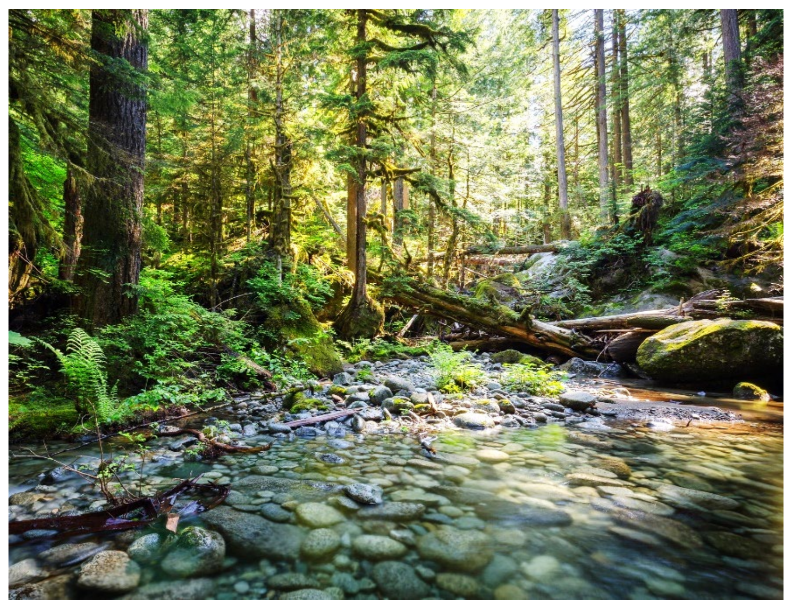
A guidebook to spatial datasets for conservation planning under climate change in the Pacific Northwest



NORTHWEST Climate Adaptation Science Center

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Cover photos (clockwise from upper left): (a) 2016 Pioneer Fire in Boise National Forest, Idaho, by Kari Greer, USDA Forest Service; (b) "A mountain lake way up high," Cascade Mountains, by Glenna Barlow, CC BY 2.0; (c) "Primordial," stream at Deception Falls, Washington, by John Westrock, CC BY 2.0; (d) Sagebrush steppe in Seedskadee National Wildlife Refuge, southwest Wyoming, by Tom Koerner, U.S. Fish and Wildlife Service

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Executive summary

This guidebook provides user-friendly overviews of a variety of spatial datasets relevant to conservation and management of natural resources in the face of climate change in the Pacific Northwest, United States. Each guidebook chapter was created using a standardized template to summarize a spatial dataset or a group of closely related datasets. Datasets were selected according to standardized criteria based on input through a collaborative process involving researchers and natural-resource managers throughout the Pacific Northwest region. In each chapter, basic spatial and temporal information is provided for the dataset, along with a conceptual overview, glossary of key terms, links to download data and supporting documentation, a brief methods summary describing how the dataset was created, guidelines for dataset interpretation, assessment of uncertainties along with evaluation of caveats and simplifying assumptions, and information about potential and actual conservation applications of the dataset. Collectively, this information provides natural-resource managers with "snapshots" of a variety of datasets representing diverse processes and conditions, including climate projections, changes in hydrologic conditions, vegetation and fire-regime shifts, animal habitat changes, species movements, and topographic and soil conditions relevant to climate change. Along with other types of data and site-specific information, the datasets described in this guidebook have the potential to inform management of valued natural resources throughout the Pacific Northwest region in the context of adaptation to changing climate conditions.

Common abbreviations

BLM: Bureau of Land Management

CMIP: Climate Model Intercomparison Project

DEM: digital elevation model

GCM: general circulation model

GIS: geospatial information systems

HLI: heat-load index

HUC: hydrologic unit code

NAD: North American Datum

NHD: National Hydrography Dataset

PCA: principal components analysis

RCP: representative concentration pathway

SDM: species-distribution model

SNOTEL: snow telemetry

SRES: Special Report on Emissions Scenarios

SSURGO: Soil survey geographic data

STATSGO: State soils geographic data

SWE: snow-water equivalent

TPI: topographic position index

USDA: United States Department of Agriculture

VIC: variable infiltration capacity

WGS: World Geodetic System

Conversion Factors

Multiply	By	To obtain
millimeter (mm)	0.0394	inch (in.)
centimeter (cm)	0.3937	inch (in.)
meter (m)	3.281	foot (ft)
kilometer (km)	0.6214	mile (mi)
square kilometer (km^2)	247.1	acre
square kilometer (km^2)	0.3861	square mile (mi^2)
cubic feet per second (ft^3/s)	0.0283	cubic meters per second (m^3/s)

Temperature in degrees Celsius (°C) may be converted to degrees Fahrenheit (°F) as follows:

$$°F = (1.8 \times °C) + 32$$

Contents

Introduction

1. Purpose and motivation

Recent advancements in climate modeling, remote sensing, and ecological science have produced a variety of digital geospatial datasets representing many aspects of climate-change ecology. New datasets are published regularly illustrating spatial patterns in climate vulnerability for terrestrial and aquatic ecosystems. Collectively, these datasets represent a wealth of valuable information that can be applied to conservation and natural-resource management in the face of climate change. The ever-increasing body of climate-ecology spatial datasets provides opportunities for natural-resource managers to anticipate climate-driven changes to ecosystems, habitats, and the larger landscape. Consideration of these projected changes may support the long-term effectiveness of management for protected areas, working lands, and other areas managed for biodiversity, recreation, or natural resources.

However, natural-resource managers face many challenges when trying to incorporate these diverse sources of information into on-the-ground decision-making. Managers must commonly juggle multiple priorities with limited resources. Urgent and time-sensitive management needs may leave limited time available to read, digest, and critically assess the technical publications (e.g. journal articles) in which newly published spatial datasets are typically presented. The computer modeling processes and methods that produce spatial datasets are often complex and may require consultation of multiple publications or technical experts to fully evaluate. Furthermore, different datasets that appear to represent similar landscape processes or characteristics may differ in the landscape patterns they depict. Such differences arise in part because different datasets are produced by different research teams with different modeling approaches, input datasets, conceptual definitions, starting assumptions, and model parameters. Furthermore, important information needed for accurate dataset interpretation may require searching through multiple sections of publications (e.g., methods and discussion sections, supplementary materials) and sometimes across multiple publications—some of which may not be readily accessible to natural-resource managers. Such critically important information can include model validation and accuracy statistics, simplifying assumptions, caveats on interpretation, and components of landscape processes that are not fully represented by the dataset. All these considerations can result in both uncertainty and information overload, creating barriers for managers seeking to apply climate-ecology spatial datasets to their decision-making.

The purpose of this guidebook is to present user-friendly overviews for a variety of published spatial datasets relevant to conservation and natural-resource management in the face of climate change for the Pacific Northwest region of the United States. Datasets are summarized and key features are described briefly, allowing readers to select datasets of interest for further investigation and potential application to their work. Ultimately, the goals of this guidebook are to:

(1) support natural-resource managers to discover and examine spatial datasets that might be relevant to their ongoing efforts,

(2) increase the usefulness and usability of climate-ecology spatial datasets for real-world conservation decision-making, and

(3) help bridge the gap between scientific publications and conservation practice.

2. Guidebook organization

This guidebook is divided into chapters, with each chapter summarizing a spatial dataset or a group of closely related datasets produced by the same research team. Each guidebook chapter is subdivided into the following sections: (1) dataset overview, including a map of the dataset and glossary of key terms; (2) data access information including hyperlinks to download datasets and accompanying documentation; (3) basic conceptual information about what the dataset represents; (4) spatial information; (5) temporal information; (6) a methods summary describing how the dataset was produced along with information on input datasets and models used; (7) guidelines for dataset interpretation; (8) evaluation of uncertainties including dataset assumptions, simplifications, and caveats; (9) peer-review information; and (10) information on potential or actual conservation applications. Because the same terms (e.g., “refugia”) were sometimes defined slightly differently by different research teams in the production of datasets, a universal glossary of terms for this guidebook was not possible; instead key terms are defined in a dedicated glossary for each chapter using the definitions most appropriate for the dataset in question. Following the guidebook chapters, appendix 1 provides detailed information on climate models used by datasets in the guidebook, appendix 2 explains greenhouse-gas scenarios used in climate-change projections, and appendix 3 discusses spatial scale considerations for applying spatial datasets to management applications.

Datasets described in the chapters of this guidebook address a wide array of landscape processes relevant to management and conservation. Datasets generally belong to one or more broad categories of information (table 1), including:

Animal habitat: datasets that provide information relevant to management of a particular taxonomic group (such as birds) or type of habitat (such as stream-dwelling animals)

Climate: datasets that rely primarily on climate projections and/or those that represent changing climate conditions such as temperature or precipitation

Fire: datasets that characterize or predict factors that influence wildfires

Hydrology: datasets that represent water-cycle processes and conditions in watersheds (such as snowpack and soil moisture) or in streams

Landscape connectivity: datasets that represent how plants or animals might move across landscapes in response to climate change, including human-made barriers to movement

Stream and riparian: datasets that represent information only for streams or riparian areas

Topoedaphic: datasets that represent topographic and soil conditions that may be relevant to changing climate conditions, for example soil drought vulnerability or the diversity of topographic settings (and hence the diversity of microclimates) across a landscape

Vegetation: datasets that provide information about changing plant communities

3. Dataset selection and guidebook design process

The following criteria were used to guide dataset selection for this guidebook:

(1) Datasets in this guidebook are spatially explicit, i.e. digital maps. This means that datasets can be plotted in geographic space using geospatial information systems (GIS) software.

(2) Because this guidebook focuses on the Pacific Northwest, datasets cover all or most of the states of Oregon, Washington, and Idaho, or they cover a major ecosystem type within that geographic area (e.g., forests or streams).
(3) The landscape processes or characteristics represented by the datasets directly relate to a feature or component of potential climate-change vulnerability for species, ecosystems, or other natural resources. These components include climate-change exposure (the magnitude and rate of climate change), sensitivity (the degree to which the fitness or health of a species, ecosystem, or other resource depends on the prevailing climate), and adaptive capacity (the ability to cope with climate change by persisting in place, shifting to other local habitats, or migrating to regions of more suitable climate). Datasets that do not explicitly address components of climate vulnerability—and thus not included in this guidebook—may still provide important information for management and conservation purposes and can be consulted in conjunction with datasets in this guidebook. Examples include land cover maps and maps of human alteration of the landscape.
(4) The spatial resolution of datasets in this guidebook is sufficiently fine to enable conservation applications at the regional scale or finer for the Pacific Northwest (Oregon, Washington, and Idaho); see appendix 3 for more information on dataset spatial resolution and conservation applications. Most datasets described in this guidebook are in a gridded (raster) format, such that dataset resolution refers to the size of an individual pixel (i.e., grid cell).
(5) All datasets are free of charge to access and use. Most datasets in this guidebook are publicly available for download; the remaining datasets are freely available by contacting the corresponding author listed in the respective chapter.
(6) In planning this guidebook, we considered including datasets that were already published or on-track to be published by April 2019. We considered datasets for inclusion that were published in 2010 or later, with an emphasis on new datasets. The majority of chapters in this guidebook (15 out of 24) represent datasets published in 2017 and 2018, with 22 out of 24 chapters representing datasets published between 2015 and 2018.
(7) To be included in the guidebook, dataset primary authors needed to be willing to assist with writing, editing, and revising their respective chapters.

Table 1. Guidebook chapters by data type category

Data-type category[1]	Guidebook chapters
Animal habitat	Chapter 4: Changes in snowpack and snow residence time Chapter 9: Stream temperature predictions and velocities of the Pacific Northwest Chapter 16: Animal species turnover Chapter 17: Spatial priorities for conserving birds of the Pacific Northwest Chapter 18: Tree and songbird macrorefugia
Climate	Chapter 1: Climate dissimilarity for North America Chapter 2: Multivariate climate velocity Chapter 3: North American climate refugia Chapter 4: Changes in snowpack and snow residence time Chapter 5: Changes in snowpack, soil moisture, and fuel moisture Chapter 6: Forest suitability for large wildfires Chapter 9: Stream temperature predictions and velocities of the Pacific Northwest Chapter 14: Species movement to analog climates Chapter 15: Minimum cumulative exposure and minimum exposure distance Chapter 16: Animal species turnover Chapter 17: Spatial priorities for conserving birds of the Pacific Northwest Chapter 18: Tree and songbird macrorefugia
Fire	Chapter 5: Changes in snowpack, soil moisture, and fuel moisture Chapter 6: Forest suitability for large wildfires Chapter 7: Projected fire regime changes for the western United States Chapter 8: Database of unburned areas within fire perimeters
Hydrology	Chapter 4: Changes in snowpack and snow residence time Chapter 5: Changes in snowpack, soil moisture, and fuel moisture Chapter 9: Stream temperature predictions and velocities of the Pacific Northwest Chapter 10: Streamflow metric projections Chapter 11: Probability of Streamflow Permanence (PROSPER)
Landscape connectivity	Chapter 12: Riparian climate corridors Chapter 13: Terrestrial permeability of the Pacific Northwest Chapter 14: Species movement to analog climates Chapter 15: Minimum cumulative exposure and minimum exposure distance
Stream and riparian	Chapter 9: Stream temperature predictions and velocities of the Pacific Northwest Chapter 11: Probability of Streamflow Permanence (PROSPER) Chapter 12: Riparian climate corridors
Topoedaphic	Chapter 19: Environmental diversity datasets for North America Chapter 20: Landforms and physiographic diversity of the United States Chapter 21: Topoclimate diversity of the Pacific Northwest Chapter 22: Soil sensitivity index for western Washington, Oregon, and California Chapter 23: Soil drought probability for Pacific Northwest forests Chapter 24: Sagebrush ecosystem resistance and resilience
Vegetation	Chapter 7: Projected fire regime changes for the western United States Chapter 18: Tree and songbird macrorefugia

[1]Some datasets belong to more than one data-type category.

Although this guidebook includes information about a diverse array of spatial datasets relevant to conservation and climate change in the Pacific Northwest, it is not exhaustive. In many cases natural-resource managers will need to consult other datasets beyond those presented here to best inform conservation planning and decision-making. Examples of datasets not included in this guidebook but of potential conservation importance include (a) coarse-resolution datasets intended for use at continental-to-global scales, (b) site-scale datasets representing specific protected areas (e.g., national parks), (c) datasets representing land cover, vegetation, fire events, hydrology, human impacts, or other landscape features that do not explicitly represent potential climate-change effects, (d) point locations of features of interest, e.g., monitoring sites or wetland locations, (e) raw remote-sensing datasets, (f) datasets that are not spatially explicit, e.g., data about particular species of conservation concern, and (g) unpublished datasets created by natural-resource managers for internal use.

Selection of datasets for inclusion in this guidebook benefited from guidance and recommendations from natural-resource managers and researchers from State and Federal agencies, Tribal organizations, non-profit organizations, landscape conservation cooperatives, and colleges and universities throughout the Pacific Northwest (see Acknowledgements section). Recommendations for potential datasets to include came from targeted outreach (e.g., to the Stakeholder Advisory Committee of the Northwest Climate Adaptation Science Center), workshops convened by the Refugia Research Coalition (https://www.climaterefugia.org/northwest), and ongoing communication with researchers and managers throughout the Pacific Northwest region. This process was participatory and focused on co-production of a useful product through collaboration between researchers and managers. However, the process was not comprehensive or systematic such that this guidebook does not represent a systematic review or a formal meta-analysis.

4. Future considerations

Because of the rapid rate at which new climate-ecology spatial datasets are published, this guidebook may have a useful lifespan of 3 to 5 years from the date of publication, after which it would benefit from updates to reflect recently published datasets. Additionally, the research processes that guide models and dataset development are continually being refined. In some cases, these research processes may be improved based on input and feedback from natural-resource managers. The contact information presented in each chapter of the guidebook for dataset corresponding authors may be useful for natural-resource managers who wish to provide such feedback. Questions that managers may wish to consider in providing feedback to dataset authors include:

(1) In what ways is the dataset in question most relevant to your work? What management questions does it help answer?
(2) Are there ways the dataset could be refined that would make it more useful or usable for on-the-ground decision-making (e.g., changes in spatial resolution, species or ecosystems represented, time periods for future projections, etc.)?
(3) Are there related or similar characteristics or processes that could be represented in future refinements of the dataset?

Chapter 1: Climate dissimilarity for North America

Authors:

R. Travis Belote (The Wilderness Society)
Jennifer Cartwright (U.S. Geological Survey)

1. Dataset overview

Climate dissimilarity is a metric of climate-change exposure that summarizes the overall change in climate based on a suite of climate variables representing temperature, moisture, and other climate attributes. For each location (pixel in the gridded dataset), climate conditions were summarized using **Principal Components Analysis**, for baseline/historical conditions and for projected future climate conditions (see chapter glossary for definitions of terms). Climate dissimilarity represents a holistic quantitative estimate of the magnitude of change between baseline and future climate (figure 1.1).

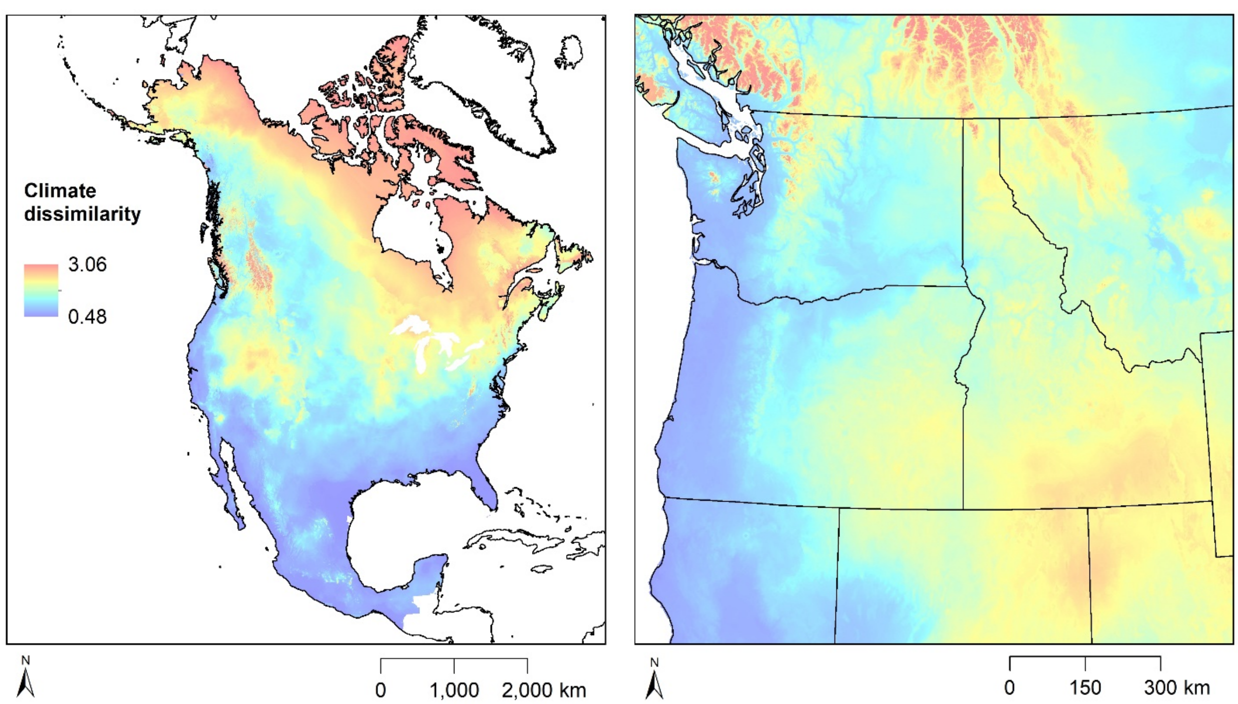

Figure 1.1. Climate dissimilarity at the end of the 21st century under the representative concentration pathway (RCP) 8.5 greenhouse-gas scenario (see appendix 2). High values represent locations where climate is projected to change dramatically (considering multiple climate variables); low values represent locations with projections of modest climate change. The left panel shows the entire extent of the dataset; the right panel shows climate dissimilarity for the Pacific Northwest.

Glossary

Principal Components Analysis (PCA): a statistical technique to reduce a large number of correlated variables to a smaller number of 'principal components' (PCs) that retain most of the information from the original set of variables.

For detailed information about these terms, please consult the dataset citation in section 2.

2. Data access information

Dataset citation:

Belote, R. T., C. Carroll, S. Martinuzzi, J. Michalak, J. W. Williams, M. A. Williamson, and G. H. Aplet. 2018. Assessing agreement among alternative climate change projections to inform conservation recommendations in the contiguous United States. *Scientific Reports* 8:1–13.

Dataset documentation link:

https://doi.org/10.1038/s41598-018-27721-6
(open access)

Data access:

The dataset can be downloaded from: https://adaptwest.databasin.org/pages/climatic-dissimilarity.

The dataset can be viewed interactively online (for mid-century) at:
https://adaptwest.databasin.org/datasets/40a584aff42f4b198403e3990c3aab27

and (for end-of-century) at:
https://adaptwest.databasin.org/datasets/fae70d00037a405f98b85eb9b561920b

Metadata access:

Formal metadata is not available for this dataset.

Dataset corresponding author:

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The Wilderness Society
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3. Conceptual information

Data type category (as defined in the Introduction to this guidebook):

Climate

Species or ecosystems represented:

This dataset does not represent any individual species or ecosystems.

Units of mapped values:

unitless

Range of mapped values:

Ranges of values vary depending on future time period and representative concentration pathway (RCP):

RCP 4.5 for mid-century: 0.134 to 1.645
RCP 8.5 for mid-century: 0.251 to 1.903
RCP 4.5 for end-of-century: 0.216 to 1.773
RCP 8.5 for end-of-century: 0.477 to 3.064

These minimum and maximum values represent climate dissimilarity created using ensembles of climate projections across 15 general circulation models (GCMs). Note that climate dissimilarity datasets are also available for eight of these individual GCMs; minimum and maximum values for these datasets vary by GCM. For more information on GCMs and RCPs, see appendices 1 and 2, respectively.

4. Spatial information

Spatial data type: a raster dataset (grid)

Data file format(s): GeoTiff (.tif)

Spatial resolution: 1 km

Geographic coordinate system: World Geodetic System (WGS) 1984

Projected coordinate system: World Geodetic System (WGS) 1984 Lambert Azimuthal Equal Area

Spatial extent:

Continental (North America) excluding Central America and the Caribbean islands

Dataset truncation:

The dataset is truncated along the border separating Mexico from Guatemala and Belize.

5. Temporal information

Time period represented: Future (later than 2020)

Future time period(s) represented: Mid-century (2041–2070), end-of-century (2071–2100)

Baseline time period (against which future conditions were compared):1981–2010

6. Methods information

Methods overview:

For each future period, climatic dissimilarity at each location (pixel) was calculated as the Euclidean distance in climate space between baseline (current) climate conditions and future climate conditions (figure 1.2). Eleven variables were selected to summarize climate conditions: mean annual temperature, mean temperature of the warmest month (MWMT), mean

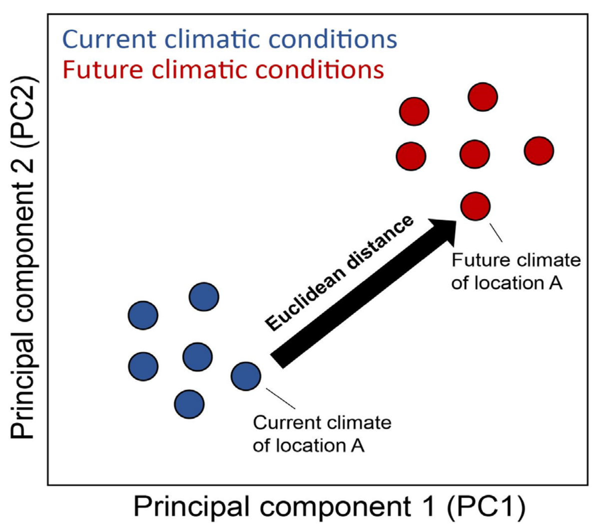

Figure 1.2. Illustration of the calculation of climate dissimilarity. Locations can be plotted in climate space based on their first two principal component scores (PC1 and PC2). Climate dissimilarity for a given location is the Euclidean distance between current climate conditions (blue point) and future climate conditions (red point).

temperature of the coldest month (MCMT), difference between MCMT and MWMT, mean annual precipitation, mean summer precipitation, mean winter precipitation, growing degree days, the number of frost-free days, Hargreaves reference evaporation, and Hargreaves climatic moisture index. Principal components analysis was used to summarize these 11 variables, and the first two principal components (PC1 and PC2) were used to represent climate. PC1 primarily represented temperature while PC2 primarily represented moisture availability. These calculations were conducted under two greenhouse-gas scenarios (RCP 4.5 and RCP 8.5) for the baseline period, and for two future time periods (mid-century and end-of-century). For more information, please consult the dataset citation listed in section 2 of this chapter.

Major input data sources for this dataset included:

Historical climate observations or models; future climate projections

This dataset used the following general circulation models (GCMs):

CanESM2*, ACCESS1.0, IPSL-CM5A-MR*, MIROC5, MPI-ESM-LR*, CCSM4*, HadGEM2-ES*, CNRM-CM5*, CSIRO-Mk3.6.0, GFDL-CM3*, INM-CM4*, MRI-CGCM3, MIROC-ESM, CESM1-CAM5, and GISS-E2R

Separate files are provided for individual GCMs marked with * and an ensemble across GCMs is also provided. More information about climate models is available in appendix 2. Detailed information about climate models, including model evaluation and comparison among models, is available from Randall *et al.* (2007) and Rupp *et al.* (2013).

This dataset used the following greenhouse-gas scenarios:

RCP 4.5, RCP 8.5

More information about greenhouse-gas scenarios is available in appendix 2 and from Knutti and Sedláček (2013).

Creation of this dataset involved the following methods to change the spatial resolution of climate models (e.g., to downscale or resample climate models):

Downscaling of climate models was not conducted as part of the study that produced this dataset, however, downscaled climate projections were used as inputs. Information on downscaling methods that produced these inputs is available from Wang *et al*. (2016).

7. Guidelines for interpretation

The mapped values of the dataset may be interpreted as follows:

High values for climate dissimilarity represent locations where climate is projected to change dramatically (considering multiple climate variables) whereas low values represent locations with projections of modest climate change. Climate-dissimilarity values can be compared across space (from one location to another) within a given greenhouse-gas scenario and time period, or alternatively can be compared for a given location across time periods and/or greenhouse-gas scenarios. For a given combination of location, greenhouse-gas scenario, and time period, the variability in climate-dissimilarity values across datasets that were created using different GCMs provides information about uncertainty in climate-change projections.

Representations of key concepts in climate-change ecology:

This dataset provides information on climate-change vulnerability by representing climate-change exposure as the overall magnitude of change across a suite of climate variables. The degree of climate-change exposure predicted for a given area is an important consideration in anticipating the nature and rate of potential ecological shifts, such as changes in species compositions (as species leave the area due to unsuitable climate or arrive from other regions tracking newly suitable climate conditions) or species' adaptations to changing conditions (such as through changes in seasonal timing). Different metrics of climate-change exposure may show different results for a given geographic area (Belote *et al.*, 2018), suggesting that there may be multiple dimensions of climate-change exposure that need to be considered in anticipating a range of possible ecological shifts over time.

8. Uncertainties

This dataset involves the following assumptions, simplifications, and caveats:

This dataset represents one component of climate-change exposure that may be complemented by also considering other metrics of exposure. Climate dissimilarity is a local metric, meaning that it primarily represents the magnitude of local climate change for an area. Other metrics of climate exposure include forward and backward velocity, which provide information on the rates at which species would need to migrate to keep pace with climate change. Also, the study that produced the climate dissimilarity datasets found considerable geographic variation in the degree of agreement or disagreement across GCMs and greenhouse-gas scenarios regarding the magnitude of climate dissimilarity. This means that confidence is higher in some regions than others about whether climate dissimilarity will be high or low (see figure 2 in Belote *et al*. 2018).

Quantification of uncertainty:

For each time period (mid-century and end-of-century) and greenhouse-gas scenario (RCP 4.5 and 8.5), uncertainty in climate dissimilarity was assessed by examining variability across eight GCMs.

Field verification:

Field verification of the mapped values in this dataset was not possible because the dataset represents a future condition. Datasets representing the baseline time period were derived from downscaled climate grids from the ClimateNA dataset (Wang *et al*. 2016). Accuracy of the baseline climate variables in the ClimateNA dataset was assessed using monthly mean observations from 4,891 weather stations across North America, located predominantly in the United States; see figure 1 and table 2 in Wang *et al*. (2016).

9. Peer review

Prior to dataset publication, peer review was conducted by external review (at least two anonymous reviewers, each from a different institution).

10. Conservation applications

Potential conservation applications of this dataset could include the following:

Climate dissimilarity is one metric of climate exposure that can provide information on climate vulnerability. Belote *et al*. (2018) suggest that climate vulnerability be considered along with conservation value for any location to determine optimal conservation strategies; see figure 1 in Belote *et al*. (2018). For example, in areas with high conservation value and low climate vulnerability (e.g., low climate dissimilarity) managers may wish to emphasize traditional reserves and protected areas, whereas in high-conservation-value areas with high climate vulnerability, greater flexibility in management approaches may be required.

The study that produced this dataset found considerable variation among three metrics of climate exposure (climate dissimilarity, and forward and backward velocity). In the context of uncertainty about climate-change exposure magnitude, "no regrets" conservation strategies (e.g., protecting lands from development, invasive species control, and human impacts mitigation) and diversified management approaches may be helpful.

Applicable scales for detailed spatial assessments:

For conservation applications requiring detailed assessment of spatial variation of the dataset within a geographic boundary (such as a protected area), the following geographic scales may be most appropriate (see appendix 3 for more information).

At the scale of: a Bureau of Land Management (BLM) district, a river watershed (8-digit hydrologic unit code [HUC-8]), an individual county, a national forest, a level-3 ecoregion (e.g., the North Cascades), a single state (Washington, Oregon, or Idaho), a region (multiple states in the Pacific Northwest or in western North America), the continental United States, the North American continent.

Applicable scales for assessing general patterns:

Due to spatial resolution, the dataset may not show detailed spatial variation at the following geographic scales, however, the dataset may be useful to assess general patterns or for comparison to other locations (see appendix 3 for more information).

At the scale of: a small (< 1 km^2) nature preserve, a state park or state wildlife area, a local watershed (12-digit hydrologic unit code [HUC-12]).

Use of the dataset in conservation applications may be limited by the following considerations:

Climate vulnerability for a given geographic area or species may be influenced by a variety of factors that were not considered in the creation of this dataset. Because this dataset primarily represents climate-change exposure rather than climate-change sensitivity or adaptive capacity, it should be considered along with other information for conservation decision-making purposes. For geographic areas, such information could include degree of human modification, landscape connectivity, and projected land-cover change. For species, such information could include physiological tolerance thresholds, population genetics and demographics, and inter-species interactions.

Past or current conservation applications:

The dataset has not yet been used in any on-the-ground conservation applications to the knowledge of the authors of this chapter.

References cited

Belote, R. T., C. Carroll, S. Martinuzzi, J. Michalak, J. W. Williams, M. A. Williamson, and G. H. Aplet. 2018. Assessing agreement among alternative climate change projections to inform conservation recommendations in the contiguous United States. Scientific Reports 8:1–13.

Knutti, R., and J. Sedláček. 2013. Robustness and uncertainties in the new CMIP5 climate model projections. Nature Climate Change 3:369–373.

Randall, D., R. Wood, S. Bony, R. Colman, T. Fichefet, J. Fyfe, V. Kattsov, and *et al*. 2007. Cilmate models and their evaluation. in S. Solomon, D. Qin, M. Manning, Z. Chen, M. Marquis, K. Averyt, M. Tignor, and H. Miller, editors. Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, New York, NY.

Rupp, D. E., J. T. Abatzoglou, K. C. Hegewisch, and P. W. Mote. 2013. Evaluation of CMIP5 20th century climate simulations for the Pacific Northwest USA. Journal of Geophysical Research 118: 884–907.

Wang, T., A. Hamann, D. Spittlehouse, and C. Carroll. 2016. Locally downscaled and spatially customizable climate data for historical and future periods for North America. PLoS One 11:e0156720.

Chapter 2: Multivariate climate velocity

Authors:

Joshua Lawler (University of Washington)
Jennifer Cartwright (U.S. Geological Survey)

1. Dataset overview

This dataset provides estimates of **climate-change velocity** (Hamann *et al*. 2015) produced in several ways (see chapter glossary for definitions of terms). **Forward velocity** provides a measure of the rate at which an organism would need to migrate over the land surface to maintain similar climate conditions, as regional climate conditions change. **Backward (or reverse) velocity** utilizes a target location (pixel) of interest and measures the rate at which an organism from similar climate conditions would need to migrate to colonize that target pixel (figure 2.1). These two types of **multivariate climate velocity** metrics can complement each other. Whereas forward velocity provides climate-change exposure information for species or populations inhabiting particular areas, backward velocity provides information for the areas themselves, in terms of the accessibility of those locations to the biotic communities that could potentially inhabit them in the future.

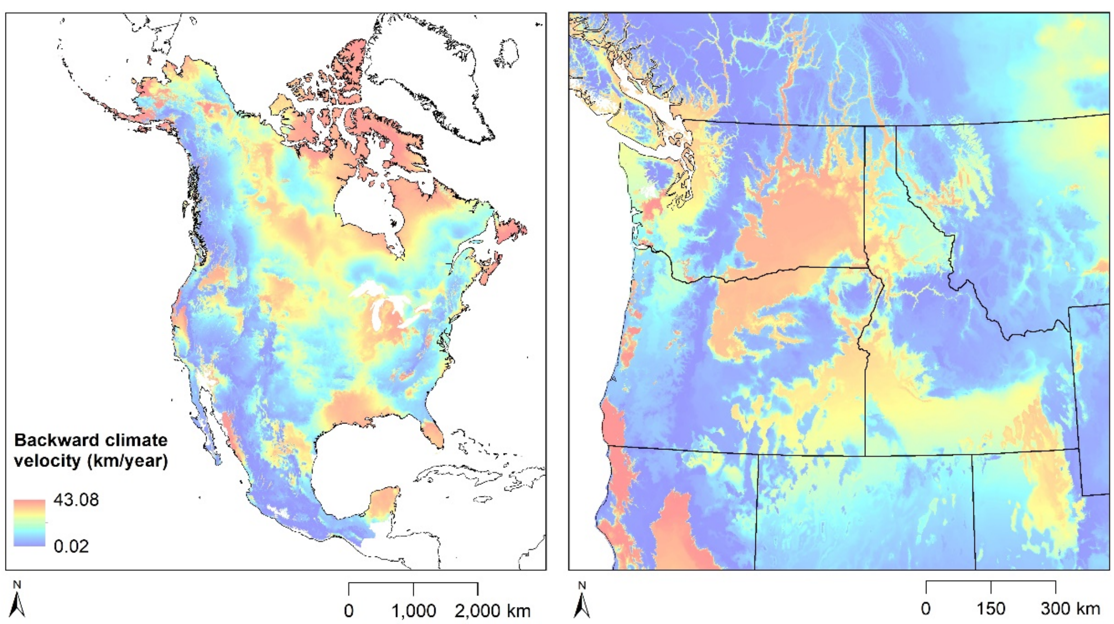

Figure 2.1. Backward (reverse) multivariate climate velocity for the representative concentration pathway (RCP) 8.5 greenhouse-gas scenario for the end of the 21st century (2017-2100). High values indicate areas into which it may be difficult for species to migrate in response to climate change, suggesting potential for future ecological communities composed of few species adapted to the new climate conditions. The left panel shows the entire extent of the dataset; the right panel shows climate dissimilarity for the Pacific Northwest.

Glossary

Climate analog: a location with a set of similar (analogous) climate conditions to a given location of interest. A location can have future climate analogs (areas that are projected to have similar climatic conditions in the future), current climate analogs (areas with similar current climatic conditions), and historical climatic analogs (areas that had similar climatic conditions in the past).

Climate-change velocity: estimates the speed at which species must migrate over the Earth's surface to maintain constant climatic conditions.

Forward velocity: the distance from current climate locations to the nearest site with an analogous future climate; note that forward velocity reflects the minimum distance an organism in the current landscape must migrate to maintain constant climate condition.

Backward (or reverse) velocity: the distance from projected future climate pixels back to analogous current climate locations; note that backward velocity reflects the minimum distance, given the projected future conditions at a site, that a climate-adapted organism would have to migrate to colonize the site.

Multivariate climate velocity: climate velocity calculated using multiple climate variables, as opposed to a single variables such as annual temperature. In this dataset, climate velocity was calculated using 11 climate variables (see section 6).

Principal Components Analysis (PCA): a statistical technique to reduce a large number of correlated variables to a smaller number of 'principal components' (PCs) that retain most of the information from the original set of variables.

For detailed information about these terms, please consult the dataset citation in section 2.

2. Data access information

Dataset citation:

Carroll, C., J. J. Lawler, D. R. Roberts, and A. Hamann. 2015. Biotic and climatic velocity identify contrasting areas of vulnerability to climate change. PLoS ONE 10:e0140486.

