# Riparian Climate-Corridors: Identifying Priority Areas for Conservation in a Changing Climate

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## Introduction

Protecting and restoring ecological connectivity is a leading climate adaptation strategy for biodiversity conservation (Heller & Zavaleta 2009, Lawler 2009), because species are expected to have difficulty tracking shifting climates across fragmented landscapes (Thomas et al. 2004). Connectivity conservation is thus a primary focus of numerous large-scale climate adaptation initiatives (e.g., U.S. Department of Interior's Landscape Conservation Cooperatives), and a core strategy of many federal climate adaptation plans (NPS 2010, USFS 2011, USFWS 2010). This has led to a growing need for approaches that identify priority areas for connectivity conservation in a changing climate.

Riparian areas have been identified as key targets for such efforts (Seavy et al. 2009), because they span the climatic gradients species are likely to follow as they track shifting areas of climatic suitability, thereby providing natural corridors for climate-induced range shifts. Riparian areas already act as critical movement corridors for diverse taxa (Hilty and Merenlender 2004), particularly within heavily modified landscapes. Riparian areas also feature micro-climates that are significantly cooler and more humid than immediately surrounding areas (Olsen et al. 2007), and thus are expected to provide micro-climatic refugia from warming (Seavy et al. 2009). Riparian areas may also offer especially effective conservation umbrellas under climate change, because they contain high levels of species richness (Naiman et al. 1993), are utilized by many upland species as well as riparian obligates, and directly contribute to the health of adjacent freshwater habitats (Pusey & Arthington 2003).

Despite these values, few methods have been proposed for identifying priority riparian areas for climate adaptation. A land facet corridor analysis designed to promote climate-resilience in Arizona included riparian corridors that were constructed by applying a fixed buffer around rivers that connected large blocks of natural habitat (Brost & Beier 2012). Similarly, a conservation planning analysis in South Africa included corridors constructed by applying a fixed buffer around rivers that connected coastal to inland habitats (Rouget et al. 2003). Riparian areas associated with 2nd order streams linking the Pacific Ocean to high elevations were also prioritized in an effort to identify climate-resilient areas in California (Klausmeyer et al. 2011). Each of these analyses used riverine connectivity as a coarse proxy for riparian connectivity, and none accounted for the variability in riparian habitat quality that should strongly influence the ability of riparian areas to facilitate range shifts and provide refugia.

To address the need for a rigorous approach to identify priority riparian areas for climate adaptation, we completed a novel, fine-resolution (90m) analysis that identifies potential riparian areas that span large temperature gradients, have high levels of canopy cover, are relatively wide, have low solar insolation, and low levels of human modification – characteristics expected to enhance their ability to facilitate climate-driven range shifts and provide micro-climatic refugia from warming. Because priority areas are likely to vary by the scale of analysis, and because scales of climate-induced range shifts and micro-climatic refugia are likely to vary among species and over time, we employed an approach that integrates results across scales, from local watersheds to the entire Pacific Northwest, USA.

## Methods

### *i. Study Area*

We completed our analysis for the Pacific Northwest hydrologic region (Water Resource Region 17; Fig. 1), excluding portions of Wyoming and Montana, but including regions in Canada (e.g., Similkameen, Pend Orielle and Kootenay Rivers) necessary to provide the hydrologic continuity required by our analysis approach.

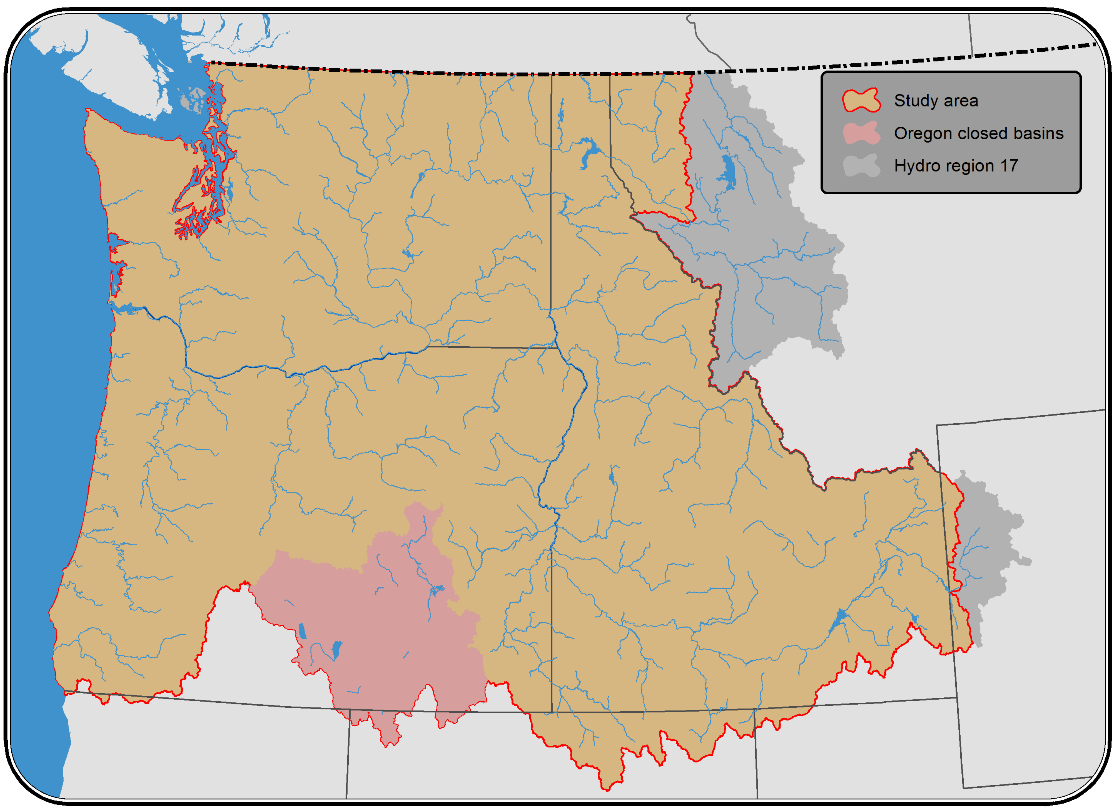


**Figure 1.** Study area. The analysis area (outlined in red) spanned the Pacific Northwest hydrologic region, excluding portions of Wyoming and Montana (dark gray).

### *ii. Model Inputs*

We analyzed potential riparian areas identified by Theobald et al. (2013), which employed a hydrological and geomorphological rather than vegetation-based approach. This fine-resolution

(30m) potential riparian data layer provides a comprehensive and consistent estimate of potential riparian area that avoids many of the data gaps and inconsistencies associated with existing maps of riparian vegetation, and provides key additional data layers (e.g., flow direction) required by our analysis.

Our analysis aimed to identify the extent to which potential riparian areas span large temperature gradients, have high levels of canopy cover, low solar insolation, low levels of human modification, and are relatively wide – characteristics expected to enhance their ability to accommodate climate-driven range shifts and provide refugia from warming. Our analysis thus included the following five parameters (Table 1): mean annual temperature, canopy cover, riparian area, potential relative radiation, and landscape condition.

**Table 1.** Model parameters, associated base layers, and data sources.

| Model Parameter | Base Layer | Source |
|---|---|---|
| Mean Annual Temperature (MAT) | PRISM Mean Annual Temperature, downscaled via Climate WNA | Daly et al. (2002) (http://prism.oregonstate.edu/)<br>Wang et al. (2012) (http://climatewna.com/) |
| Canopy Cover (CC) | NLCD Percent Canopy Cover 2006 | National Land Cover Dataset (Homer et al. 2007) |
| Riparian Area (RA) | Potential Riparian Area | Theobald et al. (2013) |
| Potential Relative Radiation (PRR) | Potential Relative Radiation | This study (following methods of Pierce et al. (2005), and using the digital elevation model from the National Elevation Dataset (http://ned.usgs.gov/)). |
| Landscape Condition (LC) | Landscape Condition | Western Governors' Association Crucial Habitat Assessment Tool (WGA 2013) |

We calculated mean annual temperature (MAT) as the 30-year mean of mean annual temperatures from 1961-1990, using a $90m^2$ digital elevation model and the ClimateWNA tool (Wang et al. 2006), which extracts and downscales PRISM (Daly et al. 2002) monthly data and calculates climate variables for specific locations based on latitude, longitude, and elevation. For canopy cover (CC), we used the percent tree canopy cover dataset from the National Land Cover Dataset (Homer et al. 2007). We used a $90m^2$ digital elevation model from the National Elevation Dataset to calculate potential relative radiation (PRR), a unit-less measure of solar radiation that takes into account temporal changes in solar orientation as well as shading effects from local topography (Pierce et al. 2005). We used the landscape condition (LC) model provided by the Western Governors' Association's Crucial Habitat Assessment Tool (WGA 2013) as a measure of the degree to which potential riparian areas have been impacted by human activities. The LC model used by the WGA (2013) is based on NatureServe's Landscape Condition model (Comer & Hak 2012), where higher values correspond to lower landscape intactness. Riparian Area (RA) was calculated directly from the potential riparian area data layer from Theobald et al. (2013).

*iii. Measuring Riparian Climate-Corridor Quality*

We calculated parameter values (PRR, LC, CC, RA) using the FlowAccumulation and FlowLength geoprocessing tools in ArcGIS Spatial Analyst (ESRI 2013), relying on the FlowDirection raster from Theobald et al. (2013). These tools provided a powerful means of addressing several technical challenges associated with measuring the climate adaptation potential of riparian areas. The FlowAccumulation tool allowed us to identify all potential riparian area cells associated with a given stream reach. We could then use FlowLength to calculate the climate adaptation potential of ecologically-meaningful units: stretches of potential riparian area between the outlet and the headwater of a stream, i.e., riparian corridors at watershed scales.

