MAPPING PACIFIC NORTHWEST RIPARIAN AREAS: MEASURING CURRENT CONDITION AND PRIORITIZING FOR CLIMATE CHANGE ADAPTATION

USFWS Agreement No.: F12AC01044

Project PI: Meade Krosby (University of Washington)

Project Period: Begins 9/12/2012 and ends 12/31/2013

Reporting Period: Final Report

Project Summary: This project extends the geographic scope of the Riparian Mapping Project currently funded by Washington Fish & Wildlife (WDFW), Idaho Fish & Game (IDFG), and the Great Northern Landscape Conservation Cooperative (GNLCC), to include areas from the Cascade Crest west to the Pacific Coast (Figure 1). Project objectives are to produce fine resolution maps identifying riparian areas, their condition, and their climate adaptation potential, for the Pacific Northwest. We have completed final data layers and a report for analyses identifying riparian areas and their condition, and are currently finalizing data layers and preparing a report for the analysis prioritizing riparian areas for climate adaptation (expected: March 2014).

Background and Need: Managing for well-connected landscapes is a key strategy to enhance resilience and ensure the long-term viability of plant and animal populations. Connectivity conservation is also a leading climate adaptation strategy; many species will require highly permeable, well-connected landscapes to maintain dispersal and complete climate-induced range shifts.

Riparian areas have been identified as particularly important targets for climate adaptation planning, as they are buffered from warming and span the climatic gradients species ranges are likely to follow as they track shifting areas of climatic suitability. They may also offer some of the best climate adaptation opportunities in flat landscapes with high levels of human modification. However, previous approaches to identifying riparian corridors for climate adaptation have been largely subjective.

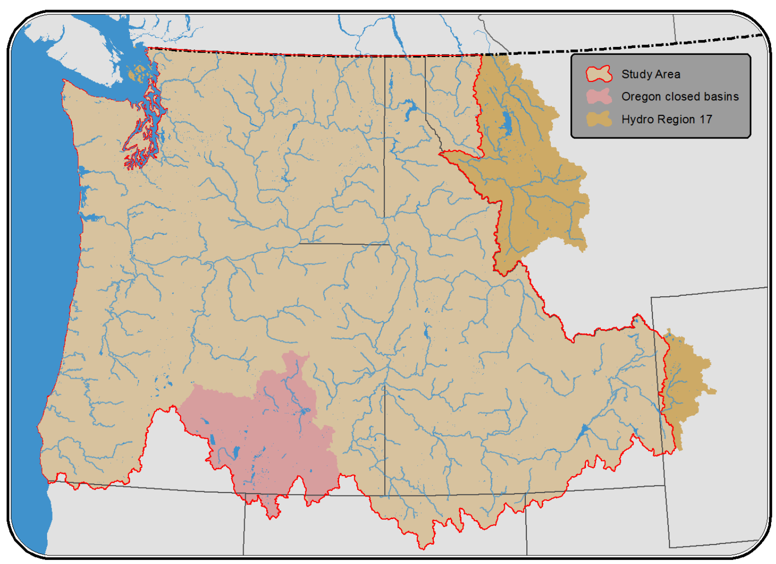


Figure 1. Project Extent. The study area includes Western Washington and Oregon, the Columbia Basin, and the Northern Rockies, defined on the basis of watersheds. Specifically, the study area covers Water Resource Region 17, except for cataloguing units in Wyoming and Montana that do not extend into Idaho.

Objectives: Our objective was to develop a novel analysis that identifies and prioritizes riparian areas important for wildlife habitat under current conditions and for climate adaptation. Doing so should advance conservation planning efforts within the NPLCC and the adjacent GNLCC.

Ultimately, this analysis is meant to act as a pilot for incorporating climate adaptation data layers into the WGA Crucial Habitat Assessment Tool.

***Objective 1.* Develop a base layer of riparian area and condition.** Using the Western Riparian Threats Assessment (WRTA) riparian datasets as a basis, we intended to generate a refined, high resolution data layer based on the USGS National Hydrography Dataset (High; 1:24,000) and 30 m DEM, that a) identifies riparian areas, and b) provides measures of riparian condition.

***Objective 2.* Prioritize riparian areas likely to increase biological resilience to climate change.** We intended to test a range of potential criteria for identifying such areas, such as the degree to which they span climatic gradients important to range shifts, or exhibit low levels of solar insolation that may buffer future warming. We would then apply these criteria to the riparian areas identified under Objective 1, to produce a map identifying Northwest riparian areas most likely to promote biological resilience to climate change.

To accomplish these objectives, we would:

1. Modify the riparian layer produced by Objective 1 as needed to complete prioritization analysis (e.g., coding riparian areas to reflect units of prioritization).
2. Test possible riparian area prioritization criteria.
3. Map locations of riparian areas meeting selected prioritization criteria.

Results and Accomplishments

***Objective 1.* Develop a base layer of riparian area and condition.**

- Our partners (David Theobald (Conservation Science Partners) and colleagues) successfully refined methods developed as part of the Western Riparian Threats Assessment (WRTA) to generate high-resolution riparian base layers using the USGS National Hydrography Dataset (High; 1:24,000) and 30 m DEM. These new base layers a) identified riparian areas, and b) provided measures of riparian condition for the Pacific Northwest.

***Objective 2.* Prioritize riparian areas likely to increase biological resilience to climate change.**

- We successfully collaborated with our partners to ensure that riparian base layers developed under Objective 1 met our analytical needs, and then further prepared them for use in our climate adaptation prioritization analysis.

- We successfully tested multiple prioritization criteria for riparian climate-corridors, including:
    - Climate gradient
    - Connectivity
    - Solar insolation
    - Area
    - Human Modification
    - Canopy Cover

- We ultimately did not include direct measures of riparian connectivity in our analysis, as our tests showed that available methods (e.g., least cost path, Circuitscape) would require significant modification for appropriate application to our analysis, which was beyond the scope of this project. Instead, we used levels of human modification along riparian stretches as a proxy for connectivity.

- We successfully mapped locations of riparian areas meeting selected prioritization criteria. We did this by creating base layers for each of the above criteria, standardizing them, and combining them into a unique climate adaptation index for every mouth-to-headwater stretch of riparian within a nested range of watershed scales (HUC12 to HUC 2). We then averaged index scores across watershed scales to compute a final climate adaptation index value for each outlet-to-headwater stretch of riparian (Fig. 2).

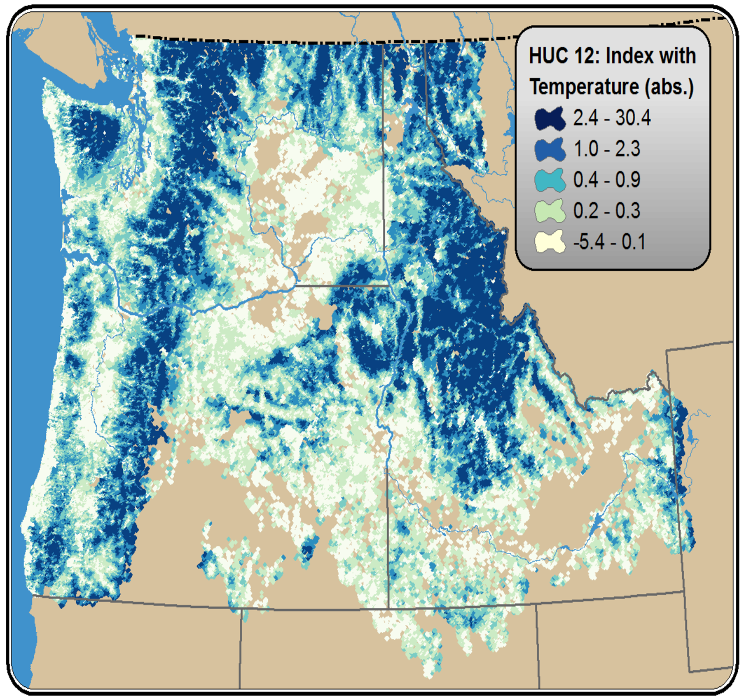


Figure 2. Riparian Climate-Corridor Index Values. Riparian stretches estimated to have higher climate adaptation potential have higher scores (dark blue = top 20% for Pacific Northwest), while those estimated to have lower potential have lower scores (cream = bottom 20%).

Project Deliverables

Objective 1*. Develop a base layer of riparian area and condition *(completed 9/2013)

- **Riparian Area Location and Condition Mapping Webinar (6/2013):** Our partners presented their draft results to a diverse audience in order to solicit feedback as we began to prepare our final products. The recorded webinar may be accessed here: https://wadismeetings.webex.com/wadismeetings/ldr.php?AT=pb&SP=MC&rID=68501022&rKey=0193f6f2b1de66ae

- **Riparian Area Location and Condition Report (9/2013):** *Detailed Datasets on Riparian and Valley-Bottom Attributes and Condition for the Great Northern and Northern Pacific LCC (WRR17) (Theobald et al. 2013; attached)*. Data layers are currently available by request from D. Theobald, but will ultimately be made publicly available via the WDFW website.

***Objective 2*. Prioritize riparian areas likely to increase biological resilience to climate change.**

- **Riparian Climate-Corridor Mapping Webinar (9/2013):** We presented our draft results to a diverse audience in order to solicit feedback as we began to prepare our final products. The recorded webinar may be accessed here: https://wadismeetings.webex.com/wadismeetings/ldr.php?AT=pb&SP=MC&rID=70560817&rKey=88a606d174e74cae

- **Riparian Climate-Corridor Report (4/2014):** *Riparian Climate-Corridors – Identifying Priority Areas for Conservation in a Changing Climate (Krosby et al. 2014; attached).* Data layers are currently available by request from M. Krosby, but will ultimately be made publicly available via the WDFW website.

Literature Cited

National Hydrography Datset Plus (NHDPlus). 2012. http://www.horizon-systems.com/nhdplus/

Krosby, M., Norheim, R., Theobald, D. M., McRae, B. Riparian Climate-Corridors – Identifying Priority Areas for Conservation in A Changing Climate.

Theobald, DM, J. Norman, D. Merritt. 2010. Western riparian threats assessment. URL: http://www.fs.fed.us/wwetac/projects/theobald.html.

Theobald, D. M., D. Mueller, and J. Norman. 2013. Detailed Datasets on Riparian and Valley-Bottom Attributes and Condition for the Great Northern and Northern Pacific LCC (WRR17).

USGS National Elevation Dataset 2013. http://ned.usgs.gov/

Detailed datasets on riparian and valley-bottom attributes and condition for the Great Northern and Northern Pacific LCC (WRR17)

2 September 2013

David M. Theobald[1,2], David Mueller[2], and John Norman

[1]*Conservation Science Partners, Truckee, CA. davet@csp-inc.org*

[2]*Department of Fish, Wildlife, and Conservation Biology, Colorado State University*

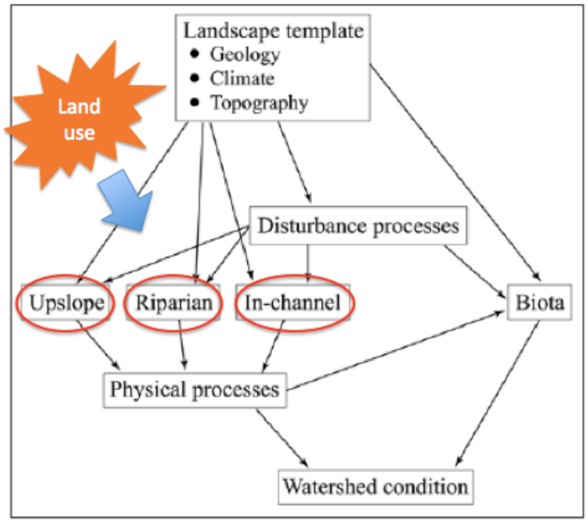
Background

Consistent, comprehensive spatial data on riparian habitat and hydrologic features are needed by local, state, and federal agencies at a detailed level, but such information is not yet available for the western US. Existing data layers (e.g., GAP, LANDFIRE, NLCD) do not adequately represent the locations of riparian areas, nor do they provide information about the condition of these areas. In particular, existing layers are inconsistent and incomprehensive across the Western US (e.g., NWI is available digitally for only ~50% of the West), map "current" and "actual" riparian/wetland areas but not potential areas, and/or are poorly mapped (i.e., erroneously exclude and/or fragment areas due to coarse resolution; this is especially true of satellite-based datasets such as GAP, LANDFIRE, and NLCD). Although the USGS National Hydrography Dataset PLUS effort has filled an important gap in data needs by providing a series of additional hydrologic attributes, it is currently linked to a medium-scale hydrology (1:100,000). Our project seeks to address the shortcomings of existing datasets by providing a consistent, comprehensive map of valley bottoms and various aspects of their characteristics and condition.

