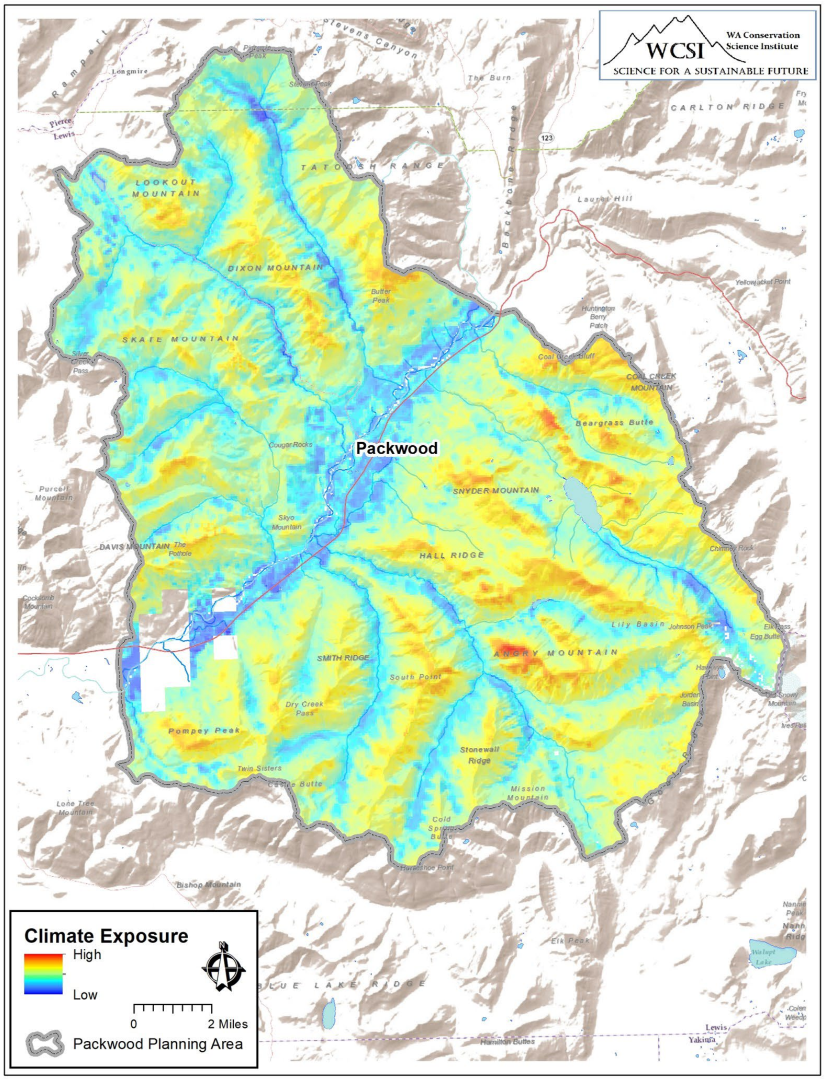
Assessing Forest Health in Western Washington Landscapes

A pilot effort to explore methodologies for aquatic and terrestrial Landscape Evaluations



WASHINGTON CONSERVATION SCIENCE INSTITUTE AND WASHINGTON DEPARTMENT OF NATURAL RESOURCES FOREST RESILIENCE DIVISION

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SECTION 1: The Landscape Evaluation Process

INTRODUCTION

Recognizing the importance of maintaining and improving forest health and resilience statewide in Washington, the state legislature directed Department of Natural Resources to establish a forest health assessment and treatment framework to proactively and systematically address the forest health issues facing the state (RCW 76.06.200). In 2017, the DNR collaboratively developed the 20-Year Forest Health Strategic Plan with an initial focus on eastern Washington (WDNR 2017). The strategic plan defined a process and methodology used to inform investments in treatments by first identifying priority landscapes and then conducting an assessment of the condition of the landscapes using a process referred to as a landscape evaluation (WDNR 2020A).

A landscape evaluation is a data driven approach to understanding the current condition of a landscape, by assessing resilience to disturbances and climate change, ability to provide an array of ecosystem services, and risks to human communities from wildfire or other disturbances (Hessburg et al. 2013, 2015; WDNR 2017, Cannon et al. 2018). Landscape evaluations are based on a set of "indicators" related to forest health, risks to communities, and other social and ecological values (Reynolds and Hessburg 2005), and can be used to estimate treatment need and identify priority treatment locations to achieve resilience, risk reduction, or other objectives. Landscape evaluations are non-regulatory and can be used to account for the management objectives of different landowners. They provide a common base of information to landowners within a landscape to inform individual and coordinated efforts to increase forest health and resilience.

In 2020, Washington's Forest Action Plan (WDNR 2020b) recognized that forest ecosystems of western Washington face unprecedented issues, challenging communities and society to find ways to address them (Haugo et al. 2015, 2018; Halofsky et al. 2018a, 2018b, Donato et al. 2019, Reilley et al. 2022). The plan commits to "Work internally across DNR divisions, with the Forest Health Advisory Committee, the Timber, Fish, and Wildlife Policy Committee, and other partners to lay the scientific, social, cultural, and economic framework for an all-lands forest health and resilience vision and approach for western Washington forestlands, building off of existing plans and strategies." While the landscape evaluation process and indicators is well developed for eastern Washington, the differences in vegetation types, fire regimes, ownership patterns, and socio-economic conditions require a different set of indicators in Western Washington. The 2020 Forest Action Plan lays out the following landscape objectives to guide landscape evaluations in Western Washington.

- Prepare the landscape for the anticipated effects of future climate change, especially drought.
- Restore landscape structure and pattern to a more resilient state including accelerating the development and connectedness of patches of mature forests and fostering the creation of high-quality early seral habitat.

- Address aquatic restoration needs and ensure forests continue to provide clean and cold water.
- Increase the understanding of the changing dynamics of fire regimes in light of climate change.
- Support rural economic development including sustainable timber production.

This report documents the technical process used to establish a preliminary set of ecological and social indicators, along with assessment tools, to inform discussions and planning towards future landscape evaluations in western Washington. These preliminary indicators and evaluation tools were applied to assess conditions within two pilot landscape planning areas, providing place-based assessment results that partners can review and enhance.

The pilot landscape evaluations in this document are the first step in developing a forest health assessment framework for Western Washington. The indicators and evaluation tools will need to be modified to address the needs of local teams within individual landscapes and as science understanding evolves. Additionally, as WDNR moves towards achieving their Forest Action Plan commitments, they will work collaboratively in defining and refining the landscape evaluation methodology and context to provide an all-hands all-lands shared vision and approach to forest health and resilience in western Washington.

WDNR welcomes input and feedback on the indicators and methods presented here.
Please send comments to: Derek.Churchill@dnr.wa.gov

Pilot landscape planning areas

The two areas selected to apply the pilot landscape evaluation methods were the Middle Snohomish and Packwood planning areas (Figure 1-1). These areas were chosen in order to capture a range of ownership and forest types in western Washington. The Middle Snohomish planning area is one of the priority planning areas identified in the 2020 Forest Action Plan and is 364,724 acres in size. Ownership is mostly small-private landowners, tribal lands, and DNR State Lands; and is primarily lower-elevation forest. The Packwood planning area, in contrast, is predominantly National Forest land with a large amount of mid- to upper- elevation forest. The Gifford Pinchot National Forest expressed interest in this area as they consider potential projects in the near future. This planning area is 149,814 acres in size.

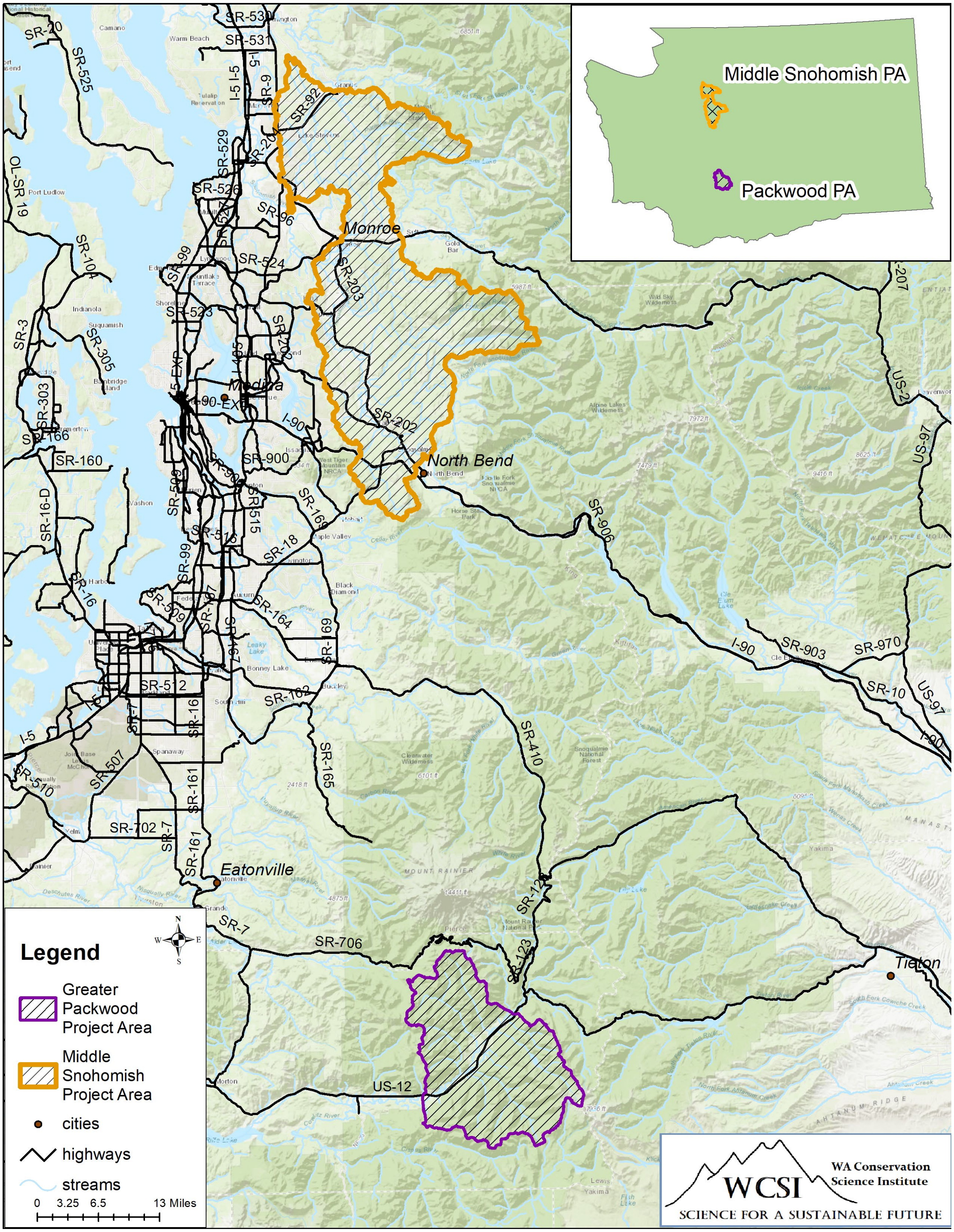


Figure 1-1. The location of the Packwood and Middle Snohomish planning areas used in the pilot landscape evaluations.

Summary of Landscape Components and Indicators

The landscape evaluation process uses a set of primary components (Figure 1-2) and a set of "indicators" to focus the assessment on issues that provide insights into the condition of ecological and social systems (Reynolds and Hessburg 2005, Hessburg et al. 2013). The primary components of the landscape evaluation were based on addressing the objectives that were identified in the Forest Action Plan for landscape evaluations (WDNR 2020b). The set of indicators used to inform each component should address the needs of local managers as they implement restorative actions under their management plans. The first step in selecting indicators, datasets, and assessment tools for the landscape evaluations was to summarize available literature from landscape evaluations in other areas (e.g., Hessburg et al. 2013, Haugo et al. 2015, WDNR 2017, Cannon et al. 2018). A technical team was convened composed of internal and external scientists (see Appendix A for technical team members) to review and modify the list of indicators and help identify relevant datasets and assessment methods. In addition, a larger workshop of interdisciplinary scientists was held in April 2023 (see Appendix C for a list of workshop participants) to present and review preliminary indicators and assessment tools that were derived from technical team. From this process, a set of preliminary indicators and tools were identified, along with additional indicators and tools to be considered in future iterations of the landscape evaluation process (Table 1-1).

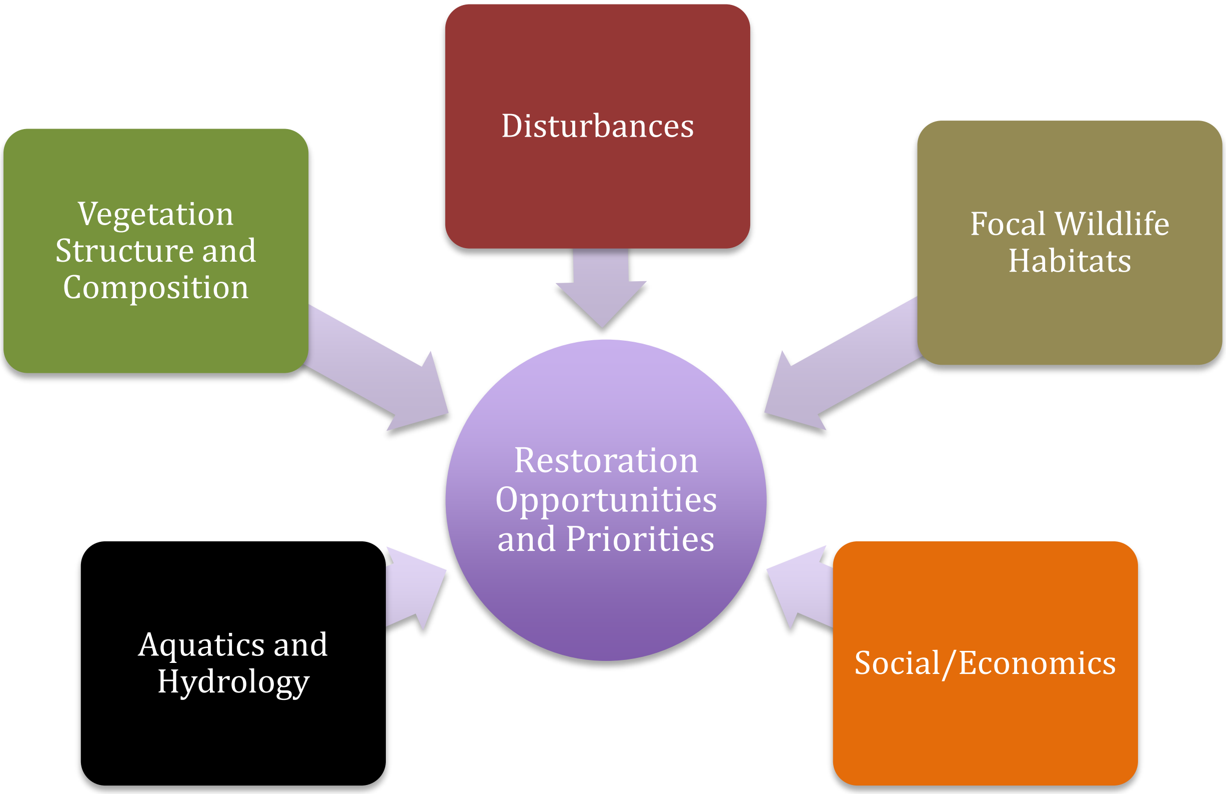


Figure 1-2. The primary components of the landscape evaluation.

Table 1-1. Preliminary indicators selected for pilot landscape evaluations.

Landscape Component	**Resource Indicator**
Aquatic and Hydrology	• Impact of roads on sediment delivery. • Impact of roads on floodplain function. • Condition of riparian habitat and wood input. • Current and projected stream temperature. • Stream flows • Watershed hydrologic regime transition • Listed fish distribution and habitat connectivity
Vegetation Structure and Composition	• Exposure of current vegetation to drought and climate change • Forest vegetation structure departure • Proportion of broadleaf tree species
Wildfire risk	• Wildfire Risk to homes and infrastructure • Amount and location of areas identified as "fire refugia"
Focal Wildlife Habitats	• Amount and spatial arrangement of complex early-seral forest habitat • Amount and spatial arrangement of late-successional forest habitat • Amount and location of unique habitats
Social and Economic	• Land ownership, infrastructure, and management objectives • Operational feasibility • Above ground carbon

Aquatics and Hydrology

The Forest Action Plan identified an objective focused on using the landscape evaluation process to "address aquatic restoration needs and ensure clean and cold water" (WDNR 2020b). A considerable body of information is available concerning the indicators that can be used in aquatic evaluations (Beechie et al. 2013a, WCSI 2017). Based on a review of the literature, and input from technical experts who participated on the technical team and in the workshop, seven indicators were used in the pilot effort to assess the current condition and effects of climate change on aquatic systems (Table 1-1). The details about the methods and specific tools that were used in the evaluation are described in Section 2.

Vegetation Structure and Composition

Vegetation structure and composition provide the foundation for many ecological functions (Franklin et al. 2002), including the resiliency of forested landscapes (Haugo et al. 2018, Donato et al. 2019, Demeo et al. 2019). The pilot landscape evaluations utilized three indicators. First, vegetation structure was assessed using three simple structure/seral classes: early, mid, and late. The current proportion of these classes was compared with estimates of historical conditions to obtain a general picture of the extent to which different classes are over- or under-represented (Donato et al. 2019). Classes were further split out using canopy cover and tree size to better understand treatment needs and opportunities. Complex early-seral was partially differentiated from simplified early-seral, but used as an indicator for wildlife species requiring this habitat type. The second indicator was the proportion of broadleaf tree species vs. conifer, which serves as a general indicator of tree species diversity. Greater abundance of broadleaf species can reduce flammability and fire spread, increase habitat breath, and provide greater resistance and resilience to insects, pathogens, and drought.

The third vegetation indicator was vulnerability of forest vegetation to drought and climate change. Impacts from climate change are one of the primary forest health concerns in western Washington. Most of our forests are light vs. moisture limited, and have high densities that are close to maximum carrying capacity. Many plant species in western Washington are not well adapted to the warmer and drier spring and summer conditions that have occurred in recent years and are predicted to intensify. Potential impacts of climate change include drought and related insect mortality of existing vegetation, lack of successful regeneration after disturbances, and shifts in species distributions and plant community assemblages. Mortality of drought intolerant species will also shift stand development and forest structure in many areas, as these species are generally the shade tolerant species that provide vertical canopy layering (e.g., western hemlock). Predicting risk of drought mortality and shifts in species distributions is challenging, however, especially at spatial scales needed by managers (e.g., stand level). We could not find an existing metric or index of climate vulnerability that could be used in these pilot evaluations. Thus, we developed our own index based primarily on climate exposure metrics. Exposure is the magnitude of predicted change in climate, as well as buffering effects from topography, and higher soil water availability in deeper soils and different slope positions. We also included a measure of vegetation density, but did not have the data to add other metrics of climate sensitivity such as species diversity or drought tolerance.

Wildfire risk

Wildfire risk to homes, infrastructure, communities, timber value, and many other resources is a growing concern in western Washington. Longer and hotter summers are creating longer periods when wildfires can occur and converge with high winds, particularly east winds that can drive large, high severity fires. The 2020 Labor Day fires in western Oregon burned 740,000 acres in a 48-hour period, mostly at high severity (Reilly et al. 2022). In 2022, 53,600 acres burned in western Washington, and fires could have been much more extensive if east wind events had been a few days longer (WDNR 2023). Despite the increasing amount of wildfire, risk in western Washington is still very low compared with eastern Washington due to low probability. While spring and summer temperatures are predicted to rise and result in lower fuel moistures, the effect of climate change on the prevalence of east wind events is hard to predict.

Unlike in eastern Washington, current fire regimes are generally not departed from historical regimes due to the nature of infrequent but large fire size with large patches of high severity (Hemstrom and Franklin 1982, Henderson et al. 1989, Agee 1993, Donato et al. 2019). Thus, the ecological basis for restoring fire-resistant forest structure over a significant portion of a landscape does not exist in most of western Washington. Fuel treatments are unlikely to stop fire spread during wind-driven fire runs and require a high level of maintenance due to rapid regrowth of vegetation. However, treatments adjacent to homes and infrastructure, along egress routes, and key potential control lines can help fire managers protect resources and facilitate fire management operations during periods of moderate to mild fire weather. Thus, for the purpose of this pilot effort the selected indicator was focused on assessment of the wildfire risk to homes and infrastructure. A Wildfire Risk Assessment (Gilbert-Day et al. 2018) and Potential Operational Delineations (PODs) where used to inform this indicators. (Note: PODs were available only for the Packwood planning area). An additional indicator was based on "fire refugia" to the potential impacts of climate change on altering fire regimes (Krawchuk et al. 2023).

Focal Wildlife Habitats

Focal wildlife habitat indicators were identified to assess broad-scale current conditions and to provide insights into habitats for key groups of species of conservation concern (Swanson et al. 2014, WDFW 2015). Species of conservation concern were identified from Region 6 Threatened, Endangered, and Sensitive Species lists (USFS 2021), and species identified as a conservation concern in the Washington Department of Fish and Wildlife Action plan (WDFW 2015). These species were then linked to focal habitats largely based on Swanson et al. (2014)(Appendix A). The focal wildlife habitat indicators included the amount and spatial arrangement of complex early-seral and late-seral habitats, and the abundance of unique habitats (e.g., wetland and broadleaf forests).

Social and Economic

There are a wide-variety of social and economic indicators that could be addressed in a landscape evaluation. The indicators selected for the pilot effort should be viewed as very preliminary and built upon as future collaborations and evaluations are completed. The social and economic indicators included land ownership, and on federal US Forest Service lands, the land use allocations. These data layers provide information on the major management emphases for various portions of the planning area and can be used to inform the types of treatments that might be used to meet differing management goals. Additionally, the outputs from the WNDR treatment feasibility tool were applied to gain an understanding of operational feasibility for wood removal treatments. The economic component of this tool may be run in the future to estimate volume outputs and potential revenues. Finally, a map of above ground carbon was included to aid managers in assessing trade-offs between carbon storage and treatment scenarios. We did not include any analysis of potential carbon sequestration.

Other Indicators

As a result of data and time limitations, not all of the resource indicators identified by the Technical Team or at the Workshop could be integrated into this pilot landscape evaluation process. However, these may be of use in future iterations of the landscape evaluation and are listed in Table 1-2. In addition, issues that involve major trade-offs among competing societal needs and are primarily policy and/or regulatory choices are challenging to include in a landscape evaluation. Among others, these include avoiding land use conversion vs. developing housing, and the dynamics between carbon storage, timber production, and revenue generation. Including these issues in a landscape evaluation would require a framework and analysis process to assess tradeoffs that was beyond the scope of this forest health driven landscape evaluation.

Table 1-2. Additional resource indicators for consideration in future iterations of the landscape evaluation for western Washington.

Landscape Component	Resource Indicator
Aquatic and Hydrology	• Cold water refugia • Water supply and retention • Timing and volume of extreme flows • Water holding capacity and erosion potential
Vegetation Structure and Composition	• Invasive plant species • Spatial pattern of structure classes and broadleaf tree species, including patch sizes
Additional disturbances	• Insect and disease risk, including non-native, invasive pests and pathogens • Wind events • Flooding
Focal Wildlife Habitats	• Habitat security
Social and Economic	• Tribal uses and priorities • Timber volume outputs from treatments. • Economic benefits to local communities. • Land use conversion

SECTION 2: Results and Data Summaries

In this section, we present results and data summaries of the existing conditions in the pilot landscapes. Our goal is to illustrate how the resource indicators could be used to gain understanding of the current and potential future conditions of the planning area. Many of these metrics can be summarized in a variety of ways and can be tailored to the management issues and questions unique to each planning area. We do not include all results here. An overview of the methods used to derive the indicators is provided at the beginning of each section.

Aquatics and Hydrology

Overview of Methods

A variety of tools and data sources were used to address the aquatic indicators (Table 2-1). To address road impacts, NetMap (Benda et al. 2007, NetMap 2017) tool called Road Erosion and sediment Delivery Index (READI) was used. This tool provides a means of determining which roads are connected to streams and have the greatest potential to deliver sediment to streams (similar to Graip-Lite). Additionally, the floodplain mapping tool in NetMap was used to assess roads that intersect floodplains. Riparian condition was assessed using LiDAR tree height information to identify where large trees (150-200 feet tall, >200 feet tall) occurred in close proximity (within 45 feet each side) to streams. The current and projected (2040) stream temperatures were derived from the NorWest (Isaak et al. 2017) data and used to identify streams that would retain cold water for listed fish. Current and projected stream flows from the North Pacific Landscape Conservation

Partnership (NPLCP) was used to identify changes in stream flows for various stream reaches. The current and projected dominant hydrologic regime was derived from the North Cascades climate change vulnerability assessment (Strauch et al. 2014) and provided information on how climate change is likely to alter hydrologic regimes in subwatersheds. Finally, a current distribution of listed fish was derived from agency databases (USFWS, NOAA, WDFW) and potential habitat was derived from the intrinsic habitat potential tools in NetMap for listed fish. The fish passage barrier database from the WDFW was used to identify potential passage barriers that interrupt habitat connectivity for listed fish.