For each of these riparian corridors, we calculated an index of climate-corridor quality via the following analytical steps:

*1. Calculate parameter values for a lateral section of potential riparian using FlowAccumulation*

We clipped the CC, PRR, and LC rasters to the potential riparian areas identified by Theobald et al. (2013). We then used the FlowAccumulation tool to calculate the lateral accumulation of each of these input parameter values across potential riparian areas into stream line cells, so that each stream line cell was attributed with the sum of the parameter values for the potential riparian cells draining into it (Fig. 2a). We then divided each accumulated parameter value by the number of accumulated cells, so that each streamline cell was ultimately attributed with the average of the parameter values within its contributing potential riparian area. RA was calculated in a similar manner, with FlowAccumulation identifying the number of potential riparian cells contributing to each streamline cell. Where there were no potential riparian area cells adjacent to a stream, parameter values were measured for streamline cells, which were given an RA value of 1. Because parameter values were only available in the USA, parameter scores were not calculated within Canada, though certain streams in Canada were included for hydrologic (and thus, analytical) continuity.

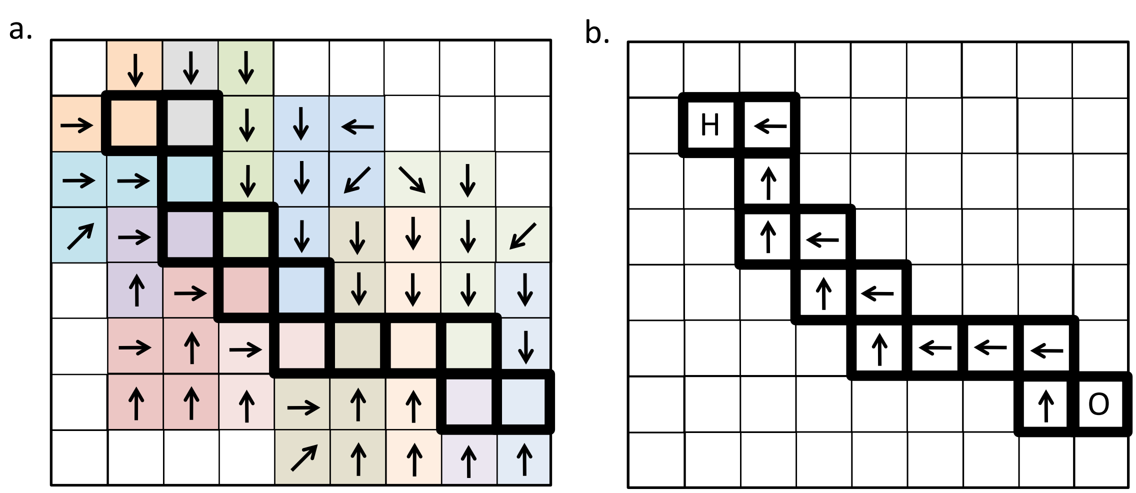


**Figure 2.** Use of FlowAccumulation and FlowLength tools. (a) FlowAccumulation laterally accumulates parameter values across potential riparian areas to streamline cells (in bold). These values are then divided by the number of accumulated cells to produce the average parameter value for contributing cells. (b) FlowLength accumulates parameter values along the streamline, from the outlet (O) to the headwater (H), to which the flow length value is extracted. Flow length values are then divided by the number of streamline cells to produce the average parameter value for the outlet-to-headwater stretch of potential riparian.

*2. Calculate parameter values for an outlet-to-headwater stretch of potential riparian using FlowLength*

The FlowLength tool was used to accumulate parameter values along streamlines, for each of the four parameters (PRR, LC, CC, and RA; Fig. 2b). These four FlowLength values were then extracted to each stream headwater, and divided by the number of contributing streamline cells, to provide an average parameter value for each outlet-to-headwater stretch of potential riparian. MAT was also extracted at each stream outlet (or sink, in the case of closed basins) and headwater, and the difference between the two calculated.

*3. Calculate Riparian Climate-Corridor Index for each outlet-to-headwater stretch of potential riparian area*

We calculated a Riparian Climate-Corridor Index for each outlet-to-headwater stretch of potential riparian area using the following formula:

$$\textit{Riparian Climate-Corridor Index} = \Delta MAT \times [(RA + CC) / (PRR + LC)]$$

where ΔMAT is the absolute difference in temperature between a riparian stretch's outlet or sink and its headwater, and all other parameters are scaled [0:1] for the stretch. Index values will thus be highest for those potential riparian areas with the greatest change in temperature from outlet to headwater, greatest width, highest percent canopy cover, lowest exposure to solar radiation,

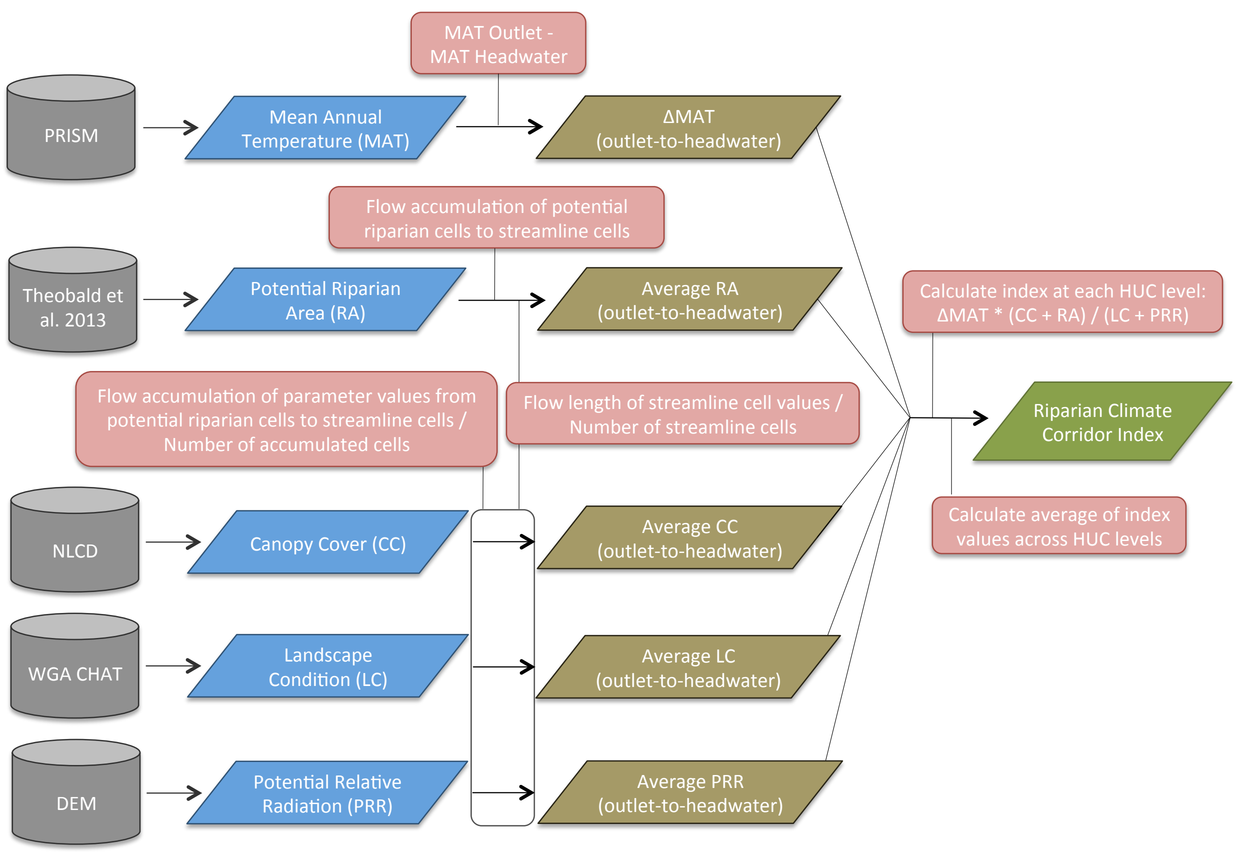


**Figure 3.** Summary of modeling approach, including key inputs, outputs, and analysis steps.

and lowest level of human modification. Where ΔMAT was negative (indicating a higher temperature at the headwater than at the outlet), the index value was set to 0. All index values were attributed to the headwater of an outlet-to-headwater stretch of potential riparian area.

*4. Account for scale effects*

To account for sensitivity to the scale of analysis, we calculated index values by the above procedure for potential riparian stretches within 1st, 2nd, 3rd, 4th, 5th, and 6th field HUCs (watersheds). This resulted in 6 index values for each headwater, corresponding to the index values of progressively longer downstream stretches of potential riparian, from the headwater to the stream's outlet at the Pacific Ocean (or sink, in the case of closed basins). We then scaled each of these index values to the range [0:1] and averaged them, so that the final index value attributed to each headwater would reflect the climate adaptation potential of all of its downstream riparian areas. High index values would thus indicate stretches of potential riparian expected to facilitate range shifts and provide refugia from local to regional scales.

To evaluate riparian climate-corridor quality at the watershed scale (rather than the scale of individual outlet-to-headwater stretches of potential riparian), we calculated the average of the index values within a given HUC polygon. To account for variance of index values among ecoregions, and to more easily identify the highest quality riparian climate-corridors within each ecoregion, we binned multi-scale index values into 5 equal-area quintiles within each ecoregion.

## Results

We found that the climate adaptation potential of riparian corridors varies considerably across the Pacific Northwest (Fig. 4). The highest index values were found in mountainous areas (e.g., the Cascade Range), while the lowest index values were found in relatively flat, lowland regions such as the Columbia Plateau (Fig. 5). This can be explained by positive correlations between many of the parameter values: relatively flat areas with low ΔMAT tended to also have lower canopy cover (CC), were in poorer landscape condition (LC), and had higher solar insolation (PRR). Indeed, removing ΔMAT from the index calculation resulted in a spatial pattern similar to that seen when the calculation included ΔMAT (Fig. 6); ΔMAT generally acted to reinforce the pattern of lower values in areas with gentler topographic relief (often near outlets) and higher values in mountains (often near headwaters).

