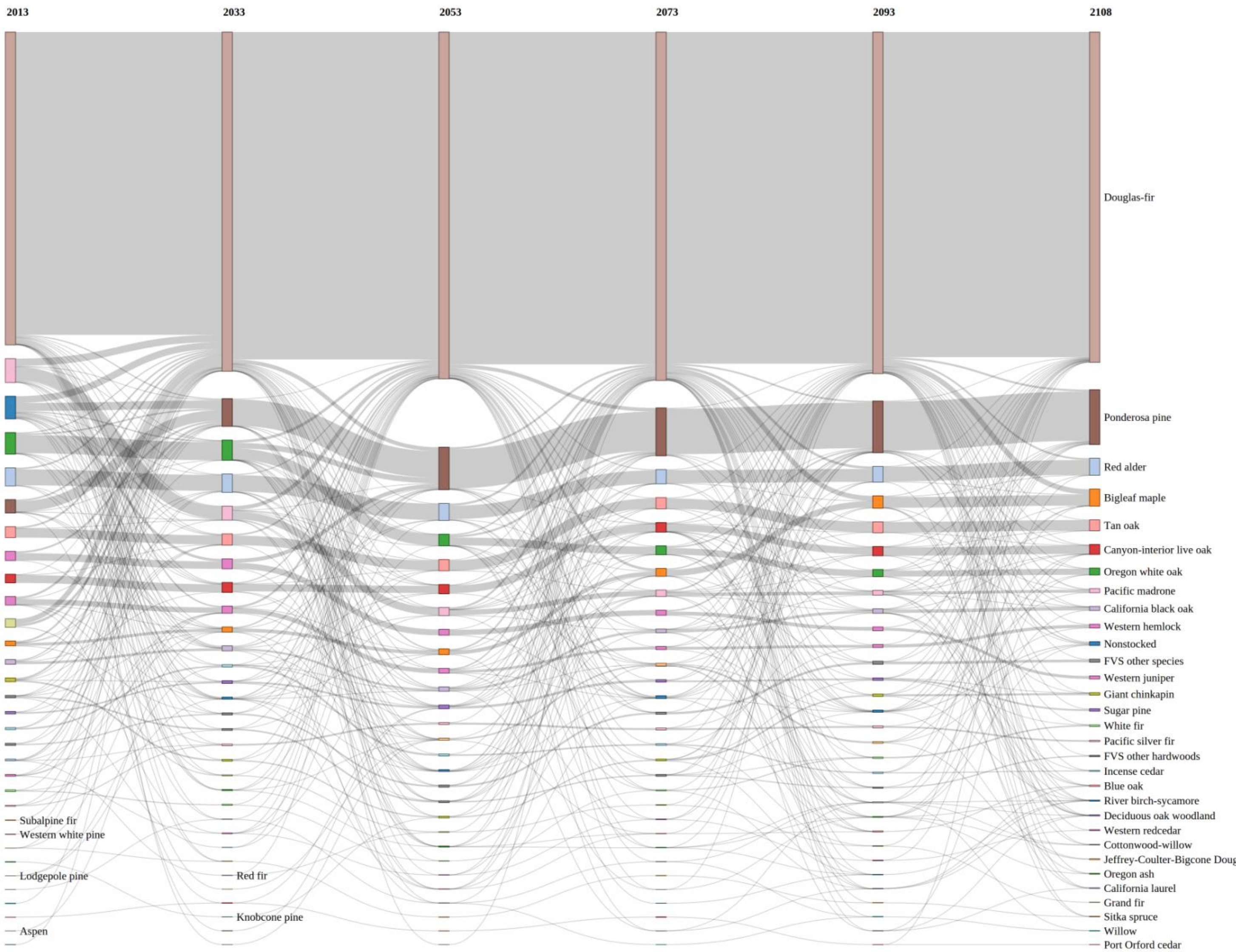
It was only under the high emissions scenario that dramatic shifts in forest type distributions were observed, primarily in the second half of the century. These shifts were comprised primarily of increases in forest type groups dominated by hardwood tree species at the expense of Douglas-fir. Douglas-fir was progressively replaced by Alder-Maple forest types in the North/Moist Districts and by Willow, Bigleaf maple, and Oak woodlands in South/Dry Districts. In Lakeview, the transition from Western juniper to Ponderosa pine was even more rapid than under the *No Climate* or low emissions scenarios. Hemlock-Sitka spruce forests were virtually absent from every District by the end of the century in the high emissions scenario. Coos Bay and Eugene Districts lost this forest type before mid-century, while Salem retained small portions of Hemlock-Sitka spruce through 2070-2080.