Foundational efforts

Our project builds strongly upon two existing datasets/projects. The first is the high resolution NHD dataset (1:24,000), as it provides features and details depicted at the high resolution necessary to guide actionable, on-the-ground decisions by terrestrial and freshwater land managers. However, the NHD High resolution data are quite challenging to work with, because they are voluminous, can be inconsistent across watersheds & quad-sheet boundaries (this is particularly notable in heavily managed lands in Washington), and include attribute and topological errors that can wreak havoc on flow-based GIS routines (hence, the need for the multi-million dollar NHD Plus effort).

We also build upon the Western Riparian Threats Assessment (WRTA), which mapped the location and condition of potential riparian areas across the West. However, this effort used slightly coarser hydrologic data (1:100,000) and did not include several key variables needed by potential users, such as stream gradient and mouth-to-headwater linkages. A key aspect of the WRTA is that it is based upon dominant upland, lateral, and longitudinal hydrologic processes (Reeves et al. 2004).



Goal and objectives

For the reasons articulated above, we developed a series of spatially-explicit products (at 30 m resolution). We felt that it was especially important to:

- Produce products at a management relevant scale;
- Represent dominant ecological processes;
- Use methods that are robust to artifacts in hydrologic flow data; and
- Provide comprehensive, consistent, and updatable datasets.

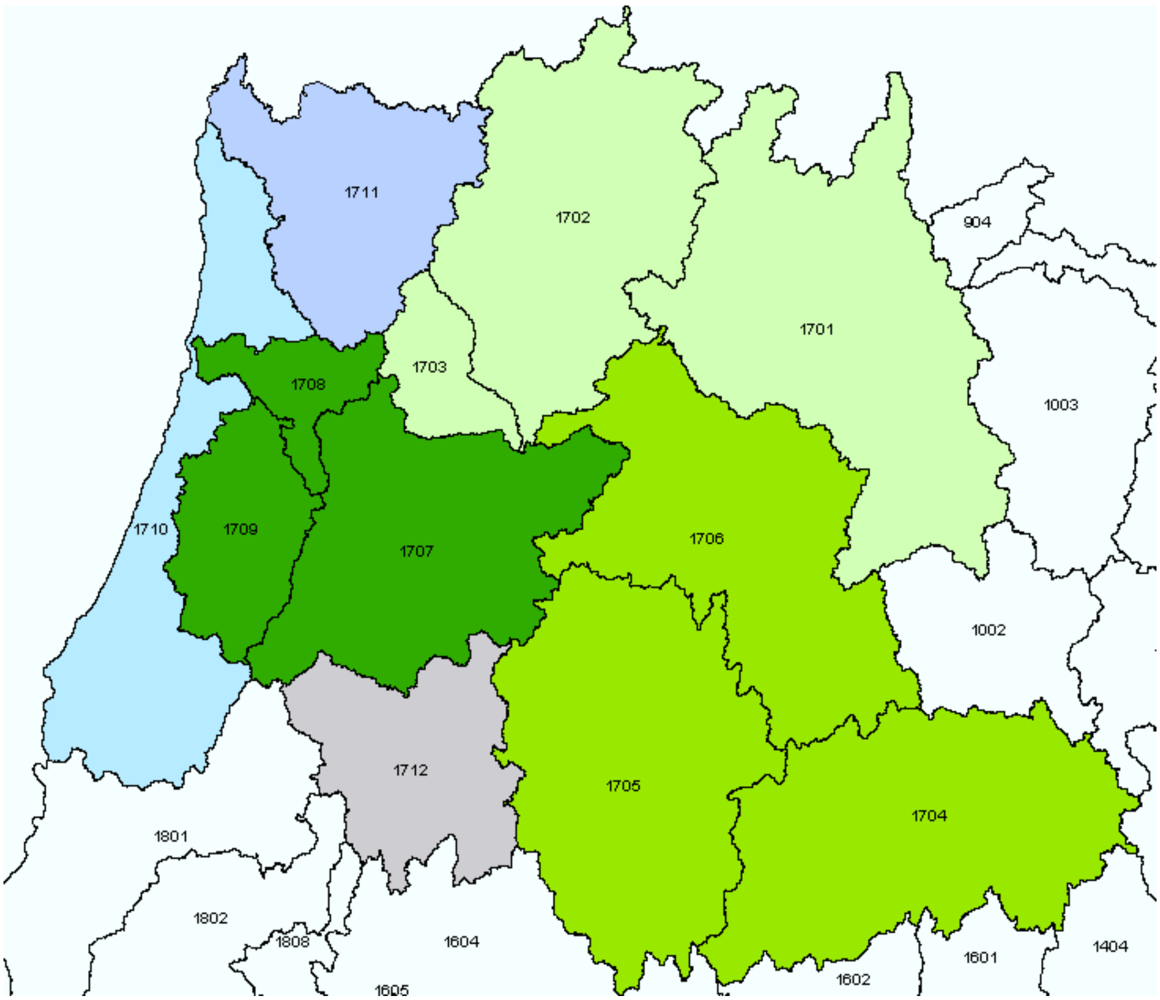
Although we report on this effort as a stand-alone effort, our work was coupled explicitly with a broader effort led by Meade Krosby (University of Washington) to generate riparian climate corridors, for which a riparian area base layer is a key input. That "sister" effort is reported separately.

Study area

Our study area is water resources region #17 (HUC17), which covers most of Washington, and parts of Oregon and Idaho. It also includes portions of Canada, for which we used coarser-resolution DEMs due to lack of availability of other datasets.

We broke HUC17 into 6 processing units based on 4th-digit HUCs:

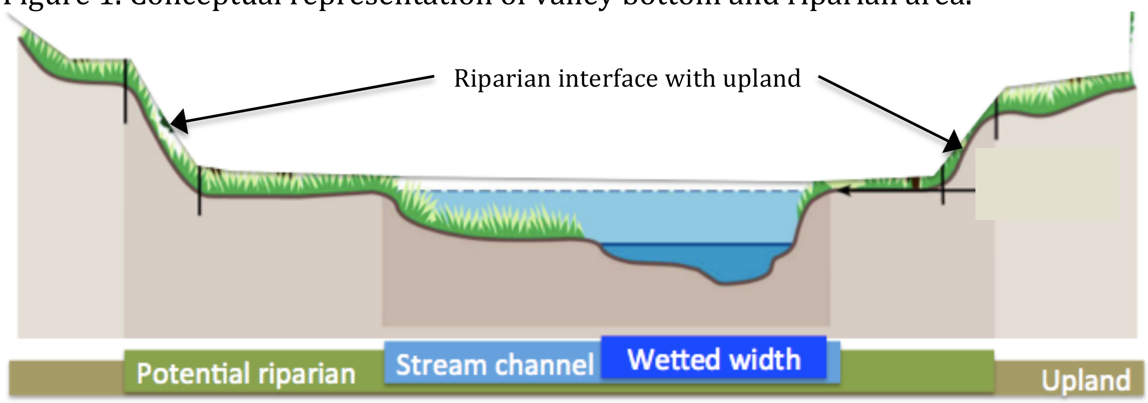
R17a = 1701, 1702, 1703
R17b = 1704, 1705, 1706
R17c = 1707, 1708, 1709
R17d = 1710
R17e = 1711
R17f = 1712



Definitions

The term “riparian areas” is frequently used as a general term for terrestrial ecosystems at the interface of rivers or streams. However, during this project we moved towards a more comprehensive and hydrological/geomorphological-based concept of a riparian area that is of one of four, hierarchically-nested components of valley-bottoms: wetted width, stream channel (or active channel), potential riparian zone, and valley bottom at the edge of or interface to the upland area (Figure 1). The *wetted width* occurs typically at the lowest elevation of a cross-section, which is likely to be filled with water at an annual time scale. The *active channel* surrounds the wetted width and occupies areas that are likely to be influenced by active channel processes such as flooding and meandering of streams, on the order of decadal time scale. The *potential riparian zone* or area surrounds the stream channel and occurs within nearby, low-gradient topography, and typically contains hydrographic soils, and is affected by processes occurring over a century or so (e.g., 100-year floodplain). Note that our analysis does not use any data on vegetation or soil types within these zones – rather it is based entirely on hydrology and geomorphological variables. Finally, the potential riparian areas are surrounded at the edge by interface *upland* areas that may be influenced by hydrology on the order of millennia.

Figure 1. Conceptual representation of valley bottom and riparian area.



An especially interesting, important, and often overlooked aspect is that typically stream features are represented as a single-cell swath of pixels. This usually takes the form of a "fat line" representation using 4-neighborhood connectivity (note that this is the default method when converting vector lines to raster in ArcGIS). For many small rivers and creeks, however, a single-cell width might over-represent the feature, resulting in area and length calculations that might be overly large. Through visual inspection, a useful measure of stream wetted-widths on 1:24k streams is that they are represented by polygons when streams are wider than 8-10 m. On the other hand, for large streams and rivers that often have large wetted widths (e.g., >30 m), a single cell width might under-represent the feature. For these reasons, we attempted to identify the width of stream (and lake) features that can be represented with 30 m resolution. That is, we differentiate wetted-width explicitly in the valley bottom data product. Note that we do not explicitly deal with small streams <30 m wide (going to 10 m resolution would help this issue, but not solve it). Note that a critical aspect of our work is the dual representation of hydrologic features as both vector (points, lines, and polygons) and raster (grid cells) data models.

Products

We generated a variety of products during this project that can be generally organized by hydrologic feature-scale -- or more precisely what the key freshwater feature is being represented:

- BASE – a series of general and base data layers used to generate the derivative products
- FDIRS – contains the flow direction rasters for the full watersheds and for the streams
- LINK – stream order, catchment area and stream gradient at the link (confluence to confluence) and/or reach (within link)
- NETWORK – uses the continuous flow accumulation representation of the streams
- VALLEY-BOTTOM – the near-stream valley bottom area that contains riparian areas
- WATERSHED – general data layers that cover the entire extent of HUC17, including stream locations, HUC watersheds, DEM, etc.

A brief note about the resolution of the data products. We conducted the analysis and provide products at two scales (resolution): 30 and 90 m. All base datasets originated at 30 m resolution, and the stream gradient, valley bottom, and link-based analyses were done at 30 m. We chose to use 90 m resolution for longitudinal aspects of the project, including the accumulated watershed area and average elevation, as well as offering link catchments at 90 m as well. Due to a computational limitation in ArcGIS, calculating accumulated flow at 30 m resolution for the entire HUC17 was prohibitive. Rather, providing the flow direction rasters at 90 m allows users to build on the framework and conduct value-added analyses that involve accumulation (typically using the FLOW ACCUMULATION tool). Note that there are some scale-based differences between the flow direction rasters at 30 m and 90 m – that is, they are not exactly the same. For longitudinal measures, these differences are very minor (~0.001% difference) – but for lateral measures such as valley bottom, they can be substantial. Users of these data are cautioned to consider the eco-hydrological process they are investigating and how resolution might effect measurement of that process.

Table 1 provides a list of the datasets produced in this project. A conceptual representation of how these products were produced within the overall project flow is provided in Figure 2. Individual data products are described below. Note that we have provided an ArcMap document file (rFLOWS_Maps_20130811.mxd) that provides additional layer files, display options and attribute values for each of the dataset products. This provides users a quick way to understand the various datasets.

Figure 2. Overall flow of primary data sources, main processing steps, and the variety of output products.