Most riparian stretches had relatively low index values (Fig. 4). The relatively high number of riparian stretches with index values equal to 0 is due in large part to the relatively cool temperatures of the Pacific Northwest coast; many interior headwaters have warmer mean annual temperatures than their coastal outlets. Because negative ΔMAT values were converted to zero and ΔMAT is multiplied by the rest of the index, such stretches receive a zero value, though they may otherwise be of high quality (Fig. 6). For example, the low index scores received by otherwise high-quality riparian areas in the western Olympic Peninsula were due to negative or relatively low ΔMAT between coastal stream outlets and headwaters (Fig. 6, Fig. A1).

Areas with no headwaters (and thus no index scores) were seen in regions lacking surface water due to high aridity and/or soil permeability (Fig. 5).

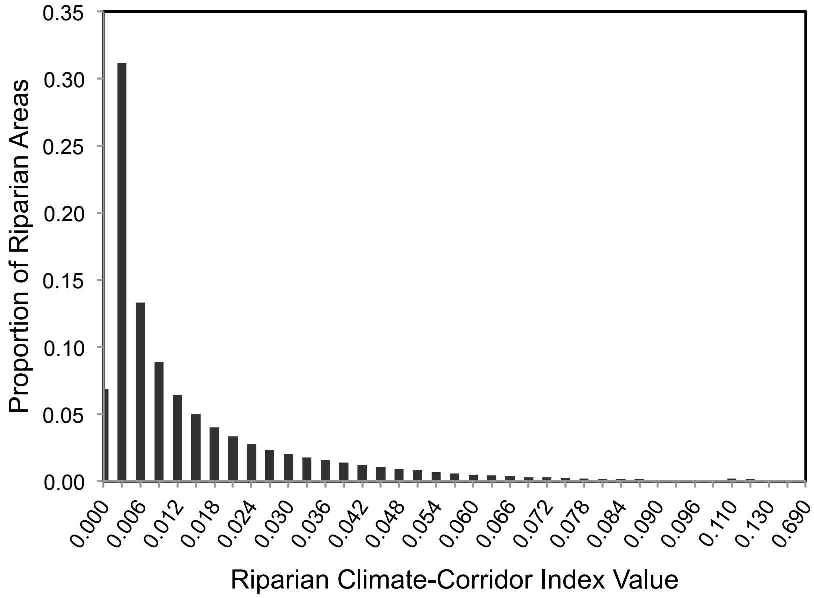


**Figure 4.** Distribution of Riparian Climate-Corridor Index values. Shown for all outlet-to-headwater stretches of potential riparian area in the Pacific Northwest.

## Discussion

Our analysis identified riparian areas that span climatic gradients, have high canopy cover, low levels of solar exposure, are in good condition, and are relatively wide – characteristics expected to facilitate climate-induced range shifts and provide micro-climatic refugia. Unsurprisingly, we found that potential riparian areas in mountainous regions – which tend to be steep, forested, topographically shaded, and in relatively good condition – had the highest riparian climate-corridor index values, while lowland areas – which tend to be flat, deforested, less topographically shaded, and in relatively poor condition – had the lowest values. The exception to this was riparian width, which tended to be higher in flatter, lower elevation areas and lower in steeper, higher elevation areas.

To better discriminate index values within non-mountainous regions such as the Columbia Plateau ecoregion, which received the lowest scores in Pacific Northwest (Fig. 5), we also identified the highest scoring riparian areas within each ecoregion (Fig. 8). High-scoring riparian stretches in areas such as the Columbia Plateau and Puget Lowlands should be considered immediate priorities for conservation action, as they may provide some of the best opportunities for species range movements and climatic refugia within highly vulnerable landscapes.

Our analysis has several limitations that should be considered before its application. First, our approach only implicitly accounts for connectivity along riparian corridors, in so far as index values will decrease as the average level of human modification increases along a stretch. Thus, while a local barrier or bottleneck (e.g., cities, gorges, cliffs) could have a profound impact on

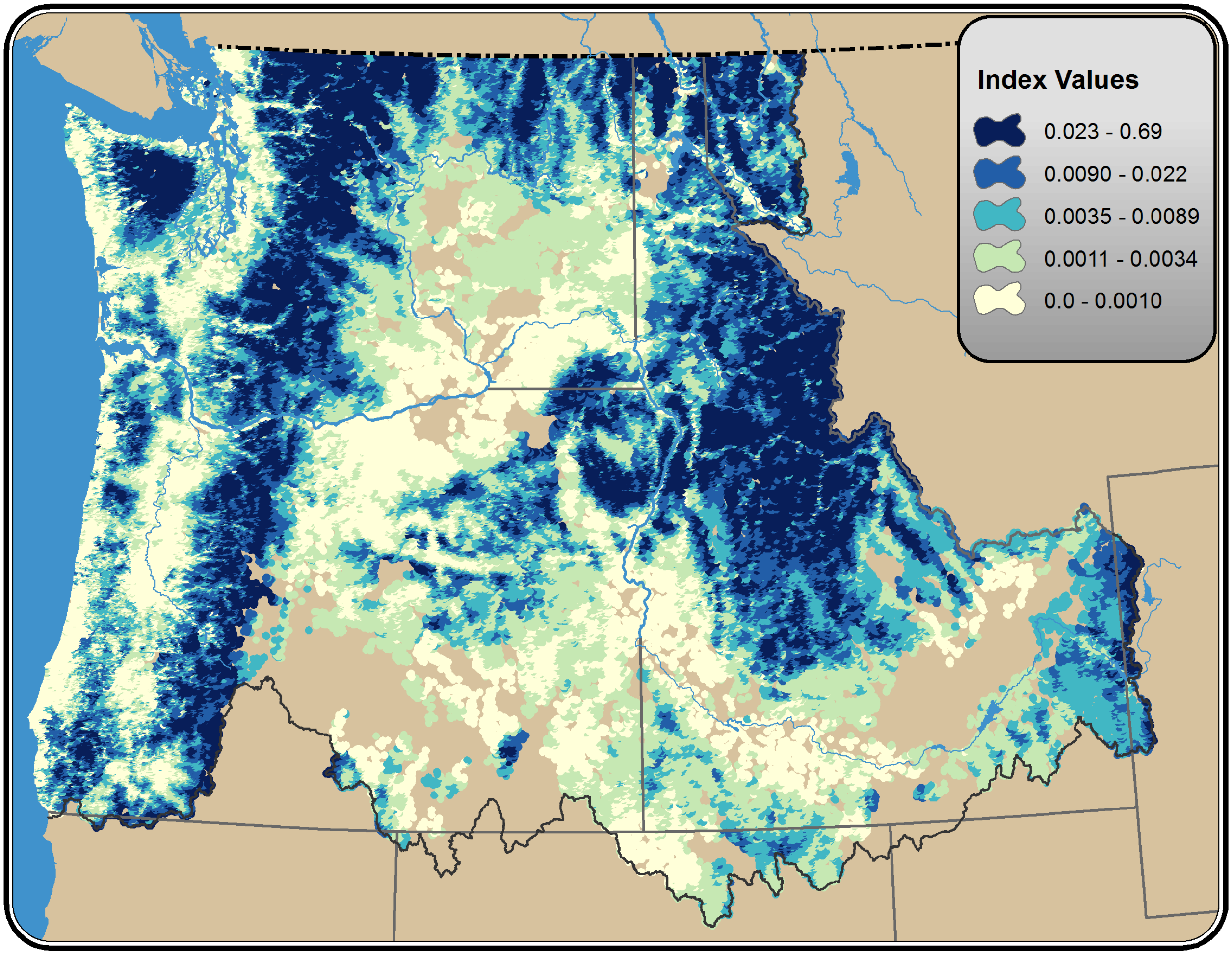


**Figure 5.** Climate-Corridor Index values for the Pacific Northwest. Values are averaged across nested watershed scales (6th to 1st field HUCs) and attributed to the headwaters of streams adjacent to potential riparian areas.

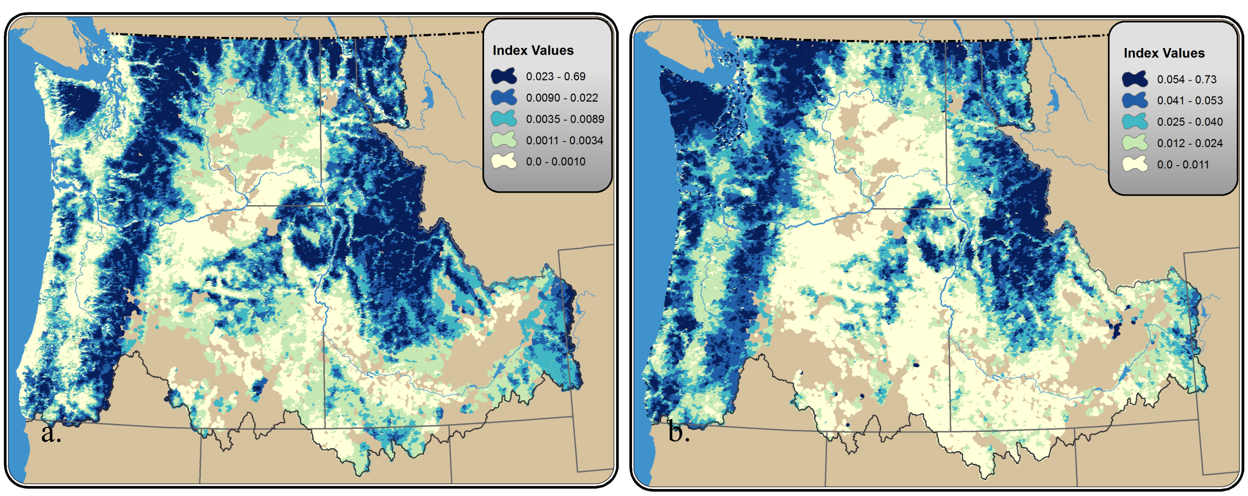


**Figure 6.** Effect of ΔMAT on index values. Index values in the map on the left (Fig. 5a) were calculated with ΔMAT included in the formula, whereas values in the map on the right (Fig. 5b) were calculated without ΔMAT in the formula.