Hamann, A., D. Roberts, Q. Barber, C. Carroll, and S. Nielsen. 2015. Velocity of climate change algorithms for guiding conservation and management. Global Change Biology 21:997–1004.

Dataset documentation links:

https://doi.org/10.1371/journal.pone.0140486
(open access)

https://doi.org/10.1111/gcb.12736
(open access)

Data access:

The dataset can be downloaded from: https://adaptwest.databasin.org/pages/adaptwest-velocitywna

Note: the two journal articles referenced above describe the general methods used to derive this dataset, however, the dataset at the link above is an updated version of an original dataset that is available from: https://adaptwest.databasin.org/pages/adaptwest-velocitywna-cmip3.

The dataset can be viewed interactively online at: https://adaptwest.databasin.org/maps/60c241443c07459589e7dab0cf482093.

Metadata access:

Formal metadata is not available for this dataset.

Dataset corresponding author:

Carlos Carroll
Klamath Center for Conservation Research
carlos@klamathconservation.org

3. Conceptual information

Data type category (as defined in the Introduction to this guidebook):

Climate

Species or ecosystems represented:

This dataset does not represent any individual species or ecosystems.

Units of mapped values:

kilometers per year (km / year)

Range of mapped values:

The range of mapped values depends on the individual data layer. Data layers are provided for both forward and backward velocity, for two future periods, and for two greenhouse-gas scenarios (see sections 5 and 6).

4. Spatial information

Spatial data type: a raster dataset (grid)

Data file format(s): GeoTiff (.tif), ASCII (.asc)

Spatial resolution: 1 km

Geographic coordinate system:

World Geodetic System (WGS) 1984

Projected coordinate system:

World Geodetic System (WGS) 1984 Lambert Azimuthal Equal Area

Spatial extent:

Continental (North America) excluding Central America and the Caribbean islands

Dataset truncation:

The dataset is truncated along the border separating Mexico from Guatemala and Belize

5. Temporal information

Time period represented: Future (later than 2020)

Future time period(s) represented:

Mid-century (2041-2070), end-of-century (2071-2100)

Baseline time period (against which future conditions were compared): 1981-2010

6. Methods information

Methods overview:

First, 11 climate variables were synthesized using **Principal Components Analysis**. These 11 variables included: mean annual temperature, mean temperature of the warmest month, mean temperature of the coldest month, mean annual precipitation, mean growing season (May to August) precipitation, degree-days above 5 °C, number of frost-free days, and several indices representing moisture conditions. The results of this analysis were used to find, for each pixel with its given current climate conditions, a set of future **climate analogs**, i.e., a set of pixels that are predicted to have similar climate conditions in the future. Then, the geographically nearest pixel with analogous future climate was selected and used to calculate climate velocity, which is the straight-line distance from the target pixel of interest to its nearest analog, divided by the time difference between the current time period and the future time period under consideration. For more information, please consult the dataset citation listed in section 2 of this chapter.

This dataset employed the following specific models:

yaImpute package in the R software environment (Crookston and Finley, 2008)

Major input data sources for this dataset included:

Historical climate observations or models, Future climate projections

This dataset used the following general circulation models (GCMs):

CanESM2, ACCESS1.0, IPSL-CM5A-MR, MIROC5, MPI-ESM-LR, CCSM4, HadGEM2-ES, CNRM-CM5, CSIRO-Mk3.6.0, GFDL-CM3, INM-CM4, MRI-CGCM3, MIROC-ESM, CESM1-CAM5, GISS-E2R

Separate files are provided for each GCM and an ensemble across GCMs is also provided. More information about climate models is available in appendix 1. Detailed information about climate models, including model evaluation and comparison among models, is available from Randall *et al.* (2007) and Rupp *et al.* (2013).

This dataset used the following greenhouse-gas scenarios:

RCP 4.5, RCP 8.5

More information about greenhouse-gas scenarios is available in appendix 2 and from Knutti and Sedláček (2013).

Creation of this dataset involved the following methods to change the spatial resolution of climate models (e.g., to downscale or resample climate models):

Downscaling of climate models was not conducted as part of the study that produced this dataset, however, downscaled climate projections were used as inputs. Information on downscaling methods that produced these inputs is available from Wang *et al*. (2016).

7. Guidelines for interpretation

The mapped values of the dataset may be interpreted as follows:

Forward climate velocity primarily represents climate-change exposure for species inhabiting the geographic areas considered. High forward climate velocity values may suggest a greater threat of local extirpation of species inhabiting a site due to the rapid migration that would be needed to track changing climate conditions. Backward (reverse) climate velocity primarily represents climate-change implications for the geographic area itself that is being considered. High backward velocity indicates that it might be difficult for species to colonize that site in the future (in response to climate change), and according to Carroll *et al*. (2015), "a site with high backward velocity is threatened with holding a depauperate complement of species adapted to its future climate, with consequent effects on ecosystem function and services".

Representations of key concepts in climate-change ecology:

This dataset represents two ways of conceptualizing climate-change vulnerability based on climate-change exposure (forward and backward climate velocity). Both types of climate velocity have implications for the adaptive capacity of organisms to respond to climate change by migrating across the landscape to track suitable climate conditions. These two types of climate velocity provide different, and potentially complementary, types of information. Locations with high forward velocity may have species at greater risk of local extirpation, whereas locations with high backward velocity may be at greater risk of having few future species adapted to the new local climate. Consideration of multiple metrics of climate-change exposure (including forward and backward velocity along with additional metrics) along with species' sensitivity to climate change and capacity to adapt to changing conditions is important for a holistic assessment of potential climate-change vulnerability for a given location, habitat, or species range.

8. Uncertainties

This dataset involves the following assumptions, simplifications, and caveats:

Unlike the related concept of "biotic velocity" (see Carroll *et al*., 2015), climate velocities in this dataset do not consider species-specific climate tolerances. Therefore, the backward and forward climate velocities in this dataset represent an upper bound on the migration rate required, because for some species slower migration rates will be enabled due to greater tolerance of changing climate conditions and potentially greater ability to persist in place. In addition, because the hypothetical migration trajectories to future climate analogs were conceptualized as straight lines, actual barriers on the landscape impeding migration were not considered. These might include human-created barriers (e.g., transportation infrastructure or land use) as well as intervening areas of inhospitable climate (e.g., a warm valley separating two cold mountain peaks).

Quantification of uncertainty:

This dataset does not include any quantification of uncertainty relating to the mapped values.

Field verification:

Field verification of the mapped values in this dataset was not possible because the dataset represents a future condition. Datasets representing the baseline time period were derived from downscaled climate grids from the ClimateNA dataset (Wang *et al*. 2016). Accuracy of the baseline climate variables in the ClimateNA dataset was assessed using monthly mean observations from 4,891 weather stations across North America, located predominantly in the United States; see table 2 in Wang *et al*. (2016).

9. Peer review

Prior to dataset publication, peer review was conducted by external review (at least two anonymous reviewers, each from a different institution).

10. Conservation applications

Potential conservation applications of this dataset could include the following:

This dataset could help inform climate-vulnerability assessments for species or geographic areas. For this application, the climate velocity metrics in this dataset would ideally be combined with other sources of information, such as species-specific information (e.g., population demographics and dispersal abilities), "biotic velocity" metrics (see Carroll *et al*. 2015), and fine-scale assessments representing possible microclimate refugia.

Applicable scales for detailed spatial assessments:

For conservation applications requiring detailed assessment of spatial variation of the dataset within a geographic boundary (such as a protected area), the following geographic scales may be most appropriate (see appendix 3 for more information).

At the scale of: a Bureau of Land Management (BLM) district, a river watershed (8-digit hydrologic unit code [HUC-8]), an individual county, a national forest, a level-3 ecoregion (e.g., the North Cascades), a single state (Washington, Oregon, or Idaho), a region (multiple states in the Pacific Northwest or in western North America), the continental United States, the North American continent.

Applicable scales for assessing general patterns:

Due to spatial resolution, the dataset may not show detailed spatial variation at the following geographic scales, however, the dataset may be useful to assess general patterns or for comparison to other locations (see appendix 3 for more information).

At the scale of: a small (< 1 km^2) nature preserve, a state park or state wildlife area, a local watershed (12-digit hydrologic unit code [HUC-12]).

Use of the dataset in conservation applications may be limited by the following considerations:

A variety of considerations that may contribute to climate vulnerability for species or geographic areas were not considered in the creation of this dataset. For example, this dataset primarily represents climate-change exposure rather than climate-change sensitivity, such that it does not represent possible differences among species in their tolerances of changing climate conditions. Other relevant considerations for climate-change vulnerability analyses may include information on population genetics and demographics, non-climate threats such as pollution and land-use change, and inter-species interactions such as the effects of invasive species.

Past or current conservation applications:

At the time of the publication of this guidebook, the dataset has not yet been used in any on-the-ground conservation applications to the knowledge of the authors of this chapter.

References cited

Carroll, C., J. J. Lawler, D. R. Roberts, and A. Hamann. 2015. Biotic and climatic velocity identify contrasting areas of vulnerability to climate change. PLoS ONE 10:e0140486.

Crookston, N., and A. Finley. 2008. yaImpute: An R Package for kNN Imputation. Journal of Statistical Software 23:1–16.

Hamann, A., D. Roberts, Q. Barber, C. Carroll, and S. Nielsen. 2015. Velocity of climate change algorithms for guiding conservation and management. Global Change Biology 21:997–1004.

Knutti, R., and J. Sedláček. 2013. Robustness and uncertainties in the new CMIP5 climate model projections. Nature Climate Change 3:369–373.

Randall, D., R. Wood, S. Bony, R. Colman, T. Fichefet, J. Fyfe, V. Kattsov, *et al*. 2007. Cilmate models and their evaluation. *in* S. Solomon, D. Qin, M. Manning, Z. Chen, M. Marquis, K. Averyt, M. Tignor, and H. Miller, editors. Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, New York, NY.

Rupp, D. E., J. T. Abatzoglou, K. C. Hegewisch, and P. W. Mote. 2013. Evaluation of CMIP5 20th century climate simulations for the Pacific Northwest USA. Journal of Geophysical Research 118: 884–907.

Wang, T., A. Hamann, D. Spittlehouse, and C. Carroll. 2016. Locally downscaled and spatially customizable climate data for historical and future periods for North America. PLoS One 11:e0156720.

Chapter 3: North American climate refugia

Authors:
Julia Michalak (School of Environmental and Forest Sciences, University of Washington)
Jennifer Cartwright (U.S. Geological Survey)

1. Dataset overview

This dataset represents potential climatic **refugia** (figure 3.1), defined as locations with future climatic conditions that are increasingly rare compared to their historical extent (see chapter glossary for definitions of terms). This dataset relies on the concept of **climate analogs**, which were identified by comparing current climate conditions to projected future climate conditions using two multivariate measures of climate. Locations (i.e., pixels) with at least 25% fewer climate analogs in the future than were present historically, within a given search radius, were deemed to represent increasingly rare climate conditions, and hence delineated as refugia (Michalak *et al*. 2018).

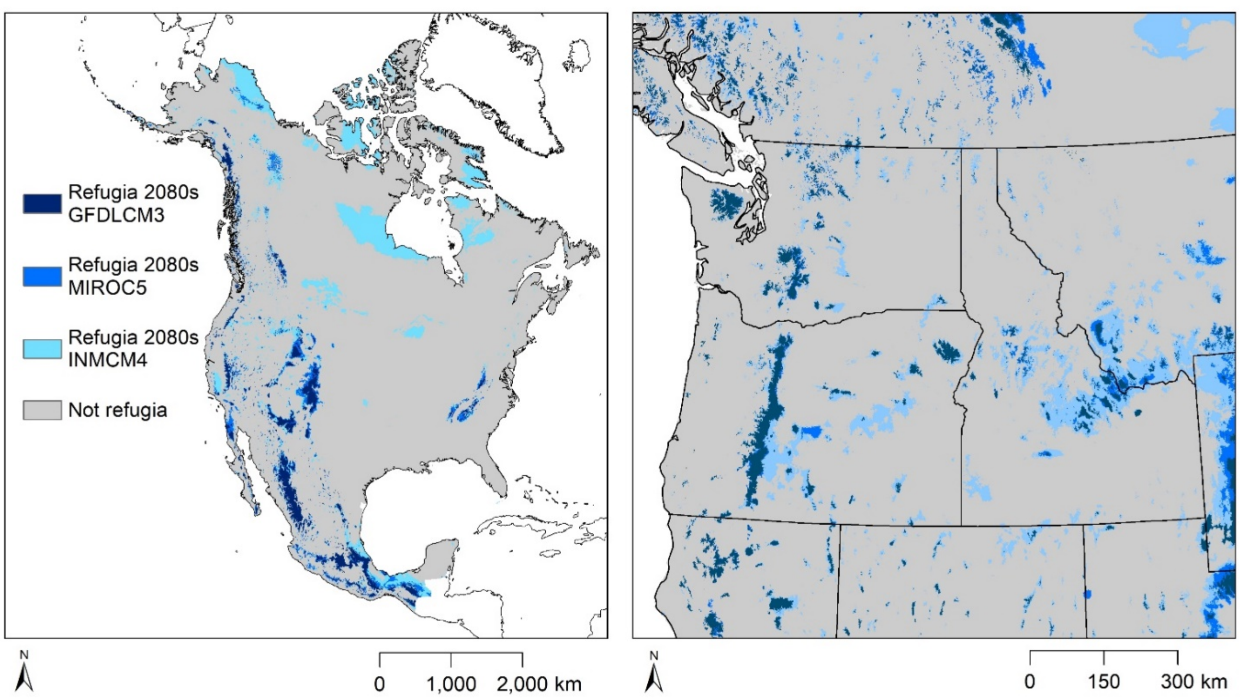

Figure 3.1. Projected refugia—locations of increasingly rare climate conditions—in the 2080s according to three general circulation models (GCMs). Darker colors are associated with GCMs that project greater changes in warming and precipitation. The left panel shows the entire extent of the dataset; the right panel shows refugia for the Pacific Northwest.

Glossary

Climate analog: a location with a set of similar (analogous) climate conditions to a given location of interest.

Principal Components Analysis (PCA): a statistical technique to reduce a large number of correlated variables to a smaller number of 'principal components' (PCs) that retain most of the information from the original set of variables.

Refugia: locations with climatic conditions that are projected to be increasingly rare in the future.

For detailed information about these terms, please consult the dataset citation in section 2.

2. Data access information

Dataset citation:

Michalak, J. L., J. J. Lawler, D. R. Roberts, and C. Carroll. 2018. Distribution and protection of climatic refugia in North America. Conservation Biology 32: 1414–1425.

Dataset documentation link:

https://doi.org/10.1111/cobi.13130
(open access)

Data access:

The dataset can be downloaded from https://adaptwest.databasin.org/pages/distribution-and-protection-climatic-refugia.

The dataset is not available for interactive online map viewing.

Metadata access:

Formal metadata is not available for this dataset.

Dataset corresponding author:

Julia Michalak
School of Environmental and Forest Sciences, University of Washington
michalaj@uw.edu

3. Conceptual information

Data type category (as defined in the Introduction to this guidebook):

Climate

Species or ecosystems represented:

This dataset does not represent any individual species or ecosystems.

Units of mapped values:

unitless

Range of mapped values:

1 = refugia; 0 = not identified as refugia

4. Spatial information

Spatial data type: a raster dataset (grid)

Data file format(s): GeoTiff (.tif)

Spatial resolution: 1 km

Geographic coordinate system:

World Geodetic System (WGS) 1984

Projected coordinate system:

World Geodetic System (WGS) 1984 Lambert Azimuthal Equal Area

Spatial extent:

Continental (North America) excluding Central America and the Caribbean islands

Dataset truncation:

The dataset is truncated along the border separating Mexico from Guatemala and Belize

5. Temporal information

Time period represented: Future (later than 2020)

Future time period(s) represented:

Mid-century (2041-2070), end-of-century (2071-2100)

Baseline time period (against which future conditions were compared): 1961–1990.

6. Methods information

Methods overview:

First, 10 biologically relevant climate variables were synthesized using **Principal Components Analysis** (PCA), such that the first two principal components represented multivariate climate conditions. Climate conditions in the baseline time period were compared to future time periods. For each pixel, climate analogs were identified as other pixels within a search radius having similar future climate conditions (i.e., differences less than a specified threshold value). In this analysis, "similar" was quantified using two different threshold values representing different niche breadths, with larger values corresponding to the concept of species with greater niche flexibility (i.e., climatic differences between pixels were allowed to be greater while being labelled "similar") and conversely smaller values representing less niche flexibility (requiring less climate difference to be considered "similar"). In this analysis, several search radii were used, representing different possible annual dispersal distances: 0.5, 1, 5, and 10 km. These annual distances were multiplied by the number of years between the reference and future time period to determine the final search radius. Pixels were identified as refugia if the projected future climatic conditions at the pixel's location were rare relative to their historical extent within the given search radius. Data layers representing refugia are available for eight generic species types (two values of niche flexibility multiplied by four dispersal distances) and for all generic species types combined (in which a pixel was identified as a refugium if it was a refugium for at least one of the eight generic types). For more information, please consult the dataset citation listed in section 2 of this chapter.

Major input data sources for this dataset included:

Species ranges or point locations, historical climate observations or models, future climate projections

This dataset used the following general circulation models (GCMs):

GFDL-CM3, MIROC5, INM-CM4

Separate files are provided for each GCM; no ensemble is provided across GCMs. More information about climate models is available in appendix 1. Detailed information about climate models, including model evaluation and comparison among models, is available from Randall *et al.* (2007) and Rupp *et al.* (2013).

This dataset used the following greenhouse-gas scenarios:

RCP 8.5

More information about greenhouse-gas scenarios is available in appendix 2 and from Knutti and Sedláček (2013).

Creation of this dataset involved the following methods to change the spatial resolution of climate models (e.g. to downscale or resample climate models):

Climate data were downscaled using ClimateNA software version 5.10 (Wang *et al*., 2016).

7. Guidelines for interpretation

The mapped values of the dataset may be interpreted as follows:

Pixels coded 1 indicate refugia, defined as locations with increasingly rare climate conditions within a given search radius (dispersal distance). Pixels coded 0 are non-refugia.

Representations of key concepts in climate-change ecology:

This dataset primarily represents climate-change exposure, in that the existence of climate analogs within a given search radius is a function of the degree and magnitude of climate change. Because various search radii and niche breadth values were considered, this analysis also incorporated ideas of climate sensitivity, by using two different thresholds to define “similar” climatic conditions. This analysis also incorporates adaptive capacity, by measuring species' abilities to migrate (track changing climate conditions by dispersing across the landscape) and/or shift their habitat-utilization patterns (exploit new habitats with similar but not identical climate conditions).

Additionally, this dataset contributes to the growing analysis of various kinds of climatic refugia. Refugia from climate change have been identified by different research teams using different definitions, approaches, and scales of analysis. However, refugia identification generally seeks to find locations that provide relatively rare opportunities for species persistence and/or adaptation under changing climate conditions. Relatively large-scale macrorefugia, as presented in this dataset, may be considered along with finer-scale microrefugia (such as could be provided in areas of diverse microclimates due to diverse local topography) to assess the potential for a given area to support species' persistence or adaptation.

8. Uncertainties

This dataset involves the following assumptions, simplifications, and caveats:

Although landscape connectivity is considered important to allow species to track changing climate conditions, the analysis that produced this dataset did not account for landscape conditions and instead used a fixed dispersal distance regardless of possible barriers to species movement. In addition, this analysis represented habitat using climate conditions only, and did not incorporate other important determinants of habitat quality and location such as soils, vegetation, and resource availability.

Quantification of uncertainty:

Refugia were identified and compared across three general circulation models (GCMs), corresponding to various magnitudes of projected climate change.

Field verification:

Field verification of the mapped values in this dataset was not possible because the dataset represents a future condition. Datasets representing the baseline time period were derived from downscaled climate grids from the ClimateNA dataset (Wang *et al*. 2016). Accuracy of the baseline climate variables in the ClimateNA dataset was assessed using monthly mean observations from 4,891 weather stations across North America, located predominantly in the United States; see table 2 in Wang *et al*. (2016).

9. Peer review

Prior to dataset publication, peer review was conducted by external review (at least two anonymous reviewers, each from a different institution).

10. Conservation applications

Potential conservation applications of this dataset could include the following:

This dataset can be used to anticipate locations that may function as climate refugia in the future, in that they harbor increasingly rare local climate conditions. The study that produced this dataset (Michalak *et al*., 2018) included an analysis of protected areas within North America and found that existing protected areas disproportionately included the projected climate refugia. A likely explanation for this is that climate refugia were disproportionately identified in high-elevation areas that are over-represented in protected area networks, because mountainous areas are more likely to be included in protected areas than lower-elevation, flat plains. However, a substantial number of predicted refugia sites remain unprotected and thus could be potential sites for future conservation investment.

Applicable scales for detailed spatial assessments:

For conservation applications requiring detailed assessment of spatial variation of the dataset within a geographic boundary (such as a protected area), the following geographic scales may be most appropriate (see appendix 3 for more information).

At the scale of: a Bureau of Land Management (BLM) district, a river watershed (8-digit hydrologic unit code [HUC-8]), an individual county, a national forest, a level-3 ecoregion (e.g. the North Cascades), a single state (Washington, Oregon, or Idaho), a region (multiple states in the Pacific Northwest or in western North America), the continental United States, the North American continent.

Applicable scales for assessing general patterns:

Due to spatial resolution, the dataset may not show detailed spatial variation at the following geographic scales, however, the dataset may be useful to assess general patterns or for comparison to other locations (see appendix 3 for more information).

At the scale of: a small (< 1 km^2) nature preserve, a state park or state wildlife area, a local watershed (12-digit hydrologic unit code [HUC-12]).

Use of the dataset in conservation applications may be limited by the following considerations:

Important components of species habitat were not included in this analysis, including soil, vegetation, and resource availability (e.g., food, nesting sites). In addition, because the study that produced this dataset did not incorporate landscape condition, species migration in areas of low landscape connectivity (e.g., urban or agricultural landscapes) might be considerably less than assumed based on the search radii (dispersal distances) in the analysis. Also, other possibly important types of refugia could exist on the landscape that are not represented in the dataset. These could include topographic microrefugia not detectable at the 1-km resolution of this dataset.

Past or current conservation applications:

The dataset has not yet been used in any on-the-ground conservation applications to the knowledge of the authors of this chapter.

References cited

Knutti, R., and J. Sedláček. 2013. Robustness and uncertainties in the new CMIP5 climate model projections. Nature Climate Change 3:369–373.

Michalak, J. L., J. J. Lawler, D. R. Roberts, and C. Carroll. 2018. Distribution and protection of climatic refugia in North America. Conservation Biology 32: 1414–1425.

Randall, D., R. Wood, S. Bony, R. Colman, T. Fichefet, J. Fyfe, V. Kattsov, *et al*. 2007. Cilmate models and their evaluation. *in* S. Solomon, D. Qin, M. Manning, Z. Chen, M. Marquis, K. Averyt, M. Tignor, and H. Miller, editors. Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, New York, NY.

Rupp, D. E., J. T. Abatzoglou, K. C. Hegewisch, and P. W. Mote. 2013. Evaluation of CMIP5 20th century climate simulations for the Pacific Northwest USA. Journal of Geophysical Research 118: 884–907.

Wang, T., A. Hamann, D. Spittlehouse, and C. Carroll. 2016. Locally downscaled and spatially customizable climate data for historical and future periods for North America. PLoS One 11:e0156720.

Chapter 4: Changes in snowpack and snow residence time

Authors:

Nathan Walker (USDA Forest Service)
Charles Luce (USDA Forest Service)
Jennifer Cartwright (U.S. Geological Survey)

1. Dataset overview

This dataset includes modeled historical (1975-2005) and future (2071-2090, RCP 8.5) projections of April 1st **snow-water equivalent (SWE)** and **snow-residence time (SRT)** (figure 4.1; see chapter glossary for definitions of terms). The model that produced these datasets uses average winter (November through March) temperature and total winter precipitation. The model was validated using data from 497 **Snow Telemetry (SNOTEL)** sites in the western United States. Changes in SWE and SRT are presented both as absolute changes (future values minus historical values) and as percent changes.

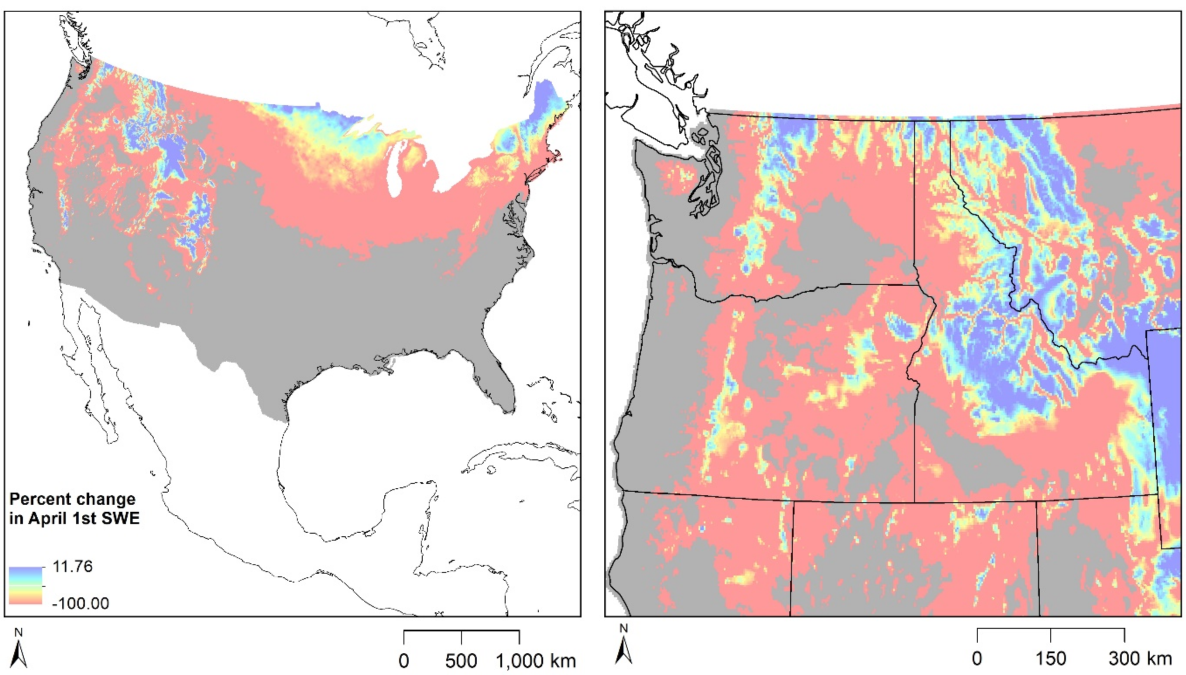

Figure 4.1. Projected percent change in April 1st snow-water equivalent (SWE) from the historical period (1975-2005 average) to end-of-century (2071-2090 average). Positive values indicate modest increases in snowpack, negative values indicate decreasing snowpack, and values of -100 indicate complete loss of April 1st snowpack. Areas in gray had no April 1st SWE in the historical period. The left panel shows the entire extent of the dataset; the right panel shows the projected change in SWE for the Pacific Northwest.

Glossary

Snow-water equivalent (SWE): a commonly used measurement of snowpack at a given point in the year (such as April 1st); it is the equivalent amount of liquid water contained within the snowpack.

Snow-residence time (SRT): a metric of the average time that a given increment of snowfall lasts. In more colloquial terms, it is the average lifespan of a snowflake. It is calculated in this study as the difference between the average timing of snow accumulation and the average timing of snow melt.

Snow Telemetry (SNOTEL): a network of climate and weather stations (SNOTEL sites) administered by the U.S. Department of Agriculture Natural Resources Conservation Service in 11 states in the western U.S.

For detailed information about these terms, please consult the dataset citation in section 2.

2. Data access information

Dataset citation:

Luce, C., V. Lopez-Burgos, and Z. Holden. 2014. Sensitivity of snowpack storage to precipitation and temperature using spatial and temporal analog models. Water Resources Research 50:2108–2123.

Lute, A., and C. Luce. 2017. Are model transferability and complexity antithetical? Insights from validation of a variable-complexity empirical snow model in space and time. Water Resources Research 53:8825–8850.

Dataset documentation links:

https://doi.org/10.1002/2013WR014844
(open access)

https://doi.org/10.1002/2017WR020752
(subscription or fee required)

Data access:

The dataset can be downloaded from:
https://www.fs.fed.us/rm/boise/AWAE/projects/NFS-regional-climate-change-maps/categories/us-raster-layers.html

Forest-specific maps are also available:

https://www.fs.fed.us/rm/boise/AWAE/projects/national-forest-climate-change-maps.html

These data can be viewed online at the U.S. Department of Agriculture (USDA) Forest Service Geospatial Data Discovery page, including historical, future, absolute change, and percent change grids (rasters) for SRT and SWE:

https://enterprisecontent-usfs.opendata.arcgis.com/datasets?q=snow%20residence%20time

https://enterprisecontent-usfs.opendata.arcgis.com/datasets?q=snow%20water%20equivalent

These are also accessible as web services:

https://apps.fs.usda.gov/fsgisx01/rest/services/RDW_Climate

A story map was created by the U.S. Forest Service Office of Sustainability and Climate to present and compare these datasets:

https://usfs.maps.arcgis.com/apps/MapSeries/index.html?appid=4d6e58342f5a451dbe9e9c946bf76f85

Metadata access:

Formal metadata can be downloaded from:

https://www.fs.fed.us/rm/boise/AWAE/projects/NFS-regional-climate-change-maps/downloads/NationalForestClimateChangeMapsMetadata.pdf

Dataset corresponding author:

Charles Luce
USDA Forest Service, Rocky Mountain Research Station
charlie.luce@usda.gov

3. Conceptual information

Data type category (as defined in the Introduction to this guidebook):

Hydrology, climate, (winter) animal habitat

Species or ecosystems represented:

This dataset does not represent any individual species or ecosystems.

Units of mapped values:

Historical April 1st SWE: millimeters (mm)
Future April 1st SWE: mm
Absolute change in April 1st SWE: mm
Percent change in April 1st SWE: percent
Historical SRT: days
Future SRT: days
Absolute change in SRT: days
Percent change in SRT: percent

Range of mapped values:

Historical April 1st SWE: 0 to 3,731.08
Future April 1st SWE: 0 to 2,579.12
Absolute change in April 1st SWE: -2,214.3 to 164.847
Percent change in April 1st SWE: -100 to 11.7575
Historical SRT: 0 to 193.961
Future SRT: 0 to 165.841
Absolute change in SRT: -115.496 to 0
Percent change in SRT: -100 to -3.20848

4. Spatial information

Spatial data type: a raster dataset (grid)

Data file format(s): GeoTiff (.tif)

Spatial resolution: 1/24 degree

Geographic coordinate system:

World Geodetic System (WGS) 1984

Spatial extent:

Conterminous United States

Dataset truncation:

The dataset is truncated along the United States borders with Canada and Mexico.

5. Temporal information

Time period represented: Historical (1975-2005); future (later than 2020)

Future time period(s) represented:

End-of-century (2071-2090)

Baseline time period (against which future conditions were compared): 1975-2005.

6. Methods information

Methods overview:

First, a model was developed using cumulative winter (November through March) precipitation and average winter temperature to predict April 1st SWE and SRT (Luce *et al*. 2014). The model was calibrated and verified using data from approximately 500 SNOTEL sites. As documented in Lute and Luce (2017), models of varying complexity (i.e., models with varying numbers of parameters to be adjusted by calibration) were compared and it was found that the simpler models (with fewer parameters) generally outperformed the more complex models. Therefore, a relatively simple model was chosen to create the spatial layers of future SWE and SRT. Using that model, gridded projections of future winter temperature and precipitation from the MACAv2-Metdata dataset (Abatzoglou and Brown 2012) were used to create gridded projections of April 1st SWE and SRT. For more information, please consult the dataset citation listed in section 2 of this chapter.

This dataset employed the following specific models:

locfit package in the R software environment (Loader, 2013)

Major input data sources for this dataset included:

Historical climate observations or models, future climate projections, hydrologic data (snowpack variables)

This dataset used the following general circulation models (GCMs):

BCC-CSM1-1, BCC-CSM1-1-M, BNU-ESM, CanESM2, CCSM4, CNRM-CM5, CSIRO-Mk3.6.0, GFDL-ESM2M, GFDL-ESM2G, HadGEM2-ES, HadGEM2-CC, INM-CM4, IPSL-CM5A-LR, IPSL-CM5A-MR, IPSL-CM5B-LR, MIROC5, MIROC-ESM, MIROC-ESM-CHEM, MRI-CGCM3, NorESM1-M

An ensemble across GCMs is provided; individual files for individual GCMs are not provided. More information about climate models is available in appendix 1. Detailed information about climate models, including model evaluation and comparison among models, is available from Randall *et al.* (2007) and Rupp *et al.* (2013).

This dataset used the following greenhouse-gas scenarios:

RCP 8.5

More information about greenhouse-gas scenarios is available in appendix 2 and from Knutti and Sedláček (2013).

Creation of this dataset involved the following methods to change the spatial resolution of climate models (e.g. to downscale or resample climate models):

The Multivariate Adaptive Constructed Analogs (MACA) downscaling method was used (Abatzoglou and Brown, 2012).

7. Guidelines for interpretation

The mapped values of the dataset may be interpreted as follows:

SWE and SRT are measured in mm and days, respectively, for both the historical and future time periods. Higher SWE values indicate more snow present on April 1st; areas with higher SRT values are projected to have snow retained for a larger number of days each winter. For the absolute change rasters, large negative values in April 1st SWE indicate the largest April 1st SWE decreases. A few areas show positive values for this layer, representing projected increases in April 1st SWE. Similarly, large negative values of absolute change in SRT indicate the largest decreases in the amount of time each winter that snow is expected to be present. For both April 1st SWE and SRT, the lowest possible percent value is -100, which indicates complete loss of snowpack in the future.

Representations of key concepts in climate-change ecology:

The data layers in this dataset primarily represent one important component of climate-change exposure, namely the degree to which areas are expected to experience reduced winter snowpack. In some areas of the Pacific Northwest, transitions from rain to snow and earlier seasonal timing of snowmelt are major concerns related to climate-change effects on ecosystems and watershed hydrology. Snow conditions are ecologically important to a number of plant and animal species in the Pacific Northwest, especially those adapted to mountain habitats (e.g., alpine and subalpine species). For animal species, the seasonal timing, depth, and spatial extent of snowpack can affect access to food resources, ability to hide or escape from predators, and ease of movement across the landscape. For plant species, these snowpack characteristics can affect growth rates, seasonal availability of soil moisture, and seedling establishment. In addition, in watersheds where streams have large contributions from snowmelt, changes in snowpack patterns can have important consequences for watershed hydrology, including changes in timing of peak streamflow or reductions in late-season streamflow.

Because of these concerns, anticipated reductions in snowpack may need to be considered along with information on species and ecosystem-level sensitivity to snowpack changes and information on species' capacity to adapt to changing snowpack conditions. Projected snowpack declines across much of the Pacific Northwest illustrate the importance of changes in watershed hydrology as a critical linkage between climate change and effects on species and ecosystems.

8. Uncertainties

This dataset involves the following assumptions, simplifications, and caveats:

In the study that produced this dataset, model validations were better for April 1st SWE than for SRT, and the dataset authors suggest this may be because there is a stronger physical basis for modeling SWE than SRT (Lute and Luce, 2017). These models used only climate variables to predict changes in snowpack and the input climate variables were at 4-km resolution. As a result, finer-scale influences on snowpack dynamics, such as those based on microclimates produced by topography, are not represented in these data layers. Additionally, this dataset does not represent sensitivity or adaptive capacity, in terms of the ways in which species or ecosystems are expected to respond to projected snowpack reductions.

Quantification of uncertainty:

Several uncertainty metrics of the underlying snow models are provided in Lute and Luce (2017). Nash-Sutcliffe efficiency (NSE) values exceeded 0.71 for SWE and 0.64 for SRT (NSE = 1 indicates a perfect match between a model and observations, whereas NSE = 0 indicates model predictive ability as accurate as the mean of the observed data). Using all data, the site-wise cross validation was 85% for SWE and 81% for SRT. Although uncertainty of the mapped values (i.e., changes in SRT and April 1st SWE) are not provided with the maps, information necessary for calculating them is available; see Lute and Luce (2017).

Field verification:

Modeled snow variables from the historical (baseline) period were field verified (Lute and Luce 2017). Field verification of the projected mapped values in this dataset was not possible because the dataset represents a future condition. Two-fold validations in Lute and Luce (2017) were designed to assess the capability of the model to extrapolate to conditions other than those of calibration.

9. Peer review

Prior to dataset publication, peer review was conducted by external review (at least two anonymous reviewers, each from a different institution). The underlying models were published in two peer-reviewed publications.