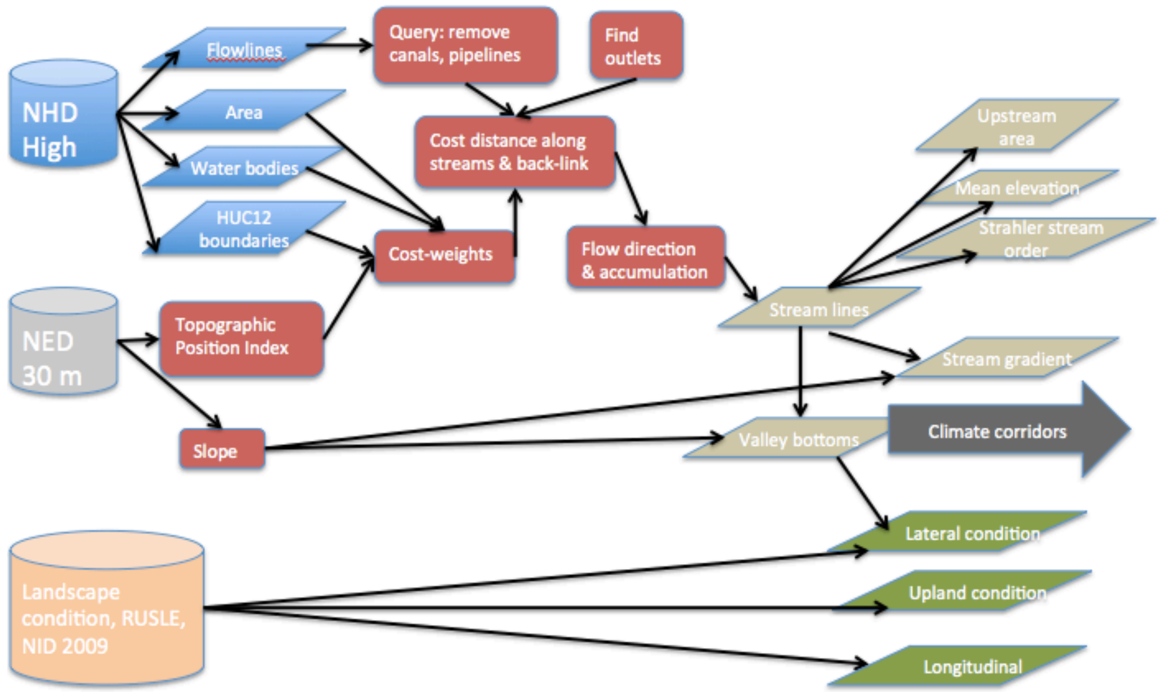

NHD
High
Flowlines
Area
Water bodies
HUC12
boundaries
Query: remove
canals, pipelines
Find
outlets
Cost distance along
streams & back-link
Cost-weights
Flow direction
& accumulation
NED
30 m
Topographic
Position Index
Slope
Upstream
area
Mean elevation
Strahler stream
order
Stream lines
Stream gradient
Valley bottoms
Climate corridors
Lateral condition
Upland condition
Longitudinal
Landscape
condition, RUSLE,
NID 2009

Table 1. List of products associated with the valley-bottom mapping effort. Key foundational datasets included the USGS National Hydrography Dataset (High Resolution) and the USGS National Elevation Dataset (30 m), and the Watershed Boundary Dataset.

Scale	Name*	Description
I – BASE	r17_area.shp	NHD river areas
	H17_FLowsNatAlbTrimmmedWoDitch	Derived from NHD flow lines, "trimmed" to remove the 1st order stream and ditches & pipelines from the High resolution NHD
	r17_dem	Elevation value for US from National Elevation Dataset, 30 m and for Canada (north of NED boundary) from GMTED dataset (~240 m resolution; http://topotools.cr.usgs.gov/gmted_viewer/)
	r17_huc12	12-digit HUCs
	r17_ocean	Mask for ocean areas, derived from the NHD High resolution coastal line
	r17_strfid2	NHD flow lines at 30 m
	h17_WB.shp	NHD water bodies, not including marsh/swamps, ice fields, and playas
	R17_strnabdsnap_points.shp	Locations of dams/reservoirs from the National Anthropogenic Barrier Dataset 2012. Locations were snapped to the flow direction 90 m raster, if within 180 m of the polyline.
II – DIR90	r17_linkcfd	Flow directions from catchments back to links
	r17_overfd	Flow directions from watershed overland to the streamlines (which have value of 0)
	r17_strfd	Flow directions for stream lines from original blue-lines (vector)
	r17_strfd5	Flow directions for just the streams represented by r17_strfai5
	r17_wsfd	Flow directions for the entire surface area, generated by cost-distance away from r17_strmfd cells using slope^2 + TPI value cost-weights
III – LINK30	R17_str_flat4	Stream cells that are relatively flat (i.e. less than 4% gradient), and these are assumed to potentially influence lateral flows, whereas >4% is assumed to have minimal to no lateral flow.
	R17_strgradh	Stream gradient (in percent * 10), Uses roughly 200-500 m reaches within each link.
	R17_strgradhc	Stream gradient classes: 0=<0.1%; 1=0.1-1%, 2=1-2%, 3=2-4%, 4=4-8%, 5=8-20%, 6=>20% (Montgomery & Buffington 1994)
	R17_strslph	Raw stream slope in % gradient * 100, calculated using 30 m resolution SLOPE tool (3x3 moving window).
III – LINK90	R17_lcat_lc	Catchment areas generated around linkages with cells storing the sum of Landscape Condition values found in the valley bottoms w/in catchment. Note that the low values in landscape condition indicate low modification (0>) and high values indicate high levels of modification (<1000).
	R17_lcat_lcw	Average weight of r17lcat_lc, calculated by sum of lc values in valley bottom divided by number of cells of flowline in catchment. These are the cost distance weights to be used in longitudinal analysis
	R17_lcat_str	Number of stream (flow line) cells that are within a catchment
	R17_lcat_vb	Number of valley bottom cells (excluding water) that are within a catchment
	R17_lcat_vbw	Average width of valley bottom (in meters) for each link catchment. These are the cost distance weights to be used in longitudinal analysis
	R17_lcat_sgrd	Average stream gradient within each catchment, units are stream gradient x 100 (based on r17_strgradh).
	R17_link	Unique IDs (regions) of each stream link (confluence to confluence) using r17_strfd5x
	R17_linkcat	Unique IDs (regions) of each stream link (confluence to confluence)
IV –	R17_ac_elev	Accumulated average elevation (m) in the watershed

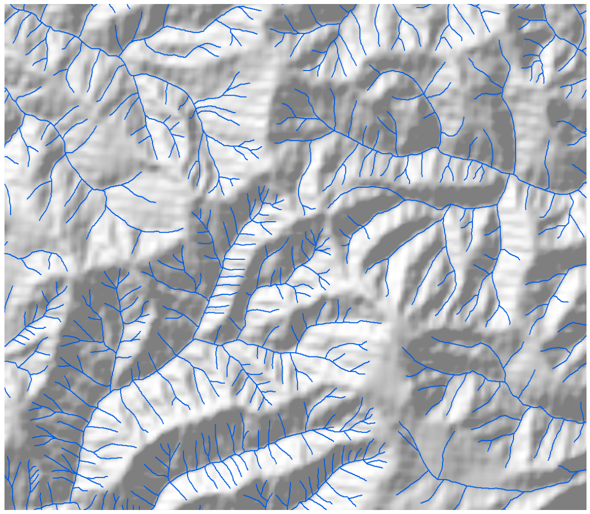
NETWORK90		
	R17_fai	Stream order indicator by calculating Int(Ln(r17_fa))
	R17_str5_headwaters.shp	Points at the headwaters or starting points of accumulation for r17_str5
	R17_strfa	Accumulated area above a location (in number of 90 m cells) for just stream cells from original r17_str
	R17_strfai	Stream order indicator for just cells on the stream by calculating Int(Ln(r17_strfa))
	R17_strnidwt, or r17_str5_strnid2str_polylines.shp	Longitudinal flow regulation due to reservoirs. Calculated as the ratio of the area of reservoir waterbodies times the Int(Ln(x)) of acre feet, divided by r17_fa, times 1000. Thus, this approximates flow regulation measures by incorporating magnitude of the storage volume, but is more akin to density calculated as the area of reservoir inundation vs. full stream (flow) line cell area. Larger values indicate much greater degree of regulation/modification. Note that r17_str5_strwb2str_polylines0.shp can be used to display all other streams that do not have a dam flow modification on them.
	R17_strrdfat, r17_strrd2str_polylines.shp	Another longitudinal flow modification, due to the presence of road crossings with streams and/or roads adjacent to streams (30 m resolution, TIGER 2010 roads). This value is the accumulated number of cells crossed/adjacent, divided by total number of accumulated number of stream cells, times 1000
	R17_strwb2str_polylines.shp, R17_strwb2str_polylines0.shp	Another longitudinal flow modification that incorporates all lakes and reservoirs represented in the NHD. This assumes that flow modification is related to proportion of the area of each waterbody (lake/reservoirs) to the total length (area) of the stream lines. This does not distinguish human vs. natural flow modifications do to water bodies. Note that r17_str5_strwb2str_polylines0.shp can be used to display all other streams that do not have any flow modification on them.
	R17_strXXX, r17_wb90XXX	Intermediate rasters to calculate the area of streams and waterbodies (reservoirs and lakes that are accumulating downstream).
	R17_wsstrfa	Accumulated number of cells along the stream lines, including overland flow (so total watershed area, but only for stream cells).
V – VB30	R17_vbcfinal2	The final valley bottom class, where 0 denotes a stream cell but >=4% grade, 1 = stream/water, 2 = active channel; 3 = potential riparian area; and 4 = interface with watershed
	R17_vbrfinal2	The final valley bottom riparian or not, where 0 = water (classes 0 and 1 in vbc and streams and streams that are >4% gradient) and 1=active channel and potential riparian (classes 2 and 3 in vbc)
V – VB90	R17_vbr23	Intermediate raster. Has Landscape Condition values for cells that intersect valley bottom classes 2 and 3, but water and watershed interface (1 and 4) are not used when calculating the average LC value in a 90 m cell (from the 30 m valley bottom raster). These values are the number of 30 m cells in each 90 m cell.
	R17_vbr23lc	Valley bottom where 0 = water (classes 0 and 1 in vbc) and 1=active channel and potential riparian (classes 2 and 3 in vbc)
	R17_vbrusle	Upland watershed condition as summarized by predicted upland soil loss. Soil loss estimated by RUSLE from Western Riparian Threats Assessment (Theobald et al. 2010).
VI – WATERSHED90	R17_hucHH	Unique id for each HUC at different HUC levels signified by HH
	R17_l_mod	Longitudinal condition where a value of 0 is little effect and 1.0 is maximum impact, averaged by link catchments. This value is estimated by converting the flow fragmentation by dams (r17_strnid) and roads

		(r17_strrds) using the SLICE command and Natural Breaks classification. The dams and roads rasters were combined by finding the maximum value.
	R17_r_mod	Landscape condition (actually reversed to be degree of human modification) for the valley bottoms (riparian) areas, where a value of 0 is little effect and 1.0 is maximum effect, averaged by link catchments. This value is simply the area-weighted proportion within each valley bottom.
	R17_w_mod	Upland watershed condition as summarized by predicted upland soil loss, where a value of 0 is little effect and 1.0 is maximum effect, averaged by link catchments. This value is estimated by converting the soil loss estimated by RUSLE from Western Riparian Threats Assessment (Theobald et al. 2010) per watershed using the SLICE command and Natural Breaks classification.
	R17_lrw_mod	An integrated, cumulative index that combines the longitudinal, riparian, and watershed modification variables into a single index. These three were combined using the "increasive" averaging provided by the fuzzy sum algorithm. Low values indicate low degrees of modification to the valley-bottom/riparian/stream systems, while high values indicate high levels of modification. These values are averaged by the link catchments.