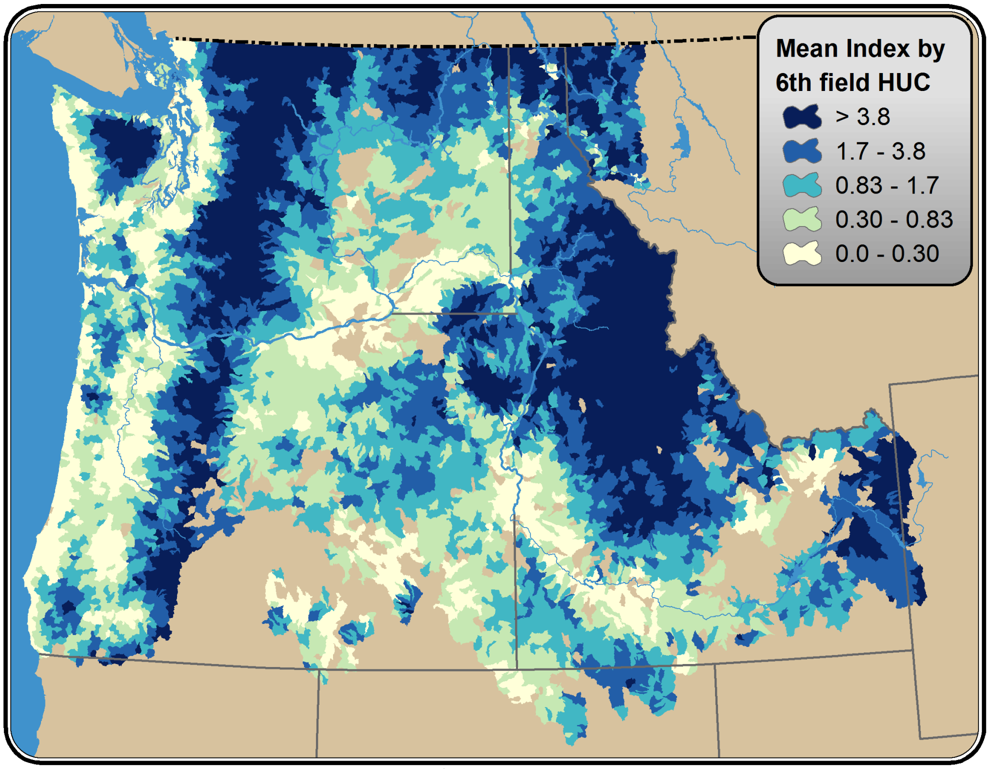


**Figure 7.** Mean Climate-Corridor Index values for 6th Field HUCs. HUCs are shaded to reflect the mean index value (shown by quintile) of all of its outlet-to-headwater stretches of potential riparian.

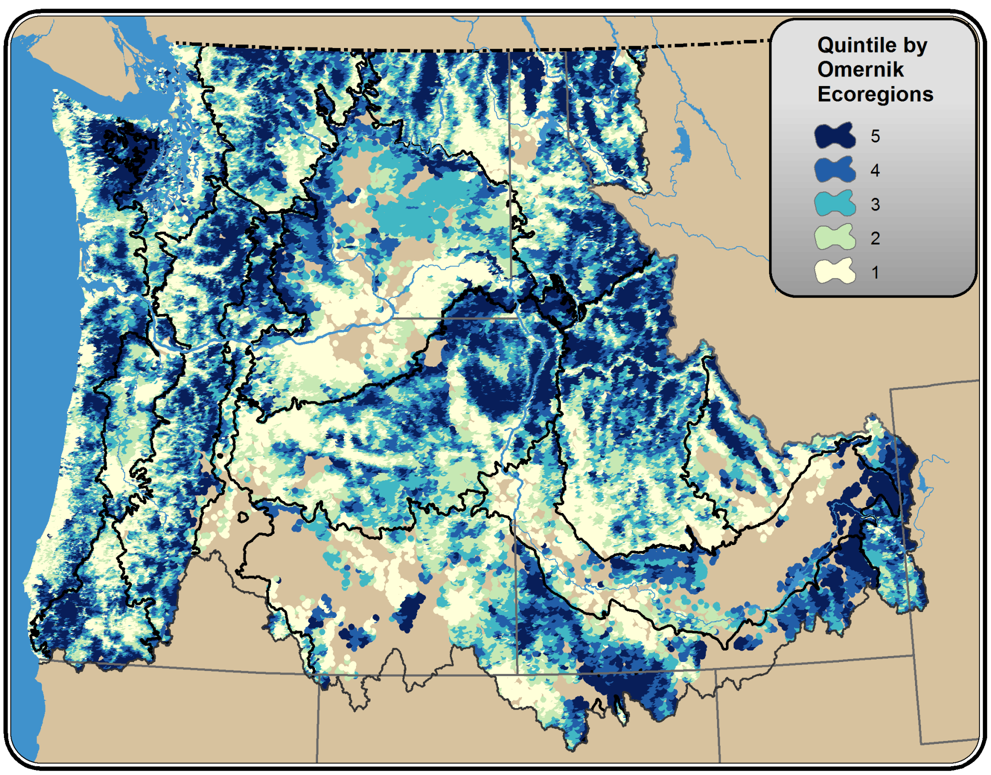


**Figure 8.** Climate-Corridor Index values by ecoregion, shown by quintile.

the permeability of a given riparian stretch to wildlife movement, the effect of local barriers on index values may be muted if high parameter values are present along the rest of the stretch, particularly at larger scales. The analysis could thus be improved by the incorporation of explicit connectivity measures that sufficiently penalize high resistance, local barriers. Our analysis has also not yet been validated by empirical tests of riparian corridor quality (e.g., via analysis of high resolution aerial photography). Model validation would greatly help to inform the interpretation and application of our results, and to guide future refinement of our methods. Until such validation is completed, we recommend using this analysis as a means of identifying priority riparian areas for additional evaluation (e.g., field validation, comparison with other data sets, integration with other conservation values) before implementing any conservation action.

While riparian areas are expected to provide critical movement corridors and refugia under climate change, they are also among the most threatened habitats in many regions (Jones et al. 2010), and may be particularly vulnerable to climatic stressors (Capon et al. 2013). Our analysis offers a first step toward identifying, for a large region, those riparian areas most likely to promote biological resilience to climate change, as well as those most vulnerable to climate change and in need of restoration measures. These results may help to inform riparian management and climate adaptation efforts across the Pacific Northwest, and to guide similar analyses in other regions.

## Acknowledgements

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## Appendix 1. Parameter base layers