10. Conservation applications

Potential conservation applications of this dataset could include the following:

This dataset can be used to envision and plan for future losses in winter snowpack. Winter snowpack reductions can ripple through the hydrologic system of watersheds throughout the year (e.g., contributing to reduced streamflow in summer). As a result, this dataset is potentially relevant to several conservation questions related to human and ecological water use. In areas where fish habitat quality and human water withdrawals are strongly dependent on streamflow that derives from snowmelt, these projections of snowpack dynamics could be used to begin planning for the implications of snowpack reduction. These changes could have implications for fire management, recreation, and agriculture, in addition to ecological effects on snow-dependent plants and animals.

Applicable scales for detailed spatial assessments:

For conservation applications requiring detailed assessment of spatial variation of the dataset within a geographic boundary (such as a protected area), the following geographic scales may be most appropriate (see appendix 3 for more information).

At the scale of: a level-3 ecoregion (e.g., the North Cascades), a single state (Washington, Oregon, or Idaho), a region (multiple states in the Pacific Northwest or in western North America), the continental United States.

Applicable scales for assessing general patterns:

Due to spatial resolution, the dataset may not show detailed spatial variation at the following geographic scales, however, the dataset may be useful to assess general patterns or for comparison to other locations (see appendix 3 for more information).

At the scale of: a small (< 1 km^2) nature preserve, a state park or state wildlife area, a local watershed (12-digit hydrologic unit code [HUC-12]), a Bureau of Land Management (BLM) district, a river watershed (8-digit hydrologic unit code [HUC-8]), an individual county, a national forest.

Use of the dataset in conservation applications may be limited by the following considerations:

This dataset portrays a future of snowpack reductions averaged over several years but does not represent variation in snowpack dynamics from one year to another. It is an independent snow model, so predicting changes in streamflow resulting from changes in snowpack dynamics would require additional hydrologic modeling. Furthermore, because of its spatial resolution and the nature of the input data used to produce the data layers, this dataset cannot be used to evaluate fine-scale differences in snowpack dynamics, such as those produced by topographic variation in rough terrain.

Past or current conservation applications:

The dataset has been used in vulnerability studies and forest planning in several national forests across the Northwest, details of which may be obtained by contacting the corresponding author.

References cited

Abatzoglou, J. T., and T. J. Brown. 2012. A comparison of statistical downscaling methods suited for wildfire applications. International Journal of Climatology 32:772–780.

Knutti, R., and J. Sedláček. 2013. Robustness and uncertainties in the new CMIP5 climate model projections. Nature Climate Change 3:369–373.

Loader, C. 2013. Locfit: Local regression, likelihood and density estimation, in R package version 1.5–9.1. http://cran.rproject.org/package5locfit.

Luce, C., V. Lopez-Burgos, and Z. Holden. 2014. Sensitivity of snowpack storage to precipitation and temperature using spatial and temporal analog models. Water Resources Research 50:2108–2123.

Lute, A., and C. Luce. 2017. Are model transferability and complexity antithetical? Insights from validation of a variable-complexity empirical snow model in space and time. Water Resources Research 53:8825–8850.

Randall, D., R. Wood, S. Bony, R. Colman, T. Fichefet, J. Fyfe, V. Kattsov, and *et al*. 2007. Cilmate models and their evaluation. in S. Solomon, D. Qin, M. Manning, Z. Chen, M. Marquis, K. Averyt, M. Tignor, and H. Miller, editors. Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, New York, NY.

Rupp, D. E., J. T. Abatzoglou, K. C. Hegewisch, and P. W. Mote. 2013. Evaluation of CMIP5 20th century climate simulations for the Pacific Northwest USA. Journal of Geophysical Research 118: 884–907.

Chapter 5: Changes in snowpack, soil moisture, and fuel moisture

Authors:

Diana R. Gergel (University of Washington)
Jennifer Cartwright (U.S. Geological Survey)

1. Dataset overview

This dataset contains future projections of snowpack (represented as **snow-water equivalent**, or SWE), soil moisture (figure 5.1), and **dead-fuel moisture (DFM)**, which is an indicator of fire potential (see chapter glossary for definitions of terms). Soil moisture projections are available on a seasonal basis (e.g., June through August). Projections of SWE are available for the first day of each month from November 1st to May 1st. DFM is projected for **100-hour fuels** and **1000-hour fuels**. These data layers were produced using hydrologic simulations from the **variable infiltration capacity (VIC)** model that were driven by downscaled climate model outputs of precipitation, maximum and minimum temperature, and wind speed. The data layers are all closely related based on hydrologic processes. For example, in areas where April 1st SWE is projected to decline, these snowpack reductions early in

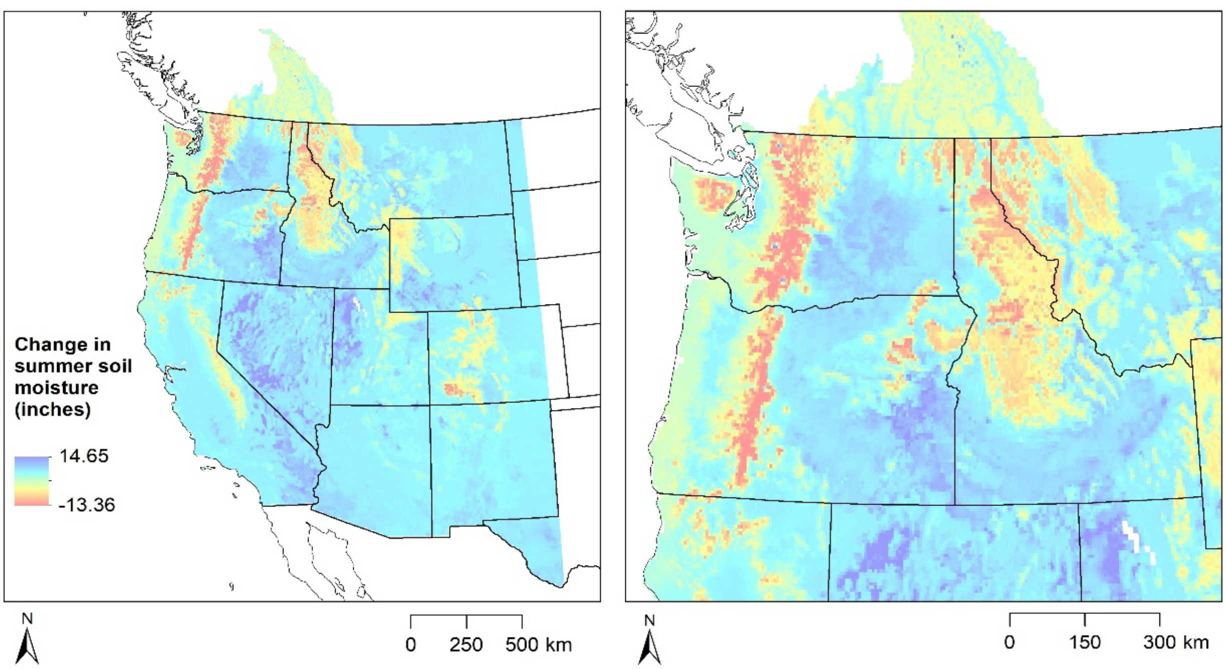

Figure 5.1. Projected change in summer (June through August) soil moisture between the historical period (1971-2000) and the future period (2070-2099) under the representative concentration pathway (RCP) 8.5 greenhouse-gas scenario using an ensemble mean across 10 climate models. Positive and negative values indicate wetter and drier future summer soil conditions, respectively. The left panel shows the entire spatial extent of the dataset; the right panel shows the projected change in summer soil moisture for the Pacific Northwest.

the growing season translate into drier soils in summer that may correspond to drier fuels and thus greater fire potential.

Glossary

Dead-fuel moisture (DFM): the moisture content of materials that may be fuel for fire. Although fire occurrence depends on many factors, lower DFM can contribute to greater fire potential.

Snow Telemetry (SNOTEL): a network of climate and weather stations (SNOTEL sites) administered by the U.S. Department of Agriculture Natural Resources Conservation Service in 11 states in the western U.S.

Snow-water equivalent (SWE): a commonly used measure of snowpack; it is the equivalent amount of liquid water contained within the snowpack.

Variable infiltration capacity (VIC) model: a macroscale, hydrologic model that models the land surface as a grid using meteorological input data to simulate land-atmosphere fluxes and the water and energy balances at the surface (see Liang *et al*. 1994).

100-hour fuels: a class of fuels that might range from approximately 1 to 3 inches (2.5 to 7.6 cm) in diameter; named because it takes fuels of this size roughly 100 hours to respond to changes in moisture conditions.

1000-hour fuels: a class of fuels that might range from approximately 3 to 8 inches (7.6 to 20.3 cm) in diameter; named because it takes fuels of this size roughly 1,000 hours to respond to changes in moisture conditions.

For detailed information about these terms, please consult the dataset citation in section 2.

2. Data access information

Dataset citation:

Gergel, D. R., B. Nijssen, J. T. Abatzoglou, D. P. Lettenmaier, and M. R. Stumbaugh. 2017. Effects of climate change on snowpack and fire potential in the western USA. Climatic Change 141:287–299.

Dataset documentation link:

https://doi.org/10.1007/s10584-017-1899-y
(subscription or fee required)

Data access:

Projections for SWE and soil moisture can be queried, viewed interactively, and downloaded from:
https://climate.northwestknowledge.net/IntegratedScenarios/vis_summarymaps.php

Projections for dead-fuel moisture may be obtained from the corresponding author.

Metadata access:

Formal metadata is not available for this dataset.

Dataset corresponding author:

Diana R. Gergel
Department of Civil and Environmental Engineering, University of Washington
dgergel@gmail.com

3. Conceptual information

Data type category (as defined in the Introduction to this guidebook):

Climate, fire, hydrology

Species or ecosystems represented:

This dataset does not represent any particular species or ecosystems.

Units of mapped values:

Snow-water equivalent: inches (in.)
Soil moisture: in.
Dead-fuel moisture: percent

Range of mapped values:

Ranges of values depend upon the variable, the season selected, the time period of analysis, the choice of greenhouse-gas scenario, and the choice of climate model (or ensemble across climate models). For example, for summer (June through August) soil-moisture projections for 2070-2099 under the RCP 8.5 scenario using a mean across the 10 available climate models, the range of values is roughly 0 to 40 inches.

4. Spatial information

Spatial data type: a raster dataset (grid)

Data file format(s): GeoTiff (.tif), NetCDF (.nc), web map service

Spatial resolution: 1/16°

Geographic coordinate system:

World Geodetic System (WGS) 1984

Spatial extent:

Regional

Dataset truncation:

The dataset is truncated along the United States borders with Canada and Mexico (except for the Pacific Northwest) and along a longitudinal line east of the eastern borders of Montana and Wyoming (103°W).

5. Temporal information

Time periods represented: Control (1960-2005), historical (1971-2000); future (2010-2099)

Future time period(s) represented:

Early 21st century (2010-2039), mid-century (2040-2069), end-of-century (2070-2099).

Baseline time period (against which future conditions were compared): 1971-2000.

6. Methods information

Methods overview:

The VIC hydrologic model (Liang *et al*. 1994) was used to simulate hydrologic processes for the western United States. With meteorological inputs consisting of downscaled climate model outputs, including precipitation, wind speed, and minimum and maximum temperature, the model produces estimates of various fluxes (movements) of energy and water as well as estimates of hydrologic state variables such as SWE and soil moisture. Downscaled outputs from 10 climate models and corresponding hydrologic model simulations were combined to create future projections of SWE, soil moisture, dead-fuel moisture, as well as dynamic processes such as snow melt, evapotranspiration, and runoff into streams. Dead-fuel moisture was calculated using the National Fire Danger Rating System (NFDRS) algorithm for calculating fuel moisture (Cohen and Deeming, 1985). For more information, please consult the dataset citation listed in section 2 of this chapter.

This dataset relied on the following general types of models:

Hydrologic models, climate models

This dataset employed the following specific models:

Variable infiltration capacity (VIC) model (Liang *et al*. 1994).

Major input data sources for this dataset included:

Historical climate observations or models, future climate projections, streamflow data or other hydrologic data

This dataset used the following general circulation models (GCMs):

BCC-CSM1-1-M, CanESM2, CCSM4, CNRM-CM5, CSIRO-Mk3.6.0, HadGEM2-CC365, HadGEM2-ES365, IPSL-CM5A-MR, MIROC5, NorESM1-M

Separate files are provided for each GCM and an ensemble across GCMs is also provided. More information about climate models is available in appendix 1. Detailed information about climate models, including model evaluation and comparison among models, is available from Randall *et al.* (2007) and Rupp *et al.* (2013).

This dataset used the following greenhouse-gas scenarios:

RCP 4.5, RCP 8.5

More information about greenhouse-gas scenarios is available in appendix 2 and from Knutti and Sedláček (2013).

Creation of this dataset involved the following methods to change the spatial resolution of climate models (e.g. to downscale or resample climate models):

The Multivariate Adaptive Constructed Analogs (MACA) downscaling method was used (Abatzoglou and Brown, 2012).

7. Guidelines for interpretation

The mapped values of the dataset may be interpreted as follows:

Higher values of SWE indicate greater mountain snowpack at a particular time in the season, e.g., higher April 1st SWE indicates greater snowpack on April 1st. Lower values of soil moisture for an individual season (e.g., summer) indicate drier soils; higher values indicate wetter soils. Similarly, lower values of fuel moisture indicate drier fuel conditions that may be more conducive to the occurrence of fires. For all variables, differences between historical and future time periods are positive for increases and negative for decreases.

Representations of key concepts in climate-change ecology:

This dataset primarily represents components of climate-change exposure related to watershed hydrology (SWE and soil moisture) and potential fire dynamics (fuel moisture). As discussed in chapter 4, projected changes in snowpack represent important linkages between changing climate conditions and effects on species and ecosystems in certain parts of the Pacific Northwest, such as mountainous areas. Changes in soil and fuel moisture have potential consequences across a range of ecosystems and at a range of elevations.

The components of this dataset can be considered together to assess multiple facets of climate-change exposure for a given area. For example, areas that are projected to experience reduced April 1st SWE may also have drier summer soils and drier fuels that can increase wildfire potential. Species inhabiting these areas might thus be faced with multiple manifestations of climate-change exposure simultaneously, which can be an important consideration in assessing overall climate-change vulnerability. Other considerations not addressed by this dataset include the possibility that different species or ecosystems may respond differently to these forms of climate-change exposure, such as by having different sensitivities to changing watershed hydrology or different capacities to adapt to changing soil and fire dynamics.

8. Uncertainties

This dataset involves the following assumptions, simplifications, and caveats:

The VIC model uses climate model projections as inputs. Although all climate models agree that temperatures will increase, there is substantial variability in precipitation projections among climate models. As a result, in some areas (such as the Northern Cascades) the spread in projected change of April 1 SWE across climate models is substantially larger than the mean projected change (see figure 3 in Gergel *et al*. 2017). This means that, for these locations, projections of change in April 1 SWE can be very different from one climate model to another, translating to substantial uncertainty concerning those SWE projections. Similarly, different climate models produce different projections of soil moisture, especially in lowland areas, and some models show increases in dead-fuel moisture in some areas while other models show decreases in dead-fuel moisture in other parts of the western United States.

Quantification of uncertainty:

In the study that produced these data layers (Gergel *et al*., 2017), uncertainty was quantified by examining patterns across the 10 climate models (GCMs) that were used and the spread in the ensemble of hydrologic model simulations with different climate models. For example, uncertainty in SWE projection was mapped across the landscape by dividing the range of future April 1 SWE across climate models by the ensemble-mean projected change in SWE. For the dead-fuel moisture projections, the number of climate models showing increases (wetter fuels) was compared to the number of models showing decreases (drier fuels).

Field verification:

Field verification of the mapped values in this dataset was not possible because the dataset represents a future condition. Simulated historical SWE values from the VIC model were compared to observed SWE records from **SNOTEL** sites (see supplementary files in Gergel *et al*., 2017).

9. Peer review

Prior to dataset publication, peer review was conducted by external review (at least two anonymous reviewers, each from different institutions).

10. Conservation applications

Potential conservation applications of this dataset could include the following:

The data layers in this dataset could be used to predict several types of hydrologic and ecological changes. For example, locations projected to experience more extreme decreases in summer soil moisture and dead-fuel moisture might be more prone to droughts and wildfires—and the ecological consequences of those types of disturbances—relative to locations projected to have moderate declines or increases in these moisture variables. Watersheds where dramatic declines in snowpack are projected might be expected to experience changes in streamflow that could affect aquatic species.

This dataset is provided through the "Integrated Scenarios of the Future Northwest Environment" website (https://climate.northwestknowledge.net/IntegratedScenarios/index.php). This project presents these hydrologic projections together with climate and vegetation projections and provides several user guides that could be helpful to conservation practitioners. For example, this website provides a tool that guides the user through a series of simple questions and provides advice as to the types of data, visualization products, and analysis that are recommended. For users that are interested in specific locations or areas, the website can produce custom scatterplots, boxplots, and streamflow projections.

Applicable scales for detailed spatial assessments:

For conservation applications requiring detailed assessment of spatial variation of the dataset within a geographic boundary (such as a protected area), the following geographic scales may be most appropriate (see appendix 3 for more information).

At the scale of: a level-3 ecoregion (e.g., the North Cascades), a single state (Washington, Oregon, or Idaho), a region (multiple states in the Pacific Northwest or in western North America).

Applicable scales for assessing general patterns:

Due to spatial resolution, the dataset may not show detailed spatial variation at the following geographic scales, however, the dataset may be useful to assess general patterns or for comparison to other locations (see appendix 3 for more information).

At the scale of: a small (<1 km^2) nature preserve, a state park or state wildlife area, a local watershed (12-digit hydrologic unit code [HUC-12]), a Bureau of Land Management (BLM) district, a river watershed (8-digit hydrologic unit code [HUC-8]), an individual county, a national forest.

Use of the dataset in conservation applications may be limited by the following considerations:

The spatial resolution of the dataset (1/16°) is fairly coarse, such that the dataset cannot be used to resolve spatial variation in the variables of interest for small protected areas. In particular, microscale and even medium-scale variation in soil moisture based on different soil characteristics (e.g., well-drained versus poorly drained soil) and topographic characteristics (e.g., warmer south-facing slopes versus cooler north-facing slopes) cannot be mapped or explored with these data layers. In addition, because climate models disagree somewhat in their projections of future precipitation patterns, use of these data layers to predict hydrologic and ecological changes should be informed by an understanding of the uncertainties surrounding model projections.

Past or current conservation applications:

The dataset has not yet been used in any on-the-ground conservation applications to the knowledge of the authors of this chapter.

References cited

Abatzoglou, J. T., and T. J. Brown. 2012. A comparison of statistical downscaling methods suited for wildfire applications. International Journal of Climatology 32:772–780.

Cohen, J., and D. Deeming. 1985. The National Fire Danger Rating System: basic equations, Gen Tech Rep PSW-82. USDA Forest Service, Pacific Southwest Forest and Range Experiment Station, Albany, CA.

Gergel, D. R., B. Nijssen, J. T. Abatzoglou, D. P. Lettenmaier, and M. R. Stumbaugh. 2017. Effects of climate change on snowpack and fire potential in the western USA. Climatic Change 141:287–299.

Knutti, R., and J. Sedláček. 2013. Robustness and uncertainties in the new CMIP5 climate model projections. Nature Climate Change 3:369–373.

Liang, X., D. P. Lettenmaier, E. F. Wood, and J. Burges. 1994. A simple hydrologically based model of land surface water and energy fluxes for general circulation models. Journal of Geophysical Research 99:14415–14428.

Randall, D., R. Wood, S. Bony, R. Colman, T. Fichefet, J. Fyfe, V. Kattsov, and *et al*. 2007. Cilmate models and their evaluation. in S. Solomon, D. Qin, M. Manning, Z. Chen, M. Marquis, K. Averyt, M. Tignor, and H. Miller, editors. Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, New York, NY.

Rupp, D. E., J. T. Abatzoglou, K. C. Hegewisch, and P. W. Mote. 2013. Evaluation of CMIP5 20th century climate simulations for the Pacific Northwest USA. Journal of Geophysical Research 118: 884–907.

Chapter 6: Forest suitability for large wildfires

Authors:
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Zhiqiang Yang (USDA Forest Service, Rocky Mountain Research Station)
Andrew Yost (Oregon Department of Forestry)
Jennifer Cartwright (U.S. Geological Survey)

1. Dataset overview

This dataset represents projections of environmental suitability for large wildfires in Pacific Northwest forests (figure 6.1). Wildfire occurrence was modeled using climate and terrain data (over the **climate normal** period 1971-2000), which was validated with area burned from 2001 to 2015 (see chapter glossary for definitions of terms). This model was projected into the future, producing maps of future suitability for large wildfires. Results from this modeling effort show predictions of increasing area conducive to occurrence of large forest wildfires under climate-change scenarios, with increases varying by ecoregion.

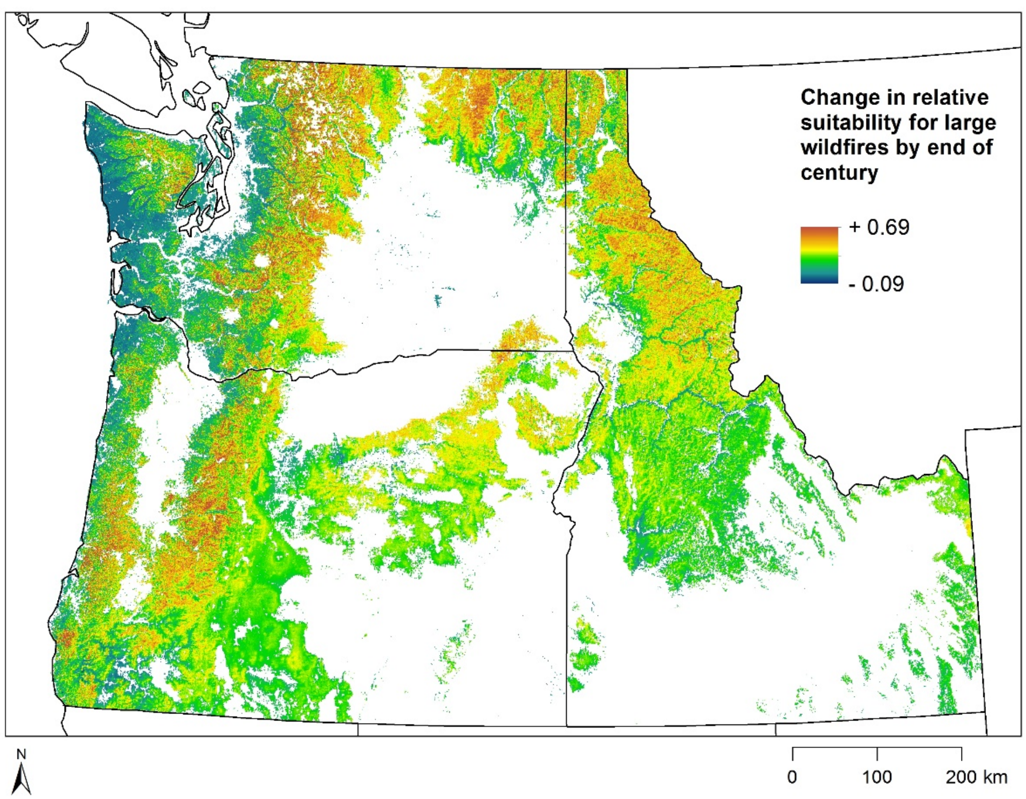

Figure 6.1. Predicted change in relative suitability for large wildfires by the end of the 21st century. Positive values indicate areas where future climate conditions indicate increased suitability for large wildfires; negative values indicate decreased future suitability.

Glossary

Climate normal: a "normal" period is typically defined as three decades, e.g., from 1971-2000. The climate or fire variables averaged across such a 30-year span can represent "normal" climate or environmental conditions during that time period.

For detailed information about these terms, please consult the dataset citation in section 2.

2. Data access information

Dataset citation:

Davis, R., Z. Yang, A. Yost, C. Belongie, and W. Cohen. 2017. The normal fire environment — modeling environmental suitability for large forest wildfires using past, present, and future climate normals. Forest Ecology and Management 390:173–186.

Note that this publication presents a version of the dataset for the states of Oregon and Washington (2-state dataset). The model algorithm was later used to expand the dataset to include the State of Idaho to produce the 3-state dataset depicted in figure 6.1.

Dataset documentation link:

https://doi.org/10.1016/j.foreco.2017.01.027
(open access)

Data access:

The 2-state dataset (Washington and Oregon) can be viewed online and downloaded from:
https://umpquawildbio.users.earthengine.app/view/nfe-web-app-v11

The 3-state dataset (which also includes Idaho) may be obtained by contacting the corresponding authors.

Metadata access:

Formal metadata is not available for this dataset.

Dataset corresponding authors:

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3. Conceptual information

Data type category (as defined in the Introduction to this guidebook):

Fire, climate

Species or ecosystems represented:

This dataset represents forested ecosystems of the Pacific Northwest.

Units of mapped values:

Continuous maps are based on an index of environmental suitability for large wildfire occurrence. Classified maps divide this index into classes of low, moderate, or high suitability.

Range of mapped values:

Continuous maps - 0 to 1
Classified maps – 1 (low), 2 (moderate), 3 (high) environmental suitability

4. Spatial information

Spatial data type: a raster dataset (grid)

Data file format(s): GeoTiff

Spatial resolution: 800 m

Geographic coordinate system:

North American Datum of 1983

Projected coordinate system:

North American Datum of 1983 Albers

Spatial extent:

Regional (Oregon, Washington, and Idaho)

Dataset truncation:

The dataset is truncated along the borders of the States of Washington, Oregon, and Idaho.

5. Temporal information

Time period represented: Future

Future time period(s) represented:

Mid-century (2031 to 2060), end-of-century (2071 to 2100)

Baseline time period (against which future conditions were compared): 1971 to 2000.

6. Methods information

Methods overview:

A MaxEnt model (Phillips *et al*., 2006) was constructed to predict occurrence of large wildfires (fires at least 40 hectares in size) using climate (temperature and precipitation) and topographic variables (elevation and slope). The model was trained using wildfire data from the period 1971 to 2000. Model performance was evaluated by predicting wildfire occurrence during the period 2001 to 2015 and comparing that prediction to real fire data from that same time period. This model validation confirmed that the model was capable of geographically predicting occurrence of large wildfires under normal environmental conditions (Davis *et al*., 2017). The model was then used to project future geographic patterns of large wildfire suitability using climate data for future climate normal time periods under different climate-change scenarios. For more information, please consult the dataset citation listed in section 2 of this chapter.

This dataset relied on the following general types of models:

Machine-learning models based on wildfire locations

This dataset employed the following specific models:

MaxEnt version 3.3 (Phillips *et al*., 2006)

Major input data sources for this dataset included:

Historical climate observations or models, future climate projections, digital elevation models (DEMs), and wildfire perimeter data.

This dataset used the following general circulation models (GCMs):

Downscaled climate projections from NEX-DCP30 used 33 GCMs, which are described in documentation available from:
https://cds.nccs.nasa.gov/nex/

More information about climate models is available in appendix 1. Detailed information about climate models, including model evaluation and comparison among models, is available from Randall *et al.* (2007) and Rupp *et al.* (2013).

This dataset used the following greenhouse-gas scenarios:

RCP 4.5, RCP 8.5

More information about greenhouse-gas scenarios is available in appendix 2 and from Knutti and Sedláček (2013).

Creation of this dataset involved the following methods to change the spatial resolution of climate models (e.g. to downscale or resample climate models):

Downscaled climate projections from NEX-DCP30 are described in Thrasher *et al*. (2013) and in documentation available from:
https://cds.nccs.nasa.gov/nex/

7. Guidelines for interpretation

The mapped values of the dataset may be interpreted as follows:

In the context of this dataset, environmental suitability for large wildfires is relative such that continuous map values can be compared from one location to another but do not have an absolute interpretation. Higher values for large wildfire suitability indicate landscapes that, based on climate and terrain, are more typically associated with large wildfire occurrence under normal climate conditions (3-decade averages). A classified map value of “low” indicates the likelihood of large wildfire occurrence under normal climate conditions is less than would be expected by random chance. The “moderate” and “high” classes indicate higher than random likelihoods of occurrence.

Representations of key concepts in climate-change ecology:

Climate change is expected to produce many varied indirect effects on forest ecosystems, including changes in disturbance regimes such as wildfires. Forested areas that have greater projected changes in wildfire suitability may be more vulnerable to this manifestation of climate change, either in terms of climate-change exposure (greater change in temperature or precipitation patterns that influence fires) or in terms of climate sensitivity (some landscape locations may be more or less sensitive to changing fire regimes based on terrain and topographic position).

Projected changes in forest wildfire dynamics resulting from climate change have a range of potential consequences for forest ecosystems and species, as well as for people. For example, some threatened and endangered species in the Pacific Northwest—including the northern spotted owl and the marbled murrelet—depend on mature, old-growth forests for habitat and may be negatively affected by stand-replacing fires. Changing fire dynamics also have potential implications for watershed processes such as erosion and influencing water quality in receiving stream reaches. Additionally, because fire suppression efforts represent substantial annual expenditures, projected changes in forest wildfire suitability over time represent a potentially important link between climate change and social, economic, and human health (e.g., air quality) considerations.

8. Uncertainties

This dataset involves the following assumptions, simplifications, and caveats:

The modeling efforts that produced this dataset used only climate and terrain variables as inputs, however, fire behavior can be influenced by a range of other landscape characteristics. Possible changes to forest fuels were not considered, such as those that could arise from previous fires, fuel-reduction programs, carbon dioxide fertilization, or transitions from forest to non-forest ecosystems resulting from climate change. Furthermore, representation of climate variables as 30-year normals does not account for interannual variability between cool/moist years and hot/dry years. It should also be noted that the models represented likelihood of large wildfire occurrence but not fire severity.

Quantification of uncertainty:

Models of fire suitability were constructed independently for each of 33 GCMs, and results were presented as median and standard deviation across models. Thus, the standard deviation of model outputs provides information about uncertainty that derives from climate-change projections.

Field verification:

Large wildfire suitability that was modeled using climate and fire data from 1971-2000 was used to predict large wildfire suitability from 2001 to 2015. These predictions were then validated with large wildfires that occurred from 2001 to 2015. Forests mapped as having low wildfire suitability burned an average of 5 times less than would be expected by chance, whereas forests with moderate and high suitability burned on average 1.5 times and 2 to 3 times more than would be expected by chance, respectively.

9. Peer review

Prior to dataset publication, peer review of the journal paper presenting the 2-state dataset for Oregon and Washington was conducted by external review (at least two anonymous reviewers, each from a different institution).

10. Conservation applications

Potential conservation applications of this dataset could include the following:

This dataset offers forest managers a way of visualizing geographic patterns of how climate change may affect geographic occurrence patterns of large forest wildfires. These projections could help inform forest management including fuels treatment, forest reserve network design, and forest carbon management. Projected changes in suitability for large wildfires could also be considered in urban planning and land-use decisions in the wildland-urban interface.

Applicable scales for detailed spatial assessments:

For conservation applications requiring detailed assessment of spatial variation of the dataset within a geographic boundary (such as a protected area), the following geographic scales may be most appropriate (see appendix 3 for more information).

At the scale of: a Bureau of Land Management (BLM) district, a river watershed (8-digit hydrologic unit code [HUC-8]), an individual county, a national forest, a level-3 ecoregion (e.g. the North Cascades), a single state (Washington, Oregon, or Idaho), a region (multiple states in the Pacific Northwest).

Applicable scales for assessing general patterns:

Due to spatial resolution, the dataset may not show detailed spatial variation at the following geographic scales, however, the dataset may be useful to assess general patterns or for comparison to other locations (see appendix 3 for more information).

At the scale of: a small (<1 km^2) nature preserve, a state park or state wildlife area, a local watershed (12-digit hydrologic unit code [HUC-12]).

Use of the dataset in conservation applications may be limited by the following considerations:

Model projections represented in this dataset did not incorporate some of the management considerations and processes that may be important in shaping wildfire patterns into the future. These include fuels management programs (e.g., controlled burns, forest thinning), as well as possible transitions from forest to non-forest ecosystems in some areas as a result of climate change. Furthermore, the dataset represents only relative suitability for large wildfires over 30-year periods and cannot generally be used to make short-term predictions for fire behavior. In addition, the dataset does not address fire severity, which may be an important management consideration in addition to fire occurrence.

Past or current conservation applications:

Conservation case study #1

This dataset was used by the Oregon Department of Forestry to show agency leaders and Oregon State legislators how projections of future climate variables can be expected to increase the threat of large forest wildfires through this century in Oregon. This application is ongoing for the agency with the first effort to expand the capacity to manage the increase in occurrence and threat of forest wildfire expected in the first half of 2019.

The process revealed how this dataset could be used to predict the specific spatial pattern and incremental increase in the relative probability for large wildfires across Oregon and Washington. The research validated the experience of increased wildfire over the past decade and showed the agency how the modeling can be used to know in which regions we can and should expect large wildfires to occur and areas where large wildfires will expand. The agency and legislators learned that the demand for extra capacity for controlling wildfire across the State will increase in the future.

For more information on this conservation case study, please contact the corresponding author listed in section 2.

Conservation case study #2

An earlier version of this dataset was used by the Department of the Interior, BLM, to inform a revision of the agency's Resource Management Plan for western Oregon (Davis *et al*., 2016). It helped answer questions on the likely general locations and extent for future large wildfires over the next five decades on forests the BLM manages within the northern spotted owl's geographic range. It supported forest economic (timber harvest) modeling and spotted owl habitat dynamics used in population models. Resource Management Plans (RMPs) are expected to inform land management over multiple years before they are revised to incorporate new information and changing conditions. The latest RMP for western Oregon was published in 2016.

A limitation of this dataset was its inability to predict fire severity, which is an important factor in how fires affect forests and habitat. Thus, the dataset was only used to predict likely locations of future large wildfires, and ancillary data and additional methods were needed to predict fire severity within those locations.

For more information on this conservation case study, please contact the corresponding author listed in section 2.

References cited

Davis, R., L. Evers, Y. Gallimore, J. Volpe, and C. Belongie. 2016. Appendix D – Modeling large stochastic wildfires and fire severity within the range of the northern spotted owl. Pages 1229–1244 in the Resource Management Plan for Western Oregon. Department of the Interior, Bureau of Land Management, Portland, OR. https://www.blm.gov/or/plans/rmpswesternoregon/files/prmp/RMPWO_Vol_3_Appendix_D.pdf

Davis, R., Z. Yang, A. Yost, C. Belongie, and W. Cohen. 2017. The normal fire environment — modeling environmental suitability for large forest wildfires using past, present, and future climate normals. Forest Ecology and Management 390:173–186.

Knutti, R., and J. Sedláček. 2013. Robustness and uncertainties in the new CMIP5 climate model projections. Nature Climate Change 3:369–373.

Phillips, S. J., R. P. Anderson, and R. E. Schapire. 2006. Maximum entropy modeling of species geographic distributions. Ecological Modelling 190:231–259.

Randall, D., R. Wood, S. Bony, R. Colman, T. Fichefet, J. Fyfe, V. Kattsov, and *et al*. 2007. Cilmate models and their evaluation. *in* S. Solomon, D. Qin, M. Manning, Z. Chen, M. Marquis, K. Averyt, M. Tignor, and H. Miller, editors. Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, New York, NY.

Rupp, D. E., J. T. Abatzoglou, K. C. Hegewisch, and P. W. Mote. 2013. Evaluation of CMIP5 20th century climate simulations for the Pacific Northwest USA. Journal of Geophysical Research 118: 884–907.

Thrasher, B., J. Xiong, W. Wang, F. Melton, A. Michaelis, and R. Nemani. 2013. Downscaled climate projections suitable for resource management. Eos, Transactions American Geophysical Union 94:321–323.

Chapter 7: Projected fire regime changes for the western United States

Authors:
Sean Parks (Aldo Leopold Wilderness Research Institute, Rocky Mountain Research Station, USDA Forest Service)
Jennifer Cartwright (U.S. Geological Survey)

1. Dataset overview

This dataset includes future projections of fire regime change in the western U.S., specifically changes in fire frequency (represented as **fire return interval, FRI**, figure 7.1) and fire severity (represented as **percent replacement severity, PRS**), as well as vegetation classes (see chapter glossary for definitions of terms). These data layers were produced using a **climate analog** approach, in which the projected future climate conditions of each pixel (i.e., each target location) were compared to other pixels' historical climate conditions. The underlying principle is that, for a given location with projected future climate conditions, that location's future vegetation and fire regime can be inferred by examining the current vegetation and fire regime of climate analogs (locations with current climate similar to the future climate of the target location).