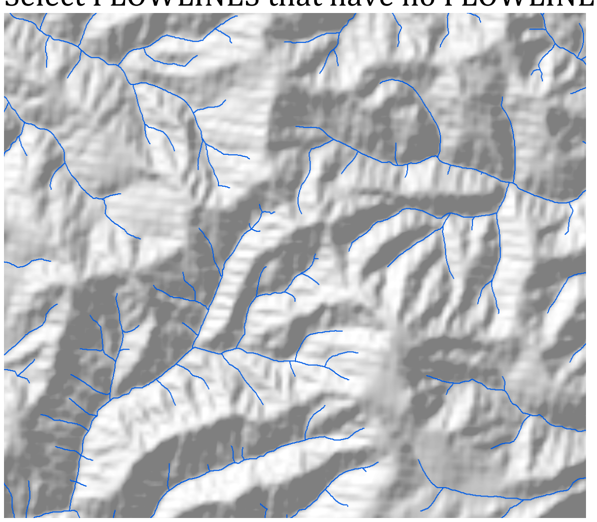
I. BASE

Processing

1. Acquired NHD high resolution (1:24,000) dataset from USGS NHD – (downloaded data August 21, 2012), including the following feature classes:
    a. FLOWLINES – streams/rivers and artificial paths (center of polygon rivers and lakes)
    b. AREA – stream/rivers represented by polygons
    c. WATERBODIES
    d. HUC12
2. Projected feature classes to USA_Contingруous_Albers_Equal_Area_Conic
3. Query FLOWLINES to find "natural" feature types and to remove coastlines, and pipelines
    a. FCODE in (33400, 33600, 46000, 46001, 46002, 46003, 46004, 46005, 46006, 46007, 46100, 55800)
    b. Con(InList("h17_strfid",[33400, 46000, 46001, 46002, 46003, 46004, 46005, 46006, 46007, 46100, 55800]), 1)

c. 

4. Query AREA to find “natural” feature types
    a. FTYPE in (431, 460)
5. Query WATERBODIES to find “natural” feature types
    a. FTYPE in (390, 436)
6. “Thin” streamlines by removing “headwater” FLOWLINE segments, which can potentially cross HUC12.
    a. Select FLOWLINES that have no FLOWLINES into them



7. Generate raster-based representation of FLOWLINES
8. Convert stream polygons (areas) to raster
    a. PolygonToRaster conversion using FCODE at 30 m resolution
9. Convert water bodies (lakes, ponds, reservoirs) over to raster
    a. PolygonToRaster conversion using FCODE at 30 m resolution
10. Create ocean as a variable to help identify stream mouths along the ocean.
    a. Used the NHD coastline data layer
11. Create DEM using USGS NED 30 m resolution raster, integerize to make the file size a bit smaller… note the raw raster with floating point values was used for all slope calculations and flow direction calculations.

Interpretation

These are base data used to generate the remaining products and are standard inputs for watershed analyses.

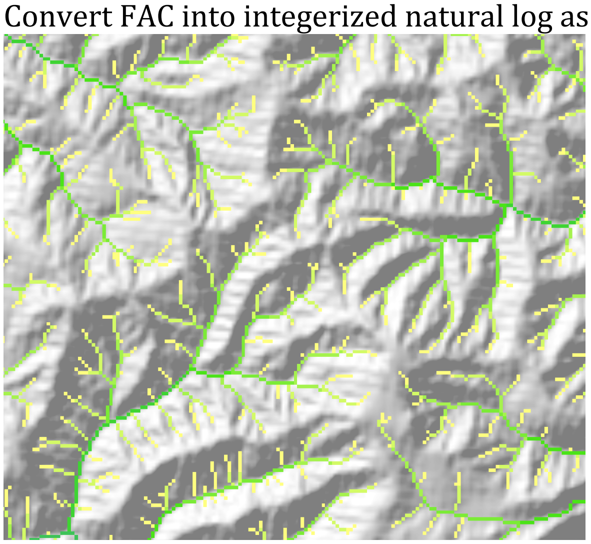
Applications

Not applicable here – as our emphasis in this report is on the derived products rather than these base products, though there are likely to be additional possible uses of them.

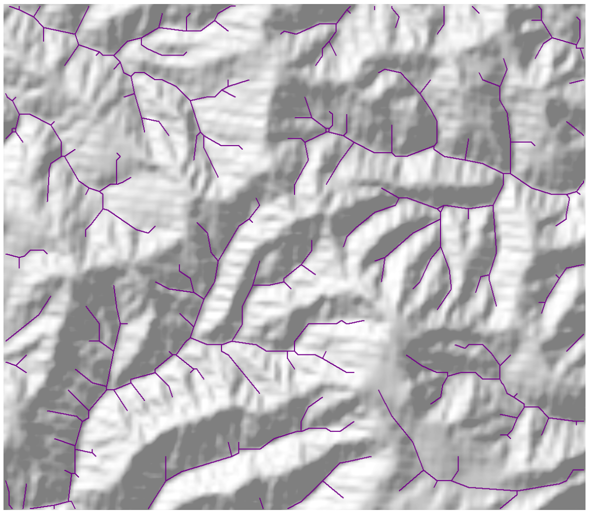
II. FDIRS – Flow direction rasters

Processing

1. Identified stream mouths for stream/ocean intersections as well as for major stream networks that terminate in the arid interior.
2. Created a cost weight raster (W) that consisted of just 90 m stream cells with a value of 1 for cells that occurred in stream "area" (or polygons) and 10 for cells that intersected the NHD thinned flow lines (X). This value was multiplied times the elevation of each cell (DEM), and then raised to the third power. This minimized potential cross-over of watershed boundaries.
   X = 10 if stream area, 1 if flowline
   W = Con (X > 0, Power(((X * DEM / 1000.0) + 1.0), 3))
3. The cost distance was calculated through the weighted stream network (W) from the starting seed locations and the backlink raster saved.
4. Some small errors occurred in the NHD blue lines (small segments missing or included that were not "natural" flowlines), or when "arc'ing" occurred between stream lines of different watersheds due to 90 m cells being adjacent to one another. These errors were removed in an iterative process by manually correcting the W raster by forcing cells in to connect flowlines or by "cutting" cells to ensure no flow between them (usually at ridgelines). Numerous QA/QC methods were used – visual examination of the flow accumulation rasters, creation of headwater cells and identifying gaps in HUC8s that had no headwaters or seeds by multiple analysts, and comparison directly to NHD Plus flow accumulations. Roughly 50 iterations were done to minimize topological errors in this dataset.
5. Calculate the flow accumulation area along the stream lines
6. Convert FAC into integerized natural log as a rough metric of stream size.

7. Apply threshold to accumulated watershed area to identify refined STREAMS
   a. If >5 cells accumulation, then retatined the stream cells – the others are filtered away to remove orthogonal cells along the stream lines (due to "FAT" line conversion) as well as other potential artifacts on the stream lines.
8. Convert raster representation of streams to polylines to generate "final" streams polyline dataset.



Interpretation

The final result of the processing of the flow direction rasters is a polyline vector shapefile that represents streams lines that are consistent with the spatial location of the original NHD flowlines, but also have been thinned so that headwater streams have a consistent upstream watershed area. This removes potential biases in the original “blueline” datasets from NHD that can result from observer differences across 7.5’ quad-sheets, or in areas where there are dramatic differences in vegetation cover that might lead to higher densities of blue-lines being drawn (e.g., clear-cut area has much higher density of blue-lines drawn in the figure above). Because the resulting streams polyline is based on 1:24,000 it is much more consistent and management-relevant, and identifies fine-grained meanders and stream features (especially polygonal or area-based streams and water bodies), especially compared to the products and reports based on NHD “medium” resolution (1:100,000) -- including the WRTA (Theobald et al. 2010) and National Fish Habitat Action Plan. Thus, this is a “hybrid” method that combines the topological and locational information from the blue-lines and complements it with the continuous-surface representation of the “synthetic blue-line” methods.

A known limitation is that because of mis-attributed stream types in the original NHD High resolution dataset, there can be some canals and/or ditches that are not removed when creating the “natural flow” representation. Through a visual QA/QC process, we identified and corrected roughly 200 mis-attributions, though there are likely some additional, though likely minor, errors remaining.

The final stream polyline dataset is appropriate for fine-scale analyses, including HUC 2 down to HUC 12 (and down to roughly 30 m).

Applications

This polyline stream dataset forms the basis for a downstream-flow-connected hydrologic network that forms the basis or “backbone” of the identification of valley bottoms that are foundational for the later identification of climate corridors.

Additional potential uses in the aquatic realm are numerous, including identifying streams that have adequate flow but were not originally mapped on 1:24,000 maps; forming the basis to calculate stream miles (or habitat area) that are unbiased by digitizing artifacts; and more robust measurement of topographic variables, such as stream gradient, because the stream line is forced (or "burned-in") to occur on the blue-line and not allowed to drift off and generate "streaks" that are artifacts of an 8-direction flow algorithm.

III. LINK – stream link or segment scale

Processing

1. Stream order
   a. Acquire the rasterized streams (r17X_rstrms) and flow direction rasters (e.g., r17X_fd1) (from above)
   b. Use the Hydrology tool: Stream Order
   c. Combine the stream order rasters using merge for processing regions a, b, and c to calculate Strahler stream for the entire Columbia watershed.
2. Stream gradient
   a. Find the elevation values of streams
   a. Using USGS NED 30 m elevation data, set the value of all non-stream cells to NODATA.
   b. Calculate the stream gradient
   c. Use SLOPE with percent rise option. This computes slope on 3x3 moving window, but only for the stream cells.
   d. Compute the average slope for each stream link (confluence to confluence segment)
   e. Calculate the average of the link and 90 m (3x3) local slope (r17a_strgrad)
   f. Reclassify the gradient into gradient classes (see below).
3. Link catchment area
   a. Acquire refined streams and flow direction rasters (from above)
   b. Use STREAM LINK to generate unique values for each confluence to confluence raster
   c. Use WATERSHED command to generate high resolution dataset - NOTES
4. Mouth to head water profiles
   a. Calculate the stream length from the headwaters down to the mouths using the r17X_fd1 raster and the FLOW LENGTH tool.
   b. Headwater locations are where the stream length value is equal to 0.
   c. Also see script rF_CreateMouth2HeadwaterRegions20130509.py.

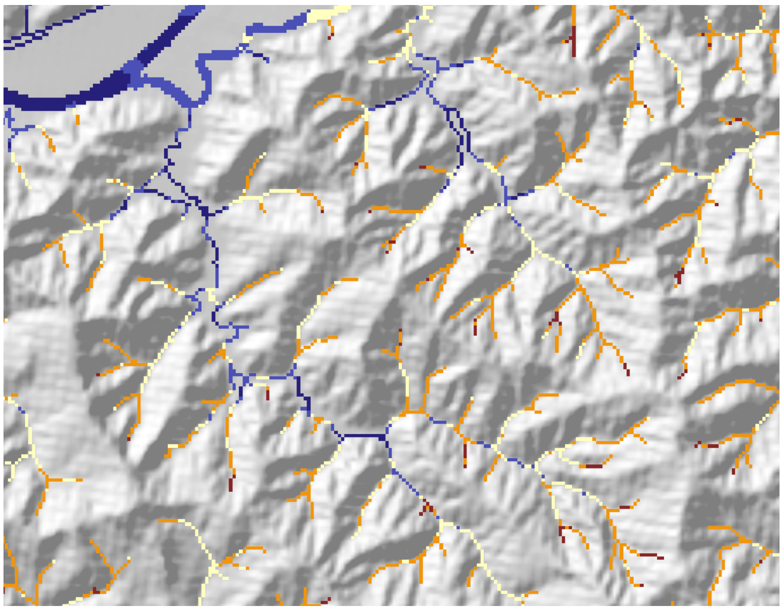
Interpretation

Strahler stream order is often used as an indication of upstream area. Because this measure is sensitive to the definition of what a stream is, it depends on the scale as well as the source. Because we calculated stream order on the refined streams lines from NHD High resolution, we believe these will be robust and consistent across the full study area (Region 17). Stream order values can often be inflated if the algorithm gets caught in a loop (e.g., NHD stream order), but the stream order presented here should be robust to braided stream channels breaks in topology.

Gradient classes are based on Montgomery and Buffington 1993 and 1997.

Slope	Colluvial	Alluvial					Bedrock
		Dune-ripple	Pool-riffle	Plane-bed	Step-pool	Cascade	
<1%			X				

1-2%		X	.	.			
2-4%				X	.		
4-8%					X	.	
8-20%						X	
>20%	X					.	



Application

Potential applications for this dataset include:

1. Development of strata that can be used to sample stream networks or to focus corridor modeling in;
2. Summarize climate corridor results or other network-based analysis to investigate whether there are stream orders that are at less risk to climate change;
3. Weight a prioritization algorithm to influence acquisition decisions towards a given suite of stream orders to target certain types of riverine ecosystems aquatic habitat.

