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MEMORANDUM

April 15, 2021

TO: Forest Practices Board

FROM: Mark Hicks, Adaptive Management Program Administrator

SUBJECT: Transmittal: Eastside Modeling Effectiveness Project

At their March, 2021 meeting, TFW Policy formally considered the final report and associated materials for the study entitled Eastside Modeling Effectiveness Project (EMEP).

The EMEP Study used modeling to predict how current riparian stands in eastern Washington might respond to the eastside riparian prescriptions rules over time. EMEP evaluated riparian stand conditions using survey data collected for the 2008 Eastern Washington Riparian Assessment Project - Phase 1 (EWRAP).

The study was designed to inform the following questions:

1. To what extent do the current riparian stands meet the size and basal area thresholds for timber harvest across regulatory habitat types (elevation bands)?
2. Are there differences in stand characteristics associated with distance to the stream?
3. What are the projected rates and characteristics of stand mortality in riparian stands with and without management intervention?
4. How susceptible to insect, disease, and crown fire are the stands sampled in EWRAP Phase1, and how does susceptibility change over time?
5. How will stand characteristics change over time with no timber harvest and with timber harvest applied to the limits that rules allow?

The study authors found that overall as riparian zone growth was simulated for 50-years, without management tree size and stand density increased along with some increases in insect and disease susceptibility and potential fire severity, but with management these factors decreased.

Across the sample sites, many riparian management inner zones were not eligible for harvest primarily because they were located within the Bull Trout Overlay (BTO) area or because they lacked sufficient shade to allow management treatments. For inner zones that could be managed, either thinning throughout the zone or only thinning the outer 25 feet along larger streams in the BTO or where shade was deficient, management with available prescriptions had minimal effects on tree growth and minimal reductions in insect and disease susceptibility. Management in outer zones, which removed more trees, increased tree growth and reduced insect and disease susceptibility, and potential wildfire severity. Higher levels of harvesting could result in forest growth and health benefits. However, potential benefits of harvesting at higher levels in riparian management zones would need to be balanced with potential negative impacts on ecological functions and processes in riparian habitats and overall aquatic system health and protection.

After reviewing the study findings, Policy agreed by consensus not to recommend the Board take any formal action in response to this study. Though no action is recommended by the Board, the study findings have been directed to the Science Advisory Group for the Eastside (SAGE) for incorporation into their eastside research strategy.

MH
Attachment

EASTSIDE MODELING EFFECTIVENESS PROJECT (EMEP)


AUG/30/2015

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October 8th, 2020

TABLE OF CONTENTS

List of Appendices

Appendix A: EWRAP to FVS Crosswalk
Appendix B: R Processing Code
Appendix C: FVS Compute Statements
Appendix D: Inner Zone Harvest Eligibility
Appendix E: FVS Harvest Keywords
Appendix F: Results Table Data Dictionary
Appendix G: Summary Statistics
Appendix H: Harvest Levels

List of Figures

List of Tables

INTRODUCTION

This report provides the results from a modeling project: The Eastside Modeling Evaluation Project (EMEP). The purpose of this project was to model how current riparian stands in eastern Washington might respond to the Washington forest practices rules eastside riparian prescriptions over time. The EMEP evaluated riparian stand conditions using survey data from the previously completed Phase 1 of the Eastern Washington Riparian Assessment Project (EWRAP). EWRAP data were used to inform Forest Vegetation Simulator (FVS) modeling as the basis for evaluating: 1) current riparian stand conditions; 2) trajectory of riparian stand conditions; 3) eligibility of stands for timber harvest; and 4) trajectory of managed stand conditions.

The EMEP is part of an ongoing program that the Scientific Advisory Group Eastside (SAGE) has implemented to validate the Eastern Washington Type F riparian prescriptions.

Background

The WAC 222-30 provides forest practice rules for regulating timber harvest in eastside fish-bearing (Type S/F) streams. Two sections of WAC 222-30-022 regulate removal of trees from eastside riparian stands along fish-bearing streams on all but exempt 20-acre parcels. WAC 222-30-040 regulates shade requirements to maintain water temperature. Within the bull trout overlay (BTO), all available shade will be retained within 75 feet of the stream. Outside the BTO, no tree may be harvested within 75 feet of the stream if existing shade is insufficient to maintain compliance with temperature standards.

Once shade requirements are met, then WAC 222-30-022 provides further regulation for timber harvest along Type S/F streams within: 1) an “inner zone” (the area measured horizontally 30 to 75 feet from the stream edge (for streams less than 15 feet wide) or 30 to 100 feet from the stream edge (for streams more than 15 feet wide); and 2) an “outer zone” (the area measured horizontally 0 to 55 feet from the outer edge of the inner zone, depending on the site class and stream width). No harvest will occur within 30 feet of the stream (core zone).

Specific riparian management zone harvest management prescriptions are described in WAC-222-30-022 for three timber habitat types: 1) ponderosa pine (PP, less than 2,500 feet elevation); 2) mixed conifer (MC, 2,500 – 5,000 feet); and 3) high elevation (HE, greater than 5,000 feet). Prescriptions describe minimum residual stocking via basal area, trees per acre, size, species, and habitat standards.

STUDY OBJECTIVES

The EMEP addresses the following study questions and objectives taken from the EMEP Study Plan:

1. *To what extent do the current riparian stands meet the size and basal area thresholds for timber harvest across regulatory habitat types (elevation bands)?*

    - *Objective 1: Determine the number of stands eligible for timber harvest in the current year and changes by decade with no silvicultural manipulation simulated.*

    - *Objective 2: Develop harvest prescriptions that meet rule requirements and maximize timber harvest for each stand. Quantify the amount of basal area per acre and the number of trees per acre that can be cut from each stand that is eligible for harvest based on rule criteria for current stands.*

2. *Are there differences in stand characteristics associated with distance to the stream?*

    - *Objective 1: Determine if there are differences in stand attributes by regulatory zone.*

    - *Objective 2: Determine if there are differences in stand attributes by ecological zone.*

3. *What are the projected rates and characteristics of stand mortality in riparian stands with and without management intervention?*

4. *How susceptible to insect, disease, and crown fire are the stands sampled in EWRAP Phase 1, and how does susceptibility change over time?*

    - *Objective 1: Quantify stand susceptibility of current stands as: 1) regulatory and, 2) ecological zones for each insect and pathogen common to eastern Washington for which risk rating systems are available in Hessburg et al. (1999)*

5. *How will stand characteristics change over time with no timber harvest and with timber harvest applied to the limits that rules allow?*

    - *Objective 1: Determine for each stand at current age and by decade to year 50: 1) basal area per acre, 2) trees per acre, 3) stand density index, 4) Curtis' relative density, 5) quadratic mean diameter, 6) cubic-foot volume per acre, and 7) board-foot volume per acre.*

Study objectives were achieved primarily through FVS simulation modeling informed by EWRAP data for regulatory riparian management zones. This report describes the data used to inform simulation a modeling of the regulatory riparian management zones and the processes used to delineate these from the data and determine harvest eligibility. Results to address each objective are then presented to describe:

- current conditions in eastern Washington riparian management zones,
- predicted changes in riparian management zones through time without management,
- eligibility of riparian management zones for harvest under the criteria in the Forest Practices Rules and the levels of harvest under applicable prescriptions,
- predicted changes in riparian management zones with management under the Forest Practices Rules, and
- a comparison of predicted unmanaged and managed conditions on those sites that were eligible for harvest.

A discussion of the data, models, and results follow to highlight salient points and synthesize the finding in the results followed by concluding remarks.

METHODS

Data Sets

Riparian Stand Data

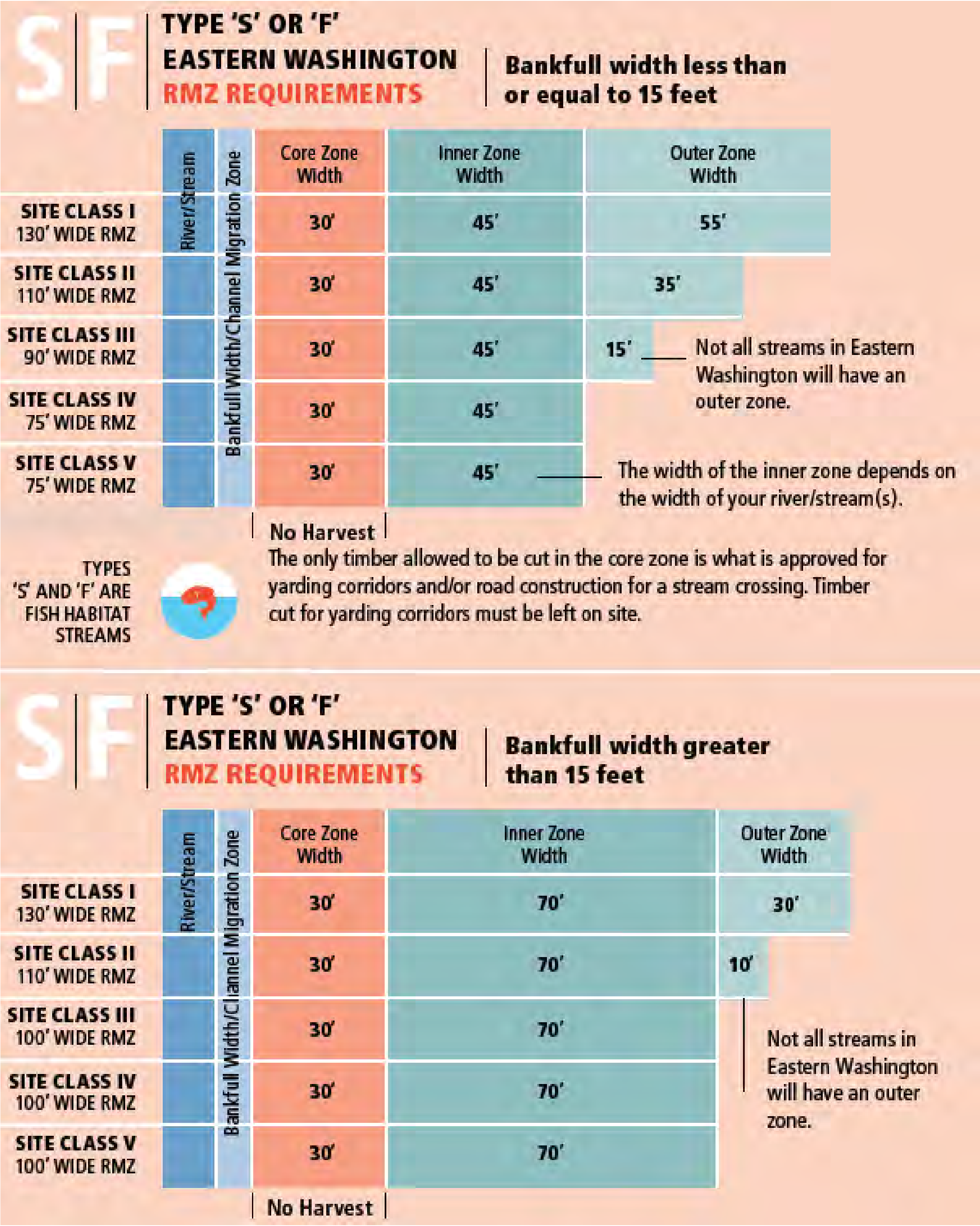
Forest Vegetation Simulator (FVS) modeling was informed by conditions inventoried in eastside riparian stands during Phase 1 of the Eastern Washington Riparian Assessment Project (EWRAP). Here we provide a summary of site selection and data collection used in this study, which were completed during previous projects. Complete details of site selection and data collection are available in Bonoff et al. (2006).

Data from the EWRAP included a sample of 103 sites along type S/F streams in eastern Washington on lands managed under the Forest and Fish Report (FFR). These sites were selected by the Scientific Advisory Group for the Eastside (SAGE) after intersecting a GIS layer representing eastern Washington FFR lands with spatially distributed random sample points (latitude and longitude), generated by the U.S. Environmental Protection Agency's Environmental Assessment Program in Corvallis, OR, using the Washington DNR's 1:24,000 hydrography layer. Following selection, sites were field validated to ensure no recent events (landslides, development, etc.) would preclude the site from inclusion in the EWRAP. The process of field validation included determining site access, and locating the monument, as well as estimations of DBH and canopy class, along with a short narrative describing the site. The resulting sample was spatially distributed across all FFR lands in eastern Washington (lands that were not federal, tribal, or covered under a Habitat Conservation Plan), providing a representative sample of riparian conditions on eastern Washington FFR lands.

Field data were collected at each site along a single 240-foot long transect installed perpendicular to the middle of the randomly-selected stream reach beginning at the edge of bankfull width at the edge of the channel migration zone. General physical data were collected at each site including: stream bankfull width to the nearest foot, stream direction to the nearest cardinal or intercardinal direction, elevation at the start of the transect, slope of each 80-foot segment of the transect, and GPS latitude and longitude. Live and dead trees with DBH > 3.0 inches were sampled along each transect using horizontal line sampling (Ducey et al. 2002) with a basal area factor (BAF) of 20 for tree selection. Data collected from each selected sample tree included: species, diameter to the nearest inch, total height to the nearest foot, crown ratio to the nearest 5%, crown class (dominant, co-dominant, etc.), condition (live, dead, etc.), damage agents, damage locations, and damage severity, decay class for dead trees, and the tree's distance along the transect from bankfull width to the nearest foot. Seedlings, shrubs, and noxious weeds were sampled using 10-foot-by-10-foot subplots located at 10-foot intervals along the transect with the first subplot center located 5 feet from the beginning of the transect. Data collected included: seedling species, DBH class to the nearest inch, tree count, and average height; and shrub and noxious weed species and percent cover to the nearest 5%. Plant associations were classified at three points along each transect (50, 130, and 210 feet for the origin) using keys provided by Kovalchick and Clausnitzer (2004) and were summarized and presented as a single value per transect.

Regulatory zones were delineated using stream bankfull width and site class with zone widths specified in WAC 222-30-022 (Figure 1) to create "stands" for each site. Sites were populated with field-sampled trees and seedlings for simulation and analysis to assess potential differences among zones within and across sites, and to simulate effects of zone-specific management under WAC 222-30-022. The number and width of zones varied by bankfull width and site class. All sites had a 30-foot wide core zone located adjacent to the location of bankfull width. All sites also had an inner zone adjacent to the core zone that was 45 feet wide for streams with bankfull widths of ≦ 15 feet, and 70 feet for streams with bankfull widths > 15 feet. Inner zones for sites on streams with bankfull width > 15 feet were further divided into two zones (45 feet wide adjacent to the core zone and a second 25-foot wide zone) to retain all shade within 75 feet of the stream to be modeled when sites fell within the bull trout overlay (BTO). An outer zone adjacent to the inner zone with width varying based on stream width and the site class of the site. For streams with bankfull width of ≤ 15 feet, the outer zones were 55, 35, and 15 feet wide for site classes I, II, and III, respectively. For streams with bankfull width > 15 feet the outer zones were 30 and 10 feet wide for site classes I and II respectively. The resulting stands for simulation and analysis were named with a combination of the EWRAP site identifier and regulatory zone. Tree data were assigned to regulatory zone stands based on distance along the transect from bankfull width. Seedling data were assigned to regulatory zone stands based on the location of the seedling subplot along the transect. When a regulatory zone boundary split a subplot, which occurred at the outer boundary of the inner zone on streams with bankfull width of ≤ 15 feet or less, all seedlings in the subplot were assigned to both regulatory stands, since the actual location of seedling was not recorded, and the tree expansion factors were halved in each stand to provide correct overall weighting. Data from trees and seedlings located in the uplands outside the regulatory riparian management zones were not used in this analysis. Insufficient data existed within the EWRAP data set to reliably classify the data into ecological zones (e.g., floodplain, terrace) so ecological zones are not included in simulations and analyses. For the purposes of modeling, analysis, and interpretation, "riparian" stands or areas were assumed to reflect areas within these regulatory zones.

Site and tree data were transformed to FVS-ready formats by translating data into FVS and FVS variant-specific formats and values. A crosswalk of EWRAP attributes to FVS attributes is provided in Appendix A. Tree per acre weights for trees ≥ 3 inches diameter at breast height (dbh) were calculated using the modified horizontal line sampling method of Ducey et al. (2002), a method similar to the variable-radius point sampling method (e.g., Avery and Burkhart 1994). Under modified horizontal line sampling, tree-specific expansion factors were calculated based on tree dbh, the plot radius factor used in sampling, and sampling transect length. When calculating tree expansion factors for regulatory zone stands, transect length in the zone (zone width) was used. Expansion factors for seedlings (trees ≤ 3 inches dbh) were calculated using subplot area. Because this study compiled tree and seedling data into regulatory stands, the tree expansion factors and tree data summary values may differ from those reported in the Bonoff et al. 2006. The resulting tables were loaded into an FVS-ready Microsoft Access database that was used as the data source for FVS simulations using the FVS Database Extension (DB-FVS; Crookston et al. 2003)



SF | TYPE 'S' OR 'F' EASTERN WASHINGTON RMZ REQUIREMENTS | **Bankfull width less than or equal to 15 feet**

	River/Stream	Bankfull Width/Channel Migration Zone	Core Zone Width	Inner Zone Width	Outer Zone Width
SITE CLASS I 130' WIDE RMZ			30'	45'	55'
SITE CLASS II 110' WIDE RMZ			30'	45'	35'
SITE CLASS III 90' WIDE RMZ			30'	45'	15'
SITE CLASS IV 75' WIDE RMZ			30'	45'	
SITE CLASS V 75' WIDE RMZ			30'	45'	

Not all streams in Eastern Washington will have an outer zone.

The width of the inner zone depends on the width of your river/stream(s).

No Harvest

The only timber allowed to be cut in the core zone is what is approved for yarding corridors and/or road construction for a stream crossing. Timber cut for yarding corridors must be left on site.

TYPES 'S' AND 'F' ARE FISH HABITAT STREAMS

SF | TYPE 'S' OR 'F' EASTERN WASHINGTON RMZ REQUIREMENTS | **Bankfull width greater than 15 feet**

	River/Stream	Bankfull Width/Channel Migration Zone	Core Zone Width	Inner Zone Width	Outer Zone Width
SITE CLASS I 130' WIDE RMZ			30'	70'	30'
SITE CLASS II 110' WIDE RMZ			30'	70'	10'
SITE CLASS III 100' WIDE RMZ			30'	70'	
SITE CLASS IV 100' WIDE RMZ			30'	70'	
SITE CLASS V 100' WIDE RMZ			30'	70'	

Not all streams in Eastern Washington will have an outer zone.

No Harvest

Figure 1: Eastern Washington regulatory zone delineation criteria based on stream bankfull width and site class. Reproduced from Forest Practices Illustrated, 2009 update.

Ancillary Data

In addition to the EWRAP data, ancillary data were compiled to support harvest eligibility determinations. Specifically, harvest eligibility relative to shade requirements in WAC 222-30-040 required additional knowledge of whether the site fell within the bull trout overlay (BTO) and represented regional stream temperature characteristics for the site. The extent of the bull trout overlay was represented by the BTO map (WAC 222-16-010). A BTO map GIS layer was not available to allow spatial classification of each site so an electronic version of the map was registered, to the best of our ability, in the GIS to determine which sites were located within the bull trout overlay. Sites were located on the Washington State Department of Natural Resources Stream Temperature Class layer[1] to determine the regional stream temperature characteristics for each site. These data were used following procedures specified in WAC 222-30-040, including procedures and nomographs in Forest Practices Board Manual Section 1, to determine required shade levels for each site. After locating the site within the BTO and stream temperature layers the resulting distribution of sites within each BTO/temperature requirement is show in Table 1.

Table 1: Numbers of EWRAP sites that are inside and outside the bull trout overlay (BTO) by forest type and temperature requirements.

	Mixed Conifer		Ponderosa Pine	
	16°C	18°C	16°C	18°C
Outside BTO	13	6	4	7
Inside BTO	18	19	15	16

FVS Simulations

Forest growth and yield, potential fire hazard, and insect and disease rating input metrics were simulated for all regulatory zone stands with no-harvest and with all applicable management alternatives based on harvest eligibility criteria in WAC 222-30-022 (1) using applicable variants of the Forest Vegetation Simulator (FVS) model (Dixon et al. 2002). Simulations occurred over a 50-year analysis window with 10-year simulation periods. FVS is a standard growth and yield model used by public and private sector forestland management agencies and companies that is localized to regional forest conditions in specific FVS variants. Three variants were used for this study: 1) Blue Mountains (BM) (Keyser and Dixon 2008a) for all sites in southeast Washington; 2) East Cascades (EC) (Keyser and Dixon 2008b) for sites in the east Cascade mountains, northcentral Washington and northeast Washington west of the Columbia River; and 3) Inland Empire (IE) (Keyser 2008) for all sites in northeast Washington east of the Columbia River. The Fire and Fuels Extension (FFE) for FVS (Rebain 2010) was also used with each variant to simulate potential fire hazard rating inputs. Insect and disease rating input metrics were calculated during growth and yield simulations using the dynamic computation (COMPUTE) functionality of FVS. While other growth and yield models were available for eastern Washington, FVS was the only publicly available, open source forest growth and yield model that provided all the simulation capabilities needed for this study. Additionally, while FVS was fit to upland conditions, FVS growth is keyed

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[1] Data downloaded from the Washington State DNR GIS Forest Practices Data web site http://www.dnr.wa.gov/programs-and-services/forest-practices/providing-gis-data-forest-practices-activities-throughout (last accessed 6/1/2016).

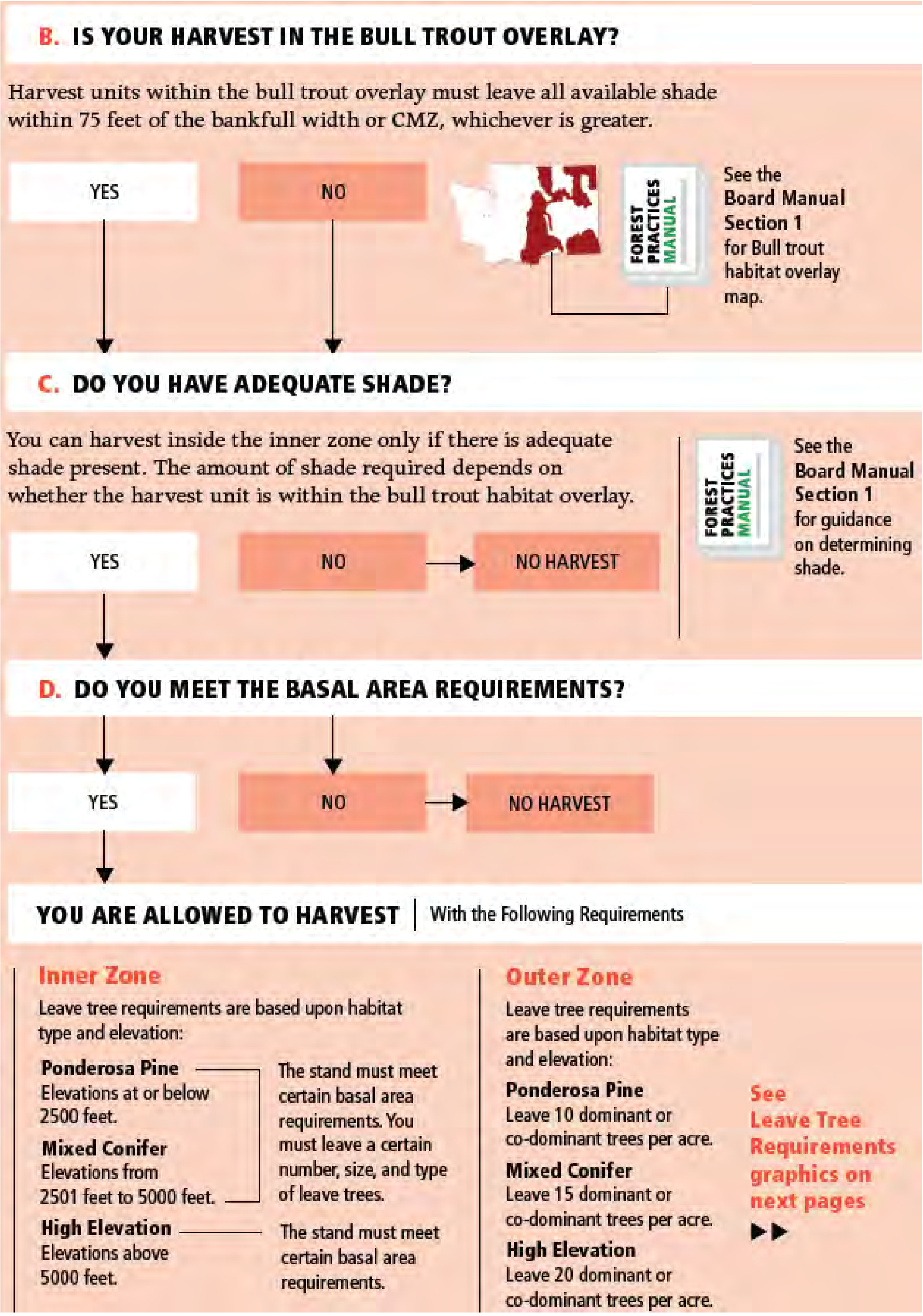
to habitat types so that when it is matched to the habitat types in the riparian zones it should predict the growth and yield of these sites well.

All FVS simulations included common configuration and parameterization to ensure comparable simulation execution and output across all sites, zones, and variants. The following keywords (Van Dyck and Smith-Mateja 2015) were used:

- NOAUTOES – Disabled automatic regeneration in the IE FVS variant – the only IE variant with automatic regeneration;
- TREELIST – Created FVS simulation tree lists;
- CUTLIST – Created tree list of all trees cut in harvest simulations;
- DATABASE – Enabled the database extension to use the FVS-ready database as data source and destination;
- COMPUTE – Specified variables to compute during the FVS simulation for post-processing (see Appendix C for a listing of all COMPUTE statements); and
- NUMCYCLE – Set the number of simulation cycles.
- POTFIRE – Enabled FFE potential fire report that provides fire hazard rating inputs.
- COMPUTE – Enabled dynamic metric calculation for insect and disease rating input metrics.
- STRCLASS – Enabled structural class variable calculations to provide input for the Hessburg insect and disease rating models used in COMPUTE (see below).

Because no growth data were collected during the EWRAP data collection and no independently collected growth data were available for this study, no height- or diameter-growth calibration were used in simulations. While regeneration may be important in growth and yield simulations, predicting regeneration accurately was complex and difficult, (Oliver and Larson 1996, Ek et al. 1997). Additionally, the location of regeneration trees would be needed to inform shade modeling so the selection of the location and density of regeneration could bias shade calculations. For these reasons the choice was made to exclude regeneration from FVS simulations. The NUMCYCLE keyword was set for six simulation cycles so that fire hazard and insect and disease rating input metrics would be output for each 50-year simulation period. The reason for this is that FFE and COMPUTE metrics are back-calculated with each simulation cycle. To calculate FFE and COMPUTE metrics for the initial year of the simulation FVS must be simulated for one cycle because FVS must calculate the initial year metrics. Calculation of FFE and COMPUTE metrics for all five simulation periods of the 50-year simulation window required FVS to simulate six cycles. During analysis and reporting only FVS outputs for the initial conditions, period 0 (year 0), and the first five simulation periods, period 1 (year 10) through period 5 (year 50), were used, including back-calculated FFE and COMPUTE metrics from the sixth growth cycle. When growth metrics were reported, only periods 1 through 5 were reported with each year representing growth that occurred in the 10-year period (period 1 growth represented growth from year 0 to year 1year10, period 2 growth from year 10 to year 20, etc.).

Two sets of FVS simulations were conducted to assess trajectories of regulatory zone stands through time both without and with management. First, simulations were performed without harvest to characterize current stand conditions, determine the trajectory of stands without management intervention, and provide data needed to determine future harvest eligibility. After no-harvest simulations were performed, the resulting data for inner and outer zones were processed to determine when the zones where eligible for harvest based on the criteria in WAC 222-30-022(1)(b) and (c) and WAC 222-30-040 (Figure 2) on a site-by-site basis for each simulation year.