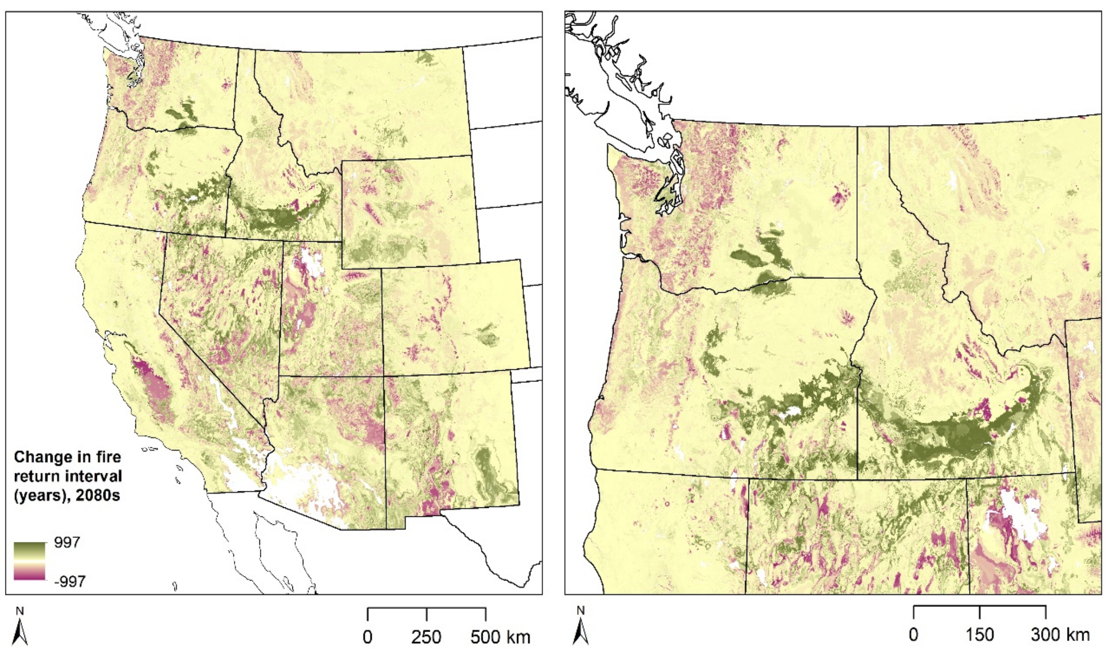

Figure 7.1. Change in fire return interval between the baseline (historical) period and the 2080s. Negative values indicate a decrease in fire-return interval corresponding to increased fire frequency in the future, whereas positive values indicate an increase in fire-return interval corresponding to decreased fire frequency. The left panel shows the entire extent of the dataset; the right panel shows change in fire return interval for the Pacific Northwest.

Glossary

Climate analogs: locations with current climate conditions similar to (analogous to) the projected future climate conditions of a target location.

Fire return interval (FRI): a metric of fire frequency representing the average number of years between fires for a given location.

Percent replacement severity (PRS): a metric of fire severity representing the percentage of fires resulting in at least 75% canopy consumption, which can be inferred as the probability of stand-replacing fire for a given location.

For detailed information about these terms, please consult the dataset citation in section 2.

2. Data access information

Dataset citation:

Parks, S. A., L. M. Holsinger, C. Miller, and M. Parisien. 2018. Analog-based fire regime and vegetation shifts in mountainous regions of the western US. Ecography 41:910–921.

Dataset documentation link:

https://www.fs.usda.gov/treesearch/pubs/55029
(open access)

Data access:

The dataset may be obtained by contacting the corresponding author.

The dataset is not available for interactive online map viewing.

Metadata access:

Formal metadata is not available for this dataset.

Dataset corresponding author:

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sean.parks@usda.gov

3. Conceptual information

Data type category (as defined in the Introduction to this guidebook):

Fire, vegetation

Species or ecosystems represented:

This dataset does not represent any individual species or ecosystems.

Units of mapped values:

Fire return interval: years
Percent replacement severity: percent
Vegetation classes

Range of mapped values:

Ranges of mapped values depend on time period under consideration. Vegetation classes are coded as follows: 1=barren; 2=mesic forest; 3=cold forest; 4=dry forest; 5=shrubland; 6=grassland.

4. Spatial information

Spatial data type: a raster dataset (grid)

Data file format(s): GeoTiff (.tif)

Spatial resolution: 1 km

Geographic coordinate system:

North American Datum of 1983

Projected coordinate system:

North American Datum of 1983 Equidistant Conic

Spatial extent:

Western United States (11 western states in the continental United States)

Dataset truncation:

The dataset is truncated along the United States borders with Canada and Mexico and along the eastern borders of Montana, Wyoming, Colorado, and New Mexico.

5. Temporal information

Time period represented: Future

Future time period(s) represented:

Mid-century (2041–2070), end-of-century (2071–2100)

Baseline time period (against which future conditions were compared): 1961–1990.

6. Methods information

Methods overview:

Estimates of reference vegetation and fire regime variables were used to represent the period from approximately 1700 to 1900. For each pixel, climate data (climatic moisture deficit and evapotranspiration) were used to identify climate analogs, i.e., pixels with historical climate conditions similar to (analogous to) the projected future climate of the target pixel. Thus, climate analogs can be thought of as "incoming climates" because they represent the climate conditions that are anticipated to occupy a target pixel in the future (Parks *et al*. 2018). For the target pixel, the three geographically nearest **climate analog** pixels were identified and fire regime variables (FRI and PRS) were averaged, to enable comparison of reference fire variables to those variables from the averaged analogs. A similar analog-based approach was also used to examine changes in vegetation, represented as broad vegetation classes. For more information, please consult the dataset citation listed in section 2 of this chapter.

This dataset relied on the following general types of models:

Climate-analog modeling.

Major input data sources for this dataset included:

Historical climate observations or models, future climate projections, variables representing fire regime characteristics (FRI and PRS) and vegetation types from LANDFIRE (Rollins 2009).

This dataset used the following general circulation models (GCMs):

CanESM2, ACCESS1.0, IPSL-CM5A-MR, MIROC5, MPI-ESM-LR, CCSM4, HadGEM2-ES, CNRM-CM5, CSIRO-Mk3.6.0, GFDL-CM3, INM-CM4, MRI-CGCM3, MIROC-ESM, CESM1-CAM5, GISS-E2R

An ensemble across GCMs is provided; individual files for individual GCMs are not available. More information about climate models is available in appendix 1. Detailed information about climate models, including model evaluation and comparison among models, is available from Randall *et al.* (2007) and Rupp *et al.* (2013).

This dataset used the following greenhouse-gas scenarios:

RCP 8.5

More information about greenhouse-gas scenarios is available in appendix 2 and from Knutti and Sedláček (2013).

Creation of this dataset involved the following methods to change the spatial resolution of climate models (e.g. to downscale or resample climate models):

Climate data were downscaled using ClimateNA software version 5.10 (Wang *et al*., 2016)

<u>7. Guidelines for interpretation</u>

The mapped values of the dataset may be interpreted as follows:

Higher values of FRI indicate longer average time periods between fires, i.e., lower fire frequency. Higher values of PRS indicate greater fire intensity or severity. Projected changes in these variables can be assessed by examining differences between a given variable in the reference time period and a future time period.

Representations of key concepts in climate-change ecology:

The dataset integrates components of climate-change exposure (in that spatial differences across the landscape in climatic moisture deficit and evapotranspiration were used to drive the analysis) and sensitivity to change (in that climate analogs were used to infer potential changes to vegetation and fire regime characteristics). These changes can inform an overall assessment of climate vulnerability for a given location, related to the expected magnitude and direction of change for fire regime characteristics.

As described in chapter 6, projected climate-driven changes to fire regimes have a range of potential consequences for species, ecosystems, and watershed processes, as well as for human society. Changes in fire frequency and/or intensity may affect different species in different ways (e.g., some species may benefit from more frequent fires while others are negatively affected). In addition, projected changes to fire dynamics may interact with other climate-driven changes to habitats, such as changes in watershed hydrology, changes to seasonal timing, and invasive species and forest pest dynamics.

8. Uncertainties

This dataset involves the following assumptions, simplifications, and caveats:

The analog-based approach used to produce this study implicitly assumes that climate, fire regimes, and vegetation are in equilibrium, and that there are no lags between changing climate and changing vegetation and fire patterns. Specifically, this analysis does not account for natural and human-caused disequilibrium between climate, vegetation, and fire. Natural disequilibrium arises, for example, when long-lived organisms such as trees can survive and persist under a warming climate even though seedlings of the same species cannot. Human-caused disequilibrium results from human actions such as fire suppression, prescribed burns, agricultural and grazing operations, and landscape fragmentation. The analog-based approach used to produce this dataset is not a process-based model and so does not explicitly represent processes of interest, such as carbon dioxide fertilization and vegetation feedbacks to fire dynamics. Notably, only two climate variables were used in the analysis to produce the dataset, although a parallel analysis with 26 climate variables (some of which represented climate extremes and seasonality) produced similar results. In addition, the reference-period fire regime and vegetation data used in the analysis have inaccuracies that are not quantified due to missing information on fire histories in some land cover types. Lastly, invasive species (some of which are known to substantially alter fire regimes) are not incorporated into this analysis.

Quantification of uncertainty:

Results from this analysis were potentially sensitive to a number of choices in the analysis, so a sensitivity analysis was conducted for several of these parameters, including bin size (the breadth of climate conditions used to define analogs), the number of analogs used for averaging of fire regime characteristics, and the number and type of climate variables used to define climate analogs.

Field verification:

Field verification of the mapped values in this dataset was not possible because the dataset represents a future condition. Historical fire regime and vegetation variables also could not be field-verified due to limited historical data.

9. Peer review

Prior to dataset publication, peer review was conducted by external review (at least two anonymous reviewers, each from a different institution).

10. Conservation applications

Potential conservation applications of this dataset could include the following:

Projections for fire regime changes represented in this dataset indicate that, rather than universal increase or decrease in fire frequency or severity, changes in these fire regime characteristics will vary based on bioclimatic domain. In relatively cool, moist forests of the Pacific Northwest, such as in the northern Cascades and the Olympic peninsula, fires are projected to become more frequent (lower FRI) and less intense (lower PRI). Conversely, in drier forests of the eastern Cascades, fires are projected to become less frequent (higher FRI). These projected changes can be used to help inform fire management policies, especially in protected areas where managers strive to restore or mimic natural fire patterns. In some cases, projected transitions from one vegetation type to another (such as from dry forest to non-forest) could be used to anticipate ecosystem-level changes with implications for ecosystem services, wildlife habitat, and other important components of ecosystem function.

Applicable scales for detailed spatial assessments:

For conservation applications requiring detailed assessment of spatial variation of the dataset within a geographic boundary (such as a protected area), the following geographic scales may be most appropriate (see appendix 3 for more information).

At the scale of: a Bureau of Land Management (BLM) district, a river watershed (8-digit hydrologic unit code [HUC-8]), an individual county, a national forest, a level-3 ecoregion (e.g. the North Cascades), a single state (Washington, Oregon, or Idaho), a region (multiple states in the Pacific Northwest or in western North America).

Applicable scales for assessing general patterns:

Due to spatial resolution, the dataset may not show detailed spatial variation at the following geographic scales, however, the dataset may be useful to assess general patterns or for comparison to other locations (see appendix 3 for more information).

At the scale of: a small (<1 km^2) nature preserve, a state park or state wildlife area, a local watershed (12-digit hydrologic unit code [HUC-12]).

Use of the dataset in conservation applications may be limited by the following considerations:

The vegetation, fire, and climate relationships represented in this dataset implicitly rely on an assumption of equilibrium. However, natural and human-caused disequilibrium will likely result in a lagged and nuanced response of fire regimes and vegetation to climate change. Instead of strictly interpreting the timing and magnitude of projected changes, users of these datasets are instead urged to consider the general direction of change. That is, users are urged to recognize that a warming climate is likely pushing the systems toward the fire regimes and vegetation depicted in these products. Nevertheless, results from the study that produced this dataset suggest a potential tipping point (at intermediate values of climatic moisture deficit generally corresponding to dry forests) at which small shifts in climate could result in forest conversion to non-forest.

Past or current conservation applications:

The dataset has not yet been used in any on-the-ground conservation applications to the knowledge of the authors of this chapter.

References cited

Knutti, R., and J. Sedláček. 2013. Robustness and uncertainties in the new CMIP5 climate model projections. Nature Climate Change 3:369–373.

Parks, S. A., L. M. Holsinger, C. Miller, and M. Parisien. 2018. Analog-based fire regime and vegetation shifts in mountainous regions of the western US. Ecography 41:910–921.

Randall, D., R. Wood, S. Bony, R. Colman, T. Fichefet, J. Fyfe, V. Kattsov, and *et al*. 2007. Cilmate models and their evaluation. *in* S. Solomon, D. Qin, M. Manning, Z. Chen, M. Marquis, K. Averyt, M. Tignor, and H. Miller, editors. Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, New York, NY.

Rollins, M. G. 2009. LANDFIRE: a nationally consistent vegetation, wildland fire, and fuel assessment. International Journal of Wildland Fire 18:235–249.

Rupp, D. E., J. T. Abatzoglou, K. C. Hegewisch, and P. W. Mote. 2013. Evaluation of CMIP5 20th century climate simulations for the Pacific Northwest USA. Journal of Geophysical Research 118: 884–907.

Wang, T., A. Hamann, D. Spittlehouse, and C. Carroll. 2016. Locally downscaled and spatially customizable climate data for historical and future periods for North America. PLoS One 11:e0156720.

Chapter 8: Database of unburned areas within fire perimeters

Authors:

Arjan Meddens (Washington State University)
Anthony Martinez (USDA Forest Service)
Jennifer Cartwright (U.S. Geological Survey)

1. Dataset overview

This dataset is a compilation of spatial polygons representing the **unburned areas** (that include **fire refugia**) within 2,298 fires from 1984 to 2014 within eastern Washington, eastern Oregon, and Idaho (see chapter glossary for definitions of terms). On average, 10% of the area within mapped **fire perimeters** are unburned areas (Meddens *et al*. 2018), yet these areas have rarely been mapped and are typically not represented in fire perimeter datasets. Therefore, this dataset is the first comprehensive database of recent unburned areas (including fire refugia) for this region of the Pacific Northwest (figure 8.1).

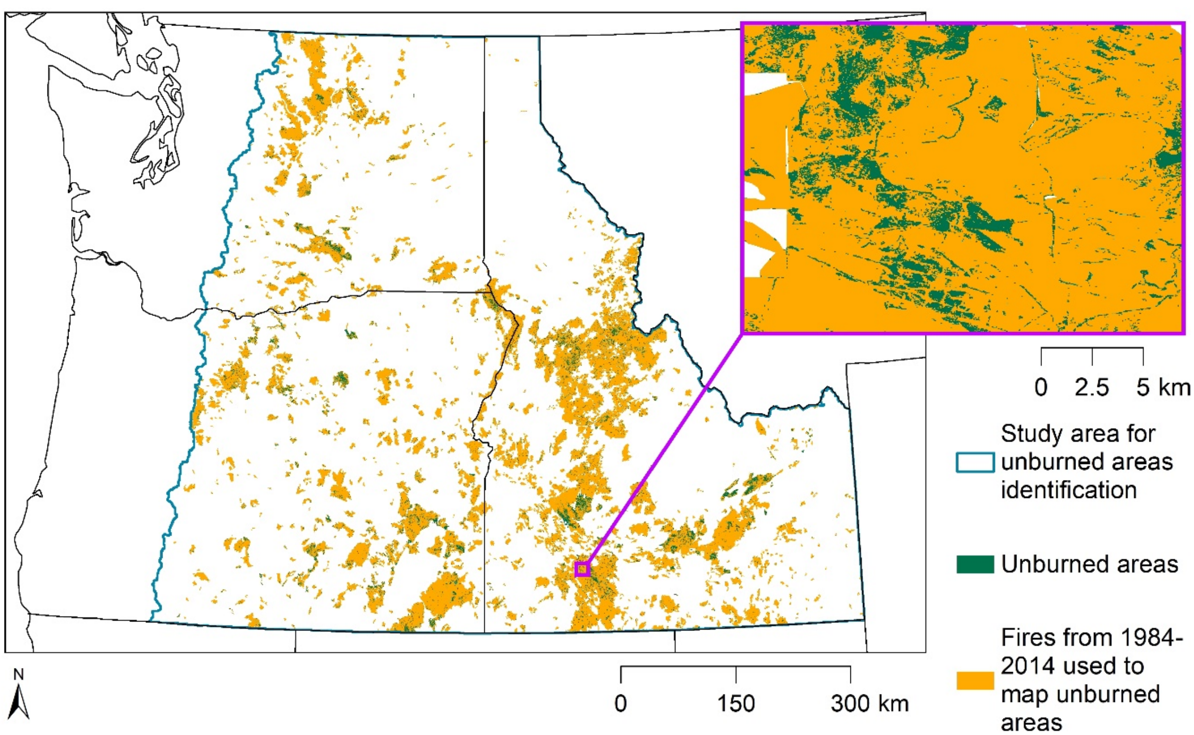

Figure 8.1. Unburned areas within fires that occurred from 1984 to 2014. The inset map (purple frame) shows an expanded subset of the unburned areas (green) within a larger fire perimeter (orange). Note that not all unburned areas are visible in the regional map as many of the unburned areas are relatively small.

Glossary

Fire refugia: "remnants of habitat that maintain ecological function following relatively low-severity fire" (Meddens *et al*. 2018).

Fire perimeter: the outer edge of a wildfire or prescribed fire.

Landsat scene: a remote-sensing image of the Earth's surface produced by the Landsat program for a location at a given time.

Unburned island (also referred to as **unburned areas**): small areas within a larger fire perimeter that did not burn, which make a useful (although non-equivalent) proxy for fire refugia.

For detailed information about these terms, please consult the dataset citation in section 2.

2. Data access information

Dataset citation:

Meddens, A., C. A. Kolden, J. A. Lutz, J. T. Abatzoglou, and A. Hudak. 2018. Spatiotemporal patterns of unburned areas within fi re perimeters in the northwestern United States from 1984 to 2014. Ecosphere 9:e02029.

Dataset documentation link:

https://doi.org/10.1002/ecs2.2029
(open access)

Data access:

The dataset can be downloaded from:
https://www.sciencebase.gov/catalog/item/59a7452ce4b0fd9b77cf6ca0.

The dataset is not available for interactive online map viewing.

Metadata access:

Metadata can be downloaded from:
https://www.sciencebase.gov/catalog/item/59a7452ce4b0fd9b77cf6ca0

Dataset corresponding author:

Arjan Meddens
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arjan.meddens@wsu.edu

3. Conceptual information

Data type category (as defined in the Introduction to this guidebook):

Fire

Species or ecosystems represented:

This dataset does not represent any individual species or ecosystems.

Units and range of mapped values:

Not applicable because this dataset does not depict a range of values. Instead it depicts unburned areas as polygons.

4. Spatial information

Spatial data type: a vector dataset (polygons)

Data file format(s): Shapefile (.shp)

Geographic coordinate system:

North American Datum of 1983

Projected coordinate system:

Universal Transverse Mercator (UTM) Zone 11 North

Spatial extent:

Regional

Dataset truncation:

The dataset is truncated along the following borders: United States border with Canada; Idaho border with Montana, Wyoming, Utah, and Nevada; Oregon border with Nevada and California.

5. Temporal information

Time period represented: Historic / recent (1984 - 2014)

6. Methods information

Methods overview:

Fire perimeters for 2,298 fires from 1984 to 2014 were obtained from the Monitoring Trends in Burn Severity (MTBS) database, which includes all fires of at least 405 hectares in the western United States. To detect **unburned islands**, pairs of **Landsat scenes** were compared: an immediate post-fire scene was compared with a scene from one year earlier from the same season, and a one-year-post-fire scene was compared to a pre-fire scene from the same season. A classification tree approach was applied to separate burned from unburned areas (fully described in Meddens *et al*. (2016), which demonstrated 89% classification accuracy when compared with field observations). Additional adjustments were made to account for the seasonal timing of vegetation greenness and to remove single isolated pixels that were identified as being fire refugia. The resulting gridded (raster) dataset was then transformed to a polygon shapefile dataset. For more information, please consult the dataset citation listed in section 2 of this chapter.

Major input data sources for this dataset included:

Remote-sensing data (Landsat)

7. Guidelines for interpretation

The mapped values of the dataset may be interpreted as follows:

Polygons represent areas of the landscape that were unburned areas within larger fire perimeters, where fire refugia may exist.

Representations of key concepts in climate-change ecology:

Over recent decades, the size of fires in the western United States and the overall area burned each year has been increasing, attributable in part to climate change (Meddens *et al*., 2018). Thus, changes in fire patterns are a way in which climate-change exposure is manifested.

To the degree that fire refugia are maintained in constant locations from one fire to another (i.e., if they are determined by landscape characteristics such as topography or water availability), they may represent areas of resistance to changing fire dynamics. They may also play a role in resilience to disturbance events (e.g., fires) because they may provide seed sources from which plant species can recolonize surrounding burned areas and they may provide post-fire animal habitat. For these reasons, areas with lower densities of fire refugia might be more sensitive to changes in fire patterns. It should be noted, however, that this dataset catalogs refugia from individual fires but does not depict longer-term spatial patterns in the likelihood of refugia to exist (i.e., to persist from one fire to another).

8. Uncertainties

This dataset involves the following assumptions, simplifications, and caveats:

The input data (Landsat scenes) used to produce this dataset had a spatial resolution of 30 m. The analysis removed single isolated pixels from being considered fire refugia. Therefore, fire refugia smaller than two Landsat pixels (1,800 m^2) could not be detected, although such small fire refugia might play ecologically important roles in post-fire ecosystem recovery. The analysis that produced this dataset did not differentiate between unburned patches that function as habitat for wildlife from those that do not (e.g., bare rock).

Quantification of uncertainty:

The classification tree approach developed by Meddens *et al*. (2016) and used to produce this dataset had a classification accuracy of 89% for the 19 wildfires studied by Meddens *et al*. (2016). The dataset described in this chapter and in Meddens *et al*. (2018) depicts refugia for a much larger number of fires (2,298 as opposed to 19); thus, it should not be assumed to have an equivalent classification accuracy.

Field verification:

This dataset was produced using an approach developed by Meddens *et al*. (2016), based on a study that analyzed field data from 19 wildfires. Field observations were used to calibrate and improve the model used to detect fire refugia from Landsat data.

9. Peer review

Prior to dataset publication, peer review was conducted by external review (at least two anonymous reviewers, each from a different institution).

10. Conservation applications

Potential conservation applications of this dataset could include the following:

The study that produced this dataset addressed a primary concern among natural-resource managers in the context of climate change: as fires have become larger and have burned larger portions of the landscape, fire refugia might be dwindling in size or prevalence. The study found no evidence of such a trend. Fire refugia are important to biodiversity conservation because they can provide shelter to wildlife during fires and habitat after fires, and because they can function as seed sources for plant recolonization of burned areas. Together with other research on fire refugia, this study is improving the understanding of how, where, and why fire refugia occur, which may lead to improved ability to predict the effects of various fuel-management strategies.

Applicable scales for detailed spatial assessments:

For conservation applications requiring detailed assessment of spatial variation of the dataset within a geographic boundary (such as a protected area), the following geographic scales may be most appropriate (see appendix 3 for more information).

At the scale of: a state park or state wildlife area, a local watershed (12-digit hydrologic unit code [HUC-12]), a Bureau of Land Management (BLM) district, a river watershed (8-digit hydrologic unit code [HUC-8]), an individual county, a national forest, a level-3 ecoregion (e.g. the North Cascades), a single state (Washington, Oregon, or Idaho), a region (multiple states in the Pacific Northwest).

Within any of the above geographic scales, the dataset cannot be interpreted for areas that did not burn between 1984 and 2014.

Use of the dataset in conservation applications may be limited by the following considerations:

This dataset depicts the locations of unburned islands within past fires but cannot independently be used to predict the locations of future fire refugia. For most unburned islands, it is unknown how likely they are to remain unburned through subsequent fires. Furthermore, the unburned islands depicted in this dataset have not been assessed in terms of their function as habitat. For example, some unburned islands in this dataset could represent bare rock or invasive species and do not provide the ecosystem services typically associated with fire refugia (i.e., wildlife habitat, critical seed sources for recolonization).

Past or current conservation applications:

Conservation case study

The greater sage-grouse (*Centrocercus urophasianus*) has experienced steady population declines for several decades, primarily due to habitat loss. To determine if mitigation of sage-grouse population decline due to habitat loss from fire might be effective, this dataset was used by the Oregon Department of Fish and Wildlife to answer the following questions:

(1) Do fires negatively affect sage-grouse population trends in southeastern Oregon?
(2) Do unburned islands reduce the negative impact of fires on these population trends?

Steenvoorden *et al*. (2019) found that fire did negatively affect sage-grouse population trends; however, in the presence of sufficiently large unburned islands within fire perimeters, sage-grouse populations remained stable. It should be noted that the binary nature of the dataset (i.e., burned or not burned) does not allow for inclusion of lightly burned patches that could still function as species-specific fire refugia.

For more information on this conservation case study, please contact the corresponding author listed in section 2.

References cited

Meddens, A. J. H., C. A. Kolden, and J. A. Lutz. 2016. Detecting unburned areas within wildfire perimeters using Landsat and ancillary data across the northwestern United States. Remote Sensing of Environment 186:275–285.

Meddens, A., C. A. Kolden, J. A. Lutz, J. T. Abatzoglou, and A. Hudak. 2018. Spatiotemporal patterns of unburned areas within fi re perimeters in the northwestern United States from 1984 to 2014. Ecosphere 9:e02029.

Steenvoorden, J., A. Meddens, A. Martinez, L. Foster, and W. Kissling. 2019. The potential importance of unburned islands as refugia for the persistence of wildlife species in fire-prone ecosystems. Ecology and Evolution 9(15): 2045-7758.

Chapter 9: Stream temperature and climate velocity predictions in the Pacific Northwest

Authors:
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Jennifer Cartwright (U.S. Geological Survey)

1. Dataset overview

These datasets contain predictions of stream temperature **climate velocity** and **stream-warming rates** throughout 222,000 km of streams and rivers in the northwestern U.S (see chapter glossary for definitions of terms). Specifically, these are predictions of the rates at which mean August water temperature isotherms (units of the same temperature) shift through streams under six climate-change scenarios (figure 9.1). The predictions are based on modeled relationships between environmental covariates and water temperature patterns that vary among streams. Climate-change scenarios include a continuation of the historical rate of warming, and multiples of that historical rate (2 and 3 times), combined with **stream sensitivity** that either mirrors historical stream sensitivity (with cold streams less sensitive to air warming than warm streams) or else stream sensitivity that is just as high for cold streams as for warm streams. The velocity scenarios were derived from the **NorWeST** stream temperature model scenarios (Isaak *et al*., 2017), which are available to describe historical and future conditions for the months of June, July, August, and September (Isaak *et al*., 2016a). The stream

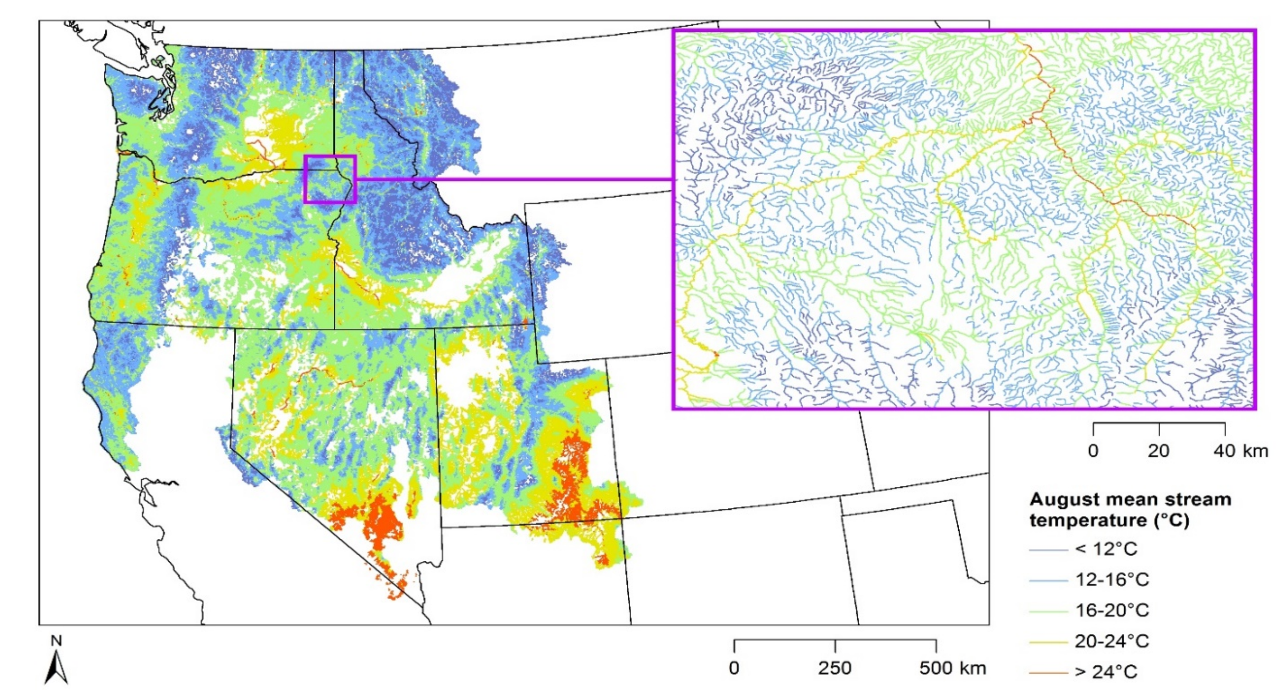

Figure 9.1. Projected August mean stream temperatures based on projected changes in August air temperature and streamflow for the A1B greenhouse-gas scenario in the 2080s (2070-2099). The inset map (purple frame) shows a zoomed-in view of mapped stream temperature projections.

temperature dataset encompassing 23,000 monitoring sites used to develop the NorWeST scenarios is also available as summaries of daily mean, maximum, and minimum temperatures (Chandler *et al*., 2016).

Glossary

Climate velocity: a metric that represents the rate at which temperature isotherms (units of the same temperature) shift in response to climate warming; in this context, climate velocity specifically refers to the rate at which August mean stream temperature isotherms shift at sites along a stream.

NorWeST database and model: a regional database for the Pacific Northwest of the United States containing observed stream temperatures and modeled stream temperature estimates for historical and future climate scenarios at 1-km resolution. See https://www.fs.fed.us/rm/boise/AWAE/projects/NorWeST.html.

Stream-warming rates: the predicted (modeled) rate of August mean water temperature increase in streams, calculated from stream sensitivity (which varies among streams) to air temperature and streamflow trends.

Stream sensitivity: a metric of how strongly stream water temperature in August responds to inter-annual variability in August air temperature. This was calculated using observed air and stream temperature data.

For detailed information about these terms, please consult the dataset citation in section 2.

2. Data access information

Dataset citations:

Chandler, G. L., S. Wollrab, D. Horan, D. Nagel, S. Parkes, D. J. Isaak, S. J. Wenger, and *et al*. 2016. NorWeST stream temperature data summaries for the western U.S. USDA Forest Service, Rocky Mountain Research Station Research Data Archive, Fort Collins, CO.

Isaak, D. J., S. J. Wenger, E. E. Peterson, J. M. Ver Hoef, S. W. Hostetler, C. H. Luce, J. B. Dunham, J. L. Kershner, B. B. Roper, D. E. Nagel, G. L. Chandler, S. P. Wollrab, S. L. Parkes, and D. L. Horan. 2016a. NorWeST modeled summer stream temperature scenarios for the western U.S., Fort Collins, CO: USDA Forest Service Research Data Archive.

Isaak, D. J., M. K. Young, C. H. Luce, S. W. Hostetler, S. J. Wenger, E. E. Peterson, J. M. Ver, M. C. Groce, D. L. Horan, and D. E. Nagel. 2016b. Slow climate velocities of mountain streams portend their role as refugia for cold-water biodiversity. PNAS 113:4374–4379.

Isaak, D., S. Wenger, E. Peterson, J. Ver Hoef, D. Nagel, C. Luce, and *et al*. 2017. The NorWeST summer stream temperature model and scenarios for the western US: A crowd-sourced database and new geospatial tools foster a user community and predict broad climate warming of rivers and streams. Water Resources Research 53:9181–9205.

Dataset documentation links:

https://doi.org/10.2737/RDS-2016-0032
(open access)

https://doi.org/10.2737/RDS-2016-0033
(open access)

https://doi.org/10.1073/pnas.1522429113
(open access)

https://doi.org/10.1002/2017WR020969
(subscription or fee required)

Data access:

Stream temperature projections for various climate-change scenarios can be downloaded from:

https://www.fs.fed.us/rm/boise/AWAE/projects/NorWeST/ModeledStreamTemperatureScenarioMaps.shtml

Climate-velocity projections may be obtained by contacting the corresponding author.

The dataset can be viewed online at:
https://usfs.maps.arcgis.com/apps/webappviewer/index.html?id=bf3ff38068964700a1f278eb9a940dce

Metadata access:

Formal metadata can be downloaded from:
https://www.fs.fed.us/rm/boise/AWAE/projects/NorWeST/downloads/ModeledStreamTemperatureMaps/metadata/NorWeST_PredictedStreamTempLines_GeneralMetadata.pdf

Additional metadata is available from:
https://doi.org/10.2737/RDS-2016-0033 and https://doi.org/10.2737/RDS-2016-0032

Dataset corresponding author:

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3. Conceptual information

Data type category (as defined in the Introduction to this guidebook):

Climate, hydrology, stream and riparian, animal habitat

Species or ecosystems represented:

This dataset represents stream and river ecosystems and the aquatic species that depend on them, including fish and aquatic invertebrates.

Units of mapped values:

Predicted stream temperatures: °C
Climate velocity: kilometers per decade (km / decade)

Range of mapped values:

For the climate velocity dataset, ranges of mapped values depend on the future time frame and warming scenarios considered (see sections 6 and 7). For example, velocity values in a scenario using the historical warming rate with historical stream sensitivity ranged from 0 to greater than 16 kilometers per decade. For the stream temperature dataset, values range from 0 °C to 30 °C.

4. Spatial information

Spatial data type: vector and point data (points, lines, or polygons)

Data file format(s): Shapefile (.shp)

Geographic coordinate system:

North American Datum of 1983

Projected coordinate system:

North American Datum of 1983 Albers

Spatial extent:

Regional

Dataset truncation:

The datasets are truncated along the border between the United States and Canada.

5. Temporal information

Time period represented: Historical (1993 – 2015) and future (later than 2020)

Future time period(s) represented:

Mid-century (2030-2059), end-of-century (2070-2099)

Baseline time period (against which future conditions were compared): 1993-2011.

6. Methods information

Methods overview:

Mean August stream temperatures were modeled based on observations from the NorWeST database of water temperatures (Isaak *et al*., 2017). The NorWeST database consists of more than 220 million temperature observations from more than 23,000 stream sites in the western United States (Chandler *et al*. 2016). Several attributes of watersheds were used to model stream temperatures, including elevation, stream reach slope, drainage area, percent of watersheds containing lakes, glaciers, precipitation, streamflow, and air temperature; see table 1 in Isaak *et al*. (2017) for detailed information. Once models were constructed, they were used to make future predictions based on projected changes in air temperatures and streamflow under various climate-change scenarios. These scenarios are described in Isaak *et al*. (2017) and can be viewed at:

https://www.fs.fed.us/rm/boise/AWAE/projects/NorWeST/downloads/NorWeST_HistoricalStreamTempScenarioDescriptions.pdf.

In general, scenarios are available for historical periods and future periods, 2030-2059 and for 2070-2099, using either a constant delta temperature increase for all streams within a region (NorWeST processing unit) or scenarios with differential warming and the smaller increases that occur in cold streams relative to warm streams. Scenarios are also presented using simple integer increments of warming applied to all streams (1°C, 2°C, and 3°C). Climate velocity was calculated using multiples (equal to, two times, and three times) of the historical warming rate (Isaak *et al*., 2016b). For more information, please consult the dataset citations listed in section 2 of this chapter.

This dataset relied on the following general types of models:

Statistical models

This dataset employed the following specific models:

The NorWeST stream temperature model (Isaak *et al*. 2017), which is a geostatistical moving average approach specific to stream networks (Ver Hoef *et al*. 2006; Ver Hoef and Peterson 2010).

Major input data sources for this dataset included:

Historical climate observations or models, future climate projections, streamflow data or other hydrologic data, stream temperature observations, digital elevation models (DEMs), current land use

This dataset used the following general circulation models (GCMs):

HadCM, CNRM-CM, CCSM3, ECHAM5, ECHO-G, CGCM-3.1_T47, PCM1, MIROC-3.2, IPSL-CM4, HadGEM1

An ensemble across GCMs is provided; individual files for individual GCMs are not available. More information about climate models is available in appendix 1. Detailed information about climate models, including model evaluation and comparison among models, is available from Randall *et al*. (2007), Hamlet *et al*. (2013), and Rupp *et al.* (2013).

This dataset used the following greenhouse-gas scenarios:

SRES A1B

More information about greenhouse-gas scenarios is available in appendix 2 and from Knutti and Sedláček (2013).

Creation of this dataset involved the following methods to change the spatial resolution of climate models (e.g. to downscale or resample climate models):

The hybrid delta method was used to downscale air temperature and streamflow information (Hamlet *et al*. 2013).