These feature classes may be used for identifying potential climate corridors, by providing their starting and ending locations.

IV. Network-based Attributes

Processing

1. Calculate the mean accumulated elevation
    a. Acquire flow direction rasters from above (r17_fd1)
    b. Rescale elevation by dividing by 1000.0 (units are then m/1000.0) to minimize "blow-out" of numerical values when weighting flow accumulation by elevation (r17_dem_d1k, etc.)
    c. Calculate elevation-weighted flow accumulation (r17_fac_e)
    d. Divide by flow accumulated number of cells and scale back to meters (r17_ac_elev, etc.)
2. Calculate the watershed area (often called flow accumulation, fac) above all locations
    a. Use the flow direction rasters from FDIR (r17_fd1).
    b. Calculate flow accumulation
3. Calculate the natural-log transformed values for streams (using r17_rstrm).
    a. Calculate Int(Ln(r17_fac1))
4. Calculate the mean upland watershed slope
    a. Get the flow direction raster from above
    b. Rescale the percent slope rasters for the sub-regions so that the maximum value is 200 (90 degrees). This will minimize issues with steep long slopes that can have very large values.
    c. Calculate slope-weighted flow accumulation
    d. Divide the accumulate slope raster by flow accumulated number of cells
5. Calculate the degree of flow regulation along the longitudinal dimension of streams.

Interpretation

The watershed area is a continuous value along the stream lines, units are in number of 90 m cells. Low values occur at stream headwaters (>134 cells), and the mouth of big rivers have the highest values. The patterns seen in the natural-log-transformed dataset are similar to the Strahler stream order (because abrupt increases in the accumulated area occur at a junction), but the total values are related to total watershed area, not to some topological aspect. Mean upland watershed slope raster represents the average percent slope that flows into a given cell based on hydrological processes.

This raster represents the average elevation that is hydrologically connected to a given cell from the headwaters to river outlet. This is useful in determining stream reaches that are dominated by a climatic regime (i.e. snowmelt vs. rain-driven) or elevation based system. Applications of the mean upland elevation raster include:

1. Identifying snow melt-influenced hydrologic systems
2. Providing insight into which climate corridors may be buffered from the effects of climate change
3. Modeling potential fish habitat ranges based on elevation or perceived water temperature breaks.

4. As a weight in a prioritization algorithm that provides a greater watershed area context as each unit of analysis.
5. As a covariate within a statistical model.

Application

This provides a continuous watershed that could be used to weight movement potential within valley bottom areas. Like stream order, it could be used as a way to summarize corridor results. This measure provides additional information beyond Strahler stream order and is typically more robust – because stream order can pick up on tributaries that add significant catchment area but that do not change the overall stream order.
Other potential uses are examining the ratio of tributary to mainstem upstream area.
For the climate corridor work, this could be a weight that provides a greater upstream context, especially if it differs from the local reach or valley bottom slope. It provides a metric that explains the greater context of the watershed and could be combined with mean upland elevation and other accumulated averages to approximate flow regimes

IV. Valley-bottoms

Processing

1. Acquire NHD high resolution dataset
2. Calculate the lateral condition for valley bottoms
    a. Acquire the valley bottom location raster and the Landscape Condition raster, prepared by NatureServe for the Western Governor's Association.
    b. For all locations within wetted width, active channel width, and riparian areas, find the landscape condition value that measures the degree of human disturbance (0 is low modification, 100 is high modification).
    c. For all locations within the active channel width and riparian areas, find the landscape condition value which measures the degree of human disturbance (0 is low modification, 100 is high modification, as above, but this measure does not include the wetted width)
3. For large rivers (defined practically by those that are represented by area-based polygons)
    a. calculate the cost-distance away from area-based rivers using slope raised to the second power as a weight.
    b. Calculate the average cost-distance away that matches the break in the hydric soil/terrace from the SSURGO datasets for 30 randomly selected HUC 8s, and round to make more general based on visual inspection: 1 is water, 2= 1-50, 3= 51-400, 4= 401-600.
    c. Find "flat" streams (those that are represented as flow lines, not area polygons) in areas that have stream gradient less than 4%. Grow cost-distance using slope^2 as well, where 3 = 1-100.
4. Calculate degree of flow regulation using NID 2009 and National Anthropogenic Barrier Database 2012.

a. Acquire RUSLE raster (present scenario) from the Assessment of threats to riparian ecosystems in the western U.S. analysis (need to add citation).
b. Extract RUSLE values for the thinned NHD 24k raster (H17_strf1) using a conditional statement.

Interpretation

This raster provides an estimate of average annual sediment yields based on current climate land cover to NHD Plus stream reaches. This was accomplished by associating a NHD 24k stream reach with a NHD 100k valley bottom and assigning a RUSLE estimated value. Note that in-stream dynamics on sediment yield and movement are not taken into account – rather overland flow of debris is modeled, until it intersects with a 1:24,000 stream line.

Literature cited

Montgomery, D. R., and J.M. Buffington. 1993. Channel Classification, Prediction of Channel Response, and Assessment of Channel Condition, Washington Dept. of Natural Resources Report TFW-SH10-93-002, Olympia, WA. 86p

National Hydrography Datset Plus (NHDPlus). 2012. http://www.horizon-systems.com/nhdplus/

Reeves, G.H., J.E. Williams, K.M. Burnett, and K. Gallo. 2006. The Aquatic Conservation Strategy of the Northwest Forest Plan. *Conservation Biology* 20:319-329.

Theobald, DM, J. Norman, D. Merritt. 2010. Western riparian threats assessment. URL: http://www.fs.fed.us/wwetac/projects/theobald.html.

USGS National Elevation Dataset 2013. http://ned.usgs.gov/

USGS National Anthropogenic Barrier Dataset. 2012. https://nccwsc.usgs.gov/display-project/51014e04e4b033b1feeb2c26/512cf142e4b0855fde669828.

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

Meade Krosby[1], Robert Norheim[1], David Theobald[2], and Brad McRae[3]

[1]Climate Impacts Group, University of Washington, Box 355674, Seattle, WA 98195-5674
[2]Conservation Science Partners, Fort Collins, CO 80524
[3]The Nature Conservancy, 1917 1st Ave, Seattle, WA, 98101

Version: 30 April 2014

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 the focus of numerous large-scale climate adaptation initiatives (e.g., U.S. Department of Interior's Landscape Conservation Cooperatives), and is a primary strategy in 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 also feature micro-climates that are significantly cooler and more humid than immediately surrounding areas (Olsen et al. 2007), and thus are also expected to provide micro-climatic refugia from climate change (Seavy et al. 2009). Despite recognition of these values, rigorous methods to identify which riparian areas are most likely to facilitate range shifts and provide refugia are currently lacking.

Only a few analytical approaches have been proposed to identify riparian corridors intended to facilitate climate-induced range shifts. A land facet corridor analysis 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 ocean to highest 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 would strongly influence the ability of riparian areas to facilitate range shifts and provide micro-climatic refugia.

To address the need for a rigorous approach to identify riparian climate-corridors, we completed a novel, fine-resolution (90m) analysis across the Pacific Northwest, USA, that identifies potential riparian areas (i.e., near-stream valley bottoms) likely to promote biological resilience to climate change by facilitating range shifts and providing climatic refugia. We identified those potential riparian areas that span large temperature gradients, have high levels of canopy cover, low solar insolation, low levels of human modification, and are relatively wide – characteristics that are expected to enhance their ability to accommodate climate-driven range shifts and provide micro-climatic refugia from warming. The results of our analysis provide valuable information for guiding on-the-ground conservation efforts aimed at increasing biological resilience to climate change.

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.

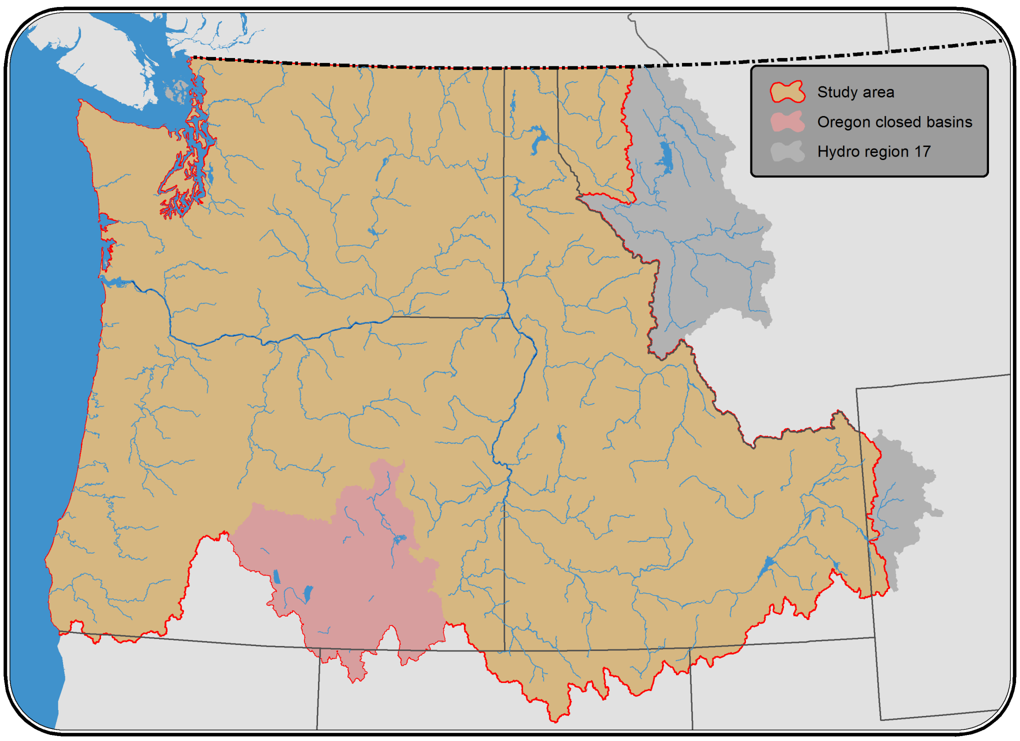


Figure 1. Study Area. The analysis area (outlined in red) spanned the Pacific Northwest hydrologic region, excluding portions of Wyoming and Montana (dark gray).

ii. Model Inputs

We analyzed potential riparian areas identified by Theobald et al. (2013) using a hydrological and geomorphological approach. This fine-resolution (30m) potential riparian data layer provides a comprehensive and consistent estimate of potential riparian areas, avoids many of the data gaps and inconsistencies associated with existing maps of riparian vegetation, and also provides key additional data layers (e.g., flow direction) required by our analysis.

Our analysis aims 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):

1. Mean Annual Temperature
2. Canopy Cover
3. Potential Relative Radiation
4. Landscape Condition
5. Riparian Area

Table 1. Model parameters and 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/) Wang et al. (2012) (http://climatewna.com/)
Canopy Cover (CC)	NLCD Percent Canopy Cover 2006	National Land Cover Dataset (Homer et al. 2007)
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)
Riparian Area (RA)	Potential Riparian Area	Theobald et al. (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 digital elevation model from the National Elevation Dataset to calculate potential relative radiation (PRR), a unitless 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). Using these tools provided a powerful means of addressing several technical challenges associated with measuring the climate adaptation potential of riparian areas. First, the FlowAccumulation tool allowed us to identify all the potential riparian area 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 the stream line, so that each stream line cell was attributed with the sum of the parameter values for potential riparian cells that drain into it (Fig. 2a). RA was also accumulated to the streamline in the same manner. We then divided each accumulated parameter value by the accumulated RA, so that each streamline cell was ultimately attributed with the average of the parameter values within its contributing potential riparian area. 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.

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

The FlowLength tool was then used to accumulate average parameter values along the streamlines associated with potential riparian areas, for each of four parameters (PRR, LC, CC, and RA) (Fig. 2b). These four FlowLength values were then extracted to each headwater. MAT was also extracted at each stream outlet (or sink, for closed basins that do not drain to the ocean) and headwater, and the difference between the two calculated.