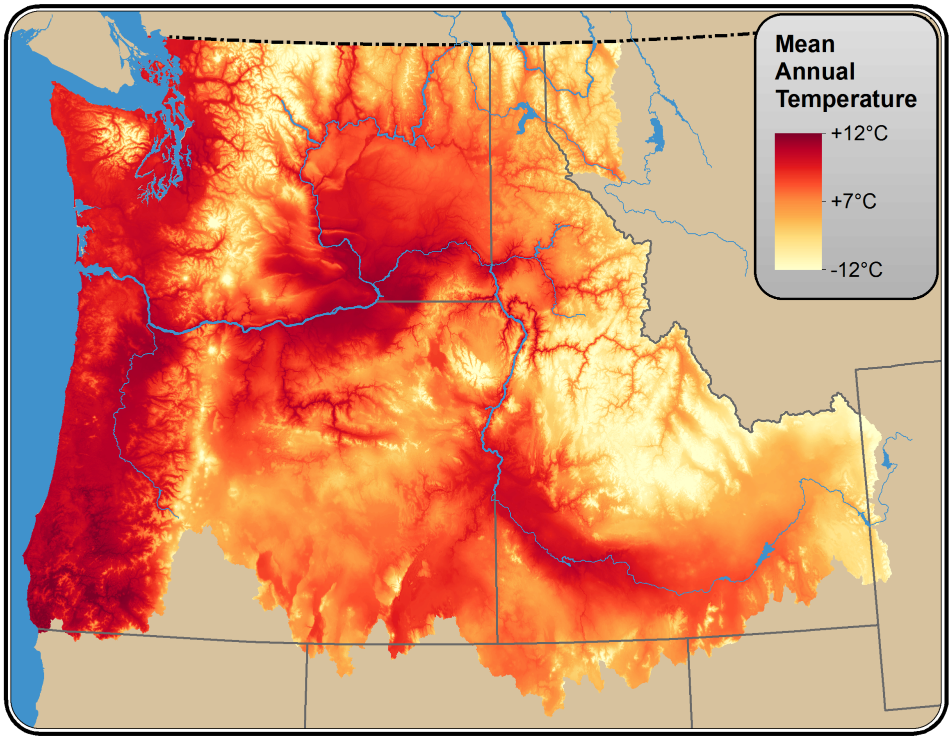


**Figure A1.1.** Mean Annual Temperature.

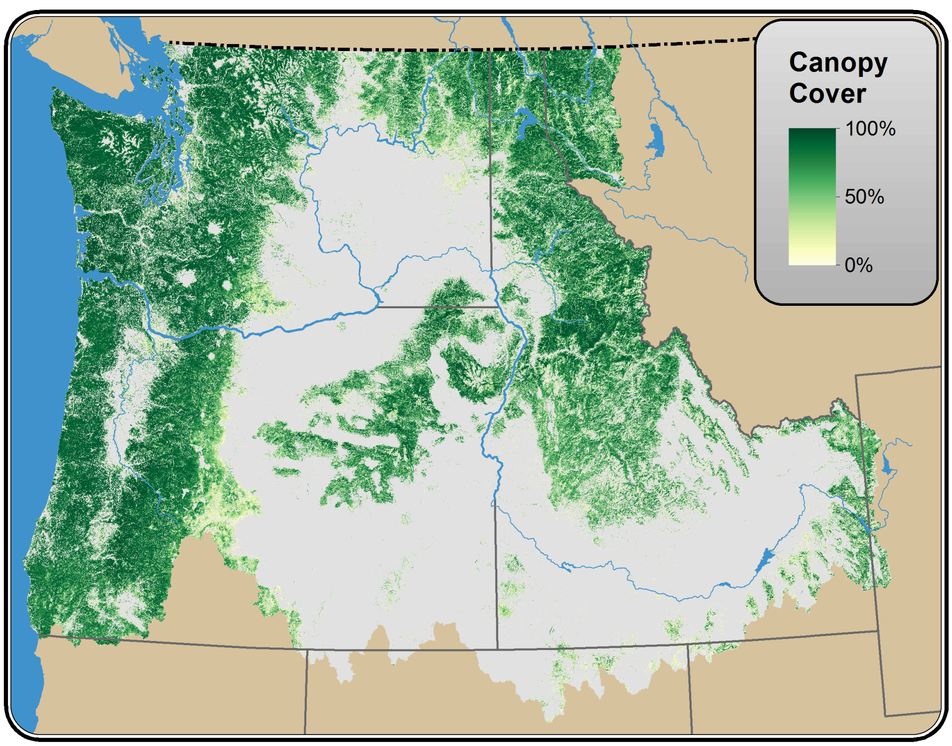


**Figure A1.2.** Canopy Cover.

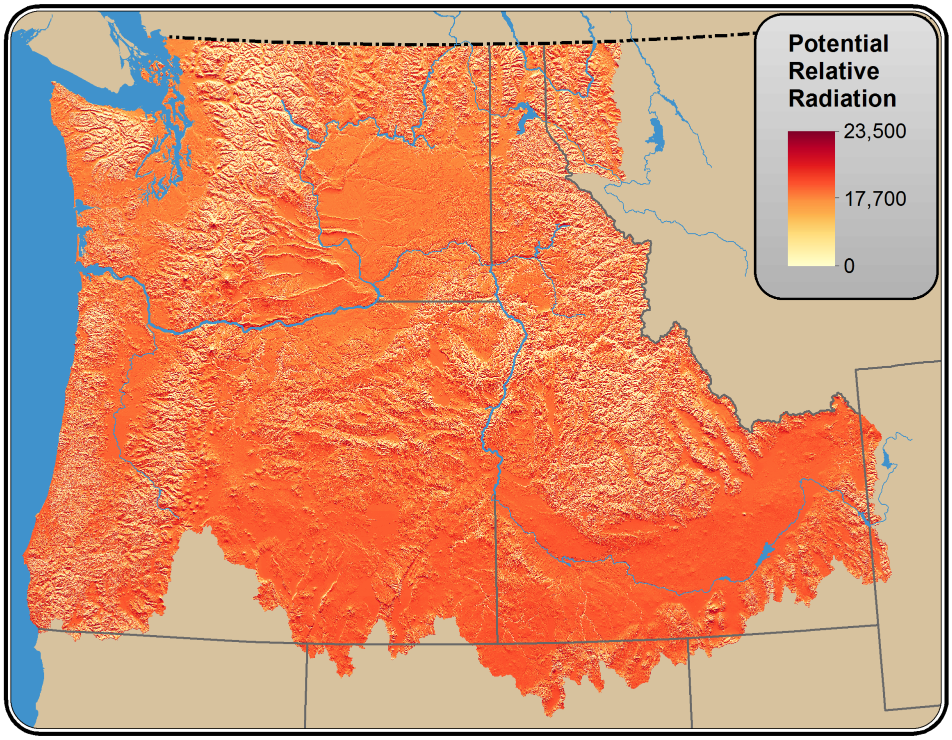

**Figure A1.3.** Potential Relative Radiation.

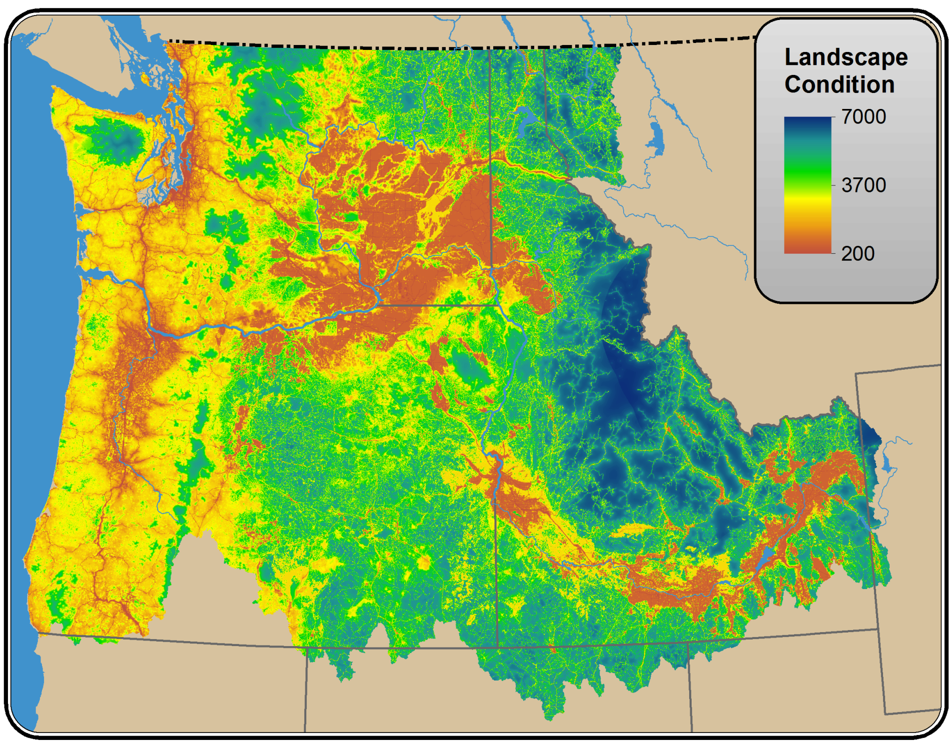

**Figure A1.4.** Landscape Condition.

## Appendix 2. Index values for each HUC level (not averaged across scales)

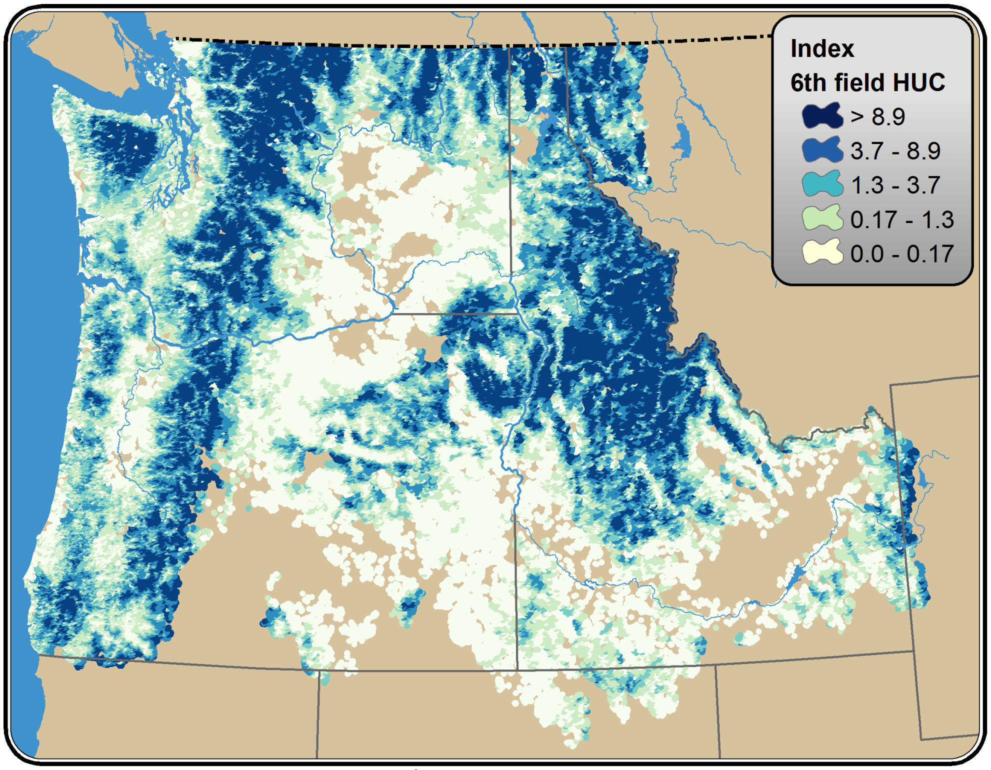


**Figure A2.1.** Index calculated at the 6th field HUC level.

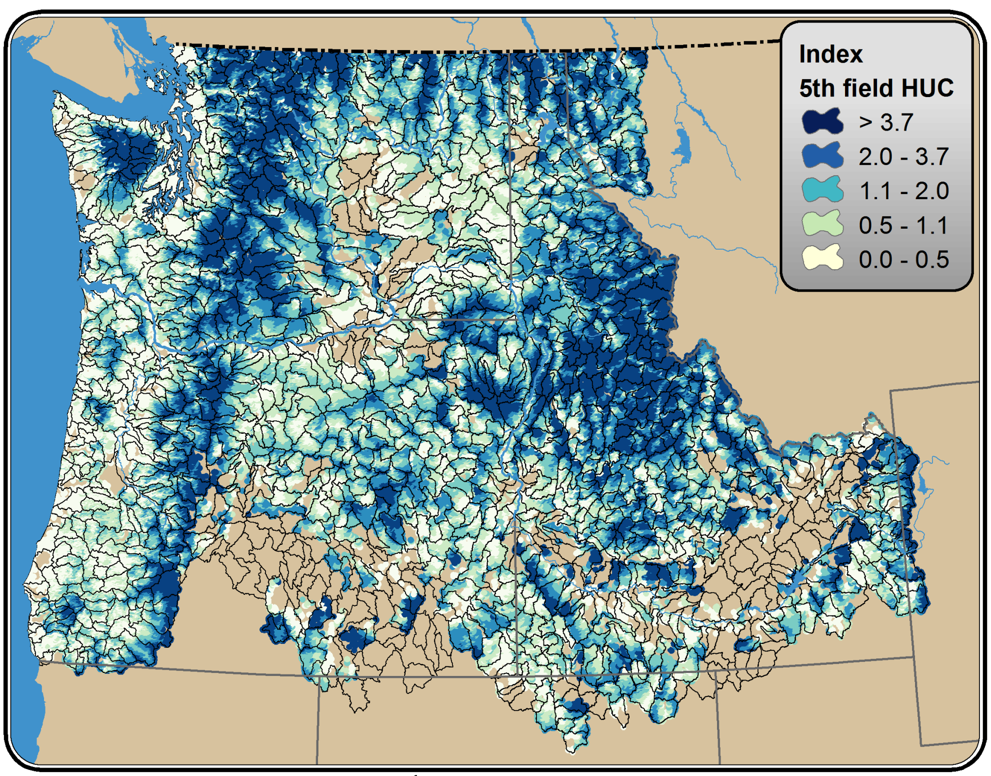