7. Guidelines for interpretation

The mapped values of the dataset may be interpreted as follows:

Historical and future predictions of summer stream temperatures are in °C; larger values are warmer and smaller values are cooler. For stream climate velocity, predictions are in km/decade; larger values indicate faster stream isotherm shift rates, and smaller values represent more gradual shift rates.

Representations of key concepts in climate-change ecology:

These datasets represent a framework with which to examine climate-change vulnerability for streams and the aquatic species that depend on them. Streams that are projected to warm faster, and those that show greater sensitivity (greater stream temperature response to increasing air temperatures) may be more vulnerable to climate change than those that warm more slowly and are less sensitive to air temperature increases.

This dataset illustrates a larger concept in climate-change ecology, namely the importance of translating changes in regional climate conditions into changes in the environmental variables that directly regulate species' habitat suitability (in this case, in-stream water temperatures). Warmer stream temperatures represent a potential threat to fish species requiring cold water for suitable habitat, including species that are important for subsistence, recreation, and commercial fisheries. Information on exposure to changing stream temperatures can be combined with information on species' sensitivities to those changes, such as thermal tolerance limits, as well as species' abilities to adapt to changing stream temperatures, such as through use of small cold-water refugia produced by springs.

8. Uncertainties

This dataset involves the following assumptions, simplifications, and caveats:

In the study that produced the stream climate velocity dataset, stream temperature sensitivity to air temperature increases was considered only based on the current temperature conditions of the stream. The dataset authors considered other variables such as elevation, canopy cover, and stream size but were not able to predict stream temperature sensitivity using these variables. Differences in stream sensitivity could be attributable to processes such as shading from forest canopy, contribution of groundwater flow, or snowmelt, but these processes were not accounted for in the modeling.

Although the models that produced these datasets did account for changes in streamflow, there is considerable uncertainty concerning streamflow responses to climate change and streamflow data were available from fewer sites than stream temperature data. These issues are particularly acute for headwater streams.

Quantification of uncertainty:

Predicted August stream temperatures from the NorWeST model were compared to observed August stream temperatures for approximately 63,000 sites. The r^2 value for this comparison was 0.91 (an r^2 value of zero would indicate no ability to predict stream temperatures; an r^2 of 1.0 would indicate perfect predictive ability). Prediction precision also varies spatially throughout the study domain networks and is dependent on the density of local temperature observations used to fit the model. One of the scenarios (S22) available at the NorWeST website contains the prediction standard errors at 1-km points along stream networks and can be used to map spatial uncertainty. Other metrics to assess the ability of the NorWeST model to predict August stream temperatures are described and presented in Isaak *et al*. (2017).

Field verification:

Cross validation was performed during model fits to compare predictions to field observations. The stream temperature scenarios have also been used with biological datasets for more than a dozen fish and amphibian species and thermal relationships match expectations based on the ecology of these species. Field verification of the future values predicted in this dataset was not possible because the dataset represents a future condition.

9. Peer review

Prior to dataset publication, peer review was conducted by external review (at least two anonymous reviewers, each from a different institution).

10. Conservation applications

Potential conservation applications of this dataset could include the following:

These datasets are broadly applicable to conservation of many types of species inhabiting streams (e.g., fish, stream-dwelling amphibians, and invertebrates) but may be particularly important for cold-water fish populations. Climate model outputs that may be appropriate for evaluating terrestrial ecosystems (e.g., climate velocities or projected future air temperatures) are often inadequate to assess the degree of climate-change exposure that aquatic organisms will experience. These projections must be translated into water temperature changes, which these datasets accomplish.

Various management options may be available to help reduce stream temperatures—or slow the rate of warming—depending on the stream in question. These options may include ensuring minimum flows in summer through the regulation of water withdrawals, reconnecting streams to floodplains through stream restoration, and increasing stream shading by establishing riparian vegetation. These datasets provide information that could help inform prioritization of streams for these various approaches.

Applicable scales for detailed spatial assessments:

For conservation applications requiring detailed assessment of spatial variation of the dataset within a geographic boundary (such as a protected area), the following geographic scales may be most appropriate (see appendix 3 for more information).

The high density of stream temperature monitoring stations enabled scenarios and climate velocities to be estimated at 1-km resolution. Possible appropriate spatial scales include small headwater streams and large rivers at the scale of: a Bureau of Land Management (BLM) district, a river watershed (8-digit hydrologic unit code [HUC-8]), an individual county, a national forest, a level-3 ecoregion (e.g. the North Cascades), a single state (Washington, Oregon, or Idaho), a region (multiple states in the Pacific Northwest or in western North America).

Applicable scales for assessing general patterns:

Due to spatial resolution, the dataset may not show detailed spatial variation at the following geographic scales, however, the dataset may be useful to assess general patterns or for comparison to other locations (see appendix 3 for more information).

At spatial scales < 1 km within streams and rivers.

Use of the dataset in conservation applications may be limited by the following considerations:

The variables used in the NorWeST model generally do not represent human changes to stream networks and the surrounding landscape that could affect stream temperatures, such as channel realignments, stream diversions, and changes to riparian canopy cover. The 1-km resolution of the NorWeST model also means that finer-scale variations in stream temperature cannot be assessed, including the possible locations of cold microrefugia (1 – 10 m) that could be important for some fish during warm summer periods. In addition, climate change could have complex effects on stream temperatures that were not accounted for in the NorWeST model, such as changing vegetation dynamics along riparian corridors with implications for canopy shading. Changing disturbance patterns, such as from floods and fires that are altered due to climate change, may also have important effects on aquatic communities that are not accounted for by these datasets. Finally, it should be stressed that different aquatic species have different sensitivities to changing stream temperatures, such that these datasets need to be combined with species-specific distribution information in cases where management goals are targeted at individual species or groups of species.

Past or current conservation applications:

Conservation case study

Numerous endeavors have used the NorWeST and climate-velocity scenarios to assess climate vulnerability for cold-water species like trout and salmon. One particularly large effort has consisted of Climate Adaptation Partnerships (http://www.adaptationpartners.org/) sponsored by the USDA Forest Service throughout 40 national forests in the northwestern United States.

NorWeST climate-velocity scenarios have also been used as covariates in species-distribution models for endangered bull trout and cutthroat trout (Isaak *et al*. 2015; Isaak *et al*. 2016b). The accuracy of the stream temperature information contributed to precise predictions (i.e., at 1-km stream-reach scale) about which stream reaches within the ranges of these species are most likely to act as long-term climate refugia. That information is used by land managers to protect key watersheds for the persistence of these species.

For more information on this conservation case study and many others that use the NorWeST datasets, please see the bibliography in the publications page at the project website: https://www.fs.fed.us/rm/boise/AWAE/projects/NorWeST/Publications.shtml

References cited

Chandler, G. L., S. Wollrab, D. Horan, D. Nagel, S. Parkes, D. J. Isaak, S. J. Wenger, and *et al*. 2016. NorWeST stream temperature data summaries for the western U.S. USDA Forest Service, Rocky Mountain Research Station Research Data Archive, Fort Collins, CO.

Hamlet, A. F., M. M. Elsner, G. S. Mauger, S.-Y. Lee, I. Tohver, and R. A. Norheim. 2013. An overview of the Columbia Basin climate change scenarios project: approach, methods, and summary of key results. Atmosphere-Ocean 51:392–415.

Isaak, D. J., S. J. Wenger, E. E. Peterson, J. M. Ver Hoef, D. E. Nagel, C. H. Luce, and *et al*. 2017. The NorWeST summer stream temperature model and scenarios for the western US: A crowd-sourced database and new geospatial tools foster a user community and predict broad climate warming of rivers and streams. Water Resources Research 53:9181–9205.

Isaak, D. J., S. J. Wenger, E. E. Peterson, J. M. Ver Hoef, S. W. Hostetler, C. H. Luce, J. B. Dunham, J. L. Kershner, B. B. Roper, D. E. Nagel, G. L. Chandler, S. P. Wollrab, S. L. Parkes, and D. L. Horan. 2016a. NorWeST modeled summer stream temperature scenarios for the western U.S., Fort Collins, CO: USDA Forest Service Research Data Archive. https://doi.org/10.2737/RDS-2016-0033.

Isaak, D. J., M. K. Young, C. H. Luce, S. W. Hostetler, S. J. Wenger, E. E. Peterson, J. M. Ver, M. C. Groce, D. L. Horan, and D. E. Nagel. 2016b. Slow climate velocities of mountain streams portend their role as refugia for cold-water biodiversity. PNAS 113:4374–4379.

Isaak, D. J., M. K., Young, D. E., Nagel, D. L., Horan, and M. C. Groce. 2015. The cold-water climate shield: Delineating refugia for preserving salmonid fishes through the 21st century. Global Change Biology 21:2540–2553.

Knutti, R., and J. Sedláček. 2013. Robustness and uncertainties in the new CMIP5 climate model projections. Nature Climate Change 3:369–373.

Randall, D., R. Wood, S. Bony, R. Colman, T. Fichefet, J. Fyfe, V. Kattsov, and *et al*. 2007. Cilmate models and their evaluation. *in* S. Solomon, D. Qin, M. Manning, Z. Chen, M. Marquis, K. Averyt, M. Tignor, and H. Miller, editors. Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, New York, NY.

Rupp, D. E., J. T. Abatzoglou, K. C. Hegewisch, and P. W. Mote. 2013. Evaluation of CMIP5 20th century climate simulations for the Pacific Northwest USA. Journal of Geophysical Research 118: 884–907.

Ver Hoef, J. M., and E. E. Peterson. 2010. A moving average approach for spatial statistical models of stream networks. Journal of the American Statistical Association 105: 6–18.

Ver Hoef, J. M., E. E. Peterson, and D.M. Theobald. 2006. Spatial statistical models that use flow and stream distance. Environmental and Ecological Statistics 13: 449–464.

Chapter 10: Streamflow metric projections

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Charles Luce (USDA Forest Service)
Jennifer Cartwright (U.S. Geological Survey)

1. Dataset overview

This dataset includes historical and projected future **streamflow metrics** for stream segments throughout the western U.S., produced from daily **runoff** and **baseflow** outputs from the **Variable Infiltration Capacity (VIC)** hydrologic model (see chapter glossary for definitions of terms). Streamflow projections are based on an ensemble of global climate models. The dataset is available for stream segments in the National Hydrography Dataset Plus Version 2 (NHDPlusV2) database (U.S. Environmental Protection Agency and U.S. Geological Survey, 2012). Available streamflow metrics in the dataset include mean annual flow, mean summer flow (figure 10.1), mean August flow, winter exceedance statistics (number of daily flows exceeding the 95th percentile of daily flows), the 1.5-, 10-,

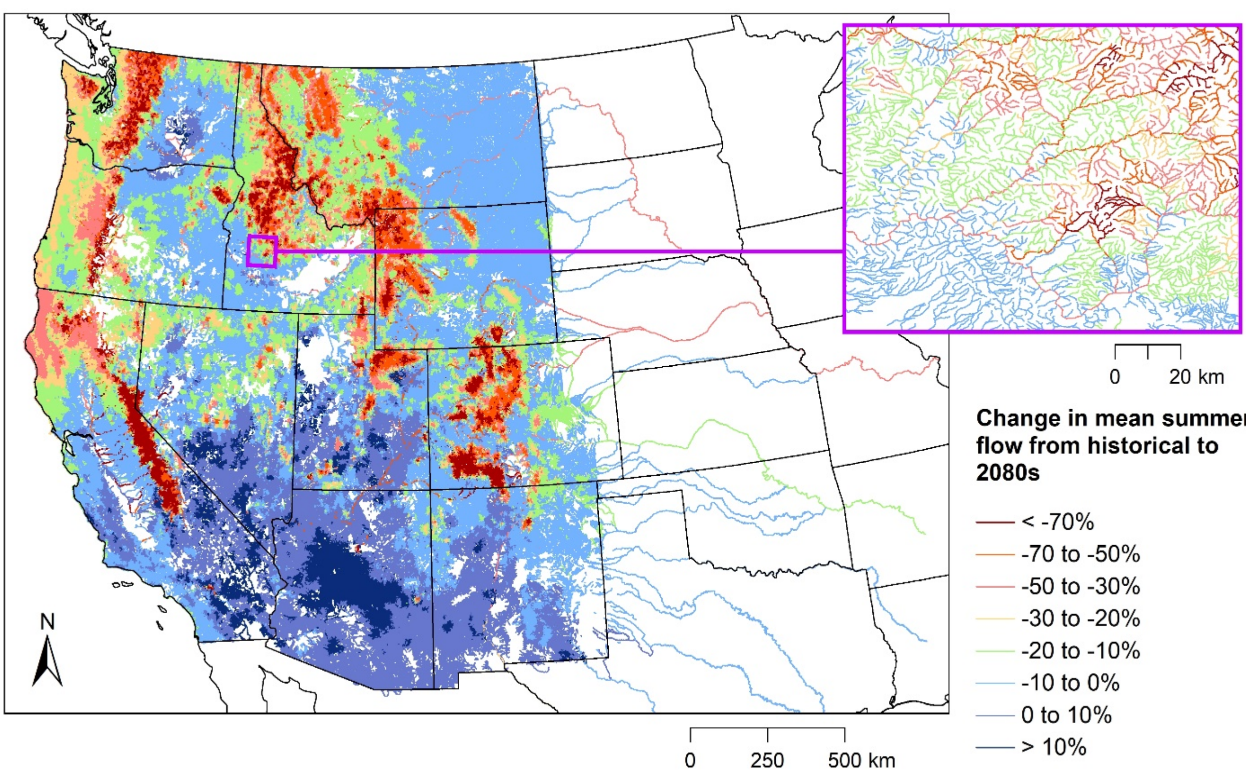

Figure 10.1. Projected percent change in mean summer streamflow between the baseline historical period (1977 to 2006) and the 2080s (2070 to 2099). For example, a value of -70% represents a 70% reduction in summer streamflow relative to the baseline period. The inset map (purple frame) shows a zoomed-in view of projected changes in summer streamflow.

25-year, and maximum modeled flood statistics, the **center of flow timing,** and the **baseflow index**. These streamflow metrics are available for historical, mid-century, and end-of-century time periods; absolute and percent changes are also available.

Glossary

Baseflow: streamflow that occurs between periods of rainfall or snowmelt. Usually this component of streamflow does not originate from surface runoff and instead originates from groundwater storage or water fluxes from the soil subsurface.

Baseflow Index: the ratio of the lowest average 7-day summer flow to the year-round average daily flow.

Center of flow timing: the center of timing of the mass of streamflow for an annual water year calculated using a weighted mean:
$(flow_1*1 + flow_2*2 + [\ldots] + flow_{365}*365) / (flow_1 + flow_2 + [...] + flow_{365})$
where $flow_d$ is the flow volume on each day d of the water year.

Hydrograph: a depiction of streamflow over time, typically by plotting streamflow on the vertical axis and days of the water year on the horizontal axis.

Runoff: contribution to streamflow from rainfall or snowmelt.

Streamflow metric (or flow metric): a quantitative descriptive statistic of the flow regime of a stream, typically calculated based on daily (observed or modeled) streamflow data.

Variable infiltration capacity (VIC) model: a macroscale hydrologic model that models the land surface as a grid using meteorological input data to simulate land-atmosphere fluxes and the water and energy balances at the surface.

Water year: the 12-month period October 1, for any given year through September 30, of the following year.

For detailed information about these terms, please consult the dataset citation in section 2.

2. Data access information

Dataset citation:

Wenger, S. J., C. H. Luce, A. F. Hamlet, D. J. Isaak, and H. M. Neville. 2010. Macroscale hydrologic modeling of ecologically relevant flow metrics. Water Resources Research 46:W09513.

Dataset documentation links:

https://doi.org/10.1029/2009WR008839
(open access)

https://www.fs.fed.us/rm/boise/AWAE/projects/VIC_streamflowmetrics/downloads/WUS_VIC_Metrics_UserGuide.pdf
(open access)

Data access:

The dataset can be downloaded and viewed from:
https://www.fs.fed.us/rm/boise/AWAE/projects/modeled_stream_flow_metrics.shtml#data

Metadata access:

A comprehensive user guide and additional metadata are available from:

https://www.fs.fed.us/rm/boise/AWAE/projects/VIC_streamflowmetrics/downloads/WUS_VIC_Metrics_UserGuide.pdf

Dataset corresponding author:

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3. Conceptual information

Data type category (as defined in the Introduction to this guidebook):

Hydrology

Species or ecosystems represented:

This dataset represents stream and river ecosystems. No individual species are represented.

Units of mapped values:

For mean-annual flow, mean-summer flow, mean August flow, and 1.5-, 10-, 25-year, and maximum modeled flood: cubic feet per second (ft^3/s).

For winter exceedance statistics: number of days

For center of flow timing: day of the **water year** (or day of calendar year)

Baseflow index: ratio

Range of mapped values:

Ranges of mapped values vary by streamflow metric.

4. Spatial information

Spatial data type: Line vector data stored as feature data in file geodatabase

Data file format(s): File geodatabase

Spatial resolution: Stream segments from the NHDPlusV2 datasets

Geographic coordinate system:

North American Datum of 1983

Projected coordinate system:

Unprojected

Spatial extent:

Regional

Dataset truncation:

The dataset is defined by hydrologic boundaries and thus is not truncated at any non-ecological borders.

5. Temporal information

Time period represented: Historical (1977-2006); future (later than 2020)

Future time period(s) represented:

Mid-century (2030-2059), end-of-century (2070-2099).

In addition to historical and future time periods, absolute and percent changes were calculated between the historical and the future time periods.

Baseline time period (against which future conditions were compared): 1977-2006.

6. Methods information

Methods overview:

Historical and projected future streamflow metrics were estimated using daily runoff and baseflow outputs from the Variable Infiltration Capacity (VIC) macroscale hydrologic model. The VIC model is a physically based model that accounts for surface energy and water fluxes. In models that created this dataset, pixels were 1/16th degree (or 1/8th degree in the Great Basin processing unit). For historical simulations, input meteorological data came from the Parameter-elevation Regressions on Independent Slopes Model (PRISM) dataset (Daly *et al*. 1994). For future simulations, meteorological data came from an ensemble of 10 global climate models (see Littell *et al*., 2011). Simulations were performed on a daily time step. For each stream segment in the NHDPlusV2 dataset, **hydrographs** were produced using the model for the historical period, mid-century, and end-of-century. From these hydrographs, summary statistics (streamflow metrics) were calculated, then absolute and percent differences were calculated between the historical and future time periods. These were joined to the NHDPlusV2 dataset (September 2012 snapshot) for each region and were then merged together into a single comprehensive dataset for each time period.

For more information, please consult the dataset citation listed in section 2 of this chapter.

This dataset relied on the following general types of models:

Hydrologic models

This dataset employed the following specific models:

Variable infiltration capacity (VIC) model (Liang *et al*., 1994)

Major input data sources for this dataset included:

Historical climate observations or models, future climate projections, streamflow data or other hydrologic data

This dataset used the following general circulation models (GCMs):

ECHAM5, BCCR, HadCM, MIROC3.2, MIROC3.2-HI, HadGEM1, ECHO-G, PCM1, CNRM-CM3, CSIRO-Mk3.5

An ensemble across GCMs is provided; individual files for individual GCMs are not available. More information about climate models is available in appendix 1. Detailed information about climate models, including model evaluation and comparison among models, is available from Randall *et al.* (2007) and Rupp *et al.* (2013).

This dataset used the following greenhouse-gas scenarios:

SRES A1B

More information about greenhouse-gas scenarios is available in appendix 2 and from Knutti and Sedláček (2013).

Creation of this dataset involved the following methods to change the spatial resolution of climate models (e.g. to downscale or resample climate models):

GCM simulations were downscaled using a spatially explicit delta method (Littell *et al*., 2011).

7. Guidelines for interpretation

The mapped values of the dataset may be interpreted as follows:

Interpretation of mapped values depends on the streamflow metric. The data show historical and future values for each metric, as well as both absolute and percent change. Stream segments that show a greater magnitude or percent change may be interpreted as streams that are projected to have greater hydrologic alteration due to climate change. For example, if mean summer flow from the historical period is compared to mean summer flow for the 2080s, streams that show the greatest decrease are anticipated to experience the most dramatic declines in summer streamflow.

Representations of key concepts in climate-change ecology:

This dataset primarily represents climate-change exposure (the magnitude of projected change in climate drivers of streamflow) and climate sensitivity of various streamflow metrics for various streams. Taken together, stream segments that show the greatest projected change across a variety of streamflow metrics could be considered especially vulnerable to climate change from a hydrologic perspective.

Changes in stream hydrology have the potential to affect aquatic communities in a variety of ways. Some species may be directly affected by changes in the timing or magnitude of streamflow. In addition, changes in streamflow can affect other characteristics of aquatic ecosystems, such as stream temperatures, water quality (e.g., dissolved oxygen and sediment loads), and connectivity of aquatic habitat. Thus, climate-driven changes to stream hydrology have the potential to produce complex, multifaceted changes in overall habitat suitability for a variety of species. These potential changes can be considered along with species-level sensitivities to changing stream hydrology (and its cascading effects) and aquatic species' abilities to cope with or adapt to changing environmental conditions.

8. Uncertainties

This dataset involves the following assumptions, simplifications, and caveats:

The VIC model does not explicitly model water fluxes into and out of deep subsurface reservoirs. The study that produced this dataset found evidence that streams with strong groundwater influence were poorly predicted by the model. Thus, model results may have low accuracy for strongly groundwater-dominated streams. Additionally, model estimates for the center of flow timing were biased early for snow-dominated streams and biased late for rainfall-dominated streams. Because the VIC model poorly predicted summer high- and low-flow metrics, historical and future projections for these metrics should be interpreted with caution.

Quantification of uncertainty:

Uncertainty resulting from choices of greenhouse-gas scenario or global climate model were not quantified. However, a comparison was conducted between two resolutions (grid sizes) of the VIC hydrologic model, which showed modest improvement in accuracy at the finer resolution (1/8th degree) relative to the coarser resolution (1/16th degree).

Field verification:

The VIC model used to produce this dataset was validated using data from 55 U.S. Geological Survey gaging stations in the Pacific Northwest, by comparing streamflow metrics calculated from observed daily hydrographs to those calculated from VIC model outputs. This comparison enabled an assessment of accuracy and bias for each modeled streamflow metric (see Wenger *et al*. 2010). In general, mean flows, winter high flows, center of flow timing, and hydrologic regime (rain-dominated or snow-dominated) were reasonably well predicted. However, summer high- and low-flow metrics were poorly predicted. Baseflow indices and flood levels greater than the 1.5-year flood were not assessed.

9. Peer review

Prior to dataset publication, peer review was conducted by external review (at least two anonymous reviewers, each from a different institution).

10. Conservation applications

Potential conservation applications of this dataset could include the following:

The set of streamflow metric projections in this dataset can be used to evaluate potential climate-driven habitat changes on a species-by-species basis. In stream ecosystems of the Pacific Northwest, different species of fish and other aquatic organisms have different streamflow metrics that are ecologically important to their life cycles. For example, fall-spawning fish may benefit from infrequent winter flooding, whereas spring-spawning fish may benefit from infrequent summer flooding. Streamflow metrics such as mean summer flow may also affect other components of habitat quality, such as stream temperatures. As a result, use of this dataset to inform aquatic conservation requires consideration of both the magnitude of projected change over time in a given streamflow metric and of the nature of that change relative to life cycles and habitat requirements of species of conservation concern.

Applicable scales for detailed spatial assessments:

For conservation applications requiring detailed assessment of spatial variation of the dataset within a geographic boundary (such as a protected area), the following geographic scales may be most appropriate (see appendix 3 for more information).

At the scale of: a Bureau of Land Management (BLM) district, a river watershed (8-digit hydrologic unit code [HUC-8]), an individual county, a national forest, a level-3 ecoregion (e.g. the North Cascades), a single state (Washington, Oregon, or Idaho), a region (multiple states in the Pacific Northwest or in western North America).

Applicable scales for assessing general patterns:

Due to spatial resolution, the dataset may not show detailed spatial variation at the following geographic scales, however, the dataset may be useful to assess general patterns or for comparison to other locations (see appendix 3 for more information).

At the scale of: a small (< 1 km^2) nature preserve, a state park or state wildlife area, a local watershed (12-digit hydrologic unit code [HUC-12]).

Use of the dataset in conservation applications may be limited by the following considerations:

For some aquatic species, changes in high and low flows during summer may be especially important, however, these metrics were not well predicted by the VIC model in producing this dataset. In addition, streamflow metrics were not well predicted in groundwater-dominated streams, suggesting that use of this dataset to guide conservation decisions in such streams could be problematic. Finally, considerations of geographic scale may be important in applying this dataset for conservation purposes. The VIC predictions that produced this dataset may exhibit bias at fine geographic scales (for individual stream reaches or small catchments) that becomes less important when integrated across larger geographic scales.

Past or current conservation applications:

This dataset has been the basis for climate-change vulnerability assessments on several national forests in Oregon and Washington (USDA Forest Service Region 6) as well as Regions 1, 4, and 5. Example conservation applications are available from http://adaptationpartners.org. This dataset was also the basis for niche modeling to project fish responses to climate change (Wenger *et al*. 2011a, 2011b).

References cited

Daly, C., R. Neilson, and D. Phillips. 1994. A statistical-topographic model for mapping climatological precipitation over mountainous terrain. Journal of Applied Meteorology 33:140–158.

Knutti, R., and J. Sedláček. 2013. Robustness and uncertainties in the new CMIP5 climate model projections. Nature Climate Change 3:369–373.

Liang, X., D. P. Lettenmaier, E. F. Wood, and J. Burges. 1994. A simple hydrologically based model of land surface water and energy fluxes for general circulation models. Journal of Geophysical Research 99:14415–14428.

Littell, J., M. Elsner, G. Mauger, E. Lutz, A. Hamlet, and E. Salathé. 2011. Regional climate and hydrologic change in the Northern US Rockies and Pacific Northwest: internally consistent projections of future climate for resource management. Project report for USFS JVA 09-JV-11015600-039. Climate Impacts Group, University of Washington, Seattle, WA.

Randall, D., R. Wood, S. Bony, R. Colman, T. Fichefet, J. Fyfe, V. Kattsov, and *et al*. 2007. Climate models and their evaluation. *in* S. Solomon, D. Qin, M. Manning, Z. Chen, M. Marquis, K. Averyt, M. Tignor, and H. Miller, editors. Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, New York, NY.

Rupp, D. E., J. T. Abatzoglou, K. C. Hegewisch, and P. W. Mote. 2013. Evaluation of CMIP5 20th century climate simulations for the Pacific Northwest USA. Journal of Geophysical Research 118: 884–907.

U.S. Environmental Protection Agency and U.S. Geological Survey. 2012. National Hydrography Dataset Plus – NHDPlus version 2.10. U.S. Environmental Protection Agency, Washington, DC.

Wenger, S. J., D. J. Isaak, J. B. Dunham, K. D. Fausch, C. H. Luce, H. M. Neville, B. E. Rieman, M. K. Young, D. E. Nagel, D. L. Horan, and G. L. Chandler. 2011a. Role of climate and invasive species in structuring trout distributions in the interior Columbia River. Canadian Journal of Fisheries and Aquatic Sciences 68:988–1008.

Wenger, S. J., D. J. Isaak, C. H. Luce, H. M. Neville, K. D. Fausch, J. B. Dunham, D. C. Dauwalter, M. K. Young, M. M. Elsner, B. E. Rieman, A. F. Hamlet, and J. E. Williams. 2011b. Flow regime, temperature, and biotic interactions drive differential declines of trout species under climate change. PNAS 108:14175–14180.

Wenger, S. J., C. H. Luce, A. F. Hamlet, D. J. Isaak, and H. M. Neville. 2010. Macroscale hydrologic modeling of ecologically relevant flow metrics. Water Resources Research 46:W09513.

Chapter 11: Probability of Streamflow Permanence (PROSPER) Model

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1. Dataset overview

The PRObability of Streamflow PERmanence (PROSPER) model is a geospatial model that predicts **streamflow permanence** for unregulated, minimally impaired streams throughout the Pacific Northwest of the United States at 30-m resolution, corresponding to the stream network represented by the medium-resolution National Hydrography Dataset (U.S. Environmental Protection Agency and U.S. Geological Survey, 2012). The PROSPER model was constructed using stream observations (wet/dry) and a suite of climate and physiographic variables to predict streamflow permanence. For each 30-m pixel of a stream, the model provides streamflow permanence probability at annual time steps from 2004 through 2016 (figure 11.1; Jaeger *et al*., 2018; Sando and Hockman-Wert 2019). Stream-network

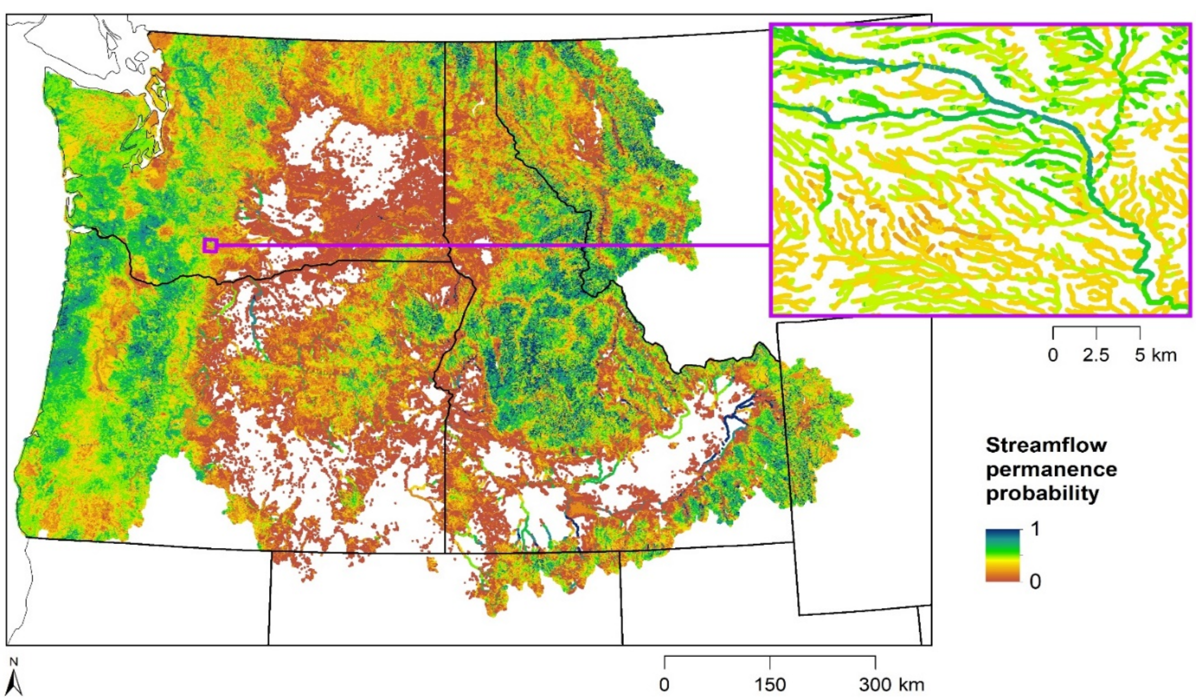

Figure 11.1. Streamflow permanence probability in the year 2015 as predicted by the PRObability of Streamflow PERmanence (PROSPER) model. High values indicate streams with predicted greater likelihood of continuous flow throughout the year, whereas low values represent streams with greater likelihood of becoming dry at some point in the year. The inset map (purple frame) shows a zoomed-in view of predicted 2015 streamflow permanence probability.

pixels were then categorized as wet (remaining wet or with flowing water throughout the year) or dry (lacking water at some point in the year) for each year using the streamflow permanence probabilities.

Glossary

Streamflow permanence: the degree to which rivers and streams maintain surface-water flow throughout the year.

Random forest classification: a machine-learning model that uses a set of explanatory (predictor) variables to predict an outcome in terms of a set of known classes (for this dataset, wet and dry).

For detailed information about these terms, please consult the dataset citation in section 2.

2. Data access information

Dataset citation:

Jaeger, K. L., R. Sando, R. R. Mcshane, J. B. Dunham, D. P. Hockman-wert, K. E. Kaiser, K. Hafen, J. C. Risley, and K. W. Blasch. 2018. Probability of Streamflow Permanence Model (PROSPER): A spatially continuous model of annual streamflow permanence throughout the Pacific Nortwest. Journal of Hydrology X 2:100005.

Sando, R., and D. P. Hockman-Wert. 2019. Probability of Streamflow Permanence (PROSPER) Model Output Layers (ver. 2.0, February 2019): U.S. Geological Survey data release. https://doi.org/10.5066/F77M0754.

Dataset documentation link:

https://doi.org/10.1016/j.hydroa.2018.100005
(open access)

https://doi.org/10.5066/F77M0754
(open access)

Data access:

The dataset can be downloaded from
https://doi.org/10.5066/F77M0754

The dataset is available for interactive viewing under the Exploration Tools in StreamStats.
https://streamstats.usgs.gov/ss/

Metadata access:

Formal metadata is available from
https://doi.org/10.5066/F77M0754

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3. Conceptual information

Data type category (as defined in the Introduction to this guidebook):

Hydrology, stream and riparian

Species or ecosystems represented:

This dataset represents stream and river ecosystems. No individual species are represented.

Units of mapped values:

Streamflow permanence probabilities
Streamflow permanence classes

Range of mapped values:

0 to 1 (for streamflow permanence probabilities)
-5 to 5 (for streamflow permanence classes)

4. Spatial information

Spatial data type: a raster dataset (grid)

Data file format(s): GeoTiff (.tif), Esri Service Definition file

Spatial resolution: 30 m

Geographic coordinate system:

North American Datum of 1983

Projected coordinate system:

Albers Conic Equal Area

Spatial extent: Regional

Dataset truncation:

The dataset is truncated at the border between the United States and Canada

5. Temporal information

Time period represented: Current or recent (2004 to 2016)

6. Methods information

Methods overview:

The PROSPER model was constructed using over 3,800 stream observations, roughly half wet (with either flowing water or pools observed after July 1) and half dry, with no observable surface water. To predict streamflow permanence, the PROSPER model used a suite of climate and physical predictor variables, representing land cover, topography, soils, permeability, temperature, precipitation, snow-water equivalent, and evapotranspiration. For climate variables that change through time, monthly or annual values were used. For each 30-m pixel in the model, all variables were summarized for the entire upstream catchment. A **random forest classification** model was used to produce a streamflow permanence probability for every stream pixel in the study area for each year (2004-2016), along with confidence intervals. Finally, each pixel was categorized into a streamflow permanence class with an associated confidence level (wet or dry) using a locally optimized threshold developed to correct for regional bias. For more information, please consult the dataset citation listed in section 2 of this chapter.

This dataset relied on the following general types of models:

Hydrologic models

This dataset employed the following specific models:

Random forest classification (Breiman 2001), Empirical Bayesian Kriging (Krivoruchko and Gribov 2014)

Major input data sources for this dataset included:

Current land use, including protected areas, historical climate observations or models, digital elevation models (DEMs) or topography, soil characteristics, streamflow data or other hydrologic data

7. Guidelines for interpretation

The mapped values of the dataset may be interpreted as follows:

For each pixel in each year, high streamflow permanence probability (SPP) values (0.5 to 1) and streamflow permanence class (SPC) values (1 to 5) indicate high likelihood of streamflow permanence, i.e., streamflow continuing throughout the year. Low SPP values (0 to 0.5) and SPC values (-5 to -1) indicate high likelihood of that location of the stream becoming dry at some point that year. Agreement between SPP and SPC values indicate more reliable predictions. For example, a pixel with a predicted SPP value of 0.7 and SPC value of 5 is more reliable than a pixel with a predicted SPP value of 0.54 and SPC of -3.

Representations of key concepts in climate-change ecology:

Outputs from the PROSPER model relate to climate-change vulnerability in that they represent predicted streamflow permanence across a range of years with varying climate conditions. From the perspective of conserving aquatic habitat, streams that remain wet during relatively dry years—and for snow-dominated basins, in years with reduced snowpack or early snowmelt—may suggest greater potential resistance (reduced vulnerability) to future climate changes. Additionally, PROSPER outputs relate to climate sensitivity by estimating interannual variability in streamflow permanence that can be directly attributed to the fluctuations in climatic variables included in the PROSPER model.

Streamflow permanence or intermittency can have important implications for aquatic ecosystems. For example, ephemeral streams (those with intermittent flow) may have unique ecological characteristics and groups of species, determined largely by seasonal patterns of streamflow availability (Datry *et al.*, 2017). Thus, categorizing streams as perennial or ephemeral can be an important step in species vulnerability assessments. Streamflow permanence can be ecologically important not only to aquatic communities, but also to terrestrial animals using streams as sources of water or food.

8. Uncertainties

This dataset involves the following assumptions, simplifications, and caveats:

PROSPER is a regional-scale model applied to streams spanning a broad range of climate, geology, and topography. For some streams, local-scale controls related to soil and geology might be very important in determining streamflow permanence, but these local-scale factors are not represented in the PROSPER model or its outputs. The most important predictors in the PROSPER model were precipitation, forest cover, and temperature. As a result, streams with consistent year-round flow in arid regions would have lower predicted streamflow permanence probabilities than streams in wetter climates, suggesting underestimation of streamflow permanence for some perennial streams (e.g., spring-fed streams) in arid landscapes. Similarly, in very wet regions such as the coast range of Oregon, there were relatively few observations of dry streams to use as inputs to train the PROSPER model. Thus, the model may not adequately predict dry streams in this region. Figure A1B in Jaeger *et al*. (2018) shows standard error of prediction values related to classifying streams as wet or dry. Dataset users may want to use the wet and dry classifications with caution in areas that have high error rates.