Figure 13.A: Projected forest types and transitions; no climate change impacts



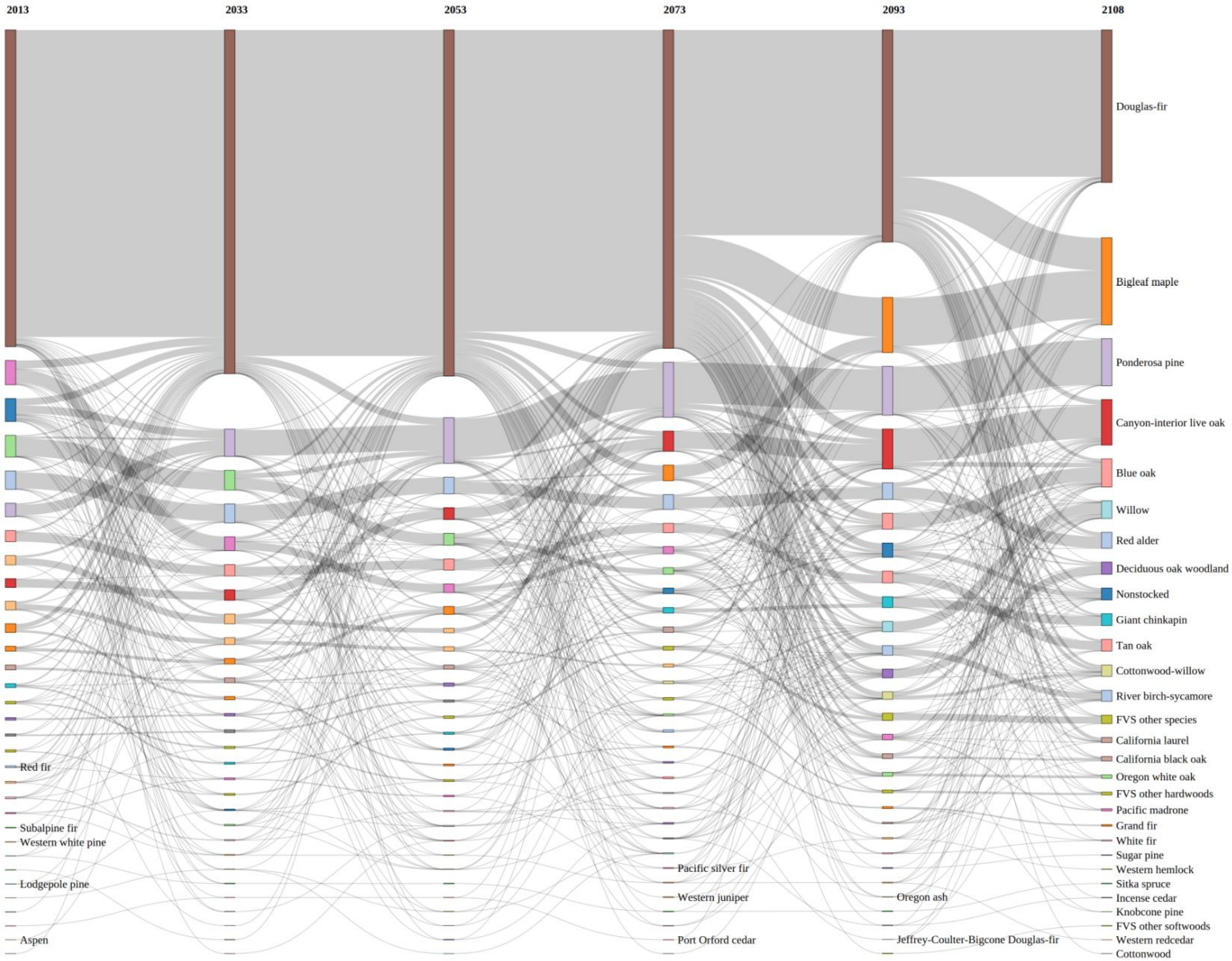
Notes: This graph shows the proportion of Western Oregon BLM forestlands (the entire study area) classified under each forest type and the transitions between these classes over time. This is based on extrapolation from the 5% sample simulated using Climate-FVS with active forest management. Forest Type Labels appear in the last timestep that each type was observed (e.g., Aspen is observed in 2013, but not 2033)

Figure 13.B: Projected forest types and transitions; low emissions scenario (RCP 4.5)



Notes: This graph shows the proportion of Western Oregon BLM forestlands (the entire study area) classified under each forest type and the transitions between these classes over time as simulated under the Ensemble GCM and low emissions scenario. This is based on extrapolation from the 5% sample simulated using Climate-FVS with active forest management. Forest types are sorted according to greatest spatial extent at the end of the century. Forest Type Labels appear in the last timestep that each type was observed (e.g., Aspen is observed in 2013, but not 2033)

Figure 13.C: Projected forest types and transitions; high emissions scenario (RCP 8.5)



Notes: This graph shows the proportion of Western Oregon BLM forestlands (the entire study area) classified under each forest type and the transitions between these classes over time as simulated under the Ensemble GCM and high emissions scenario. This is based on extrapolation from the 5% sample simulated using Climate-FVS with active forest management. Forest types are sorted according to greatest spatial extent at the end of the century. Forest Type Labels appear in the last timestep that each type was observed (e.g., Aspen is observed in 2013, but not 2033)

Figure 14:Projected change in distribution of forest type groups with climate change

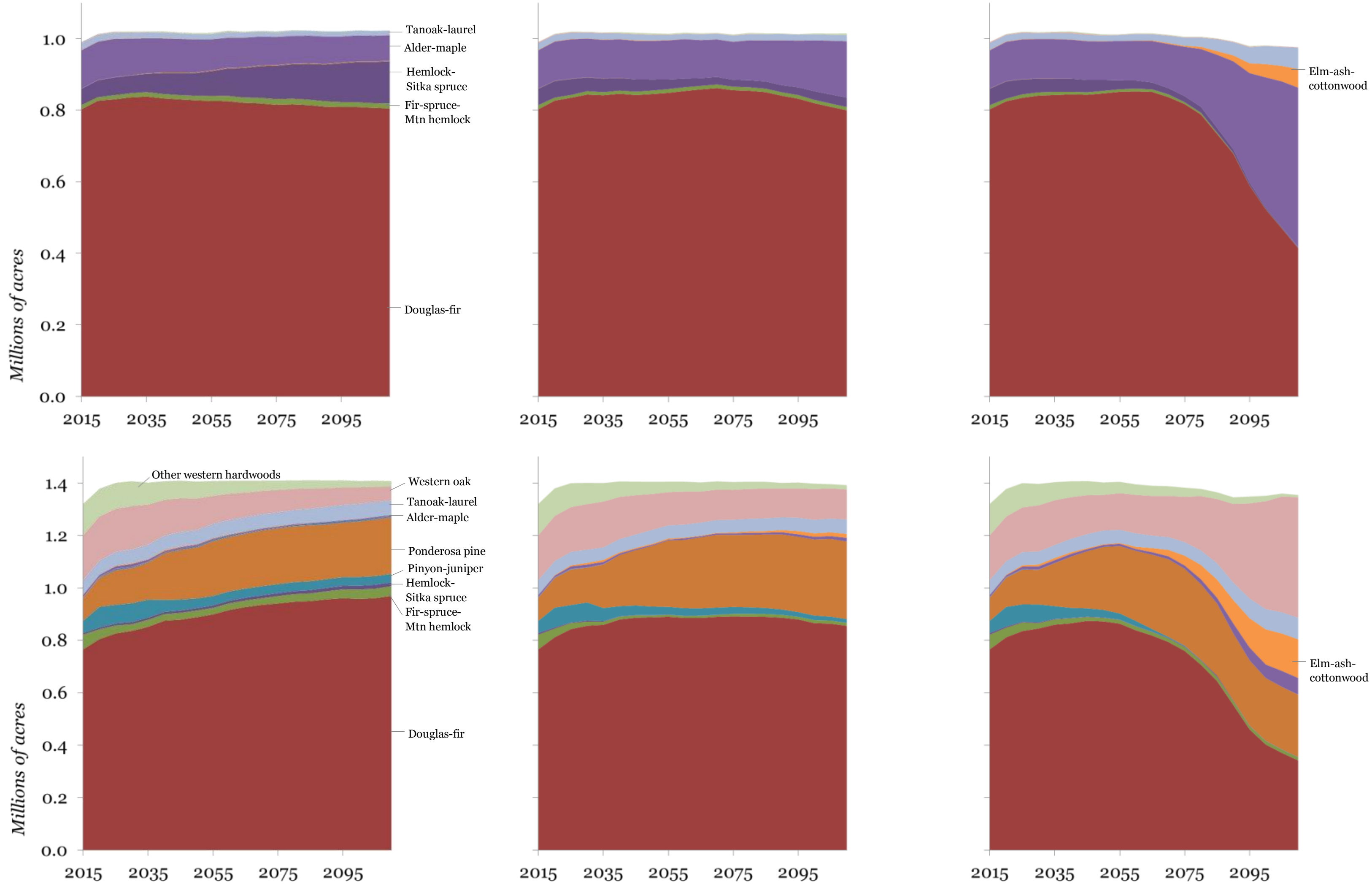
Region | **No Climate Change** | **Low Emissions (RCP 4.5)** | **High Emissions (RCP 8.5)**