**Figure A2.2.** Index calculated at the 5th field HUC level.

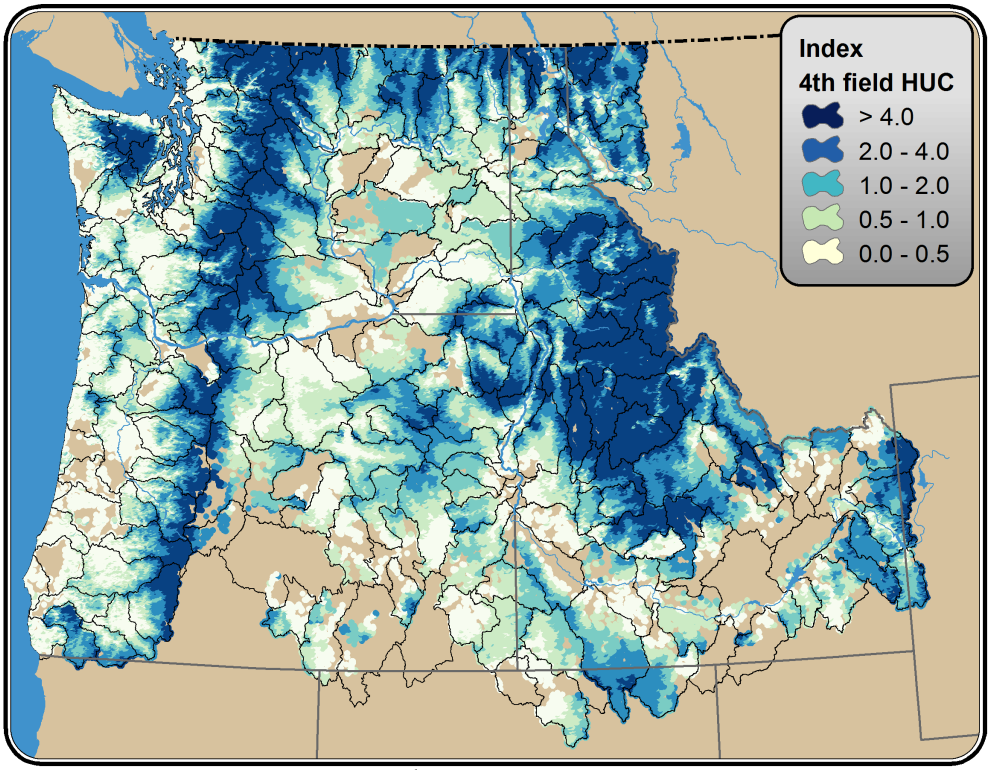

**Figure A2.3.** Index calculated at the 4th field HUC level.

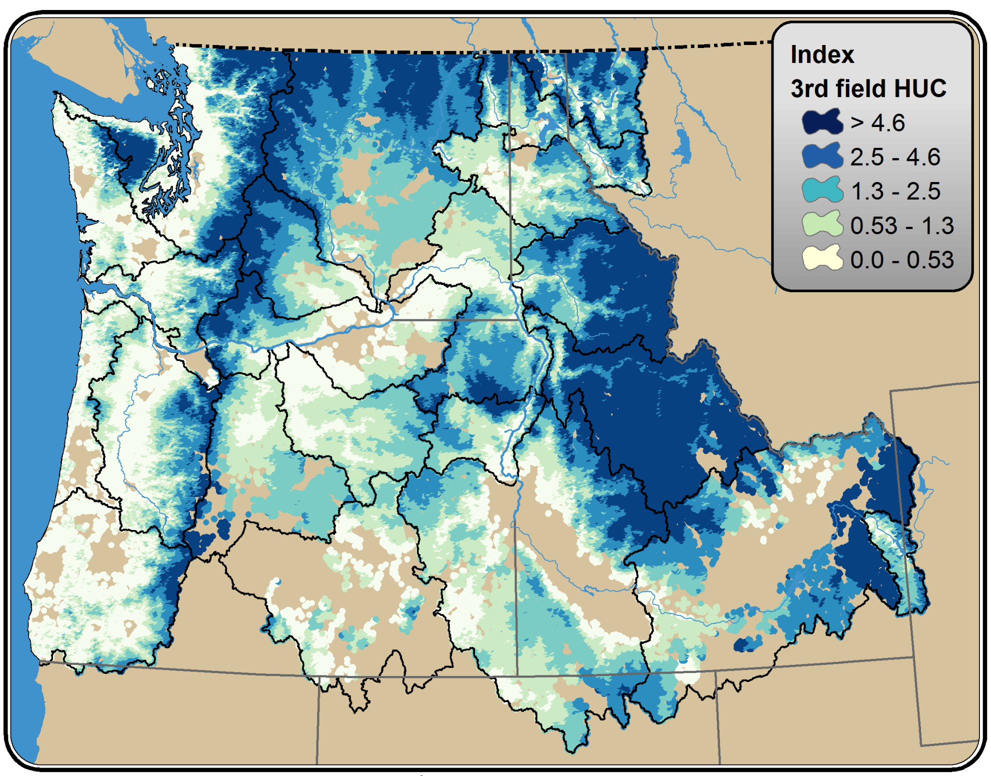

**Figure A2.4.** Index calculated at the 3rd field HUC level.

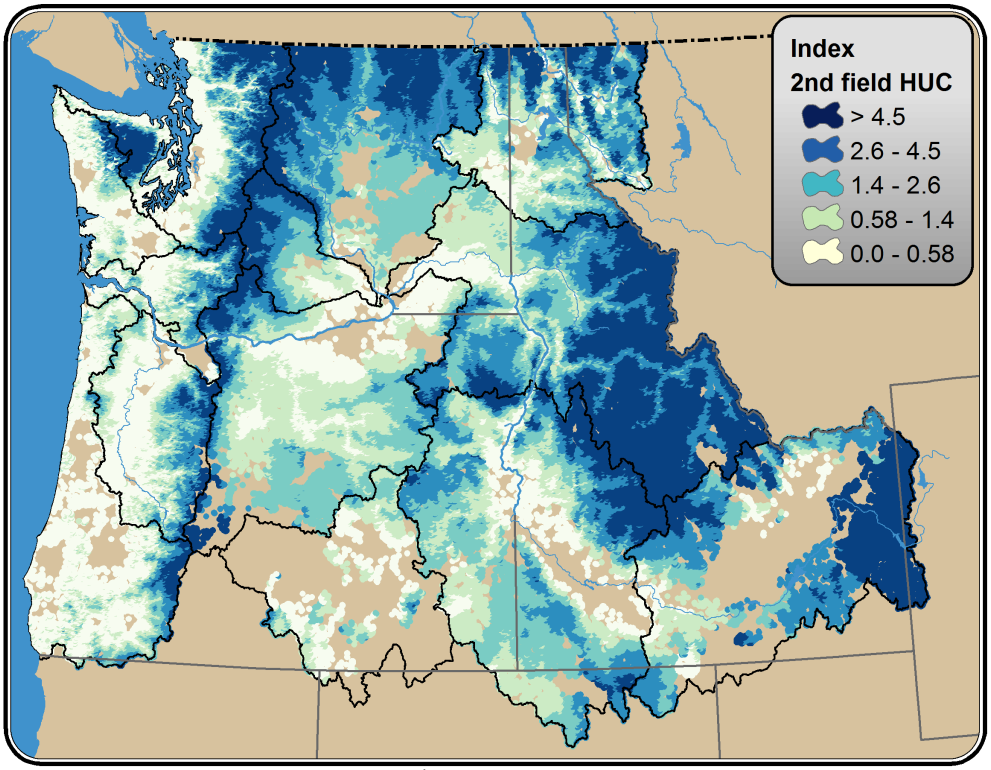

**Figure A2.5.** Index calculated at the 2nd field HUC level.

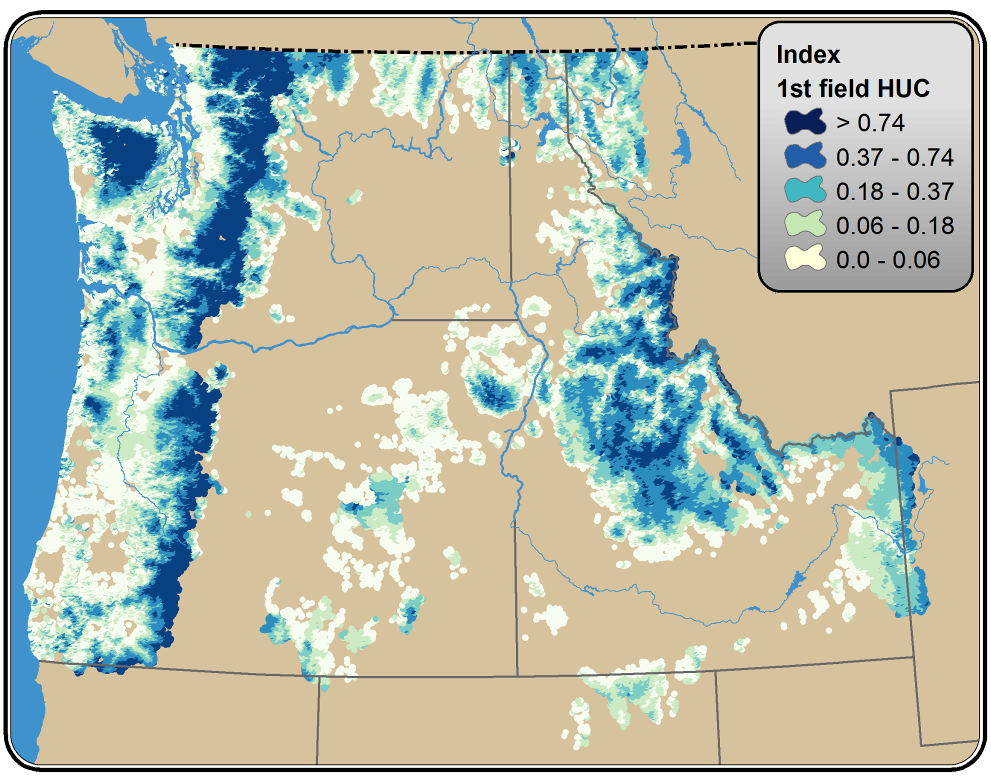

**Figure A2.6.** Index calculated at the 1st field HUC level. Missing data west of the Cascade Range is largely due to warmer temperatures at interior headwaters vs coastal outlets.