B. IS YOUR HARVEST IN THE BULL TROUT OVERLAY?

Harvest units within the bull trout overlay must leave all available shade within 75 feet of the bankfull width or CMZ, whichever is greater.

See the Board Manual Section 1 for Bull trout habitat overlay map.

C. DO YOU HAVE ADEQUATE SHADE?

You can harvest inside the inner zone only if there is adequate shade present. The amount of shade required depends on whether the harvest unit is within the bull trout habitat overlay.

See the Board Manual Section 1 for guidance on determining shade.

D. DO YOU MEET THE BASAL AREA REQUIREMENTS?

YOU ARE ALLOWED TO HARVEST | With the Following Requirements

Inner Zone

Leave tree requirements are based upon habitat type and elevation:

Ponderosa Pine
Elevations at or below 2500 feet.

Mixed Conifer
Elevations from 2501 feet to 5000 feet.

The stand must meet certain basal area requirements. You must leave a certain number, size, and type of leave trees.

High Elevation
Elevations above 5000 feet.

The stand must meet certain basal area requirements.

Outer Zone

Leave tree requirements are based upon habitat type and elevation:

Ponderosa Pine
Leave 10 dominant or co-dominant trees per acre.

Mixed Conifer
Leave 15 dominant or co-dominant trees per acre.

High Elevation
Leave 20 dominant or co-dominant trees per acre.

See Leave Tree Requirements graphics on next pages ▶▶

Figure 2: Process diagram for determining inner and outer zone harvest eligibility under WAC 222-30-022 (1) (b) and (c) and WAC 222-30-040. Reproduced from Forest Practices Illustrated, 2009 update.

Harvest Eligibility

Each site was first evaluated to determine shade requirements to maintain water temperature under WAC 222-30-040: determine if the site falls in the BTO, determine the stream water temperature classification, then determine minimum canopy closure requirements based on the site's temperature classification and elevation. Each site was located within the spatially referenced BTO map described above to determine whether it fell within the BTO. If a site was located within the BTO, prescriptions were generated to retain all available shade within 75 feet of the stream per WAC 222-30-040(1) making the entire inner zone of sites with small streams and the inner 45 feet of the inner zones of sites with large streams ineligible for harvest. Stream temperature classification was determined by the location of each site according to the Washington State Department of Natural Resources Stream Temperature described above. Minimum canopy closure requirements were determined using the eastern Washington canopy cover nomograph from the Forest Practices Board Manual Section 1 using the temperature classifications and elevation data.

Instream shade canopy closure data were not collected as part of the EWRAP project and therefore had to be estimated for each stand. Shade assessments were performed using methods from the Washington Forest Practices Watershed Analysis Manual Riparian Function Module for wide streams. With this approach, the angle from the center of the stream to the simulated top of a tree in the riparian zone was calculated and used to determine the percent of sky blocked by that tree. For stream shade estimates we used each tree's distance from the stream centerline, tree height, crown ratio, crown width, along with the number of trees per acre (TPA) and transect segment slopes to approximate the percent of sky above the stream that was blocked by trees in the riparian zone.

Several simplifying assumptions regarding trees in the riparian zone were made in this process:

- All trees in the riparian zone represented by a sample tree in the tree list were uniformly distributed in the riparian zone at the same distance from the stream as the sample tree. All trees were uniformly spaced, with spacing determined by the number of trees per acre represented by the sample tree. For example, if a sample tree represented 10 TPA then each tree accommodated an average of 4,356 square feet of the acre (one tenth of an acre), resulting in an average spacing of 66 feet between trees.
- Because additional sample trees are added when moving away from the stream, the number of trees potentially blocking the sky is additive. With each additional sample tree added to the estimation process, the average distance between trees parallel to the stream centerline decreases.
- When the average crown width of sample trees used to estimate the amount of sky blocked was at least the average tree spacing, adding additional sample trees will not increase the amount of sky blocked. At this point the riparian zone trees created a "wall" of tree crowns that blocked sky.
- The average amount of sky above the stream that was blocked by trees was representative of and proportional to the amount of shade provided to the stream by the riparian zone.

Estimating the percent of sky blocked by riparian zone trees was performed by:

1. Ranking sample trees for all regulatory stand zones by distance from the stream.
2. For each sample tree, calculating calculate the total number of TPA represented by that tree and all trees closer to the stream to determine average tree spacing as each additional sample tree was added.
3. For each sample tree calculate average crown width of the sample tree and all sample trees closer to the stream using sample TPA as weights in the average calculations.
4. For all sample trees where average crown width was less than average spacing, we:
    a. Calculated the total height of each sample tree above the stream level (total tree height plus topographic elevation of the riparian zone above the bankfull stream surface) using the tree's total height, distance from the stream and the slopes of each 80-foot transect segment.
    b. Calculated the elevation angle to the top of each tree as the arctangent of total tree height above the stream and distance from stream centerline.
    c. Calculated the elevation angle to a point on the outside of the crown based on crown width estimated by (?)FVS at the top of the bottom third of the crown. This angle was larger than the angle to the top of the tree if the crown was close to or overhung the stream.
    d. Determined the percent of the sky blocked by each sample tree by dividing the larger of the tree top and crown elevation angles by 90 degrees.
5. Calculating the overall amount of the sky blocked as a weighted average of the sky blocked by each sample tree, using sample TPA as weights.

The resulting amount of blocked sky was assumed to approximate stream shading and was used to determine harvest eligibility. Shade calculations were performed for each site using the current year of data and for each no-harvest FVS simulation period to estimate when a site initially became eligible for harvest, if the site was not eligible under current conditions.

If a site was determined to provide adequate shade, inner zone harvest eligibility was estimated to determine whether there was adequate stocking per WAC 222-030-022(1)(b). Using the tree and seedling data from the initial year and from each decade of the no-harvest FVS simulations, basal area per acre of trees $\geq$ 6 inches dbh and total TPA were calculated for the inner zone to determine if the stand had sufficient basal area to be eligible for high basal area or low basal area, high density harvest. Harvest eligibility criteria included:

- High basal area harvest:
    - 110 ft^2/ac. and 50 TPA for PP (WAC 222-030-22 (1)(b)(i)(C)(I)),
    - 110 ft^2/ac., 130 ft^2/ac., or 150 ft^2/ac. for site indices <90, between 90 and 110, and > 110, respectively, and 50 TPA for MC (WAC 222-030-22 (1)(b)(ii)(C)(I)), and
    - sufficient basal area to meet the desired future condition of 325 ft^2/ac. at 140 years (WAC 222-30-021 (1)(b)) for HE
- Low basal area high density harvest:
    - < 60 ft^2/ac. and more than 100 TPA for PP (WAC 222-030-22 (1)(b)(i)(D),

    - < 110 ft^2/ac., 130 ft^2/ac., or 150 ft^2/ac. for site indices < 90, between 90 and 110, and greater than 110, respectively, and more than 120 TPA for MC (WAC 222-030-22 (1)(b)(ii)(D)).

Outer zones could be harvested independently of inner zone shade and stocking requirements. Outer zones were evaluated at each time step to determine if they had enough dominant or co-dominant trees according to WAC 222-030-22 (1)(c). Dominant and co-dominant TPA were derived from FVS simulation output for outer zone stands and were eligible for harvest if there were enough dominant and co-dominant trees with dbh $\geq$ 10.0 inches to meet the leave tree requirements in WAC 222-030-22 (1) (c) (e.g.), 10 trees pre acre of PP or 12 trees per acre for MC, or WAC 222-030-21 (1)(b), 20 $\geq$ 12 inch dbh trees per acre in HE sites.

Based on harvest eligibility requirements, regulatory stands could have one of the following prescription types:

- No-harvest (NA) – No harvest is applied to the regulatory zone stand. This was the baseline condition for all stands.
- Retain all shade (RAS) – No harvest within 75 feet of the stream. This was used when the site fell within the BTO.
- Forest and Fish Report (FFR) – Thinning to the specifications in WAC 222-30-022 (1) (b) and (c).
- A combination of RAS and FFR (RAS-FFR). This was used at sites with large streams in the BTO that had sufficient shade to allow harvesting in the outer 25 feet of the inner zone.

Harvest Simulations

For all simulation periods at which inner and outer zone stands were estimated to be eligible for harvest, pre-processing was performed. This involved using FVS keywords to simulate the required leave tree specifications based on timber habitat type and regulatory zone (WAC 222-30-022 (1)).

Generally, the following FFR prescriptions were simulated:

- Because high basal area thinning specifications in the inner zone were too complex to specify as FVS keywords directly, they required stand- and harvest period-specific keyword configurations. Prescriptions specified using one of three options to meet basal area leave targets—60 ft^2/acre of basal area in ponderosa pine timber habitat type stands or 70 ft^2/acre, 90 ft^2/ac or 110 ft^2/ac in low, moderate, or high site class mixed conifer sites:
    - If 50 TPA met or exceeded the basal area target, thin from below leaving the largest 50 trees per acre. This option was specified using the THINBTA (thin from below to TPA target) FVS keyword with a target of 50 TPA and a minimum dbh of 6 inches;
    - If 50 TPA did not meet basal area targets, leave additional trees until targets are met. This option was specified using the THINBBA (thin from below to basal area target) FVS keyword with a target of 60 ft^2/acre of basal area in PP timber habitat

    type sites or 70 ft^2/acre, 90 ft^2/ac or 110 ft^2/ac in low, moderate, or high site class MC sites and minimum dbh of 6 inches; or
    - If more than 100 TPA were needed to meet basal area targets, leave 100 TPA. This option was specified using the THINBTA FVS keyword with a target of 100 TPA and a minimum dbh of 6 inches.
- For low basal area high density prescriptions in the inner zone leave the 100 largest TPA for PP sites and the largest 120 TPA for MC sites. These options were specified using the THINBTA FVS keyword with the target of 100 or 120 TPA, depending on the site's timber habitat type.
- Outer zone thinning leaves 10 dominant or co-dominant TPA in ponderosa pine sites or 12 dominant or co-dominant TPA in mixed conifer sites. These options were specified using the THINBTA FVS keyword with the target of 10 or 12 TPA, depending on the site's timber habitat type and a minimum dbh of 10 inches.
- Logging damage was simulated by removing 50% of all trees with dbh < 6 inches using the THINBTA keyword with a target of 0 trees per acre, a cutting efficiency of 0.5, and a maximum dbh of 6 inches. This value assumes that there are many small trees that would be damaged when falling and removing understory trees, which is based on professional judgement and applied to all harvested stands for consistency.

Harvest eligibility using the foregoing logic was determined by using no-harvest simulations for each simulation period where there had been no prior management simulated. Different harvest eligibility and/or harvest prescriptions could be determined on up to five simulation periods for each site and zone. When a stand was determined to be harvest-eligible, FVS keyword files were generated that included common FVS keywords (as described under no-harvest simulations) along with harvest prescription keywords. See Appendix E for FVS keywords used to simulate each harvest type. Post-harvest simulations were conducted for the number of periods necessary to produce an overall 50-year simulation period. Because no high elevation sites met harvest eligibility requirements, harvest was not simulated for these sites.

Post-Processing and Data Analysis

Simulation results were compiled into one comprehensive table. (See Appendix F for a data dictionary for the comprehensive results table). To facilitate interpretation of harvest eligibility and prescription, the following information was captured for harvest records:

- Stream width from the EWRAP Phase 1 database;
- Whether the stand was in the bull trout overlay based on BTO map;
- Stream temperature class from the DNR stream temperature layer;
- Site class from EWRAP Phase 1 data;
- Elevation from the EWRAP Phase 1 data;
- Timber habitat type calculated from elevation (WAC 222-16-010);
- Minimum shade requirement for the site (WAC 222-30-040 and Forest Practices Board Manual Section M-1); and,

- Prescription type for inner and outer zones from application of WAC 222-030-022(1)(b) WAC 222-030-022(1)(c) respectively.

The following simulation output was then captured for each site, simulation type (no-harvest or harvest), harvest period (harvest simulations only), simulation period, and tree category (live/dead, by dbh class), by regulatory zone:

- Standing tree quadratic mean diameter, basal area per acre, trees per acre, stand density index, Curtis' relative density, board-foot, and cubic-foot volume;
- Harvested tree quadratic mean diameter, basal area per acre, TPA, board-foot volume, and cubic-foot volume; and,
- Forest health and risk metrics included:
  - Predicted surface and total flame lengths
  - Risk rating for each insect and pathogen from Hessburg et al. (1999).

Stand density, tree volume, and flame length metrics were calculated by FVS using internal FVS functions. For sites in the east Cascades, north central Washington, and northeast Washington, methods based on Behre's Hyperbola model were used to calculate tree volumes (USDS Forest Service 1978). For sites in southeast Washington, methods based on Flewelling's Stem Profile model were used (Flewelling and Raynes 1993; Flewelling 1993). Merchantability specifications for board-foot volume included a 1-foot stump and 4.5-inch top inside bark for all species, a 6-inch minimum dbh for lodgepole pine, and a 7-inch minimum dbh for all other species. Cubic-foot volumes included the top and stump.

Hessburg et al. (1999) risk ratings represented the susceptibility of vegetation to alteration from various insect and disease pathogens. They were calculated within FVS using COMPUTE statements developed for this project (see above). Information regarding landscape parameters in the Hessburg et al. (1999) risk ratings, host connectivity, logging disturbance, and topographic setting, did not exist so were held constant at 2 (moderate connectivity), 1 (no logging), and 1 (other settings or no host present) respectively. Stand level parameters were informed by FVS output. Parameters and risk ratings varied for the 20 pathogens evaluated. For more information on risk ratings, see Hessburg et al. (1999).

Tests for statistically significant differences between timber habitat types, regulatory zones, growth periods, and/or harvest timing were performed with ANOVA, using the aov function in the R statistical software environment (R Core Team 2018), for current and year 50 conditions, and repeated measures ANOVA, using the aov_car function in the afex R package (Singmann et al. 2018) for growth trajectories. All analyses used an alpha level of 0.05. All ANOVA models included, in order, timber habitat type and regulatory zone with growth year and harvest year added as needed. Because outer zones were not present at all sites it was necessary to use two repeated measures ANOVA tests: one to test differences between core and inner zones using all sites, and a second to test differences between core, inner, and outer zones. We used only the sites with outer zones to avoid errors related to a sparse error matrix. Where significant differences were found, pair-wise comparisons were performed using the Tukey Honestly Significant Difference test following ANOVA or pairwise t-tests with Bonferroni corrections, following repeated measures ANOVA. Pair-wise comparisons were limited to: among timber habitat types, regulatory zones, growth periods, and/or harvest timings across all sites and among regulatory zones, growth periods, and/or harvest timings across sites within timber habitat types separately if there were significant differences between habitat types.

RESULTS

Summary of Current Riparian Stand Conditions

Most sites sampled in the EWRAP occurred within the ponderosa pine (PP, N=42) and mixed conifer timber habitat types (MC, N = 58) as defined in WAC 222-16-010. Overall, stand ages in the EWRAP data set ranged from 23 to 155 years (Figure 3), including include two MC plots with no live trees and no stand age. Stand ages at most sites ranged from 40 and 120 years old. The PP timber habitat type sites tended to have a higher proportion of young stands than the MC sites, with 73% and 65% of the stands $\leq$ 80 years old, respectively. Only three sites were sampled within the high elevation timber habitat type (HE). Of these, only two sites had trees as one site burned prior to sampling. None of the HE sites were eligible for harvesting within the next 50 years according to the WAC described in the previous section. Therefore, these sites were excluded from further analyses. Additionally, two MC sites (3256 and 23562) had, no trees in any regulatory zone and were also excluded from further analyses. After excluding the HE sites and sites without trees, data from 42 PP sites and 56 MC sites were used for analyses.

Not all sites had outer zones, as reported in the EWRAP Phase 1 Report (Bonoff et al. 2008). Outer zones were not required on any streams at class IV and V sites or on large steams at class III sites. Among the 42 PP timber habitat type sites, 22 had outer zones, including 3 of 15 sites on large streams and 19 of 27 sites on small streams. Among the 56 MC timber habitat type sites, 21 had outer zones, including 9 of 25 sites on large streams and 12 of 31 sites on small streams.

Stand density and tree size

Distributions of stand density and size of trees > 6 inches dbh on EWRAP sites as measured with basal area per acre (BA), quadratic mean diameter (QMD), trees per acre (TPA), Reinike's Stand Density Index (SDI) and Curtis' Relative Density (RD) were summarized **Error! Reference source not found.**by timber habitat type and regulatory zone. Statistics are listed in Appendix G. Overall, stand BA, QMD, TPA, SDI and RD were comparable among zones, with some small non-significant differences between timber habitat types and across zones. For instance, the overall mean basal area across all sites regardless of timber habitat type or zone was 122 ft^2/ac. Mean basal areas for PP and MC sites were nearly identical at 122 ft^2/ac and 121 ft^2/ac respectively. Across regulatory zones, regardless of timber habitat type, basal areas generally decreased moving away from the stream, with mean basal area values of 128 ft^2/ac, 116ft^2/ac, and 123 ft^2/ac for core, inner, and outer zones respectively. Basal area patterns varied across regulatory zones in different timber habitat types. For example, basal area on PP sites decreased moving away from the water, with mean basal areas of 127 ft^2/ac, 126 ft^2/ac, and 106 ft^2/ac in the core, inner, and outer zones, respectively. Conversely, basal area on MC sites generally increased moving away from the stream, with mean basal areas 128 ft^2/ac, 108 ft^2/ac, and 141 ft^2/ac in the core, inner and outer zones respectively. These trends generally held for all size and density metrics within these two timber habitat types.

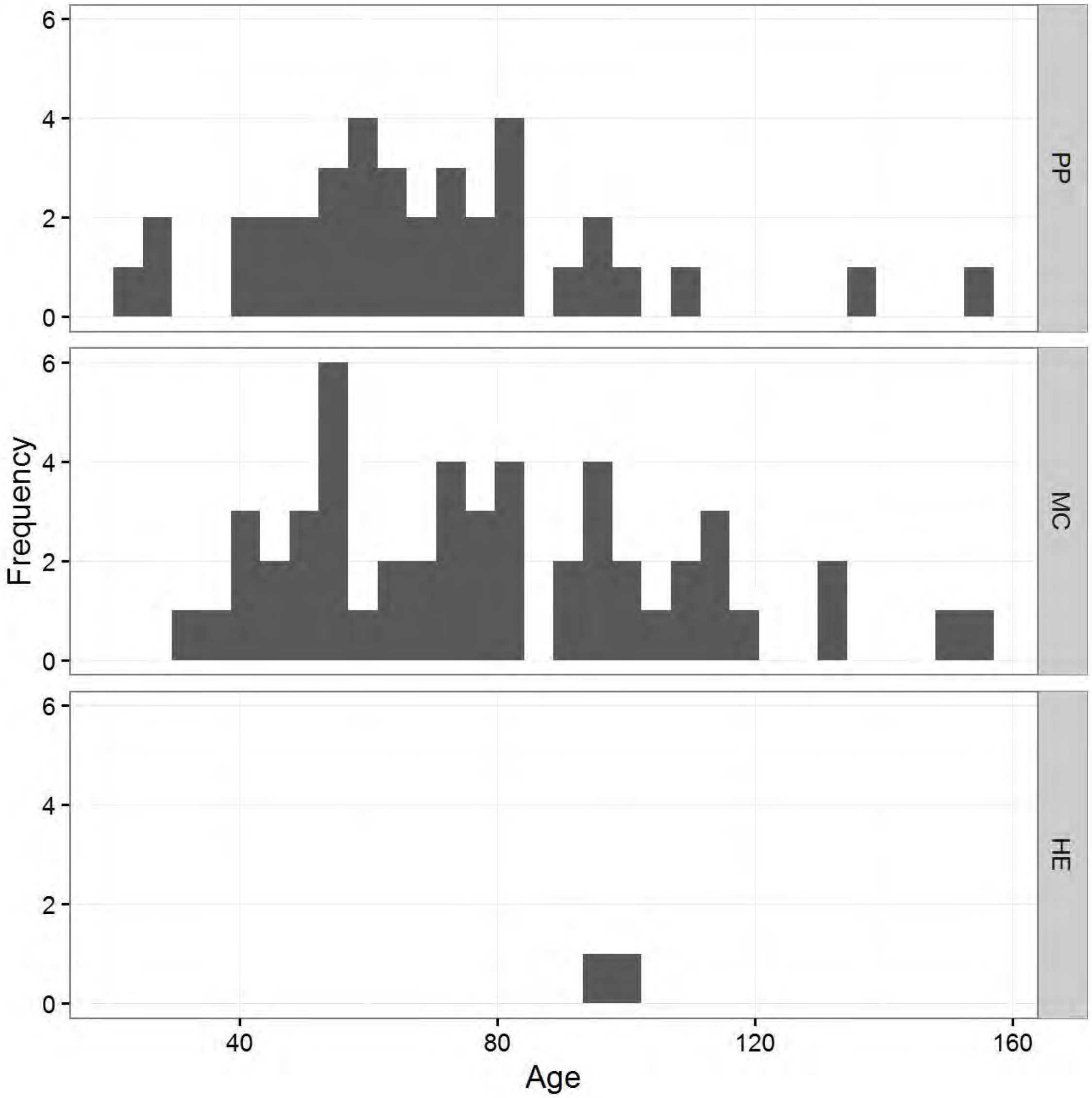


Figure 3: Age distributions for sites where age was measured for ponderosa pine (PP, N = 37 of 42) , mixed conifer (MC, N = 52 of 58), and high elevation (HE, N = 2 of 3) timber habitat types.

Standing volume

Trends in standing volume on EWRAP sites, in terms of board-foot and cubic-foot volumes per acre (Figure 5), were similar to those found for stand density metrics. Analysis of standing volume revealed small non-significant differences between timber habitat types and regulatory zones. On average, standing volume decreased with increasing distance from stream, moving from the core zone to the inner zone. For example, the overall mean cubic-foot volume across all sites regardless of timber habitat type or zone was 3,924 ft^3/ac. Mean cubic-foot volumes for PP and MC sites were nearly identical at 3,917 ft^3/ac and 3,930 ft^3/ac respectively. Across regulatory zones, regardless of timber habitat type, cubic-foot volumes generally decreased moving away from the stream with 4,153 ft^3/ac, 3,694 ft^3/ac, and 3,927 ft^3/ac for core, inner, and outer zones respectively. Between timber habitat types there were different patterns across regulatory zones. For PP sites, basal area decreased moving away from the stream with mean basal areas of 4,066 ft^3/ac, 4,059 ft^3/ac, and 3,361 ft^3/ac in the core, inner, and outer zones respectively. For MC sites, basal area generally increased moving away from the stream with mean basal areas of 4,218 ft^3/ac, 3,421 ft^3/ac, and 4,521 ft^3/ac in the core, inner and outer zones respectively. These trends generally held for board-foot volume across both timber habitat types.

All stand size, density, and volume metrics had high levels of variability and some large outliers (Figure 4 and Figure 5) that may have been specific to conditions in eastern Washington riparian zones or artifacts of the sampling and data compilation procedures. High levels of variability were accompanied by large coefficients of variability. Overall, coefficients of variation for size, density, and volume metrics range from 0.9 to 1.7 for board-foot volume and QMD, respectively. As the data were segregated by timber habitat type and/or regulatory zone, the range expanded, reaching a range of 0.7 to 2.2 for board-foot volume in outer zones at PP sites and QMD from inner zones at PP and MC sites.

A few sites had unusually high QMD, TPA, BA, SDI, and RD values that could have been outliers:

- 11 sites (6 PP and 5 MC) had QMDs of over 25 inches for trees $\geq$ 6 inches dbh;
- 18 sites (7 PP and 11 MC) had over 300 TPA for trees $\geq$ 6 inches dbh;
- 14 sites (7 PP and 7 MC) had basal area values of over 300 ft^2/ac for trees $\geq$ 6 inches dbh;
- 9 sites had SDI values of over 500 for trees $\geq$ 6 inches dbh; and
- 12 sites (5 PP and 7 MC) had RD values over 80, including two sites with RD values of 108 and 160.

Similar outlier patterns were seen in the board-foot and cubic-foot volume estimates. These high levels of variability and outliers may have influenced mean value calculations and statistical tests.

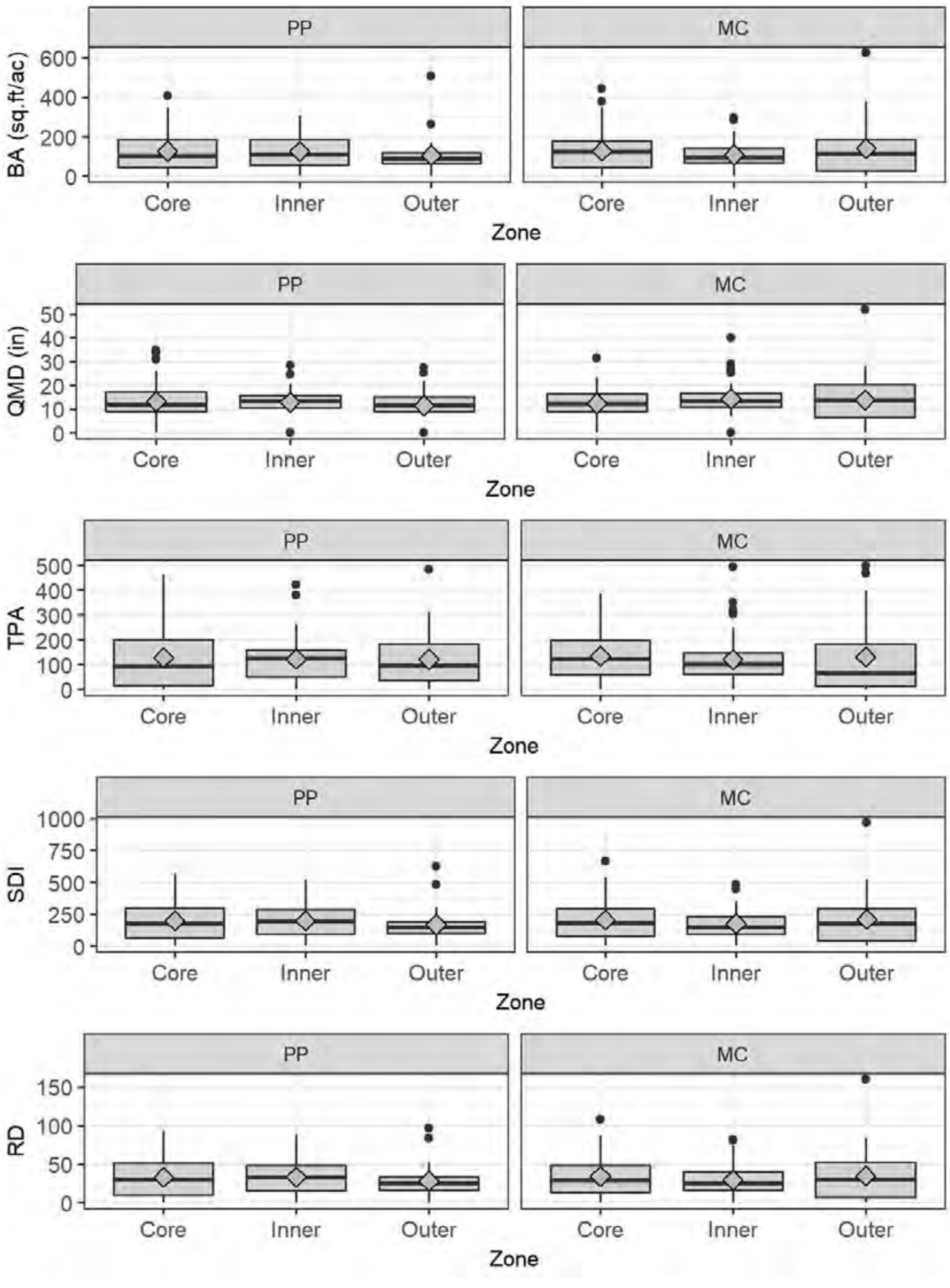


Figure 4: Distributions of basal area per acre (BA), quadratic mean diameter (QMD), trees per acre (TPA), Stand Density Index (SDI), and Curtis' Relative Density (RD) for core, inner, and outer regulatory riparian zones by ponderosa pine (PP) and mixed conifer (MC) timber habitat types. The gray boxes represent the 25th and 75th percentiles and the horizontal black lines the median of the data. The vertical lines extend to the range of the data or 1.5 time the interquartile range (the range from the 25th to the 75th percentile). Black points are potential outliers. The gray diamonds are the means of the data.