In addition, the PROSPER model does not account for streamflow regulation through dams or diversions. Stream segments downstream from reservoirs likely have greater streamflow permanence than is predicted by PROSPER because their hydrology has been altered by humans. Conversely, streams with substantial water withdrawals would likely have lower streamflow permanence that is predicted by PROSPER.

Quantification of uncertainty:

Out-of-bag error rates from an internal cross-validation process in the random forest classification algorithm were used to assess the accuracy of the PROSPER model at the locations of the calibration data.

To translate predicted streamflow permanence probability (a continuous variable ranging from 0 to 1) to a binary streamflow permanence classification of wet versus dry, a threshold probability value was needed below which pixels would be categorized as dry, and above which they would be categorized as wet. This threshold varied throughout the study area and was accompanied by a standard error of prediction value, presented in figure A1 of Jaeger *et al*. (2018). Regions with relatively low standard error of prediction values are associated with greater confidence for the wet/dry stream classifications, whereas regions with high standard error of prediction values indicate less confidence in the wet/dry classification. Several watersheds were flagged with particularly high standard error rates suggesting users should exercise caution in interpreting wet/dry classifications in these regions.

Field verification:

Streamflow permanence probabilities from the PROSPER model were compared to flow classifications (flowing versus not flowing) from U.S. Geological Survey (USGS) gage locations across a range of climate conditions for time periods outside the modeling time period of PROSPER (2004-2016). In five of six climate classes (all except the wettest climate class), the streamflow permanence probabilities predicted by PROSPER were statistically significantly different between the flowing and non-flowing USGS stream gages, helping to validate the relative streamflow permanence probabilities within those climate classes. In the wettest climate class, flowing and non-flowing USGS gages had predicted streamflow permanence probabilities that were not statistically different, probably due to a relatively limited number of dry observations.

9. Peer review

Prior to dataset publication, peer review was conducted by external review (at least two anonymous reviewers, each from a different institution).

10. Conservation applications

Potential conservation applications of this dataset could include the following:

Outputs from the PROSPER model could be combined with local knowledge of stream networks in an area to assess vulnerability of streams to summer drying under a range of climate conditions, i.e., in wet years and dry years. Because streamflow permanence (whether or not flow is maintained throughout the year) can be an important influence on riverine ecosystems, including habitat for some species of conservation concern, PROSPER-derived estimates of streamflow permanence probabilities could be used to guide assessments of riverine habitat, community dynamics, and species vulnerability to changing environmental conditions such as droughts and climate change. Additionally, flow-permanence regime (perennial, ephemeral, and intermittent) is a primary consideration in decisions related to the application of chemical herbicides and pesticides. PROSPER results can be used to better inform decisions about the location and quantity of herbicides and pesticides applied on the landscape.

Applicable scales for detailed spatial assessments:

For conservation applications requiring detailed assessment of spatial variation of the dataset within a geographic boundary (such as a protected area), the following geographic scales may be most appropriate (see appendix 3 for more information).

At the scale of: a state park or state wildlife area, a local watershed (12-digit hydrologic unit code [HUC-12]), a Bureau of Land Management (BLM) district, a river watershed (8-digit hydrologic unit code [HUC-8]), an individual county, a national forest, a level-3 ecoregion (e.g. the North Cascades), a single state (Washington, Oregon, or Idaho), a region (multiple states in the Pacific Northwest).

Applicable scales for assessing general patterns:

Due to spatial resolution, the dataset may not show detailed spatial variation at the following geographic scales, however, the dataset may be useful to assess general patterns or for comparison to other locations (see appendix 3 for more information).

At the scale of a small (< 1 km^2) nature preserve.

Use of the dataset in conservation applications may be limited by the following considerations:

Actual streamflow permanence for a section of a river network may not be accurately described by the PROSPER model outputs as described in section 8 above. Thus, PROSPER outputs should be combined with local knowledge, other streamflow permanence datasets (e.g., National Hydrography Dataset Plus), and field observations for conservation planning purposes. Additionally, the PROSPER model outputs do not represent hydroperiod—the length of time a stream remains flowing—which can be critically important to riverine ecosystems and to individual species of conservation concern. Other important characteristics that shape riverine habitat include water temperature, water quality (e.g., dissolved oxygen, nutrients, suspended sediment), timing and magnitude of streamflow characteristics such as flooding, stream bed and bank characteristics, and characteristics of the riparian environment.

Past or current conservation applications:

The dataset has not yet been used in any on-the-ground conservation applications to the knowledge of the authors of this chapter.

References cited

Breiman, L. 2001. Random forests. Machine learning 45:5–32.

Datry, T., N. Bonada, and A.Boulton. 2017. Chapter 1 – General introduction. Pages 1-20 *in* T. Datry, N. Bonada, and A. Boulton, editors. Intermittent Rivers and Ephemeral Streams: Ecology and Management. Academic Press, London

Jaeger, K. L., R. Sando, R. R. Mcshane, J. B. Dunham, D. P. Hockman-wert, K. E. Kaiser, K. Hafen, J. C. Risley, and K. W. Blasch. 2018. Probability of Streamflow Permanence Model (PROSPER): A spatially continuous model of annual streamflow permanence throughout the Pacific Northwest. Journal of Hydrology X 2:100005.

Krivoruchko, K., and A. Gribov. 2014. Pragmatic Bayesian kriging for non-stationary and moderately non-Gaussian data. Pages 61–64 *in* E. Pardo-Igúzquiza, C. Guardiola-Albert, J. Heredia, L. Moreno-Merino, J. Durán, and J. Vargas-Guzmán, editors. Mathematics of Planet Earth. Springer, Berlin.

Sando, R., and D. P. Hockman-Wert. 2019. Probability of Streamflow Permanence (PROSPER) Model Output Layers (ver. 2.0, February 2019): U.S. Geological Survey data release. https://doi.org/10.5066/F77M0754.

U.S. Environmental Protection Agency and U.S. Geological Survey. 2012. National Hydrography Dataset Plus – NHDPlus version 2.10. U.S. Environmental Protection Agency, Washington, DC.

Chapter 12: Riparian climate corridors

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Jennifer Cartwright (U.S. Geological Survey)

1. Dataset overview

Riparian areas are expected to be important for promoting adaptive responses to climate change because they often provide cool microclimates and may serve as **corridors** to facilitate species range movements (Krosby *et al*., 2014; see chapter glossary for definitions of terms). This dataset represents an integrated assessment—called a riparian index—of how well specific riparian areas may serve as corridors (figure 12.1). The riparian index integrates five attributes that were considered important for riparian areas to support climate adaptation for species: (1) the degree to which riparian areas span temperature gradients, (2) how much canopy cover they have, (3) their levels of solar exposure, i.e., how much sunlight they receive, (4) how wide they are, and (5) how much they have been altered by human activities. Based on these five considerations, the riparian index scores are presented for

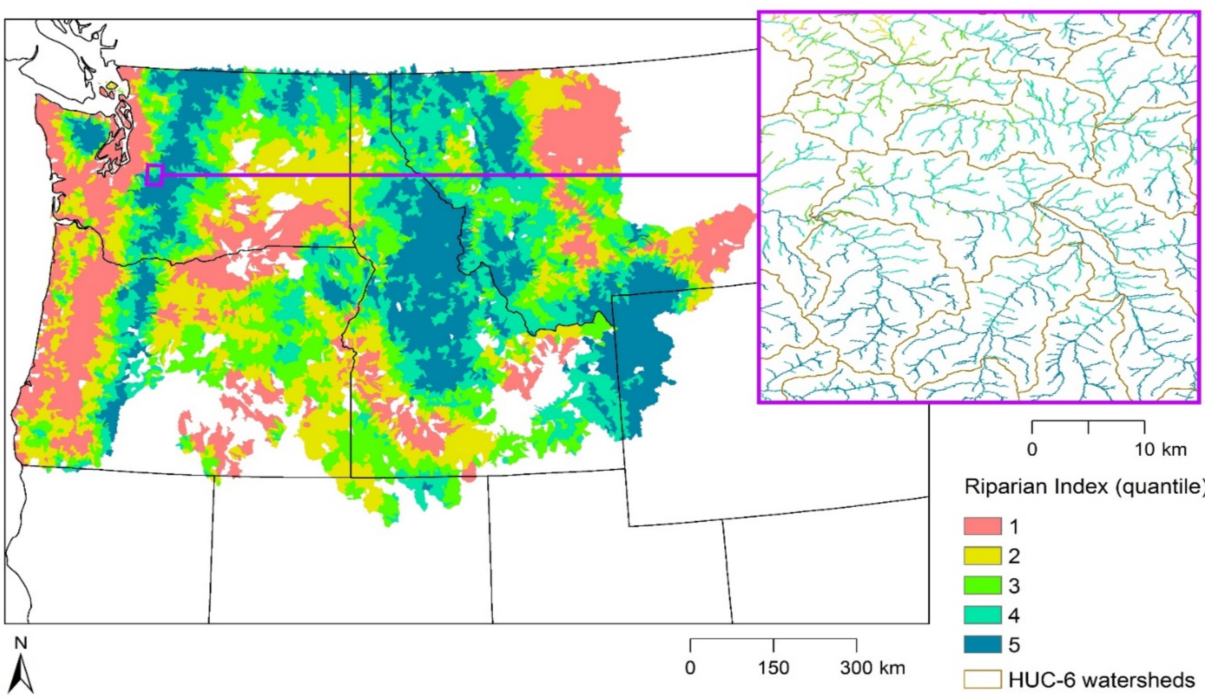

Figure 12.1. Riparian climate-corridor index values. Higher values indicate riparian areas that are considered most likely to support climate-change adaptation because they have some combination of: large temperature gradients, high canopy cover, low sunlight exposure, wide stream channel, and/or minimal human alteration. The map on the left depicts the full extent of the dataset with index values shown averaged over six-digit hydrologic unit code (HUC-6) watersheds. The inset map (purple frame) shows a zoomed-in view of index values attributed to stream lines.

stream lines and also aggregated to 6-digit hydrologic unit code (**HUC-6**) watersheds. Using riparian index scores for individual streams, priority riparian areas were identified within each HUC-6 watershed.

Glossary

Riparian areas: lands immediately bordering streams or rivers; these areas act as an interface between streams and the surrounding upland landscape.

Corridors (or conservation corridors): links of habitat that connect larger habitat patches and facilitate species movements across the landscape.

HUC: hydrologic unit code. Hydrologic units exist within a nested hierarchy from large regions (2-digit hydrologic units; HUC-2) to small watersheds (12 or higher-digit hydrologic units). In practice, "HUC-6" refers to watersheds of intermediate size.

For detailed information about these terms, please consult the dataset citation in section 2.

2. Data access information

Dataset citation:

Krosby, M., R. A. Norheim, D. M. Theobald, and B. McRae. 2014. Final report: riparian climate-corridors: identifying priority areas for conservation in a changing climate. North Pacific Landscape Conservation Cooperative.

Krosby, M., R. Norheim, and D. Theobald. 2015. Riparian climate-corridors: analysis extension, improvements, and validation. North Pacific Landscape Conservation Cooperative.

Krosby, M., D. M. Theobald, R. Norheim, and B. H. McRae. 2018. Identifying riparian climate corridors to inform climate adaptation planning. PloS ONE 13:e0205156.

Dataset documentation links:

https://www.sciencebase.gov/catalog/item/53c938c6e4b092c1b256558f
(open access)

https://doi.org/10.1371/journal.pone.0205156
(open access)

Data access:

The dataset can be downloaded from:
https://www.sciencebase.gov/catalog/item/53c93990e4b092c1b2565592

The dataset can be viewed interactively at:
https://nplcc.databasin.org/datasets/46caec8762194138a8a6421322ea170d

Metadata access:

Formal metadata is not available for this dataset.

Dataset corresponding author:

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3. Conceptual information

Data type category (as defined in the Introduction to this guidebook):

Landscape connectivity and permeability, stream and riparian

Species or ecosystems represented:

This dataset represents riparian ecosystems and the species that use them for habitat and movement corridors.

Units of mapped values:

unitless

Range of mapped values:

Riparian index values attributed to stream lines: 0.00033546 to 0.829571
Riparian index values attributed to HUC-6 watersheds: 0.000414698 to 0.656893

4. Spatial information

Spatial data type: a raster dataset (grid)

Data file format(s): GeoTiff (.tif)

Spatial resolution: 90 m

Geographic coordinate system:

North American Datum of 1983

Projected coordinate system:

North American Datum of 1983 Albers

Spatial extent: Regional

Dataset truncation:

The dataset is truncated along the border between the United States and Canada.

5. Temporal information

Time period represented: Current or recent (2000 to 2018)

Note that the metrics used to develop the riparian index in this dataset represent some landscape characteristics that are relatively static (e.g., topographic shading) as well as others that represent current or recent conditions (e.g., temperature gradients, canopy cover).

6. Methods information

Methods overview:

First, potential riparian areas were identified using the topography of the landscape. Then, five metrics for these riparian areas were developed, as follows. (1) The gradient of temperatures spanned by riparian areas was represented by the temperature difference between the headwaters and the stream outlet. (2) Riparian area size and width were calculated. (3) Canopy cover for riparian areas was derived from the National Land Cover Dataset (NLCD). (4) Human alteration of riparian areas was derived from an existing land-cover condition dataset. (5) Potential radiation was calculated from the topography of the landscape to represent how sunny or shaded a riparian area might be based on the surrounding terrain. These five metrics were synthesized into a riparian index. Values were presented for 90-m pixels along stream lines and were aggregated for HUC-6 watersheds. For more information, please consult the dataset citation listed in section 2 of this chapter.

This dataset employed the following specific models:

FlowAccumulation and FlowLength geoprocessing tools in ArcGIS Spatial Analyst (Esri 2013)

Major input data sources for this dataset included:

Indicators of human presence on the landscape, historical climate observations or models, digital elevation models (DEMs) or topography, current land cover

7. Guidelines for interpretation

The mapped values of the dataset may be interpreted as follows:

High values of the riparian index, which were generally found in mountainous areas, indicate riparian areas that are most expected to support climate-change adaptation because they: (1) span large temperature gradients, (2) have high canopy cover, (3) have low levels of solar exposure (sunlight), (4) are relatively wide, and/or (5) have minimal human alteration.

Representations of key concepts in climate-change ecology:

This dataset does not represent climate-change exposure or sensitivity, in that it does not quantify the magnitude of climate change that various riparian areas will experience nor how sensitive they will be to climate change. Instead, the dataset primarily represents adaptive capacity to climate change, in that riparian areas with higher index values may better enable species to move across the landscape in response to climate change, or to seek out cooler riparian microenvironments.

Adaptive capacity represents the degree to which a species is able to cope with climate change by persisting in place (such as through behavioral changes or changes in seasonal timing), seeking out more suitable microhabitats nearby, or migrating to other regions with more suitable climate. Human alterations to landscapes and ecosystems can constrain adaptive capacity in some cases (Beever *et al*. 2016). For example, species that might otherwise be able to use riparian corridors as migration routes to track favorable climates might be constrained from doing so if some riparian areas are degraded or too close to developed areas. These considerations are incorporated into this dataset, which may be relevant to a wide variety of aquatic and terrestrial species that rely on intact riparian habitats.

8. Uncertainties

This dataset involves the following assumptions, simplifications, and caveats:

Local barriers to species movement along riparian corridors could be present on the landscape that were not accounted for in this dataset, such as cliffs or cities. In addition, the quality of habitat provided by riparian areas could be affected by other considerations that were not included in the development of this dataset, such as water quality, human influences from recreation, presence of invasive species, and other factors. It should be noted that the metrics of riparian condition were not independently verified, such as by using high-resolution aerial imagery.

Quantification of uncertainty:

This dataset does not include any quantification of uncertainty relating to the mapped values.

Field verification:

Validation of riparian areas was conducted by comparing modeled riparian area locations and condition (degree of human modification) to high-resolution aerial photographs from 2011 through 2014. Validation was conducted at 30 random locations within 100 randomly selected 1-km^2 squares within the study area, for a total of 3,000 validation locations. Validation results are presented in Krosby *et al*. (2015).

9. Peer review

Prior to publication, peer review of Krosby *et al*. (2018) was conducted by external review (at least two anonymous reviewers, each from a different institution).

10. Conservation applications

Potential conservation applications of this dataset could include the following:

This dataset could be used to identify riparian areas that warrant further examination for their potential role in supporting adaptation to climate change. Because priority riparian areas were identified within HUC-6 watersheds, assessments of individual riparian corridors at the watershed scale could be guided by this dataset. For example, riparian areas with high riparian index scores could be evaluated in the field, studied from the perspective of known species of conservation concern that use those riparian areas for habitat, and monitored over time. Riparian areas with high index values that also demonstrate a capacity to support climate adaptations (e.g., by serving as microrefugia for species seeking cooler or moister microclimates, or by facilitating species movements across the landscape) might be priorities for conservation.

Applicable scales for detailed spatial assessments:

For conservation applications requiring detailed assessment of spatial variation of the dataset within a geographic boundary (such as a protected area), the following geographic scales may be most appropriate (see appendix 3 for more information).

At the scale of: a local watershed (12-digit hydrologic unit code [HUC-12]), a Bureau of Land Management (BLM) district, a river watershed (8-digit hydrologic unit code [HUC-8]), an individual county, a national forest, a level-3 ecoregion (e.g. the North Cascades), a single state (Washington, Oregon, or Idaho), a region (multiple states in the Pacific Northwest).

Applicable scales for assessing general patterns:

Due to spatial resolution, the dataset may not show detailed spatial variation at the following geographic scales, however, the dataset may be useful to assess general patterns or for comparison to other locations (see appendix 3 for more information).

At the scale of: a small (<1 km^2) nature preserve, a state park or state wildlife area.

Use of the dataset in conservation applications may be limited by the following considerations:

Development of the five metrics used to create the riparian index was grounded in conceptual ideas about what might best support climate adaptation (and species movements in particular). This conceptual model has not yet been validated, such as by tracking actual species movements with telemetry.

In addition, the riparian index represented in this dataset does not incorporate possible future changes in climate, land use, or land cover. As a result, it cannot be used to differentiate riparian areas that will experience more dramatic climate change (e.g., based on high climate velocity) from those that will not.

Past or current conservation applications:

The dataset has not yet been used in any on-the-ground conservation applications to the knowledge of the authors of this chapter.

References cited

Beever, E., J. O'Leary, C. Mengelt, J. M. West, S. Julius, N. Green, D. Magness, L. Petes, B. Stein, A. B. Nicotra, J. J. Hellmann, A. L. Robertson, M. D. Staudinger, A. Rosenberg, E. Babij, J. Brennan, G. W. Schuurman, and G. E. Hofmann. 2016. Improving conservation outcomes with a new paradigm for understanding species' fundamental and realized adaptive capacity. Conservation Letters 9: 131–137.

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

Krosby, M., R. A. Norheim, D. M. Theobald, and B. McRae. 2014. Final report: riparian climate-corridors: identifying priority areas for conservation in a changing climate. North Pacific Landscape Conservation Cooperative.

Krosby, M., R. Norheim, and D. Theobald. 2015. Riparian climate-corridors: analysis extension, improvements, and validation. North Pacific Landscape Conservation Cooperative.

Krosby, M., D. M. Theobald, R. Norheim, and B. H. McRae. 2018. Identifying riparian climate corridors to inform climate adaptation planning. PLoS ONE 13:e0205156.

Chapter 13: Terrestrial permeability of the Pacific Northwest

Authors:
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Ken Popper† (The Nature Conservancy in Oregon)
Jennifer Cartwright (U.S. Geological Survey)

† through February 2019

1. Dataset overview

This dataset provides a map of **landscape permeability**, which represents how easy it is for a variety of organisms to move through or across the landscape (figure 13.1; see chapter glossary for definitions of terms). In addition, the concept of permeability can extend to ecological processes such that more permeable landscapes are those with fewer geographic barriers to those processes. The process to calculate permeability involved the creation of a resistance dataset based on land use, infrastructure features, transportation networks, and other landscape features that might serve as deterrents or barriers to the movement of organisms.

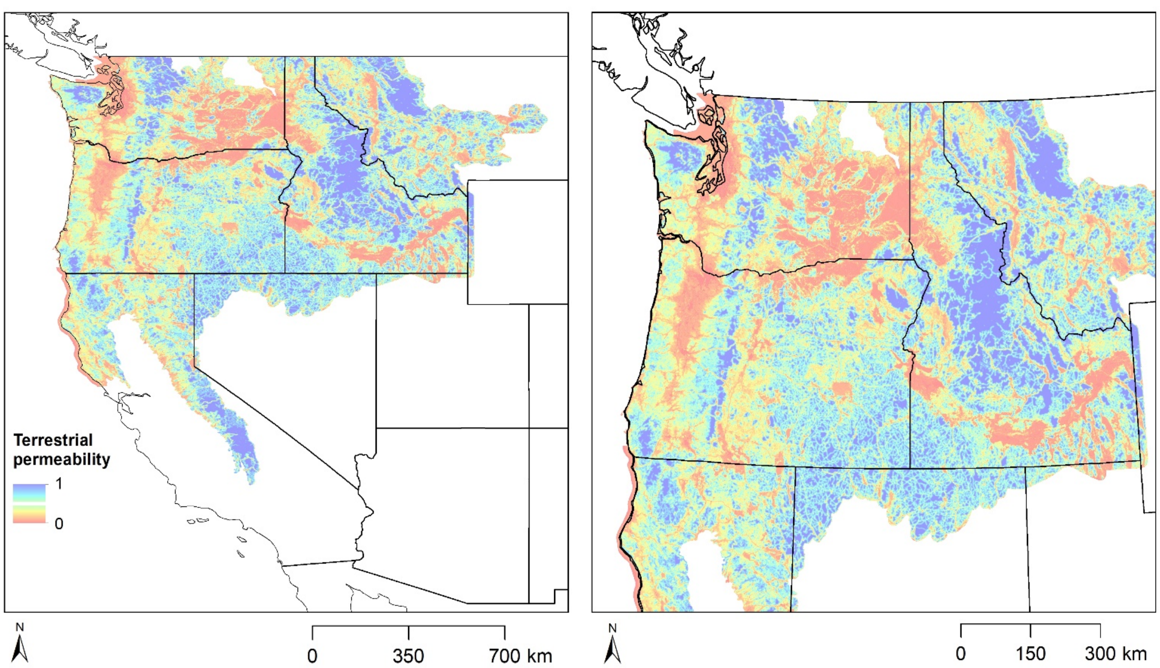

Figure 13.1. Terrestrial permeability values for the Pacific Northwest. Higher values indicate greater connectedness of natural systems, which may facilitate species movement and help sustain ecological processes over time. The left panel shows the entire extent of the dataset; the right panel shows terrestrial permeability for the Pacific Northwest.

Glossary

Landscape permeability: "the degree to which regional landscapes, encompassing a variety of natural, semi-natural and developed land cover types, will sustain ecological processes and are conducive to the movement of many types of organisms" (see dataset citation).

Land facets: unique combinations of geophysical factors that stratify the landscape into discrete classes relevant to the needs of an analysis.

Ecofacet: the portion of a land facet found within an ecoregion; in the study that produced this dataset, 162 land facets were stratified by 11 ecoregions to produce 794 ecofacets.

For detailed information about these terms, please consult the dataset citation in section 2.

2. Data access information

Dataset citation:

Buttrick, S., K. Popper, M. Schindel, B. McRae, B. Unnasch, A. Jones, and J. Platt. 2015. Conserving nature's stage: identifying resilient terrestrial landscapes in the Pacific Northwest. The Nature Conservancy, Portland, Oregon, USA.

Dataset documentation link:

http://nature.org/resilienceNW
(open access)

Data access:

The dataset can be downloaded from https://s3-us-west-1.amazonaws.com/orfo/resilience/PNW_Scripts_BaseData_Results.zip.

The zipped folder linked above contains scripts used in the study that produced the dataset and a geodatabase containing several geospatial files. Terrestrial permeability is represented by the data layer PERM_90_ALL_ECOREG. Please consult the dataset citation for explanations for each file.

The dataset available for interactive online map viewing at https://databasin.org/galleries/e41a3ea84e78463bbf9f03ce2f8e9205

Metadata access:

Formal metadata files are included with the datasets available from https://s3-us-west-1.amazonaws.com/orfo/resilience/PNW_Scripts_BaseData_Results.zip

Dataset corresponding authors:

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Ken Popper
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kjpopper@yahoo.com

3. Conceptual information

Data type category (as defined in the Introduction to this guidebook):

Landscape connectivity

Species or ecosystems represented:

This dataset does not represent any individual species or ecosystems.

Units of mapped values:

unitless

Range of mapped values:

0 to 1.0

4. Spatial information

Spatial data type: a raster dataset (grid)

Data file format(s): GeoTiff (.tif)

Spatial resolution: 90 m

Geographic coordinate system:

North American Datum of 1983

Projected coordinate system:

USA Contiguous Albers Equal Area Conic

Spatial extent: Regional (Pacific Northwest of the United States)

Dataset truncation:

The dataset is truncated at non-ecological borders along the northern edge at the United States border with Canada.

5. Temporal information

Time period represented: Current or recent (2000 to 2018)

6. Methods information

Methods overview:

Spatial information on land use, infrastructure features, and transportation networks were compiled and assigned resistance values. Higher resistance values were assigned to features or land-use types believed to impose greater barriers to movement of organisms and ecological processes. To this resistance data layer (originally at 30-m resolution, then resampled to 90-m resolution), kernel analysis was applied (Compton *et al*., 2007; Compton, 2012). This analysis produces, for each pixel, a measure of the extent to which movement outward from the pixel to neighboring pixels is impeded (low permeability) or enabled (high permeability). For more information, please consult the dataset citation listed in section 2 of this chapter.

This dataset relied on the following general types of models:

Connectivity models

This dataset employed the following specific models:

Conservation Assessment and Prioritization System (CAPS) traversability model (Compton *et al*., 2007; Compton, 2012)

Major input data sources for this dataset included:

Indicators of human presence on the landscape; current land use

7. Guidelines for interpretation

The mapped values of the dataset may be interpreted as follows:

Higher values indicate higher landscape permeability, i.e., greater connectedness of natural systems, which facilitates movement of many species and helps sustain ecological processes. Higher values are generally found in areas with more natural land cover, while lower values are generally found in areas of more intensive human land use (e.g., urban areas and agriculture) and in the vicinity of infrastructure and transportation networks.

Representations of key concepts in climate-change ecology:

This dataset primarily represents climate-change adaptive capacity, in that it seeks to quantify the ease with which species can move across the landscape in response to climate change and thus sustain ecological processes. The dataset does not represent climate-change exposure, in that it does not represent the direction or magnitude of projected climate change. The dataset may represent climate-change sensitivity to the extent that areas of more intensive human land use are more sensitive to climate change. Because sensitivity and adaptive capacity are components of climate-change vulnerability, this dataset can help contribute to an assessment of climate-change vulnerability (i.e., less permeable areas may be more vulnerable because they may have lower adaptive capacity and/or higher sensitivity).

The capacity for species to adapt to climate change, such as through migration to other regions with more suitable climate, can be constrained by human influences on the landscape (Beever *et al.*, 2016). This dataset incorporates some of those constraints on adaptive capacity by showing reduced landscape permeability in areas of more intensive human land use. However, species may face other potential constraints on their adaptive capacity not represented in this dataset, such as changing pest and pathogen dynamics, invasive species, and changes to disturbance (e.g., fire) regimes.

8. Uncertainties

This dataset involves the following assumptions, simplifications, and caveats:

The permeability values in this dataset were created using spatial data layers representing land cover, infrastructure features, and transportation networks that were current at the time the study was conducted (i.e., input data layers were generally from 2010-2014). Permeability values in this dataset thus do not reflect possible future land use, such as urban sprawl. In addition, the dataset does not consider barriers to movement created by other characteristics of the landscape, such as topographic features (e.g., cliffs) or areas of inhospitable climate (e.g., warm valleys separating cold microclimates on mountain summits). The dataset represents permeability only for terrestrial areas and should not be used to evaluate aquatic or marine ecosystems including streams, lakes, or estuaries.

Quantification of uncertainty:

This dataset does not include any quantification of uncertainty relating to the mapped values.

Field verification:

Creation of this dataset did not involve any field verification of the mapped values.

9. Peer review

Prior to dataset publication, peer review was conducted by internal review (reviewers were from the same institution).

10. Conservation applications

Potential conservation applications of this dataset could include the following:

This dataset could be used to evaluate the potential of a current network of protected areas to facilitate species' movements. For example, the study that produced this dataset (Buttrick *et al*., 2015) examined how well an existing biodiversity-based portfolio of protected areas performed in representing sites with high permeability and high topoclimate diversity. The study found that, using a 30% conservation target, **ecofacets** with high topoclimate diversity and high permeability were well represented in the portfolio in 9 of the 11 ecoregions examined.

This dataset can also be used to identify the types of **land facets** and ecofacets that are underrepresented in the current protected area network. For example, Buttrick *et al*. (2015) discussed the possibility that protection and ecological restoration of some ecofacets with low permeability, e.g., those currently used for agriculture, could improve representation of those ecofacets in the overall protected-area network. Buttrick *et al*. (2015) also provided a conceptual example of a process for conservation planning that incorporates current protection status, a conservation risk assessment, current biodiversity, and the data layers produced in the study (topoclimate diversity and landscape permeability).

Applicable scales for detailed spatial assessments:

For conservation applications requiring detailed assessment of spatial variation of the dataset within a geographic boundary (such as a protected area), the following geographic scales may be most appropriate (see appendix 3 for more information).

At the scale of: a local watershed (12-digit hydrologic unit code [HUC-12]), a Bureau of Land Management (BLM) district, a river watershed (8-digit hydrologic unit code [HUC-8]), an individual county, a national forest, a level-3 ecoregion (e.g. the North Cascades), a single state (Washington, Oregon, or Idaho), a region (multiple states in the Pacific Northwest).

Applicable scales for assessing general patterns:

Due to spatial resolution, the dataset may not show detailed spatial variation at the following geographic scales, however, the dataset may be useful to assess general patterns or for comparison to other locations (see appendix 3 for more information).

At the scale of: a small (< 1 km^2) nature preserve, a state park or state wildlife area.

Use of the dataset in conservation applications may be limited by the following considerations:

Because different species disperse across the landscape in different ways (e.g., with different modes of dispersal, at different rates, and with different sensitivities to different types of barriers), this dataset cannot necessarily be used to evaluate movement potential for an individual species. If conservation decision-making requires predictions of species-specific movement potential, this dataset could be used to supplement species-specific information on dispersal and habitat requirements.

When applied to long-range conservation planning in the face of climate change, it may be important to remember that this dataset was created using input data layers (i.e., land cover and locations of infrastructure and transportation networks) that were current at the time the study was conducted (these datasets were generally from 2010-2014). Because the creation of the permeability data layer did not incorporate any models of future land use, landscape permeability in some regions by mid-century (i.e., 2050s) or by the end of the 21st century could be substantially different than what is depicted in this dataset.

Conservation case study

This dataset has been used in conservation planning by The Nature Conservancy, Idaho Department of Fish and Game, Oregon Department of Fish and Wildlife, and multiple land trusts in the Pacific Northwest of the United States.

For example, The Nature Conservancy (TNC) is managing a $6 million grant program from the Doris Duke Charitable Foundation (DDCF) for land trusts in Oregon, Washington and Idaho to protect areas that are more likely to be resilient to climate change, defined by topoclimate diversity, local permeability, and regional connectivity (Buttrick *et al*. 2015). Similar information and investments are being made in the eastern United States through a TNC-DDCF-Open Space Institute grant program. Also, in Oregon and Idaho, topoclimate diversity data are being incorporated into updates of State Wildlife Action Plans, and multiple land trusts in the Pacific Northwest of the United States are using this dataset along with others described in Buttrick *et al*. (2015) to update their conservation priorities.

For more information on this conservation case study, please contact the corresponding authors listed in section 2.

References cited

Beever, E., J. O'Leary, C. Mengelt, J. M. West, S. Julius, N. Green, D. Magness, L. Petes, B. Stein, A. B. Nicotra, J. J. Hellmann, A. L. Robertson, M. D. Staudinger, A. Rosenberg, E. Babij, J. Brennan, G. W. Schuurman, and G. E. Hofmann. 2016. Improving conservation outcomes with a new paradigm for understanding species' fundamental and realized adaptive capacity. Conservation Letters 9: 131–137.

Buttrick, S., K. Popper, M. Schindel, B. McRae, B. Unnasch, A. Jones, and J. Platt. 2015. Conserving nature's stage: identifying resilient terrestrial landscapes in the Pacific Northwest. The Nature Conservancy, Portland, Oregon, USA.

Compton, B. 2012. CAPS traversability metric in R. Landscape Ecology Program. University of Massachusetts, Amherst, MA.

Compton, B. W., K. McGarigal, S. A. Cushman, and L. R. Gamble. 2007. A resistant-kernel model of connectivity for amphibians that breed in vernal pools. Conservation Biology 21:788–799.

Chapter 14: Species movement to analog climates

Authors:
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Jennifer Cartwright (U.S. Geological Survey)

1. Dataset overview

This dataset identifies areas that may facilitate species movement across western North America as species track changing climate conditions (figure 14.1). The dataset was produced with a connectivity model based on **electrical circuit theory** and considers **climate analogs**, **landscape permeability**, and species dispersal capacities (see chapter glossary for definitions of terms).

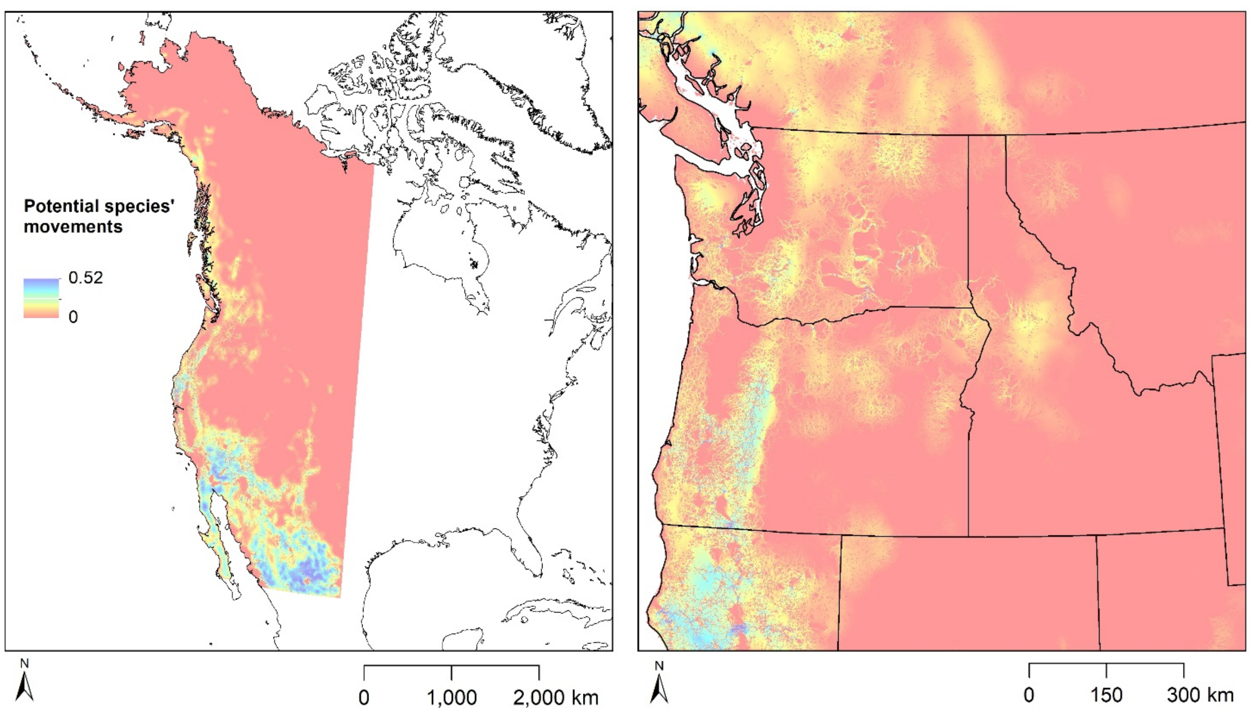

Figure 14.1. Potential species' movements (scaled values) between areas of historical climates and their 2080s climate analogs under the representative concentration pathway (RCP) 8.5 greenhouse-gas scenario as implemented in the global circulation model MIROC5. High values indicate potentially important routes for species migrations in response to climate change. The left panel shows the entire extent of the dataset; the right panel shows potential movements for the Pacific Northwest.

Glossary

Climate analogs: climatic conditions in the future that are analogous to those that exist today, or future locations that will harbor the climatic conditions of today.