Table 2-1. Aquatics and hydrology indicators and tools used in the pilot landscape evaluations for the Middle Snohomish and Packwood planning areas.

Indicator	Spatial Data	Tools and Analysis	Application
Impact of roads on sediment delivery.	Roads, streams, digital elevation model	NetMap – READI sediment delivery	Identify and prioritize most impactful road segments and stream crossings.
Impact of roads on floodplain function.	Roads, streams, digital elevation model	NetMap – floodplains, sediment delivery	Identify and prioritize most impactful road segments
Condition of riparian habitat and wood input.	Streams, riparian management zones, LiDAR tree sizes, potential tree heights	Compare abundance and current sizes of trees to potential.	Identify where to conserve or restore large trees for input to streams.
Current and projected stream temperature.	Streams, NorWest stream temperature data for current and 2040, fish distribution, barriers, intrinsic potential	Overlay stream temperature data with fish distribution, barriers, and intrinsic potential	Identify best places to retain cold water and remove barriers to provide fish access to cold water.
Stream flows	Stream layers, fish distribution, stream flows for current and projected	NPLCP current and projected stream flows overlaid with current and potential fish distribution	Identify where stream flows may limit fish distribution into the future.
Watershed hydrologic regime transition	Subwatersheds, NCAP hydrology modeling	Compare current and projected dominant hydrologic regime for each subwatershed.	Changes in hydrologic regime has implications for road-stream interactions and landslides.
Listed fish distribution and habitat connectivity	Roads, streams, fish distribution, intrinsic habitat potential, fish barriers	NetMap – intrinsic potential for listed fish, WDFW barrier database	Identify and prioritize most impactful road segments and stream crossings.

Impacts of Roads-Sediment Delivery

There are 462.7 miles of road in the Packwood planning area with potential to deliver sediment to streams. Of these miles, 73% have low sediment delivery potential, while 84.6 miles (18%) have moderate sediment delivery potential, and 41.3 miles (9%) have high sediment delivery potential (Table 2-2, Figure 2-1). There are four subwatersheds with >10% of the road miles identified with high sediment delivery potential: Butter Creek, Johnson Creek, Smith Creek, and Williams Creek. The road segments with moderate and high sediment delivery potential have been mapped and could be used to assess road restoration or maintenance actions to reduce sediment delivery to streams.

Table 2-2. Miles of road with Low, Moderate, and High potential for sediment delivery to streams for each subwatershed in the Packwood planning area.

Subwatershed	Low Sediment Delivery (miles)	Moderate Sediment Delivery (miles)	High Sediment Delivery (miles)
Butter Creek	9.4	3.1	2.2
Coal Creek-Cowlitz River	34.3	6.8	2.8
Hall Creek-Cowlitz River	67.4	18.5	6.3
Johnson Creek	37.8	13.6	8.5
Kilborn Creek-Cowlitz River	48.0	6.7	3.0
Lake Creek	13.2	4.6	1.9
Skate Creek	58.2	15.8	4.0
Smith Creek	17.9	7.6	3.4
Williams Creek	50.6	7.9	9.3
Total Miles	336.8	84.6	41.3

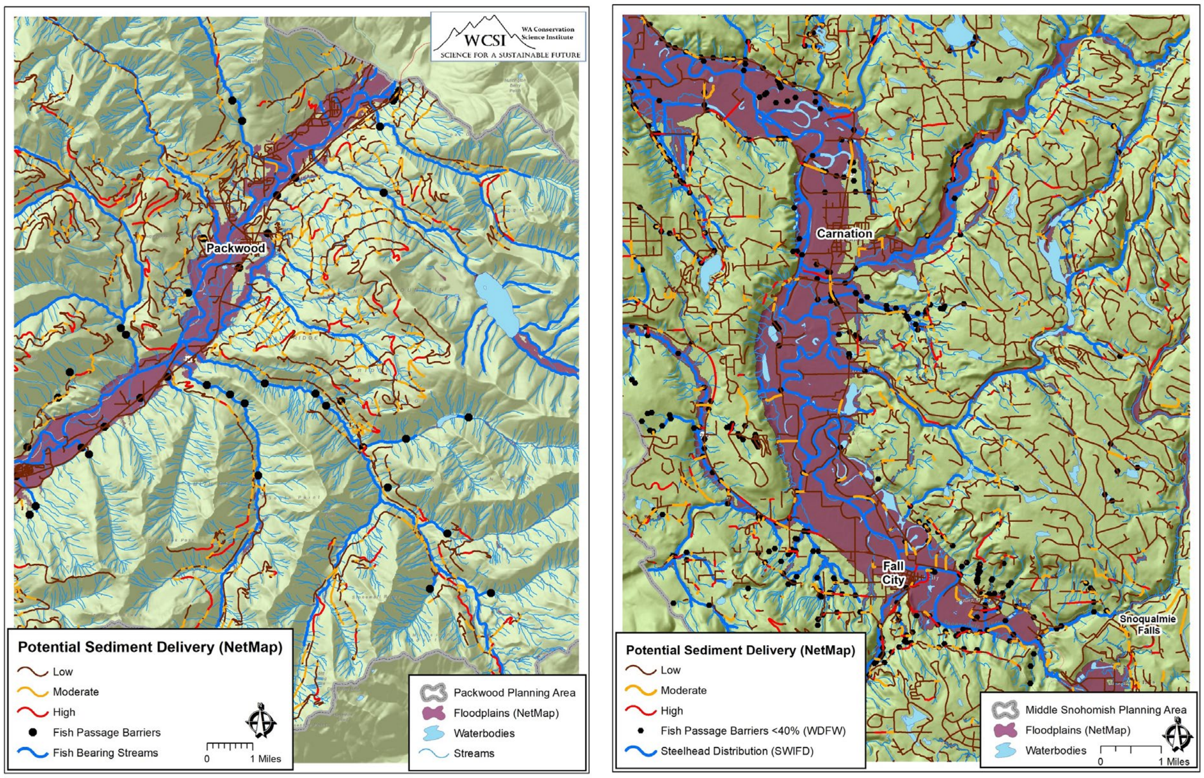


Figure 2-1. An example of potential sediment delivery from roads within a portion of the Packwood planning area (left) and the Middle Snohomish planning area (right).

There are 2,922.3 miles of road in the Middle Snohomish planning area. Most of these miles (87%) have low potential for sediment delivery to a stream (Table 2-3, Figure 2-1).

However, there are 310.3 miles (10%) with a moderate potential for sediment delivery and 95.1 miles (1%) with a high potential for sediment delivery. In the Upper North Fork Tolt River and Upper South Fork Tolt River subwatersheds >10% of the road miles have high sediment delivery potential. All road segments with moderate and high sediment delivery potential have been mapped and could be assessed for potential actions to reduce sediment delivery.

Table 2-3. Miles of road with Low, Moderate, and High potential for sediment delivery to streams for each subwatershed in the Middle Snohomish planning area.

Subwatershed	**Low Sediment Delivery (miles)**	**Moderate Sediment Delivery (miles)**	**High Sediment Delivery (miles)**
Cherry Creek	127.2	19.3	3.9
Elwell Creek-Skykomish River	212.4	24.5	9.4
Griffin Creek	88.7	8.2	1.5
Harris Creek-Snoqualmie River	160.2	14.8	6.5
Little Pilchuck River	165.5	10.9	0.6
Lower North Fork Tolt River	111.1	18.0	5.7
Lower Pilchuck River	157.0	20.7	3.4
Lower South Fork Tolt River	56.1	5.0	4.1
Patterson Creek-Snoqualmie River	233.5	32.2	12.9
Raging River	172.5	15.1	2.5
Ricci Creek-Snoqualmie River	102.0	10.9	2.6
Stossel Creek-Tolt River	72.5	5.8	0.6
Tokul Creek	160.9	31.0	10.7
Upper North Fork Tolt River	68.9	11.2	10.7
Upper Pilchuck River	271.1	45.7	9.9
Upper South Fork Tolt River	44.8	7.5	6.6
Woods Creek	312.3	29.6	3.4
Total	2,516.6	310.6	95.1

Impacts of Roads-Floodplains

The Coal Creek-Cowlitz River, Hall Creek-Cowlitz River, and Kilborn Creek-Cowlitz River subwatersheds in the Packwood planning area all have a considerable amount of floodplains (Table 2-4, Figure 2-2). A total of 62.1 miles of roads occurs in floodplains in the Packwood planning area and 86% of these miles are in the Coal Creek-Cowlitz River, Hall Creek-Cowlitz River, and Kilborn Creek-Cowlitz River subwatersheds. These roads have been mapped and could be assessed for restoration actions to reduce impacts of floodplain habitats.

Table 2-4. The acres of floodplain and miles of roads in floodplains for each of the subwatersheds in the Packwood planning area.

Subwatershed	Acres of Floodplain	Total Miles of Road in Floodplain
Butter Creek	279.6	1.3
Coal Creek-Cowlitz River	1,554.7	12.8
Hall Creek-Cowlitz River	2,434.7	14.7
Johnson Creek	414.2	0.6
Kilborn Creek-Cowlitz River	3,235.2	26.0
Lake Creek	573.9	0.3
Skate Creek	685.5	5.4
Smith Creek	185.5	0.6
Willams Creek	147.6	0.5
Total	9,510.7	62.1

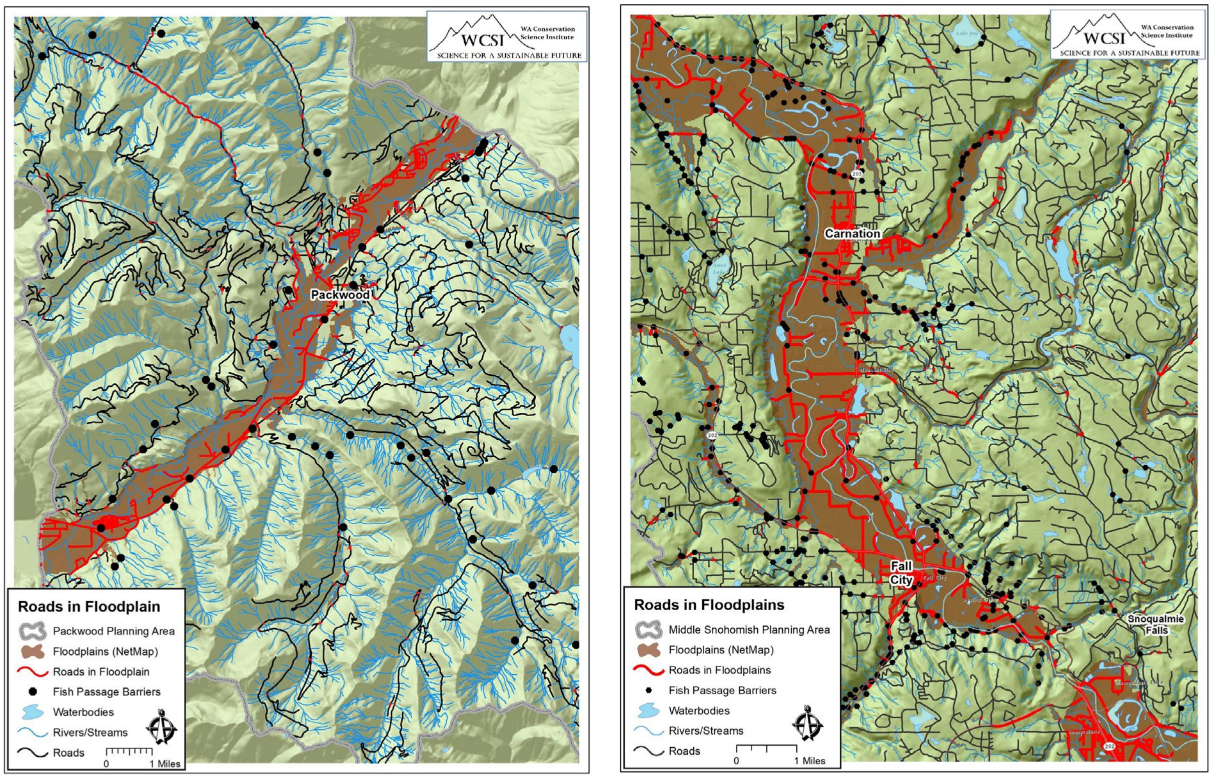


Figure 2-2. Roads that occur within floodplain within a portion of the Packwood planning area (left) and Middle Snohomish planning area (right).

A total of 290 miles of roads in the Middle Snohomish planning area occur within floodplain habitats (Table 2-5, Figure 2-2). The Elwell Creek-Skykomish River, Harris Creek-Snoqualmie River, Lower Pilchuck River, Patterson Creek-Snoqualmie River, Ricci Creek-Snoqualmie River, Upper Pilchuck River, and Woods Creek subwatersheds all have considerable amounts of floodplain habitats and 81% of the roads that occur in floodplains are in these subwatersheds.

Table 2-5. The acres of floodplain and miles of roads in floodplains for each of the subwatersheds in the Middle Snohomish planning area.

Subwatershed	Acres of Floodplain	Total Miles of Road in Floodplain
Cherry Creek	1,480.6	6.8
Elwell Creek-Skykomish River	7,377.8	42.0
Griffin Creek	845.5	2.7
Harris Creek-Snoqualmie River	5,579.8	36.2
Little Pilchuck River	2,239.7	12.2
Lower North Fork Tolt River	646.9	1.9
Lower Pilchuck River	4,010.6	28.7
Lower South Fork Tolt River	553.9	2.5
Patterson Creek-Snoqualmie River	9,177.8	70.8
Raging River	1,465.5	5.8
Ricci Creek-Snoqualmie River	5,410.9	21.0
Stossel Creek-Tolt River	1,180.3	5.5
Tokul Creek	1,106.2	11.7
Upper North Fork Tolt River	777.1	3.8
Upper Pilchuck River	3,430.1	14.9
Upper South Fork Tolt River	1,379.8	1.6
Woods Creek	3,435.5	21.4
Total	50,097.9	289.6

Riparian Habitat Condition

Considerable proportions of the riparian habitats in the Packwood planning area have large trees with the exception of the Smith Creek subwatershed (Table 2-6, Figure 2-3). In general, large trees are lacking within the riparian habitats in many of the subwatersheds in the Middle Snohomish planning area (Table 2-7, Figure 2-3).

Table 2-6. The acres of riparian habitat and acres with large trees (based on the canopy height model) for the subwatersheds in the Packwood planning area.

Subwatershed	Riparian habitat (acres)	Canopy Height Model 150-200 Feet (acres)	Canopy Height Model >200 Feet (acres)
Butter Creek	4,127.2	255.4	10.4
Coal Creek-Cowlitz River	4,085.2	174.2	16.6
Hall Creek-Cowlitz River	5,130.2	152.8	12.5
Johnson Creek	5,754.9	575.5	63.2
Kilborn Creek-Cowlitz River	3,348.2	529.9	44.3
Lake Creek	3,259.1	184.5	18.4
Skate Creek	11,749.8	840.4	44.0
Smith Creek	7,548.4	75.1	2.3
Willame Creek	3,166.4	309.2	44.1

Table 2-7. The acres of riparian habitat and acres with large trees (based on the canopy height model) for the subwatersheds in the Middle Snohomish planning area.

Subwatershed	Riparian habitat (acres)	Canopy Height Model 150-200 Feet (acres)	Canopy Height Model >200 Feet (acres)
Cherry Creek	3,711.9	172.3	0.2
Elwell Creek-Skykomish River	5,966.7	98.3	0.2
Griffin Creek	2,395.1	15.2	0.0
Harris Creek-Snoqualmie River	4,609.5	35.7	0.0
Little Pilchuck River	2,698.8	8.3	0.2
Lower North Fork Tolt River	3,864.4	179.8	0.0
Lower Pilchuck River	5,020.0	22.6	0.1
Lower South Fork Tolt River	2,111.8	12.3	0.2
Patterson Creek-Snoqualmie River	6,608.5	47.7	0.3
Raging River	4,401.5	11.0	0.0
Ricci Creek-Snoqualmie River	3,218.7	25.3	0.0
Stossel Creek-Tolt River	1,911.2	34.7	0.1
Tokul Creek	5,257.3	137.2	0.3
Upper North Fork Tolt River	4,318.8	20.7	4.8
Upper Pilchuck River	11,291.7	346.5	0.2
Upper South Fork Tolt River	4,022.3	10.8	1.8
Woods Creek	7,689.5	157.6	0.0

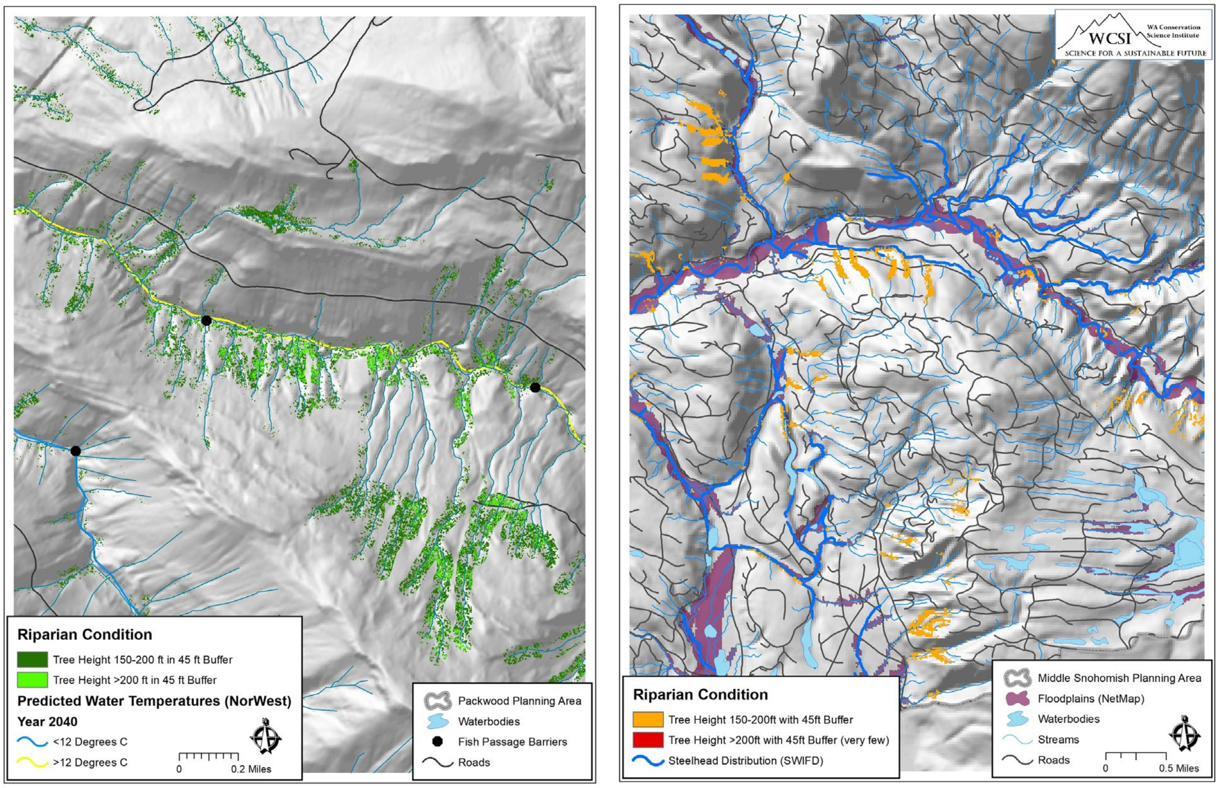


Figure 2-3. Example of riparian habitat and large trees within a portion of the Packwood planning area (left) and the Middle Snohomish planning area (right).

Stream Temperature

Stream temperatures are projected to increase considerably in the Packwood planning area (Table 2-8, Figure 2-4). The subwatersheds in which mean summer stream temperatures are expected to increase to >12^{0}C (considered harmful to fish) and reduce the miles of streams with cold water (<12^{0}C) by >50% include Lake Creek, Butter Creek, Skate Creek, Johnson Creek, Smith Creek, and Williams Creek. The identification of cold-water refugia areas would be important for managers.

Stream temperatures are projected to increase considerably in the Middle Snohomish planning area (Table 2-9, Figure 2-4). The subwatersheds in which mean summer stream temperatures are expected to increase to >12^{0}C (considered harmful to fish) and reduce the miles of streams with cold water (<12^{0}C) by >50% include Lower North Fork Tolt River, Upper North Fork Tolt River, and Upper South Fork Tolt River. The identification of cold-water refugia areas would be important for managers.

Table 2-8. A comparison of historical and projected mean stream temperatures and historical and projected miles of stream with temperatures >12 degrees C for the subwatersheds that occur in the Packwood planning area.

Subwatershed	Mean Historical Temp	Mean 2040 Temp	Historical Stream Miles >12 Degree C	2040 Stream Miles >12 Degree C
Lake Creek	8.8	10.1	3.1	8.7
Coal Creek-Cowlitz River	10.6	11.8	5.4	10.0
Butter Creek	11.1	12.3	1.0	2.3
Skate Creek	8.6	9.9	3.3	8.4
Johnson Creek	11.3	12.6	0.5	4.5
Hall Creek-Cowlitz River	9.2	10.5	9.4	11.6
Smith Creek	9.7	11.0	0.0	1.3
Willams Creek	8.4	9.7	4.1	10.2
Kilborn Creek-Cowlitz River	10.6	11.8	14.7	16.4

Table 2-9. A comparison of historical and projected mean stream temperatures and historical and projected miles of stream with temperatures >12 degrees C for the subwatersheds that occur in the Middle Snohomish planning area.

Subwatershed	Mean Historical Temp	Mean 2040 Temp	Historical Stream Miles >12 Degree C	2040 Stream Miles >12 Degree C
Cherry Creek	14.6	15.9	38.1	38.1
Elwell Creek-Skykomish River	15.4	16.7	49.3	53.0
Griffin Creek	13.6	14.9	16.6	16.6
Harris Creek-Snoqualmie River	15.0	16.3	26.6	28.1
Little Pilchuck River	15.2	16.5	31.1	31.1
Lower North Fork Tolt River	11.9	13.2	10.2	27.0
Lower Pilchuck River	15.9	17.2	48.4	48.4
Lower South Fork Tolt River	11.7	13.0	9.5	17.0
Patterson Creek-Snoqualmie River	15.1	16.4	52.3	53.5
Raging River	13.3	14.6	27.3	27.3
Ricci Creek-Snoqualmie River	16.8	18.1	29.1	29.1
Stossel Creek-Tolt River	14.2	15.5	12.9	12.9
Tokul Creek	13.4	14.7	34.6	44.1
Upper North Fork Tolt River	11.3	12.6	2.4	26.6
Upper Pilchuck River	12.6	14.0	39.1	60.0
Upper South Fork Tolt River	10.8	12.1	0.5	9.4
Woods Creek	14.7	16.0	50.7	52.0

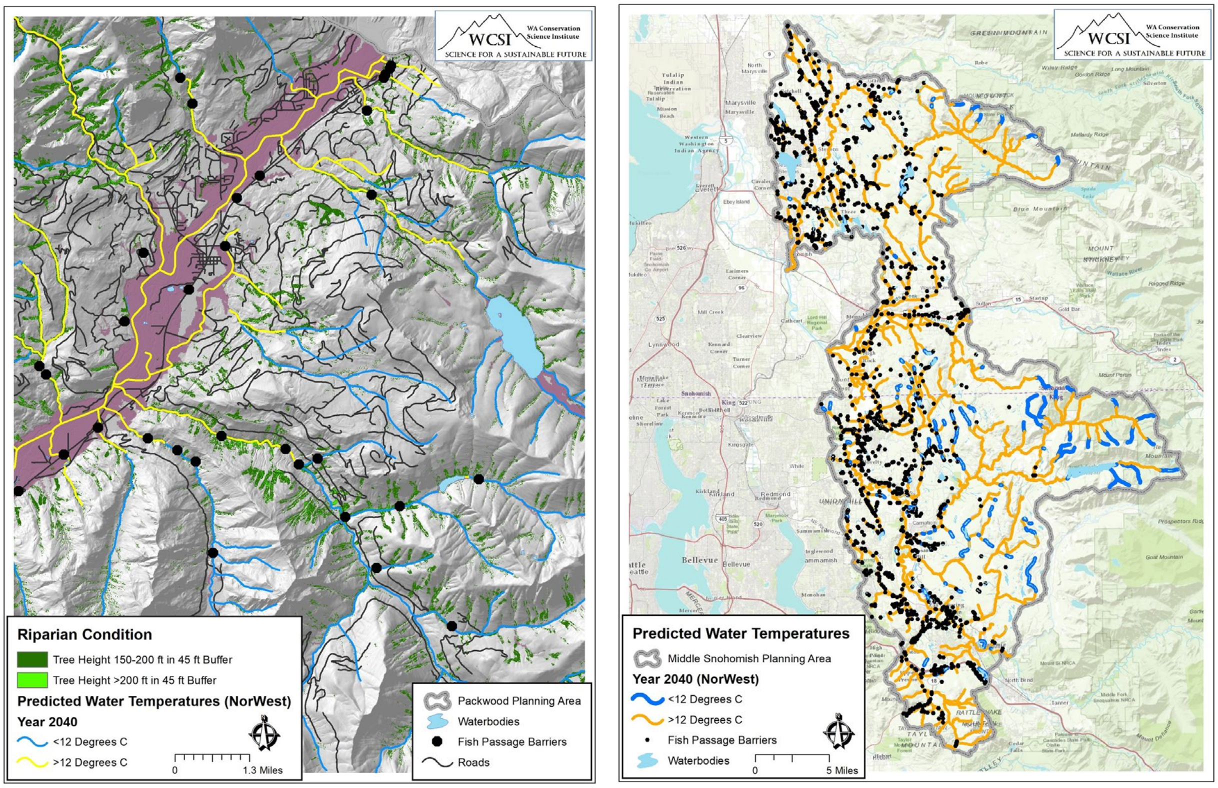


Figure 2-4. Example of predicted stream temperature changes in a portion of the Packwood planning area (left) and the Middle Snohomish planning area (right).