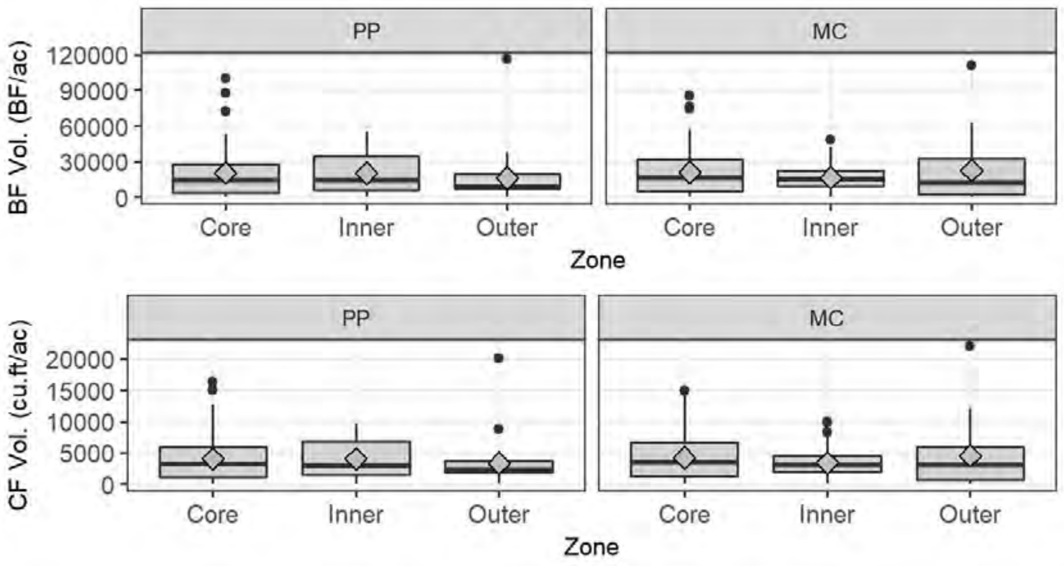


Figure 5: Distributions of board-foot volume (BV Vol.) and cubic-foot volume (CF Vol.) for core, inner, and outer regulatory riparian zones by ponderosa pine (PP) and mixed conifer (MC) timber habitat types. The gray boxes represent the 25th and 75th percentiles and the horizontal black lines the median of the data. The vertical lines extend to the range of the data or 1.5 time the interquartile range (the range from the 25th to the 75th percentile). Black points are potential outliers. The gray diamonds are the means of the data.

Insect and disease susceptibility

Based on the models of Hessburg et al. (1999), overall ratings of susceptibility to insects and disease were generally low. The number of sites rated as high, moderate, or low susceptibility were presented by regulatory zone for PP and MC sites (**Error! Reference source not found.**Figure 6). However, among PP sites, higher susceptibility ratings occurred in the core and inner zones. Core and inner zones tended to have moderate susceptibility to western and mountain pine beetles (T1WPB, T2WMPB, T1MPB), spruce beetle (SB), Armillaria root disease (AROS), laminated root rot (PHWE), S-group *annosum* root disease (HEANS), and *Schweinitzii* root and butt rot (SRBR). Among MC sites, there were some moderate and occasional high susceptibility ratings in the core and inner zones. Higher susceptibility to western spruce budworm (WSB), *Armillaria* root disease (AROS), and laminated root rot (PHWE) was also seen in the core and inner zones.

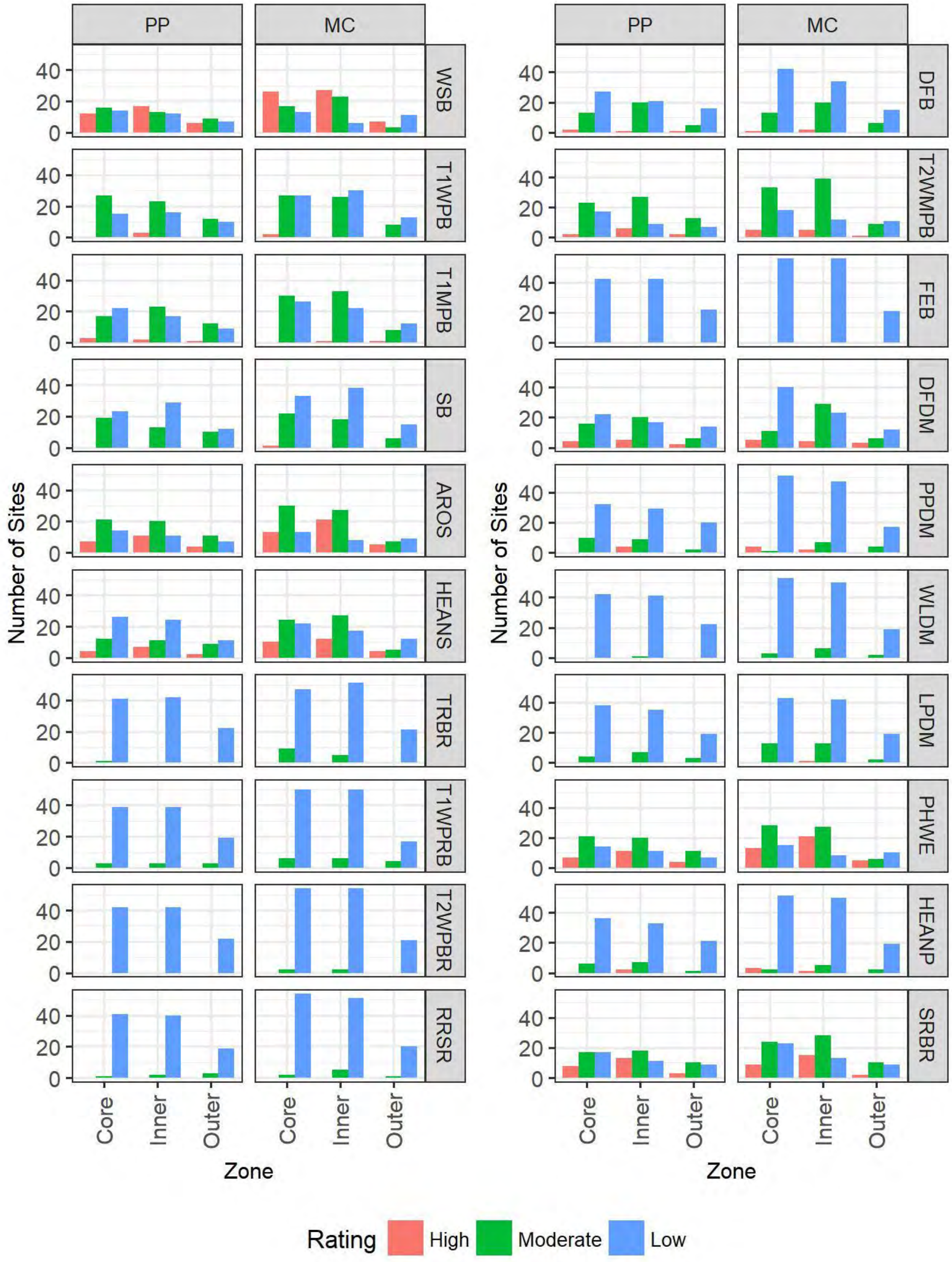


Figure 6: Insect and disease rating counts for ponderosa pine (PP, left column) and mixed conifer (MC, right column) by regulatory zone. Ratings are based on Hessburg *et al.* (1999). Definitions of insect and disease codes are defined in Table 2.

Table 2: Definitions for the Hessburg et al. (1999) insect and disease codes used in insect and disease summary tables.

Code	Insect or Disease
WSB	Western spruce budworm
DFB	Douglas-fir beetle
T1WPB	Western pine beetle in mature and old ponderosa pine stands
T2WMPB	Western pine beetle and mountain pine beetle in immature, high density ponderosa pine stands
T1MPB	Mountain pine beetle in immature, high density lodgepole pine stands
FEB	Fir engraver beetle
SB	Spruce beetle
DFDM	Douglas-fir dwarf mistletoe
PPDM	Western dwarf mistletoe
WLDM	Western larch dwarf mistletoe
LPDM	Lodgepole pine dwarf mistletoe
AROS	*Armillaria* root disease
PHWE	Laminate root rot
HEANS	S-group *annosum* root disease
HEANP	P-group *annosum* root disease
TRBR	*Tomentosus* root and butt rot
SRBR	*Schweinitzii* root and butt rot
T1WPRB	White pine blister rust in western white pine
T2WPBR	White pine blister rust in whitebark pine
RRSR	Rust-red stringy rot

Wildfire risk

Distributions of potential wildfire total flame lengths were summarized by timber habitat type and regulatory zone (Figure 7). Total flame length was used as a surrogate for fire-related mortality susceptibility, with the assumption that flame length is proportional to susceptibility of the sites to fire-related morality. Accordingly, sites with lower total flame lengths should burn with lower intensity, thereby killing fewer trees, than sites that burn with longer flame lengths. Mean total flame length was not significantly different among timber habitat types or among regulatory zones. Total flame lengths ranged from 1 to 114 feet, with an overall mean of approximately 31 feet. Although many sites had relatively short flame lengths, which did not present high levels of risk, values at other sites indicated high susceptibility to wildfire-related mortality.

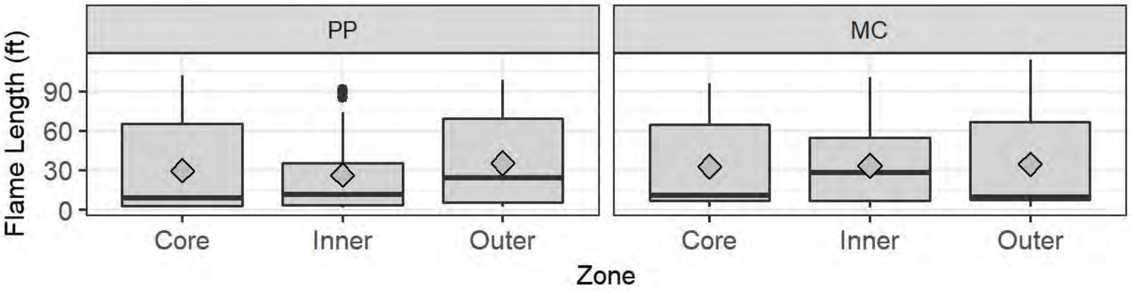


Figure 7: Wildfire potential total flame length, in feet, distributions for core, inner, and outer regulatory riparian zones by ponderosa pine (PP) and mixed conifer (MC) timber habitat types. The gray boxes represent the 25th and 75th percentiles and the horizontal black lines the median of the data. The vertical lines extend to the range of the data or 1.5 time the interquartile range (the range from the 25th to the 75th percentile). Black points are potential outliers. The gray diamonds are the means of the data.

Trajectory of Riparian Stand Conditions Without Management

Without management, stands continue to increase in stand density and tree size, on average (Figure 8) over the 50-year simulation period. Overall basal area per acre periodic annual increment (PAI) for inner and outer zones was 1.6 ft^2/ac, or 1.6%, per year, with significant differences among core and inner zones across all sites among timber habitat types ($p = 0.019$), regulatory zones ($p = 0.002$), and growth periods ($p = 0.048$) for core and inner zones at all sites and among zones ($p = 0.004$) for those sites with an outer zone. Among PP sites, basal area PAI averaged approximately 1.4 ft^2/ac., or 1.3%, per acre per year, while among MC sites, basal area PAI averaged about 1.8 ft^2/ac, or 1.8% per year. Among regulatory zones, basal area PAI increased moving away from the stream with core, inner, and outer zones averaging 1.3 ft^2/ac, or 1.3%, per year, and 1.8 ft^2/ac, or 1.7%, per year, and 2.1 ft^2/ac, or 1.9%, per year respectively. Among sites with an outer zone, outer zone basal PAI was significantly different from core zone PAI ($p < 0.0001$) but marginally not significantly different than inner zone PAI ($p = 0.521$). Over the 50-year growth simulations, basal area PAI initially increased, beginning at 1.5 ft^2/ac, or 2.1%, per year to 1.8 ft^2/ac, or 1.5-2.0%, per year during the second and third periods, before declining to 1.5 ft^2/ac, or 1.0%, per year during the fifth period as available growing space decreased within sites. Although differences among growth periods were marginally significant, none of the pairwise comparisons were significant after Bonferroni correction for multiple comparisons. Across all sites, QMD PAI averaged 0.07 inches, or 0.6%, per year, with significant differences in interaction of timber habitat type and regulatory zone ($p = 0.02$). However, PAI comparisons between regulatory zones within timber habitat types were not significantly different after Bonferroni corrections. Trees per acre with dbh $\geq$ 6 inches increased during growth simulation as trees grew into the 6-inch and greater size class at a rate greater than mortality. Overall, trees per acre PAI was 0.5 trees per acre, or 1.6% per year, with significant differences between timber habitat types ($p = 0.03$) and regulatory zones ($p = 0.01$). Between timber habitat types, trees per acre PAI for PP sites average 0.3 trees per acre, or 1.0%, per year and 0.7 trees per acre or 2.1% for MC sites where more seedlings and advanced regeneration occurred. Among regulatory zones, trees per acre PAI increased moving away from the stream where the core, inner, and outer zones were 0.03 trees per acre, or 0.8%, 0.8 trees per acre, or 2.6%, and 0.8 trees per acre, or 0.7%, per year respectively. However, no pairwise comparisons were significant after Bonferroni corrections.

As stands develop, size-density relationship metric values for Reinike's Stand Density Index (SDI) and Curtis' Relative Density (RD) increased (Figure 9). Overall SDI PAI averaged 2.2 units, or 1.4%, per year with significant differences among timber habitat types ($p = 0.01$), regulatory zone ($p = 0.001$). Among timber habitat types, SDI PAI in PP sites averaged 1.9 units, or 1.1%, per year, which was less than SDI PAI in MC sites, where it averaged 2.4 units, or 1.6%, per year. Among regulatory zones, SDI PAI increased moving away from the stream with core zone PAI being significantly different than inner ($p < 0.0001$) and outer zones ($p = 0.0001$). SDI PAI averaged 1.6 units, or 1.1% per year, 2.5 units, or 1.6% per year, and 2.8 units, or 1.6%, per year for core zones, inner, and outer zones respectively.

Similar patterns were seen in RD. Overall, RD PAI averaged 0.4 units, or 1.4% per year with significant differences among timber habitat type ($p = 0.012$) and regulatory zone ($p = 0.001$). Among timber habitat types, RD PAI averaged 0.3 units or 1.1% per year, %, and 0.4 units or 1.6%, per year for PP sites and MC sites, respectively. RD PAI also increased moving away from the stream with core zone PAI significantly different than inner ($p < 0.0001$) and outer ($p < 0.0001$) zones, where they were present, averaging 0.3 units, or 1.0%, 0.4 units, or 1.6%, and 0.5 units, or 1.5%, for core, inner, and outer zones respectively.

Board-foot and cubic-foot volumes increased as stands develop, following trajectories that were comparable to basal area and size-density measures (Figure 10). Overall, board-foot volume PAI averaged 393 board-feet acre, or 2.3%, per year with significant differences among regulatory zones ($p = 0.01$) and growth periods ($p = 0.0002$). Among regulatory zones, board-foot volume increased moving away from the stream, with core zone PAI being significantly different than inner zones ($p = 0.001$) and outer zones ($p = 0.005$) where they were present. Board-foot PAI in the core, inner, and outer zones averaged 340 board-feet per acre, or 2.1%, 409 board-feet per acre, or 2.3% and 480 board-feet per acre, or 2.7%, per year respectively. As stands developed, board Board-foot volume PAI increased from 326 board-feet per acre, or 3.2%, per year during the first period to a maximum of 420 board-feet per acre, or 1.8%, per year in the fourth period. After applying Bonferroni corrections no pairwise comparisons were significantly different. Cubic-foot volume PAI followed similar trajectories with an overall average of 69 cubic-feet per acre, or 2.1%, per year with significant differences among regulatory zones ($p = 0.004$) and growth periods ($p = 0.047$). Among regulatory zones, cubic-foot volume also increased moving away from the stream, with core zone PAI values being significantly different than inner zone ($p < 0.0001$) and outer zone ($p = 0.0006$) values, which averaged 58 cubic-feet per acre, or 1.7%, 73 cubic-feet per acre, or 2.1% and 85 cubic-feet per acre, or 2.7%, per year respectively. Board-foot volume PAI increased as stands developed, beginning at 61 cubic-feet per acre, or 2.8%, year during the first period then increasing to a maximum of 73 cubic-feet per acre or 2.0% per year in the third period and declining to 69 cubic-feet per acre or 1.3%, per year as available growing space decreased. After applying Bonferroni corrections no pairwise comparisons were significantly different.

Mortality of trees with dbh $\geq$ 6 inches, measured as basal area per acre and trees per acre, and the size of mortality trees, measured as quadratic mean diameter, were projected to increase in stands without management as stand density and competition-related mortality increased (Figure 11). Overall basal area mortality rate was relatively low, averaging 1.1 ft^2/acre or 0.5%, per year, with significant differences among growth periods ($p < 0.0001$) and non-significant differences among timber habitat types and regulatory zones. Basal area mortality rate increased through time, beginning at 0.8 ft^2/ac, or 0.4%, per year in the first growth period then increasing to 1.5 ft^2/ac, or 0.6%, per year during the final growth period as available growing space decreased and competition mortality increased. Mortality differed significantly between: 1) the first fourth ($p = 0.0014$),)and fifth ($p < 0.0001$) growth periods; 2) the second forth ($p < 0.0001$),) and fifth ($p < 0.0001$) growth periods;), and 3) the third and fifth ($p < 0.0001$) growth periods.). Trees per acre mortality rate was relatively low, averaging 1.2 trees per acre, or 0.6% per year, with significant differences among growth periods ($p < 0.0001$) but no significant differences among timber habitat types or regulatory zones. Initially, mortality averaged 1.1 trees per acre, or 0.5%, per year and increased to 1.7 trees per acre or 0.8% per year during the final growth period. Trees per acre mortality rate also differed significantly: 1) between the first, fourth ($p = 0.0008$) and fifth ($p < 0.0001$) periods; 2) the second and fifth periods ($p = 0.0003$); and 3) the third and fifth periods ($p = 0.0009$). Over time, the median size of mortality trees increased from approximately 13.3 inches dbh to 15.4 inches dbh.

Increases in moderate and high susceptibility to insect and disease risk (Figure 12 through Figure 16, and Appendix G) were expected as stands developed without management, growing space decreased, and competition increased. Among PP sites, the greatest increases in susceptibility were predicted for: 1) western pine beetle (Figure 12) susceptibility with 25% and 14% of the inner and outer zones respectively, moving to moderate; 2) western spruce budworm (Figure 12) with 7%, 10% and 25% of the core, inner and outer zones respectively, moving to high; and 3) *Schweinitzii* root and butt rot (Figure 16) with 20% of the inner zones moving to moderately year 50.

Among MC sites, the greatest increases in susceptibility were predicted for:

- Western pine beetle (Figure 12), with 33% and 23% of the inner and outer zones respectively, moving to moderate;
- Douglas-fir beetle (Figure 12) with 14% of the inner zones moving to moderate,
- Mountain pine beetle (Figure 13) with 10% of the inner zones moving to moderate;
- Western spruce budworm (Figure 12) with 22% of the inner zones moving to high,
- *Armillaria* root disease (Figure 14) with 19% of the inner zones moving to high, and

Laminated root rot (Figure 15) with 17% of the inner zones moving to high in the inner zone by year 50.

Similarly, as stands develop without management or natural disturbances such as wind storms or low intensity fires, total flame length, a surrogate metric for susceptibility to fire-related mortality, were predicted to increase (see Figure 17and Appendix G). Overall, total flame lengths average 39 feet with significant differences among growth years ($p < 0.0001$) but no significant differences between timber habitat types or regulatory zones occurred. Through time, average total flame lengths increased from 31 feet to 43 feet, with significant differences between current conditions and projected conditions at year 30 (p = 0.004), year 40 (p = 0.001) and year 50 (p = 0.002). These differences were driven by increases in PP sites where average total flame lengths increased from 28 feet to 47 feet over the 50-year simulation in core and inner zones respectively.

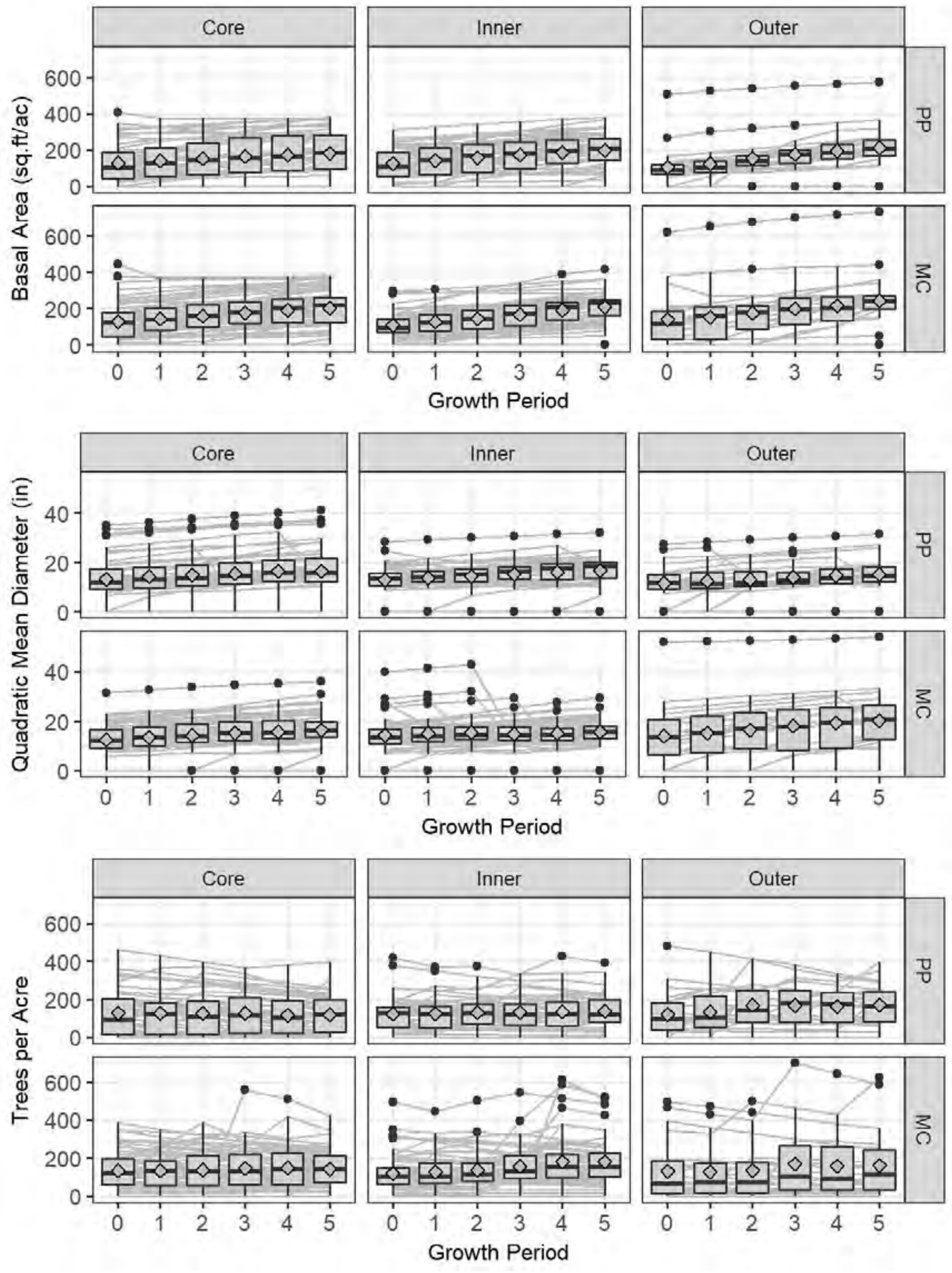


Figure 8: Basal area, quadratic mean diameter and trees per acre distributions for core, inner, and outer regulatory riparian zones by ponderosa pine (PP) and mixed conifer (MC) timber habitat types. The gray boxes represent the 25th and 75th percentiles and the horizontal black lines the median of the data. The vertical lines extend to the range of the data or 1.5 time the interquartile range (the range from the 25th to the 75th percentile). Black points are potential outliers. The gray diamonds are the means of the data. Gray lines are trajectories of individual regulatory zone stands.

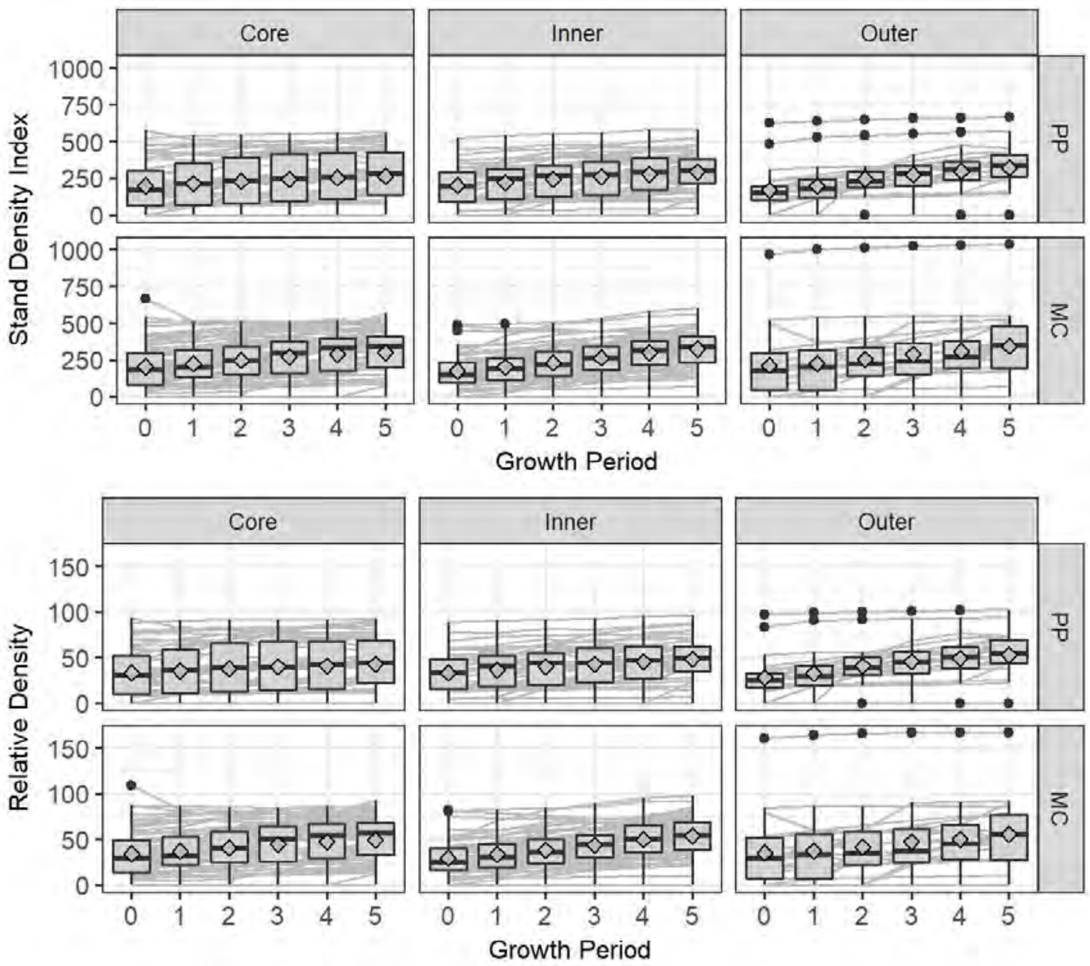


Figure 9: Reineke's Stand Density Index and Curtis' Relative Density distributions for core, inner, and outer regulatory riparian zones by ponderosa pine (PP) and mixed conifer (MC) timber habitat types. The gray boxes represent the 25th and 75th percentiles and the horizontal black lines the median of the data. The vertical lines extend to the range of the data or 1.5 time the interquartile range (the range from the 25th to the 75th percentile). Black points are potential outliers. The gray diamonds are the means of the data. Gray lines are trajectories of individual regulatory zone stands.