Electrical circuit theory: a concept borrowed from electrical circuitry that treats landscapes and conductive surfaces across which species can travel, analogous to electrical current moving through a network of circuits.

Landscape permeability: the potential for species movement, which may be decreased by human modification of the landscape.

For detailed information about these terms, please consult the dataset citation in section 2.

2. Data access information

Dataset citation:

Littlefield, C. E., C. Carroll, B. H. McRae, J. L. Michalak, and J. J. Lawler. 2017. Connecting today's climates to future climate analogs to facilitate movement of species under climate change. Conservation Biology 31:1397–1408.

Dataset documentation link:

https://doi.org/10.1111/cobi.12938
(subscription or fee required)

Data access:

The dataset can be downloaded from https://adaptwest.databasin.org/pages/climate-connectivity-priorities-omniscape

The dataset is not available for interactive online map viewing.

Metadata access:

Formal metadata is not available for this dataset.

Dataset corresponding author:

Caitlin Littlefield
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caitlin.littlefield@umontana.edu

3. Conceptual information

Data type category (as defined in the Introduction to this guidebook):

Climate, landscape connectivity

Species or ecosystems represented:

This dataset does not represent any individual species or ecosystems

Units of mapped values:

Potential species' movements, available with scaled or unscaled units. Unscaled units represent current flow in amps. Scaled units have been scaled from 0-1, where higher values indicate greater potential for species' movements.

Range of mapped values:

The range of unscaled mapped values varies depending on the climate model used and inclusion/exclusion of landscape permeability. Mapped values that have been scaled from 0-1 are also available for each climate model. All mapped values should be interpreted with regard to the relative importance of specific areas for potential movement.

4. Spatial information

Spatial data type: a raster dataset (grid)

Data file format(s): GeoTiff (.tif)

Spatial resolution: 1 km

Geographic coordinate system:

World Geodetic System (WGS) 1984

Projected coordinate system:

World Geodetic System (WGS) 1984 Lambert Conformal Conic

Spatial extent: Regional (western North America)

Dataset truncation:

The dataset is truncated at non-ecological borders along the eastern and southern edges, which limits the geographic extent to western North America.

5. Temporal information

Time period represented: Future (later than 2020)

Future time period(s) represented:

End-of-century (2071 to 2100)

Baseline time period (against which future conditions were compared): 1961 to 1990.

6. Methods information

Methods overview:

First, climate analogs were identified by comparing historic (1961-1990) to future (2071-2100) climate conditions. Then, connectivity between climate analogs was modeled by considering landscape permeability and species dispersal capacities (Littlefield *et al*., 2017). For more information, please consult the dataset citation listed in section 2 of this chapter.

This dataset relied on the following general types of models:

Connectivity models

This dataset employed the following specific models:

Circuitscape (McRae *et al*., 2016; Shah and Mohapatra, 2013)

Major input data sources for this dataset included:

Current land use, historical climate observations or models, future climate projections, biologically-informed dispersal and climate analog similarity parameters

This dataset used the following general circulation models (GCMs):

INM-CM4, MIROC5, GFDL-CM3

Separate files are provided for each GCM; no ensemble is provided across GCMs. More information about climate models is available in appendix 1. Detailed information about climate models, including model evaluation and comparison among models, is available from Randall *et al.* (2007) and Rupp *et al.* (2013).

This dataset used the following greenhouse-gas scenarios:

RCP 8.5

More information about greenhouse-gas scenarios is available in appendix 2 and from Knutti and Sedláček (2013).

Creation of this dataset involved the following methods to change the spatial resolution of climate models (e.g. to downscale or resample climate models):

The study that produced this dataset relied on climate data from the ClimateNA version 5.10 software package, which had been downscaled from 4 km to 1 km (Wang *et al.*, 2016).

7. Guidelines for interpretation

The mapped values of the dataset may be interpreted as follows:

High values indicate important movement routes for species to track changing climate conditions, with human modification largely determining the underlying permeability of the landscape and thus which parts of the landscape species may traverse. Low values indicate areas that may be relatively less important for climate-induced movements.

Representations of key concepts in climate-change ecology:

The dataset identifies important movement routes for species to track suitable climatic conditions, which may be a critical adaptive response under climate change. Greater connections between future climate analogs (indicated by higher values of current in this dataset) suggest areas may be especially important in supporting the adaptive capacity of species that are migrating to track favorable climate conditions. The dataset may be related to climate-change resilience in that greater movement potential could help populations rebound after disturbances such as droughts. The dataset also relates to climate-change sensitivity in that areas with greater movement potential might be less sensitive to climate-change impacts on ecosystems, which help mitigate overall climate-change vulnerability.

As explained in chapter 13, the ability of species to move across landscapes in response to climate change is one component of adaptive capacity, which can also include species' abilities to persist in place or to use newly favorable nearby habitats. This dataset can help assess constraints to adaptive capacity because areas of more intensive human land use are generally represented as less permeable and so are less likely to be identified as important migration areas. Another important determinant of adaptive capacity—species' dispersal abilities—is also incorporated into this dataset. All else equal, species that can disperse rapidly over long distances may be better able to adapt to climate change by shifting their ranges than are species with limited dispersal.

8. Uncertainties

This dataset involves the following assumptions, simplifications, and caveats:

Pathways between future climate analogs did not account for intervening climate conditions or physical barriers (e.g., mountains) that could, in reality, limit species movement. This probably caused the models to overestimate species movement in some locations. In addition, the model did not incorporate fine-scale diversity in climate that could provide microclimate refugia to some species. Also, human modification was represented as static even though it will likely change over time.

Although this dataset was informed by climate niches and dispersal abilities for many species, it does not represent individual species and may fail to represent certain types of species for which there are limited data available.

This dataset is less meaningful at the inland edges of the study area because species movement into and out of the study area was not modeled. The dataset is also less meaningful in locations with unusual climate gradients.

Quantification of uncertainty:

This dataset does not include any quantification of uncertainty relating to the mapped values.

Field verification:

Field verification of the mapped values in this dataset was not possible because the dataset represents a future condition. Datasets representing the baseline time period were derived from downscaled climate grids from the ClimateNA dataset (Wang *et al*. 2016). Accuracy of the baseline climate variables in the ClimateNA dataset was assessed using monthly mean observations from 4,891 weather stations across North America, located predominantly in the United States; see table 2 in Wang *et al*. (2016).

9. Peer review

Prior to dataset publication, peer review was conducted by external review (at least two anonymous reviewers, each from a different institution).

10. Conservation applications

Potential conservation applications of this dataset could include the following:

This dataset could be used to help prioritize land areas for conservation based on the objective of maximizing species' abilities to track changing climatic conditions. This research shows that incorporating future climate projections highlights some areas that will be important for species movement that may not otherwise emerge as important if species movement is modeled only based on human modification of the landscape.

Applicable scales for detailed spatial assessments:

For conservation applications requiring detailed assessment of spatial variation of the dataset within a geographic boundary (such as a protected area), the following geographic scales may be most appropriate (see appendix 3 for more information).

At the scale of: a Bureau of Land Management (BLM) district, a river watershed (8-digit hydrologic unit code [HUC-8]), an individual county, a national forest, a level-3 ecoregion (e.g. the North Cascades), a single state (Washington, Oregon, or Idaho), a region (multiple states in the Pacific Northwest or in western North America).

Applicable scales for assessing general patterns:

Due to spatial resolution, the dataset may not show detailed spatial variation at the following geographic scales, however, the dataset may be useful to assess general patterns or for comparison to other locations (see appendix 3 for more information).

At the scale of: a small (< 1 km^2) nature preserve, a state park or state wildlife area, a local watershed (12-digit hydrologic unit code [HUC-12]).

Use of the dataset in conservation applications may be limited by the following considerations:

This dataset cannot be used to represent species movement for individual species. For long-range planning, it should be noted that this dataset did not incorporate likely future changes to landscape permeability due to changes in human modification of the landscape.

Past or current conservation applications:

The dataset has not yet been used in any on-the-ground conservation applications to the knowledge of the authors of this chapter.

<u>References cited</u>

Knutti, R., and J. Sedláček. 2013. Robustness and uncertainties in the new CMIP5 climate model projections. Nature Climate Change 3:369–373.

Littlefield, C. E., C. Carroll, B. H. McRae, J. L. Michalak, and J. J. Lawler. 2017. Connecting today's climates to future climate analogs to facilitate movement of species under climate change. Conservation Biology 31:1397–1408.

McRae, B., K. Popper, A. Jones, M. Schindel, S. Buttrick, K. Hall, R. Unnasch, and J. Platt. 2016. Conserving nature's stage: mapping omnidirectional connectivity for resilient terrestrial landscapes in the pacific northwest. The Nature Conservancy, Portland, OR.

Randall, D., R. Wood, S. Bony, R. Colman, T. Fichefet, J. Fyfe, V. Kattsov, and *et al*. 2007. Cilmate models and their evaluation. *in* S. Solomon, D. Qin, M. Manning, Z. Chen, M. Marquis, K. Averyt, M. Tignor, and H. Miller, editors. Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, New York, NY.

Rupp, D. E., J. T. Abatzoglou, K. C. Hegewisch, and P. W. Mote. 2013. Evaluation of CMIP5 20th century climate simulations for the Pacific Northwest USA. Journal of Geophysical Research 118: 884–907.

Shah, V. and T. Mohapatra. 2013. Circuitscape 4 user guide. The Nature Conservancy, Arlington, VA.

Wang, T., A. Hamann, D. Spittlehouse, and C. Carroll. 2016. Locally downscaled and spatially customizable climate data for historical and future periods for North America. PLoS One 11:e0156720.

Chapter 15: Minimum cumulative exposure and minimum exposure distance

Authors:
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1. Dataset overview

This dataset includes five spatial data layers produced in one study. **Minimum exposure distance (MED)** represents the distance traveled by an organism that migrates in response to climate change, assuming that the organism does not necessarily travel in a straight line but instead travels so as to

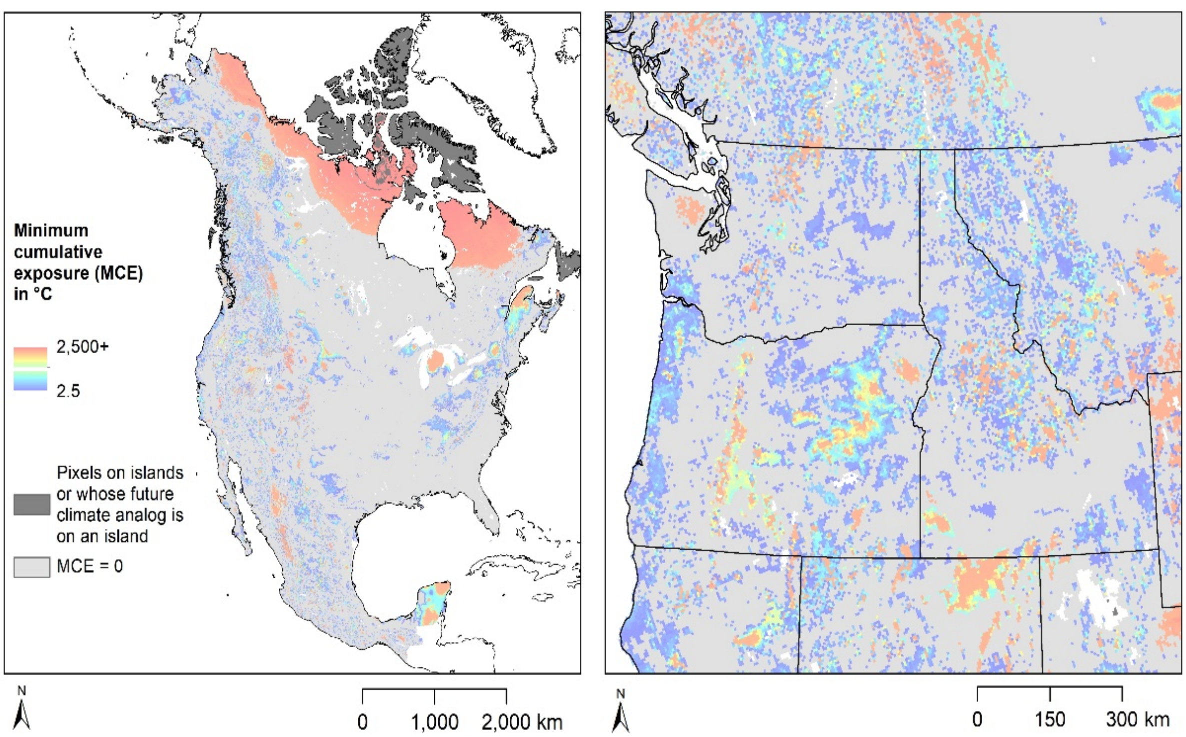

Figure 15.1. Minimum cumulative exposure (MCE). Higher values indicate that organisms migrating in response to climate change will be exposed to greater cumulative levels of unsuitable temperature conditions along the migration route, whereas lower values indicate less cumulative exposure to unsuitable temperatures during the migration. The left panel shows the entire extent of the dataset; the right panel shows MCE values for the Pacific Northwest.

minimize its exposure to dissimilar climate (in this study, dissimilar temperature) along its route (see chapter glossary for definitions of terms). **Minimum cumulative exposure (MCE)** represents the total exposure to dissimilar climate experienced by that organism along its route (figure 15.1). **Euclidean-distance velocity** is a measure of **climate-change velocity** assuming an organism migrates in a straight line, whereas **MED-based velocity** measures that exposure along the (possibly non-linear) route taken to minimize exposure to dissimilar climate. Finally, the dataset includes a ratio of MED-based velocity to Euclidean-distance velocity.

Glossary

Climate-change velocity: the direction and rate at which organisms must move to maintain a given climate through time.

Euclidean-distance velocity: climate-change velocity, assuming that organisms travel in straight lines.

Least-cost modeling: an approach to identifying potential movement routes that minimize the "cost" associated with travel. "Cost" can be conceptualized and quantified in many ways; in this study it represents the exposure of an organism to unsuitable climate conditions (i.e., too warm or too cool compared to the climate conditions the organism is tracking as it migrates).

Minimum cumulative exposure (MCE): the total exposure to dissimilar climate that an organism experiences as it responds to climate change by migrating to newly favorable climate, assuming the organism follows a path that minimizes exposure to dissimilar climate.

Minimum exposure distance (MED): the distance along the route followed by an organism migrating in response to climate change, assuming the organism follows a path that minimizes exposure to dissimilar climate.

MED-based velocity: climate-change velocity, assuming that organisms travel so as to minimize their total exposure to dissimilar climate, and not necessarily in straight lines.

For detailed information about these terms, please consult the dataset citation in section 2.

2. Data access information

Dataset citation:

Dobrowski, S. Z., and S. A. Parks. 2016. Climate change velocity underestimates climate change exposure in mountainous regions. Nature Communications 7:1–8.

Dataset documentation link:

https://www.nature.com/articles/ncomms12349
(open access)

Data access:

The dataset can be downloaded from:
https://adaptwest.databasin.org/pages/adaptwest-velocitymed

The dataset is not available for interactive online map viewing.

Metadata access:

Formal metadata is not available for this dataset.

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3. Conceptual information

Data type category (as defined in the Introduction to this guidebook):

Climate, landscape connectivity

Species or ecosystems represented:

This dataset does not represent any individual species or ecosystems.

Units of mapped values:

MED: kilometers (km)
MED-based velocity: km/year
MCE: °C
Euclidean-distance velocity: km/year
Ratio of MED-based velocity to Euclidean-distance velocity: ratio

Range of mapped values:

MED: 0 to 6,401
MED-based velocity: 0 to 71.122
MCE: 0 to 32,706
Euclidean-distance velocity: 0 to 34.367
Ratio of MED-based velocity to Euclidean-distance velocity: 1 to 10.4296

Note: Pixels on islands and whose future climate analog is on an island are coded -9999 in the MED dataset and are coded -1 in all other datasets.

4. Spatial information

Spatial data type: a raster dataset (grid)

Data file format(s): GeoTiff (.tif)

Spatial resolution: 5 km

Geographic coordinate system:

World Geodetic System (WGS) 1984

Projected coordinate system:

World Geodetic System (WGS) 1984 Lambert Conformal Conic

Spatial extent:

Continental (North America) excluding Central America and the Caribbean islands

Dataset truncation:

The dataset is truncated along the border separating Mexico from Guatemala and Belize.

5. Temporal information

Time period represented: Future (later than 2020)

Future time period(s) represented:

End-of-century (2071-2100)

Baseline time period (against which future conditions were compared): 1981-2010.

6. Methods information

Methods overview:

Using baseline and projected future values for mean annual temperature (MAT), climate analogs (destination pixels) were identified as any pixel with future MAT that is ±0.25 °C from the baseline MAT for the pixel of interest (source pixel). **Least-cost modeling** was then used to identify potential migration routes from source pixels to destination pixels. These potential migration routes are the paths that organisms could take to track changing climate conditions while minimizing the "cost" of their migration, where "cost" is conceptualized as the experience of travelling through pixels of unfavorable climate. MED is the length of these potential migration routes and MED-based velocity is MED divided by 90 years (the time between baseline year 1995 and future projections in 2085). MCE was calculated using an equation (see equation 3 in the dataset citation) that includes "cost", MED, and a penalty value based on climate dissimilarity. MED-based velocity for each pixel was compared to Euclidean-distance (straight-line) velocity using a ratio. For more information, please consult the dataset citation listed in section 2 of this chapter.

This dataset relied on the following general types of models:

Least-cost models

This dataset employed the following specific models:

raster, rgdal, and gdistance packages in the R software environment (van Etten, 2015)

Major input data sources for this dataset included:

Historical climate observations or models, future climate projections

This dataset used the following general circulation models (GCMs):

CanESM2, ACCESS1.0, IPSL-CM5A-MR, MIROC5, MPI-ESM-LR, CCSM4, HadGEM2-ES, CNRM-CM5, CSIRO-Mk3.6.0, GFDL-CM3, INM-CM4, MRI-CGCM3, MIROC-ESM, CESM1-CAM5, GISS-E2R

The dataset was produced using input climate data ensembles across these GCMs, therefore individual files for individual GCMs are not available. More information about climate models is available in appendix 1. Detailed information about climate models, including model evaluation and comparison among models, is available from Randall *et al.* (2007) and Rupp *et al.* (2013).

This dataset used the following greenhouse-gas scenarios:

RCP 8.5

More information about greenhouse-gas scenarios is available in appendix 2 and from Knutti and Sedláček (2013).

Creation of this dataset involved the following methods to change the spatial resolution of climate models (e.g. to downscale or resample climate models):

No climate downscaling was performed in this study. The mean-annual temperature input data had a resolution of 1 km, which was resampled to 5 km prior to analysis.

7. Guidelines for interpretation

The mapped values of the dataset may be interpreted as follows:

MED: high MED values indicate that organisms must travel long distances in order to reach locations with suitable climate in the future as they minimize their exposure to unsuitable climates along the way, i.e., exposure to temperatures that are too warm or too cold relative to the optimal temperature range that the organism is tracking. Conversely, low MED values indicate that suitable climates in the future are available nearby and/or without having to navigate around regions of unsuitable climate.

MED-based velocity: see interpretation of MED above. Higher MED-based velocity values mean that organisms will have to travel faster to "keep pace" with changing climate.

MCE: higher MCE values indicate that, over the course of their migration to track favorable climate as climate conditions change, organisms will be exposed to high levels of unsuitable climate; lower values represent lesser exposure to unsuitable climate along the migration route.

Euclidean-distance velocity: Higher values mean organisms will have to travel faster to "keep pace" with changing climate, assuming that they travel in straight lines.

Ratio of MED-based velocity to Euclidean-distance velocity: The higher this ratio, the greater the degree to which the migration route for an organism deviates from a straight line due to avoidance of unfavorable climate or open water.

Representations of key concepts in climate-change ecology:

The data layers in this dataset (MCE, MED and MED-based velocity, and Euclidean-distance velocity) represent various ways of conceptualizing climate-change vulnerability based on climate-change exposure (how rapidly climate conditions are predicted to change) and organisms' adaptive capacity (their ability to respond to climate change by tracking suitable climate conditions through time). For example, climate-change vulnerability may be especially great for species in areas with high velocity (because poorly dispersing species may not be able to "keep pace" with climate change) and/or in areas with high MCE (because species with narrow ranges of temperature tolerance would be subjected to possibly damaging levels of unsuitable temperature along migration routes).

Climate-change velocity is an important consideration in climate vulnerability assessments because it indicates the rate at which species would need to move to track favorable conditions. However, species may be forced to cross areas of less favorable conditions in their movement routes, as demonstrated by this dataset. While mountainous areas generally have relatively low velocity (because diverse microclimates are available nearby and can be reached by organisms traveling relatively short distances), these areas can have relatively high MCE values because organisms are exposed to unfavorable conditions as they travel to new microhabitats. Conversely, flat landscapes with high velocity generally have low MCE values because relatively homogenous climate conditions pose few barriers to species' movements. Thus, MCE and MED in this dataset can be useful complements to climate-velocity datasets for evaluating constraints to species' adaptive capacity.

8. Uncertainties

This dataset involves the following assumptions, simplifications, and caveats:

The data layers in this dataset were all created using MAT to represent climate conditions, whereas actual climate conditions important to organisms may also include measures of moisture and other factors. In addition, MAT represents average temperature by definition, so this dataset does not account for exposure to temperature variability or extremes that may be important to organisms' experiences of climate change.

This dataset represents a "coarse-filter" approach to assessing climate vulnerability that does not apply to any individual species or differentiate among species. Thus it does not account for the likelihood that within a given geographic area, some species (those that can tolerate a wider range of temperatures) will actually experience lower MCE, lower MED, and lower velocity because more of their immediate surroundings will represent favorable climate conditions, whereas other species (those that are more sensitive to temperature) will experience greater MCE, MED, and velocity.

Although MED-based velocity and MCE can be used to evaluate how accessible a site is to migrating organisms, in practice that accessibility will also be influenced by non-climate landscape attributes (such as physical barriers and human land use) and the dispersal of organisms (the means by which they disperse, over what distances they are able to disperse, and the speed at which they do so).

Calculation of MCE and the velocity data layers in this dataset is sensitive to the spatial resolution of the input climate data and to several parameters used in least-cost modeling (see supplementary material in Dobrowski and Parks 2016).

Quantification of uncertainty:

Uncertainty was not quantified in the sense that the potential effects on MCE or MED owing to variability among GCMs or across greenhouse-gas scenarios was not calculated. However, the study that produced the dataset did involve a sensitivity analysis that examined the effects of the resolution of the climate data used as inputs and two parameters used in least-cost modeling (see supplementary material in Dobrowski and Parks, 2016).

Field verification:

Field verification of the mapped values in this dataset was not possible because the dataset represents a future condition. Mean annual temperature values for the baseline time period were obtained from the ClimateNA dataset (Wang *et al*. 2016). Accuracy of the baseline climate variables in the ClimateNA dataset was assessed using monthly mean observations from 4,891 weather stations across North America, located predominantly in the United States; see table 2 in Wang *et al*. (2016).

9. Peer review

Prior to dataset publication, peer review was conducted by external review (at least two anonymous reviewers, each from a different institution).

10. Conservation applications

Potential conservation applications of this dataset could include the following:

A primary conservation application of this dataset concerns the ways in which land managers and conservation planners think about mountainous areas versus flat terrain. Previous studies have indicated that mountainous areas may serve as climate refugia because they contain steep climate gradients (i.e., large changes in climate over short distances, such as on steep mountain slopes). These steep climate gradients, it has been argued, will provide opportunities for species to find newly favorable climates nearby, without having to migrate long distances. This study raises an important additional consideration: although favorable climates may be located nearby (e.g., two adjacent mountain peaks with cold temperatures), they may not be easily accessible to migrating organisms if they are separated by inhospitable climate (e.g., a warm valley in between). Dobrowski and Parks (2016) argue that although mountainous areas may provide refugia in the near term (or under relatively mild climate-change scenarios), they will only be temporary "holdouts", meaning that they will eventually cease functioning as refugia once climate change exceeds the local climate gradients that mountains provide. Conversely, for flat areas that have previously been considered highly vulnerable to climate change because they contain little spatial variation in climate, an additional consideration raised in this study is that they may be relatively free of climate-based barriers to species movement, making it easier for species to move through flat landscapes.

Applicable scales for detailed spatial assessments:

For conservation applications requiring detailed assessment of spatial variation of the dataset within a geographic boundary (such as a protected area), the following geographic scales may be most appropriate (see appendix 3 for more information).

At the scale of: a level-3 ecoregion (e.g., the North Cascades), a single state (Washington, Oregon, or Idaho), a region (multiple states in the Pacific Northwest or in western North America), the continental United States, the North American continent.

Applicable scales for assessing general patterns:

Due to spatial resolution, the dataset may not show detailed spatial variation at the following geographic scales, however, the dataset may be useful to assess general patterns or for comparison to other locations (see appendix 3 for more information).

At the scale of: a small (< 1 km^2) nature preserve, a state park or state wildlife area, a local watershed (12-digit hydrologic unit code [HUC-12]), a Bureau of Land Management (BLM) district, a river watershed (8-digit hydrologic unit code [HUC-8]), an individual county, a national forest.

Use of the dataset in conservation applications may be limited by the following considerations:

This dataset cannot be used to evaluate climate-change vulnerability for individual species or ecosystems. Because this dataset does not incorporate information on species dispersal or barriers to species movement based on human land use, conservation practitioners should understand that actual experiences of organisms moving across landscapes in response to climate change may vary widely across species and, for some species, may not be well represented by these datasets.

Past or current conservation applications:

The dataset has not yet been used in any on-the-ground conservation applications to the knowledge of the authors of this chapter.

References cited

Dobrowski, S. Z., and S. A. Parks. 2016. Climate change velocity underestimates climate change exposure in mountainous regions. Nature Communications 7:1–8.

Knutti, R., and J. Sedláček. 2013. Robustness and uncertainties in the new CMIP5 climate model projections. Nature Climate Change 3:369–373.

Randall, D., R. Wood, S. Bony, R. Colman, T. Fichefet, J. Fyfe, V. Kattsov, and *et al*. 2007. Cilmate models and their evaluation. *in* S. Solomon, D. Qin, M. Manning, Z. Chen, M. Marquis, K. Averyt, M. Tignor, and H. Miller, editors. Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, New York, NY.

Rupp, D. E., J. T. Abatzoglou, K. C. Hegewisch, and P. W. Mote. 2013. Evaluation of CMIP5 20th century climate simulations for the Pacific Northwest USA. Journal of Geophysical Research 118: 884–907.

van Etten, J. 2015. gdistance: Distances and routes on geographical grids. R package version 1.1-9.

Wang, T., A. Hamann, D. Spittlehouse, and C. Carroll. 2016. Locally downscaled and spatially customizable climate data for historical and future periods for North America. PLoS One 11:e0156720.

Chapter 16: Animal species turnover

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1. Dataset overview

This dataset represents future projections of **species turnover** of vertebrate animals in western North America (figure 16.1; see chapter glossary for definitions of terms). These species turnover projections were derived from **habitat suitability models** for 366 terrestrial animals, which in turn were derived from the combination of projections of climate suitability with projections of vegetation (biome) change. For each pixel in the study area, each species was projected to experience contraction, expansion, or stability in habitat suitability. The species turnover rate value was then calculated for each pixel, representing the cumulative result of the projected habitat suitability change for all 366 species. Pixels with high species turnover rate values represent areas that may experience a high degree of change in species representation, whereas low species turnover rates represent areas of relative projected

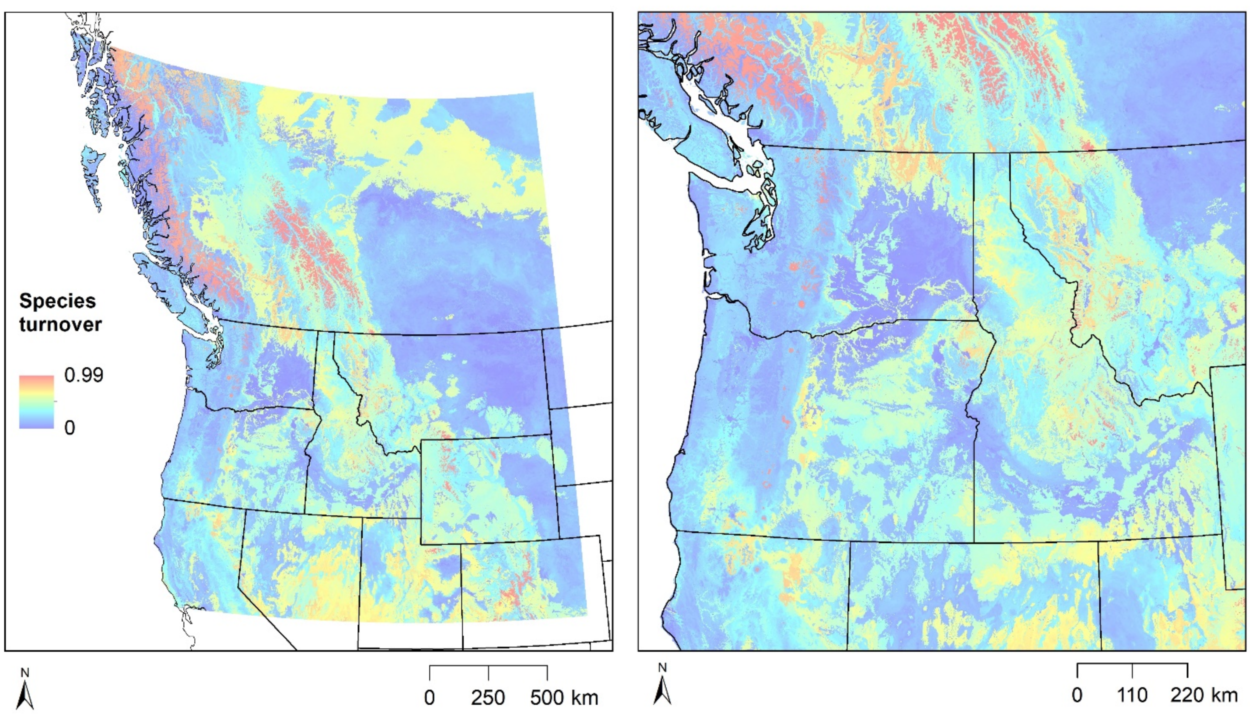

Figure 16.1. Species turnover rate projections based on the A2 greenhouse-gas scenario and the Hadley CM3 general circulation model. High values indicate large predicted changes in the composition of species between the baseline period (1961 to 1990) and the end of the century (2070 to 2099), including both potential gains and losses of species. Low values represent areas where species composition is projected to remain relatively stable over time. The left panel shows the entire extent of the dataset; the right panel shows species turnover rate projections for the Pacific Northwest.

stability. Two versions of the dataset are available, based on two future global circulation models (GCMs) - the Hadley CM3 GCM and CGCM 3.1 GCM.

Glossary

Species turnover: a metric that represents the degree to which species are projected to be gained or lost in a given geographic area.

Habitat suitability models: a type of model that projects future suitable habitat for each study species, based on observed associations between locations where species currently exist, and the climate, land cover, and other environmental features found at those locations.

For detailed information about these terms, please consult the dataset citation in section 2.

2. Data access information

Dataset citation:

Langdon, J., and J. Lawler. 2015. Assessing the impacts of projected climate change on biodiversity in the protected areas of western North America. Ecosphere 6:87.

Dataset documentation link:

https://doi.org/10.1890/ES14-00400.1
(open access)

Data access:

The CGCM 3.1 GCM version of the dataset can be downloaded from:
https://databasin.org/datasets/85722cc00ad445d680b8d50f90eb1bca

The Hadley CM3 GCM version of the dataset can be downloaded from:
https://databasin.org/datasets/bbb18483b81f4b2c9cb36154f2605d48

Metadata access:

Formal metadata is not available for this dataset.

Dataset corresponding author:

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3. Conceptual information

Data type category (as defined in the Introduction to this guidebook):

Animal habitat, climate

Species or ecosystems represented:

This dataset is an integrated assessment for 366 terrestrial animal species, including 12 amphibians, 237 birds, and 117 mammals.

Units of mapped values:

unitless

Range of mapped values:

For the Hadley CM3 GCM: 0 to 0.985507
For the CGCM 3.1 GCM: 0 to 0.980583

4. Spatial information

Spatial data type: raster dataset (grid)

Data file format(s): GeoTiff (.tif)

Spatial resolution: 30 seconds

Geographic coordinate system:

World Geodetic System (WGS) 1984

Spatial extent:

Regional

Dataset truncation:

The dataset is truncated along lines of latitude (northern and southern boundaries of the dataset) and longitude (eastern boundary of the dataset).

5. Temporal information

Time period represented: Future (later than 2020)

Future time period(s) represented:

End-of-century (2070 to 2099).

Baseline time period (against which future conditions were compared): 1961 to 1990.

6. Methods information

Methods overview:

Habitat suitability models were constructed for each of the animal species, and animal species presence and absence were correlated with 23 variables representing environmental conditions. For each species, habitat suitability was assessed using an approach that combined future climate suitability (from species-distribution models) with future vegetation (biome) suitability. Future biome suitability represented both (a) whether a biome was deemed suitable for a given species, and (b) whether that biome was projected to change in the future to another biome. These assessments produced spatial grids for each species that predicted contraction, expansion, or stability of habitat suitability for each pixel. Species turnover was calculated using these predictions. The equation for species turnover is available in Langdon and Lawler (2015). For more information, please consult the dataset citation listed in section 2 of this chapter.

This dataset relied on the following general types of models:

Habitat suitability models; bioclimatic niche models

This dataset employed the following specific models:

Vegetation change was assessed using biome maps from Rehfeldt *et al*. (2012).

Major input data sources for this dataset included:

Species ranges or point locations, historical climate observations or models, future climate projections, current and future projections of vegetation types (biomes)

This dataset used the following general circulation models (GCMs):

CGCM 3.1, Hadley CM3

Separate files are provided for each GCM; no ensemble is provided across GCMs. More information about climate models is available in appendix 1. Detailed information about climate models, including model evaluation and comparison among models, is available from Randall *et al.* (2007) and Rupp *et al.* (2013).

This dataset used the following greenhouse-gas scenarios:

SRES A2

More information about greenhouse-gas scenarios is available in appendix 2 and from Knutti and Sedláček (2013).

Creation of this dataset involved the following methods to change the spatial resolution of climate models (e.g. to downscale or resample climate models):

Climate data were downscaled using a geographic distance-weighted bilinear interpolation method.

7. Guidelines for interpretation

The mapped values of the dataset may be interpreted as follows:

High values represent landscape areas where large changes are predicted in the species that will be present in the future under climate change. This can include both gain of new species migrating in from other areas and loss of species. Low values represent landscape areas where species composition is projected to remain largely stable.

Representations of key concepts in climate-change ecology:

Species turnover is one possible component of climate-change vulnerability, in that locations with high species turnover may demonstrate increased susceptibility of animal communities to climate change. Species turnover can reflect several interrelated processes. First, climate-change exposure helps shape species turnover because greater changes in climate are more likely to require greater numbers of species to shift their ranges in response, and possibly for those range shifts to cover greater geographic distances. Second, species sensitivity to climate change may also shape species turnover, because the breadth of climatic conditions tolerated by a species is reflected in the geographic scope of its historic and projected future distributions.

Species turnover incorporates both increases and decreases in climatic suitability for species. This dataset did not include metrics of species' dispersal abilities and thus does not directly represent species presence or absence under future conditions. Dispersal abilities are an important component of adaptive capacity, because favorable climate alone does not ensure that a species will be present in an area in the future if that species is not able to effectively colonize that area. Along with changes in habitat suitability, information on species dispersal abilities could also be considered in order to anticipate species arrivals (i.e., species migrating into an area because its climate has become favorable) and departures (i.e., species migration out of an area to seek favorable climate elsewhere). While both arrivals and departures would affect the overall change in community structure in a given area, they may have different types of ecological implications and necessitate different management approaches. For example, if a keystone species moves away from an area due to climate change there could be cascading effects on other species in local food webs. New species arriving in an area may disrupt relationships between existing species, for example by competing for resources with existing species.

8. Uncertainties

This dataset involves the following assumptions, simplifications, and caveats:

This dataset was created in part by using climate suitability models, which only assess the degree to which future climate conditions will be similar or different to climate conditions associated with a current species range; they do not account for many complex ways in which climate change could affect species or their habitats such as changing disturbance regimes (e.g., fires, droughts), changes in seasonal timing of life cycles, inter-species relationships, changes in parasites or pathogen dynamics, and many other factors that will likely shape species distributions in addition to climate. In addition, these models do not consider differences among species in the rates at which species will be able to disperse to new habitats or adapt in place to changing conditions. These models essentially assume equilibrium, meaning an assumption that a given species or vegetation type will exist in a given climate, not accounting for potential time lags in transitions from one vegetation type to another.

Quantification of uncertainty:

Uncertainty in projected species turnover was assessed by conducting the analysis using two GCMs and comparing the results.

Field verification:

Species presence and absence data used in climate suitability models were not independently field verified.

9. Peer review

Prior to dataset publication, peer review was conducted by external review (at least two anonymous reviewers, each from a different institution).