Stream Flows

Mean summer baseflows in the Packwood planning area are projected to decrease substantially, especially in the Coal Creek-Cowlitz River, Hall Creek-Cowlitz River, and Kilborn Creek-Cowlitz River subwatersheds (Table 2-10, Figure 2-5). Mean summer baseflows in the Middle Snohomish planning area are projected to decrease substantially, especially in the Elwell Creek-Skykomish River, Harris Creek-Snoqualmie River, Patterson Creek-Snoqualmie River, and Ricci Creek-Snoqualmie River subwatersheds (Table 2-11, Figure 2-5).

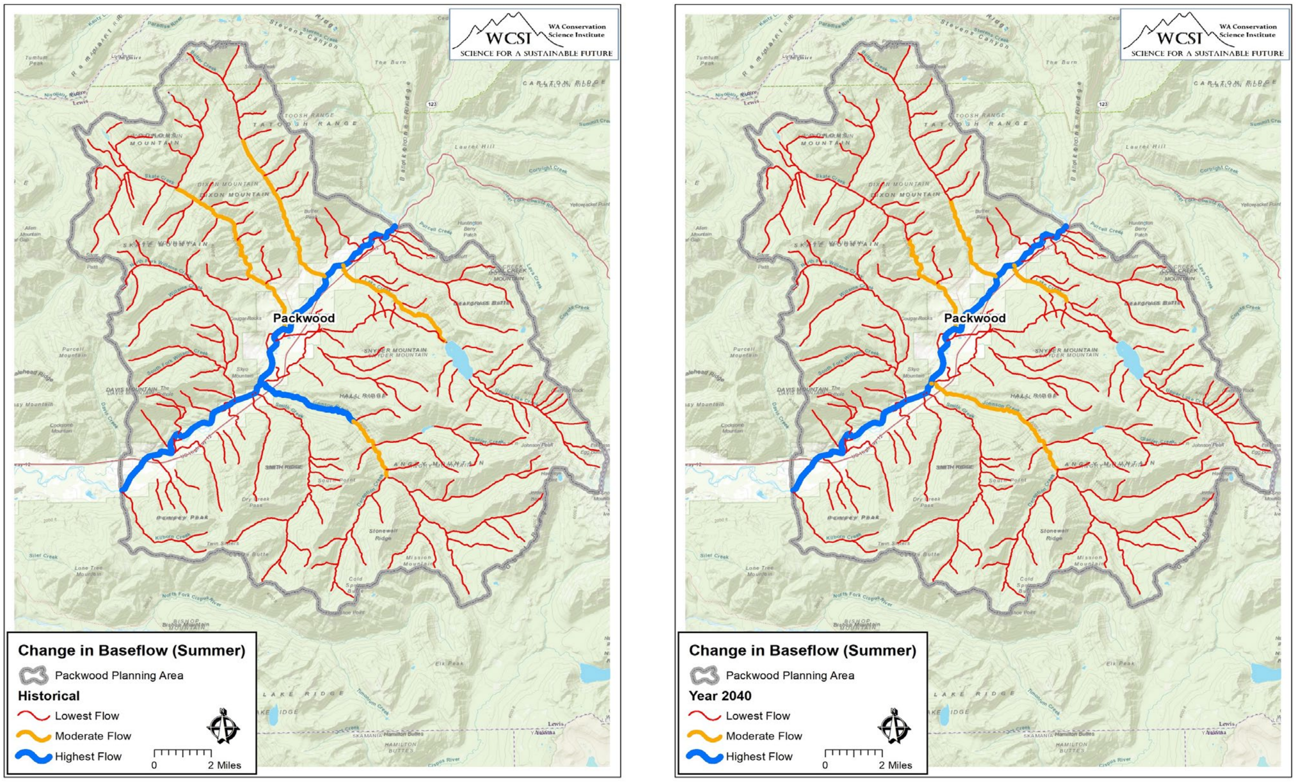
Table 2-10. Changes in historical and projected mean summer baseflows for each subwatershed within the Packwood planning area.

Subwatershed	Total Mean Summer Historical Baseflow	Total Mean Summer predicted 2040 Baseflow	Change in Flow
Butter Creek	1,436.9	1,250.9	-186.0
Coal Creek-Cowlitz River	6,583.7	5,961.1	-622.7
Hall Creek-Cowlitz River	4,964.6	4,327.6	-637.0
Johnson Creek	349.4	249.2	-100.2
Kilborn Creek-Cowlitz River	12,808.8	10,342.1	-2,466.7
Lake Creek	402.6	280.3	-122.2
Skate Creek	2,470.5	2,104.8	-365.7
Smith Creek	86.4	62.1	-24.3
Willame Creek	90.1	66.4	-23.7

Table 2-11. Changes in historical and projected mean summer baseflows for each subwatershed within the Middle Snohomish planning area.

Subwatershed	Total Mean Summer Historical Baseflow	Total Mean Summer predicted 2040 Baseflow	Change in Flow
Cherry Creek	175.3	147.8	-27.5
Elwell Creek-Skykomish River	51,722.0	32,979.5	-18,742.5
Griffin Creek	121.1	101.8	-19.3
Harris Creek-Snoqualmie River	19,205.3	12,012.0	-7,193.3
Little Pilchuck River	244.2	201.3	-43.0
Lower North Fork Tolt River	871.0	637.6	-233.4
Lower Pilchuck River	1,389.8	1,102.3	-287.5
Lower South Fork Tolt River	238.8	188.7	-50.2
Patterson Creek-Snoqualmie River	27,228.2	16,102.7	-11,125.5
Raging River	192.1	157.8	-34.3
Ricci Creek-Snoqualmie River	19,764.8	12,506.4	-7,258.5
Stossel Creek-Tolt River	2,833.6	2,166.9	-666.7
Tokul Creek	397.1	322.1	-75.0
Upper North Fork Tolt River	503.2	337.5	-165.8
Upper Pilchuck River	671.5	501.0	-170.5
Upper South Fork Tolt River	205.1	154.8	-50.3
Woods Creek	479.9	404.0	-75.9

Packwood planning area



Middle Snohomish planning area

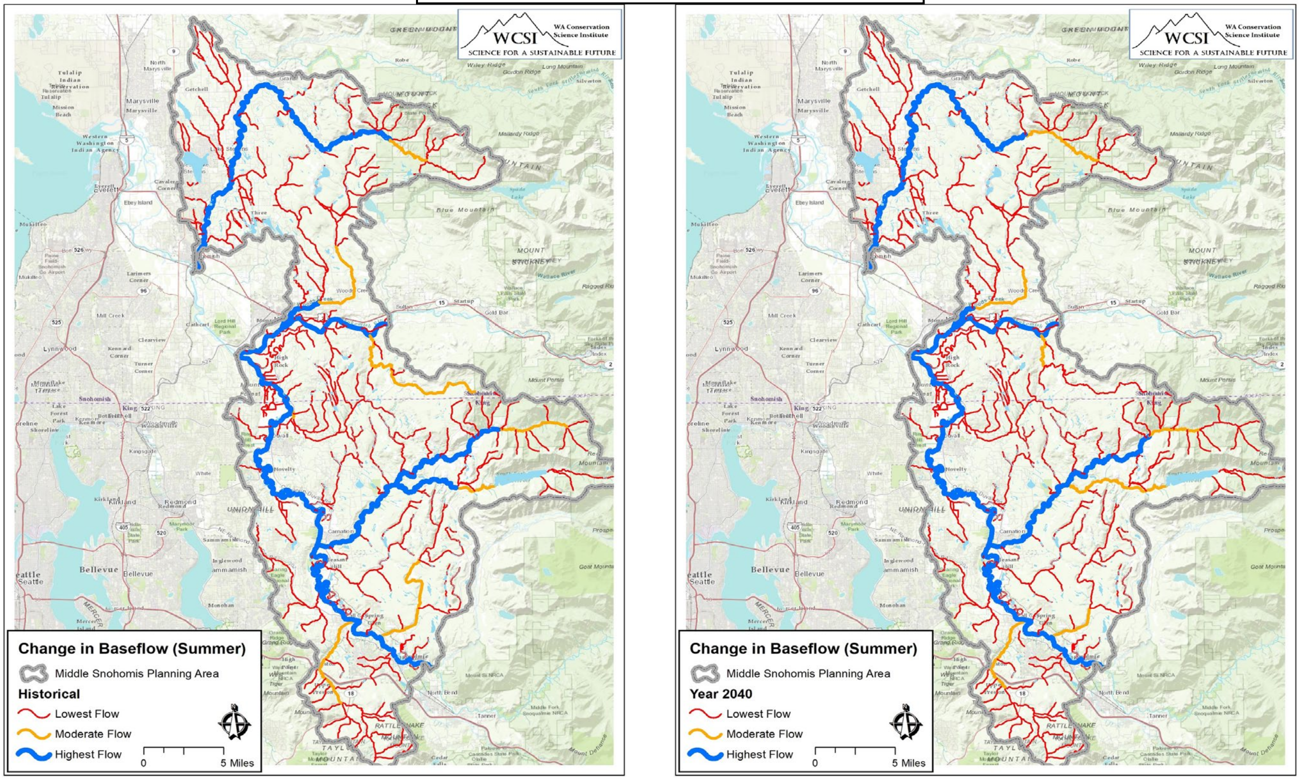


Figure 2-5. Potential change in baseflow from historical levels (left) to future flow levels (right) for the Packwood (upper) and Middle Snohomish (lower) planning areas.

Watershed Hydrological Transitions

The Packwood planning area is currently classified as a rain-snow dominant watershed and the Middle Snohomish as a rain dominant watershed (Strauch et al. 2014). Flooding potential from extreme storm events and high flows are expected to increase (Strauch et al. 2014).

Listed Fish Distribution

There are no listed fish or potential habitat for listed fish in the Packwood planning area. In the Middle Snohomish planning area, steelhead, Chinook salmon, and bulltrout have been documented, and considerable amounts of potential habitat occur in most of the subwatersheds (Table 2-12, Figure 2-6). A total of 1,640 fish passage barriers (<60% passable) were identified in the Middle Snohomish planning area (Table 2-13). Many of these occur in subwatersheds with listed fish species present. An assessment of these barriers in relation to current and potential fish habitat and access to cold water may help managers identify priorities for restoration actions.

Table 2-12. Miles of current and potential habitat for listed fish species within each subwatershed in the Middle Snohomish planning area. D indicates documented occurrence. IP refers to intrinsic potential.

Subwatershed	**Steelhead**		**Chinook**		**Bulltrout**	
	D	**HIGH_IP**	**D**	**HIGH_IP**	**D**	**Presumed**
Cherry Creek	13.9	7.1	6.7	2.4	0.0	20.4
Elwell Creek-Skykomish River	56.3	8.5	34.2	14.1	14.6	31.4
Griffin Creek	27.3	5.2	1.1	0.0	0.0	18.2
Harris Creek-Snoqualmie River	38.8	14.3	13.1	11.2	12.2	36.0
Little Pilchuck River	27.6	9.7	0.0	0.0	3.9	26.0
Lower North Fork Tolt River	7.7	3.1	2.3	1.2	2.6	1.5
Lower Pilchuck River	43.2	15.1	35.9	18.0	21.4	31.4
Lower South Fork Tolt River	18.4	12.3	1.5	2.5	8.4	3.8
Patterson Creek-Snoqualmie River	55.5	6.0	23.6	14.0	15.2	29.1
Raging River	1.7	0.9	0.8	0.0	0.0	0.8
Ricci Creek-Snoqualmie River	34.9	3.1	14.2	12.1	12.4	30.8
Stossel Creek-Tolt River	29.4	7.1	10.0	8.4	10.0	8.2
Tokul Creek	34.5	12.7	9.8	3.0	0.0	23.4
Upper North Fork Tolt River	0.0	0.0	0.0	0.0	0.0	0.0
Upper Pilchuck River	48.0	29.4	32.1	13.4	15.0	23.8
Upper South Fork Tolt River	0.0	0.0	0.0	0.0	0.0	0.0
Woods Creek	50.5	18.3	35.9	6.0	0.0	44.2

Table 2-13. Identified fish passage barriers (<60% passable) in the subwatersheds that occur in the Middle Snohomish planning area.

Subwatershed	Total number of barriers
Cherry Creek	110
Elwell Creek-Skykomish River	92
Griffin Creek	8
Harris Creek-Snoqualmie River	196
Little Pilchuck River	223
Lower North Fork Tolt River	1
Lower Pilchuck River	211
Lower South Fork Tolt River	3
Patterson Creek-Snoqualmie River	302
Raging River	15
Ricci Creek-Snoqualmie River	117
Stossel Creek-Tolt River	25
Tokul Creek	127
Upper North Fork Tolt River	0
Upper Pilchuck River	60
Upper South Fork Tolt River	0
Woods Creek	150

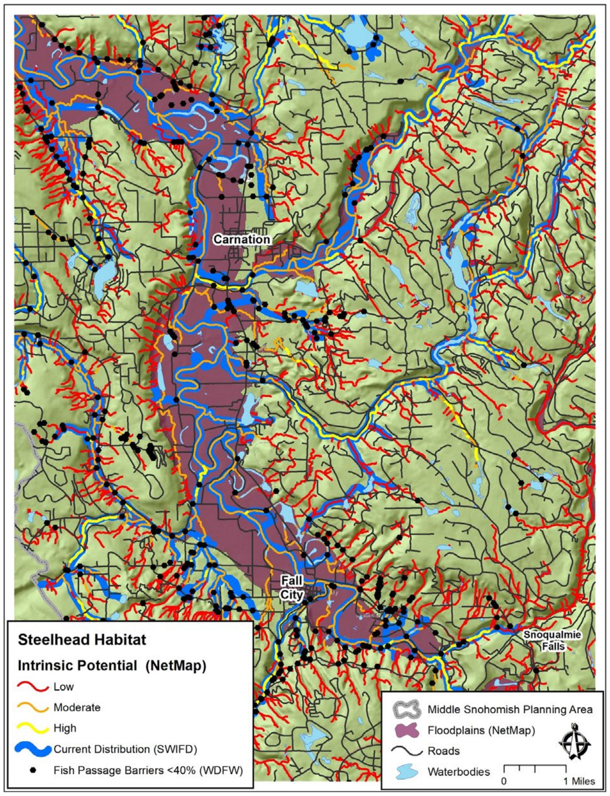


Figure 2-6. Example of habitat data for one fish species of concern: potential steelhead habitat and fish passage barriers within the Middle Snohomish planning area.

Vegetation Structure and Composition

Overview of Methods

Forest vegetation was assessed using a variety of data sources (Table 2-14). Forest structure classes were based on canopy cover and tree size derived from 1ft canopy height models from LiDAR that were generated by WA DNR. Structure classes were derived at the scale of 90x90ft pixels. Tree size was based on the 95thpercentile height of the 1ft pixels from the canopy height model. Height thresholds to define the late, mid, and early classes (Table 2-15) were based on expert opinion from past projects and were informally validated using aerial imagery. Canopy cover for each pixel was based on the percentage of 1ft pixels from the canopy height model that had a height greater than 6ft. Measuring LiDAR based cover with this method results in higher cover compared with the more standard of method of using the percent of returns over 6ft. The threshold we used to define closed vs. open canopy, 75%, equated to approximately 60% using the standard method that was comparable to field-based methods. LiDAR from 2020 was used for almost all the Packwood PA. For the Middle Snohomish PA, LiDAR from 2021 was used for the southern half and from 2017 for the northern half. These classes were compared to the historical range of variability estimates in Donato et al. (2019).

Table 2-14. Vegetation structure and composition indicators and tools used in the pilot landscape evaluations for the Middle Snohomish and Packwood planning areas.

Indicator	**Spatial Data**	**Tools and Analysis**	**Application**
Forest vegetation structure departure	Structure classes from LiDAR,	Compare current to estimates of HRV for early-, mid-, and late-seral structure classes. Mid- and early-seral were split into additional classes.	Assess the current condition to identify where treatments are needed or time can be used to develop under-represented structure classes.
Proportion of broadleaf tree species	GNN -2021	Amount and location of broadleaf tree species vs conifer	Identify relative abundance of broadleaf vs. conifer tree species & potential need to expand broadleaf.
Exposure of current vegetation to drought and climate change	Predicted shifts in potential vegetation type, topographic variables, changes in moisture deficit and snow water equivalent, and tree density.	Climate exposure index that combines a subset of the spatial datasets	Determine locations in each landscape that are more or less likely to experience drought mortality and vegetation transitions.

Table 2-15. Tree height thresholds used to identify forest structure classes.

Structure Class	Successional Stage	Height (ft)	Canopy Cover (%)
Late	Old	>125	0-100
Mid 100-125' - Closed	Mid Closed	100-125	75-100*
Mid 100-125' - Open	Mid Open	100-125	0-75
Mid 40-100' - Closed	Mid Closed	40-100	75-100*
Mid 40-100' - Open	Mid Open	40-100	0-75
Early - Closed	Early	<40	75-100*
Early - Open	Early	<40	0-75

*Equates to ~60% cover using standard lidar methods.

Proportion of broadleaf tree species was derived from the Gradient Nearest Neighbor data (GNN_VegClass_2021) (LEMMA 2020) by combining all conifer classes and using the mixed and broadleaf classes to create three classes. The spare and open classes contain no tree species data but are shown in the tables and figures.

We could not find a suitable metric or index to quantify the vulnerability of vegetation to climate change for western Washington. Thus, we created our own index at a spatial scale small enough to inform management prioritization (90m pixels). Vulnerability consists of exposure, sensitivity, and adaptive-capacity (Glick et al. 2011). Exposure is the magnitude of predicted change in climate, as well as buffering effects from topography, and higher soil water availability in deeper soils and different slope positions. Sensitivity is the ability of current vegetation at a site to survive such changes and maintain sufficient growth rates and vigor to persist over time. Adaptive capacity is how quickly new vegetation communities can emerge, that combine current and new species, that are better adapted to new climates, which is most likely to occur after major disturbances.

We based on index primarily on climate exposure metrics due to the lack of suitable datasets for sensitivity and adaptive capacity. We selected metrics based on a similar index in the Cedar River Watershed (SPU 2023), climate change vulnerability assessments and management guidelines for western Washington (Halofsky et al. 2011, Hudec et al. 2019, Raymond et al. 2022), and a recent study of factors driving largescale mortality in western Oregon (Bennett et al. 2023). Six exposure metrics were initially chosen, including predicted changes in potential vegetation type (PVT) from Halofsky et al. (2018), topographic wetness index, topographic position index, solar radiation, and predicted absolute change in climatic water balance deficit and April snow water equivalent (WA DNR 2020) (Figure 2-7). Many of these metrics, however, were highly correlated due to inclusion of the same underlying climate and topographic (e.g., temperature, precipitation, aspect). We thus selected change in water balance deficit and snow water equivalent, and topographic position index for the final index.

We also included a fourth metric that is part of sensitivity to climate change: tree density as measured by Curtis relative density (Curtis 1982). Relative density quantifies the amount of available growing space occupied by trees relative to the maximum carrying capacity of the site. While species composition is key factor driving sensitivity, sufficiently accurate datasets for this metric do not exist. Structural metrics such as tree size and tree size diversity also influence sensitivity, but the empirical basis for how to include these metrics is uncertain. The 4 metrics were standardized (0-1 scale) by dividing by the 95th percentile value. All values above the 95th percentile where set to 1. The four metrics were then added together in an equally weighted manner to create the final index. This index was then classified into low, medium and high bins using the 33rd and 66th percentile values from all of western Washington.

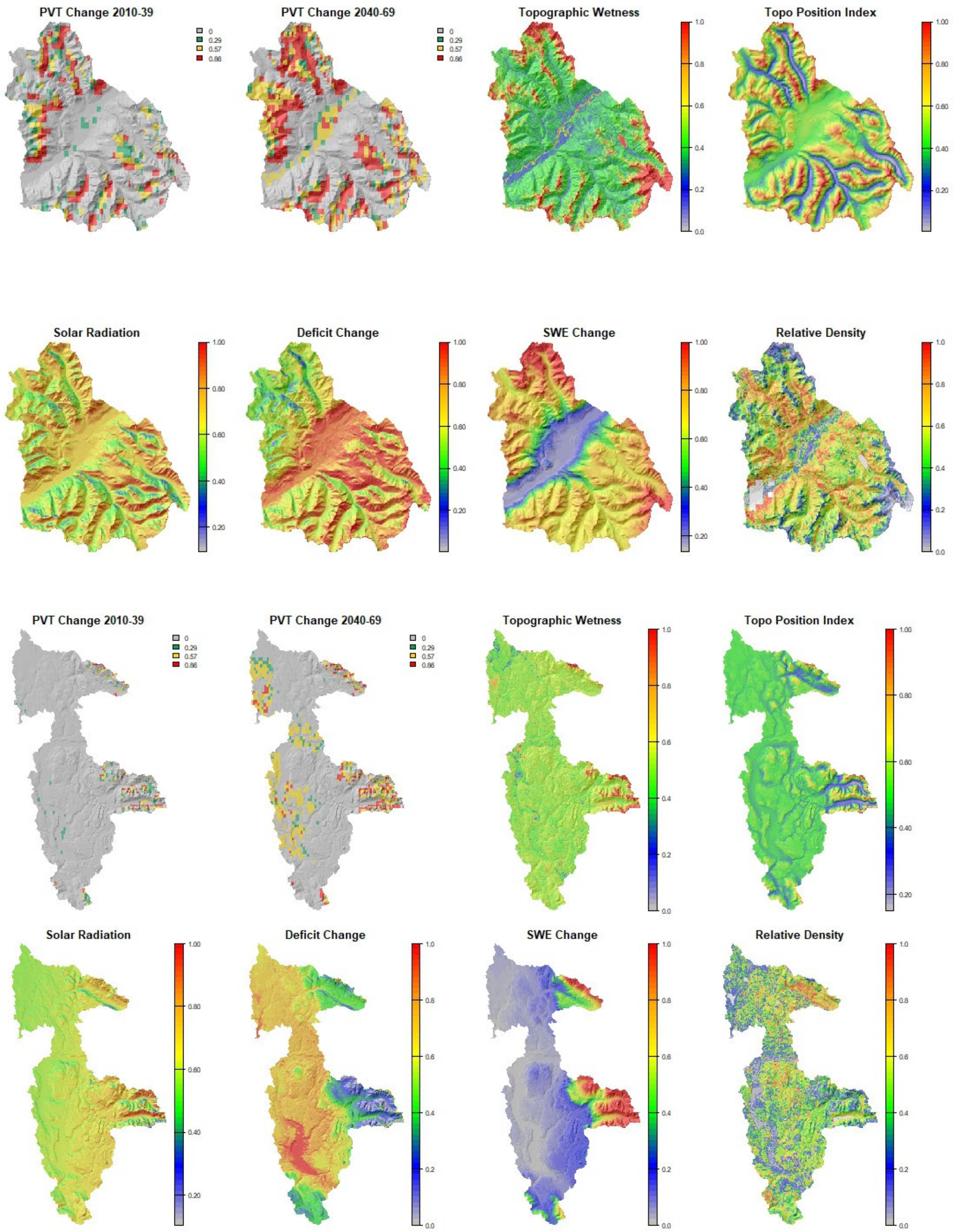


Figure 2-7. Input metrics used to assess the vulnerability of forests to climate change in the Packwood (top) and Middle Snohomish (bottom) planning areas. Predicted change in potential vegetation type (PVT) for the 2010-2039 and 2040-69 time periods is from Halofsky et al (2018). Values relate to the number of GCMs where pixels are predicted to move into a drier PVT. Topographic wetness, solar radiation, deficit change, and snow water equivalent change were developed by Sean Jeronimo for the 20 Year Plan (WA DNR 2020). Relative density is Curtis Relative Density (Curtis 1982) from DNR's remote forest resource inventory system.

Forest Vegetation Structure Departure

The distribution of early-, mid- and late-seral vegetation structure classes is depicted in Table 2-16 and Figure 2-8. Figure 2-9 shows the departures for vegetation structure for each planning area. These results show an overabundance of mid-seral structure relative to the historical ranges, while late-seral forest is low. This is common in most of western Washington and Oregon (Demeo et al. 2018). The Middle Snohomish planning area, in particular, has over 70% in mid-seral and only 15% in late-seral. Early-seral is within range for both planning areas. However, most of the early-seral structure is structurally simple, and not in a condition that would have resulted from a natural disturbance due to a lack of large-live trees, standing snags, and downed wood. See focal wildlife habitat section for a breakdown of structurally complex vs. simple early-seral habitats.