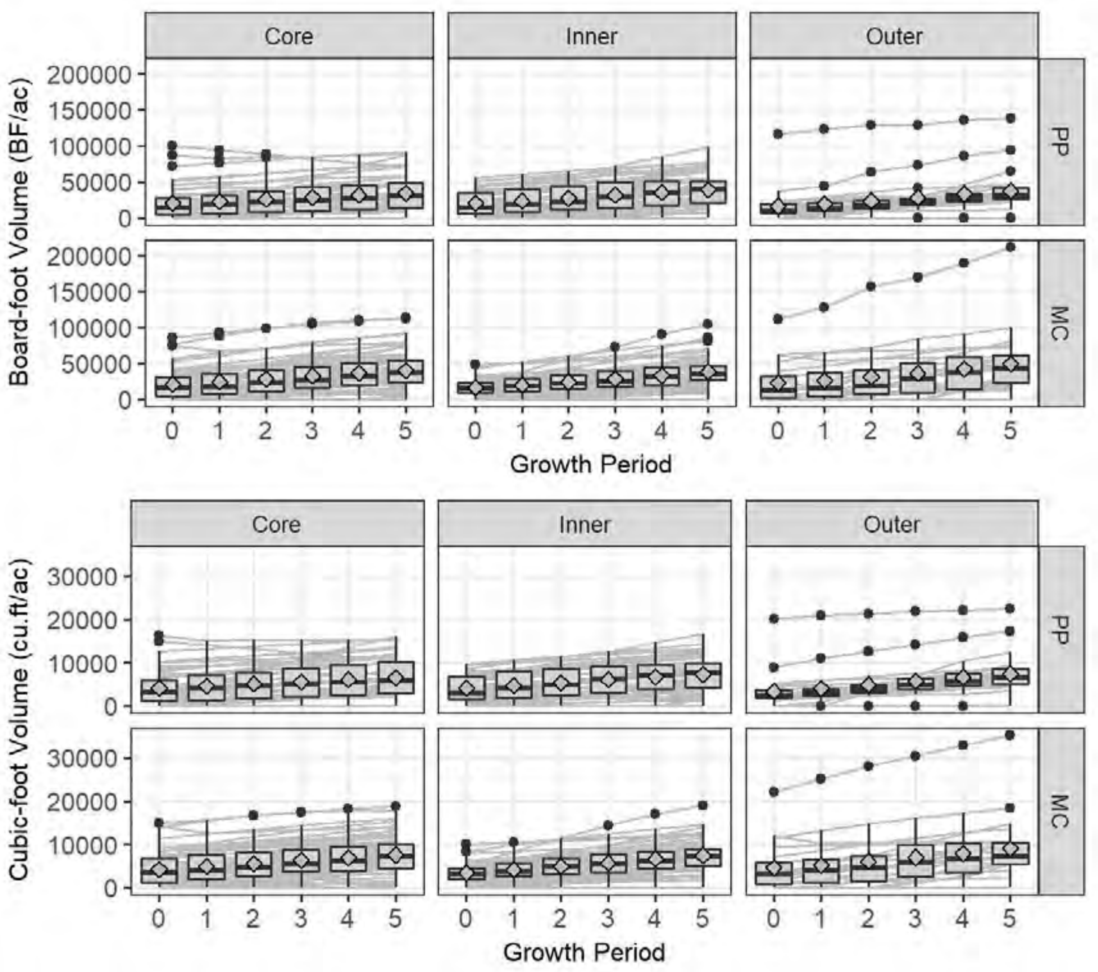


Figure 10: Board-foot volume and cubic-foot volume distributions for core, inner, and outer regulatory riparian zones by ponderosa pine (PP) and mixed conifer (MC) timber habitat types. The gray boxes represent the 25th and 75th percentiles and the horizontal black lines the median of the data. The vertical lines extend to the range of the data or 1.5 time the interquartile range (the range from the 25th to the 75th percentile). Black points are potential outliers. The gray diamonds are the means of the data. Gray lines are trajectories of individual regulatory zone stands.

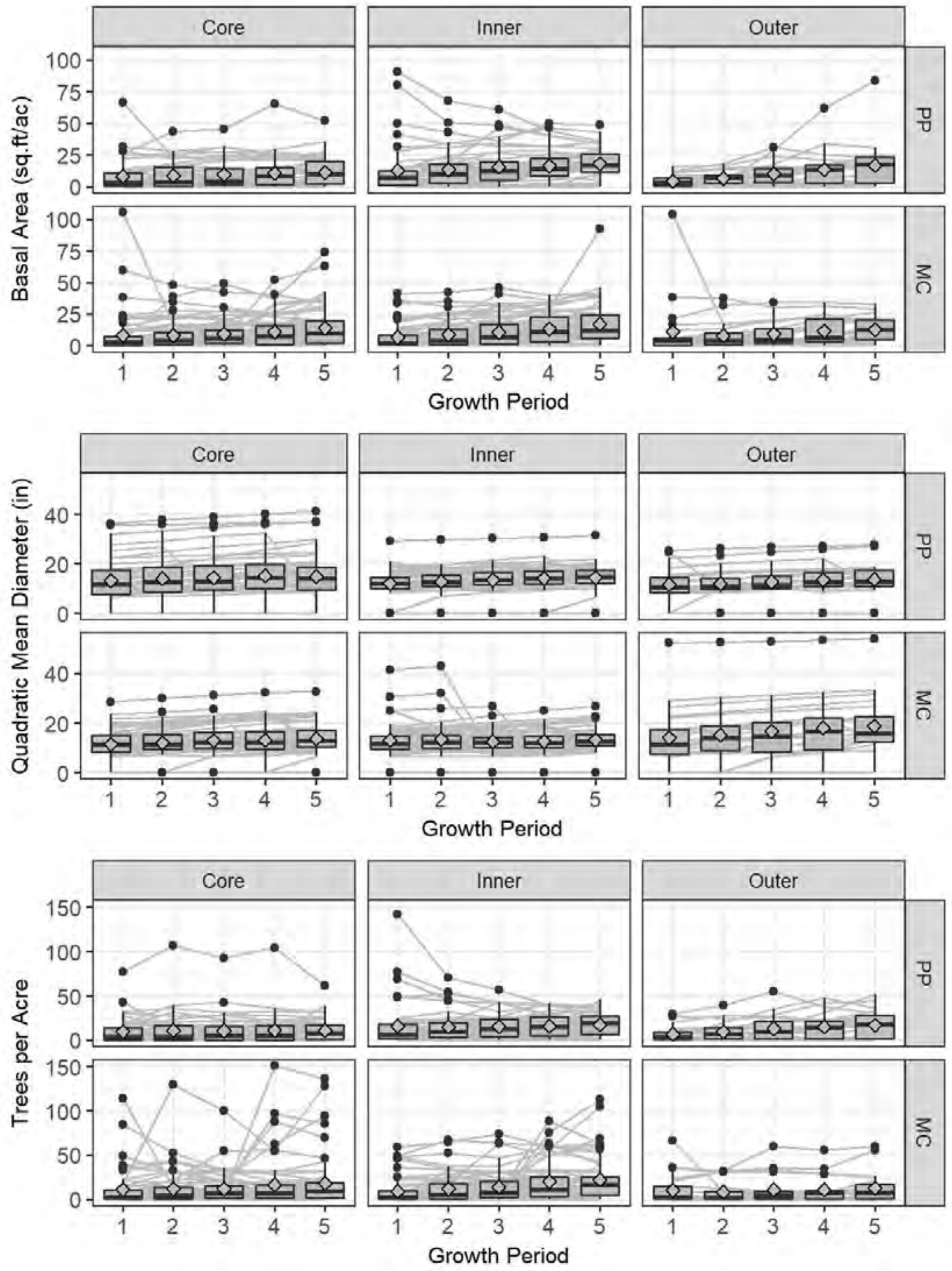


Figure 11: Basal area, quadratic mean diameter and trees per acre distributions or mortality trees with dbh >= 6 inches for core, inner, and outer regulatory riparian zones by ponderosa pine (PP) and mixed conifer (MC) timber habitat types. The gray boxes represent the 25th and 75th percentiles and the horizontal black lines the median of the data. The vertical lines extend to the range of the data or 1.5 time the interquartile range (the range from the 25th to the 75th percentile). Black points are potential outliers. The gray diamonds are the means of the data. Gray lines are trajectories of individual regulatory zone stands.

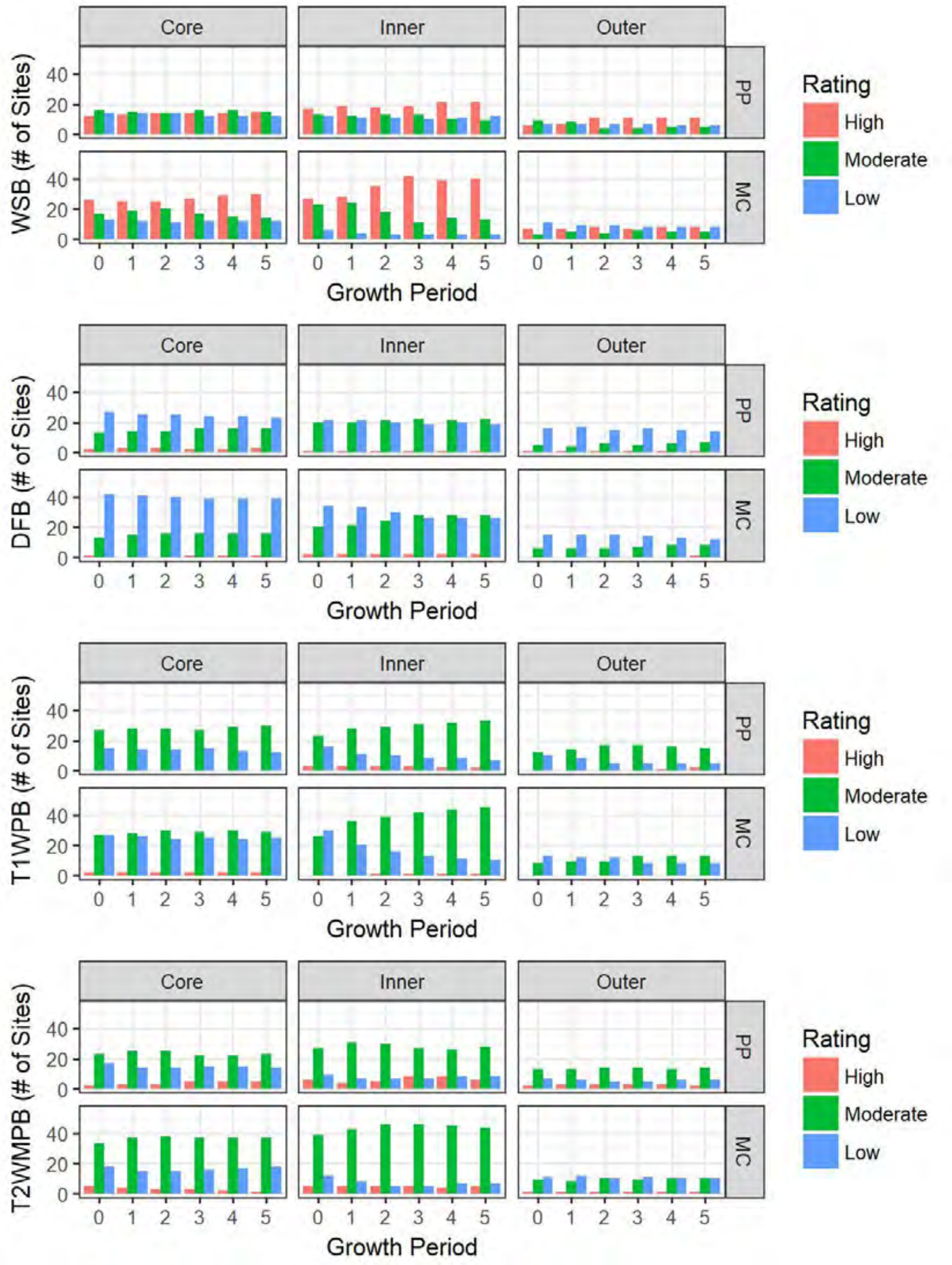
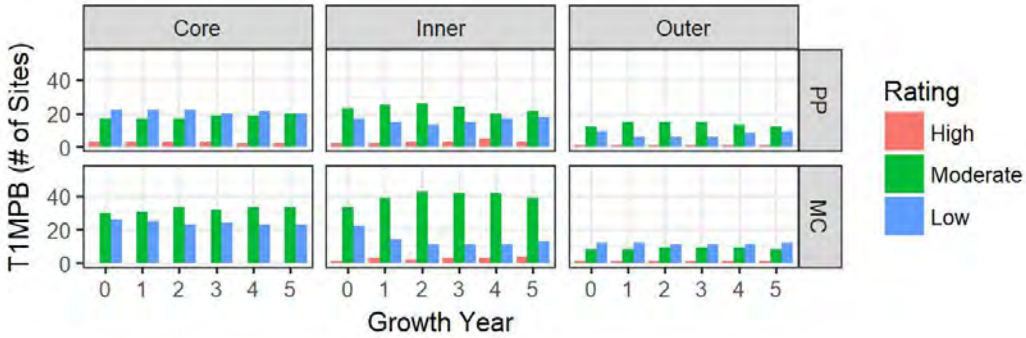
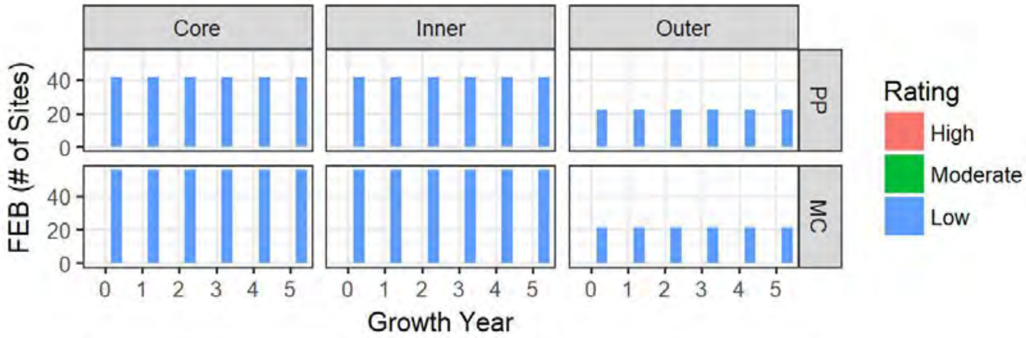
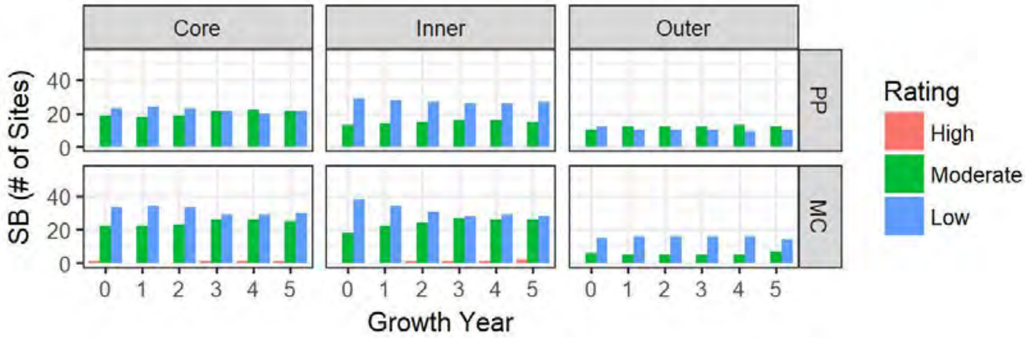
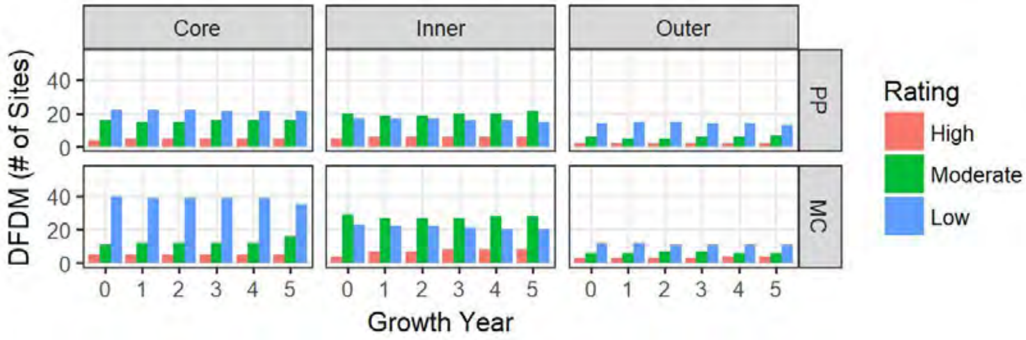


Figure 12: Counts of sites with high, moderate, and low insect susceptibility ratings in core, inner, and outer regulatory riparian zones for ponderosa pine (PP) and mixed conifer (MC) sites for each growth period of a 50-year simulation. Definitions of insect codes are in Table 2.


Core
Inner
Outer
PP
MC
T1MPB (# of Sites)
0
20
40
0
1
2
3
4
5
Growth Year
Rating
High
Moderate
Low


Core
Inner
Outer
PP
MC
FEB (# of Sites)
0
20
40
0
1
2
3
4
5
Growth Year
Rating
High
Moderate
Low


Core
Inner
Outer
PP
MC
SB (# of Sites)
0
20
40
0
1
2
3
4
5
Growth Year
Rating
High
Moderate
Low


Core
Inner
Outer
PP
MC
DFDM (# of Sites)
0
20
40
0
1
2
3
4
5
Growth Year
Rating
High
Moderate
Low

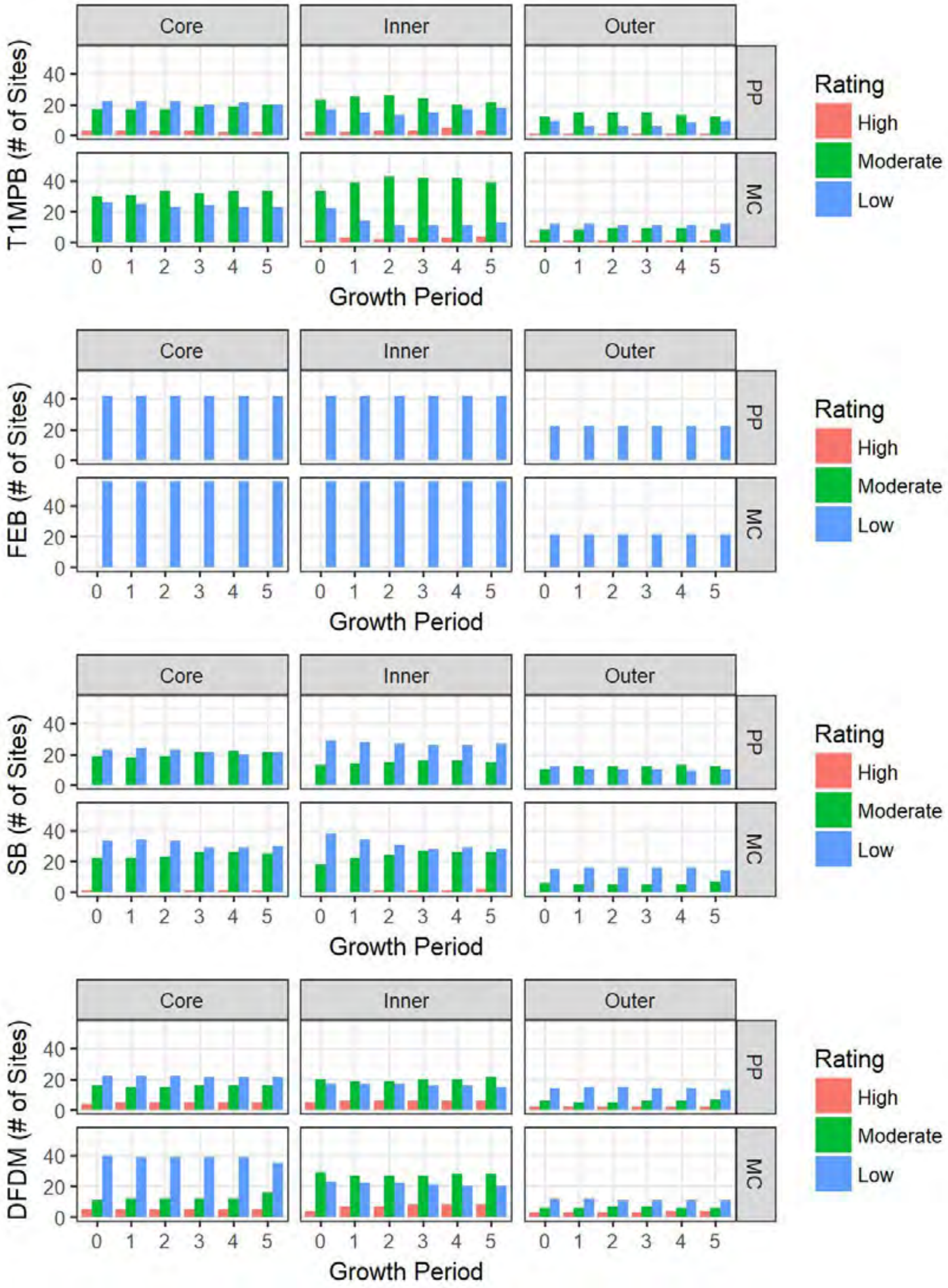
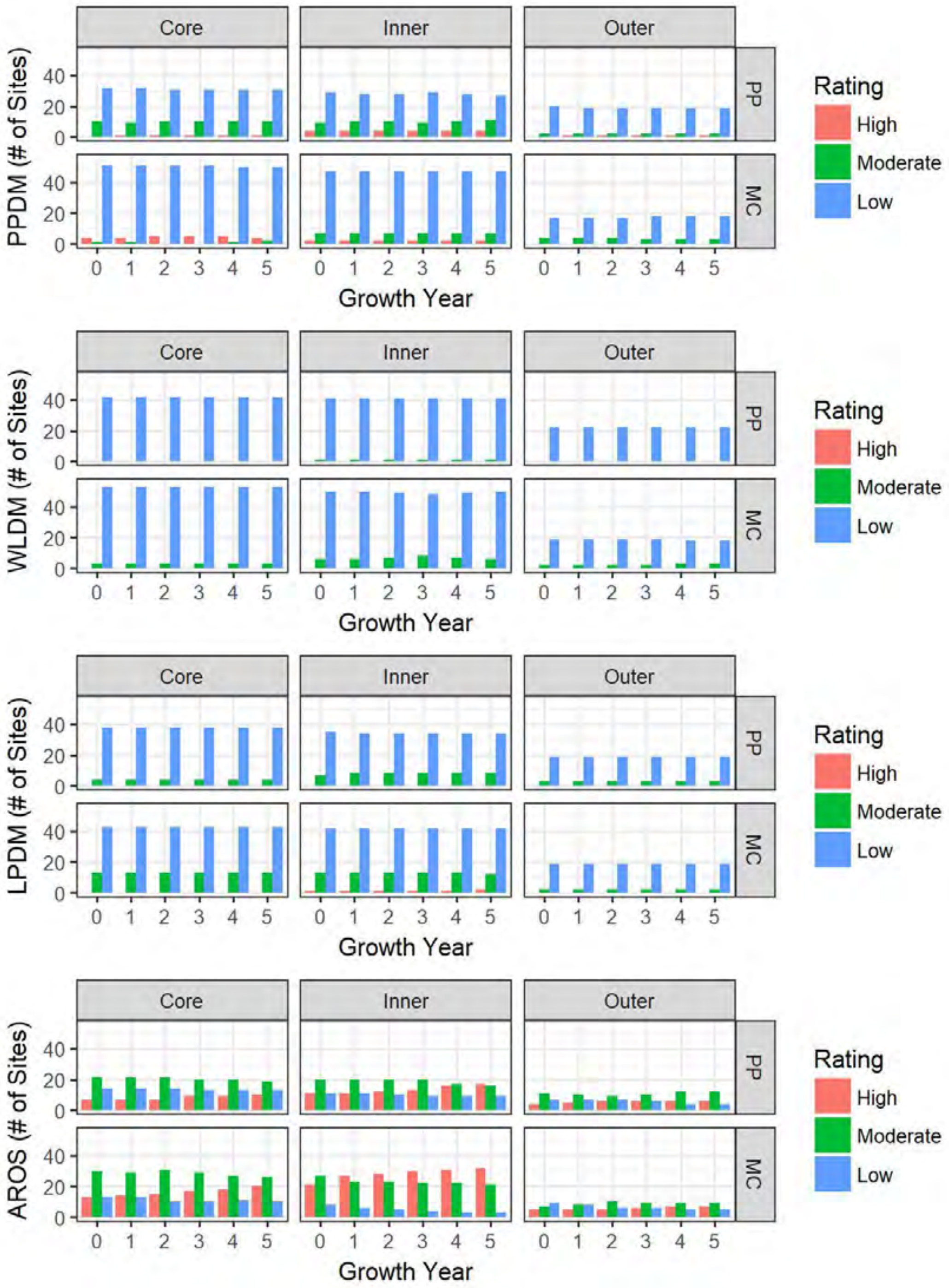


Figure 13: Counts of sites with high, moderate, and low insect and disease susceptibility ratings in core, inner, and outer regulatory riparian zones for ponderosa pine (PP) and mixed conifer (MC) sites for each growth period of a 50-year simulation. Definitions of insect codes are in Table 2.