North/ Moist

Salem, Eugene, & Coos Bay

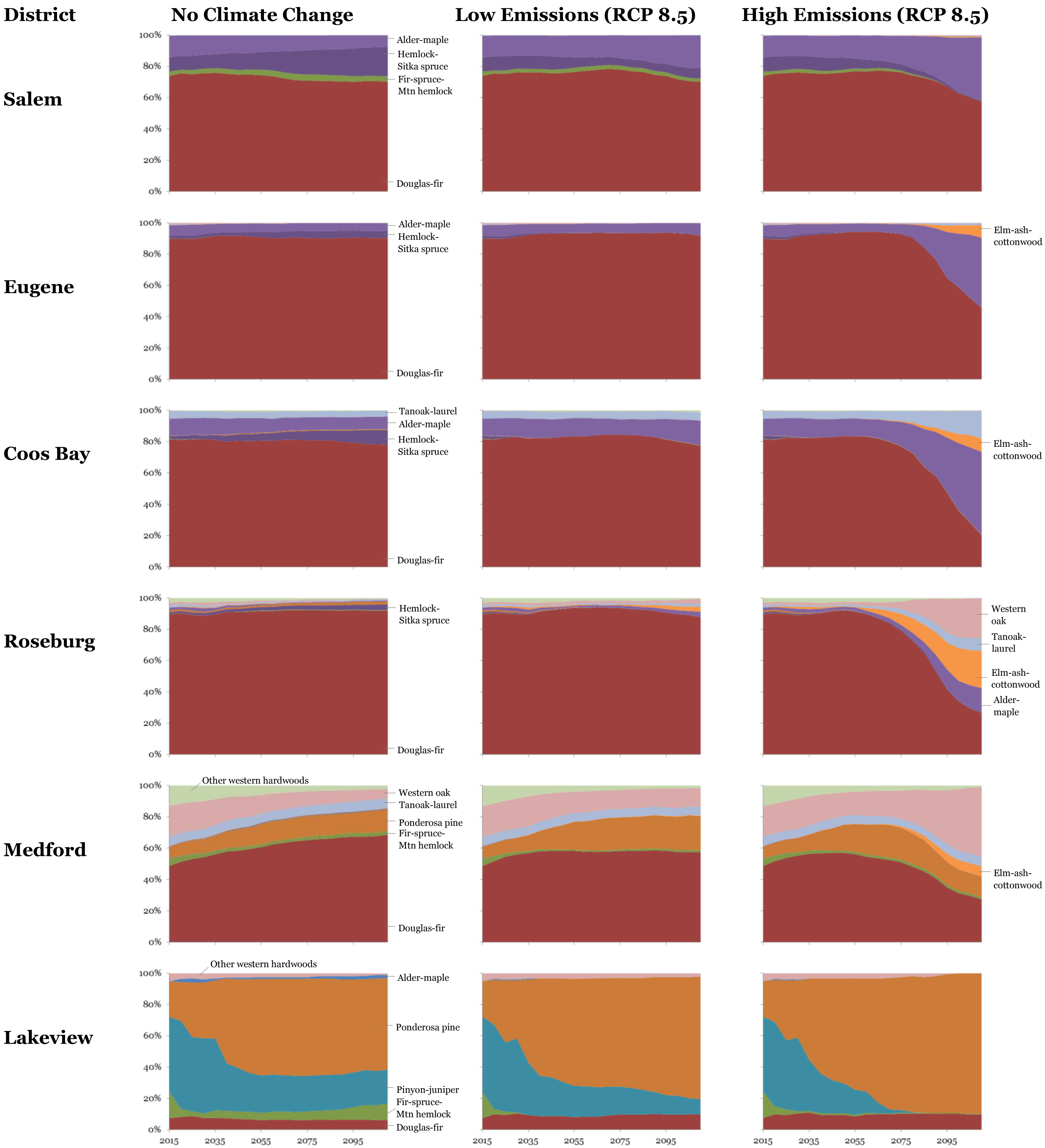
South/ Dry

Roseburg, Medford, & Lakeview



Note: These graphs show the distribution of forest type groups projected over time with scheduled forest management under each emissions scenario for the Ensemble GCM. The y-axis displays millions of acres in each forest type group. The order of stacking for forest types groups is the same for all graphs.