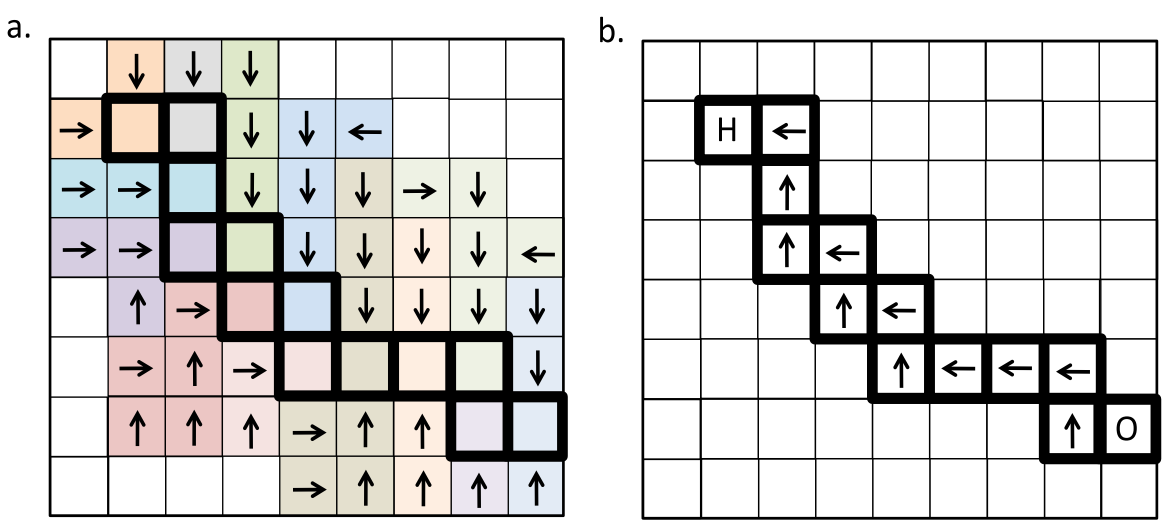


Figure 2. Use of FlowAccumulation and FlowLength Tools. (a) FlowAccumulation laterally accumulates parameter values across potential riparian areas into streamline cells (in bold), so that each streamline cell is attributed with the sum of the parameter values for potential riparian cells that drain into it. (b) FlowLength is used to accumulate parameter values along the streamlines associated with potential riparian areas, from the outlet (O) to the headwater (H), to which the FlowLength value is extracted.

3. Calculate riparian climate-corridor quality 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 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, and lowest level of human modification. Where ΔMAT is 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

We accounted for sensitivity to the scale of analysis in the following ways:

First, we calculated index values following the above procedure for riparian stretches within 1st, 2nd, 3rd, 4th, 5th, and 6th field HUCs (watersheds), resulting in 6 index values for each headwater. We then scaled each of these index values to the range [0:1] and averaged them, so that each headwater was ultimately attributed with a final index reflecting scales ranging from local watersheds to the entire Pacific Northwest hydrologic region. High index values thus indicated relatively high quality of riparian climate corridors at a range of scales, from the coast to the highest elevations of riparian associated with a given streamline.

Second, we calculated the average index value for all stretches of potential riparian area within a given HUC polygon, to allow evaluation of riparian climate-corridor quality at the watershed scale (rather than the scale of individual outlet-to-headwater stretches of potential riparian).

Finally, we binned multi-scale index values into 5 equal-area quantiles within each ecoregion, to account for high variance in index scores across ecoregions, and to allow for easy identification of the highest quality riparian corridors within each ecoregion.

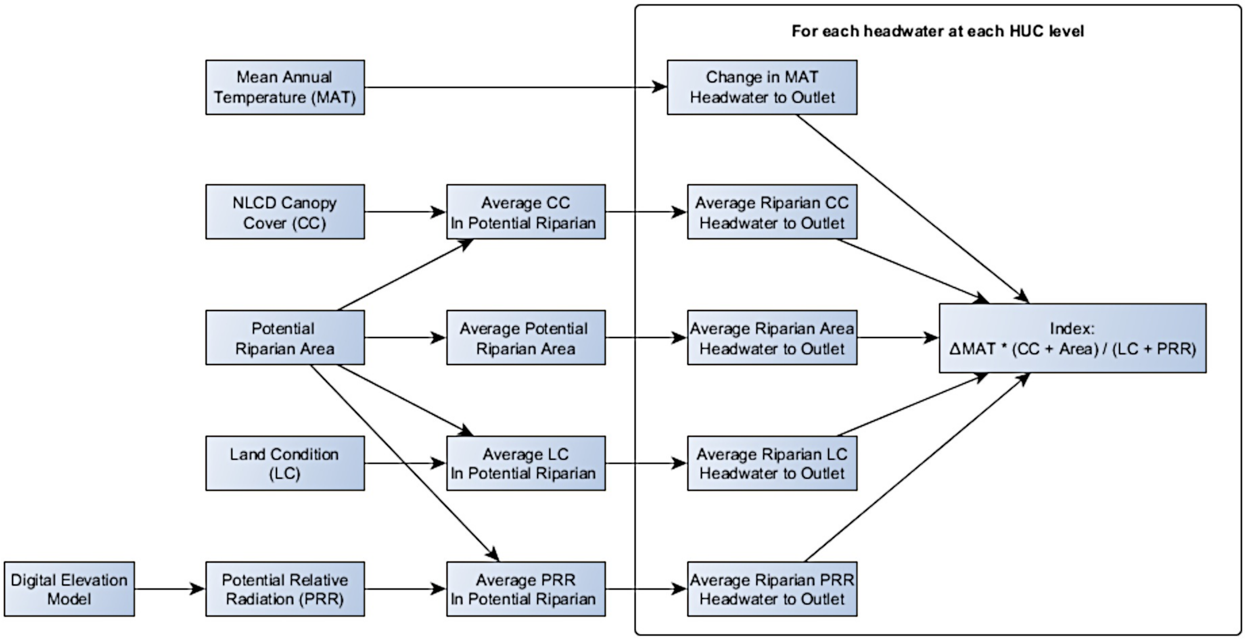


Figure 3. Summary of Modeling Approach.

Results

We found that the climate adaptation potential of riparian corridors varies considerably across the Pacific Northwest (Fig. 4). Highest index values were found in mountainous areas (e.g., the Cascade Range), while 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). Removing ΔMAT from the index calculation indeed resulted in a similar pattern to calculation that included ΔMAT; including 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) (Fig. 6).

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 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).

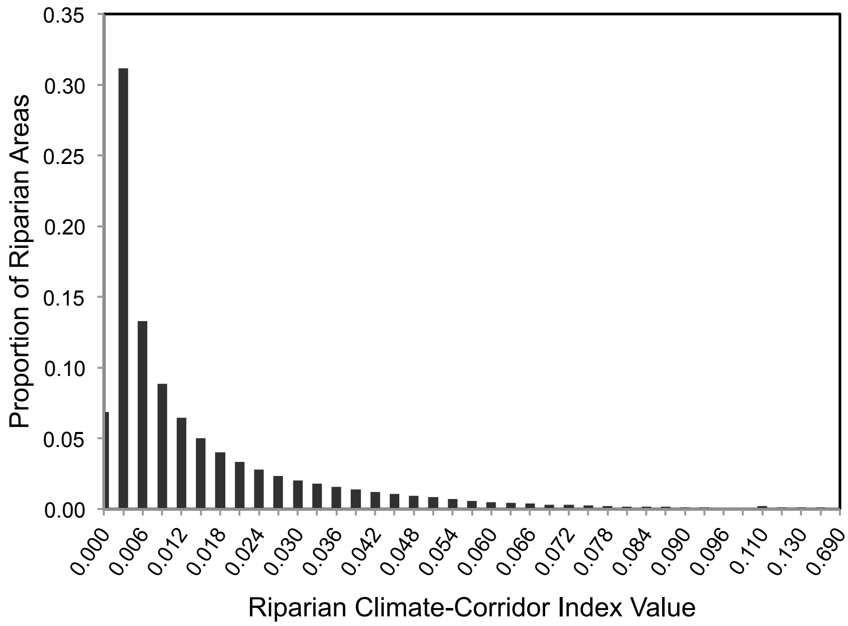


Figure 4. Distribution of Riparian Climate-Corridor Index Values. Shown for all outlet-to-headwater stretches of potential riparian area.

Discussion

Our analysis effectively 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 good condition – had the highest riparian climate-corridor index values, while lowland areas – which tend to be flat, deforested, exposed to solar radiation, and modified by human activities – had the lowest values. The exception to this was riparian width, which tended to be greater in flatter, lower elevation areas and narrower in steeper, higher elevation areas.

For this reason, we also identified the highest scoring riparian areas within each ecoregion (Fig. 8), as it is within flat, highly-converted landscapes that species might benefit most from the riparian climate-corridors identified by our analysis. This allowed us to better discriminate climate-corridor index scores within non-mountainous regions such as the Columbia Plateau ecoregion, which received the lowest scores in the full Pacific Northwest analysis (Fig. 5). High-scoring riparian stretches in areas such as the Columbia Plateau and Puget Lowlands should be considered immediate priorities for conservation action, as they provide some of the best opportunities for species to traverse and find refugia within otherwise inhospitable landscapes.

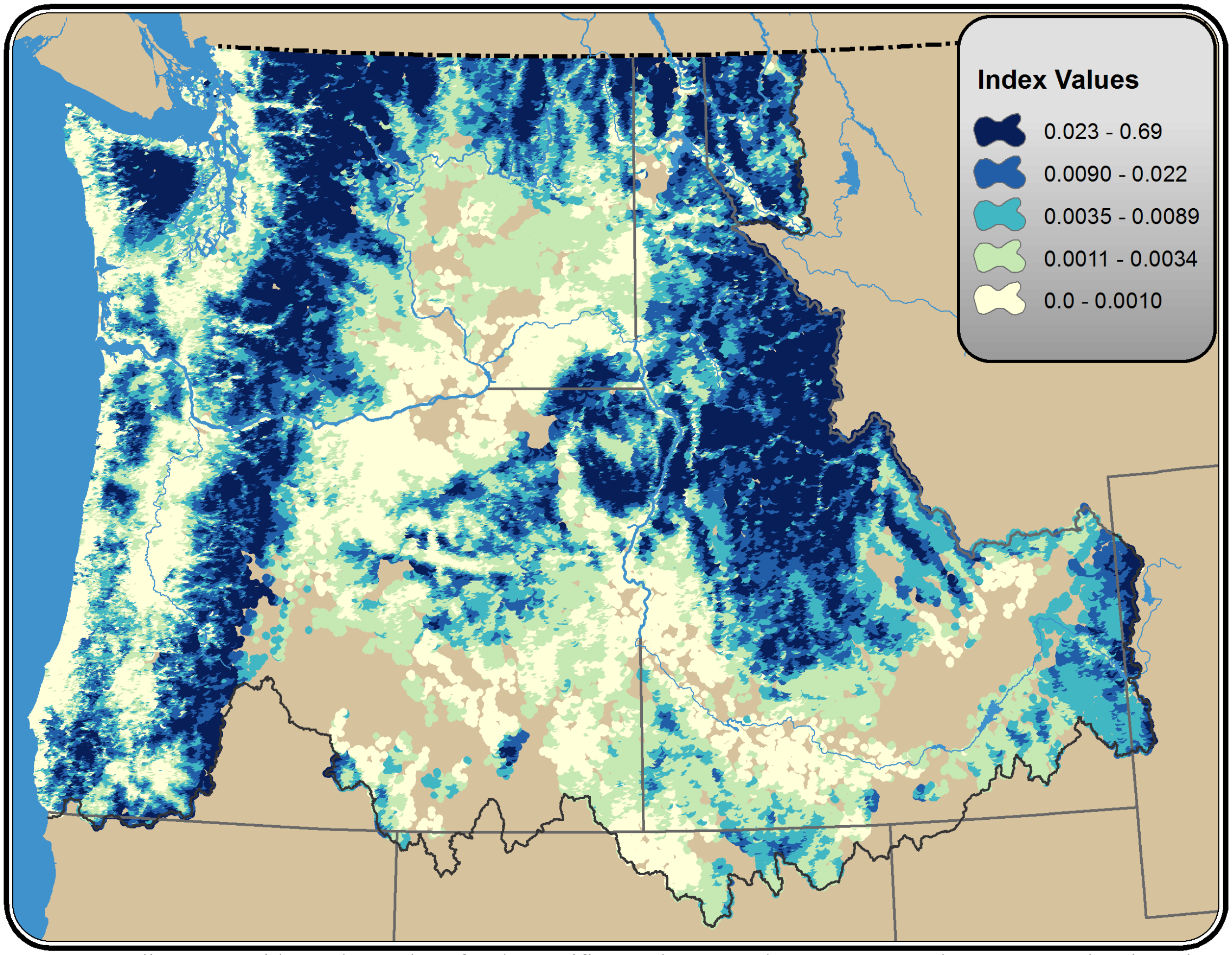


Figure 5. Climate-Corridor Index Values for the Pacific Northwest. Values are averaged across HUC levels and attributed to the headwater of streams associated with outlet-to-headwater stretches of potential riparian area.