Table 2-16. The amount and proportion of structure classes for the Packwood and Middle Snohomish planning areas.

Structure Class	**Packwood planning area**		**Mid Snohomish planning area**	
	Acres	**Percent**	**Acres**	**Percent**
Early Seral	14,897	10%	72,070	24%
Mid-Open	14,708	10%	58,759	19%
Mid-Closed	59,018	40%	128,036	42%
Late Seral	59,134	40%	46,933	15%

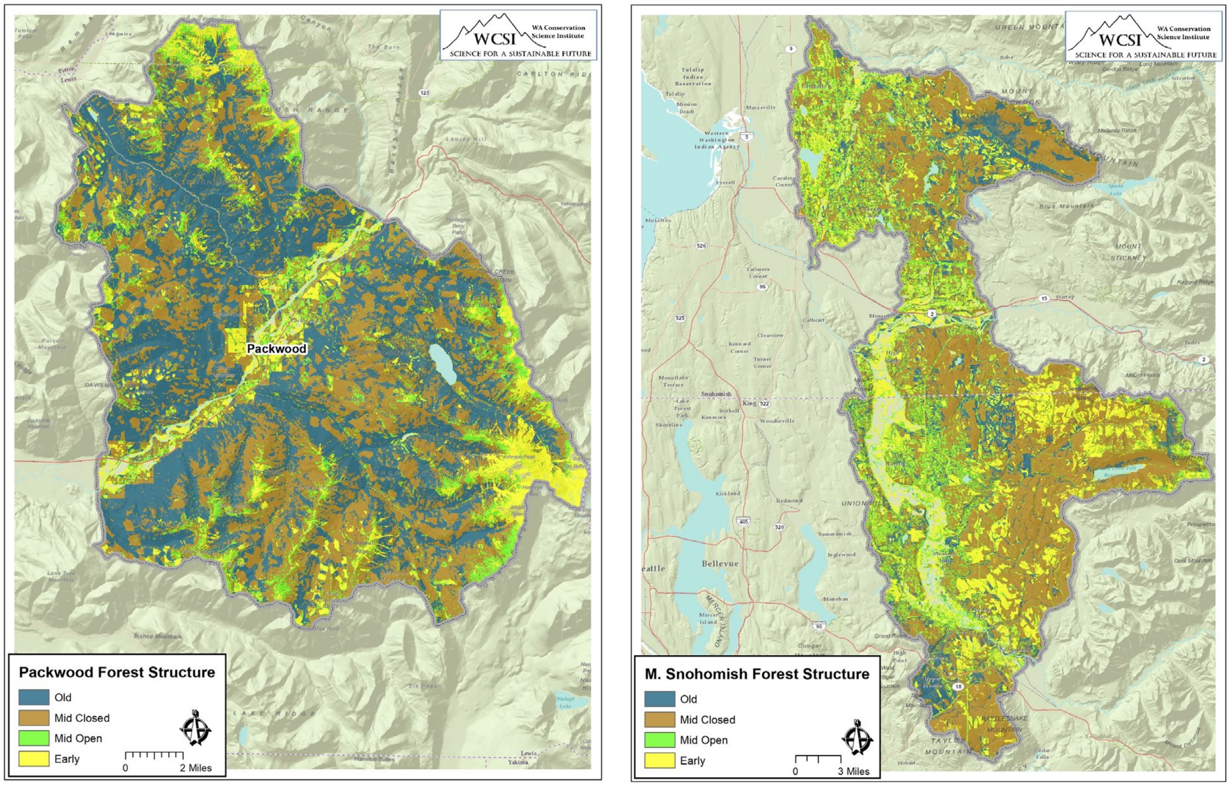


Figure 2-8. Forested structure classes within the Packwood planning area (left) and the Middle Snohomish planning area (right).

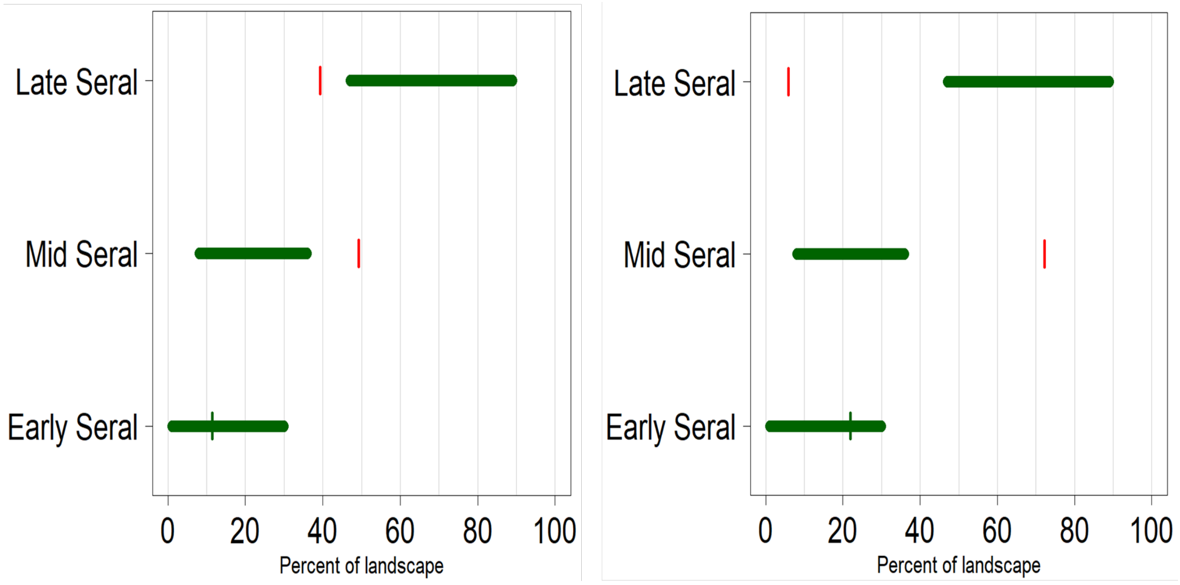


Figure 2-9. Forest vegetation structure departure for the Packwood planning area (left) and the Middle Snohomish planning area (right). Green horizontal lines represent estimates of the

historical range of variability (HRV) expressed as the percent of the landscape. Red vertical marks represent the current percent of a structure class in the landscape that is outside HRV and green vertical marks represent current percent within HRV. Note that most of the early-seral structure is structurally simple, and not in a condition that would have resulted from a natural disturbance due to a lack of large-live trees, standing snags, and downed wood. See focal wildlife habitat section for a breakdown of structurally complex vs. simple early-seral habitats.

Proportion of Broadleaf Tree Species

The distribution of conifer dominated, mixed conifer (conifer and broadleaf) and broadleaf dominated (i.e. deciduous) forested areas for each subwatershed within the Packwood and Middle Snohomish planning areas is presented in Table 2-17, Table 2-18 and Figure 2-10. The abundance of broadleaf tree species is often below historical estimates due to fire suppression, intensive forestry, the application of herbicides, and/or tree planting which can all reduce or eliminate this vegetation class. Broadleaf forests can also influence fire behavior as these forests tend to not burn as intensely as conifer forests and provide important habitat for many wildlife species. There is considerably more broadleaf forest available (a higher proportion of the planning area) in the Middle Snohomish planning area, particularly on the western portions, while broadleaf forests are quite limited in the Packwood planning area.

Table 2-17. The abundance (acres) of broadleaf, mixed and conifer tree species in the Packwood planning area.

Subwatershed	Sparse (canopy cover <10%)	Open (canopy cover 10-39%)	Broadleaf	Mixed	Conifer
Butter Creek	254	869.6	68.5	599.8	9,686.1
Coal Creek-Cowlitz River	295	391.4	125.0	630.9	10,084.7
Hall Creek-Cowlitz River	479	292.0	352.7	1,649.5	8,995.8
Johnson Creek	328	1,062.8	52.7	730.6	28,024.1
Kilborn Creek-Cowlitz River	452	293.1	590.5	1,688.9	14,398.8
Lake Creek	289	635.4	30.2	546.0	13,490.3
Skate Creek	287	538.7	238.2	1,453.2	19,514.0
Smith Creek	140	292.9	17.8	380.3	9,312.1
Willame Creek	59	148.1	70.1	886.5	12,276.4

Table 2-18. The abundance (acres) of broadleaf, mixed and conifer tree species in the Middle Snohomish planning area.

Subwatershed	Sparse (canopy cover <10%)	Open (canopy cover 10-39%)	Broadleaf	Mixed	Conifer
Cherry Creek	1154	452	4153	3814	6890
Elwell Creek-Skykomish River	2026	732	3872	4754	11626
Griffin Creek	651	540	1268	2708	5386
Harris Creek-Snoqualmie River	1851	980	5912	4302	4673
Little Pilchuck River	2628	996	6680	2013	2594
Lower North Fork Tolt River	795	475	1062	2067	10364
Lower Pilchuck River	2504	1265	6878	3409	4670
Lower South Fork Tolt River	416	295	818	1443	4935
Patterson Creek-Snoqualmie River	3141	1815	8831	7938	7447
Raging River	1164	984	1944	3848	12675
Ricci Creek-Snoqualmie River	1073	535	3381	2315	2886
Stossel Creek-Tolt River	634	349	1924	2892	4337
Tokul Creek	978	521	2575	5111	10767
Upper North Fork Tolt River	1096	918	421	968	12773
Upper Pilchuck River	2478	883	3983	5229	27580
Upper South Fork Tolt River	67	264	102	562	9607
Woods Creek	3207	975	7632	7948	11287

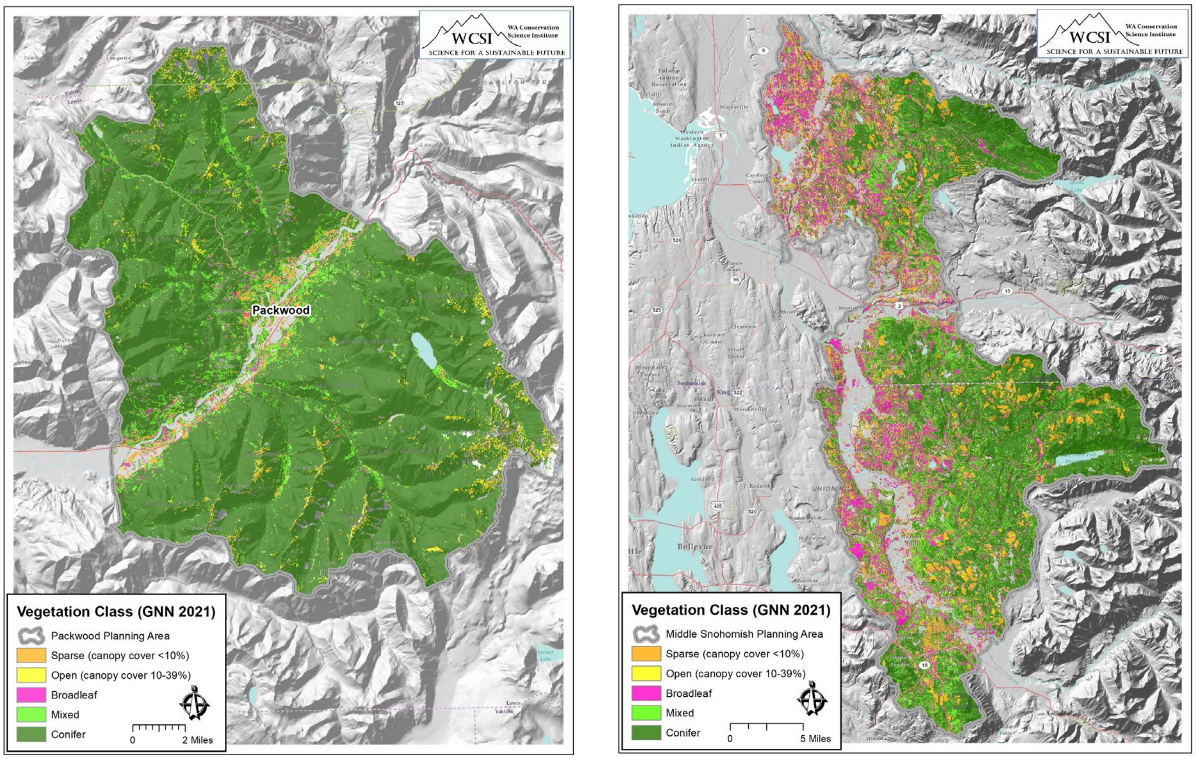


Figure 2-10. Diversity of tree species classes within the Packwood planning area (left) and Middle Snohomish planning area (right).

Exposure of Current Vegetation to Drought and Climate Change

The results of the climate exposure assessment are shown for each planning area in Table 2-19 and Figure 2-11. The Packwood planning area has primarily high (60%) and moderate (31%) exposure to the impacts of climate change, while the Middle Snohomish planning area has predominantly low exposure (79%) (Table 2-19). These results show that mid- to high-elevation areas have higher exposure, especially on south facing slopes. This is due to higher scores from greater decreases in snowpack (April snow water equivalent), higher topographic position index values that reflect thinner soils on ridge tops and mid-slope positions, and greater increases in water balance deficit on slope facing slopes. Relatively, density either accentuates or ameliorates the three other metrics. These results are broadly consistent with projected PVT changes from Halofsky et al. (2018) shown in Figure 2-7.

Table 2-19. Climate exposure for the Packwood and Middle Snohomish planning areas.

Climate exposure	**Packwood**		**Middle Snohomish**	
	(acres)	**%**	**(acres)**	**%**
Low	88,438	9%	7,627	79%
Moderate	46,558	31%	69,747	19%
High	12,974	60%	284,659	2%

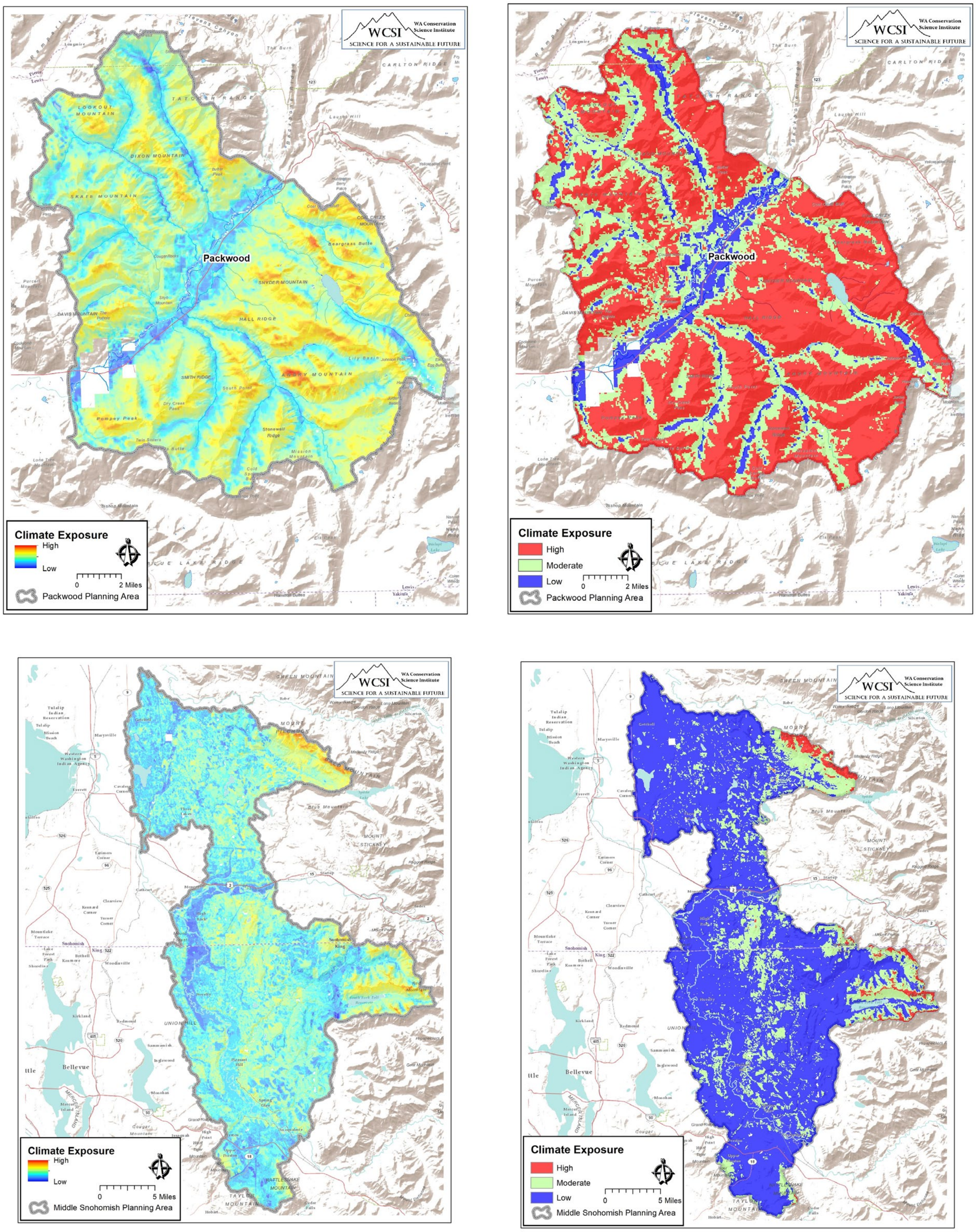


Figure 2-11. Estimated climate exposure for the Packwood (top) and Middle Snohomish (bottom) planning areas. The left panels show the continuous index. The right panel show the index classified into low, medium, and high based on thresholds from all of Western Washington.

Note that these maps show the relative differences in climate exposure. The actual likelihood and thus risk of drought mortality is hard to quantify due to data limitations (e.g., accurate maps of species composition), and scientific uncertainties related to drought tolerance and adaptive capacity of individual plants and populations, as well as disturbance interactions (e.g. drought related pathogen and insect outbreak dynamics). Additional research is needed to improve this climate vulnerability index. This should include investigating where drought-related mortality and declines have occurred in recent years and the factors driving them.

Wildfire risk

Overview of Methods

The assessment of wildfire risk was done using data from the Quantitative Wildfire Risk Assessment: People and Places data layer (Gilbert-Day et al. 2018) (Table 2-20). This data layer shows fire probability in relation to existing homes and infrastructure. Home and infrastructures were then buffered by ¼ mile and the amount of area within the buffer was summarized for each Potential Operational Delineation (POD). The amount of area identified as "fire refugia" was also assessed using recently developed tools from Oregon State University (firerefugia.forestry.oregonstate.edu). Comparing fire refugia under moderate fire weather scenarios (p50W, scenario) with fire refugia from extreme (p90W, scenario) fire weather scenarios provides insights into how climate change is likely to impact fire behavior (Krawchuk et al. 2023).

Table 2-20. Wildfire risk indicators and tools used in the pilot landscape evaluations for the Middle Snohomish and Packwood planning areas.

Indicator	Spatial Data	Tools and Analysis	Application
Wildfire Risk to homes and infrastructure	Quantitative Wildfire Risk Assessment data layers: People and Places layer, Potential Operational Delineations	Expected Net value change	Identify areas adjacent to homes and infrastructure for potential treatments to reduce risks.
Amount and location of areas identified as "fire refugia"	"Fire refugia" for moderate and high fire weather conditions from OSU.	Amount and location for each fire weather condition.	Provide managers with information on how fire may influence forests in the planning area.

Risk to Homes and Infrastructure

The areas adjacent (within ¼ mile) to human developments and infrastructure were identified within each of the Potential Operational Delineations (PODs) in order to assess where treatments may be focused to reduce risks to homes (Table 2-21, Figure 2-12). The data for fire risk and infrastructure (people and places) was taken from the quantitative wildfire risk assessment (QWRA) (Gilbertson-Day et al. 2018). At the time of this assessment, PODs were only available for the Packwood planning area.

Table 2-21. The acres of infrastructure (based on people and places in Gilbertson-Day et al. 2018) and acres within a ¼ mile buffer of infrastructure within the Potential Operational Delineations for the Packwood planning area.

Potential Operational Delineations Number	Infrastructure (acres)	1/4 Mile Buffer (acres)
34WAGPF	222.0	997.2
31WAGPF	0.9	84.3
28WAGPF	149.7	1,017.0
25WAGPF	129.9	508.4
4WAGPF	187.3	823.3

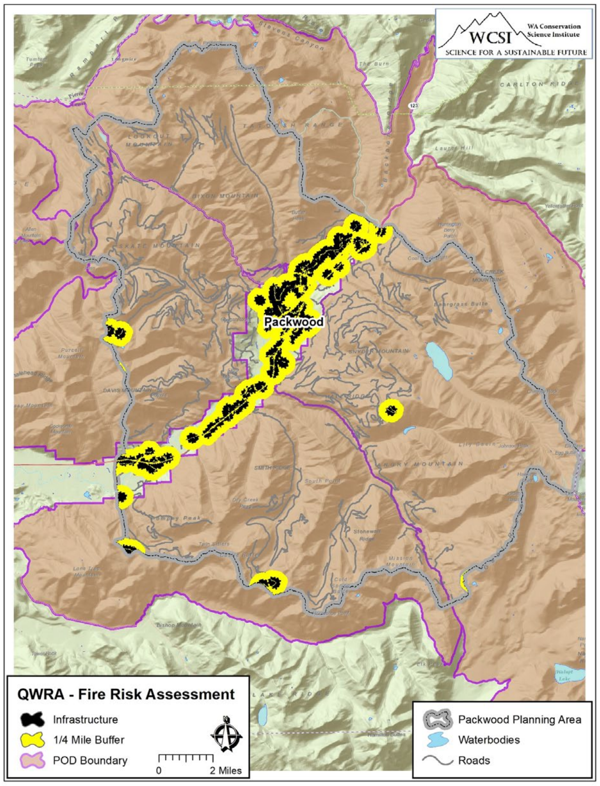


Figure 2-12. Results of QWRA Fire Risk Assessment within the Packwood planning area.

Fire Refugia

The amount of area identified as potential fire refugia under a "moderate" wildfire growth scenario (using wildfire growth under the 50th percentile, *p*50W, scenario) and "extreme" fire weather scenario (using fire weather under the 90th percentile, *p*90W, scenario, Krawchuk et al. 2023) for both planning areas is shown in Table 2-22, Table 2-23 and Figure 2-13. These areas are useful to managers in identifying places where some kinds of forest structure and habitats (e.g., late-seral forest) are most likely to persist and areas that are the most vulnerable to fire impacts.

Table 2-22. Acres of "fire refugia" under a moderate wildfire growth scenario (50th percentile, p50W – wildfire growth) and an extreme wildfire growth scenario (90th percentile, p90W – fire weather) in the Packwood planning area. Categories refer to the probability of the area functioning as fire refugia. Low=0-33%, Moderate=34-66%, High=>66%.

Subwatershed	Moderate Fire Weather			Extreme Fire Weather		
	Low	Mod	High	Low	Mod	High
Butter Creek	8,690	2,766	10	11,416	50	0
Coal Creek-Cowlitz River	7,168	4,312	46	11,363	159	5
Hall Creek-Cowlitz River	7,322	4,404	42	11,491	268	10
Johnson Creek	20,180	9,900	119	30,068	129	2
Kilborn Creek-Cowlitz River	9,837	7,467	119	16,848	544	31
Lake Creek	9,923	4,982	82	14,725	258	4
Skate Creek	15,227	6,734	70	21,950	79	3
Smith Creek	6,051	3,986	107	10,028	112	4
Willame Creek	9,550	3,864	26	13,418	21	0

Table 2-23. Acres of "fire refugia" under a moderate wildfire growth scenario (50th percentile, p50W – wildfire growth) and an extreme wildfire growth scenario (90th percentile, p90W – fire weather) in the Middle Snohomish planning area. Categories refer to the probability of the area functioning as fire refugia. Low=0-33%, Moderate=34-66%, High=>66%.