Figure 15:Simulated distributions of forest type groups, by District

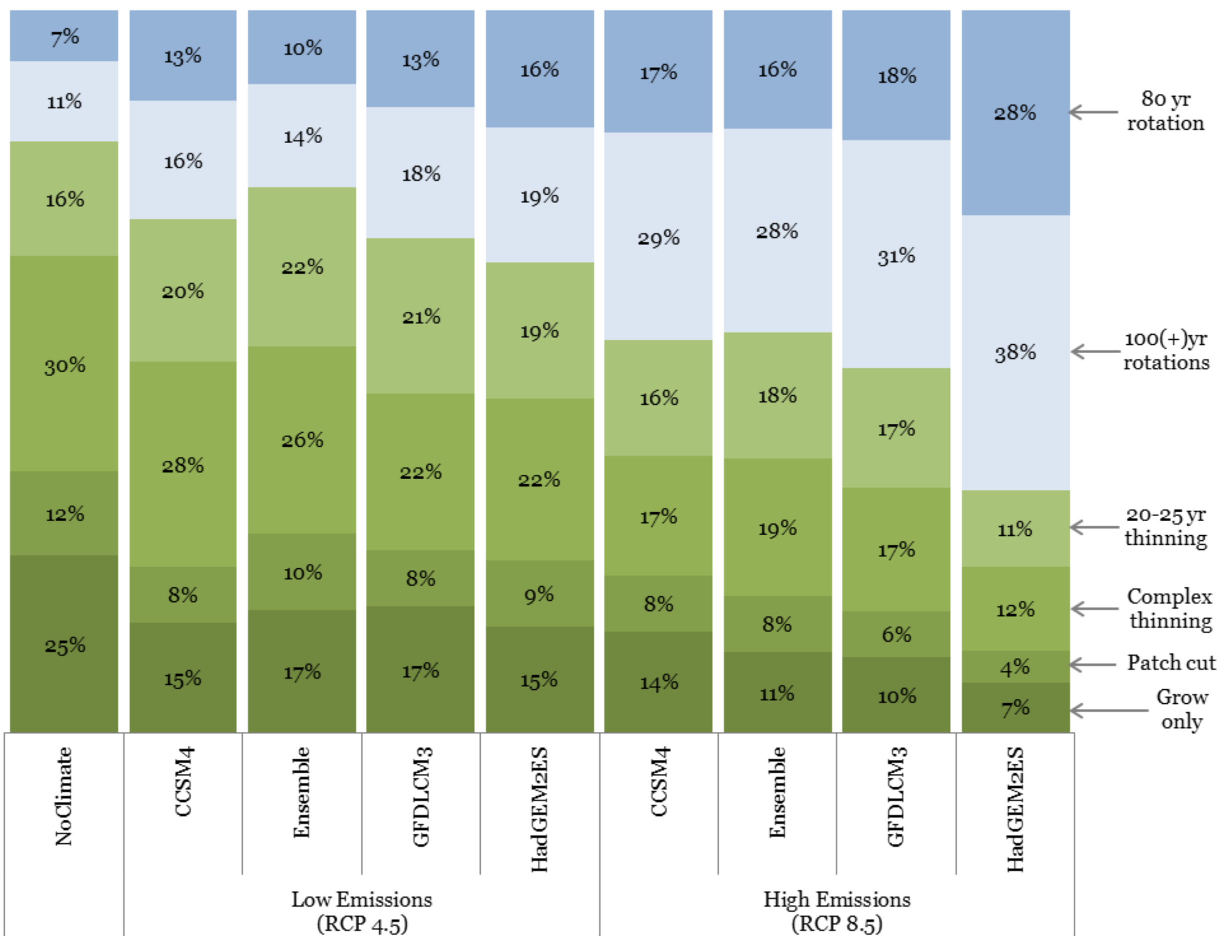


Note: These graphs show the distribution of forest type groups projected over time with scheduled forest management under each emissions scenario for the Ensemble GCM. The y-axis displays the percentage of forestland in each District classified by forest type group. The order of stacking for forest types groups is the same for all graphs.

Management practices chosen to optimize multiple management objectives
As shown in Figure 16, the combination of management practices chosen by the scheduling model to satisfy the various management objectives and constraints under the *No Climate* scenario used a fairly limited footprint of regeneration harvest, covering 18% of unrestricted BLM lands by area. One quarter of unrestricted land area was left without active management, and 58% were managed using thinning-only or patch cut prescriptions.

Across the four GCMs simulated, regeneration harvesting was expanded to 24-35% of unrestricted lands under the low emissions scenario, and up to 44-66% in the high emissions scenario, as the area of land treated using thinning-only, patch cut, and no active management successively declined. These results are consistent with expectations that simulated decreases in annual growth would necessitate increasing harvest intensity and decreasing even-age rotation intervals to maintain a constant timber yield over time.

Figure 16: Management prescriptions chosen to achieve multiple objectives under climate change: Unrestricted lands



Note: Each stacked bar within the low and high emissions scenarios represents a separate general circulation model (GCM).

Tradeoffs among competing management objectives

Figures 17 and 18 highlight the tradeoffs among several management objectives observed at the regional and district scale with and without climate change impacts. Although there was a fair amount of variability in projections among the different GCMs, climate change impacts led to lower growth rates and higher mortality rates at the regional scale for both the low and high emissions scenarios compared to the *No Climate* scenario. The progressive decreases in productivity with climate change discussed earlier also translated to lowered carbon storage and standing timber volumes over time, while the areas of high fire hazard highlight the increasing abundance of snags or downed dead wood, increasing fuels loading particularly in the South/Dry region.

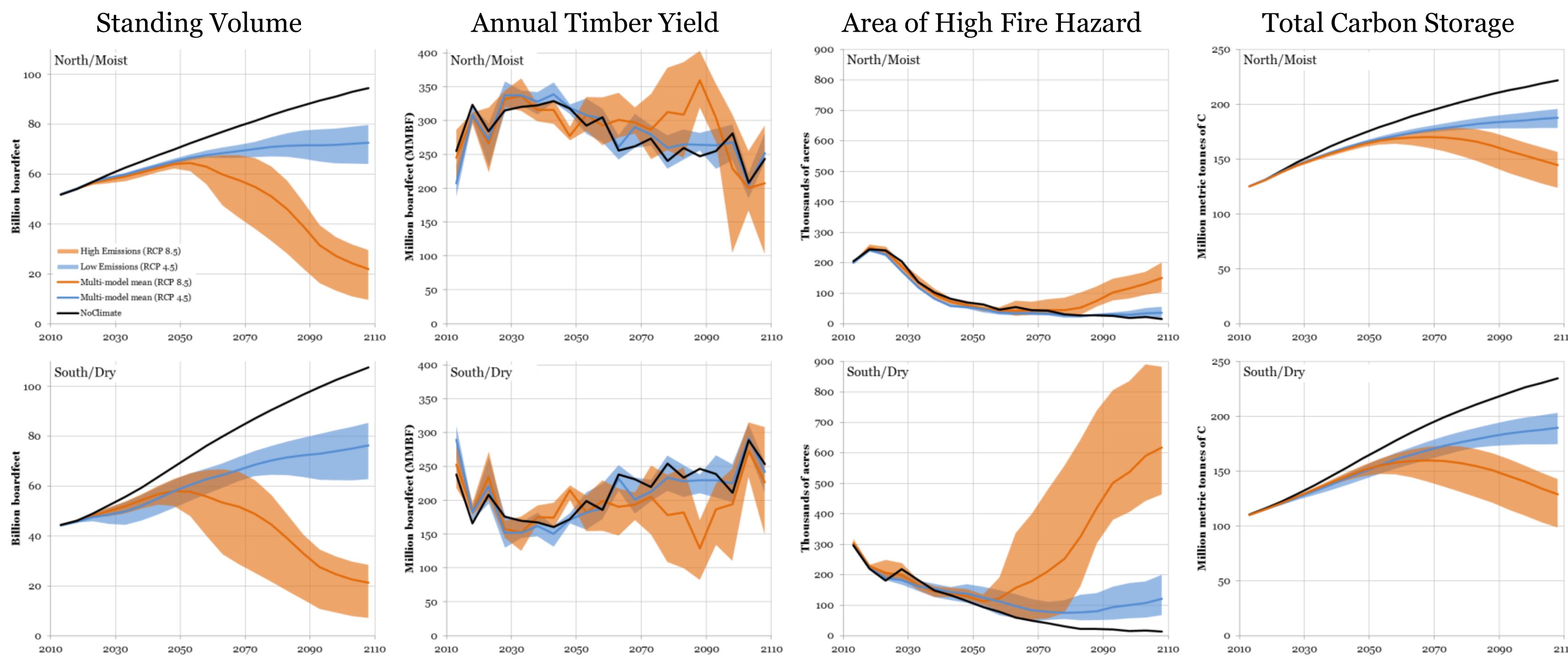
When considered at the regional level, the flexibility for the scheduling model to hit the global timber yield target led to an increasing reliance on harvesting from the North/Moist region and less harvesting from the South/Dry region.[8] This was observed in both low and high emissions scenarios, although it was particularly pronounced in the high emissions scenario. It was only through examination of the District-level data in Figure 18, however, that the tradeoffs between specific areas to achieve the global timber yield target became apparent. There it could be seen that increased timber yields were primarily coming from the Salem District, and to a lesser extent from the Lakeview and Eugene Districts. Coos Bay, Roseburg, and Medford supplied proportionally less timber under climate change, particularly in the high emissions scenario.