## Appendix 3. Mean index values within HUCs

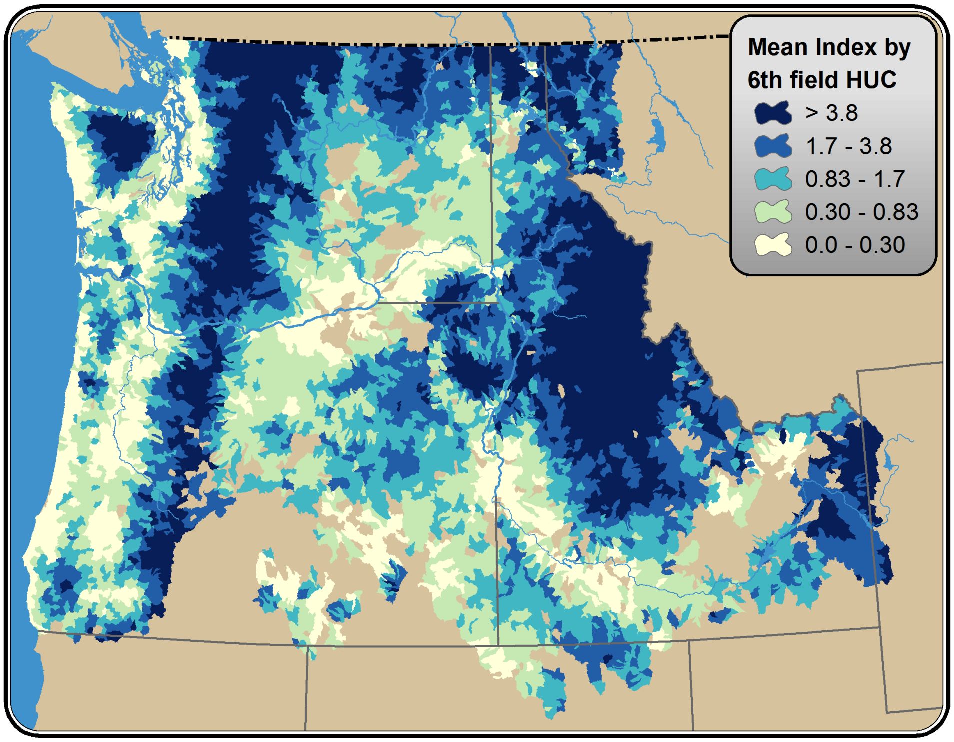


**Figure A3.1.** Index values averaged for all headwaters within each 6th field HUC.

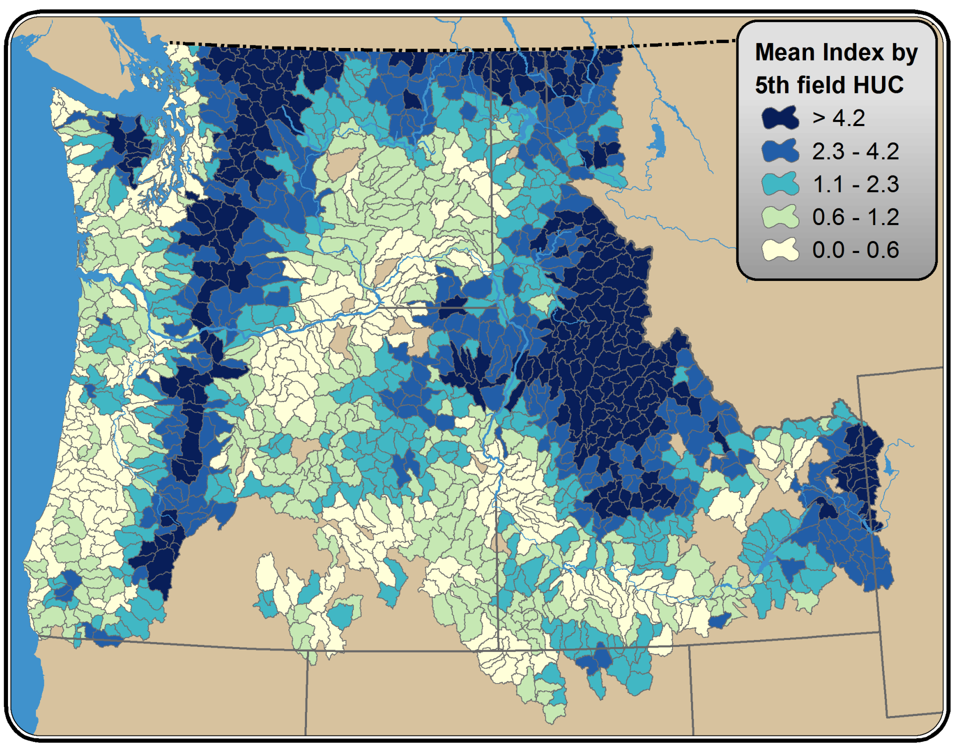


**Figure A3.2.** Index values averaged for all headwaters within each 5th field HUC.

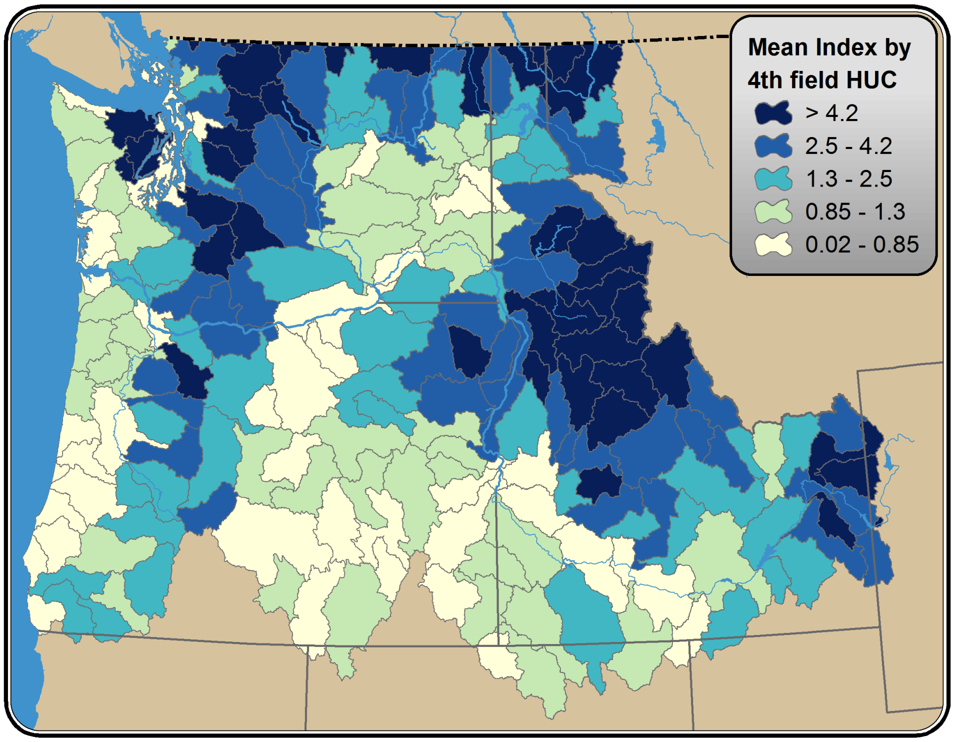

**Figure A3.4.** Index values averaged for all headwaters within each 4th field HUC.

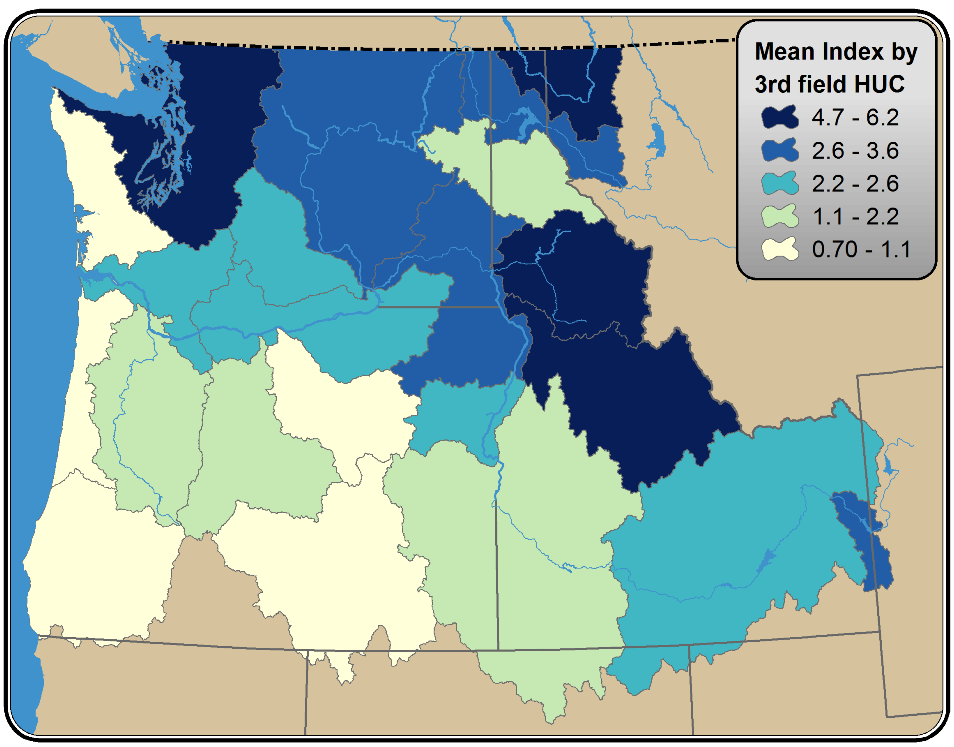

**Figure A3.5.** Index values averaged for all headwaters within each 3rd field HUC.

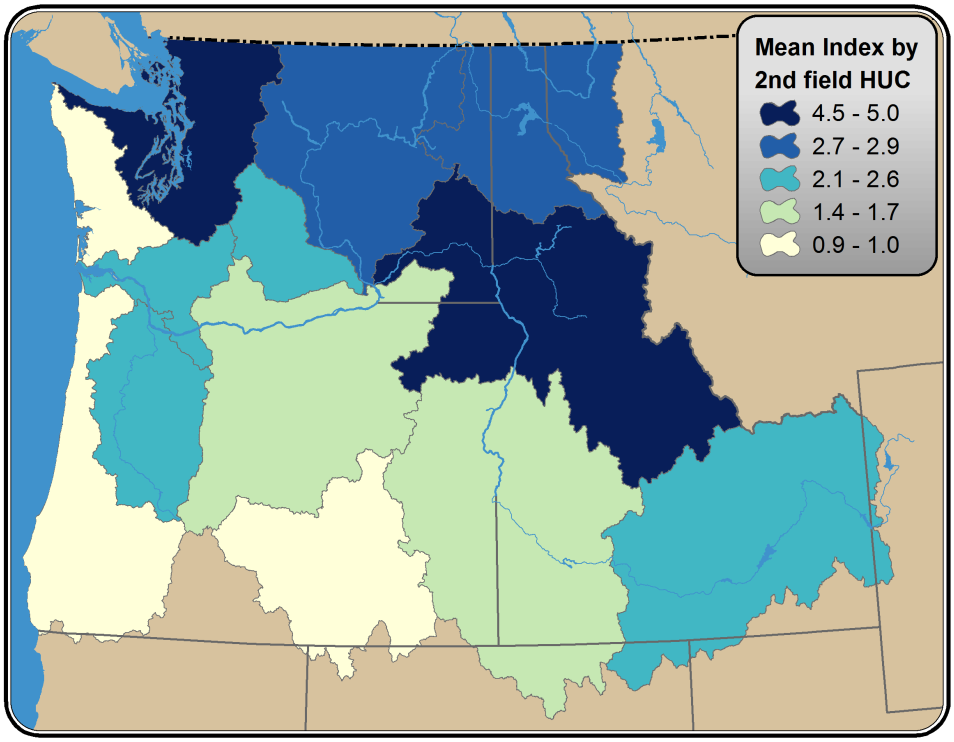