PPDM (# of Sites)
WLDM (# of Sites)
LPDM (# of Sites)
AROS (# of Sites)
Core
Inner
Outer
PP
MC
0
20
40
0 1 2 3 4 5
Growth Year
Rating
High
Moderate
Low

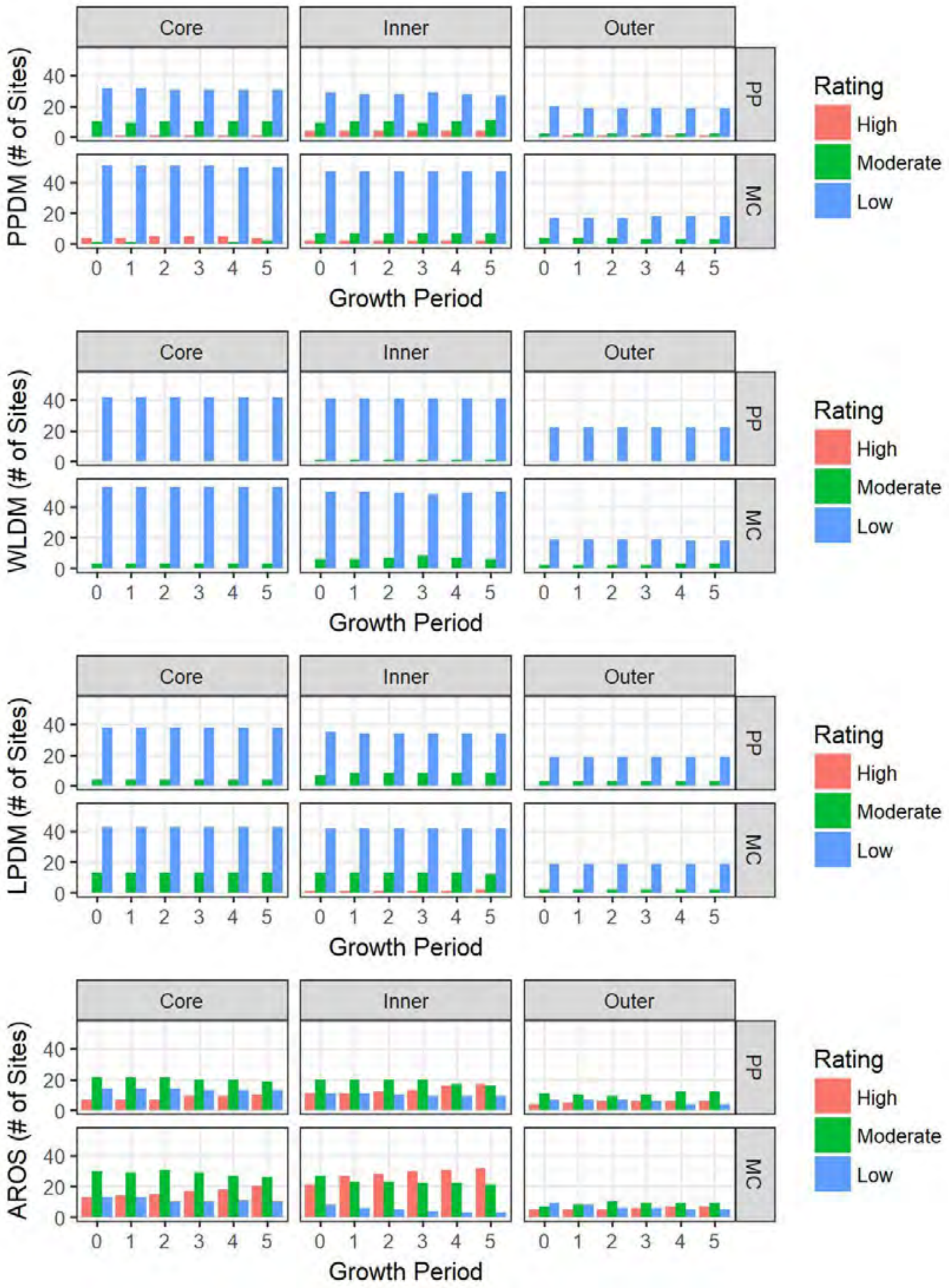
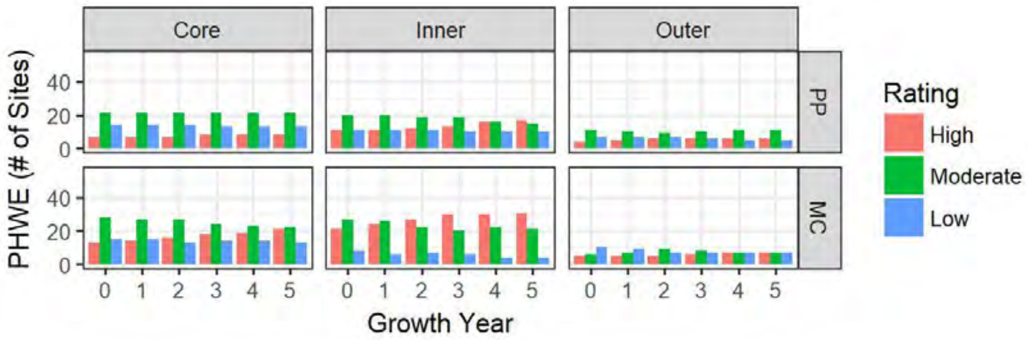
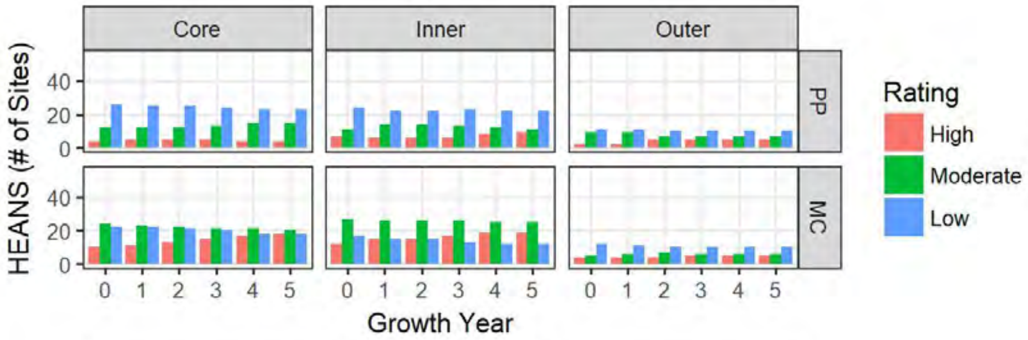
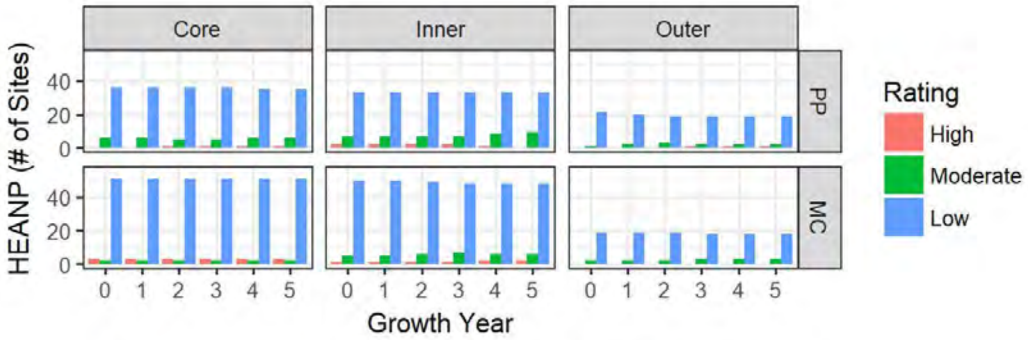
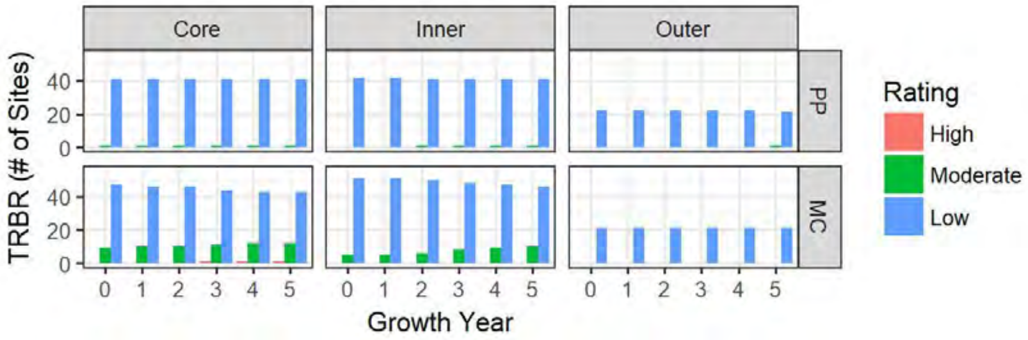


Figure 14: Counts of sites with high, moderate, and low disease susceptibility ratings in core, inner, and outer regulatory riparian zones for ponderosa pine (PP) and mixed conifer (MC) sites for each growth period of a 50-year simulation. Definitions of insect codes are in Table 2.


Core
Inner
Outer
PP
MC
PHWE (# of Sites)
0
20
40
0 1 2 3 4 5
Growth Year
Rating
High
Moderate
Low


Core
Inner
Outer
PP
MC
HEANS (# of Sites)
0
20
40
0 1 2 3 4 5
Growth Year
Rating
High
Moderate
Low


Core
Inner
Outer
PP
MC
HEANP (# of Sites)
0
20
40
0 1 2 3 4 5
Growth Year
Rating
High
Moderate
Low


Core
Inner
Outer
PP
MC
TRBR (# of Sites)
0
20
40
0 1 2 3 4 5
Growth Year
Rating
High
Moderate
Low

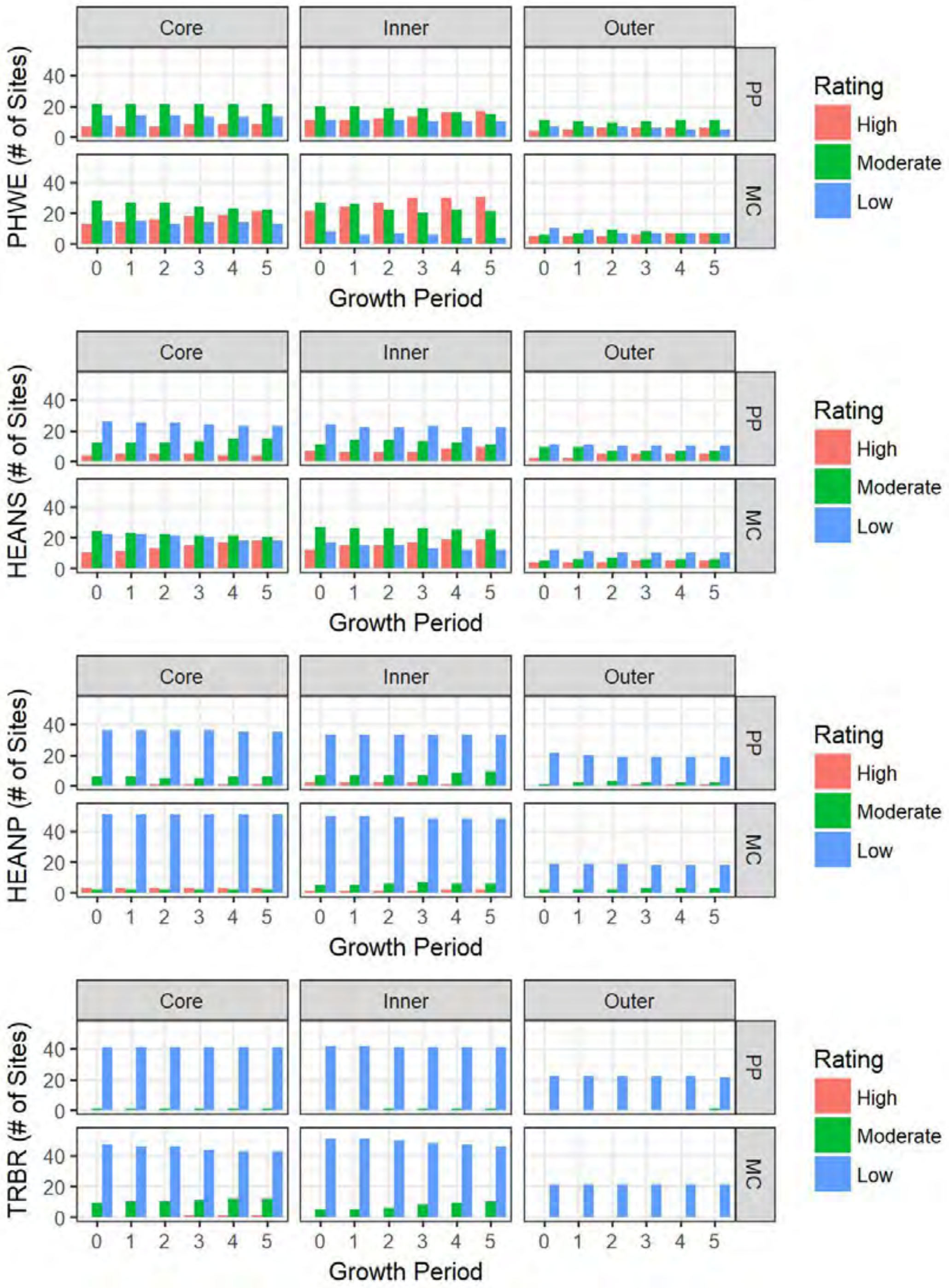
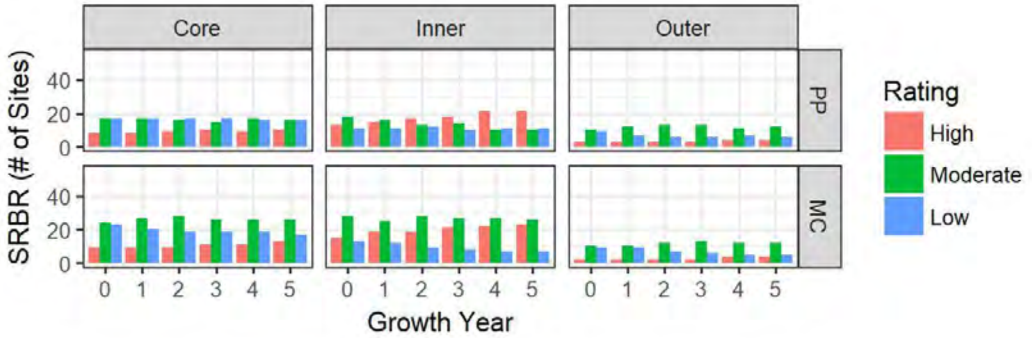
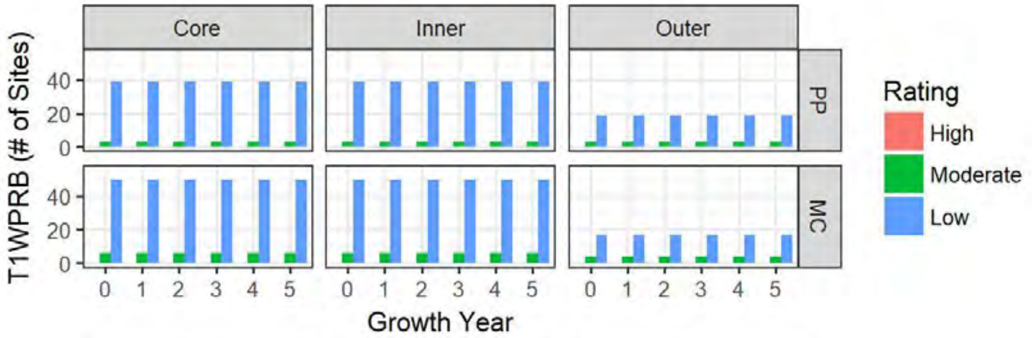
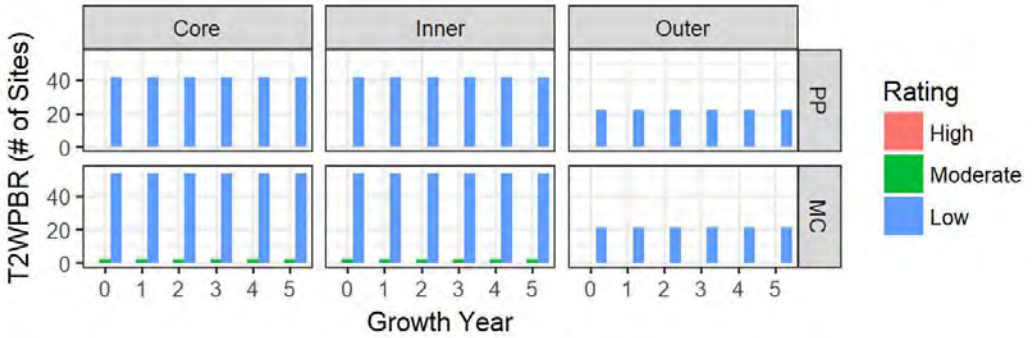
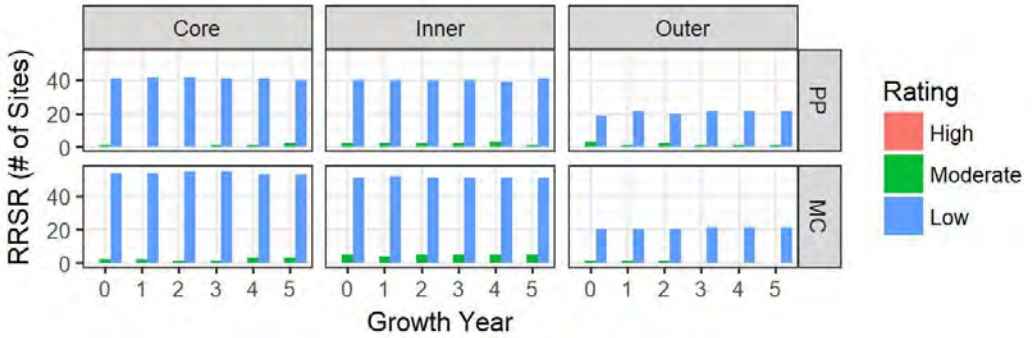


Figure 15: Counts of sites with high, moderate, and low disease susceptibility ratings in core, inner, and outer regulatory riparian zones for ponderosa pine (PP) and mixed conifer (MC) sites for each growth period of a 50-year simulation. Definitions of insect codes are in Table 2.


Core
Inner
Outer
PP
MC
SRBR (# of Sites)
0
20
40
0 1 2 3 4 5
Growth Year
Rating
High
Moderate
Low


Core
Inner
Outer
PP
MC
T1WPRB (# of Sites)
0
20
40
0 1 2 3 4 5
Growth Year
Rating
High
Moderate
Low


Core
Inner
Outer
PP
MC
T2WPBR (# of Sites)
0
20
40
0 1 2 3 4 5
Growth Year
Rating
High
Moderate
Low


Core
Inner
Outer
PP
MC
RRSR (# of Sites)
0
20
40
0 1 2 3 4 5
Growth Year
Rating
High
Moderate
Low

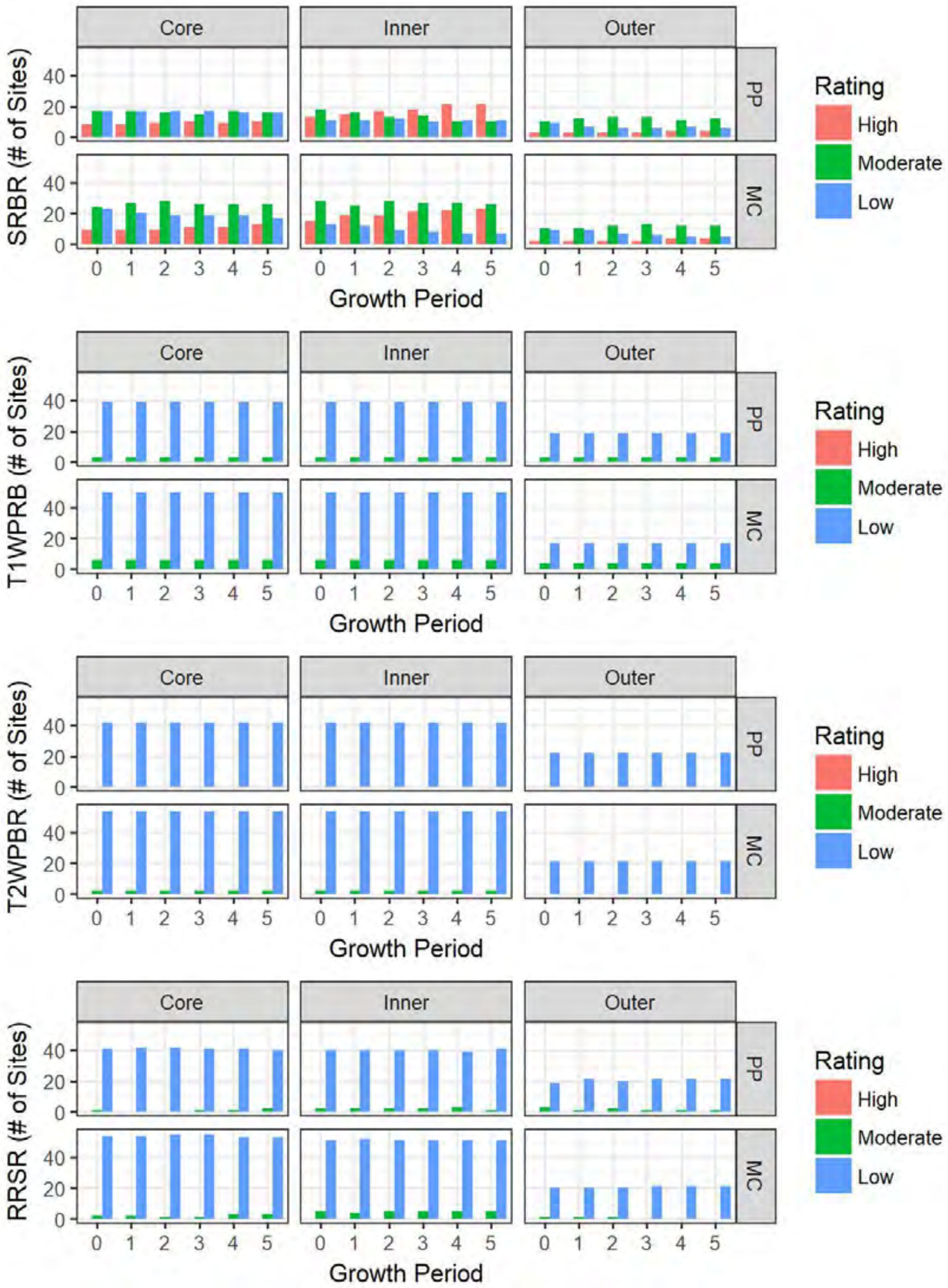


Figure 16: Counts of sites with high, moderate, and low disease susceptibility ratings in core, inner, and outer regulatory riparian zones for ponderosa pine (PP) and mixed conifer (MC) sites for each growth period of a 50-year simulation. Definitions of insect codes are in Table 2.

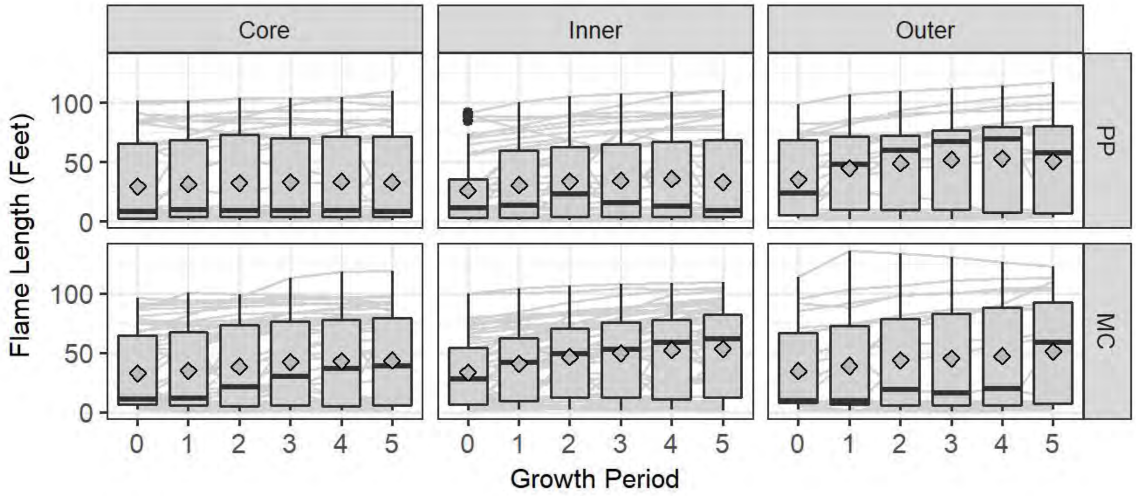


Figure 17: Wildfire potential total flame length distributions for core, inner, and outer regulatory riparian zones by ponderosa pine (PP) and mixed conifer (MC) timber habitat types. The gray boxes represent the 25th and 75th percentiles and the horizontal black lines the median of the data. The vertical lines extend to the range of the data or 1.5 time the interquartile range (the range from the 25th to the 75th percentile). Black points are potential outliers. The gray diamonds are the means of the data. Gray lines are trajectories of individual regulatory zone stands.

Eligibility of Stands for Timber Harvest

As described in the Methods section, determining the eligibility of stands for harvest is complex, following WAC 222-30-040 for the area within 75 feet of bankfull width, WAC 222-030-022(1)(b) for inner zones, and WAC 222-030-022(1)(c) for outer zones. Once eligible, harvest prescriptions were determined following WAC 222-030-022(1)(b) for inner zones and WAC 222-030-022(1)(c) for outer zones. The following summarizes, by regulatory zone, stands eligible for harvest, and the amount of harvest were generated over the 50-year simulation period. Detailed listings of harvest levels by stand are provided in Appendix H.

Inner Zone

Eligibility for harvest in the inner zone was determined by whether the site provided adequate shade under WAC 222-30-040 and whether the site had adequate stocking under WAC 222-030-022(1)(b). Table 3 summarizes the number of sites meeting eligibility requirements under these rules, over time. The greatest regulators of harvest eligibility were shade requirements (retaining all shade within 75 feet of the stream in the BTO or meeting nomograph shade requirements). Fifty-five sites were located within the BTO while another 12 sites outside of the BTO during this study timeframe did not provide adequate shade under WAC 222-30-040. The total number of shade-limited sites varied little over the 50-year simulation period. At shade-limited sites, harvest in the inner zone was limited to thinning the outer 25 feet of the inner zone, which was permissible only along large streams where stocking requirements were met under WAC 222-030-022(1)(b). Initially, about half of the shade-limited sites had sufficient stocking to permit even this limited amount of harvesting. In contrast, about 30 sites met shade requirements, and of these sites, the proportion of sites that met stocking requirements increased from about 50 percent during year 0 to about 95 percent in year 50. On these sites, thinning could occur throughout the inner zone.

Table 3: Number of EWRAP stands eligible for harvest in the inner riparian management zone meeting shade requirements under WAC 222-30-040 and stocking requirements under WAC 222-030-022(1)(b).

		Year 0		Year 10		Year 20		Year 30		Year 40		Year 50	
Meets Shade Requirements		N	Y	N	Y	N	Y	N	Y	N	Y	N	Y
		67	31	68	30	67	31	66	32	65	33	64	34
Meets Stocking Requirements	N	35	16	26	13	21	9	15	6	14	4	10	2
	Y	32	15	42	17	46	22	51	26	51	29	54	32

Basal area per acre and trees per acre removals from inner zones (Figure 18) when only the outer 25-feet of are harvested on shade-limited sites were significantly less than removals when thinning throughout the inner zone on sites where shade was not limiting ($p < 0.0001$). Removals from shade-limited sites averaged 43 ft^2/ac of basal area comprised 50 trees per acre while removals when thinning throughout the inner zone averaged 82 ft^2/ac comprised of 123 trees per acre. These estimates were consistent through time with some small non-significant differences between potential harvest years. Removals on PP timber habitat type sites were removals are slightly higher than on MC sites, although though differences were not significant.

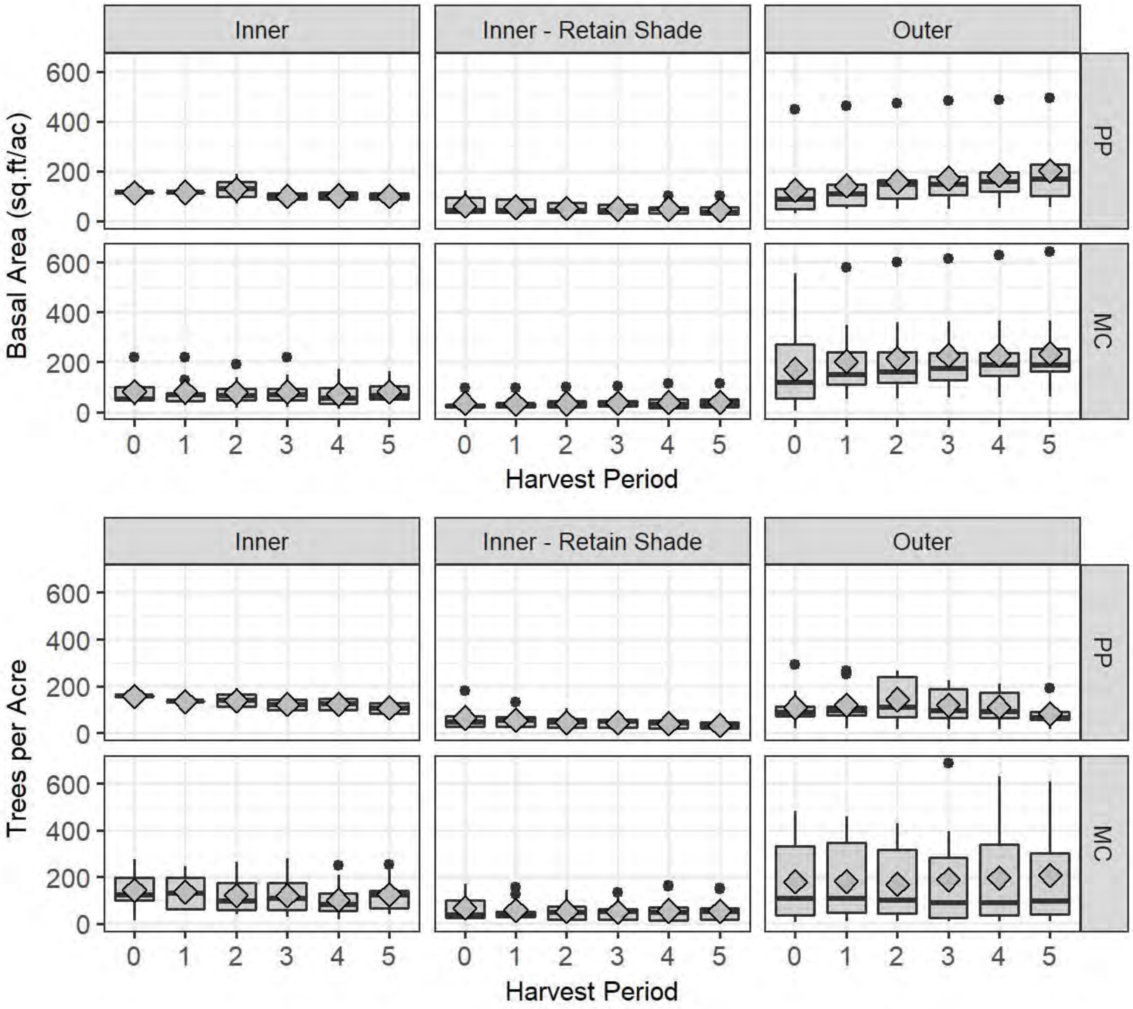


Figure 18: Potential basal area and trees per acre with dbh >= 6 inches distributions for inner zone, with thinning throughout or retain shade treatment, and outer regulatory riparian zones by ponderosa pine (PP) and mixed conifer (MC) timber habitat types for each possible harvest. The gray boxes represent the 25th and 75th percentiles and the horizontal black lines the median of the data. The vertical lines extend to the range of the data or 1.5 time the interquartile range (the range from the 25th to the 75th percentile). Black points are potential outliers. The gray diamonds are the means of the data.