In both Figures 17 and 18, a clear shift in model behavior is apparent between the low and high emissions scenario. The high emissions scenario showed much more dramatic declines in productivity and increases in fire hazards, diverging strongly from simulations under the low emissions scenario by mid-century.

[8] As mentioned above, in practice, BLM does not define annual sale quantities (ASQs) across multiple Districts or Sustained-Yield Units, and does not shift ASQs from one unit to another. This is an important distinction to the approach of global optimization with a single timber yield target in this study.

Figure 17: Stocking, timber yields, fire hazard, and carbon storage by region:

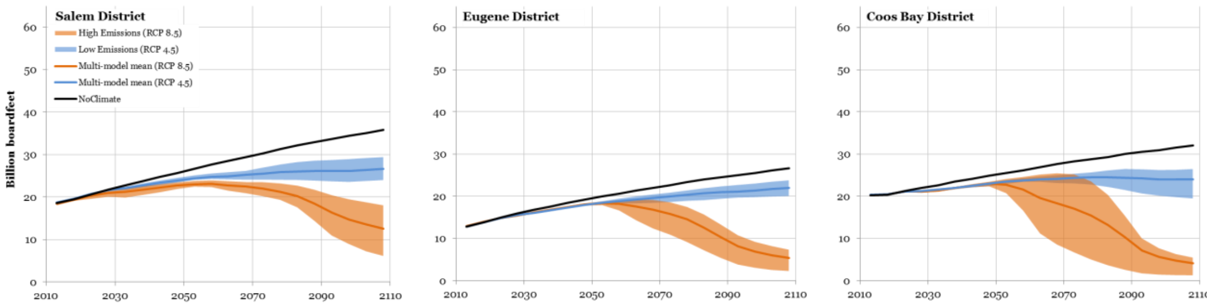
North/Moist (Salem, Eugene, & Coos Bay) and South/Dry (Roseburg, Medford, & Salem)



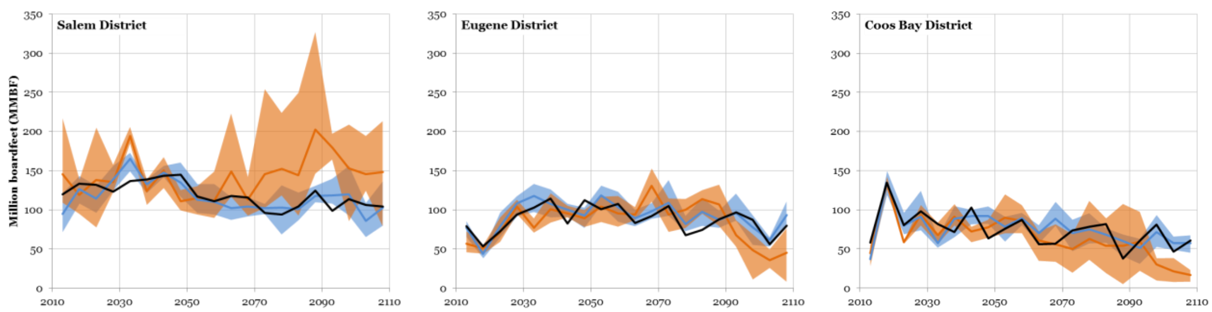
Note: These graphs show results of scheduled forest management with and without climate change impacts simulated in Climate-FVS. The black line in each graph shows results observed without climate change impacts. The blue cloud shows the range of results obtained from 4 GCMs under the low emissions scenario (RCP 4.5) and red cloud for high emissions scenario (RCP 8.5).

Figure 18.A: Stocking, yields, fire hazard, and carbon storage: Salem, Eugene, & Coos Bay Districts