**Figure A3.6.** Index values averaged for all headwaters within each 2nd field HUC.

## Appendix 4. Mean index values within HUCs, by ecoregion

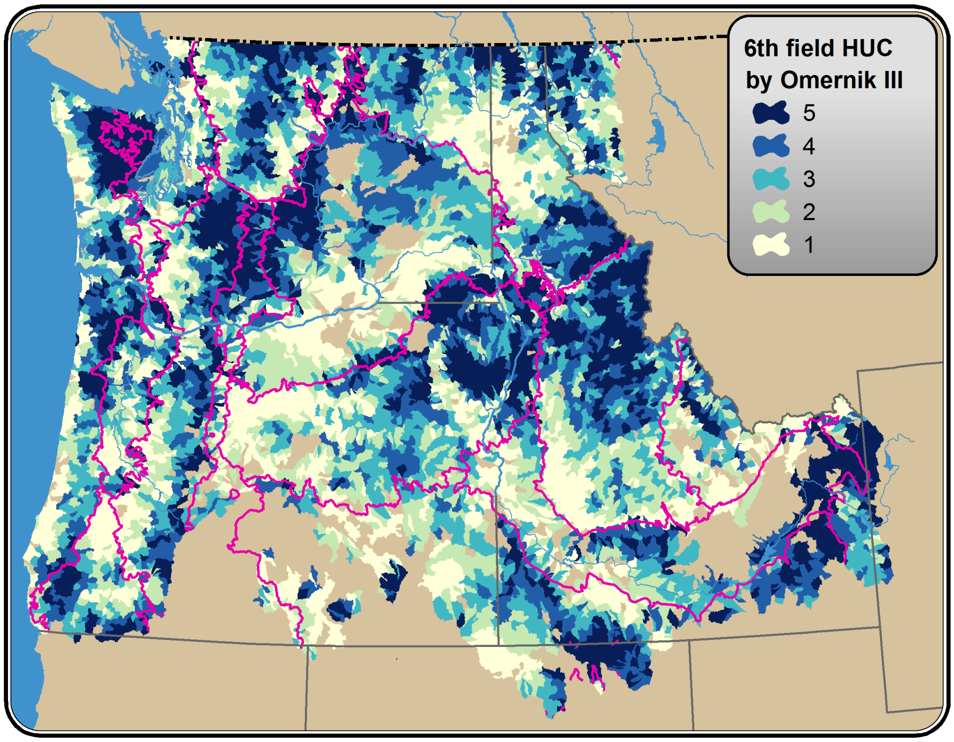


**Figure A4.1.** Index values averaged for all headwaters within each 6th field HUC, shown as quintiles calculated within ecoregions.

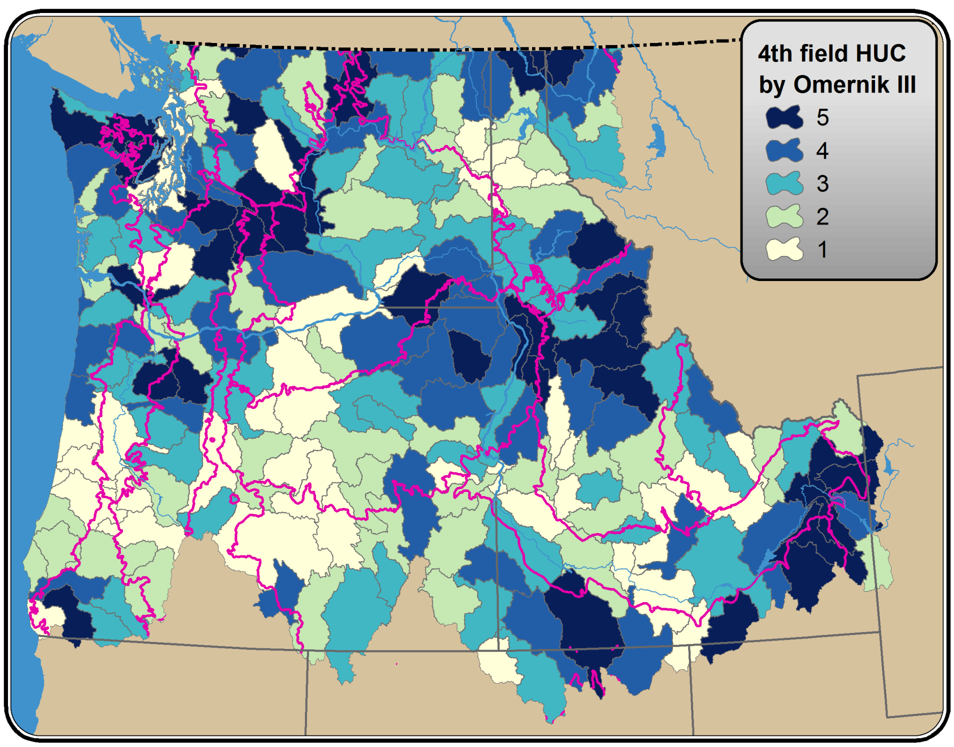


**Figure A4.2.** Index values averaged for all headwaters within each 4th field HUC, shown as quintiles calculated within ecoregions.