Outer Zone

Because there are no shade restrictions under WAC 222-30-040 and residual stocking targets are lower under WAC 222-030-022(1)(c), harvesting in the outer zone removed significantly more trees and more basal area per acre (Figure 18) than the inner zone harvest forecasts ($p < 0.0001$). Harvests during the initial year removed approximately 188 ft^2/ac of basal area, comprising comprised of 155 trees per acre from PP and MC timber habitat type sites. As stands develop over time, trees per acre harvest levels remained consistent but basal area harvest levels increased over time as trees grew in size. However, there were no significant differences in trees per acre and basal area per acre harvest levels among time periods for either timber habitat type.

Trajectory of Managed Stand Conditions

Overall, predicted QMD growth was very stable under post-harvest growing conditions created by following forest practice rules. With management, stands continued to increase in stand density, tree size, and tree volume, on average, over the 50-year simulation period. Among sites where inner zones were harvested, either thinning throughout or only within the outer 25' of the inner zone along large streams, basal area (Figure 19) periodic annual increment (PAI) averaged 1.4 ft^2/ac, or 1.1%, per year with significant differences between thinning only the outer 25 feet and thinning throughout the inner zone ($p < 0.0001$). No significant differences occurred among timber habitat types or harvest years. Higher residual stocking when retaining all shade within 75 feet of the stream resulted in an average basal area per acre PAI of 1.6 ft^2/ac, or 1.2%, per year compared to 1.2 ft^2/ac, or 1.6%, per year when thinning throughout the inner zone. Quadratic mean diameter (Figure 19) growth was highly variable, with a mean approaching 0 that was largely driven by decreases in QMD as small trees grew into the six inches and greater dbh size class. Significant differences did occur between timber habitat types ($p = 0.004$) and harvest type ($p = 0.0003$) with small increases in QMD on PP timber habitat type sites or when retaining all shade within 75' of large stream and small decreases in QMD on MC sites or when thinning throughout the inner zone was used. Differences in QMD among timber habitat types were driven by significant differences in trees per acre (Figure 19) PAI among timber habitat types ($p = 0.025$) with an average increase of 0.3 trees per acre, or 0.9%, per year on PP sites and an average increase of 1.0 trees per acre, or 2.3%, per year on MC sites.

Among sites with outer zones, harvest basal area per acre and trees per acre increased while quadratic mean diameter decreased overall (Figure 19). No significant differences occurred between timber habitat types or harvest years, with the exception of quadratic mean diameter where there were significant differences between timber habitat types ($p = 0.007$). Outer zone basal area PAI after harvest averaged 1.5 ft^2/ac, or 3.0%, per year and trees per acre PAI averaged 2.2 trees per acre, or 10.8%, per year, which were driven by trees growing into the 6 inch and greater dbh size class. While not statistically significant, differences were seen in trees per acre PAI between PP and MC timber habitat type sites (2.6 and 1.8 trees per acre per year respectively) that resulted in QMD PAI of -0.1 and 0.04 inches per year, respectively, as the number of small trees increased. Although simulations removed a substantial number of small trees during harvesting in both timber habitat types to reflect logging damage, substantial recruitment of trees from the seedling and sapling size classes into the 6 inches and greater dbh class still occurred after treatment in mixed conifer sites. Overall, these trends were heavily weighted by simulated changes in small trees during the first period after harvest.

Stand density as measured by Reinike's Stand Density Index and Curtis' Relative Density (Figure 20), increased through time with growth rates in inner zones that were very stable after harvest (averaging 2.1 units per year, and 0.3 units per year, respectively). Small but non-significant differences between timber habitat types and zones when the outer was harvested. Among the MC timber habitat type, SDI and RD growth rates averaged 2.2 units per year and 0.4 units per year respectively, while among PP sites averaged 1.9 units per year and 0.3 units per year respectively. Across sites with outer zones, rates of SDI and RD increase were non-significantly higher than in outer zones than in inner zones, which averaged averaging 2.5 units per year and 0.4 units per year. No significant differences in SDI and RD were detected between timber habitat types.

Board-foot and total cubic-foot standing volumes (Figure 21) increased as stands grew. Across all sites with inner zone harvest there were significant differences in board-foot and cubic-foot PAI across timber habitat types ($p < 0.0001$ and $p = 0.0004$ for board-foot and cubic-foot, respectively) and harvest types ($p < 0.0001$ for both volumes). Volume growth rates were higher on PP sites, averaging 457 board-feet per acre, or 1.4%, per year and 72 cubic-feet acre, or 1.2%, per year than on MC sites, averaging 330 board-feet per acre, or 1.4%, per year, and 59 cubic-feet per acre, or 1.3%, per year. PP sites had fewer instances of extremely high volume PAIs that may have influenced the average PP volume PAIs.

Projected decreases in trees per acre (Figure 22) occurred in stands after treatment due to density-dependent mortality and random background mortality in FVS simulations. Decreases in TPA did not include mortality from episodic events such as windthrow that could occur post-harvest. Across all sites where inner zone harvest occurred, basal area per acre mortality averaged a relatively low rate of 1.2 ft^2/ac, or 0.7%, per year, with significant differences between timber habitat types ($p = 0.003$) and inner zone treatment type ($p < 0.0001$). Basal area per acre mortality on PP sites averaged 1.4 ft^2/ac, or 0.7%, per year, which was slightly higher than mortality rate on MC sites, which averaged 1.2 ft^2/ac, or 0.6%, per year. With the higher retention requirements when retaining all shade with 75 feet of large steams, basal area mortality averaged 1.6 ft^2/ac, or 0.8%. Lower retention requirements when thinning throughout the inner zone resulted in a lower average mortality rate of 0.6 ft^2/ac, or 0.5%, per year. Trees per acre mortality averaged 1.3 trees per acre, or 1.0%, per year with significant differences between harvest types ($p < 0.0001$) but not between timber habitat types or harvest years. Retaining all shade within 75 feet of the stream resulted in average trees per acre mortality rate of 1.7 trees per acre, or 1.1%, per year, while thinning throughout the inner zone reduced mortality to 0.6 trees per acre, or 0.8%, per year. The QMD of mortality trees remained consistent, averaging 15.4 inches, with no significant differences among post-harvest growth years. Across sites with outer zone harvest basal area mortality averaged 0.4 ft^2/ac, or 0.7%, per year with small, but statistically significant ($p < 0.0001$), differences between timber habitat types, 0.4 ft^2/ac, or 0.8%, per year and 0.5 ft^2/ac, or 0.6%, per year for PP and MC sites, respectively, and harvest years ($p < 0.0001$), with average basal area mortality increasing from 0.3 ft^2/ac, or 0.2%, per if harvest occurs at year 0, to 0.7 ft^2/ac, or 1.3%, per year if harvest occurs at year 40. Trees per acre mortality was also relatively low and consistent averaging 0.6 trees per acre, or 1.0%, per year with an average QMD of 21.9 inches.

Harvesting in the inner and outer zones reduced high and moderate susceptibility ratings in year 50 (Figure 23 through Figure 27 and Appendix G) when thinning throughout the inner zone and thinning the outer zone with lesser reductions when all shade was retained within 75 feet of the steam. When all shade was retained within 75 feet of the stream, the distribution of risk ratings at year 50 among sites was comparable to year 50 when the inner zones developed without management. Timing of harvest generally had little impact on the number of sites rated as high, moderate, or low susceptibility. Exceptions to this pattern included western spruce budworm, western pine beetle, and mountain pine beetle (Figure 23 and Figure 24) where harvesting earlier resulted in less high susceptibility to western spruce budworm, and less moderate susceptibility to pine beetles. Lower retention levels when thinning throughout the inner zone, which primarily occurred on MC sites, and thinning in the outer zone resulted in larger proportions of sites rated as low or moderate susceptibility. This was especially true for Douglas-fir, western pine, mountain pine, and spruce beetles (Figure 23 and Figure 24). Unlike retaining all shade within 75 feet of the stream, there were differences in ratings for these beetles at year 50 among harvest years. Harvesting later, such as in years 30 or 40, often resulted in a larger number of sites rated as low susceptibility, particularly in the outer zone, where reductions related to thinning were ameliorated by stand growth and development after thinning in earlier years.

Similarly, as stands developed with management, predicted changes occurred in mean total flame length, a surrogate metric for susceptibility to fire-related mortality (Figure 28, and Appendix G). While highly variable, overall flame length values lengths remained relatively consistent, averaging 30 feet, with significant differences between timber habitat types ($p = 0.005$) and inner zone harvest types ($p < 0.0001$). Average flame lengths among PP sites were shorter than those on mixed conifer sites at 27 and 31 feet, respectively. Harvesting only the outer 25 feet of the inner zone resulted in an average total flame length of 41 feet while thinning throughout the inner zone reduced total flame length to 20 feet. Outer zone total flame lengths averaged 13 feet after treatment.

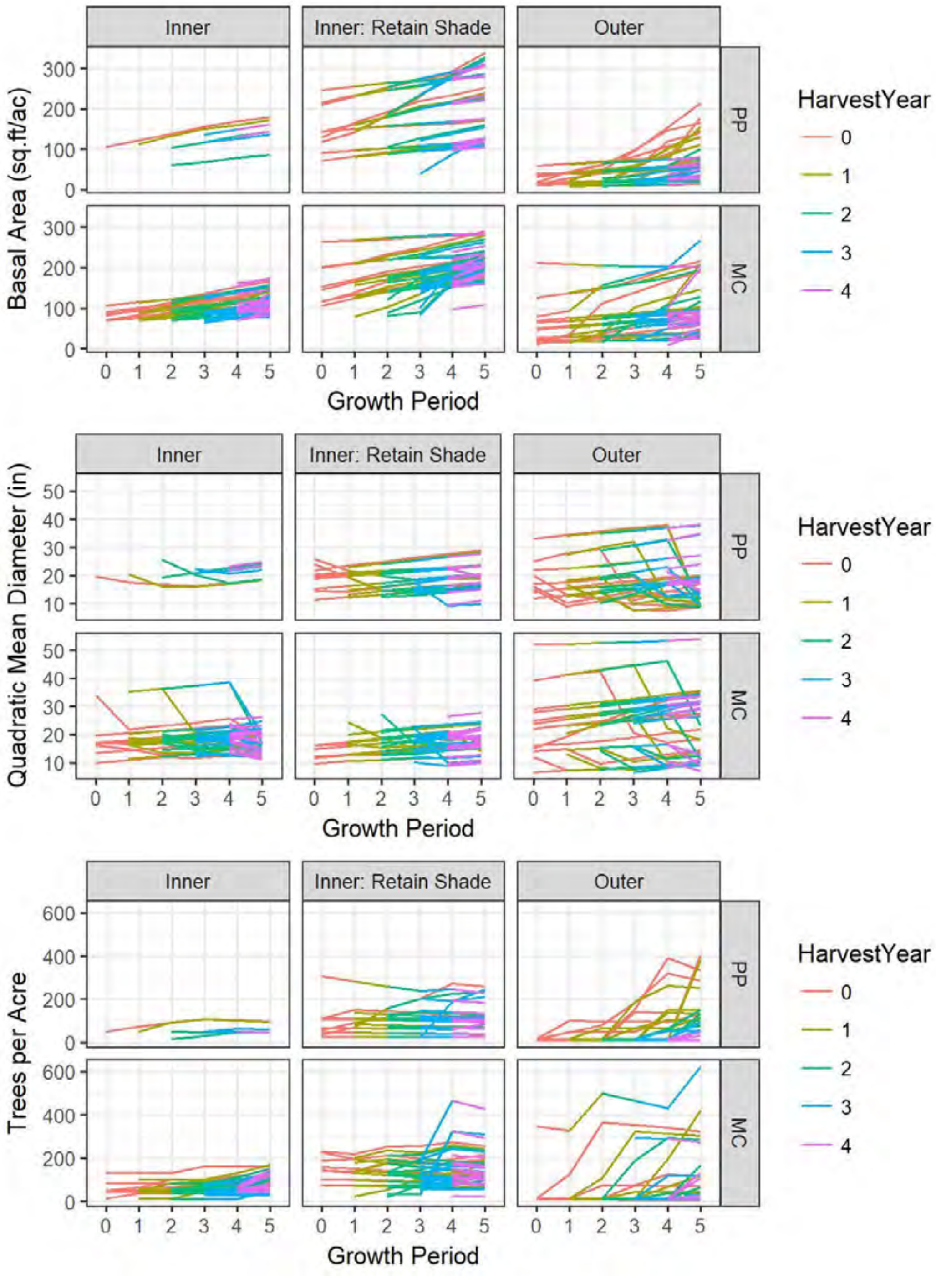


Figure 19: Trajectories of basal area per acre, quadratic mean diameter, and trees per acre of trees with dbh >= 6 inches on ponderosa pine (PP) and mixed conifer (MC) timber habitat type sites after thinning throughout the inner zone (Inner), thinning only the outer 25’ of the inner zone (Inner: Retain Shade), and harvesting in the outer zone after harvesting in growth period 0 (red), 1 (yellow), 2 (green), 3 (blue), or 4 (purple). Trajectories are not shown for stands prior to harvest and trajectories for harvest in later years may overlay those from earlier years.

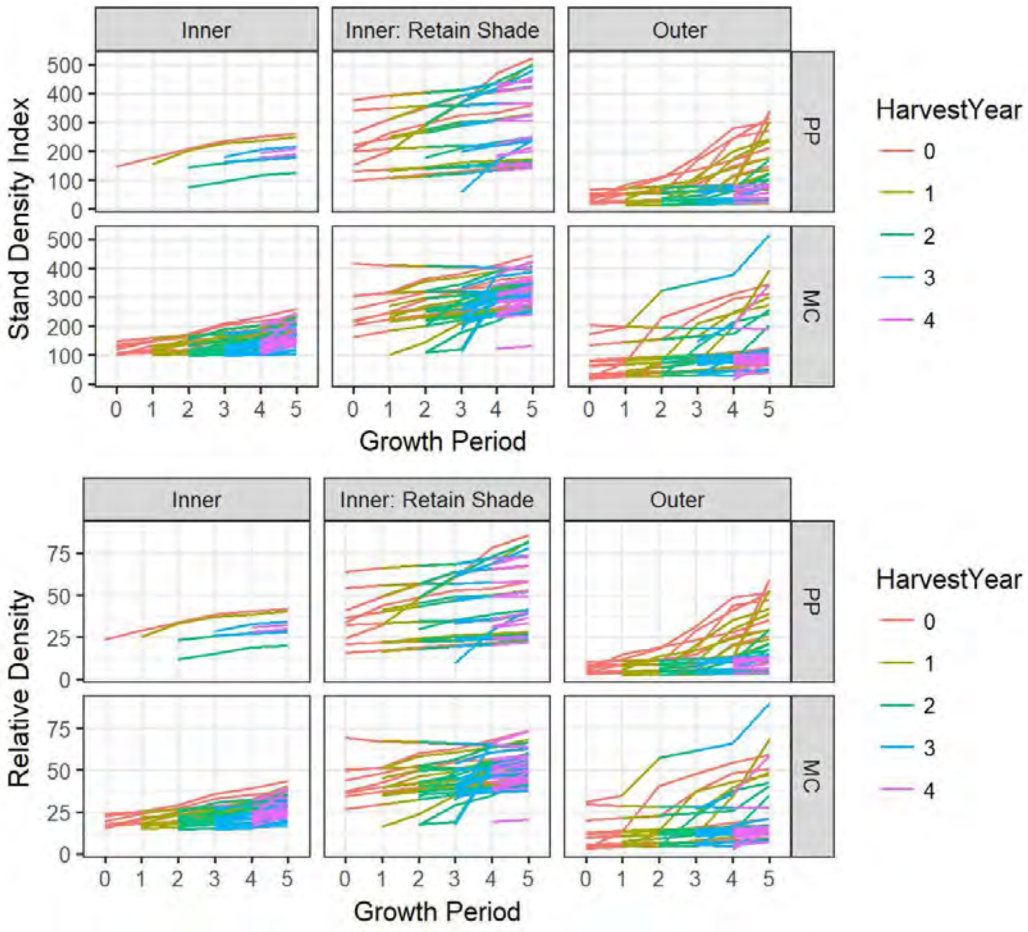


Figure 20: Trajectories of Reineke's Stand Density Index and Curtis' Relative Density for trees with dbh >= 6 inches on ponderosa pine (PP) and mixed conifer (MC) timber habitat type sites after thinning throughout the inner zone (Inner), thinning only the outer 25' of the inner zone (Inner: Retain Shade), and harvesting in the outer zone after harvesting in growth period 0 (red), 1 (yellow), 2 (green), 3 (blue), or 4 (purple). Trajectories are not shown for stands prior to harvest and trajectories for harvest in later years may overlay those from earlier years.

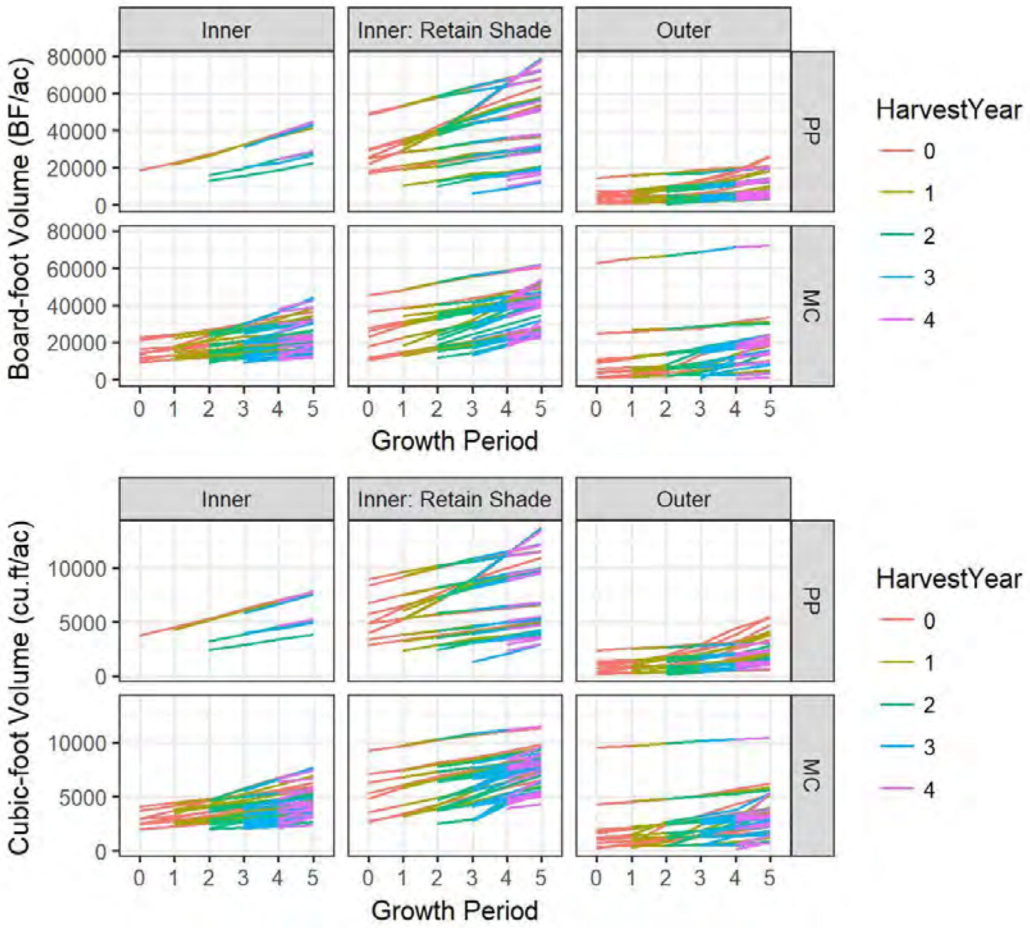


Figure 21: Trajectories board-foot volume and cubic-foot volume per acre of trees with dbh >= 6 inches on ponderosa pine (PP) and mixed conifer (MC) timber habitat type sites after thinning throughout the inner zone (Inner), thinning only the outer 25' of the inner zone (Inner: Retain Shade), and harvesting in the outer zone after harvesting in growth period 0 (red), 1 (yellow), 2 (green), 3 (blue), or 4 (purple). Trajectories are not shown for stands prior to harvest and trajectories for harvest in later years may overlay those from earlier years.

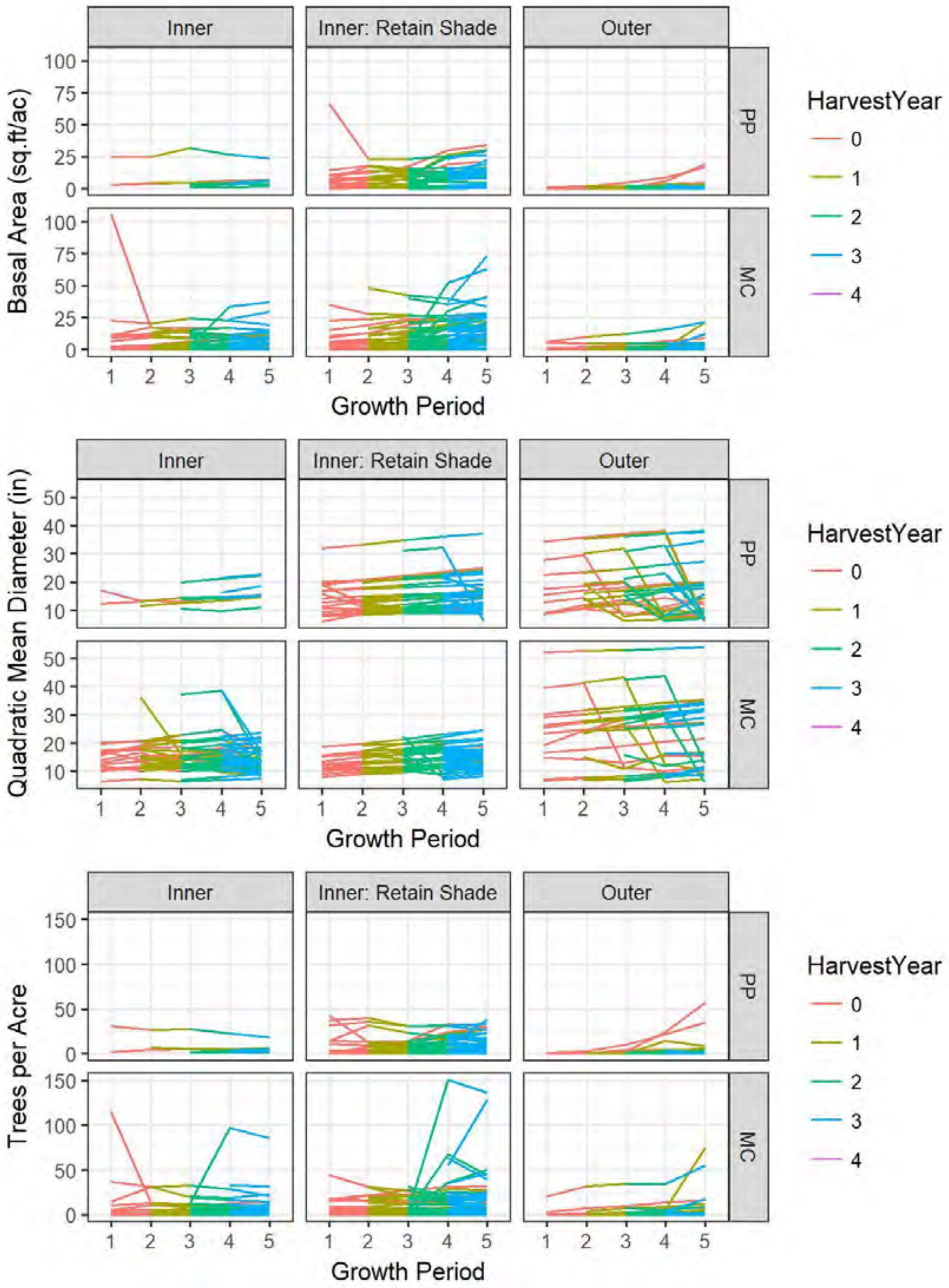


Figure 22: Trajectories of basal area per acre, quadratic mean diameter, and trees per acre mortality of trees with dbh >= 6 inches on ponderosa pine (PP) and mixed conifer (MC) timber habitat type sites after thinning throughout the inner zone (Inner), thinning only the outer 25' of the inner zone (Inner: Retain Shade), and harvesting in the outer zone after harvesting in growth period 0 (red), 1 (yellow), 2 (green), 3 (blue), or 4 (purple). Trajectories are not shown for stands prior to harvest and trajectories for harvest in later years may overlay those from earlier years.