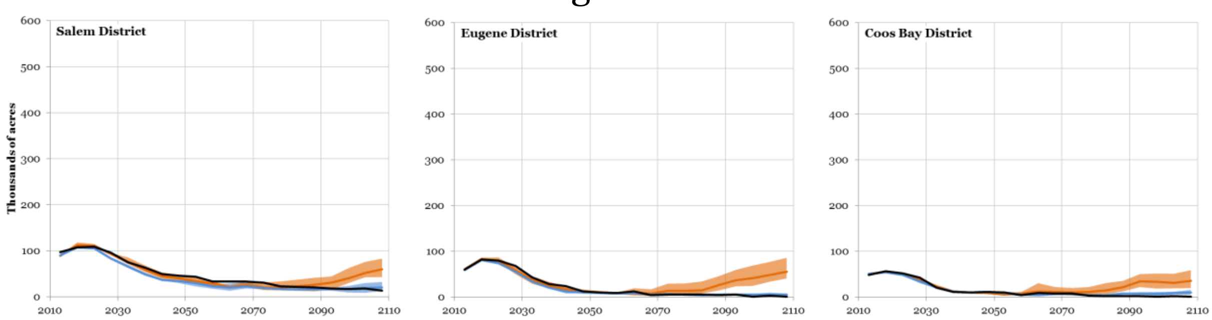
Standing Volume



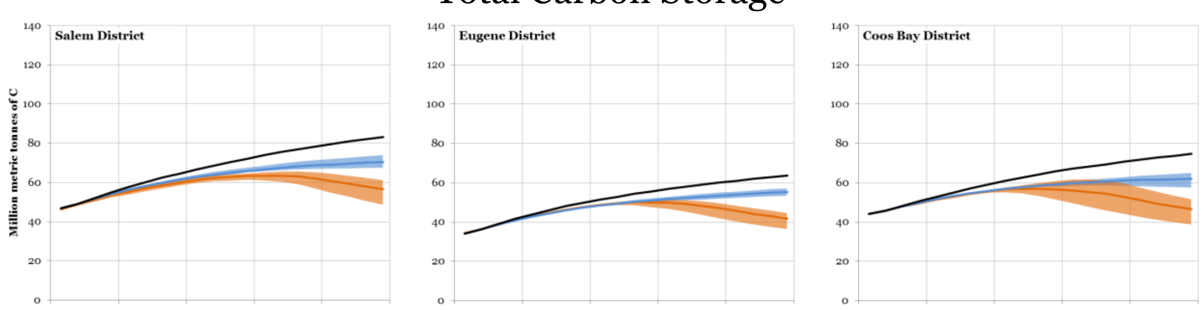
Annual Timber Harvest



Area of High Fire Hazard



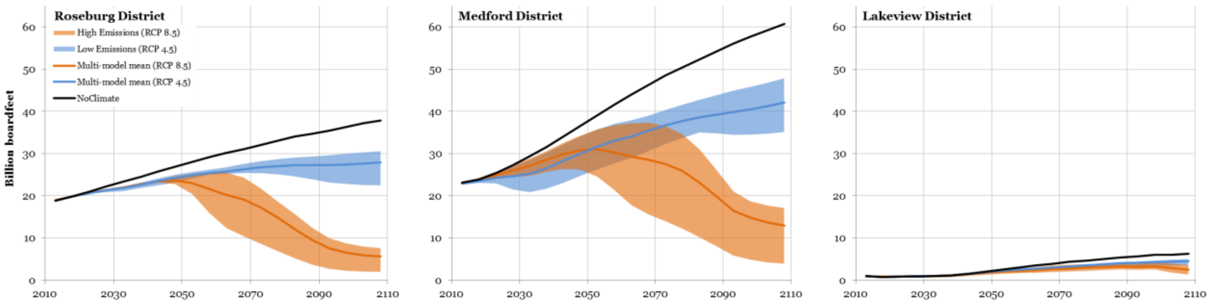
Total Carbon Storage



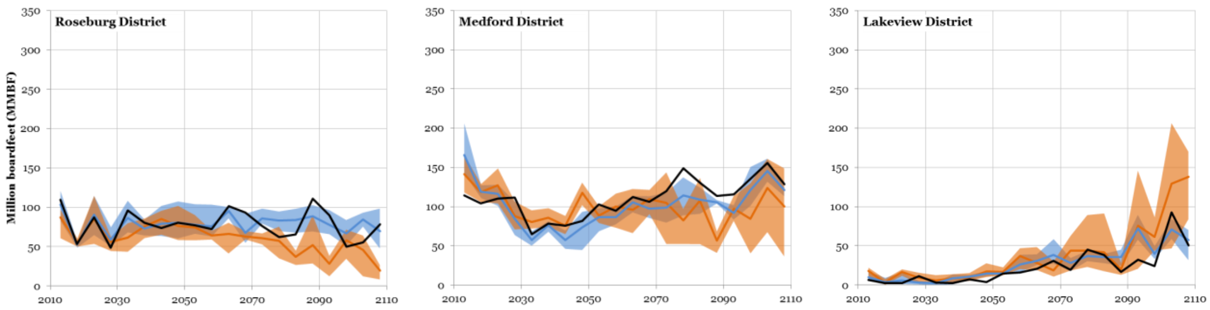
Note: These graphs show results of scheduled forest management with and without climate change impacts simulated in Climate-FVS. The black line in each graph shows results observed without climate change impacts. The blue cloud shows the range of results obtained from 4 GCMs under the low emissions scenario (RCP 4.5) and red cloud for high emissions scenario (RCP 8.5).

Figure 18.B: Stocking, yields, fire hazard, and carbon storage: Roseburg, Medford, & Lakeview Districts

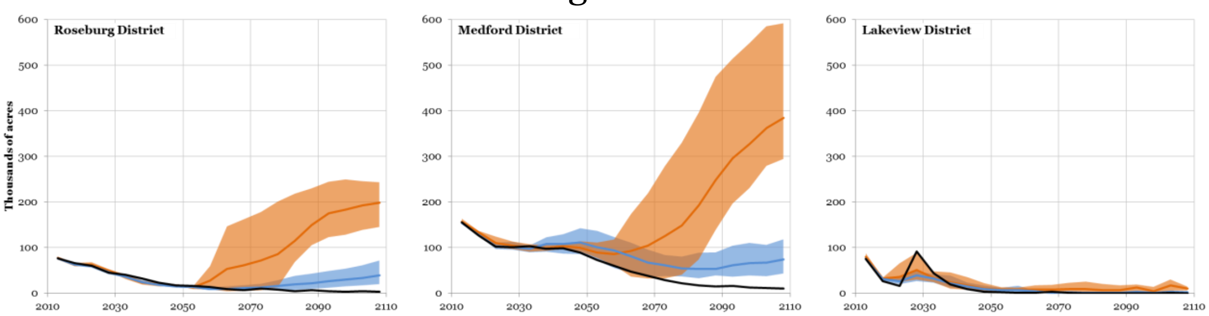
Standing Volume



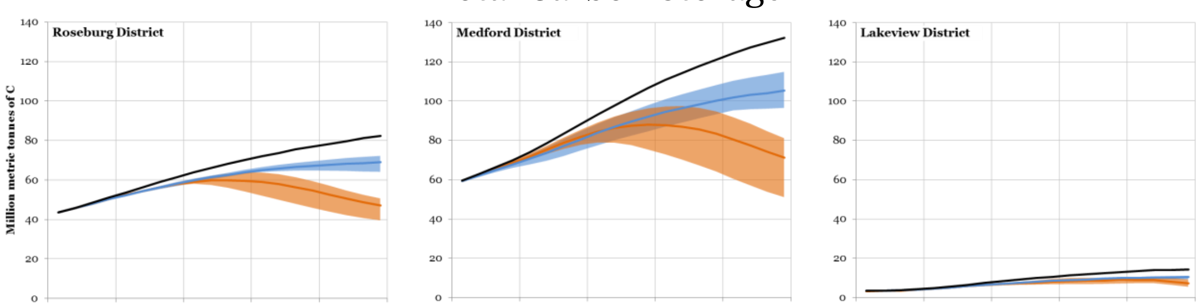
Annual Timber Harvest



Area of High Fire Hazard



Total Carbon Storage



Note: These graphs show results of scheduled forest management with and without climate change impacts simluated in Climate-FVS. The black line in each graph shows results observed without climate change impacts. The blue cloud shows the range of results obtained from 4 GCMs under the low emissions scenario (RCP 4.5) and red cloud for high emissions scenario (RCP 8.5).