Subwatershed	Moderate Fire Weather			Extreme Fire Weather		
	Low	Mod	High	Low	Mod	High
Cherry Creek	1,634	9,726	5,083	16,030	404	9
Elwell Creek-Skykomish River	2,674	13,214	7,122	22,041	937	31
Griffin Creek	792	6,225	3,535	10,118	433	2
Harris Creek-Snoqualmie River	1,063	9,971	6,680	16,787	905	21
Little Pilchuck River	212	8,680	5,972	12,365	2,430	68
Lower North Fork Tolt River	2,306	8,845	3,612	14,567	195	0
Lower Pilchuck River	571	9,954	8,200	15,697	2,903	125
Lower South Fork Tolt River	901	4,355	2,650	7,761	141	5
Patterson Creek-Snoqualmie River	1,358	15,442	12,368	27,503	1,629	36
Raging River	1,295	11,586	7,734	19,974	632	8
Ricci Creek-Snoqualmie River	407	5,490	4,265	9,540	608	14
Stossel Creek-Tolt River	802	5,643	3,691	9,653	479	4
Tokul Creek	1,414	11,114	7,423	19,688	258	4
Upper North Fork Tolt River	5,078	8,239	2,859	15,888	287	1
Upper Pilchuck River	2,043	18,407	19,703	38,498	1,606	48
Upper South Fork Tolt River	4,784	4,590	1,229	10,434	167	3
Woods Creek	1,462	18,587	10,999	29,141	1,860	31

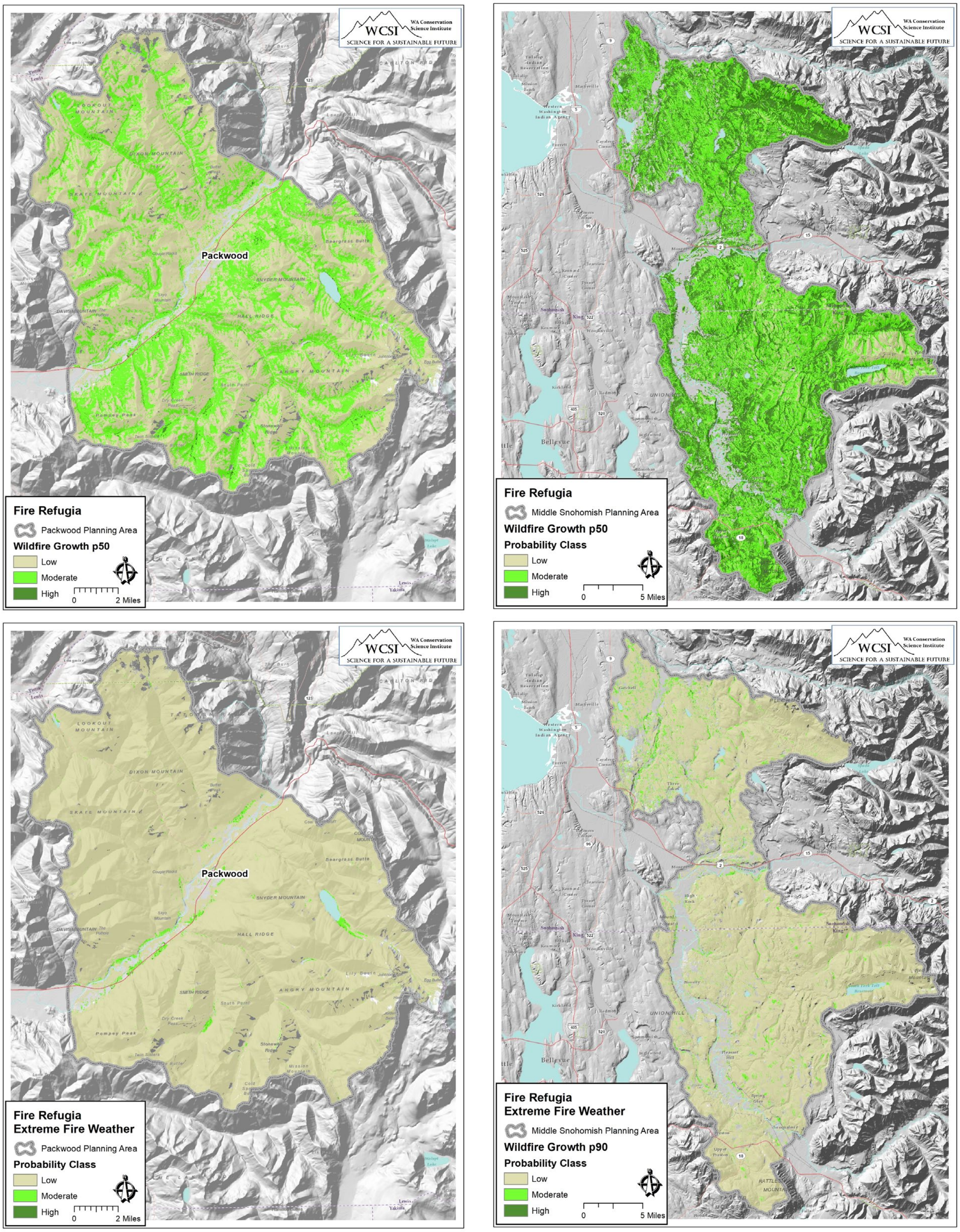


Figure 2-13. Potential fire refugia within the Packwood planning area (left) and the Middle Snohomish planning area (right), based on the moderate wildfire growth scenario (50th percentile, p50 with growth) (upper) and extreme wildfire growth scenario (90th percentile, p90 with growth) (lower).

Focal Wildlife Habitats

Overview of Methods

There have been a number of studies showing that the amount of complex early-seral and late-seral habitats are well below their historical abundances in western Washington forests (Haugo et al. 2015, Demeo et al. 2019, Donato et al. 2019) and that these habitats provide for high levels of biodiversity (Swanson et al. 2014). Late successional forests also provide important habitats for some species (Spies et al. 2018). Late successional forest habitats were identified using the LiDAR structure data (see Vegetation Section).

Mapping complex vs. simple early-seral habitat with LiDAR or other remotely sense data is challenging due to the difficulty of detecting snags and downed wood and differentiating between young trees and non-tree vegetation. Vertical height diversity, however, can be accurately mapped with LiDAR and indicates the presence of live overstory trees that were retained after a harvest or survived a fire or wind disturbance. Also, large snags often appear in LiDAR canopy height models (CHM) and thus add to vertical height diversity. Thus, to define and map complex-seral, we first selected 90ft pixels with less than 50% canopy cover using the CHM derived cover layer. This equates to approximately 35% cover using the standard method of calculating LiDAR cover with returns that is comparable to field-based methods. Then we derived the coefficient of variation (CV) of height for each 90ft pixel using the 1ft CHM. Based on examination of this layer using aerial imagery, we created three classes of vertical complexity: low (0-1.6 CV), medium (>1.6-2CV), and high (>2-3 CV). This layer performed well in distinguishing between recently clear-cut areas with little retention (and fields and open meadows), and harvested areas with more retention. It also picked up high-severity burned areas in the high complexity category, as well as parkland areas with a mix of meadows and trees.

In order to make this layer more useful in a management context, we converted the pixel layer into a layer of patches classified into low, medium, and high vertical complexity. To do this, we first converted the layer of pixels with <50% cover into patches using a simple 8 neighbor rule. Patches less than 1 acre in size were removed. We then calculated the average of the low , moderate, and high complexity pixels within each patch using values of 1,2, and 3 respectively. The final step was to classify these patch-level scores into low, moderate, and high vertical complexity. Note that these are preliminary methods to map complex early-seral and only quantify one aspect of habitat complexity in early-seral systems. The extent to which vertical height diversity correlates with diversity of shrub, herbaceous, and broadleaf tree abundance and diversity, as well as downed logs and snags, is not known. Methods may be improved in the future by incorporating additional LiDAR information, spectral information from satellite or serial imagery, disturbance history, vegetation type, ownership, and other layers.

Unique habitats included wetland from the National Wetlands Inventory (Cowardin et al. 1979) and broadleaf forests (see Vegetation section).

Table 2-24. Focal wildlife habitat indicators and tools used in the pilot landscape evaluations for the Middle Snohomish and Packwood planning areas.

Indicator	Spatial Data	Tools and Analysis	Application
Amount and spatial arrangement of complex early-seral forest habitat	LiDAR structure, GNN for species composition	Departure analyses using reference conditions	Identify opportunities to enhance habitat conditions for early-seral forest associated species.
Amount and spatial arrangement of late-successional forest habitat	LiDAR structure, GNN for species composition	Departure analyses using reference conditions	Identify opportunities to enhance habitat conditions for late-successional forest associated species.
Amount and location of unique habitats	GNN for broadleaf, riparian; national wetland inventory	Map showing the location and amount of unique habitats	Identify unique habitats for restoration and protection.

Complex Early Seral Habitats

Complex early seral pre-forests provide important habitats for a wide-variety of biodiversity (Swanson et al. 2014: Table 4-2). Therefore, to evaluate focal wildlife habitats, the early-seral structure class was further broken out into moderately and highly complex structural conditions. In both planning areas, the amount of highly complex early-seral habitats is very low (≤5%, Table 2-25, Table 2-26 and Figure 2-14) and at the low end of the historical range of variability.

Table 2-25. The amount and proportion of early-seral habitats in non-complex, moderately-complex, and highly-complex conditions in the Packwood planning area.

	Not Complex		Moderately Complex		Highly Complex	
Forest Type	Acres	Percent	Acres	Percent	Acres	Percent
Forested	8,357.4	58%	1,627.2	11%	586.6	5%
Subalpine Parkland	3,549.2	24%	251.4	2%	13.9	<1%
Total	11,906.6	82%	1,878.6	13%	600.6	5%

Table 2-26. The amount and proportion of early-seral habitats in non-complex, moderately-complex, and highly-complex conditions in the Middle Snohomish planning area.

	Not Complex		Moderately Complex		Highly Complex	
Forest Type	Acres	Percent	Acres	Percent	Acres	Percent
Forested	53,356.8	79%	9,338.3	14%	3,346.6	5%
Subalpine Parkland	704.3	1%	95.5	<1%	3.5	<1%
Total	54,061.1	80%	9,433.8	14%	3,350.1	5%

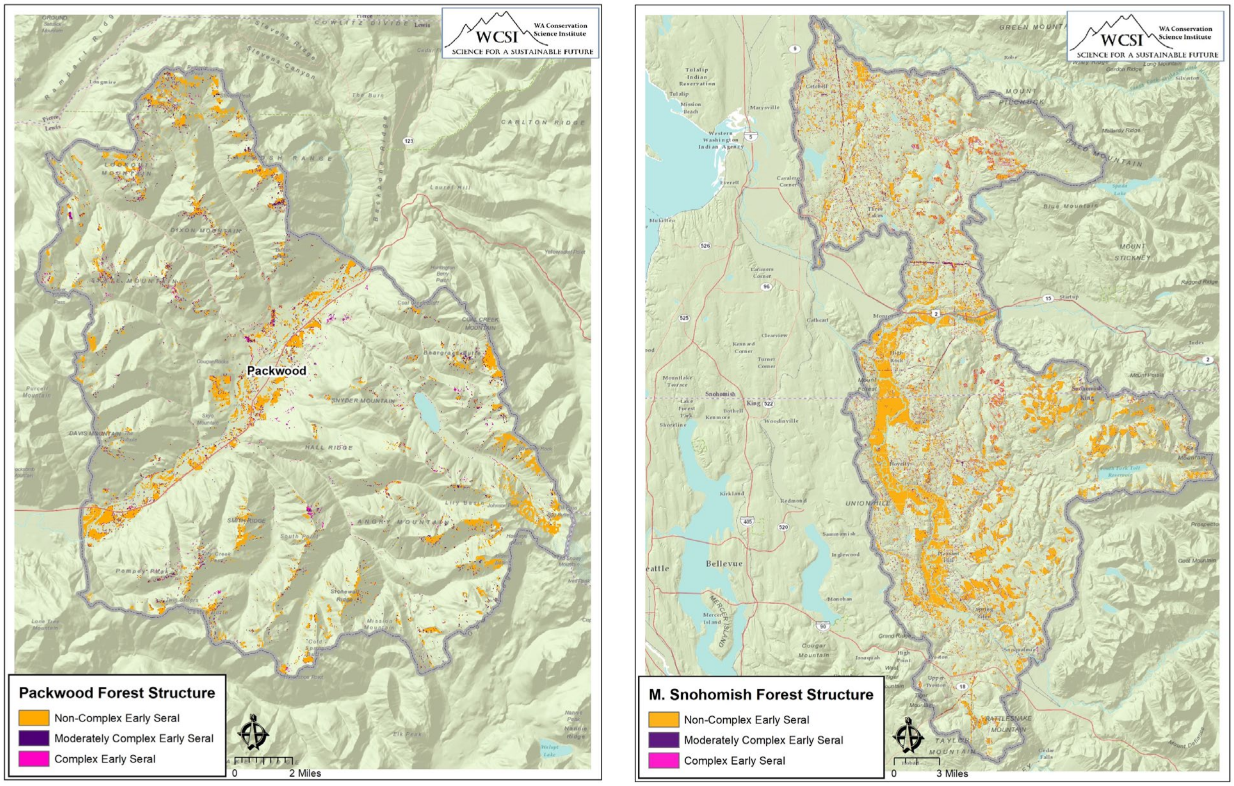


Figure 2-14. Distribution of different types of early seral forest structure within the Packwood planning area (left) and the Middle Snohomish planning area (right).

Late Seral Habitats

Late seral forests provide habitat for a wide-variety of associated species (Swanson et al. 2014, Lawler et al. 2014, Table 4-2). However, these habitats are also vulnerable to the effects of climate change. An important interaction for managers to consider is to overlay the late seral forest type with the potential fire refugia locations in order to assess where these habitats may be most sustainable and where they may be most vulnerable to the increasing risks of high-severity fires (Krawchuk et al. 2023). The amount of late seral forest is summarized for each planning area in Table 2-27 and the location of these habitats shown in Figure 2-15.

Table 2-27. Amount of late-seral habitat within the Packwood and Middle Snohomish planning areas.

Structure Class	Packwood planning area		Middle Snohomish planning area	
	Acres	Acres	Percent	Percent
Late-Seral	59,134	46,933	15%	40%

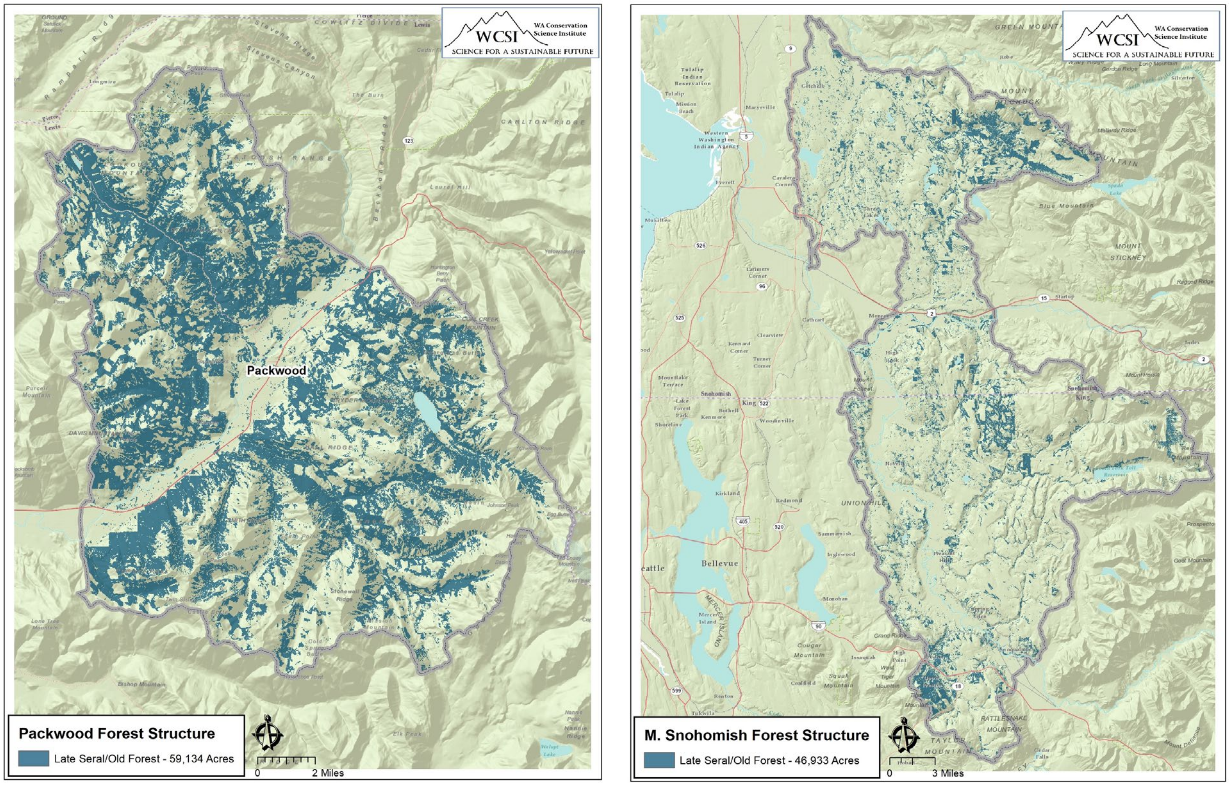


Figure 2-15. Distribution of late-seral forest structure within the Packwood planning area (left) and the Middle Snohomish planning area (right).

Unique Habitats – Wetlands

Wetlands provide habitats for a number of species that are of conservation concern. There are considerable amounts of wetland habitats in each planning area (Table 2-28, Table 2-29, and Figure 2-16) that require special consideration when designing treatments.

Table 2-28. The amount of wetland habitats in the Packwood planning area.

Subwatershed	Freshwater Emergent Wetland (acres)	Freshwater Forested/Shrub Wetland (acres)	Freshwater Pond (acres)	Lake (acres)
Butter Creek	3.2	1.0	5.0	0.0
Coal Creek-Cowlitz River	3.3	105.1	27.1	0.0
Hall Creek-Cowlitz River	92.3	227.5	16.5	0.0
Johnson Creek	17.2	33.2	9.9	32.0
Kilborn Creek-Cowlitz River	38.4	188.3	3.3	0.0
Lake Creek	9.2	222.1	5.7	445.7
Skate Creek	78.4	81.4	8.4	0.0
Smith Creek	5.4	59.0	1.0	0.0
Willame Creek	4.2	39.3	11.5	0.0
Grand Total	251.7	957.0	88.4	477.7

Table 2-29. The amount of wetland habitats in the Middle Snohomish planning area.

Subwatershed	Freshwater Emergent Wetland (acres)	Freshwater Forested/Shrub Wetland (acres)	Freshwater Pond (acres)	Lake (acres)
Cherry Creek	119.8	349.6	86.8	125.0
Elwell Creek-Skykomish River	297.3	1,065.3	79.1	38.8
Griffin Creek	51.4	432.0	35.2	0.0
Harris Creek-Snoqualmie River	435.3	522.8	100.9	211.7
Little Pilchuck River	303.9	1,035.9	107.8	1,132.9
Lower North Fork Tolt River	44.8	156.6	21.2	34.1
Lower Pilchuck River	222.2	616.7	93.3	239.9
Lower South Fork Tolt River	14.3	116.5	22.6	0.0
Patterson Creek-Snoqualmie River	544.5	1,744.7	147.9	62.2
Raging River	125.7	683.7	58.0	123.9
Ricci Creek-Snoqualmie River	312.3	483.4	71.8	14.7
Stossel Creek-Tolt River	32.3	330.8	105.6	40.4
Tokul Creek	11.8	90.5	49.1	31.7
Upper North Fork Tolt River	11.0	24.0	12.7	0.0
Upper Pilchuck River	186.2	455.4	46.2	193.9
Upper South Fork Tolt River	0.0	12.9	19.1	999.2
Woods Creek	395.5	1,023.5	47.4	396.7
Grand Total	3,108.2	9,144.4	1,104.7	3,645.0

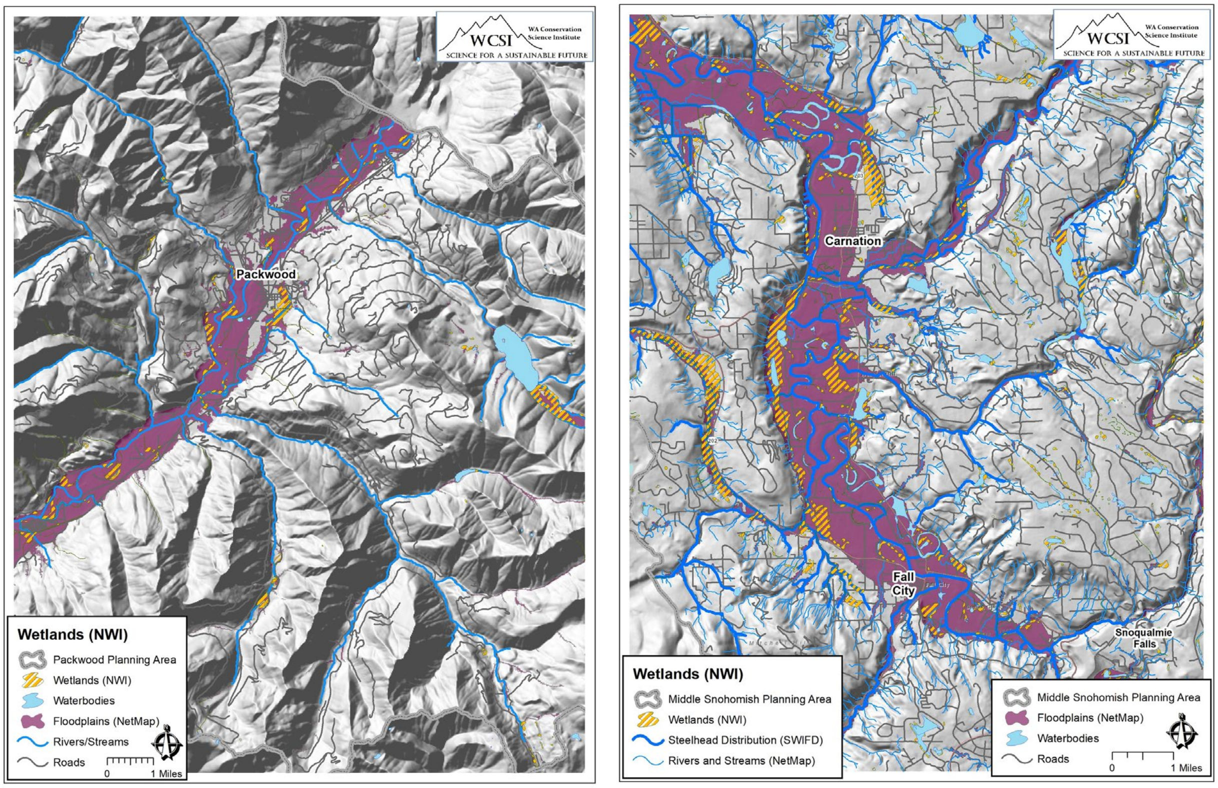


Figure 2-16. Distribution of wetland habitats within a portion of the Packwood planning area (left) and the Middle Snohomish planning area (right).

Social and Economic

Overview of Methods

A variety of tools and data sources were used to address the social and economic indicators (Table 2-30). Land ownership and land use allocations are important in determining the management objectives and emphasis. Land use allocations were derived from the Northwest Forest Plan for federal lands. The DNR treatment feasibility tool was used to identify potential treatment options and harvest methods (WADNR 2020). Above ground carbon is based on 2021 GNN data (LEMMA 2020).

Table 2-30. Social and economic indicators and tools used in the pilot landscape evaluations for the Middle Snohomish and Packwood planning areas.

Indicator	**Spatial Data**	**Tools and Analysis**	**Application**
Land ownership, infrastructure, and management objectives	Homes, recreation sites, other infrastructure, land allocations	Identify major management emphasis	Aid in determining where different types of management actions best fit management emphasis in planning area; identify key areas of human use.
Operational feasibility	Roads, slope	DNR operational treatment feasibility tool	Information to assist managers in assessing feasibility for different treatment types
Above ground carbon	GNN, forest volume inventory, LiDAR	Estimate above ground carbon and locations where additional carbon could be sequestered.	Information to assist managers in assessing tradeoffs.

Landownership and Land Use Allocations

The ownership patterns and Northwest Forest Plan (USFS) land use allocations within each planning area are considerably different (Table 2-31, Table 2-32, Figure 2-17, Figure 2-18). The Packwood planning area is primarily National Forest lands (90%) with private lands (6%) concentrated in the valley bottoms. In the Packwood planning area, the primary Land Use Allocations are Administratively Withdrawn (AW), Late Successional Reserve (LSR), and Matrix. The Middle Snohomish planning area is primarily private land (45%), industrial forest land (25%) and DNR Trust lands (21%). Much of the industrial forest land has been transferred to tribal ownership. The ownership patterns have greatly influenced the vegetation patterns, in particular the distribution of structural stages and will influence the management options available to create more resilient landscapes and habitats.

Table 2-31. Landownership within the Packwood planning area and Land Use Allocations within the US Forest Service portion of the planning area.

	Packwood planning area		USFS Land Use Allocation		
Owner/Manager	**Acres**	**Proportion**	**LUA**	**Acres**	**Proportion**
DNR-Trustlands	447	0.00	AMA	20,689	0.15
State	282	0.00	AW	2,650	0.02
Private	9,205	0.06	CR	38,309	0.28
Industrial	2,187	0.01	LSR	45,730	0.34
Federal	3,094	0.02	LSR4	801	0.01
USFS	134,599	0.90	Matrix	29,413	0.22

Table 2-32. Landownership within the Middle Snohomish planning area and Land Use Allocations (LUA) within the US Forest Service portion of the planning area.