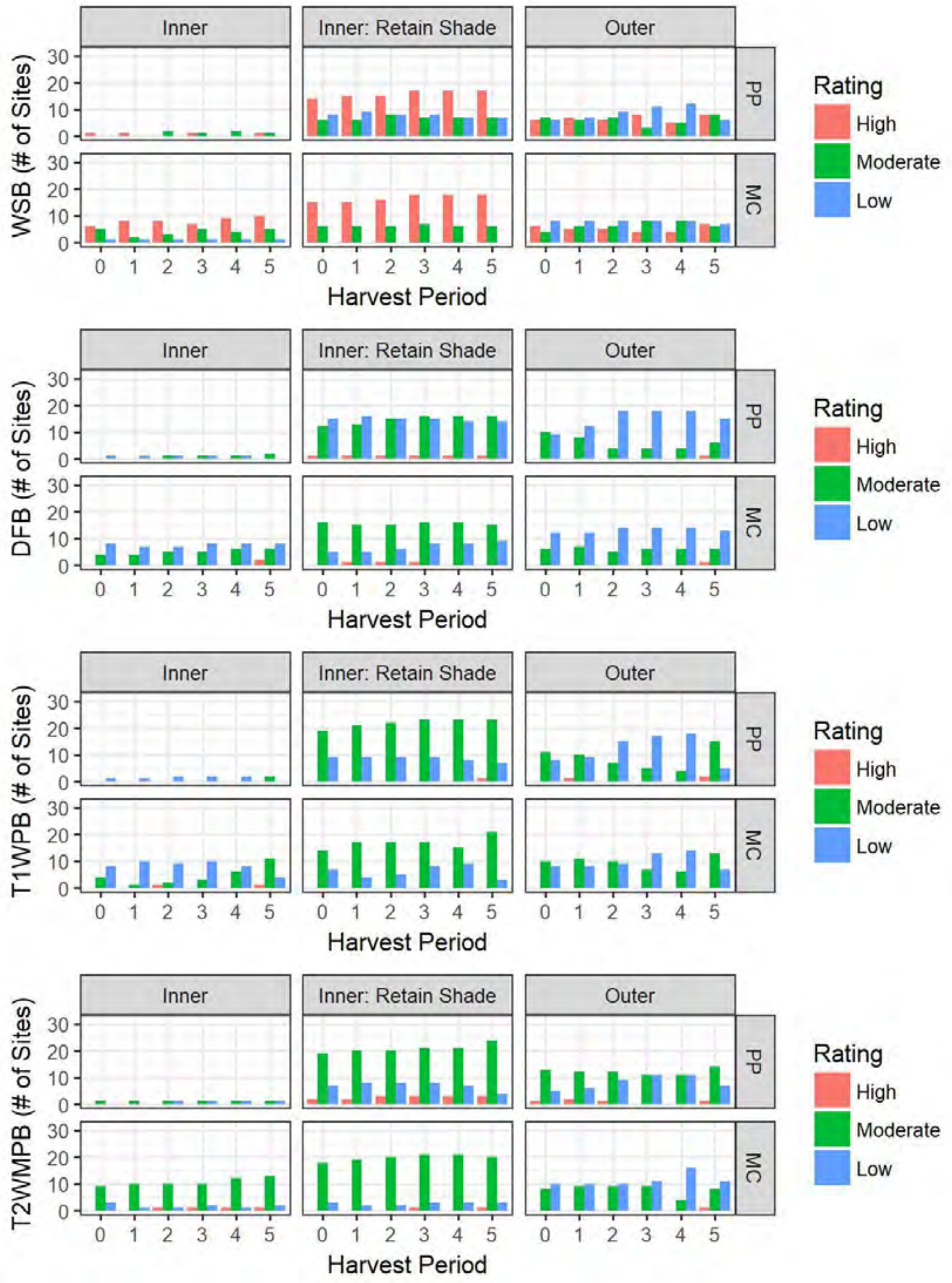


Figure 23: Counts of sites with high, moderate, and low insect susceptibility ratings in (PP) and mixed conifer (MC) timber habitat type sites after thinning throughout the inner zone (Inner), thinning only the outer 25' of the inner zone (Inner: Retain Shade), and harvesting in the outer zone sites at the end of a 50-year simulation by harvest year. Definitions of insect codes are in Table 2.

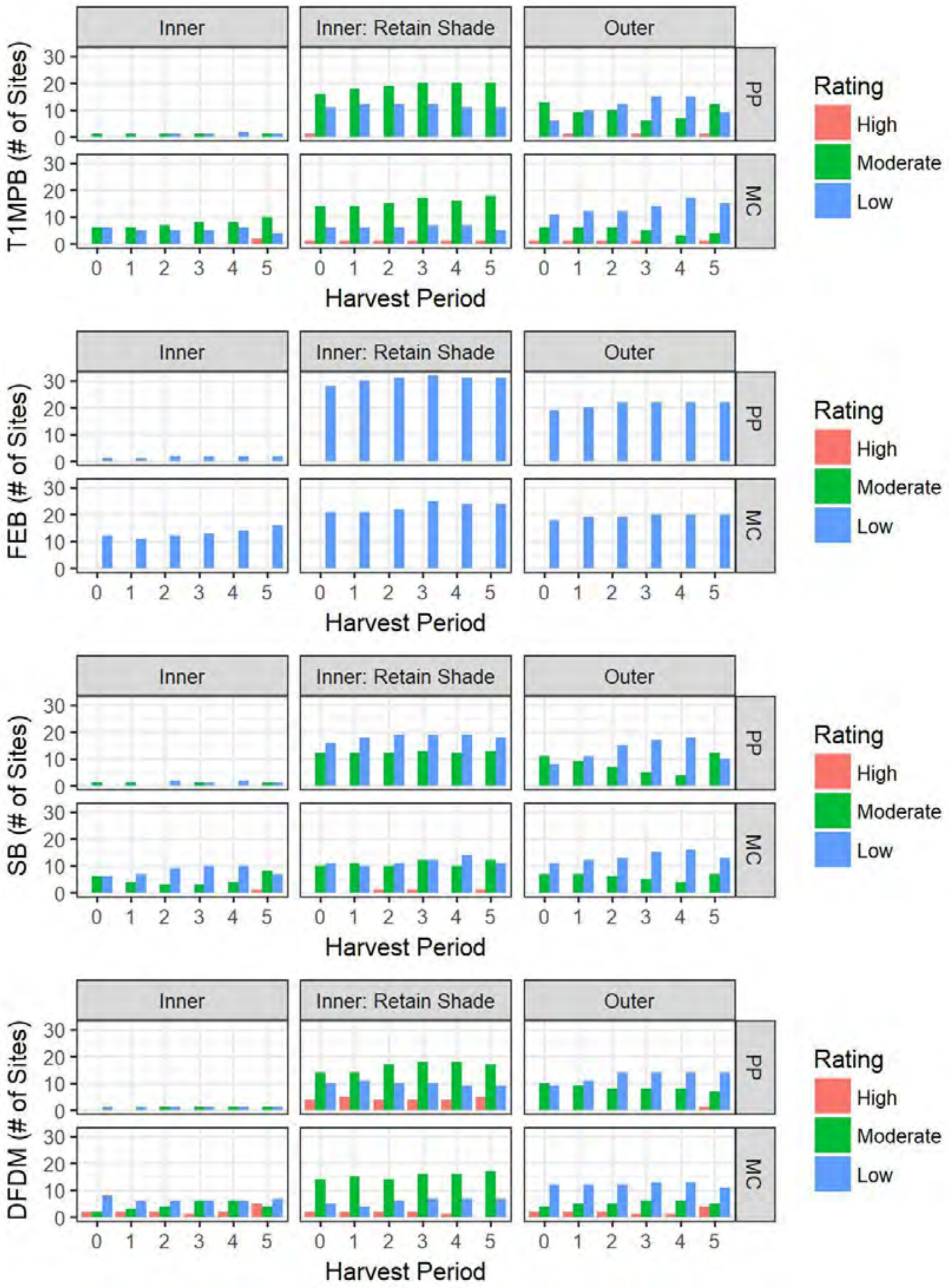


Figure 24: Counts of sites with high, moderate, and low insect and disease susceptibility ratings (PP) and mixed conifer (MC) timber habitat type sites after thinning throughout the inner zone (Inner), thinning only the outer 25’ of the inner zone (Inner: Retain Shade), and harvesting in the outer zone at the end of a 50-year simulation by harvest year. Definitions of insect codes are in Table 2.

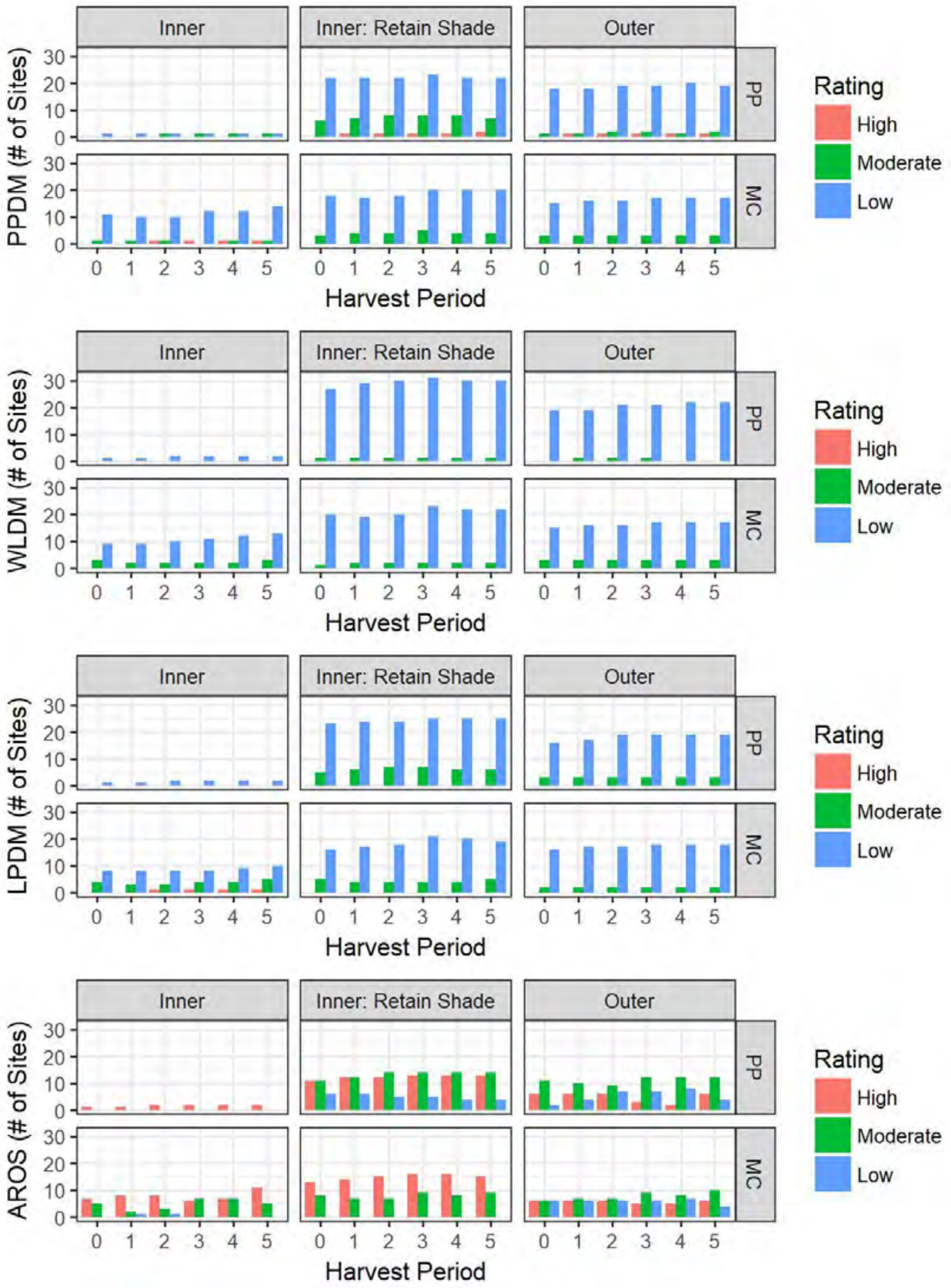


Figure 25: Counts of sites with high, moderate, and low disease susceptibility ratings in (PP) and mixed conifer (MC) timber habitat type sites after thinning throughout the inner zone (Inner), thinning only the outer 25’ of the inner zone (Inner: Retain Shade), and harvesting in the outer zone at the end of a 50-year simulation by harvest year. Definitions of insect codes are in Table 2.

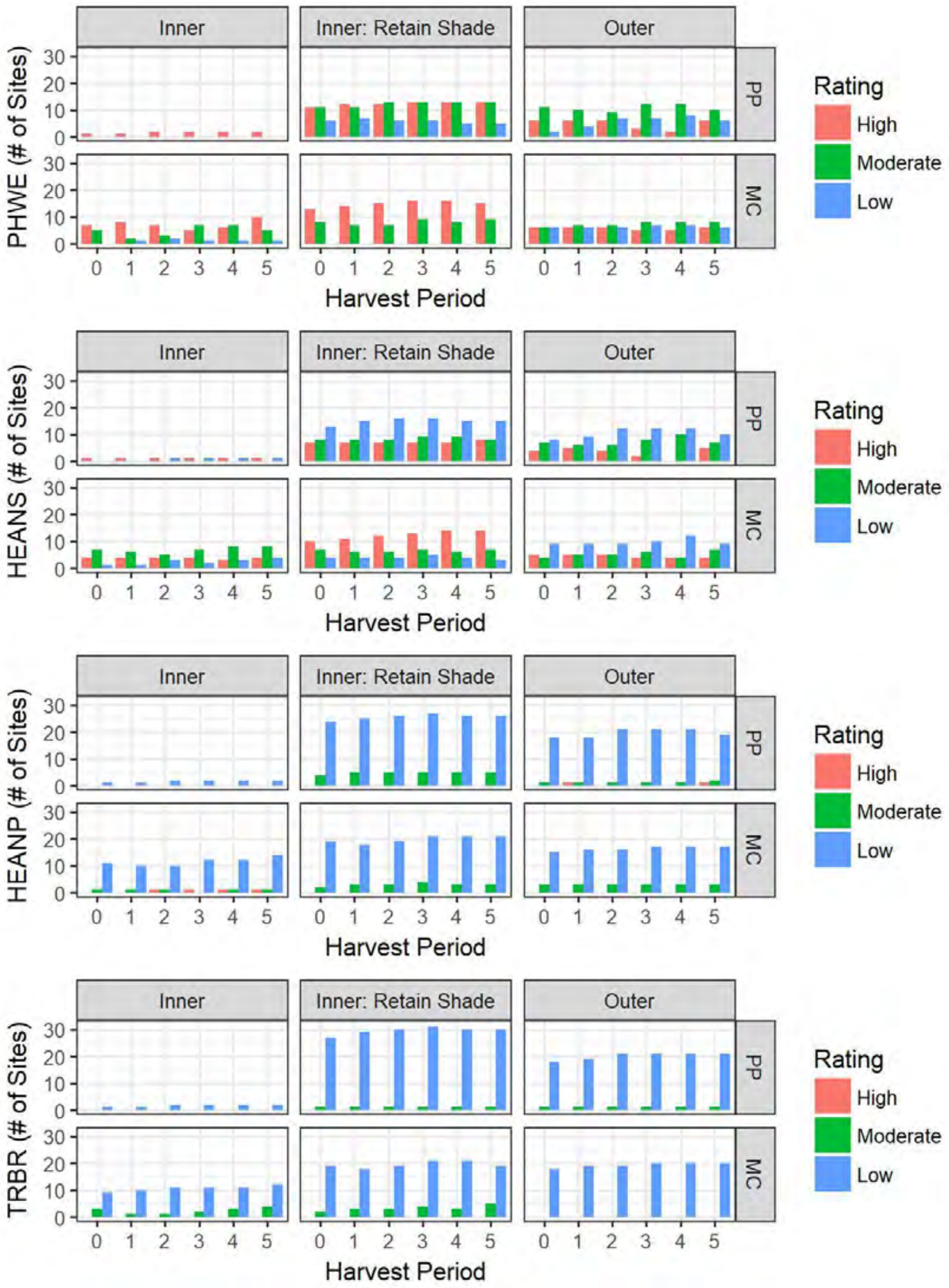


Figure 26 Counts of sites with high, moderate, and low disease susceptibility ratings in inner zones, with thinning throughout or retain shade treatment, and outer regulatory riparian zones for ponderosa pine (PP) and mixed conifer (MC) sites at the end of a 50-year simulation by harvest year. Definitions of insect codes are in Table 2.

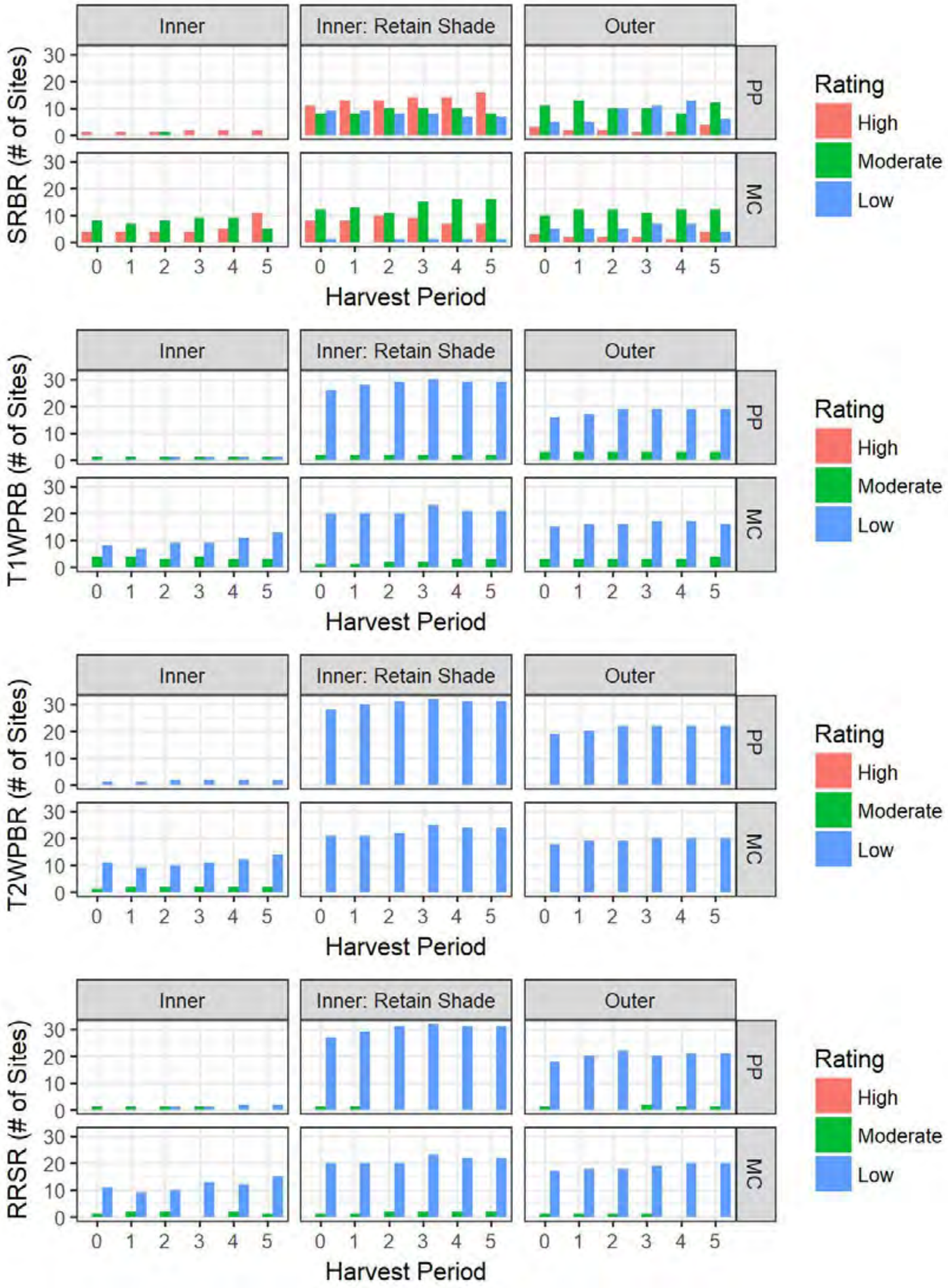


Figure 27 Counts of sites with high, moderate, and low disease susceptibility ratings in inner zones, with thinning throughout or retain shade treatment, and outer regulatory riparian zones for ponderosa pine (PP) and mixed conifer (MC) sites at the end of a 50-year simulation by harvest year. Definitions of insect codes are in Table 2.

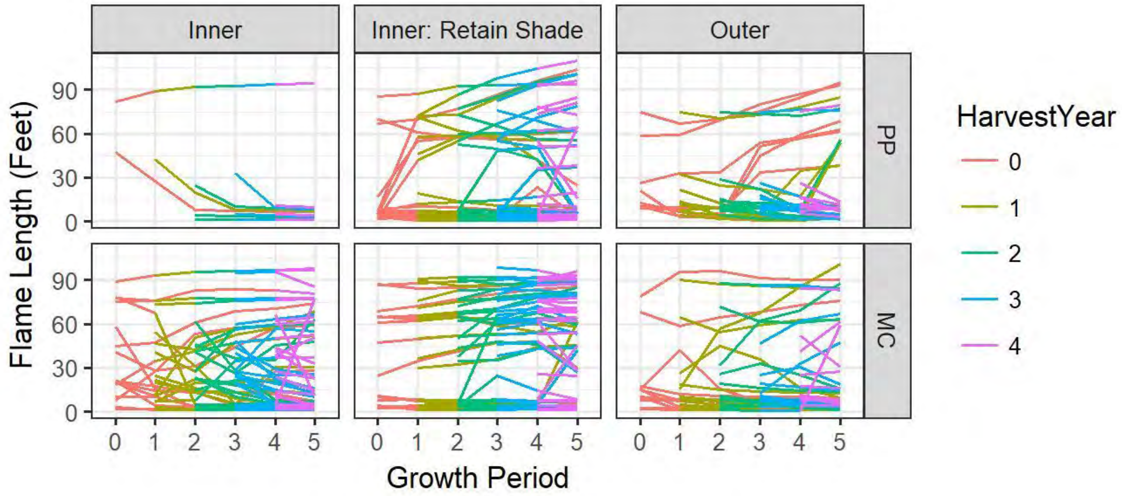


Figure 28: Trajectories of total flame length on ponderosa pine (PP) and mixed conifer (MC) timber habitat type sites after thinning throughout the inner zone (Inner), thinning only the outer 25’ of the inner zone (Inner: Retain Shade), and harvesting in the outer zone after harvesting in growth period 0 (red), 1 (yellow), 2 (green), 3 (blue), or 4 (purple). Trajectories are not shown for stands prior to harvest and trajectories for harvest in later years may overlay those from earlier years.

Unmanaged/Managed Stand Comparisons

Comparisons of unmanaged and managed conditions at sites that received a treatment that either retained shade, or thinned throughout the inner zone and/or outer zone, during the 50-year FVS simulation provided a rigorous analytical platform to examine the effects of various prescriptions on a suite of riparian forest conditions. Mean percent PAI growth rates were comparable for all metrics other than QMD, with or without treatment in the inner zone (Figure 29). With treatment, basal area per acre, SDI, RD, board-foot volume per acre, and cubic-foot volume per acre were slightly reduced relative to untreated sites regardless of timber habitat type. This was a counterintuitive result, since growth is typically expected to increase after thinning due to increased availability of growing space. Growth rates increased after treatment in outer zones for all metrics except QMD. Increases were more pronounced at PP sites than at MC sites. For example, average basal area per acre growth rate at PP sites increased from almost 2% per year without management to nearly 5% per year after management. Similarly, growth increased from about 2% per year without management to about 3% per year after management at MC sites. QMD growth rates decreased in inner and outer zones at PP sites after thinning. These trends appeared to be related to increased post-treatment increases TPA as small trees grew into the ≥ 6-inch dbh class.

Treatment had a predicted effect on susceptibility to insect and disease as per the risk rating system described by Hessburg et al. (1999). Among sites eligible for harvest, predicted decreases in moderate and high susceptibility to insect and disease in response to even low levels of management were observed (Figure 30 and Figure 31). Compared to unmanaged stands, management in stands eligible for harvest yield reduced proportions of high and moderate susceptibility to many evaluated insects or pathogens at year 50. The magnitude of treatment effects was generally greater in reducing susceptibility to insects (western spruce budworm, western pine beetle, and mountain pine beetle) in both inner and outer zones on PP sites than on MC sites. However, limited effects on reducing susceptibility to root diseases (*Armillaria*, *Phellinus*, *Annosum*, and *Schweinitzii*) were also observed but generally for harvested outer zones. Similar reductions were predicted among stands eligible for harvest in the MC timber habitat type. However, the magnitude of these reductions on MC sites was not as dramatic as seen among PP sites, where responses were also greater than those observed among the harvested versus unmanaged sites. These results were generally consistent with the different treatment effects on growth rates between inner and outer zones.

Among sites eligible for harvest, treatment also had a predicted positive effect on fire behavior, including decreased flame length values in response to thinning throughout the inner and outer zones (Figure 32). Low removal levels when retaining shade within 75 feet of the stream resulted in very similar flame lengths to those without management. However, thinning tended to reduce average total flame lengths. This was especially true in inner zones were thinned throughout where average total flame length was reduced from approximately about 37 feet to about 12 feet at PP sites and from about 50 feet to about 20 feet on MC sites. Smaller reductions in total flame length were also seen at outer zone sites. Overall, simulated riparian forest management prescriptions generally improved conditions for growth and reduced the levels of risk associated with insects, pathogens, and fire.

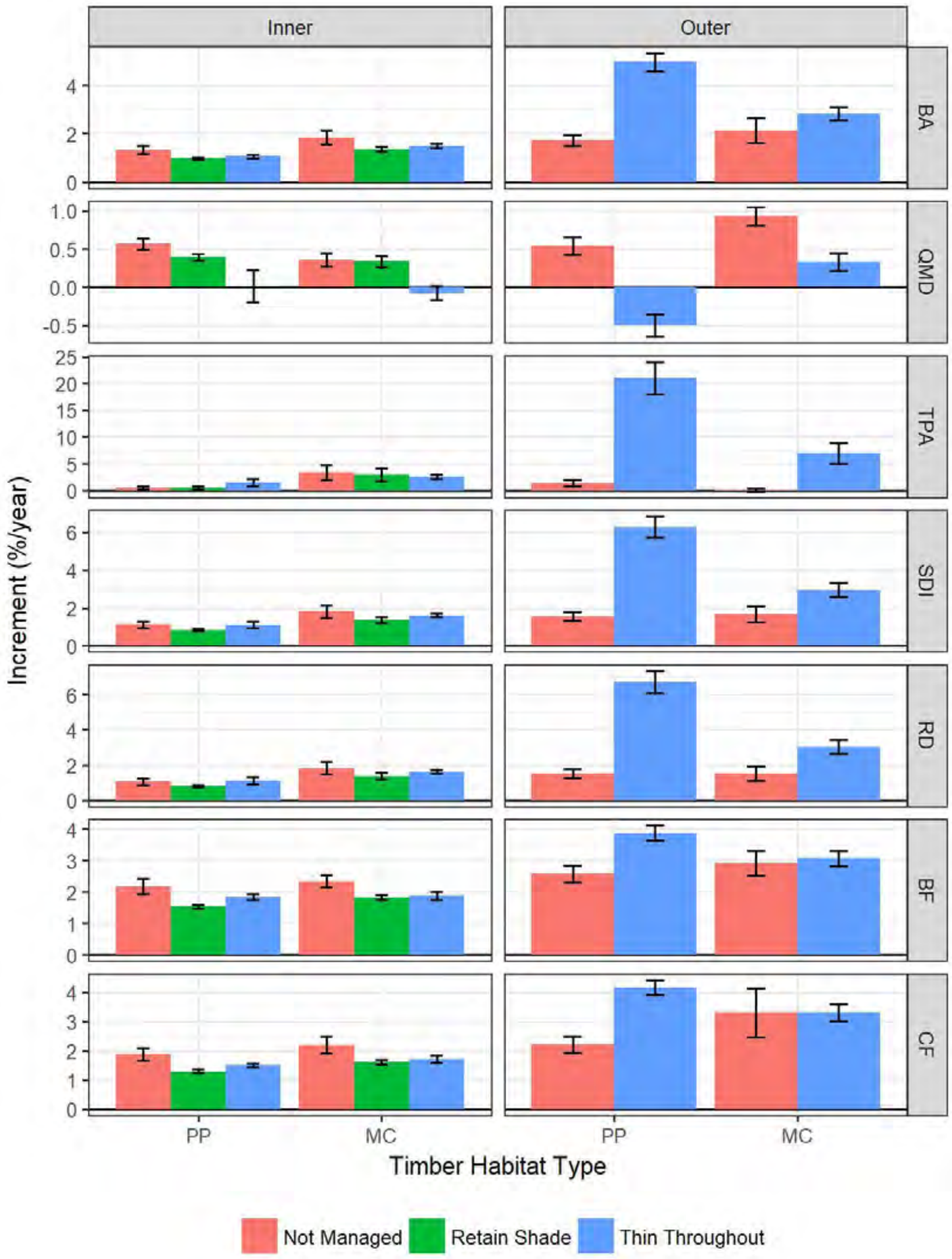


Figure 29: Comparisons of mean percent periodic annual increment of basal area per acre (BA), quadratic mean diameter (QMD), trees per acre (TPA), Reineke's Stand Density Index (SDI), Curtis' Relative Density (RD), board-foot volume per acre (BF) and total cubic-foot volume per acre (CF) of trees with dbh ≥ 6 inches for inner and outer regulatory zone stands that were not managed, inner zones where shade is retained, and inner and outer zones that were thinned throughout. Error bars represent one standard error.