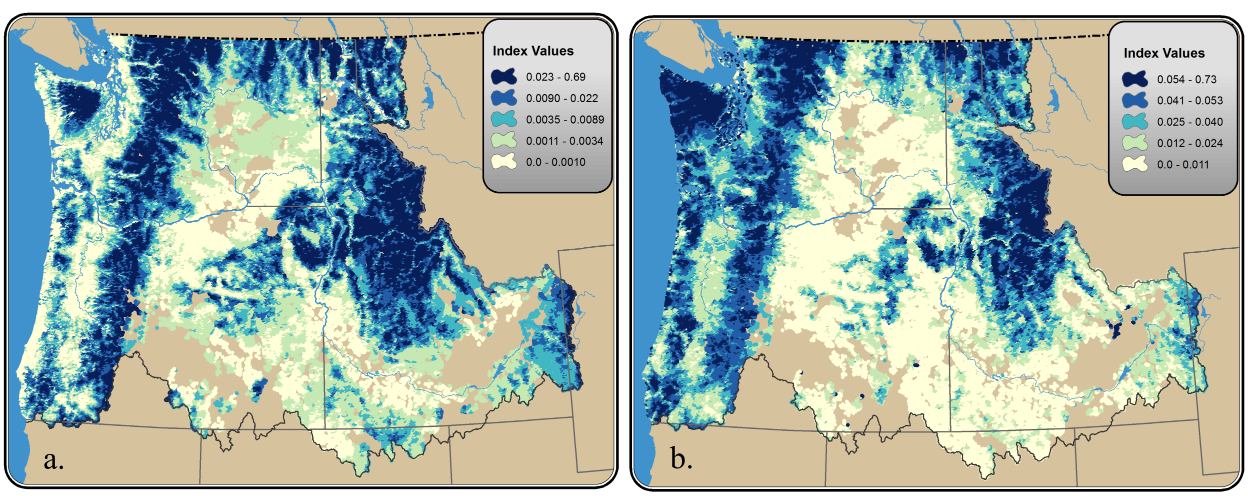


Figure 6. Effect of ΔMAT on Index Values. Index values in the map on the left (Fig. 5a) were calculated with ΔMAT included in the index formula, whereas values in the map on the right (Fig. 5b) were calculated without ΔMAT in the formula. Values are averaged across watershed (i.e., HUC) levels and attributed to the headwater of streams associated with outlet-to-headwater stretches of potential riparian area.

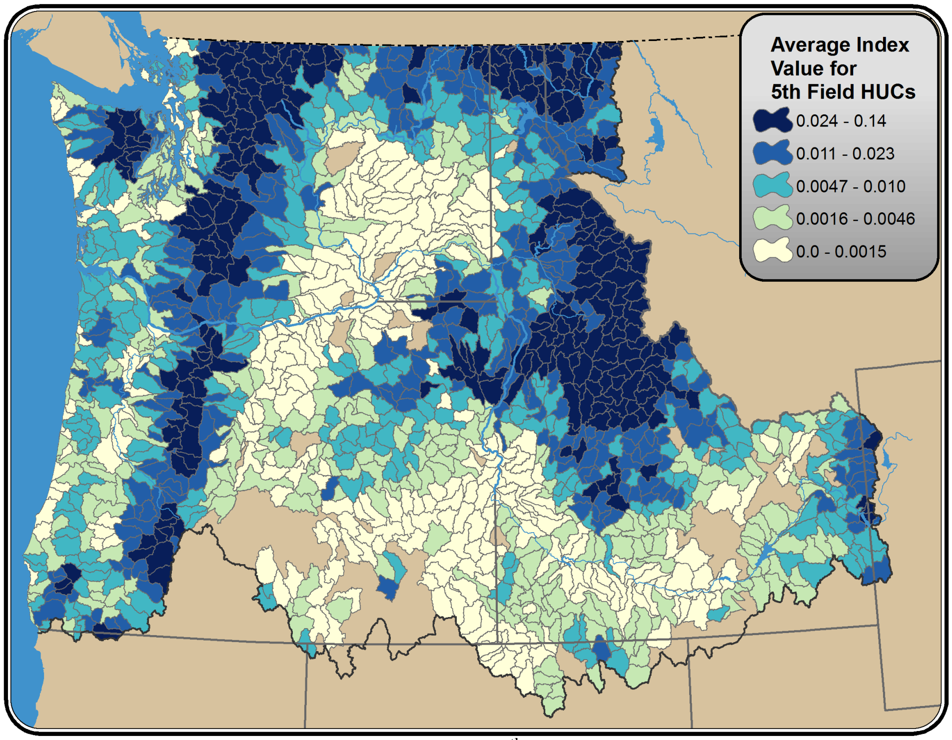


Figure 7. Climate-Corridor Index Values Averaged Across 5th Field HUCs. Index values are averaged for every outlet-to-headwater stretch of potential riparian within each 5th Field HUC.

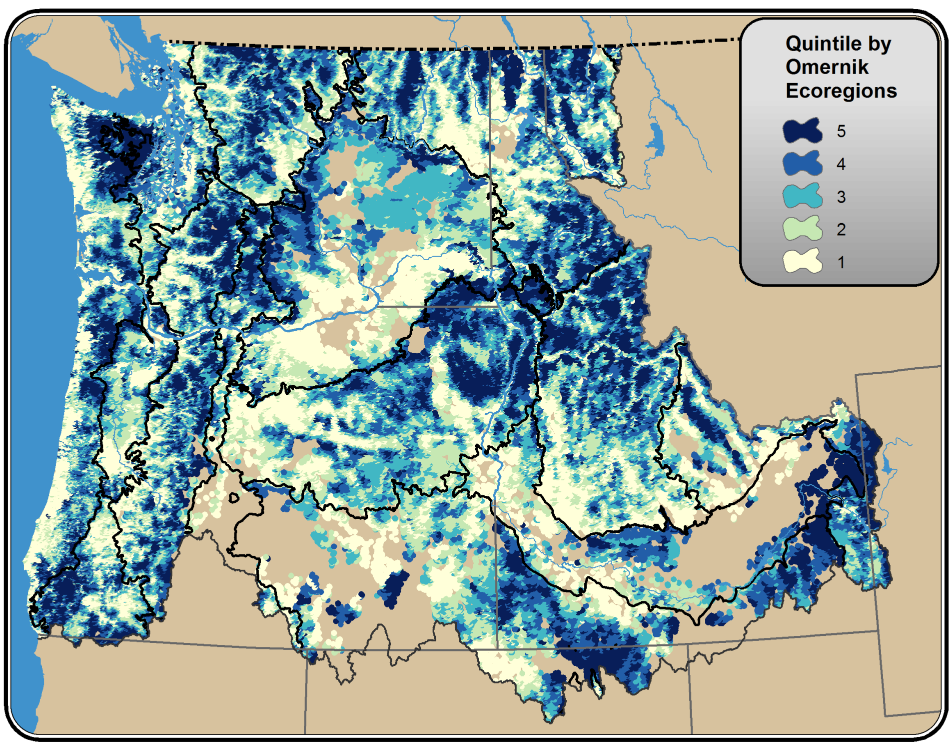


Figure 8. Climate-Corridor Index Values By Ecoregion. Index values are attributed to headwaters of outlet-to-headwater stretches of potential riparian area. Highest index values for each ecoregion are shown in dark blue, lowest values are shown in beige.

However, there are several limitations associated with our analysis. First, averaging parameter values across riparian stretches provides only a coarse estimate of their quality, particularly at larger scales. Our approach also only implicitly accounts for connectivity along riparian stretches by averaging across watershed scales. It therefore does not reflect the full impact likely to be presented by local barriers and bottlenecks (e.g., cities, gorges, cliffs) that would interfere with directional range movements along a given riparian stretch, as local impacts may not result in low overall scores. Our results are thus coarse and preliminary, and would benefit from additional sensitivity testing and model validation to better gauge its accuracy. We therefore encourage using these products as an initial means of identifying riparian areas deserving further, on-the-ground investigation for potential conservation action.

We employed a coarse-filter approach using current conditions to minimize uncertainty associated with bioclimatic-modeling approaches to identifying climate-resilient areas, and to maximize the diversity of species likely to benefit from the areas identified. Riparian areas may offer especially effective umbrella habitats for climate change adaptation due to their high levels of biodiversity, their use as corridors by upland species, and their importance to the health of aquatic habitats. Riparian areas already act as movement corridors for diverse taxa (Hilty and Merenlender 2004), including both riparian-dwelling and upland species. They also contain disproportionate levels of biodiversity relative to upland habitats (Naiman et al. 1993). Riparian areas also often contain some of the last natural vegetation in heavily modified landscapes, thus offering rare opportunities for movement across human-dominated areas. Riparian areas identified by our analysis should also be expected to confer benefits to aquatic organisms as climates change.

At the same time, riparian areas are among the most threatened habitats in many regions (Jones et al. 2010), and may be vulnerable to climatic stressors (Capon et al. 2013). Efforts to identify 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, will thus be key to informing regional riparian management and climate adaptation efforts.

Acknowledgements

This work was generously supported by grants from Washington Department of Fish & Wildlife, Idaho Department of Fish & Game, Great Northern Landscape Conservation Cooperative, North Pacific Landscape Conservation Cooperative, and Wilburforce Foundation.

References

Brost, B.M., and P. Beier. 2012. Use of land facets to design linkages for climate change. *Ecological Applications* **22**:87–103.

Capon, S.J., Chambers, L.E., Mac Nally, R., Naiman, R.J., Davies, P., Marshall, M., Pittock, J., Reid, M., Capon, T., Douglas, M., Catford, J., Baldwin, D.S., Stewardson, M., Roberts, J., Parsons, M., and S. E. Williams. 2013. Riparian Ecosystems in the 21st Century: Hotspots for Climate Change Adaptation? *Ecosystems* **16**:359-381.

Comer, P. J. and J. Hak. 2012. Landscape Condition in the Conterminous United States. Spatial Model Summary. NatureServe, Boulder, CO.

Daly. C., Gibson. W.P., Taylor, G.H., Johnson, G.L., and P. Pasteris. 2002. A knowledge-based approach to the statistical mapping of climate. *Climate Research* **22**:99-113.

ESRI 2013. ArcGIS Spatial Analyst: Release 10.2. Redlands, CA: Environmental Systems Research Institute.

Heller, N. E., and E. S. Zavaleta. 2009. Biodiversity management in the face of climate change: A review of 22 years of recommendations. *Biological Conservation* **142**:14-32.

Hilty, J.A., and A.M. Merenlender. 2004. Use of riparian corridors and vineyards by mammalian predators in northern California. *Conservation Biology* **18**:126-135.

Homer, C., Dewitz, J., Fry, J., Coan, M., Hossain, N., Larson, C., Herold, N., McKerrow, A., VanDriel, J.N., and J. Wickham. 2007. Completion of the 2001 National Land Cover Database for the Conterminous United States. *Photogrammetric Engineering and Remote Sensing* **73**:337-341.

Jones, K. B., Slonecker, E. T., Nash, M. S., Neale, A. C., Wade, T. G., and S. Hamann. 2010. Riparian habitat changes across the continental United States (1972–2003) and potential implications for sustaining ecosystem services. *Landscape Ecology* **25**:1261-1275.

Klausmeyer, K. R., Shaw, M. R., MacKenzie, J. B., and D.R. Cameron. 2011. Landscape-scale indicators of biodiversity's vulnerability to climate change. *Ecosphere* **2**:art88.