	Middle Snohomish planning area		USFS Land Use Allocation		
Owner/Manager	**Acres**	**Proportion**	**LUA**	**Acres**	**Proportion**
DNR-Trustlands	77,630	0.21	AW	4,193	0.42
Tribal	129	0.00	LSR	3,467	0.34
State	887	0.00	Matrix	2,362	0.23
DFW	1,368	0.00			
Private	165,365	0.45			
Industrial	91,757	0.25			
Federal	83	0.00			
City-County	17,426	0.05			
USFS	10,079	0.03			

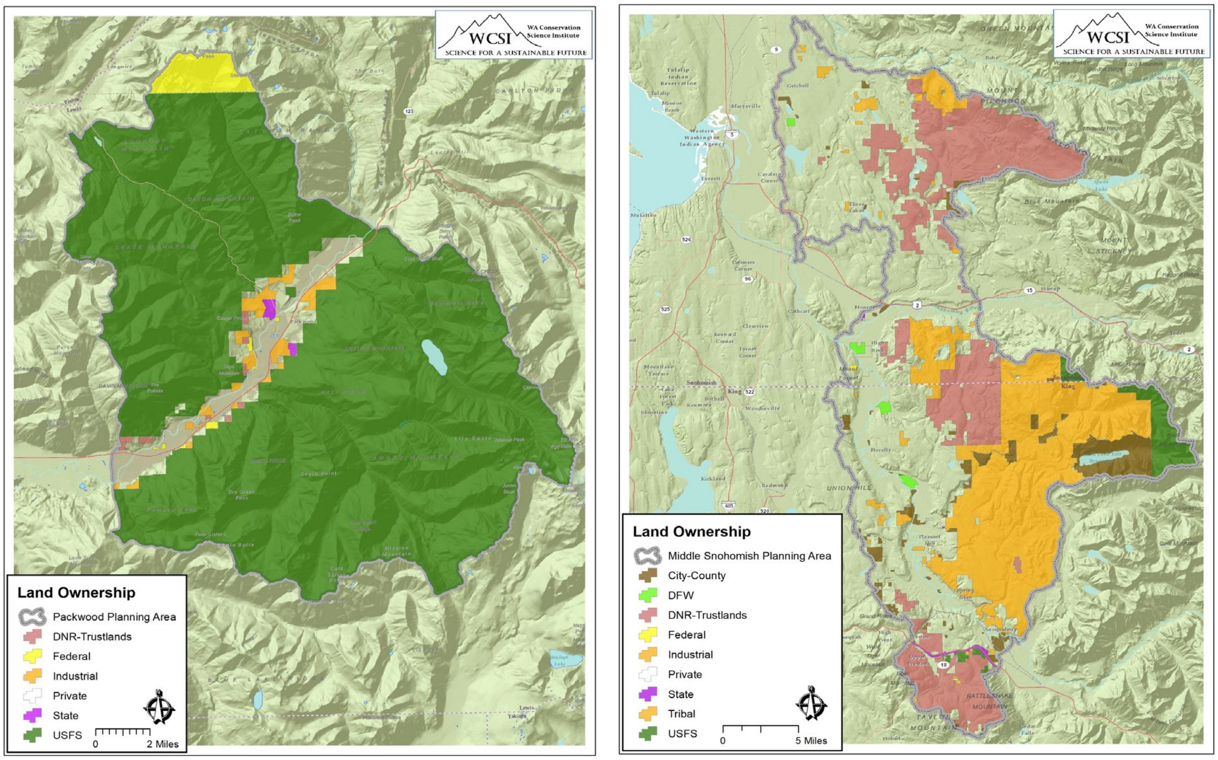


Figure 2-18. Land ownership within the Packwood planning area (left) and the Middle Snohomish planning area (right).

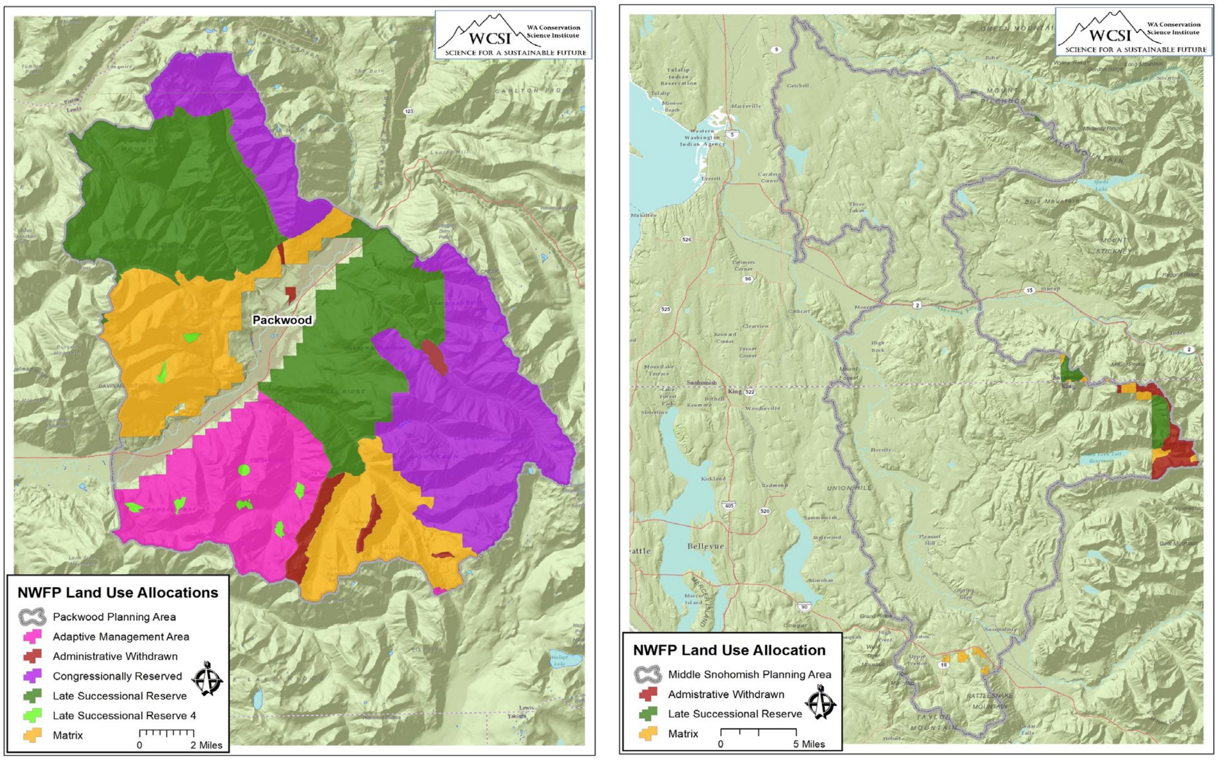


Figure 2-17. Northwest Forest Plan land use allocation within the Packwood planning area.

Treatment Feasibility

Figures 2-28 and 2-29 show the potential treatment methods that could be used in each planning area. Treatment feasibility is an important consideration relative to the actual likelihood of the application of a treatment to improve conditions for different resources. The treatment tool uses roads, topography, and stream GIS information, as well as user defined parameters on maximum yarding distance and other factors, to identify units that could be treated with different logging systems. The economic component of this tool may be run in the future to estimate volume outputs and potential revenues.

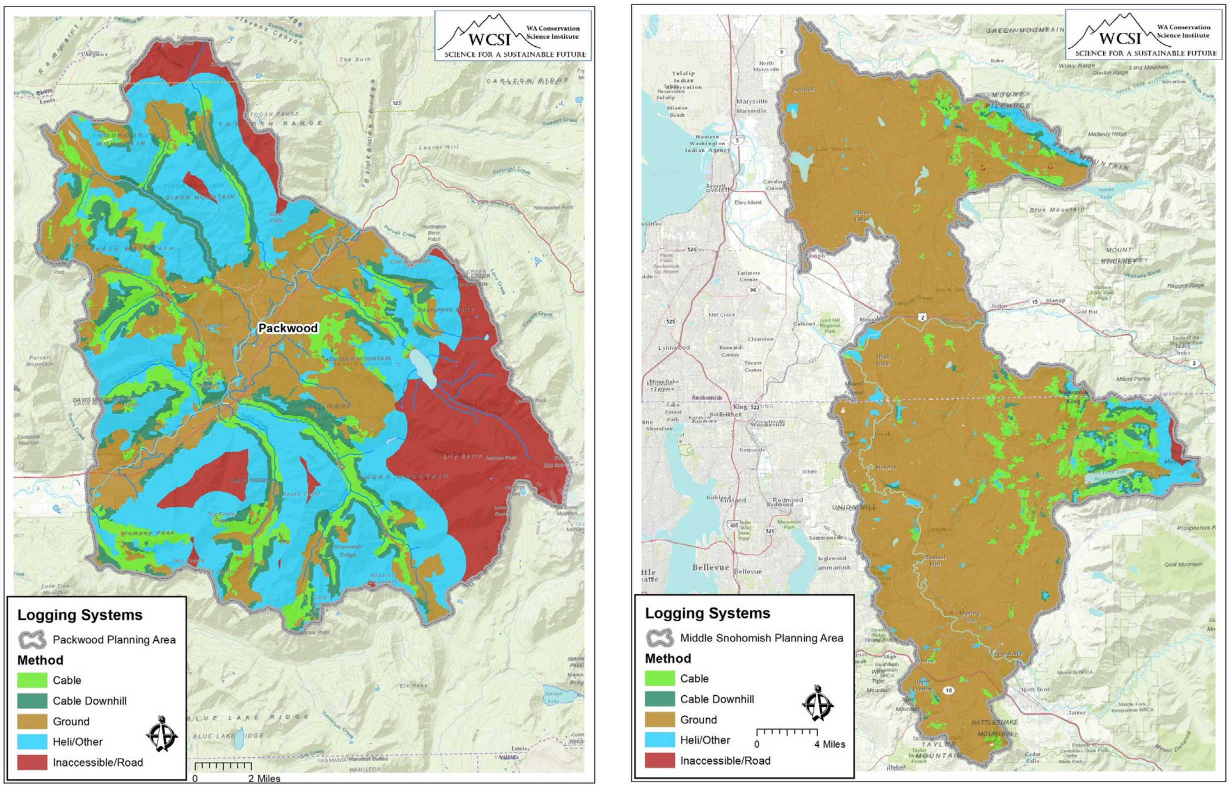


Figure 2-19. An example of potential treatment methods that could be used within the Packwood planning area (left) and the Middle Snohomish planning area (right).

Above Ground Carbon

Table 2-33 and Table 2-34 summarize the amount of above growth carbon (biomass) in each subwatershed for each planning area. Figure 2-20 displays how the carbon (biomass) is distributed across the two planning areas. It is important to note that these estimates do not account for below ground carbon which can be considerable in many western Washington forests.

Table 2-33. Acres of forest in each carbon storage category within the Packwood planning area.

Subwatershed	Acres of Forest by Carbon Storage Category		
	Low	**Moderate**	**High**
Butter Creek	3,565	4,133	4,524
Coal Creek-Cowlitz River	2,051	3,738	6,312
Hall Creek-Cowlitz River	3,052	4,779	5,009
Johnson Creek	5,143	11,412	14,582
Kilborn Creek-Cowlitz River	3,753	5,975	9,218
Lake Creek	4,441	5,206	6,799
Skate Creek	3,168	7,793	11,336
Smith Creek	1,644	4,091	4,621
Willame Creek	1,224	5,230	7,025

Table 2-34. Acres of forest in each carbon storage category within the Middle Snohomish planning area.

Subwatershed	Acres of Forest by Carbon Storage Category		
	Low	**Moderate**	**High**
Cherry Creek	4,993	9,272	3,728
Elwell Creek-Skykomish River	13,361	12,455	3,773
Griffin Creek	3,943	5,664	1,280
Harris Creek-Snoqualmie River	10,565	9,052	4,201
Little Pilchuck River	11,827	8,767	902
Lower North Fork Tolt River	4,847	7,240	2,984
Lower Pilchuck River	11,163	11,072	2,233
Lower South Fork Tolt River	2,552	4,412	1,113
Patterson Creek-Snoqualmie River	16,160	14,343	6,405
Raging River	7,029	11,952	2,951
Ricci Creek-Snoqualmie River	8,689	4,983	2,668
Stossel Creek-Tolt River	3,143	5,976	1,770
Tokul Creek	5,723	10,519	4,449
Upper North Fork Tolt River	5,579	7,254	3,696
Upper Pilchuck River	8,800	15,914	17,076
Upper South Fork Tolt River	2,872	5,628	3,546
Woods Creek	13,756	18,095	4,216

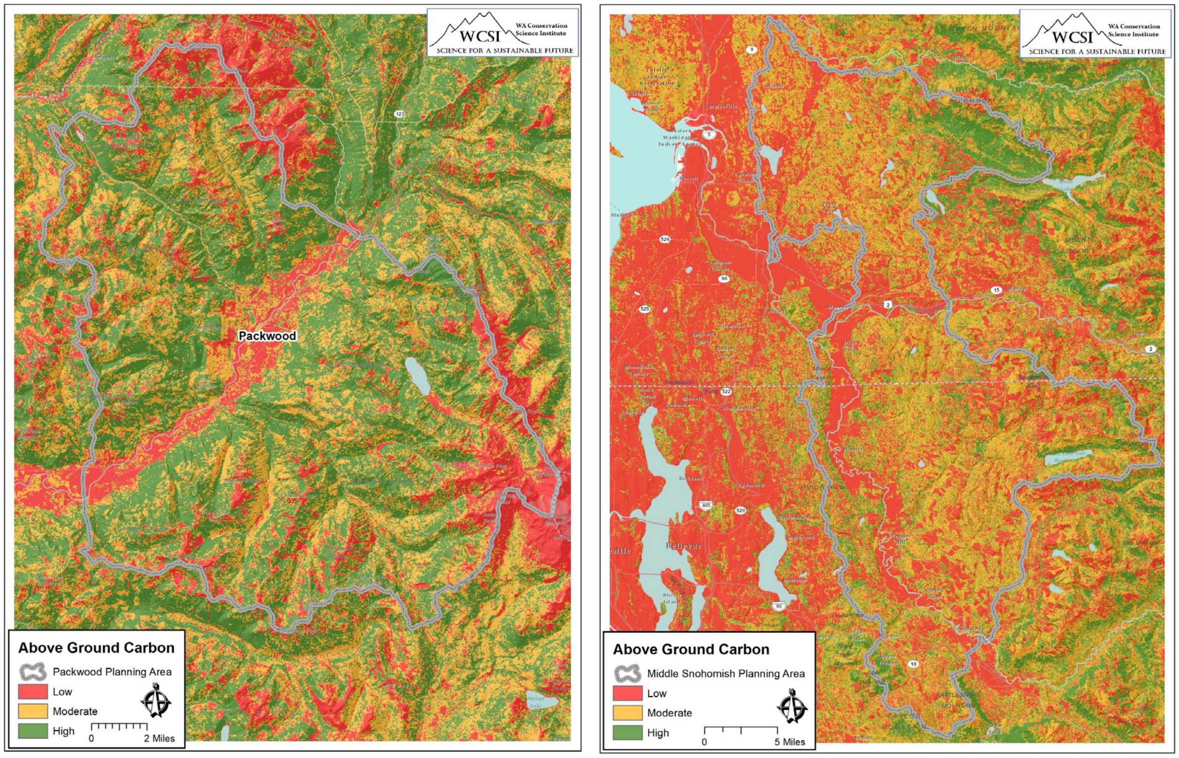


Figure 2-1. Availability of above ground carbon based on biomass within the Packwood planning area (left) and the Middle Snohomish planning area (right).

SECTION 3: Integration of Resource Indicators to Inform Restoration Opportunities and Priorities

An important component of the landscape evaluation process is the ability to combine results from individual resource indicators to evaluate management options and priorities for restoration. In this section, examples of combining resource indicators are shown for different components of the aquatics and hydrology evaluation, terrestrial evaluation, and an example that integrates information from the aquatic and terrestrial evaluations. This section is not intended to provide a comprehensive approach to integration across resources. Integration across resources is best used to answer questions of local managers regarding specific landscapes and may require that different resources be given more emphasis than others in order to identify restoration priorities. Rather, this section provides examples of different ways in which the data layers generated through the landscape evaluation can be used to inform questions local managers may have about different aspects of aquatic and terrestrial restoration and how to inform priorities. For example, how could a local manager identify road segments for rehabilitation that are impacting aquatic habitats (Figure 3-1)? Or which fish passage barriers are priority to address in order to provide access to potential fish habitat and cold water (Figure 3-3)? Or where should large trees be retained or recruited in riparian habitats to conserve future cold-water areas (Figure 3-4)? Or what data layers can be used to inform the best locations for vegetation treatments to enhance landscape resiliency (Figure 3-7)?

Road Impacts and Rehabilitation Options

Evaluating the impacts of roads on aquatic habitats is an important component of a landscape evaluation. Road segments that would reduce impacts to aquatic habitats can be identified (Figure 3-1 and Figure 3-2) by identifying road segments that intersect with floodplains and integrating information on road segments that have moderate and high potential for sediment delivery to streams, and streams with current fish habitat.

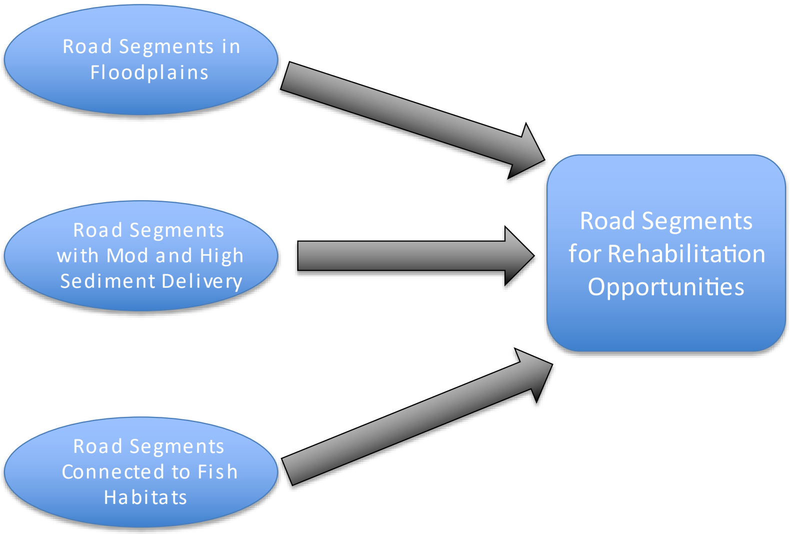


Figure 3-2. Example of a process to integrate resource indicators to identify road segments for rehabilitation to reduce impacts to aquatic habitats.

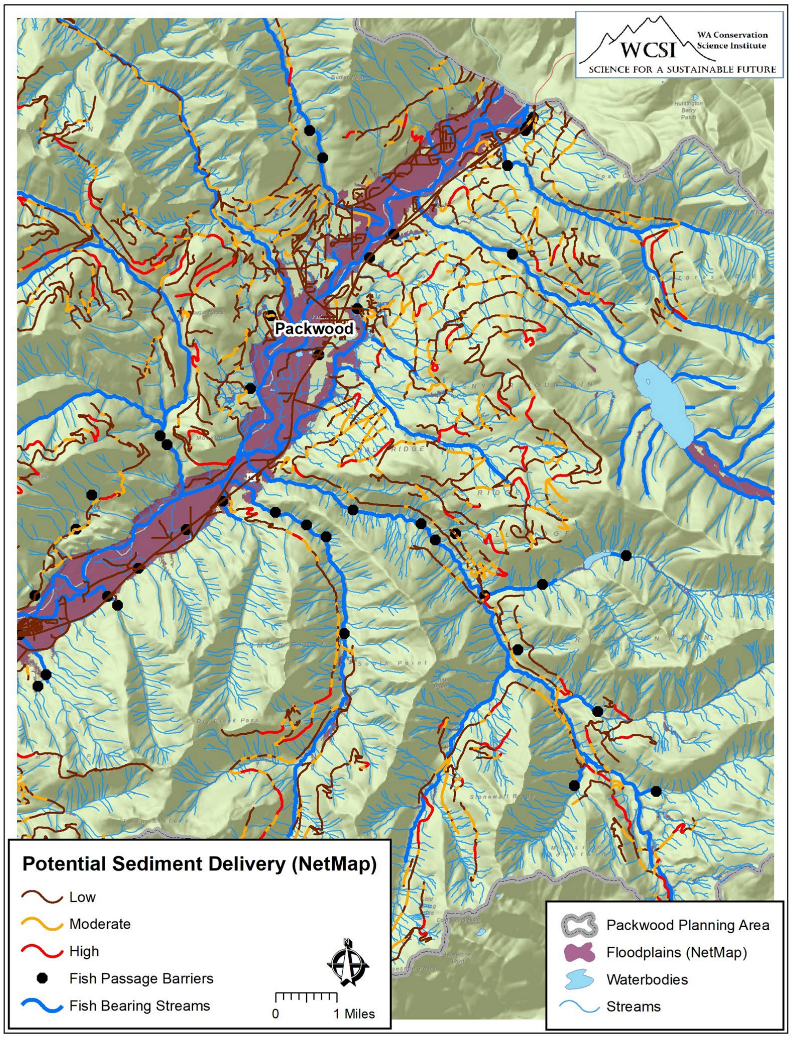


Figure 3-3. Potential sediment delivery from roads in the floodplain, within a portion of the Packwood planning area.

Passage Barriers and Access to Cold Water and Potential Fish Habitats

Fish passage barriers can be evaluated to determine which ones, if removed, would benefit aquatic habitats. The amount of potential habitat for listed fish can be interacted with the current and future cold water data layer to determine which barriers would provide access to the most habitat and cold water (Figure 3-3 and Figure 3-4).

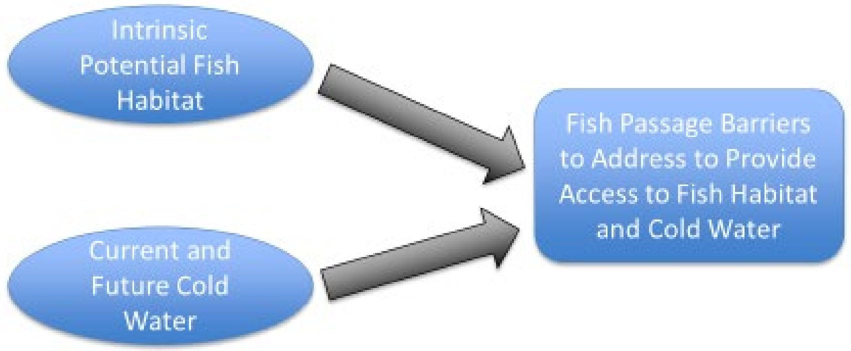


Figure 3-4. The interaction of resource indicators that can be used to inform which fish passage barriers could be removed to enhance aquatic habitats.

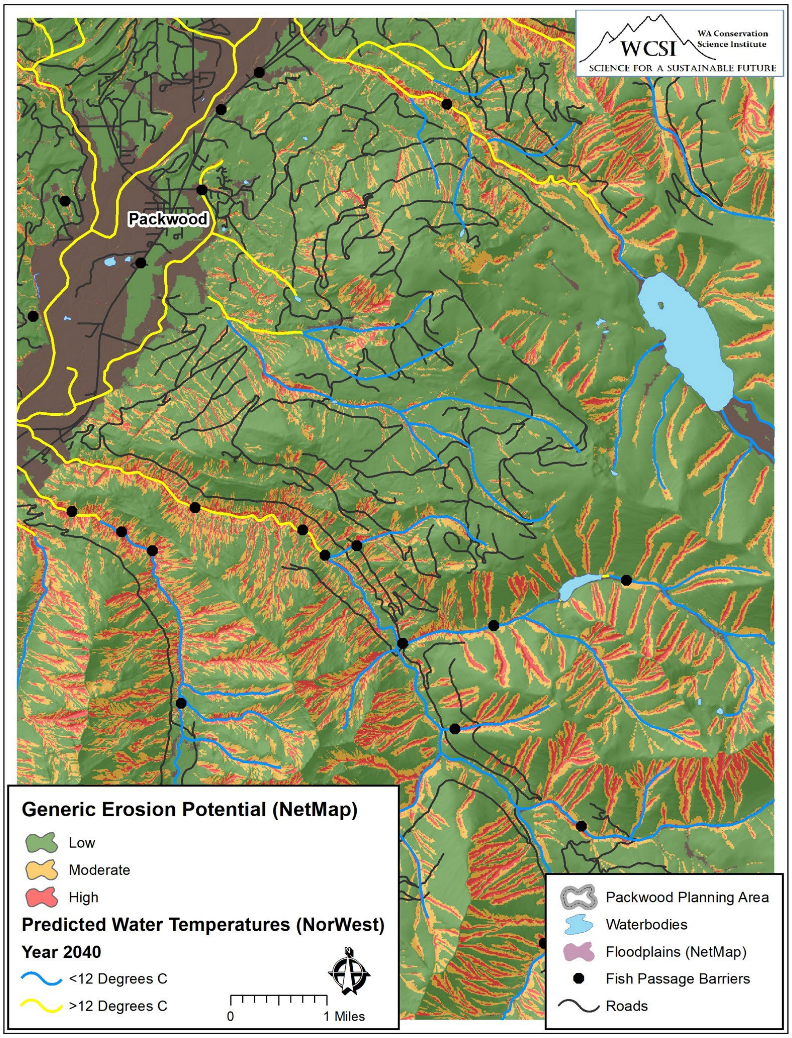


Figure 3-5. An example of predicted future stream temperature changes relative to fish passage barriers (40% blocked) within a portion of the Packwood planning area.