Discussion: Study 2 (Simulations of active forest management)

In our simulations of active forest management scenarios, the most striking finding is the generally one-directional influence of climate change impacts on forest productivity. The cloud of results from multiple GCMs relatively consistently fell beneath the *No Climate* scenario. Declines in productivity and increases in mortality were observed broadly across low and high emissions scenarios through mid-century, at which point the high emissions scenario produced a much gloomier outlook due to greatly declining growth rates. Although substantial variability exists among the various circulation models used, the overall behavior of the model seemed to be much more strongly driven by the emissions scenarios chosen than by the choice of individual GCMs.

Within 40 years under the high emissions scenario, every BLM District except for Lakeview was projected to be losing more volume through harvest and mortality than was generated through new growth. This finding implies that the 500 mmbf annual harvest target across western Oregon, given existing land-use designations and constraints on management practices, may exceed longer-term sustained yield if climate changes continue to progress under the business-as-usual, or high emissions (RCP 8.5) scenario that reflects our current emissions trajectory.

Although the 500 mmbf annual yield could be sustained under both low and high emissions scenarios through the end of the century, the climate change impacts simulated by Climate-FVS suggest that maintaining these yields may involve increasing tradeoffs between timber yields and other values, such as carbon storage and standing volume as well as other ecosystem service values not presented in this study. Under the *No Climate* scenario, carbon storage and standing timber volumes increased throughout the simulation period, while simulations under the low emissions scenario suggested the yield target may be met in all regions, but that both standing timber volumes and carbon storage would be lower—under all GCMs—than under the *No Climate* case. Further, under the high emissions scenario, maintaining a 500 mmbf/yr yield resulted not only in mortality and harvest removals outpacing growth within 50-60 years, but in a net reduction of standing timber volume compared to current stocking toward the end of the century in all BLM Districts except Lakeview.

To maintain a 500 mmbf annual harvest across western Oregon, simulated management activities within unrestricted BLM lands intensified progressively through low and high emissions scenarios compared to *No Climate* scenario. This was observed through the increasing use and shortening of even-age rotations and decreasing use of thinning-only or grow-only management on unrestricted BLM lands. Increases in the intensity of harvests and shortening of even-age rotations should be expected to have direct implications for non-timber resource values including carbon storage, fish and wildlife habitat, and other ecosystem services.

It is also important to recognize that Climate-FVS is designed with the assumption that trees are adapted to local climates at the onset of the simulation. Climate change impacts are introduced into the model over time as the underlying climatic conditions and scores for each species in each location change. Although the magnitude of the future changes in climatic suitability remain uncertain, it is apparent from several independent lines of research that climatic changes are already being observed to produce impacts on forests in the Pacific Northwest (e.g., van Mantgem *et al.* 2009; Waring, Coops & Running

2011). Further, the shifts in forest composition projected by Climate-FVS are consistent with a similar shift from conifer to hardwood suitability recently observed in a field study simulating CO_2 enrichment and warming in Minnesota, which led the authors to conclude:

> *In these ecologically realistic field settings, species growing nearest their warm range limit exhibited reductions in net photosynthesis and growth, whereas species near their cold range limit responded positively to warming…. These responses are consistent with the hypothesis, from observational data and models, that warming will reduce the competitive ability of currently dominant southern boreal species compared with locally rarer co-occurring species that dominate warmer neighbouring regions.* (Reich *et al.* 2015)

It is also important to consider that the modeling conducted in this study does not include any changes in the frequency or severity of forest disturbances due to fire, pests, or pathogens, which are widely expected to play a much larger role in shaping the coming decades for our forests (Vose, Peterson & Patel-Weynand 2012).

Conclusion

The findings presented here are among the first using v2.0 of Climate-FVS, and the first study we are aware of applying Climate-FVS at this large of a scale. The simulations conducted in this study also identified the default setting for *dClim*—introduced in Climate-FVS v2.0 to trigger additional mortality based on localized predictions of climatic unsuitability for each tree species when the equivalent of a thousand-foot change in elevation is experienced—to dominate the behavior of Climate-FVS through dramatic mortality rates. In light of these observations, we opted to turn off *dClim* entirely.

Our earlier report on bioclimate envelopes, which are used as inputs to Climate-FVS, led us to expect a bias toward the model overpredicting negative climate change impacts (Diaz *et al.* 2014). Although climatic shifts should be expected to alter growth conditions, the accuracy of the simulated effects growth and mortality rates in the future are not known. In light of our expectation of model overprediction of shifts in climatic suitability for many tree species, we opted to constrain the default natural regeneration logic within Climate-FVS to more conservatively model natural shifts in forest composition under future climate scenarios.

Although bioclimate envelope projections cannot provide a quantifiable level of certainty of future growth and mortality conditions, they do reflect negative impacts attributed to climate change that have already been observed with increased disturbances and detections of increased mortality (van Mantgem *et al.* 2009; Waring *et al.* 2011) and reflect our best approximation of the future. Several choices in parameterizing and applying Climate-FVS in this study (e.g., natural regeneration logic, absence of disturbance events, assuming no additional mortality under substantial localized shifts in climate) reflect conservative efforts to constrain climate change impacts within the model.

Growth-and-yield modeling using Climate-FVS projected several significant impacts for BLM forestlands in western Oregon. In particular, the southern Oregon coast and the Klamath Mountains regions were projected to undergo significant shifts in forest composition due to changing climatic conditions. If the climatic conditions in these regions become increasingly less suitable for Western hemlock and Western redcedar and increasingly better suited for hardwood species historically more abundant in northern California—as the models used here predict—this shift would raise several important commercial and ecological concerns for forests in southern Oregon.

The results of Climate-FVS simulations in this study highlight the important potential for climate change to not only affect forest management outcomes through increasing fire hazard and mortality rates, but also more subtly by introducing new climatic conditions that our current forests may be capable of surviving in, but in which historical growth rates may not be sustained. Even without significant rapid mortality events due to natural disturbances, broad declines in annual growth potential and increases in mortality rates were projected across all BLM Districts compared to simulations that did not consider climate impacts.

The high emissions scenario evaluated in this study, which reflects our current global emissions trajectory, offered a distinctly bleak picture of declining productivity, large-scale shifts in forest composition, and increases in tree mortality and fire hazards. These effects were observed even without the consideration of natural disturbances including wildfire or pest and pathogen spread which are generally expected to play a stronger role in shaping our forests in decades to come than the gradual shifts in tree growth and mortality simulated here (Vose *et al.* 2012).