Lawler, J.J. 2009. Climate change adaptation strategies for resource management and conservation planning. *Annals of the New York Academy of Sciences* **1162**:79-98.

Naiman, R.J., Decamps, H., and M. Pollock. 1993. The role of riparian corridors in maintaining regional biodiversity. *Ecological Applications* **3**:209-212.

NPS. 2010. *National Park Service Climate Change Response Strategy*. National Park Service Climate Change Response Program, Fort Collins, Colorado.

Olson, D. H., Anderson, P. D., Frissell, C. A., Welsh Jr, H. H., and D. F. Bradford. 2007. Biodiversity management approaches for stream–riparian areas: Perspectives for Pacific Northwest headwater forests, microclimates, and amphibians. *Forest Ecology and management* **246**:81-107.

Pierce Jr., K. B., Lookingbill, T., and D. Urban. 2005. A simple method for estimating potential relative radiation (PRR) for landscape-scale vegetation analysis. *Landscape Ecology* **20**(2):137-147.

Rouget, M., Cowling, R. M., Pressey, R.L., and D.M. Richardson. 2003. Identifying spatial components of ecological and evolutionary processes for regional conservation planning in the Cape Floristic Region, South Africa. *Diversity and Distributions* **9**:191-210.

Sabo, J.L., Sponseller, R., Dixon, M., Gade, K., Harms, T., Heffernan, J., Jani, A., Katz, G., Soykan, C., Watts, J., and J. Welter. 2005. Riparian zones increase regional species richness by harboring different, not more, species. *Ecology* **86**:56–62.

Seavy, N.E., Gardali, T., Golet, G.H., Griggs, F.T., Howell, C.A., Kelsey, R., Small, S.L., Viers, J.H. and J.F. Weigand. 2009. Why climate change makes riparian restoration more important than ever: recommendations for practice and research. *Ecological Restoration* **27**:330-338.
.

Theobald, D. M., Merritt, D., and J. Norman. 2010. Assessment of Threats to Riparian Ecosystems in the Western U.S.

Theobald, D. M., Mueller, D., and J. Norman. 2013. Detailed datasets on riparian and valley-bottom attributes and condition for the Great Northern and Northern Pacific LCC (WRR17).

Thomas, C.D., Cameron, A., Green, R.E., Bakkenes, M., Beaumont, L.J., Collingham, Y.C., Erasmus, B.F.N., et al. 2004. Extinction risk from climate change. *Nature* **427**:145-148.

Wang, T., Hamann, A., Spittlehouse, D., and T.N. Murdock. 2012. ClimateWNA - High-Resolution Spatial Climate Data for Western North America. *Journal of Applied Meteorology and Climatology* **51**:16-29.

USFS. 2011. *National roadmap for responding to climate change*. Report FS-957b. Washington, DC. http://www.fs.fed.us/climatechange/roadmap.shtml

USFWS. 2010. *Rising to the Urgent Challenge: Strategic Plan for Responding to Accelerating Climate Change*. http://www.fws.gov/home/climatechange/strategy.html

Appendix I. Parameter Base Layers

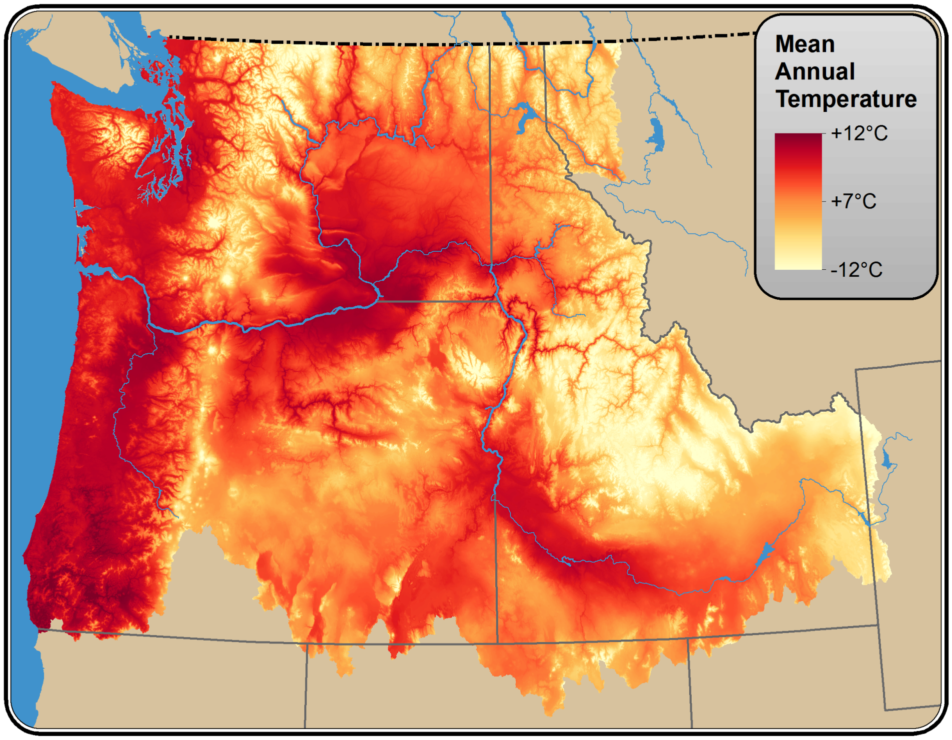


Figure A1. Mean Annual Temperature.

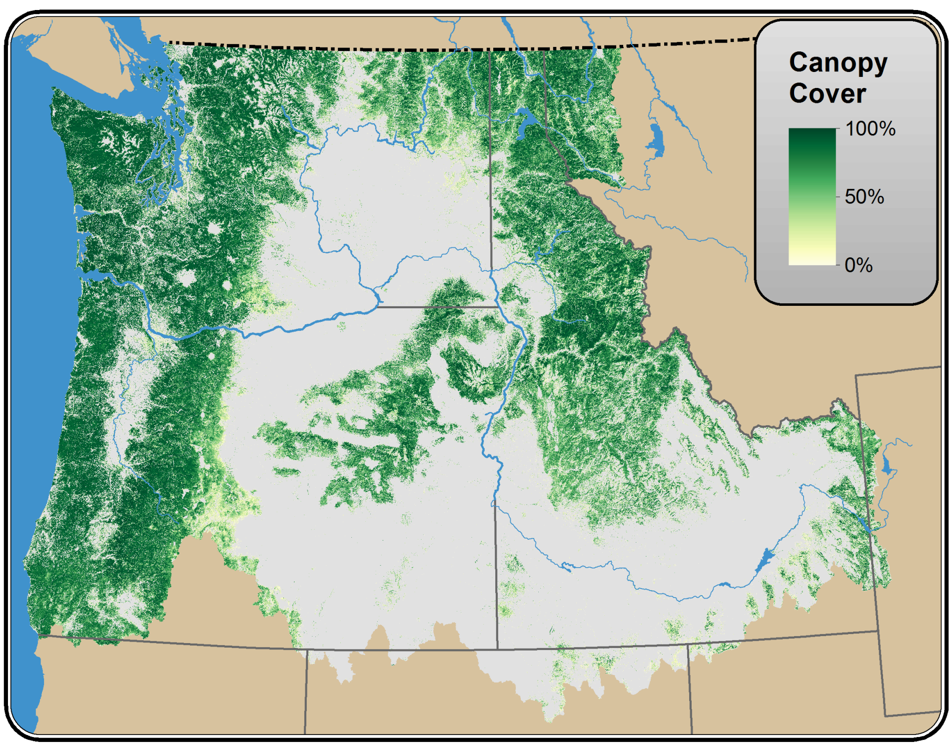


Figure A2. Canopy Cover.

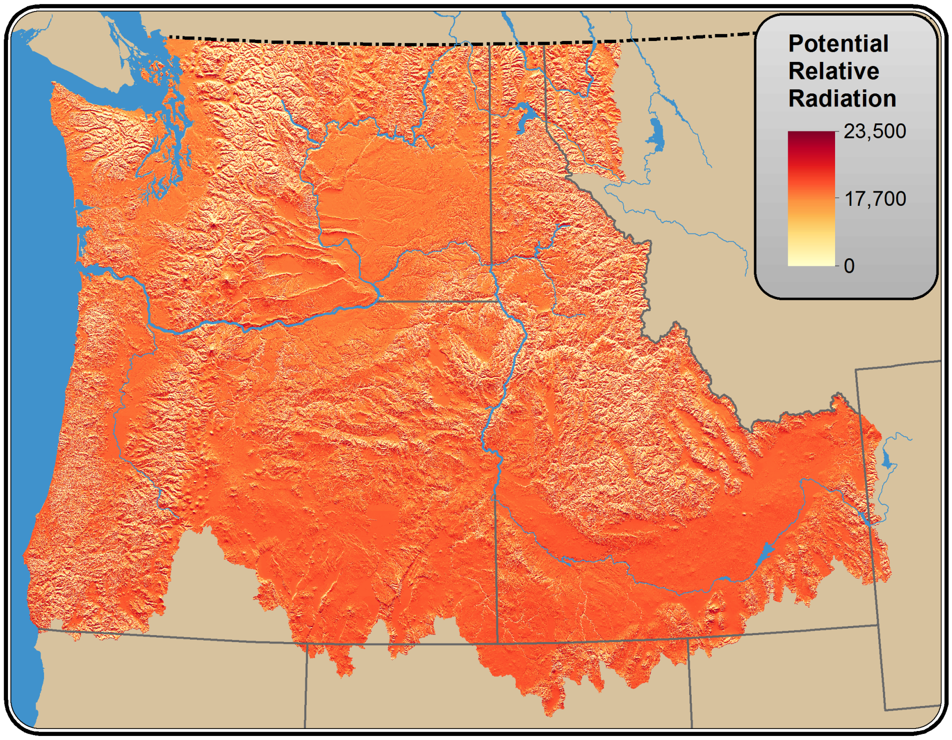


Figure A3. Potential Relative Radiation.

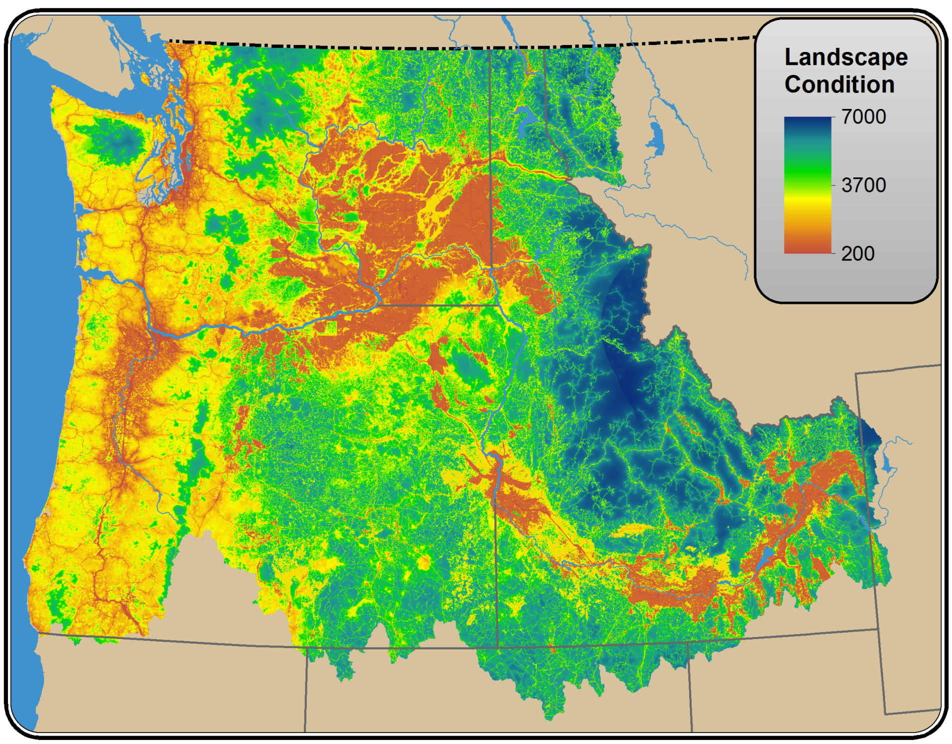


Figure A4. Landscape Condition.