Large Wood and Riparian Restoration to Conserve Cold Water

Tall trees and large wood can provide shade adjacent to streams to conserve cold water. Data on the location of large trees in riparian habitats can be interacted with current and future cold water locations to identify places to retain and recruit large trees and large wood inputs to streams (Figure 3-5 and Figure 3-6)

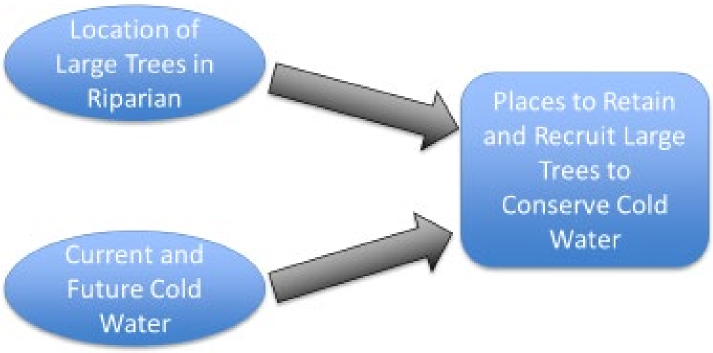


Figure 3-6. The interaction of resource indicators that can be used to inform where to retain and recruit large trees to conserve cold water.

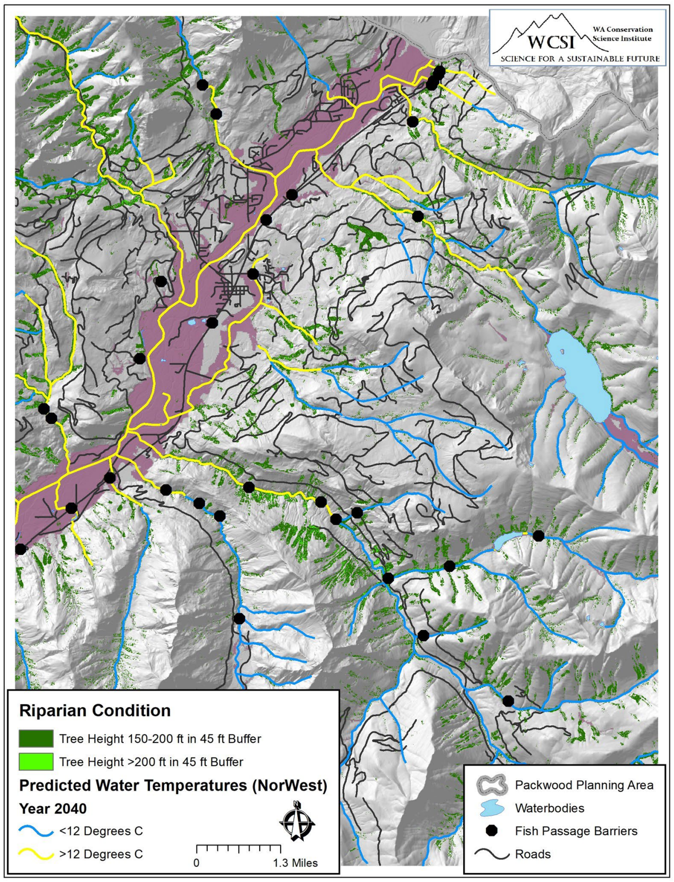


Figure 3-7. Example of distribution of large trees within riparian habitat relative to predicted future stream temperature changes and fish passage barriers in a portion of the Packwood planning area.

Summary of Terrestrial Vegetation Needs

The indicators of forest health used for these landscape evaluations highlight both similarities and differences between the two planning areas that stem from the underlying ownership patterns, landforms, vegetation types, and management histories. The Packwood planning area is predominantly US Forest Service ownership and has a relatively high proportion of late-seral forest (40% - just below the HRV). Mid-seral forest is above HRV, with 40% of the landscape in mid-closed forest and 10% in mid-open. Patch sizes for both mid and late-seral are generally large. Complex early-seral structure is very low and found in mid-to-high elevation meadows, openings within past forest management actives, and in a few small fire footprints. Conifer forests heavily dominate the planning area with some mixed broadleaf-conifer forests in valley bottoms and very few acres of broadleaf. Exposure to climate change is highest at middle to upper elevations, especially on south slopes. Conversely, valley bottoms have relatively low exposure and higher likelihood of being fire refugia.

These results point towards treating dense mid-seral forest to accelerate the development of late-seral forest through variable density thinning, especially in valley bottoms and adjacent to existing late-seral patches. Complex early-seral structure can be increased through mid to large size openings within thinning treatments, variable retention regeneration harvests, and through wildfires, windstorms, or other disturbances. Retaining live and dead trees and allowing a diverse understory to develop and persist after these disturbances will increase habitat functionality. Also, a combination of natural regeneration and planting can promote climate adapted tree phenotypes and species, including broadleaf trees, although tree densities should ideally be kept low to avoid rapid canopy closure and shading out of understory plants. Monitoring for and being prepared to treat invasive species is also important. Thinning and regeneration treatments in mid-elevation silver fir forests can increase resilience to climate change by lowering tree competition for moisture and promoting more drought and fire-tolerant species such as Douglas-fir, big leaf maple, noble fir, and to a lesser extent, western red cedar and western hemlock. Silver fir forests on south facing slopes, areas with poor soils, and at lower elevations are likely most vulnerable to climatic warming. Finally, defensible space treatments adjacent to homes, structures, and along key potential control lines can lower risk of wildfire impacts.

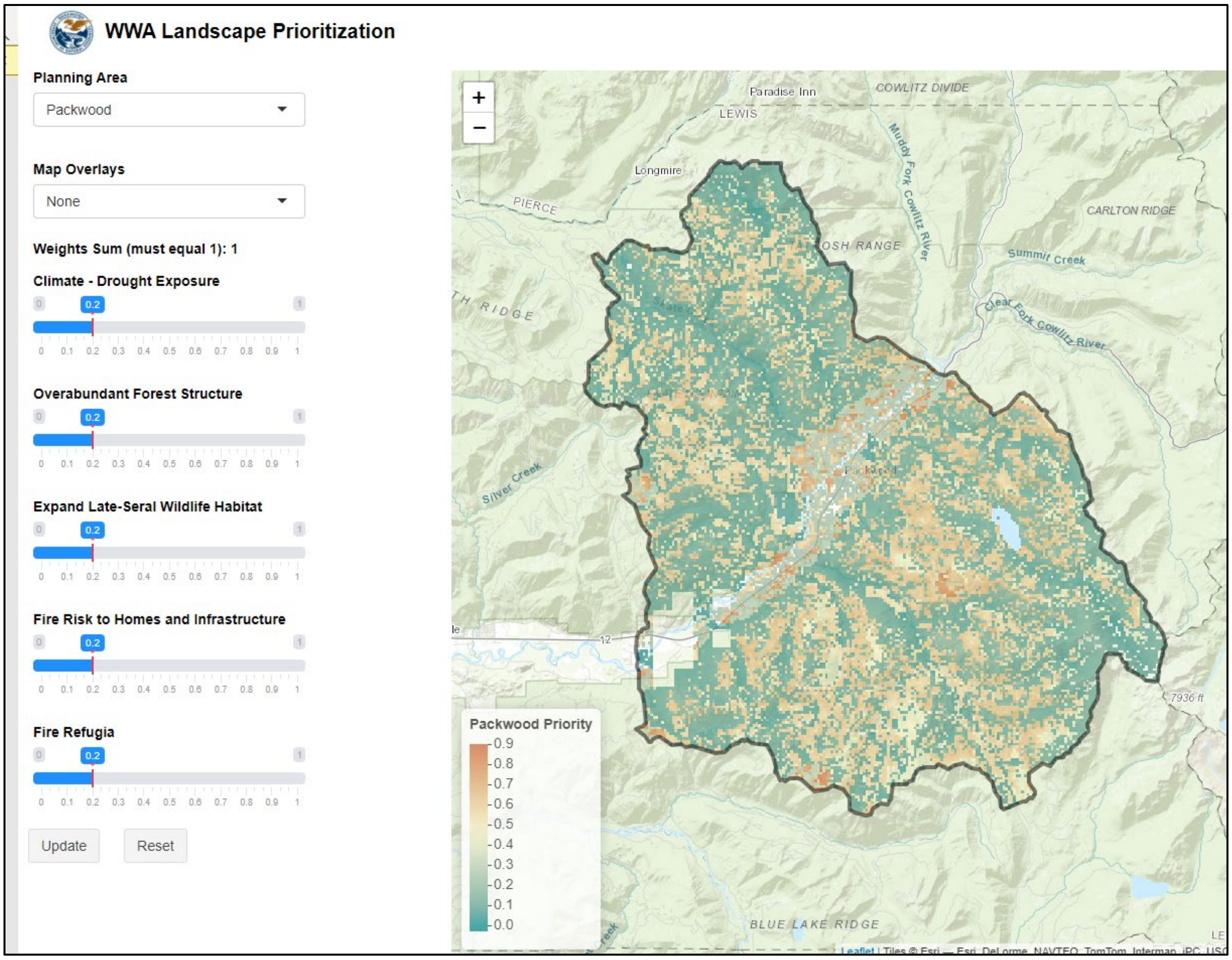
In contrast to Packwood, the Middle Snohomish planning area is predominantly comprised of small-private landowners, DNR Trustland, and tribal land that was private industrial forestland until very recently. The amount of late-seral forest is much lower (15%), and late-seral patches are generally small and fragmented. Mid-seral forest makes up 71% of the forested area, with 42% in mid-closed. Early-seral is relatively abundant, but the majority is structurally simple early-seral. Broadleaf and mixed forest are abundant, especially in the western 2/3rds of the planning area. Exposure to climate change is higher in the areas with topographic complexity, especially on south facing slopes. Valley bottoms and low-lying areas have lower exposure and greater probability of being fire refugia.

Where consistent with landowner objectives, mid-closed structure in proximity to late-seral could be treated to enhance late-seral patch sizes, especially in valley bottom areas that are identified as fire refugia and have low climate exposure. Complex early-seral could also be created through regeneration treatments or allowed to persist after other disturbances. Non-commercial thinning in existing structurally simple early-seral could delay or altogether avoid canopy closure and promote understory plant development. The high amount of broadleaf and mixed conifer-broadleaf forest and mid-open structure should convey significant resilience to climate change. However, forests dominated by mature red alder are susceptible to drought and may benefit from regeneration treatments to increase relative conifer and big-leaf maple abundance. Big leaf maple decline is also a concern, especially as maple is a dominant species in most of the broadleaf and mixed forest in this planning area. Regeneration treatments in broadleaf forests to increase relative conifer abundance can also create complex early-seral. In conifer dominated forests, thinning and promoting climate adapted phenotypes and species on south facing slopes, areas with poor soils, and at the lower end of the silver-fir zone will also enhance resilience to climate change. Monitoring and controlling invasive species after any treatment is essential in this planning area that has high road density and land use diversity.

Across both planning areas, the amount, location, and types of treatments will depend on landowner objectives and priorities; operational access and feasibility; regulatory and policy constraints, and other management considerations. To assist land managers and partners in identifying areas that may be a priority for different kinds of treatments, we created a web-based tool that allows users to experiment with different weights for different indicators (Figure 3-7). This tool can be accessed at this LINK.

This tool uses a subset of the terrestrial indicators. These include:

- Climate Exposure: as described in section 2.
- Overabundant Forest Structure: This includes mid-seral closed forest (Table 2-16). Mid-seral forest is overabundant relative to HRV in each planning area, and treating closed-canopy areas can accelerate the development of older forest characteristics, create complex-early seral habitat, and favor, or allowing for planting of, broadleaf species and drought-tolerant conifer species.
- Opportunities to expand patches of late-seral habitat: this layer identifies mid-seral closed forest that could be treated to accelerate development of late-seral forests that is within 1,350 feet of existing late-seral patches. These late-seral patches must be at least 10 acres in size. The score is higher for mid-seral closed forest closer to a late-seral patch within the 1,350 feet distance.
- Fire risk to homes and infrastructure: as described in section 2.
- Fire Refugia: under the moderate wildfire growth scenario (p50 with growth), section 2.



WWA Landscape Prioritization

Planning Area: Packwood

Map Overlays: None

Weights Sum (must equal 1): 1

Climate - Drought Exposure: 0.2

Overabundant Forest Structure: 0.2

Expand Late-Seral Wildlife Habitat: 0.2

Fire Risk to Homes and Infrastructure: 0.2

Fire Refugia: 0.2

Figure 3-8. Screenshot of web-based prioritization tool that can be used to help determine locations for treatments to address forest health needs identified in the landscape evaluation. Users can experiment with different weights for different indicators. This tool is available for both pilot landscapes at this [LINK.]

A final consideration is to note that the map products from these pilot landscape evaluations are preliminary and have not been field validated. Site level assessment and interpretation of these maps is essential. The climate exposure index and complex early seral layers, in particular, should be treated as initial map products. The climate index will likely be modified and improved as more empirical data and greater understanding of climate vulnerability in western Washington emerges. Mapping snags, downed wood, and the shrub component of complex vs. structurally simple early-seral is challenging using remotely sensed input data.

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Appendix A: Scientific Basis for the Selection and Evaluation of Resource Indictors

In this section the scientific basis for the selection and evaluation of resource indicators is presented. This section is intended to provide managers with information to aid in the interpretation of some of the landscape evaluation results and clarify the underlying science and assumptions so that as science understanding evolves, managers can determine if updates are needed.

Aquatic and Hydrologic Indicators

The concept of process-based river restoration has gained momentum in recent years, with many researchers and managers pressing for more holistic restoration efforts that better address root causes of ecosystem degradation and may more cost-effectively restore river ecosystems (Beechie and Bolton 1999, Brierly et al. 2002, Wohl et al. 2005, Palmer and Allan 2006, Kondolf et al. 2006). Ecosystem processes are the biological, geochemical, and physical factors and components that take place or occur within an ecosystem (Appendix A. Table A-1). Therefore, the aim of process-based restoration is to re-establish normative rates and magnitudes of physical, chemical, and biological processes that create and sustain river and floodplain ecosystems (Beechie et al. 2010). Process-based restoration is guided by four basic principles (Beechie et al. 2010): 1) Target root causes of habitat and ecosystem change; 2) Tailor restoration actions to local potential; 3) Match the scale of restoration to the scale of physical and biological processes; and 4) Clearly define expected outcomes, including recovery time and durability of the restored state given location conditions. The next section describes the watershed and stream processes identified as being important to address at a watershed scale and to inform restoration planning.

Watershed/Landscape Processes

Forests and streams are tightly linked through a range of critical ecological processes and functions (Naiman and Turner 2000). These include the transfer of materials and energy that influence habitat structure (large wood and coarse sediment), food webs and trophic dynamics (nutrients and organic carbon supply) and water quality and temperature (riparian shade)(Rieman et al. 2010). Forests can also strongly influence stream hydrology through impacts on snowpack dynamics, runoff, evapotranspiration, soil moisture, floodplain functioning, and groundwater infiltration, among other processes (Luce et al. 2012, Lundquist et al. 2013).

Aquatic habitats are structured by interactions among terrestrial and aquatic processes and climate (Bisson et al. 2003). For example, wildfires influence hillslope erosion, stream sedimentation, and large woody debris recruitment to streams (Benda et al. 2003, Miller et al. 2003). Certain types of disturbances, such as fires and landslides, are essential in the creation and maintenance of channel and riparian landforms (Benda et al. 2003, Miller et al. 2003, Bisson et al. 2009). When human activities such as stream cleaning, log drives, diking, riparian logging, and damming have simplified channels, disturbances such as fires and landslides may be a benefit in the long term because they may increase physical and biological diversity (Benda et al. 2003, Bisson et al. 2009, Flitcroft et al. 2016). Land uses such as timber harvest, fire suppression, and road networks, can alter the frequency and magnitude of natural disturbances (Benda et al. 2003, Rieman et al. 2010).

Stream Process Groups

Beechie et al. (2013b) provided a means of identifying and grouping key processes that influence stream ecosystems. This classification was used to inform the selection of aquatic and hydrologic resource indicators. The stream process classification was used to describe the linkages between stream processes, watershed-scale assessments, and tools used to evaluate the condition of stream processes within subwatersheds. A brief description of the grouped processes is provided below.

Runoff, Infiltration, and Stream Flow

Stream flow regimes are defined by the magnitude, frequency, duration, timing, and rate of change of flow events (Poff et al. 1997). These components are primarily controlled by the timing and magnitude of precipitation or snowmelt events, but are also moderated by interception, infiltration, and evapotranspiration processes. There are three main runoff pathways: overland flow, subsurface flow, and groundwater flow. Annual patterns of stream flow, referred to as flow regimes, are controlled by annual patterns of precipitation and temperature. Cold regions receive most precipitation as snow, and most runoff occurs during spring snowmelt (Wohl 2000). Lundquist et al. (2013) conducted a meta-analysis using both a synthesis of other studies and modeling to show how forest cover influences snow cover and duration. They found that in regions with average December-January-February temperatures greater than -1^{0}C, forest cover reduces snow duration by 1-2 weeks compared to adjacent open areas (Lundquist et al. 2013). This occurs because the dominant effect of forest cover shifts from slowing snowmelt by shading the snow and blocking the wind to accelerating snowmelt from increasing longwave radiation. This is likely to become more widespread as climates continue to warm (Lundquist et al. 2013).

Stream Flow and Flood Storage

Stream flow and hydrologic regime exert strong influences on potential life history strategies and community structure of riparian and aquatic species and communities (Schlosser 1985, Doyle et al. 2005). The magnitude, frequency, duration, timing and rate of stream flow also influence a variety of physical and ecological functions in streams and floodplains (Karr 1991, Bertoldi et al. 2009). For example, low- and high-flow magnitudes influence riparian vegetation establishment and maintenance, development of floodplain habitats, formation of in-channel habitats, and structure of ecological communities (Poff et al. 1997, Richter et al. 2003, Beechie et al. 2006b).

Erosion and Sediment Supply

Erosion processes include soil creep, surface erosion, and mass wasting. (Note: bank erosion is considered under the Channel, Floodplain, and Habitat Dynamics process group). Mass wasting and surface erosion can be influenced by human activities such as logging, road building, grazing, and land clearing (Sidle et al. 1985, Bradford and Huang 1994, Imaizumi et al. 2008) as well as natural disturbance processes such as wildfire that alter characteristics of vegetation and soils. A multitude of factors influence rates and magnitudes of erosion and sediment supply, including landform, slope, parent geology, soil type, precipitation patterns, and vegetation.

Nutrient Delivery

Nutrient dynamics are governed by parent geology, landforms, precipitation and runoff, and vegetative cover (Beechie et al. 2013b). Leaf-fall from riparian vegetation is a dominant process of nutrient delivery to streams in forested regions. Wildfire can reduce the uptake of nutrients by vegetation and increase rates of nutrient delivery to a stream channel (Nitschke 2005). Where anadromous fish are present, nutrient delivery from carcasses of post-spawning adults can be important in spawning areas, as well as downstream.

Riparian Vegetation Functions and Dynamics

Colonization, succession, and natural disturbance dynamics are processes that structure riparian vegetation communities (Hughes 1997). The interplay of physical, hydrological, and successional processes create a patchwork of forest ages and successional states within the riparian zone (Gregory et al. 1991, Corenblit et al. 2007, Osterkamp and Hupp 2010). For example, colonization and succession processes lead to predominately mature vegetation along headwater streams (Agee 1988). Conversely, on larger streams that migrate across their floodplains, floodplain forests predominately comprise colonizing species on braided channels, late successional species on straight channels, and a high diversity of both species and stand ages on meandering and island-braided channels (Beechie et al. 2006, Naiman et al. 2010). Riparian processes and functions that affect stream ecosystems include root reinforcement of banks, wood supply to streams, sediment retention, leaf litter supply, and shading (Beechie et al. 2013). Forest management, including road-related impacts, can reduce potential large wood available for in-channel wood and shade from riparian areas (Trombulka and Frissell 2000, Wondzell 2001, Meredith et al. 2014).

Natural pieces of wood enhance habitat conditions and promote key ecosystem functions in streams (Merten et al. 2010). Wood pieces provide substrate for invertebrates, entrap leaves and other organic matter, provide cover for fish, enhance hydraulic heterogeneity, and encourage pool formation and channel meandering (Beechie and Sibley 1997, Johnson et al. 2003, Vaz et al. 2013). However, only a subset of wood pieces actually influence stream hydraulics, channel morphology, sediment and organic matter retention, flow routing and storage, habitat heterogeneity, and biological communities (Gregory et al. 2003, Vaz et al. 2013). The processes that reduce the availability of wood in streams include fluvial transport, decay, physical breakdown, and removal by humans (Hyatt and Naiman 2001, Merten et al. 2013).

Sediment Transport and Storage

The rate of sediment transport relative to the rate of sediment supply determine whether any individual stream reach is accumulating sediment, exporting sediment, or is relatively stable (Beechie et al. 2013b). Shifts in sediment transport capacity can result from changes in sediment supply or stream flow. Increases in sediment supply shifts reaches to the oversupplied or aggrading state, whereas decreased sediment supply shifts reaches to the undersupplied or degrading state (Beechie et al. 2013b). Increases in stream flow can result in relative sediment supply shifting to the undersupplied state, while decreases in stream flow can result in oversupply (Beechie et al. 2013b).

The compacted surface of roads can lower infiltration capacity, alter and concentrate overland flow, and increase erosion and delivery of sediment to the stream system, which can degrade fish habitat quality (Dunham and Rieman 1999, Furniss et al. 1991, Luce and Black 1999, Jones et al. 2000, Luce et al. 2001, Trombulka and Frissell 2000, Meredith et al. 2014). Roads can also intercept subsurface flow and convert it to rapid surface runoff, extending channel networks and increasing watershed efficiency (Luce and Black 1999, Trombulka and Frissell 2000, Wondzell 2001). Roads reduce vegetative cover in streamside areas and result in the removal of large wood (Bunnell and Houde 2010, Meredith et al. 2014, Pollock and Beechie 2014). In addition, roads can accelerate delivery of water and increase erosion and sedimentation into streams (Trombulka and Frissell 2000, Wondzell 2001). Accelerated erosion, runoff, and sediment delivery from roads increases streambed fine sediment, which affects aquatic habitat and macroinvertebrates, and makes streambeds and banks more susceptible to erosion during high flow events (Luce and Black 1999, Wondzell 2001).

Channel, Floodplain, and Habitat Dynamics

Dynamic processes and continuous change are characteristic of natural stream ecosystems (Jungwirth et al. 2002), and these dynamics create a shifting habitat mosaic (Ward et al. 2002). In a naturally shifting habitat mosaic, some habitats are lost while others are created, but the pattern and distribution of habitats remains more or less the same over time (Ward et al. 2002, Beechie et al. 2006a). Human development and climate change may alter this balance, leading to directional changes in the pattern and distribution of habitats. The most important processes that influence channel, floodplain, and habitat dynamics include lateral channel migration, avulsion, channel switching, floodplain building, variations in stream discharge, wood accumulation, and beaver dam building (Beechie et al. 2013).

Beavers can profoundly influence stream ecosystem processes (Muller-Schwarze and Sun 2003). For example, beaver dams can influence water chemistry (Hodkinson 1975, Ford and Naiman 1988), alter how sediment and wood move through stream systems (Naiman et al. 1986), and create habitat for a wide-variety of aquatic and terrestrial organisms (Barnes and Dibble 1988, Johnston and Naiman 1990). Beavers were removed by trapping throughout much of the Pacific Northwest by the mid-1800s and populations are still recovering (Muller-Schwarze and Sun 2003).

Organic Matter Transport and Storage

The dynamics of organic matter transport and storage are influenced by channel structure and floodplain interactions in much the same way as sediment. Particulate organic matter is a key basal resource in stream ecosystems, and its storage within a reach affects local ecosystem productivity (Beechie et al. 2013b). Fine organic particulates are trapped by filter-feeding organisms and processed through the food web (Vannote et al. 1980, Beechie et al. 2013b).

Instream Biological Processes

A wide range of instream biological processes influence the structure and function of stream ecosystems including habitat selection, feeding, competition, and predation (Beechie et al. 2013b). These processes influence the behavior of individuals, and, when viewed at larger scales, the collective behaviors of many species and individuals interact to structure biological communities and food webs (Beechie et al. 2013b). The ability of stream organisms to exploit shifting habitat mosaics is essential to the full expression of potential species distributions and diversity in stream ecosystems (McGarvey and Hughes 2008). Instream biological processes vary with riparian conditions, stream flow, and habitat diversity, which can in turn, alter food webs and community structure. Food webs in streams are based on two key basal resources: materials that enter from the riparian area and primary production within streams (Vannote et al. 1980, Richardson et al. 2010). Interactions between instream processes and riparian, sediment and hydrologic influences can be very complex and may result in unexpected changes to stream ecosystems. For example, when steelhead are present in sufficient numbers they can reduce the number of small fish through predation, which releases invertebrate populations who then consume most of the algae (Power 1990). Thus, changes at the top level of the food web can have influences several trophic steps away through cascading effects (Beechie et al. 2013b). Two aspects of in-stream biological processes are particularly important: habitat connectivity and the current and potential distribution of listed fish species.