In terms of methodology and replicability, the batch modeling and harvest scheduler optimization framework employed in this study offer a robust and open source environment for investigating and testing climate adaptation options for forestry that can be used to leverage further research to improve the bioclimate envelope projections that feed Climate-FVS, as well as the potential for hybrid approaches to integrate process models such as BGC, MC2, LANDIS II, 3PG, or others either into the bioclimate envelope projections or directly into the growth-and-yield Climate-FVS environment.

Finally, if the results from these simulations offer any clear message, it is that a disregard for climate change impacts on future growth-and-yield may likely produce unrealistically optimistic expectations. The potential severity of climate change, particularly under our current high emissions trajectory, exerted a dramatic difference on projected forest management outcomes, which may introduce difficult tradeoffs that would not otherwise be apparent if climate change were not directly considered in management planning. Additional work on climate adaptation planning and vulnerability assessment may help to further clarify these issues.

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Appendix I: How Climate-FVS works

The development and features of Climate-FVS have been described in detail for v1.0 (Crookston *et al.* 2010) and in an updated user guide for v2.0 (Crookston 2013). In this report, the main features will be briefly reviewed, but readers are encouraged to consult these references for more context and specific issues than are addressed here.

Bioclimate envelope inputs

Climate-FVS is driven at a fundamental level by climatic suitability scores generated using the Random Forests regression approach described in Crookston et al. (2010). This approach was also evaluated in detail in an earlier report prepared by this project team (Diaz *et al.* 2014). In brief, the Random Forests method uses a machine learning approach to build a large number of regression trees to relate the presence and absence of individual tree species observed in FIA plots to climatic variables. This method effectively captures the *realized* climatic niche for each tree species based on historical conditions, which are then projected forward to estimate the suitability of future climatic conditions to support each species.

Although this approach offers great accuracy in fitting current forest inventory plot data and very-high-resolution for future projections, purely statistical bioclimate envelope methods have been observed to produce more pessimistic projections (i.e., contractions) of suitable ranges for many species for a variety of reasons (Morin & Thuiller 2009; Keenan *et al.* 2011; Cheaib *et al.* 2012). These findings were confirmed in our earlier review (Diaz *et al.* 2014) comparing the Crookston et al. (2010) approach in the BLM western Oregon study area with the hybrid statistical/process-model approach of Coops et al. (2009; 2011).

Nevertheless, we remain confident that despite several important caveats and sources of uncertainty, these methods remain “a useful first approximation as to the potentially dramatic impacts of climate change on biodiversity” (Pearson & Dawson 2003).

As it relates to Climate-FVS, the Random Forests approach produces a climatic suitability score for every species at several timesteps based on future climate projections under four different General Circulation Models (GCMs) and emissions scenarios (referred to in the latest rounds of climate modeling research as Representative Concentration Pathways, or RCPs). These scores give an indication of the resemblance of future climatic conditions to those historical conditions under which the species has been observed. Higher scores indicate a greater similarity of climatic conditions to those historically fitting the species’ realized climatic niche, while lower scores indicate climatic conditions where that species has less commonly been observed.

How changing climatic suitability scores are integrated into growth-and-yield

Site Index and Carrying Capacity

Changes in climatic conditions are incorporated to update both site productivity and maximum Stand Density Index (SDI) within Climate-FVS. A custom function displayed in Crookston (2013) relates the proportional change in a growth rate multiplier to a change in climatic variables. These climatic influences on Site Index were generated using a similar Random Forests approach, but are not synonymous with climatic suitability scores. The effect of this factor on site productivity for each BLM District is visualized in Figure 7.

FVS also calculates a composite maximum SDI for each stand based on a stand's current species composition. This value is updated in each simulation timestep based on the proportional change in climatic suitability scores for each species present and weighted according to the contribution of each species to current SDI.

Growth

Climate-FVS incorporates three values into a growth multiplier that modifies the growth rates of the Base FVS growth-and-yield model. These include:

- the change in site quality (as captured by the Site Index multiplier mentioned above);
- the change in 10-year probability of survival for a species, based directly on its climatic suitability score; and
- a function that estimates the proportional change in growth potential based on the genetic adaptability of a seed source to a changes from current environment conditions.

If any of these scores is less than 1.0, the minimum factor is used to define the growth rate multiplier for that species. As described by Crookston (2013):

> *The rationale is that if nothing is limiting growth, then the factor that results in the most growth is working in the ecosystem. Growth decreases if (1) the climate at the site becomes unsuitable to the species, (2) the site quality deteriorates, or (3) the seed source becomes maladapted to the climate.*

Mortality

Changes in mortality rates based on climate change in Climate-FVS are calculated through two separate factors.

The first factor is comparable to the change in 10-year probably of survival mentioned above to constrain additional growth based on the climatic suitability score. When a species viability score reaches half the value of its starting viability score, mortality rates will increase linearly up to the point where, once the viability score reaches 20% of the original value, the species will be extirpated from the stand. These thresholds were originally defined based on the observation that fewer than 0.5% of species occurrences were observed in FIA plots where climatic suitability scores were estimated at 0.5 or less.

The *dClim* Factor

In version 2.0 of Climate-FVS, a new mortality factor, referred to as *dClim*, was introduced. This factor ramps up the mortality rate for trees if the change of climate in a particular location exceeds the equivalent of a 1,000ft change in elevation. This feature was added based on experience modeling a forest in western Washington:

> *Those simulations allowed Douglas-fir to persist on the landscape in the face of large changes in climate. Indeed, the climate remained within that tolerance for Douglas-fir as a species, but it [sic] not for the population of Douglas-fir that was adapted to the site at the beginning of this century.* (Crookston 2013)

That is, these simulations using v1.0 of Climate-FVS were seen as providing insufficient sensitivity to changing climate. In v1.0, mortality would only be triggered if the climatic suitability score for a particular species, based on the climatically suitable range calculated for that species entire range, fell below 0.5, which corresponds to the climatic niche where fewer than 0.5% of field-based observations of that species occurred. The addition of the *dClim* mortality factor provides model behavior recognizing that a particular tree is not likely to be adaptable to the full climatic range exhibited across the whole species distribution, but is rather more likely to be constrained to a subset of that climatic niche based on the adaptability of its subspecies genetic variant or seed source.

According to Crookston, the 1,000ft threshold was defined based on the average elevation change between seed zones. In effect, *dClim* will trigger mortality for trees in a particular location if climate changes in this location exceed the equivalent of a 1,000ft change in elevation, even if the underlying climatic suitability score remains high (i.e., even if this species occurs commonly in other areas with this combination of climatic factors).

Regeneration

Climate-FVS does have an optional natural regeneration logic based on climatic suitability scores and current stand densities, although it has been turned off in this study, so is not discussed in more detail here.