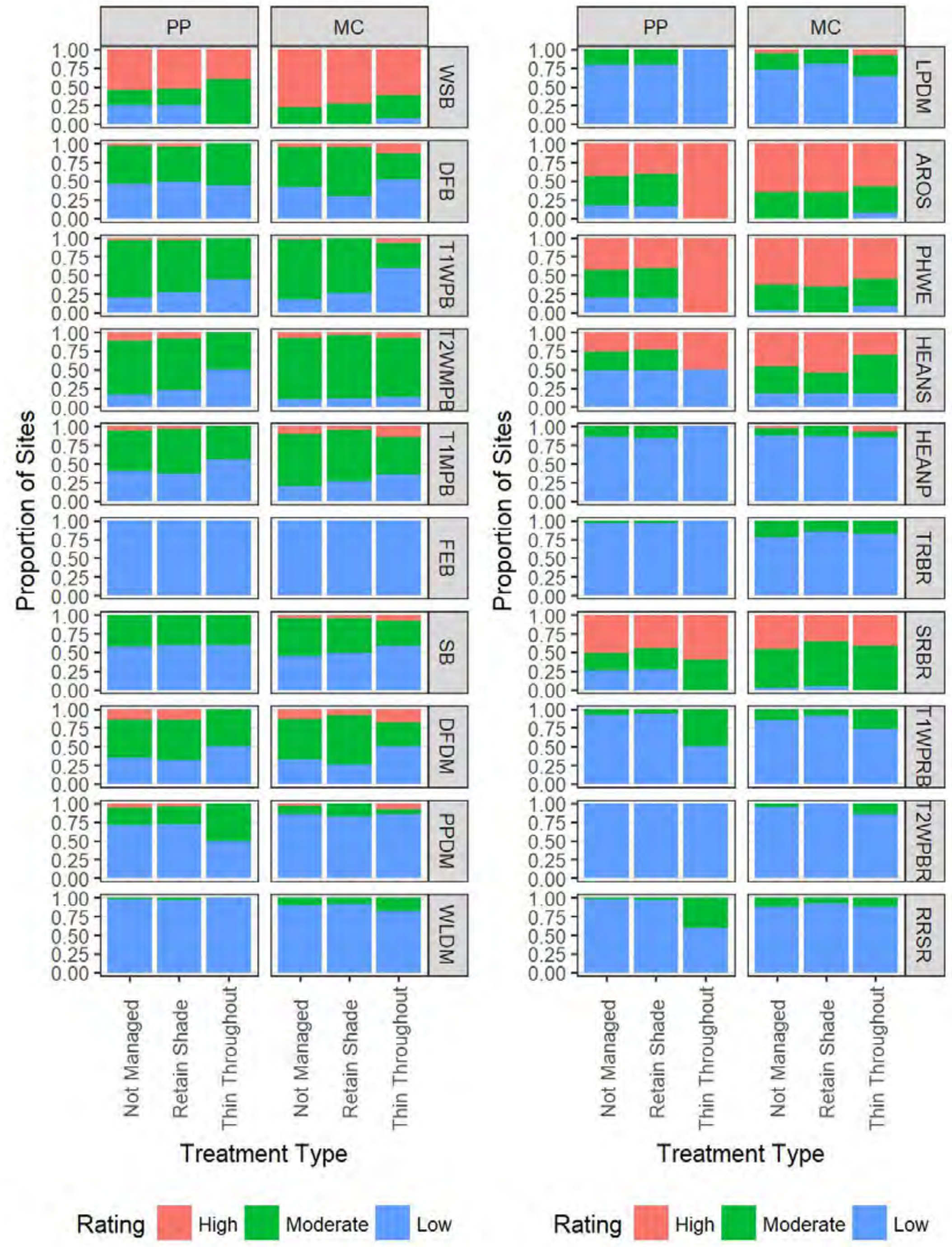


Figure 30: Comparisons of the proportion of inner regulatory zone stands in high, moderate, or low insect and disease susceptibility that were not managed shade was retained, or were thinned throughout. See Table 2 for insect and disease code definitions.

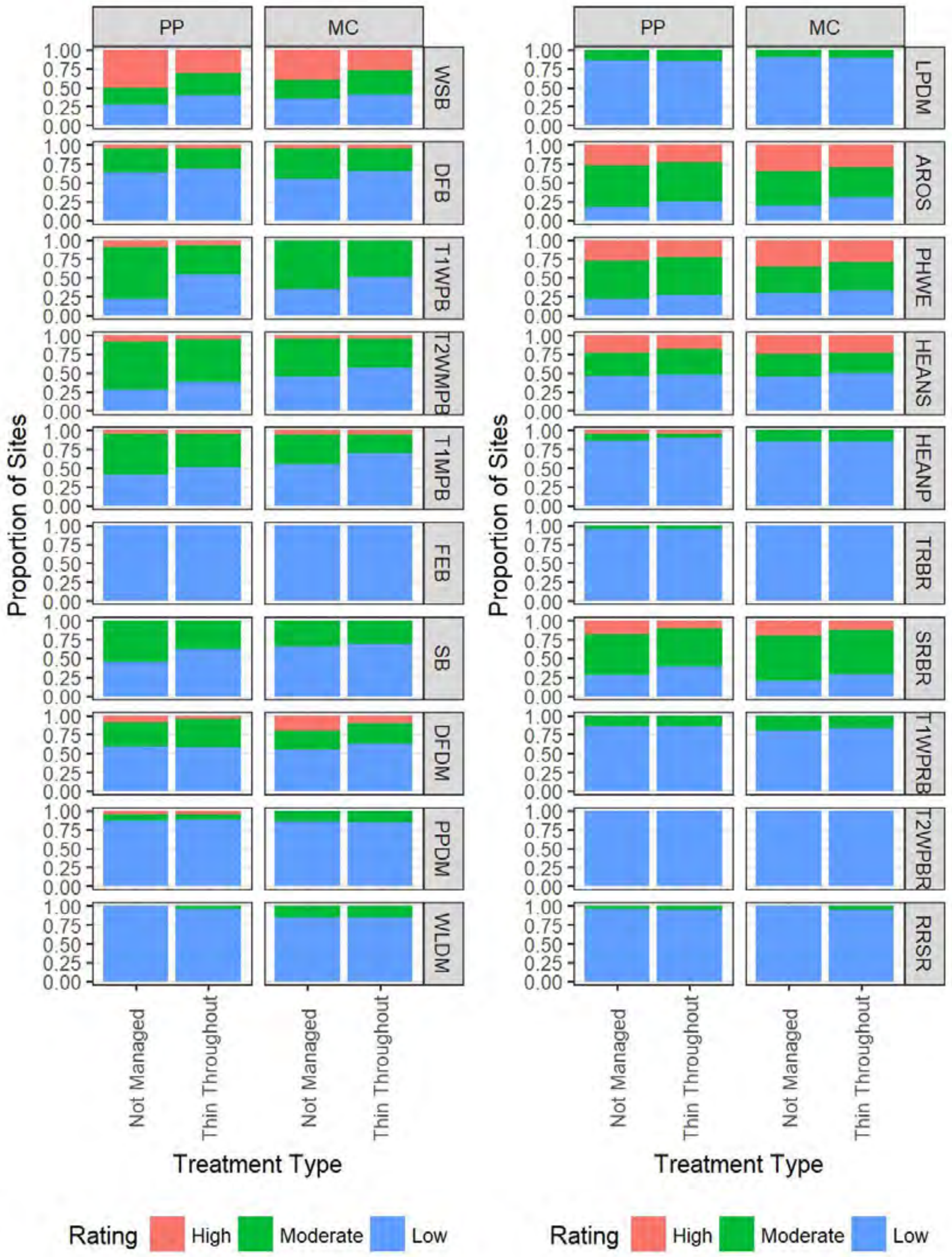


Figure 31: Comparisons of the proportion of outer regulatory zone stands in high, moderate, or low insect and disease susceptibility that were not managed or were thinned throughout. See Table 2 for insect and disease code definitions.

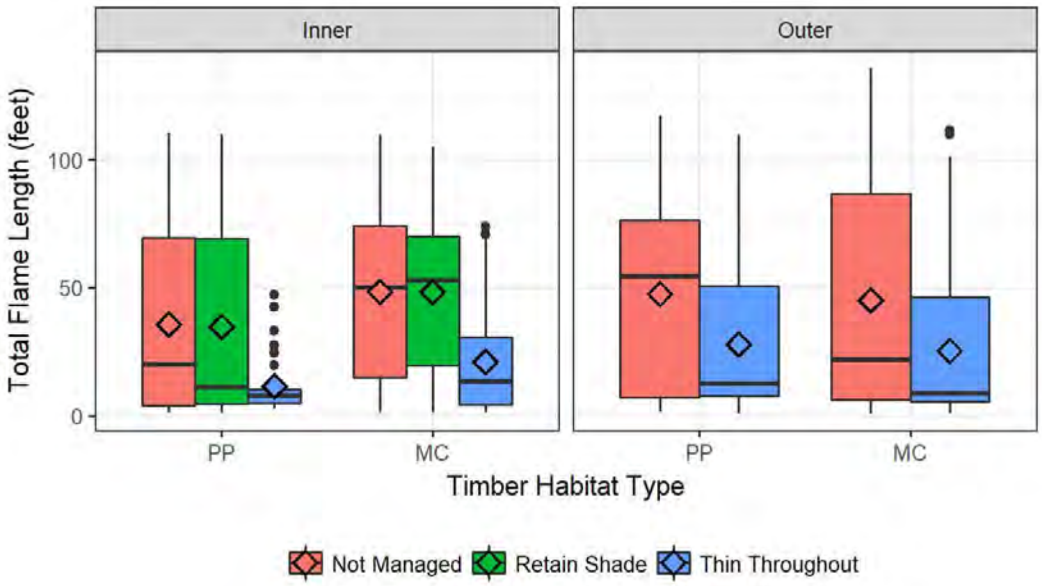


Figure 32: Comparisons total flame length distributions for sites that were not managed (red), inner zones where shade is retained (green), and inner and outer zones that were thinned throughout (blue) for ponderosa pine (PP) and mixed conifer (MC) timber habitat types. The boxes represent the 25th and 75th percentiles and the horizontal black lines the median of the data. The vertical lines extend to the range of the data or 1.5 time the interquartile range (the range from the 25th to the 75th percentile). Black points are potential outliers. The diamonds are the means of the data.

DISCUSSION

This project evaluated current stand conditions and simulated stand conditions, with and without various management treatments. Current stand conditions were based on a survey conducted by Bonoff et al. (2008) for lands in eastern Washington covered by the Forest and Fish Report (FFR). Projected stand conditions were based on projections using the Forest Vegetation Simulator (Keyser and Dixon 2008a, Keyser and Dixon 2008b, Keyser 2008) to simulate forest growth and stand dynamics over a 50-year timeframe with 10-year time steps. Additional simulations were implemented to evaluate shade levels using methods following those in the Washington Forest Practices Watershed Analysis Manual Riparian Function Module, and to evaluate susceptibility of stands to insects and disease per Hessburg et al. (1999). Management was simulated in FVS by applying Washington Forest Practice rules WAC 222-30-040 for the area within 75 feet of bankfull width, WAC 222-030-022(1)(b) for inner zones, and WAC 222-030-022(1)(c) for outer zones. Results of this study were based on a combination of: 1) field evidence in the form of currently available riparian datasets; 2) the application of the rules for managing stands to the minimum permitted under the WACs; and 3) statistical models designed to predict outcomes under managed and unmanaged conditions.

In the following sections, we discuss the extent to which each of these factors may have influenced our study results and the interpretation of these results when applied to our study objectives. We also synthesize the results to discuss the potential effects of harvest under

Washington Forest Practice rules, as predicted by FVS. We then discuss the attributes and limitations of the riparian datasets and statistical models available for use in this study, and conclude with a short section regarding management implications of our study results.

Riparian Data Sets

The EWRAP Phase 1 data set characterized riparian stand conditions in eastern Washington forests. Using data from 98 of the 103 ERWAP sites (five sites were removed because they lacked trees or were high elevation), we analyzed a broad range of conditions and geographic areas and evaluated the utility of the available data and sample sizes used in this study. Sites predominantly occurred within ponderosa pine and mixed conifer timber habitat types, with little representation of high elevation timber habitat type. This was largely expected due to the relatively small amount of managed state and private lands above 5,000 feet elevation. Within the PP and MC timber habitat types, there may have been some inconsistency with the true ecological types within each elevation zone. In other words, some PP ecological plant associations and habitat types may have existed in the MC timber habitat types and vice versa. Overall, the models employed in this EMEP study did not distinguish between WAC-based timber habitat types. Rather, they used information collected at the site level, including ecological plant associations and habitat types, to evaluate growth, insect and disease susceptibility, and fire behavior irrespective of timber habitat type. Therefore, the typing inconsistency did not influence raw results. However, in summarizing by timber habitat type, this inconsistency could introduce variability to summary results. Based on best professional judgement, the authors assumed that timber habitat types adequately captured ecological differences at a coarse meaningful scale, ensuring that reported differences and trends were ecologically informative and meaningful. However, these strata were not as representative as they could be if ecological plant associations or habitat types were used and data were limited to pursue any further analytical refinements. From a statistical standpoint, increased variability may bias test statistics such that statistical differences and treatment effect magnitudes were understated. That is, there may have been more statistically significant differences due to ecological reasons than were reported here, which may have been muted by ecological overlap between timber habitat types.

Despite the range of conditions analyzed and the sample sizes available for this study, we found current average stocking levels to be remarkably low. Average stocking in this study was lower than published maximum stocking levels for the region (e.g., Powell 1999), and lower than maximum stocking assumed by FVS. Existing stocking averaged 40% of the maximum stocking assumed by FVS with a range from 5 – 97% depending on habitat type. While explanations for this outcome within the data set were limited, available information on stand age indicated a relatively high percentage of young stands in this study. Perhaps stands were not fully developed towards maximum stocking levels. We also had information on the sampling methods. It was possible that the stand inventory sampling methods in the EWRAP, modified horizontal line sampling, which is known to be unbiased, may have contributed to unintended inaccuracies. In a comparison of several sampling methods Marquardt et al. (2010) found horizontal line sampling to be the least accurate and the most variable when estimating variability in basal area per hectare and trees per hectare that involved over 500 sample simulations. Schreuder et al. (1987)

suggested that longer transects with horizontal line sampling would lead to more accurate samples. Compiling the ERWAP data into regulatory zones, as was done in this study, effectively created a shorter transect length, which could be expected reduced sample accuracy, especially in the narrower core and outer zones. This may explain the large outliers seen in the data. We also believe there was the potential for undersampling small trees using this method, thereby potentially lowering resulting tree count estimates. Horizontal line sampling selects trees with a probability that is proportional to tree size (Husch et al. 2003) whereby small trees are less likely to be sampled than large trees. If small trees were not uniformly distributed in the riparian zones, the single transect and lower sampling probability of small trees could have underestimated small tree density, which would have been better sampled using fixed area plot methods. Higher potential variability resulting from the horizontal line sampling and data compilation methods may have influenced statistical tests and obscured meaningful differences that could have been better detected or more accurately quantified by alternative methods. Would it be so systematic as to influence overall results? Probably not in aggregate. There could be other reasons not explained by the data. For instance, Bonoff et al. (2008) speculated about the effect of past harvest on EWRAP sites. Stand densities in the core and inner zones tend to be higher than the outer zone. Is this an ecological effect or a management effect? Information did not exist in the survey to test this. Overall, whereas study objectives were addressed by the results, conditions and trends reported in this study were tempered by these concerns. One key implication was that the employed methods may have underrepresented the number of stands eligible for harvest if smaller diameter trees were undersampled and not included in shade and basal area per acre calculations when determining harvest eligibility.

The employed survey method also had potential implications for determining stands eligible for harvest based on adequate shade under the rules. Specifically, because in-stream shade data were not collected by Bonoff et al. (2008), we had to simulate shade using survey information about near-stream trees. While we used a recognized method for determining stream shade, the method was designed for field use, not simulation. Of concern is that, when using the variable-width line method to survey trees, not all trees along the line were sampled. Only "in" trees were sampled, trees large enough and/or close enough to the transect centerline to have their dbh equal to or greater than the angle of the angle gage. Therefore, many "out" trees along the sampling transect may not have been represented and included in the analysis. This is important when calculating instream shade. In some instances, we may have been using "in" trees that were farther from the stream and therefore provided a greater view-to-sky under our simulation method than if we had used "out" trees, including smaller trees closer to the stream that may have been undersampled. These "out" trees can still provide riparian function, including shade, and likely would have been sensed by any one of several shade measurement techniques in the field. This effect could have been exacerbated by the fact that only one transect per site was surveyed in the EWRAP data. Alternatively, more than one point would be sampled under WAC 222-30-040(2), which would lead to a more representative estimate of shade. Overall, our concern was that if the number and the coverage of near-stream trees were under-represented, the extent of shade provided by the riparian stand may also be underrepresented, and, hence, the number of stands providing adequate shade under WAC 222-30-040(2) may have also been underestimated. This, along with the potentially low stocking levels represented by the EWRAP data may have led to an underestimation of the number of inner zones eligible for harvest under the shade and stocking provisions of the WACs.

However, we believe that the effects of stocking and shade simulation on inner zone eligibility may have been muted in our analysis by: 1) the number of sites in the BTO, and 2) the practical uncertainty one faces in determining levels of shade adequate for protecting stream temperature. About two-thirds of the EWRAP sites occurred within the BTO. Within these sites, concerns about stocking and shade simulation were not serious issues. In simulation, harvesting only occurred in a limited number of instances along large streams in the outer 25 feet of the inner zone. Legally, there are no “no-harvest” zones under the BTO stipulations of WAC 222-30-040. However, it is very difficult to defensibly discern which trees that can be harvested within 75 feet of the stream while retaining shade. Available shade models did not support such tree-level precision on input or on output. However, even with tree-level precision, detailed stem and canopy mapping would be needed to reliably evaluate inter-tree interactions as light is diffused through the entire riparian canopy (Teply and McGreer 2013). Addressing such issues can also be cost-prohibitive and this discernment is difficult in the field. Anecdotally, the authors understand that attempts to identify individual trees that could be removed within BTO buffers is difficult to accomplish technically and can be contentious. Consequently, this practice was not employed. Nonetheless, while this practice was not legally prohibited, the authors felt that the effects on harvest eligibility were reasonably represented in this study.

Among sites outside the BTO, our concern about shade determinations became more of an issue. About 40% of sites outside the BTO could not be thinned throughout the inner zone due to inadequate shade under WAC 222-30-040(2). This prohibition occurred over all time periods and across a range of stocking levels. In contrast, of those 60 percent of stands outside the BTO that were determined to have adequate shade by our simulation method, about one-third had insufficient stocking under WAC 222-30-022(1)(b) to be harvested at the onset of simulation.

These issues raise several important questions. For example, how can a poorly stocked stand have adequate shade while otherwise well stocked stands have inadequate shade? And, will shade ever improve in the future so as to permit harvest in previously ineligible stands? As analysts, we try to answer these questions by simulating shade using the EWRAP data as described above. The effect of these concerns was amplified given the importance of near-stream trees. Teply and McGreer (2013) demonstrated this in central Idaho. If there are limited near-stream trees there will be limited instream shade provided currently and in the future until adequate shade trees are recruited. In this EMEP analysis, we were left with the simplifying assumption that currently insufficient shade may predict inadequate shade in the future. Because FVS does not support spatially explicit tree recruitment, uncertainty exists regarding estimated harvest eligibility given currently available data and tools.

As practitioners, we recognize that the lack of information in the EWRAP data and uncertainty inherent in current shade models resembles the lack of certainty one can have in the field when determining adequate shade under the rules. In simulation, adequate shade is determined only when we have certainty about the presence of near-stream trees and the shade they provide. In practice, we speculate that a similar level of certainty is sought by foresters when implementing the forest practice rules. Only when shade requirements are clearly met could inner zone harvesting be entertained. Therefore, in that regard, the simulations may in fact be representative of practical determinations of harvest eligibility in the field.

Statistical Models

Although three different FVS variants were used in this study, we did not expect major differences in estimated effects due to the variants. These variants all used similar sets of predictive equations and were parameterized at the local level (i.e. national forest administrative unit). Therefore, as expected, the shape of the response was generally the same across variants, but the magnitude could vary from forest to forest. While no published comprehensive validation studies of the variants used in our study were found, we believe growth response was largely influenced by the large-tree diameter growth model in FVS. Factors in this model that vary between unmanaged and managed situations included stand density, individual tree size, and individual tree live crown ratio. Stand density negatively affects tree growth (i.e., higher density, lower growth rates), while tree and crown size positively affect tree growth (i.e., larger trees and crowns, higher growth rates). Under the WACs, outer zones can be thinned to lower residual stocking levels than inner zones. Therefore, the large tree diameter growth model reflected this by simulating higher growth rates in the outer zone than in the inner zone. Furthermore, because simulated harvest occurs from below (i.e., thinning smaller diameter trees first until the stocking target is met), there would be a greater number of small diameter, suppressed trees left in inner zone harvests than in outer zone harvests. WAC 222-030-022(1)(c) specifies the retention of 10 to 15 dominant or codominant trees to be retained in the outer zone—the largest, healthiest trees in the stand. Therefore, the large tree diameter growth model of FVS reflected this by simulating higher growth rates in the outer zone compared to the inner zone. Though simulated, this stand growth dynamic reflects well-recognized principles (e.g., Oliver and Larson 1996; Smith *et al.* 1997; Tappeiner *et al.* 2015). Therefore, this predicted response to treatment represents a plausible outcome. However, results remain modeled simulation outcomes, and as such, should be regarded as inferential and as hypotheses to be tested by field experimentation.

FVS predictions are based on statistical models developed using data sets with stand conditions very similar to those encountered in the EWRAP data set. EWRAP stands are generally not excessively overstocked (see earlier concerns) and do not develop to stand densities beyond the predictive ability of FVS, with the exception of some outliers. While proprietary growth and yield models do exist (e.g., FPS) and may provide more accurate predictions, such models were not available to us for this project. Therefore, predictions in should be regarded as the best publicly available science.

Looking forward, a major concern that could affect the reliability of FVS predictions include current and future effects of climate change. While a climate extension to FVS does exist and could be used to model the effects of climate change, such work was outside the scope of this study. Generally, we would expect FVS output from the climate extension application to show reduced growth rates for species susceptible to climate change. For instance, decreased growth and increased mortality may likely be predicted for grand fir as conditions become warmer and drier. Compared to results presented in this report, growth rates predicted under climate change could be lower, mortality could be higher, susceptibility to insects and disease could be higher, and fire risk and severity could be higher. An important addition consequence could be that fewer stands would develop to become eligible for future harvest under the current rules or they could become eligible later than predicted by analyses reported here. However, for such stands to currently be eligible for harvest, we would still expect similar responses to management, albeit at slightly lower levels. That is, managed stands would be more resilient to the effects of climate change than unmanaged stands.

Concerns have also been expressed regarding the use of FVS, FVS-FFE, and the insect and disease ratings within "strips" created by riparian stands at the scale of regulatory zones. Regarding FVS, this individual tree growth model is parameterized using data from plots that would fit within regulatory zones. Therefore, we would expect it to be responsive to conditions that would vary among zones. However, at the spatial margins of each zone, there would be increasing influence of stand conditions in adjacent zones. While this was not captured by the modeling approach, reported differences may be overstated. This would be of greatest concern for trees along the outer margin of the outer zone adjacent to an upland clearcut. In such cases, FVS projections would likely underestimate individual tree growth. As stated earlier, FVS is not a spatially explicit model, making emulation of these spatial differences problematic. Nonetheless, overall, the authors felt that results reflect meaningful differences among regulatory zones and acknowledge the presence of some inherent error. A similar disclaimer should be stated for use of FVS-FFE. However, given the limited overall effect of treatment on fire behavior, the practical implications are limited. Finally, similar concerns have been expressed regarding insect and disease ratings, which are calculated using expert models meant to be applied at a landscape scale. However, they are heavily influenced by stand-level parameters, which are reasonably expressed at a regulatory zone level. The authors feel that whereas the results may not reliably predict the changes of an actual insect or disease infestation (which may occur on a larger scale than a riparian stand), they do meaningfully represent differences in the susceptibility of trees within each regulatory zone. Overall, concerns regarding scale of application are valid, but are of insufficient magnitude to invalidate our results for the purposes of this study.

Management Implications

Differences between modeled stand conditions with and without management for the sites that were eligible for harvest highlighted the range and direction of potential effects of management actions in riparian zones. Among inner zones, growth rates were predicted to decrease with management, which seems counterintuitive since management should reduce competition and thereby increase growth. Inner zone prescriptions appeared to remove trees without reducing competition sufficiently to increase growth. However, growth among outer zones increased after management. Retention levels in outer zones were much lower and appeared to reduce competition to the point where growth rates of the leave trees increased. In stating this, it is important to remember that these attributes of simulated growth responses, absent random effects that could be encountered in field trials. Nonetheless, our simulations indicated that by harvesting to lower levels, growth could be increased.

The models also suggested that by harvesting to lower levels in PP sites, greater reductions in susceptibility to insects and disease could occur. The observed muted response to harvest effects among MC sites was likely due to the susceptibility to insects and disease generally being lower than in PP sites. This may have been because observed stocking relative to maximum stocking that can be supported in these timber habitat types. It was also possible that PP sites were closer to their biological maximum, hence more stressed and more susceptible to negative effects of insects and disease.

Fire behavior estimated in the FVS-FFE model were heavily driven by fuel loads including standing dead wood, down wood, fine fuels, live surface fuels, and canopy fuels. Collectively, these factors influence fire behavior and all factors typically require substantial reductions to produce a meaningful change in fire behavior (i.e., a change from crown fire to surface fire). Treatments under the forest practices rules have mixed effects on these factors. Reductions in flame length are greatest when thinning throughout the inner and the outer management zones where there would be the greatest reduction in tree density. By thinning trees from below and removing understory trees to simulate logging damage, connectivity between the ground and canopy may be reduced resulting in lower potential flame lengths. Nevertheless, predicted flame lengths that would result under management remain tall and would likely not limit wildfire behavior to surface fires. Given these average flame lengths, there remains a high probability that crown fires could occur even at managed sites. However, the reduced fire behavior would improve the chances of successful fire suppression.

CONCLUSIONS

The Eastside Modeling Evaluation Project (EMEP) was built on the previously completed Phase 1 of the Eastern Washington Riparian Assessment Project (EWRAP) with the objectives of describing current conditions in eastern Washington riparian management zones, as defined in WAC 222-030. The eligibility of riparian management zones was based on current and modeled conditions based on criteria in WAC 222-030 and WAC 222-040, and changes in riparian management zones with growth, and where possible, management with prescriptions available in WAC 222-030. Data collected for the EWRAP provided a spatially distributed data set representative of riparian management zone conditions for eastern Washington lands covered by the Forest and Fish Report (FFR) used as the basis for simulation modeling to meet the EMEP study objectives. These data were highly variable, as may be expected for an area as diverse as eastern Washington but may have also included effects due to the sampling methods used. This variability would not have systematically biased the results but may have obscured differences among conditions among timber habitat types, riparian management zones, and prescriptions.

Overall, as riparian zone growth was simulated with FVS for 50-years with and without management, tree size and stand density increased (Study Objective 5), along with some increases in insect and disease susceptibility and potential fire severity without management and decreases with management (Study Objective 4). Across the EWRAP sites, many inner riparian management zones were not eligible for harvest primarily because they were located within the BTO or lacked sufficient shade to allow management treatments, which was consistent throughout management simulations (Study Objective 1). When inner zones could be managed, either thinning throughout the zone or only thinning the outer 25 feet along larger streams in the BTO or where shade was deficient, management with available prescriptions had minimal effects on tree growth and minimal reductions in insect and disease susceptibility (Study Objective 2, Study Objective 5). Management in outer zones, which removed more trees, increased tree growth and reduced insect and disease susceptibility, and potential wildfire severity (Study Objective 2, Study Objective 5). Higher levels of harvesting could result in forest growth and health benefits. However, potential benefits of harvesting at higher levels in riparian management zones would need to be balanced with potential negative impacts on ecological functions and processes in riparian habitats and overall aquatic system health and protection.

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