Habitat Connectivity

The role of physical and biotic connectivity in freshwater ecosystems is widely acknowledged to be essential for maintaining habitat dynamics and species responses (Lowe et al. 2006, Bisson et al. 2009, Waples et al. 2009). Connectivity includes migratory pathways along rivers and their tributary systems (longitudinal connectivity) as well as unimpeded lateral connections between main channels, secondary channels, and floodplains (Bisson et al. 2009). Ecological connectivity is critical for processes and functions that include a wide variety of complex aquatic and terrestrial interactions that influence channel dynamics, food webs, and water quality (Naiman and Bilby 1998, Power and Dietrich 2002). Removing barriers to movement and improving natural linkages between terrestrial and aquatic ecosystem processes to re-create normative riverine conditions is an important conceptual foundation for salmon restoration (Williams et al. 2006, Bisson et al. 2009). The primary objective of this component of aquatic landscape evaluations is to identify and prioritize the most influential barriers to aquatic organisms for restoration of habitat connectivity (Dunham et al. 2003, Fausch et al. 2009). For example, at road-stream crossings, excessive flow velocities and undersized culverts can alter stream channel function and fragment fish habitat (Furniss et al. 1998).

Distribution of Current and Potential Habitat for Listed Fish Species

The current distribution of listed fish species and the identification of areas that are potential habitat, but not currently occupied, provides an assessment of the ability of streams to contribute to the recovery of listed fish species (NMFS 2008, USFWS 2015). In addition, site-specific data from fish surveys, monitoring, or research may be used to identify important spawning reaches or other attributes that may be important in determining restoration opportunities and priorities.

Appendix A. Table A-1. Key watershed-scale and reach-scale processes that drive habitat formation and biological responses in river ecosystems (based on Beechie et al. 2013).

Process Group	Specific Processes	Description
Watershed-scale Processes		
Runoff, stream flow, and water storage	Interception	Rain/snow fall captured in tree canopy where it evaporates
	Snow accumulation and melt	Storage of water as snow through winter and release to streams during spring or summer melt
	Surface runoff	Water delivered to streams by overland flow
	Subsurface flow	Water delivered to streams by flow through the soil layer
	Groundwater flow	Water delivered to streams by flow below the soil layer
Erosion and sediment supply	Surface erosion	Erosion of the soil surface by rain splash and overland flow
	Mass wasting	Mass movement of soil by landslide, debris flows, and gullying
	Soil creep	Gradual downslope movement of the soil mantle by gravity
Nutrient delivery	Nutrient production and delivery	Nutrient delivery to streams via litter fall, photosynthesis, dissolved nutrients, or anadromous fishes
Reach-scale Processes		
Riparian processes	Shading	Blockage of solar insolation by vegetation
	Root reinforcement of banks	Additional soil cohesion of river banks provided by roots
	Wood supply	Delivery of dead trees to streams and rivers
	Sediment retention	Trapping of sediment on bars or floodplains by vegetation
	Litter fall	Leaf litter, needles and branches to streams
Stream flow and flood storage	Routing and stream flow	Movement of water through stream and river channels
	Flood storage	Slowing and temporary storage of flood waters on floodplains and in side-channels
Sediment transport and storage	Sediment transport	Movement of sediment by river flow, either in suspension or as bedload
	Sediment storage or retention	Deposition and storage of suspended sediment or bedload sediment in the river channel, sometimes induced by wood jams, aquatic vegetation, or beaver dams

Process Group	Specific Processes	Description
	Floodplain building	Deposition of suspended sediments on floodplain surfaces, sometimes augmented by the influence of vegetation
Channel, floodplain, and habitat dynamics	Channel movement	Channel movement by bank erosion and avulsion
	Pond formation	Construction of beaver dams creates ponds
Organic matter transport and storage	Transport and storage of seeds and plant propagules	Seeds and plant propagules transported by stream flow, and trapped in backwaters and on bars
	Transport and storage of detritus	Organic detritus transported by stream flow and trapped by bed material, wood jams, and in pools or backwaters
Instream biological processes	Primary production	Algae and aquatic plant production by photosynthesis can drive aquatic food webs
	Secondary production	Production of aquatic invertebrates that consume algae and plants, or leaf litter and other allochthonous organic matter
	Feeding/predation	Consumption of algae, plants, or invertebrates by fishes and other organisms; also predation of fishes by other fishes
	Competition	Competition among taxa for space or food resources

Climate Change and Stream Processes

Climate change is expected to increasingly alter stream processes in the interior Columbia Basin (ISAB 2007, Bisson 2008, Gaines et al. 2012, Strauch et al. 2014). These altered processes include: 1) warmer temperatures which will result in more precipitation falling as rain rather than snow; 2) diminished snowpack in many watersheds and subsequent altered streamflow timing; 3) increased peak stream flow intensity; and 4) water temperatures will continue to rise.

Climate change may be contributing cumulative impacts to forage, migration, and overwintering habitat for listed salmon, steelhead and bull trout through changes in water temperature and stream flow patterns (Mantua and Raymond 2014). In addition, climate change interacts to change aquatic and terrestrial disturbance regimes that greatly influence habitat conditions for listed fish (Mantua and Raymond 2014, Falke et al. 2015). Thus maintaining or restoring connectivity, and increasing habitat patch sizes, will be key for recovery so that fish can adjust their ranges to access cold-water (Rieman et al. 2007, Falke et al. 2015).

There are three key climate change adaptations that could be informed by conducting the Landscape Evaluation: 1) Reduction of the negative impacts of roads (non-climatic stressors) on aquatic and riparian systems (Dunham and Rieman 1999, Luce and Black 1999, Jones et al. 2000, Luce et al. 2001, Trombulka and Frissell 2000, Wondzell 2001, Meredith et al. 2014), including road-related barriers that may limit access to cold-water (Mantua and Raymond 2014, Isaak et al. 2015); 2) Consideration of the cumulative interactions of vegetation management treatments and climate change on stream flow and temperature (Cristea and Burges 2010, Beechie et al. 2012, Isaak et al. 2015, Perry et al. 2015); and 3) Integration of terrestrial and aquatic restoration objectives to account for the short-term and long-term influences of fires on aquatic systems in dry fire-prone provinces (Benda et al. 2003, Miller et al. 2003, Rieman et al. 2010, Flitcroft et al. 2016).

Vegetation Structure and Composition Indicators

Forest Vegetation Structure Departure

The natural range of variation is well established as an important reference for assessing ecosystem conditions (Landres et al. 1999, Keane et al. 2009). Comparing the current condition of a landscape to the natural range of variation (NRV) has been used to identify ecological restoration needs, establishing baselines for assessing current and future change, setting habitat goals for species of concern, and assessing the resilience of systems to change (Demeo et al. 2018, Donato et al. 2019, Haugo et al. 2019). However, determining a management-relevant estimate of NRV is particularly challenging for forested regions where wildfires are infrequent but large in size and severity (Halofsky et al. 2018a,b, Donato et al. 2019, Reilly et al .2022). For this assessment, estimates of NRV for forests of western Washington were derived from the theory and methodology of Donato et al. (2019).

A key metric relevant to restoration is the abundance and distribution of seral stages across a given landscape, and the degree to which current conditions depart from those ranges (Haugo et al. 2016, Donato et al. 2019, Demeo et al. 2019). A State-Transition-Model (STM) was used to estimate the historical range of three major forest structure classes on the landscape: the percentage of early seral, mid-seral, and late seral forest. These results are consistent with similar studies in western Oregon (Ripple 1994, Wimberly et al. 2000, Nonaka and Spies 2005). Finer classes do exist in the model, but these were combined into three broad classes for simplicity. In particular, the late seral class includes both mature forest (greater than 80-120 years old) and old growth (greater than 180-200 years old). In some cases, the range of variability is assessed for future conditions based on ongoing and expected climate change (Gartner et al. 2008, Hessburg et al. 2015). However, Donato et al. (2019) found “broad consistency in NRV estimates among widely varied fire regime parameters” suggesting that the estimated ranges “are likely relevant even under changing climatic conditions, both historical and future”.

Proportion of Broadleaf Tree Species

In some areas, the practice of intense forestry and fire suppression has resulted in a reduction in the complexity and diversity of native vegetation (Franklin et al. 2008, Betts et al. 2010). For example, favoring conifers in production forests neglects the function of broadleaf vegetation, which is important habitat for some forest wildlife species (Betts et al. 2010, Drapeau et al. 2000, Hagar 2007). In addition, broadleaf forests can influence fire behavior as these forest tend to not burn as intensely as conifer forests. To assess the abundance of broadleaf tree species, areas with high levels of cover of broadleaf species, areas with mixed conifer and broadleaf species, and areas with primarily conifer species were identified and mapped.

Spatial Pattern

A variety of ecosystem functions and processes are driven by both the amount of different structural stages on a landscape and the pattern in which they are arranged (Lindenmeyer and Franklin 2002, Lundquist et al. 2013). The STM we utilized to estimate HRV is not a spatially explicit model, however, and thus cannot estimate historical landscape pattern. Historical westside forests are thought to have been characterized by large patches of similar seral stage, arising from infrequent but large disturbance events (Ripple 1994). In contrast, in most westside watersheds, dispersed clear cutting and small unit sizes (e.g., 40 acres) have fragmented and reduced patch sizes and thus habitat value of remaining old forests (Franklin and Forman 1987, Nonaka and Spies 2005). As discussed above, a general principal for westside restoration is thus to build larger patches of late seral forest over time, which requires larger and more heterogeneous patches of mid and early seral stages to develop into late seral forest over time. However, explicit targets for patch sizes of different structural stages are not known.

To address this uncertainty and provide guidance for restoration, the availability of early 20th century aerial photography that could be used to determine pre-management landscape pattern, as well as corroborate the percentage of different structural stages estimated from the STMs was researched. However, after conducting a thorough search, it was determined that spatially extensive, high quality aerial photography does not exist for western Washington that was flown prior to major timber harvesting.

In order to obtain some information about historical landscape pattern, we derived patch size information from a recent low to mid elevation westside fire; the 8,500 acre Goodell Creek fire in the North Cascades National Park that burned in the summer of 2015. We used stereo, aerial imagery for this analysis and developed a protocol that could be used to document fire severity patch sizes on other recent westside fires in Washington and Oregon. Results indicated there were high and mixed severity patch sizes in the range of 25- 1000 acres, with a mean patch size of 300 acres. Also, all patches had individual and clumps of live trees scattered within them. However, the Goodell Creek fire is only one fire at the smaller end of the historical fire size distribution, and thus the conclusions we can draw from it are limited. Future efforts to assess patch sizes in large fires is set to be initiated in the next year and may provide a more comprehensive understanding of how to integrate patch sizes into management planning.

Climate Vulnerability

Forests in the western portion of Washington have been described as having a high degree of ‘landscape inertia’ or as ‘high inertia’ forests (Halofsky et al. 2018b). This is because these forests have longer disturbance-free periods, fewer broad-scale regeneration opportunities, and long-lived tree species that, in mature form, can tolerate suboptimal conditions for longer time periods (Brubaker 1986, Halofsky et al. 2018b). This region is experiencing the effects of climate change, including higher temperatures (Abatzoglou et al. 2014), reduced snowpack (Mote et al. 2006), transition from snow to rain-dominated watersheds (Mantua et al. 2010), decrease in mountain precipitation (Luce et al. 2013), and lower summer stream flows (Luce et al. 2009). To examine the potential impacts of changing climate, Halofsky et al. (2018) modeled potential changes in the distribution of forest zones and early- and late-seral stages across the forest types of eastern Washington under different climate scenarios from 2010-2100. They incorporated landscape inertia in their models by using more details species distribution models (Henderson et al. 2011, Halofsky et al. 2018b).

Halofsky et al. (2018b) found that their projections resulted in relatively stable mid-elevation forests despite anticipated increases in wildfire. The largest changes were projected at the lowest and uppermost forest boundaries, with upward expansion of the driest low-elevation forests and contraction of cold, high-elevation subalpine parklands. They also found that while forests were overall relatively stable across simulations, increases in early-seral conditions and decreases in late-seral conditions occurred as wildfire became more frequent. Their models provide a means of identifying forests that are the most vulnerable to the impacts of climate change that can then be applied to landscape evaluations.

Another important aspect of climate change impacts involves changes to tree mortality. For example, Bennett et al. (2023) studied recent increases in Douglas-fir mortality. They found increased rates of mortality in Douglas-fir forests related to increased exploitation by fir borers as a result of increased temperature and drought. They developed a risk score that integrates several environmental variables associated with drought and heat stress to predict the likelihood and intensity of mortality (Bennett et al. 2023). This index was used, along with the forest zone vulnerability described above to assess potential vulnerabilities of forests to climate change.

Wildfire Risk Indicators

Risk to Homes and Infrastructure

Data products from the 2017 Pacific Northwest Quantitative Wildfire Risk Assessment (Gilbertson-Day et al. 2018) were used to quantify fire risk across each planning area. DNR staff calculated fire risk (expected net value change) by combining annual fire or burn probability, expected fire intensity as measured by flame length, and the response of different resources to flame length (Scott et al. 2013). Risk to homes and infrastructure was calculated and then combined. Risk levels were placed in six categories based on relative values across all planning areas: extreme, very high, high, moderate, low, and beneficial. Maps of conditional net value change – the risk of loss or benefit without fire probability factored in – were generated to examine expected loss or gain irrespective of fire probability in each planning area. Burn probability and intensity were derived from large-fire simulator FSim models that used patterns of fire weather, ignitions, and large fire spread from 1992-2015 (Scott et al. 2013, Gilbertson-Day et a. 2018). This assessment did not directly include fire effects on wildlife habitat, watershed function, or other resources. Fire probabilities in much of the western Washington forests are low due to long fire return intervals, limiting the value of the fire modeling to discern management priorities and options.

Wildland fire Potential Operational Delineations (PODs) is a framework to conduct cross-boundary pre-fire analysis and planning to increase wildfire response safety and efficiency (Thompson et al. 2016, 2022). In a PODs framework fire operations personnel define large landscape areas that are surrounded by potential control lines, i.e., natural and artificial areas that provide strategic opportunities for fire operations. Potential control lines can be roads, ridgelines, old fires, and treated areas. There are multiple uses for PODs landscape areas, including pre-fire response planning and development of fire response plans for each landscape based on quantitative assessments of value at risk.

Fire Refugia

Fire refugia are areas within a burn mosaic that experience comparatively low-severity fire or remain unburned, and can contribute important habitats for species sensitive to fire, and support populations that contribute to the reassembly of biotic communities following fire (Camp et al. 1997, Krawchuk et al. 2016, Vanbianchi et al. 2017, Lesmeister et al. 2021, Krawchuk et al. 2023). Multiple studies have shown that fire refugia areas are often associated with topographical settings, fire-resistant forest structures, and interior forest conditions that influence fire behavior and severity (Camp et al. 1997, Krawchuk et al. 2016, Lesmeister et al. 2021). Identification of potential fire refugia may help managers to determine the best landscape locations where mature and old growth trees have the greatest probability of survival in future wildfire events (Camp et al. 1997, Krawchuk et al. 2016, Lesmeister et al. 2019, 2021). Information from the Oregon State University cooperative fire refugia project was accessed to identify potential fire refugia areas in the landscape planning areas (https://firerefugia.forestry.oregonstate.edu/).

Focal Wildlife Habitats

The concept of using focal wildlife habitats has been used in climate vulnerability and adaptation assessments (Singleton et al. 2019). A similar application of this concept was used here as a means of selecting habitats that represent a range of landscape conditions relevant to western Washington planning areas.

Complex Early-Seral Habitats

Naturally regenerating post-disturbance (early-seral) habitats are increasingly recognized as being associated with a diverse set of vertebrate and invertebrate animal taxa (Swanson et al. 2014). These habitats are currently rare relative to their historical levels (Takaoka and Swanson 2008, Donato et al. 2019). Complex early-seral habitats are characterized by being structurally complex with abundant biological legacies created by natural disturbances (Swanson et al. 2014). Post-disturbance salvage harvest removes much of the structure and biological legacies, resulting in greatly simplified pre-forest patches and lower habitat quality for many post-fire associated species (Haggard and Gaines 2001, Swanson et al. 2014). Early-seral forests subjected to regeneration harvest generally lack much of the structure and biological legacies resulting in greatly simplified post-harvest structure (Swanson et al. 2014). Key structural attributes associated with "archetypal" early-seral habitats in the Pacific Northwest include (1) abundant, con-dominant, short-statured broadleaf vegetation associated with a lack of conifer canopy closure, and (2) abundant biological legacies (residual structures from the pre-disturbance ecosystem, Franklin et al. 2000) dominated by a hyper-abundance of large snags and logs (Swanson et al. 2014). Swanson et al. (2014) identified a wide-variety of animal species of conservation concern that are associated with complex early-seral habitats (Table 4-2).

Late Successional and Old Forest Habitats

A wide-variety of wildlife species are associated with late-successional and old growth forests (Appendix A. Table A-2, SAT 1993, Swanson et al. 2014), including the federally threatened northern spotted owl and marbled murrelet. Climatic change is increasing the frequency and severity of wildfires that reduces late-successional habitats for associated species (Lawler et al. 2014). Both the northern spotted owl and marbled murrelet are considered to be very sensitive to climate change as a result of past habitat loss from timber harvest and as the distribution and connectivity of their habitats are altered by wildfires (Lawler et al. 2014). Evaluating the amount and spatial configuration of late-successional and old growth forests is an important component of a landscape evaluation.

Appendix A. Table A-2. Wildlife species of conservation concern associated with complex early-seral and late-successional forest habitats (based on Swanson et al. 2014).

Species Common Name	**Scientific Name**	**Fine-Scale Habitat Requirements**
Complex Early-Seral Habitat Associates		
Olive-sided Flycatcher	*Contopus cooperi*	Abundant insect prey associated with broadleaf vegetation
Black-backed Woodpecker	*Picoides arcticus*	Insect prey and nesting in abundant snags
Three-toed Woodpecker	*Picoides trydactylus*	Insect prey and nesting in abundant snags
Western Bluebird	*Sialia mexicana*	Insect prey and nesting in snags
Pacuvius' duskywing	*Erynnis pacuvius lilius*	Larval stage requires forb/herb/broadleaf vegetation
Taylor's Checkerspot	*Euphydryas editha taylori*	Larval stage requires forb/herb/broadleaf vegetation
Western Tiger Swallowtail	*Papilio rutulus*	Larval stage requires forb/herb/broadleaf vegetation
Mardon Skipper	*Polites mardon*	Larval stage requires forb/herb/broadleaf vegetation
Oregon Silverspot Butterfly	*Speyeria zerene hippolyta*	Larval stage requires fire-renewed grassland on forest-potential sites
Late-Successional Forest Habitat Associates		
Tailed Frog	*Ascaphus truei*	Coarse substrates, cold water in forested watersheds
Cascades torrent salamander	*Rhyacotriton cascadae*	Forested small streams

Larch Mountain Salamander	*Plethodon larselli*	Use a diversity of habitat including late-successional forests in the Cascades
Northern Goshawk	*Accipiter gentilis*	Late-successional forest for nesting
Marbled Murrelet	*Brachyramphus marmoratus*	Late-successional forest in proximity to coast
Pileated Woodpecker	*Dryocopus pileatus*	Late-successional forest with large snags
Great Gray Owl	*Strix nebulosa*	Structurally complex older forest for nesting and other activities
Northern Spotted Owl	*Strix occidentalis caurina*	Structurally complex older forest for nesting and prey
Johnson's Hairstreak	*Callophrys johnsoni*	Dwarf mistletoe in late-successional forest
Pacific Marten	*Martes caurina*	Structurally complex forest and small mammal prey
Fisher	*Martes pennanti*	Structurally complex forest and small mammal prey

Unique Habitats-Riparian and Wetland

A wide array of wildlife species are associated with wetland and riparian habitats (Lawler et al. 2014). Climate change is expected to alter the temperature and hydrology of wetland habitats which, in turn, will directly affect wildlife through habitat and food availability, population dynamics and life history selection (Lawler et al. 2014). Pond-breeding amphibians, freshwater invertebrates, waterfowl, semi-aquatic mammals and fish will be directly affected, with cascading effects to mammals, birds, and reptiles that feed on them (Lawler et al. 2014). Pond-breeding amphibians are of particular concern because of their reliance on wetlands (Lawler et al. 2010, Stuart et al. 2004).

Social and Economic

Several indicators were selected to assess social and economic factors.

Landownership and Land Use Allocation

Landownership and land use allocation can help establish the priority and emphasis for various restoration treatments.

Treatment Feasibility

This tool provides a means of determining the access to and economic values associated with different potential treatment options.

Carbon Storage

This provides an initial estimate of the amount of above ground carbon. This information is provided to aid managers in assessing treatment tradeoffs. The ability to estimate below-ground carbon is limited at this time and was not included.

Appendix B: Technical Team Members and Support Team Members

Technical Team

Team Member	Organization	Area of Expertise
Michael Case	The Nature Conservancy	Forest Ecology
Josh Chapman	Gifford-Pinchot National Forest	Wildlife Biology
Dan Donato	Washington Department of Natural Resources	Forest Ecology
Rolf Gersonde	City of Seattle	Forest Ecology
Josh Halofsky	Washington Department of Natural Resources	Forest Ecology
Kevin James	Mount Baker-Snoqualmie National Forest	Area Ecology
Amy LaBarge	City of Seattle	Forest Ecology
Garrett Meigs	Washington Department of Natural Resources	Forest/Disturbance Ecology
Dave Peterson	Pacific Northwest Research Station-Emeritus	Climate Vulnerability and Adaptation

Support Team

Team Member	Organization	Area of Expertise
Jen Watkins	Washington Department of Natural Resources	Division Manager
Chuck Hersey	Washington Department of Natural Resources	Forestry
Derek Churchill	Washington Department of Natural Resources	Forest Ecology - CoLeader
Bill Gaines	Washington Conservation Science Institute	Wildlife Biology, CoLeader
James Begley	Washington Conservation Science Institute	GIS Analyst, Spatial Ecology
Andrea Lyons	Washington Conservation Science Institute	Wildlife Biology

Appendix C: Workshop Attendees (in addition to those in Appendix B)

Workshop Member	Organization	Area of Expertise
Matt Dehr	Washington Department of Natural Resources	Meteorology
Kelsey Ketcheson	Washington Department of Natural Resources	Forestry
Csenka Favorini-Csorba	Washington Department of Natural Resources	Policy Director
Brian Harvey	University of Washington	Forest Ecology, Climate Change
Glenn Kohler	Washington Department of Natural Resources	Entomology
Kate McBurney	Washington Department of Natural Resources	Planner
Jon Bakker	University of Washington	Climate Change, Vegetation Ecology
Josh Lawler	University of Washington	Landscape Ecology
Cynthia Catton	Washington Department of Natural Resources	Aquatic Ecology
Emily Howe	The Nature Conservancy	Aquatic Ecology
Josh Jones		Aquatic Ecology
Rebecca Brown	Washington Department of Natural Resources	Aquatic Ecology
Jessica Halofsky	Pacific Northwest Research Station	Climate Vulnerability and Adaptation
Greg Ettl	University of Washington	Forest Ecology
Matt Rollins	USFS – PNW Research	Wildfire Risk
Klaus Puettman	Oregon State	Forestry
Robyn Darbyshire	Pacific Northwest Region	Regional Silviculture
Matt Eberlein	Washington Department of Natural Resources	Fire Management
Ana Barros	Washington Department of Natural Resources	Fire Ecology
Jessica Hudak	Gifford-Pinchot National Forest	Hydrology
Janet Gorrel	Washington Department of Fish and Wildlife	Section Manager
Mike Kuttle	Washington Department of Fish and Wildlife	Regional Director
Cheryl Friesen	Pacific Northwest Region	Wildlife Biology

Appendix D: Subwatersheds in the Middle Snohomish and Packwood planning areas.

Planning area	Subwatershed	Acres
Middle Snohomish	Cherry Creek	17,981
	Elwell Creek-Skykomish River	30,821
	Griffin Creek	10,880
	Harris Creek-Snoqualmie River	23,807
	Little Pilchuck River	21,489
	Lower North Fork Tolt River	15,060
	Lower Pilchuck River	24,455
	Lower South Fork Tolt River	8,072
	Patterson Creek-Snoqualmie River	36,891
	Raging River	21,915
	Ricci Creek-Snoqualmie River	18,405
	Stossel Creek-Tolt River	10,882
	Tokul Creek	20,682
	Upper North Fork Tolt River	16,518
	Upper Pilchuck River	41,768
	Upper South Fork Tolt River	12,041
	Woods Creek	36,043
Total Acres		364,724
Packwood	Butter Creek	12,212
	Coal Creek-Cowlitz River	12,092
	Hall Creek-Cowlitz River	12,837
	Johnson Creek	31,121
	Kilborn Creek-Cowlitz River	18,938
	Lake Creek	16,433
	Skate Creek	22,287
	Smith Creek	10,346
	Willame Creek	13,472
Total Acres		149,814