10. Conservation applications

Potential conservation applications of this dataset could include the following:

This dataset can be combined with other related climate-change projections to anticipate the magnitude of climate-driven change in animal species composition for a given area. For example, the study that produced this dataset (Langdon and Lawler, 2015) also examined climate projections and biome-change projections to evaluate protected areas throughout western North America and explore possible management approaches for different predicted magnitudes of change (Langdon and Lawler, 2015). Continuation of current management practices may be appropriate for protected areas where species turnover is predicted to be low, whereas protected areas with greater predicted species turnover may require more active or innovative management approaches such as habitat improvements, increasing connectivity between protected areas and other habitat patches, and in some cases assisted migration.

Applicable scales for detailed spatial assessments:

For conservation applications requiring detailed assessment of spatial variation of the dataset within a geographic boundary (such as a protected area), the following geographic scales may be most appropriate (see appendix 3 for more information).

At the scale of: a Bureau of Land Management (BLM) district, a river watershed (8-digit hydrologic unit code [HUC-8]), an individual county, a national forest, a level-3 ecoregion (e.g., the North Cascades), a single state (Washington, Oregon, or Idaho), a region (multiple states in the Pacific Northwest or in western North America).

Applicable scales for assessing general patterns:

Due to spatial resolution, the dataset may not show detailed spatial variation at the following geographic scales, however, the dataset may be useful to assess general patterns or for comparison to other locations (see appendix 3 for more information).

At the scale of: a small (< 1 km^2) nature preserve, a state park or state wildlife area, a local watershed (12-digit hydrologic unit code [HUC-12]).

Use of the dataset in conservation applications may be limited by the following considerations:

Because this dataset was generated using habitat suitability models that simply associate species presence or absence with environmental variables, this dataset does not represent many important and complex processes that may influence species changes over time. These include disturbances such as fires and droughts, interactions between species, parasite and pathogen dynamics, and differences among species in how they may disperse to new areas or persist in place despite changing climate conditions. Therefore, managers may need to consider locally relevant conditions such as these when using this dataset to help inform management decisions.

Past or current conservation applications:

The dataset has not yet been used in any on-the-ground conservation applications to the knowledge of the authors of this chapter.

References cited

Knutti, R., and J. Sedláček. 2013. Robustness and uncertainties in the new CMIP5 climate model projections. Nature Climate Change 3:369–373.

Langdon, J., and J. Lawler. 2015. Assessing the impacts of projected climate change on biodiversity in the protected areas of western North America. Ecosphere 6:87.

Randall, D., R. Wood, S. Bony, R. Colman, T. Fichefet, J. Fyfe, V. Kattsov, and *et al*. 2007. Cilmate models and their evaluation. in S. Solomon, D. Qin, M. Manning, Z. Chen, M. Marquis, K. Averyt, M. Tignor, and H. Miller, editors. Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, New York, NY.

Rehfeldt, G., N. Crookston, S. Saenz-Romero, and E. Campbell. 2012. North American vegetation model for land-use planning in a changing climate: a solution to large classification problems. Ecological Applications 22:119–141.

Rupp, D. E., J. T. Abatzoglou, K. C. Hegewisch, and P. W. Mote. 2013. Evaluation of CMIP5 20th century climate simulations for the Pacific Northwest USA. Journal of Geophysical Research 118: 884–907.

Chapter 17: Spatial priorities for conserving birds of the Pacific Northwest

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Jennifer Cartwright (U.S. Geological Survey)

1. Dataset overview

This dataset represents an integrated assessment of spatial priorities for conserving 27 bird species identified as species of greatest conservation need in Idaho, Oregon, and/or Washington (figure 17.1). Priority areas for conservation were identified using species-distribution models for several different climate scenarios and future time periods. This produced multiple data layers that were synthesized to produce an overall **spatial prioritization** layer to support **bet-hedging** in the context of uncertainties concerning how species will respond to climate change (see chapter glossary for definitions of terms).

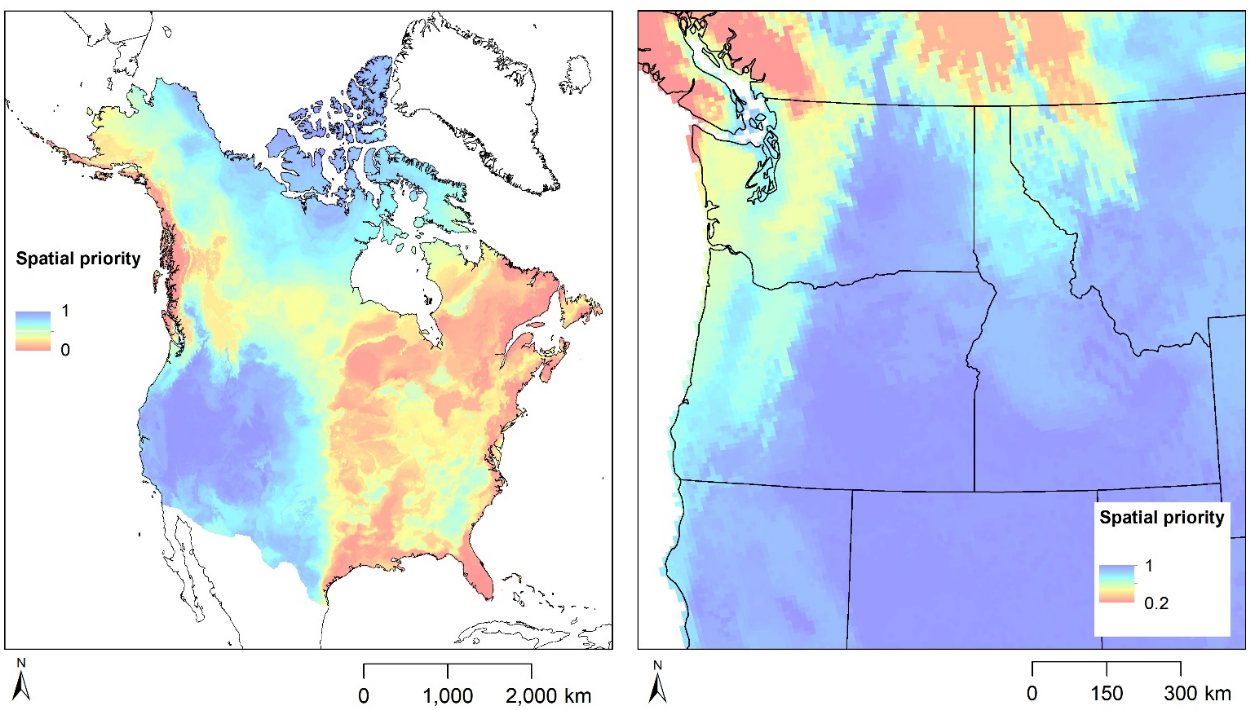

Figure 17.1. Spatial priorities for conserving 27 bird species of greatest conservation need in Washington, Oregon, and Idaho. Larger values represent areas that are considered higher priorities for conservation based on an integrated assessment of multiple climate scenarios, future time periods, and assumptions about species' responses to climate change.

Glossary

Bet hedging: a strategy for decision-making with known uncertainties whereby conservation actions are identified that could provide benefits under a range of possible future scenarios such as those associated with climate change.

Prioritization (or spatial prioritization): a map of the landscape in which higher values represent higher benefit for meeting conservation objectives, such as conserving a particular set of species under climate change.

Species of greatest conservation need (SGCN): species that have been identified in State Wildlife Action Plans as being most in need of conservation action.

For detailed information about these terms, please consult the dataset citation in section 2.

2. Data access information

Dataset citation:

Schuetz, J., G. Langham, C. Soykan, C. Wilsey, T. Auer, and C. Sanchez. 2015. Making spatial prioritizations robust to climate change uncertainties: a case study with North American birds. Ecological Applications 25:1819–1831.

National Audubon Society. 2015. Audubon's birds and climate change report: a primer for practitioners. National Audubon Society, New York, NY. Contributors: Gary Langham, Justin Schuetz, Candan Soykan, Chad Wilsey, Tom Auer, Geoff LeBaron, Connie Sanchez, Trish Distler. Version 1.3.

Dataset documentation links:

https://doi.org/10.1890/14-1903.1
(open access)

http://climate.audubon.org/sites/default/files/NAS_EXTBIRD_V1.3_9.2.15%20lb.pdf
(open access)

Data access:

The dataset can be downloaded from:
https://www.sciencebase.gov/catalog/item/5a9ed7dee4b0b1c392e500bc

The dataset is not available for interactive online map viewing.

Metadata access:

Formal metadata can be download from:
https://www.sciencebase.gov/catalog/item/5a9ed7dee4b0b1c392e500bc

Dataset corresponding author:

Chad Wilsey
National Audubon Society
science@audubon.org

3. Conceptual information

Data type category (as defined in the Introduction to this guidebook):

Animal habitat, climate

Species or ecosystems represented:

This dataset focuses on 27 bird species: Bobolink; Brown Pelican; Burrowing Owl; Common Loon; Common Nighthawk; Ferruginous Hawk; Franklin's Gull; Grasshopper Sparrow; Horned Lark; Loggerhead Shrike; Long-billed Curlew; Marbled Murrelet; Mountain Quail; Olive-sided Flycatcher; Purple Martin; Red-necked Grebe; Sage Sparrow; Sage Thrasher; Sharp-tailed Grouse; Upland Sandpiper; Vesper Sparrow; Western Bluebird; White-breasted Nuthatch; White-headed Woodpecker; Yellow-billed Cuckoo; Great Gray Owl; Greater Sage-Grouse

Units of mapped values:

unitless

Range of mapped values:

0 to 1

4. Spatial information

Spatial data type: a raster dataset (grid)

Data file format(s): Imagine image (.img)

Spatial resolution: 10 km

Geographic coordinate system:

North American Datum of 1983

Projected coordinate system:

North American Datum of 1983 Albers

Spatial extent:

Continental (United States and Canada)

Dataset truncation:

The dataset is truncated along the border between the United States and Mexico.

5. Temporal information

Time period represented: Future (later than 2020)

Future time period(s) represented:

This dataset does not represent any single future time period. Instead, it integrates the following future time periods: 2020s (2010-2039), 2050s (2040-2069), and 2080s (2070-2099).

Baseline time period (against which future conditions were compared): 2000.

6. Methods information

Methods overview:

Species-distribution models were constructed for each of the 27 bird species in this study (see section 3; (Distler *et al*., 2015; Langham *et al*., 2015; Schuetz *et al*., 2015). Species distributions were projected into the future for three time periods (2020s, 2050s, and 2080s) using three greenhouse-gas scenarios (B2, A1B, and A2), two seasons (summer and winter), and three different sets of assumptions (scenarios) about how species might respond to climate change (National Audubon Society, 2015). In the "suffer in place" scenario, species were sensitive to climate change but unable to effectively track changing climate by shifting their distributions. In the "track and move" scenario, species distributions tracked their preferred climates across the landscape. In the "adapt in place" scenario, species remained in place geographically and adapted to the changing climate conditions. For each combination of future time period, season, greenhouse-gas scenario, and species-response scenario, species richness (the total number of species predicted for each pixel) was calculated. A spatial prioritization was built for each of these scenarios using the Zonation software (Moilanen *et al*., 2009). Finally, the three prioritization grids for the three approaches were integrated to produce a "bet hedging" prioritization grid. For more information, please consult the dataset citation listed in section 2 of this chapter.

This dataset relied on the following general types of models:

Species-distribution models; bioclimatic niche models

This dataset employed the following specific models:

ZONATION software (Moilanen *et al*., 2009)

Major input data sources for this dataset included:

Species ranges or point locations, historical climate observations or models, future climate projections

This dataset used the following general circulation models (GCMs):

CCCMA-CGCM3.1T47, CSIRO-Mk3.0, IPSL-CM4, MPI-ECHAM5, NCAR-CCSM3.0, HadCM3, HadGEM1, NIES

An ensemble across GCMs is provided; individual files for individual GCMs are not available. More information about climate models is available in appendix 1. Detailed information about climate models, including model evaluation and comparison among models, is available from Randall *et al.* (2007) and Rupp *et al.* (2013).

This dataset used the following greenhouse-gas scenarios:

SRES A1B, SRES A2, SRES B2

More information about greenhouse-gas scenarios is available in appendix 2 and from Knutti and Sedláček (2013).

Creation of this dataset involved the following methods to change the spatial resolution of climate models (e.g. to downscale or resample climate models):

The study that produced this dataset did not involve downscaling of climate data, however, the study used downscaled climate data that were downscaled using the delta method as described by Ramirez-Villegas and Jarvis (2010).

7. Guidelines for interpretation

The mapped values of the dataset may be interpreted as follows:

High values represent areas that are the greatest priorities for conservation based on an integration across multiple future time periods, seasons, climate scenarios, and scenarios of species' responses to climate change.

Representations of key concepts in climate-change ecology:

Climate-change exposure is represented indirectly in this dataset through the downscaled climate models used in the species-distribution modeling process. Climate sensitivity and adaptive capacity of bird species is more difficult to assess, for example because (a) species may vary widely in their tolerance of changing climate and their abilities to cope with or adapt to environmental change; (b) projected climate changes may be outside the historical range of variation such that adequate data do not exist to assess species' responses to future climate changes; and (c) adaptive capacity may be constrained by a range of factors, such as habitat degradation, invasive species, and changing disturbance regimes. The study that produced this dataset attempted to account for these sources of uncertainty (and others) using a scenario approach representing multiple possibilities for how species might respond to climate change (i.e., "suffer in place", "track and move", and "adapt in place"). Scenario-based approaches can be particularly useful in the context of multiple forms of uncertainty and can allow scientists and managers to evaluate a range of possible future outcomes and related management options.

8. Uncertainties

This dataset involves the following assumptions, simplifications, and caveats:

The spatial prioritization depicted in this dataset was produced using species-distribution models that were informed by bioclimatic variables that primarily represented temperature and precipitation. These species-distribution models did not incorporate current or future land use or land cover into projections of species distributions. Nor did they model inter-species interactions such as competition between species, avoidance of predators, or the biological effects of pathogens or parasites. The relatively coarse spatial resolution (10 km) also means that microclimatic effects on species distributions were not accounted for.

In addition, the study that produced this dataset considered three possible species responses to climate change ("suffer in place", "track and move", and "adapt in place"). In reality, other species responses may be possible, including intermediary responses that incorporate some components of these three named responses. It is also possible that responses will vary based on geography, habitat, time, or other factors. For example, "adapt in place" might be a plausible response to moderate climate change but become nonviable once a certain threshold of climate change has been surpassed, in which case "suffer in place" would become the new response.

Quantification of uncertainty:

Uncertainty regarding the intermediate variables in the analysis (i.e., species distributions, species richness projections) were not directly quantified. However, Schuetz *et al*. (2015) demonstrated that biological uncertainty (such as the alternative sets of assumptions about species' responses to climate change included in this prioritization) was considerably greater than the uncertainty represented by greenhouse-gas scenarios. Also, the study that produced this dataset examined a number of factors that could contribute to uncertainty in conservation decision-making. For example, a metric of conservation efficiency was developed that represents how well a spatial prioritization for an individual species is represented by a prioritization for many species. In addition, prioritizations were compared across the three approaches to highlight areas where the three approaches most closely agreed and areas where they disagreed.

Field verification:

Field verification of the mapped values in this dataset was not possible because the dataset represents a future condition. Bird species-distribution models used as inputs to generate spatial priorities were evaluated by Distler *et al*. (2015) and Langham *et al*. (2015) using historical species observations from 1980 to 1999; see table 1 and appendix S2 in Distler *et al*. (2015) and appendices S8 and S9 in Langham *et al* (2015).

9. Peer review

Prior to dataset publication, peer review was conducted by external review (at least two anonymous reviewers, each from a different institution).

10. Conservation applications

Potential conservation applications of this dataset could include the following:

This dataset directly supports conservation of bird **species of greatest conservation need** in Washington, Oregon, and Idaho and can be used to compare areas on the landscape in terms of their conservation value for these 27 species. In addition, further value could be derived from the study that produced this dataset (Schuetz *et al.*, 2015) by applying a similar approach to other conservation problems (e.g., other types of species). This study provides a generalized framework for dealing with uncertainty around possible species' responses to climate change that could be applied to create spatial prioritizations in a variety of other contexts.

Applicable scales for detailed spatial assessments:

For conservation applications requiring detailed assessment of spatial variation of the dataset within a geographic boundary (such as a protected area), the following geographic scales may be most appropriate (see appendix 3 for more information).

At the scale of: a single state (Washington, Oregon, or Idaho), a region (multiple states in the Pacific Northwest or in western North America), the continental United States, the North American continent.

Applicable scales for assessing general patterns:

Due to spatial resolution, the dataset may not show detailed spatial variation at the following geographic scales, however, the dataset may be useful to assess general patterns or for comparison to other locations (see appendix 3 for more information).

At the scale of: a small (< 1 km^2) nature preserve, a state park or state wildlife area, a local watershed (12-digit hydrologic unit code [HUC-12]), a Bureau of Land Management (BLM) district, a river watershed (8-digit hydrologic unit code [HUC-8]), an individual county, a national forest, a level-3 ecoregion (e.g., the North Cascades).

Use of the dataset in conservation applications may be limited by the following considerations:

This dataset represents conservation priorities only for the 27 bird species considered. Therefore, it is likely that other (possibly competing) conservation priorities will also need to be considered, including conservation priorities for other bird species, for non-bird species, and conservation priorities based on "coarse-filter" approaches such as habitat connectivity and landscape diversity. In addition, the priorities in this dataset would need to be weighed against the costs of conservation. Because of the spatial resolution of the dataset (10 km), it is best used for discerning general regional patterns and cannot necessarily be used to guide small-scale conservation investments, which would require more high-resolution data.

Past or current conservation applications:

This dataset has not yet been used in any on-the-ground conservation applications to the knowledge of the authors of this chapter. However, Audubon North Carolina is using a similar analysis to prioritize conservation action and advocacy across their State (http://nc.audubon.org/conservation/climate/climate-strongholds).

References cited

Distler, T., J. G. Schuetz, and J. Vel. 2015. Stacked species distribution models and macroecological models provide congruent projections of avian species richness under climate change. Journal of Biogeography 42:976–988.

Knutti, R., and J. Sedláček. 2013. Robustness and uncertainties in the new CMIP5 climate model projections. Nature Climate Change 3:369–373.

Langham, G. M., J. G. Schuetz, T. Distler, C. U. Soykan, and C. Wilsey. 2015. Conservation status of North American birds in the face of future climate change. PLoS ONE 10:e0135350.

Moilanen, A., H. Kujala, and J. Leathwick. 2009. The zonation framework and software for conservation prioritization. Pages 196–210 *in* A. Moilanen, K. Wilson, and H. Possingham, editors. Spatial conservation prioritization: quantitative methods and computational tools. Oxford University Press, Oxford, UK.

National Audubon Society. 2015. Audubon's birds and climate change report: a primer for practitioners. National Audubon Society, New York, NY. Contributors: Gary Langham, Justin Schuetz, Candan Soykan, Chad Wilsey, Tom Auer, Geoff LeBaron, Connie Sanchez, Trish Distler. Version 1.3.

Ramirez-Villegas, J., and A. Jarvis. 2010. Downscaling global circulation model outputs: the delta method decision and policy analysis working paper No. 1. International Center for Tropical Agriculture, Cali, Colombia.

Randall, D., R. Wood, S. Bony, R. Colman, T. Fichefet, J. Fyfe, V. Kattsov, and *et al*. 2007. Cilmate models and their evaluation. *in* S. Solomon, D. Qin, M. Manning, Z. Chen, M. Marquis, K. Averyt, M. Tignor, and H. Miller, editors. Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, New York, NY.

Rupp, D. E., J. T. Abatzoglou, K. C. Hegewisch, and P. W. Mote. 2013. Evaluation of CMIP5 20th century climate simulations for the Pacific Northwest USA. Journal of Geophysical Research 118: 884–907.

Schuetz, J., G. Langham, C. Soykan, C. Wilsey, T. Auer, and C. Sanchez. 2015. Making spatial prioritizations robust to climate change uncertainties: a case study with North American birds. Ecological Applications 25:1819–1831.

Chapter 18: Tree and songbird macrorefugia

Authors:

Diana Stralberg (Department of Renewable Resources, University of Alberta)
Jennifer Cartwright (U.S. Geological Survey)

1. Dataset overview

This dataset maps spatial patterns of **macrorefugia** for trees and songbirds in North America (figure 18.1; see chapter glossary for definitions of terms). The dataset was created using species-distribution models for 324 trees and 268 songbirds, and results can be accessed for individual species or by species group. The study that produced this dataset also identified the climate and topographic characteristics that were associated with macrorefugia (Stralberg *et al*., 2018).

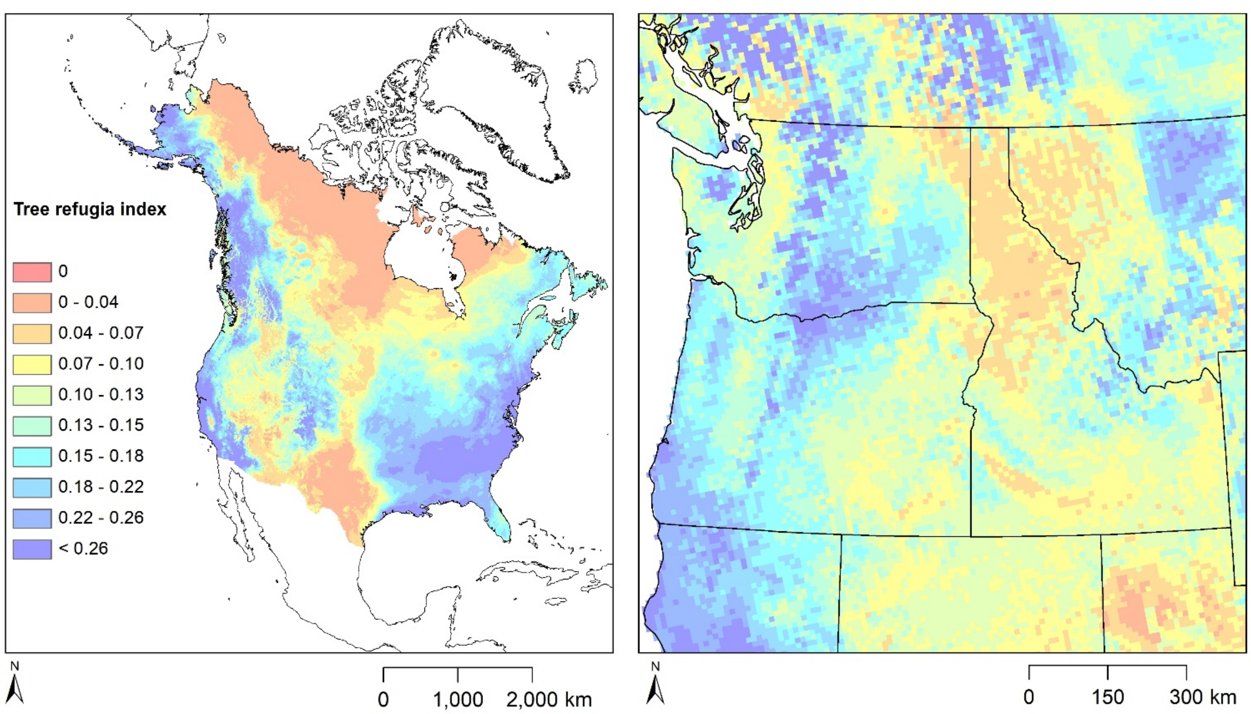

Figure 18.1. End-of-century tree refugia index values for the representative concentration pathway (RCP) 8.5 greenhouse-gas scenario. Higher values indicate areas with greater potential to provide refugia—regions of relative climate stability—for multiple tree species under climate change. The left panel shows the entire extent of the dataset; the right panel shows the tree refugia index values for the Pacific Northwest.

Glossary

Backward velocity: the speed at which a climate or species niche must travel to reach a particular future location.

Refugia: "regions of relative stability for multiple species under climate change" (see dataset citation).

***In situ* refugia:** "characterized by relatively constant climate conditions that facilitate species persistence or, for individual species, overlap between current and future climatic niches" (see dataset citation).

***Ex situ* refugia:** locations with suitable climate that are geographically removed from a species current distribution; "may vary in proximity to a species' current distribution, with consequent implications for their overall value" (see dataset citation).

Macrorefugia: "defined by sustained climatic suitability along broad spatial and temporal gradients"; distinct from microrefugia, which "suggest a decoupling of local climate conditions from the surrounding landscape" (see dataset citation).

Multispecies refugia index: a representation of the potential for a location to serve as a refugium to multiple species within a taxonomic or functional group (e.g., trees or songbirds).

For detailed information about these terms, please consult the dataset citation in section 2.

2. Data access information

Dataset citation:

Stralberg, D., C. Carroll, J. H. Pedlar, C. B. Wilsey, D. W. McKenney, and S. E. Nielsen. 2018. Macrorefugia for North American trees and songbirds: climatic limiting factors and multi-scale topographic influences. Global Ecology and Biogeography 27:690–703.

Dataset documentation link:

https://doi.org/10.1111/geb.12731
(subscription or fee required)

Data access:

The dataset can be downloaded from:
https://adaptwest.databasin.org/pages/climatic-macrorefugia-for-trees-and-songbirds

The dataset can be viewed online at:
https://adaptwest.databasin.org/maps/new#datasets=af2b472e8c6a4dcd8f9ff064d6ab0bb7

Metadata access:

Formal metadata is available from:
https://adaptwest.databasin.org/datasets/af2b472e8c6a4dcd8f9ff064d6ab0bb7/layers/a6139408117e445897a1152b1825c1d6/metadata/fgdc

Dataset corresponding author:

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Department of Renewable Resources, University of Alberta, Edmonton, Alberta, Canada
diana.stralberg@ualberta.ca

3. Conceptual information

Data type category (as defined in the Introduction to this guidebook):

Animal habitat, climate, vegetation

Species or ecosystems represented:

The macrorefugia indices presented in this dataset were created using species-distribution models for 324 individual tree and 268 songbird species and are thus intended to represent **refugia** potential for multiple species. Combined indices are available for four specific habitat-based groups of songbirds: forest, open woodland, grassland, and shrub, as well as for individual species.

Units of mapped values:

unitless

Range of mapped values:

0 to 1.13 (songbird refugia index, mid-century)
0 to 0.98 (songbird refugia index, end-of-century)
0 to 1.24 (tree refugia index, mid-century)
0 to 1.22 (tree refugia index, end-of-century)

4. Spatial information

Spatial data type: a raster dataset (grid)

Data file format(s): GeoTiff (.tif)

Spatial resolution: 10 km

Geographic coordinate system:

World Geodetic System (WGS) 1984

Projected coordinate system:

World Geodetic System (WGS) 1984 Lambert Azimuthal Equal Area

Spatial extent:

National (USA and most of Canada)

Dataset truncation:

The dataset is truncated along the border between the United States and Mexico, and at the boundary between southern and high arctic ecoregions, as mapped by the Commission for Environmental Cooperation (1997).

5. Temporal information

Time period represented: Future

Future time period(s) represented:

Mid-century (2041-2070), end-of-century (2071-2100)

Baseline time period (against which future conditions were compared): 1971–2000.

6. Methods information

Methods overview:

Species-distribution models for 324 trees and 268 songbirds were used to project locations of future presence for each species. **Backward velocity** for each species was calculated using these presence projections, as the distance in kilometers (km) from each future distribution pixel to the nearest current distribution pixel. This was done for each combination of species and global climate model (GCM) for two representative concentration pathways (RCPs). An equation was used to translate backward velocity into a refugia index based on hypothetical long-distance dispersal distributions (see equation 1 in the dataset citation). For each RCP, refugia index values from four GCMs were averaged to produce an average refugia index for each species. Then, in averaging across species to produce an overall (multi-species) refugia index, species were weighted based on the projected proportional change in the total area of their distributions. For more information, please consult the dataset citation listed in section 2 of this chapter.

This dataset relied on the following general types of models:

Species-distribution models

This dataset employed the following specific models:

Species-distribution models for songbirds were from Distler *et al*. (2015) and were developed using boosted regression trees. Species-distribution models for trees were from McKenney *et al*. (2011) and were developed using Maxent (Phillips *et al*., 2006).

Major input data sources for this dataset included:

Species point locations (presence/absence for birds based on Breeding Bird survey; presence only for trees based on various sources), historical climate observations or models, future climate projections

This dataset used the following general circulation models (GCMs):

CanESM2, CESM1-CAM5, HadGEM2-ES, MIROC-ESM

Separate files are provided for each GCM and an ensemble across GCMs is also provided. More information about climate models is available in appendix 1. Detailed information about climate models, including model evaluation and comparison among models, is available from Randall *et al.* (2007) and Rupp *et al.* (2013).

This dataset used the following greenhouse-gas scenarios:

RCP 4.5, RCP 8.5

More information about greenhouse-gas scenarios is available in appendix 2 and from Knutti and Sedláček (2013).

Creation of this dataset involved the following climate model downscaling methods:

Downscaling of climate models was not conducted as part of the study that produced this dataset, however, downscaled climate projections were used as inputs. Information on downscaling methods that produced these inputs is available from McKenney *et al*. (2011).

7. Guidelines for interpretation

The mapped values of the dataset may be interpreted as follows:

Higher values indicate greater potential for a location to serve as a future macrorefugium for multiple species (i.e., multiple species of songbirds or of trees). For an individual species, an index value of 1 indicates high-probability ***in situ* refugia** (i.e., all GCMs in agreement). Lower values indicate that ***ex situ* refugia** are farther away and thus more difficult for species to access in response to climate change. Multispecies index values are weighted by projected changes in climatic suitability for each species; i.e., climate-increasing species are down-weighted with respect to climate-decreasing species.

Representations of key concepts in climate-change ecology:

This dataset contributes to the growing body of work focused on identifying and managing climate-change refugia as one component of climate adaptation to conserve biodiversity. The dataset is influenced by climate-change exposure because it is driven by projections of future climate change. The dataset is relevant to climate-change resistance and, inversely, climate-change vulnerability because areas with higher *in situ* or *ex situ* refugia potential for a species may promote that species' ability to cope with or respond to climate change. The dataset is also relevant to climate-change adaptive capacity in that it represents the availability of *ex situ* refugia to which species might migrate in response to climate change.

While availability of both *in situ* or *ex situ* refugia have the potential to mitigate species' vulnerability to climate change, these refugia types represent different potential options for species and may require different management considerations. Availability of *in situ* refugia, identified as areas of overlap between current and future suitable habitats, may enable species to persist within parts of their current ranges. These areas may be important for conservation and management, for example to mitigate potentially negative effects from invasive species or habitat degradation. Availability of *ex situ* refugia may need to be considered along with the distances to those refugia from the current species range as well as species dispersal abilities. In addition, areas that are identified as potential refugia for many species may be of heightened ecological and conservation importance.

8. Uncertainties

This dataset involves the following assumptions, simplifications, and caveats:

The dataset resolution (10 km) was limited by the resolution of the input climate model projections; therefore finer-scale microrefugia cannot be identified with this dataset.

The study that produced the dataset indicated that the results (i.e., the maps of multi-species refugia index) were highly sensitive to the species information used as inputs, including the number and types of species represented, and the data quality (accuracy or reliability) of the species location data. In other words, if different groups of species had been used then the resulting maps of refugia index would likely be different. Imperfect knowledge of current species locations also affects the results. The dataset authors indicated lower confidence in the results for the northernmost portion of the study area (arctic and boreal regions of Alaska and Canada) due to sparse location information for species.

Because the dataset was produced using species-distribution models (SDMs), assumptions made by these models may have affected the resulting dataset. For example, the SDMs assumed that species are currently in equilibrium with climate, that correlations between species locations and climate are meaningful, and that interactions between species are captured by climate. In cases where an SDM more closely represents a species' fundamental niche (the climate conditions for which it is suited) than its actual distribution, the dataset may overestimate refugia potential. In addition, human obstacles to species movements, differing migration rates among species, and differences among species in their ability to move through unsuitable climates in pursuit of more suitable climates were not incorporated into the production of the dataset.

Quantification of uncertainty:

The **multispecies refugia index** values were compared across GCMs and RCPs. In general, refugia index values were similar across the four GCMs used as indicated by pairwise correlations and the standard deviation of values across the four GCMs. Refugia index values were higher under RCP 4.5 compared to RCP 8.5 but showed similar geographic patterns.

Field verification:

Field verification of the mapped values in this dataset was not possible because the dataset represents a future condition. Bird species-distribution models used as inputs to calculate the refugia indices were validated by Distler *et al*. (2015) using historical species observations from 1980 to 1999 (see table 1 and appendix S2 in Distler *et al*., 2015). Input tree species-distribution models are described in McKenney *et al*. (2007 and 2011). Climate variables used as inputs to these models were validated using withheld datasets (McKenney *et al*., 2007). Tree-species occurrence datasets used as inputs to these models were screened by comparison to range maps from Little (1971 and 1977).

9. Peer review

Prior to dataset publication, peer review was conducted by external review (at least two anonymous reviewers, each from a different institution).

10. Conservation applications

Potential conservation applications of this dataset could include the following:

This dataset could be used to identify areas that may serve as macrorefugia for multiple bird and/or tree species in the future as climate conditions change. Given the spatial resolution of the dataset (10 km) and its focus on multiple species, it is probably most suitable for large-scale (i.e., regional) conservation planning, such as prioritizing land areas for future acquisition and protection. In some cases, the dataset may provide regional-scale information relevant to potential efforts to translocate species (assist their migration) in response to climate change.

Applicable scales for detailed spatial assessments:

For conservation applications requiring detailed assessment of spatial variation of the dataset within a geographic boundary (such as a protected area), the following geographic scales may be most appropriate (see appendix 3 for more information).

At the scale of: a single state (Washington, Oregon, or Idaho), a region (multiple states in the Pacific Northwest or in western North America), the continental United States and Canada.

Applicable scales for assessing general patterns:

Due to spatial resolution, the dataset may not show detailed spatial variation at the following geographic scales, however, the dataset may be useful to assess general patterns or for comparison to other locations (see appendix 3 for more information).

At the scale of: a small (< 1 km^2) nature preserve, a state park or state wildlife area, a local watershed (12-digit hydrologic unit code [HUC-12]), a Bureau of Land Management (BLM) district, a river watershed (8-digit hydrologic unit code [HUC-8]), an individual county, a national forest, a level-3 ecoregion (e.g., the North Cascades).

Use of the dataset in conservation applications may be limited by the following considerations:

In the context of identifying and prioritizing areas for future land acquisition and protection, this dataset does not consider current or future land-use patterns, economic feasibility of protecting new land areas, or the role of conservation priorities other than songbird and tree habitat (e.g., aquatic and wetland habitats, fish, amphibian, reptile, mammal, and invertebrate species). Importantly, this dataset does not represent locations of microrefugia (e.g., based on local variations in topography or soil) that may influence species responses to climate change. Also, because of the dataset spatial resolution and focus on multiple species, it may not be suitable for local conservation planning or application to a particular species.

Past or current conservation applications:

The dataset has not yet been used in any on-the-ground conservation applications to the knowledge of the authors of this chapter.

References cited

Commission for Environmental Cooperation. 1997. Ecological Regions of North America: Toward a Common Perspective. Commission for Environmental Cooperation, Montreal, Canada.

Distler, T., J. G. Schuetz, and J. Vel. 2015. Stacked species distribution models and macroecological models provide congruent projections of avian species richness under climate change. Journal of Biogeography 42:976–988.

Knutti, R., and J. Sedláček. 2013. Robustness and uncertainties in the new CMIP5 climate model projections. Nature Climate Change 3:369–373.

Little, E. 1971. Atlas of United States Trees, vol. 1: Conifers and important hardwoods. Washington (DC): U.S. Department of Agriculture. Miscellaneous publication no. 1146.

Little, E. 1977. Atlas of United States trees, vol. 4: Minor eastern hardwoods. Washington (DC): U.S. Department of Agriculture. Miscellaneous publication no. 1342.

McKenney, D., J. Pedlar, R. Rood, and D. Price. 2011. Revisiting projected shifts in the climate envelopes of North American trees using updated general circulation models. Global Change Biology 17:2720–2730.

McKenney, D., J. Pedlar, K. Lawrence, K. Campbell, and M. Hutchinson. 2007. Potential impacts of climate change on the distribution of North American trees. BioScience 57: 939–948.

Phillips, S. J., R. P. Anderson, and R. E. Schapire. 2006. Maximum entropy modeling of species geographic distributions. Ecological Modelling 190:231–259.

Randall, D., R. Wood, S. Bony, R. Colman, T. Fichefet, J. Fyfe, V. Kattsov, and *et al*. 2007. Cilmate models and their evaluation. *in* S. Solomon, D. Qin, M. Manning, Z. Chen, M. Marquis, K. Averyt, M. Tignor, and H. Miller, editors. Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, New York, NY.

Rupp, D. E., J. T. Abatzoglou, K. C. Hegewisch, and P. W. Mote. 2013. Evaluation of CMIP5 20th century climate simulations for the Pacific Northwest USA. Journal of Geophysical Research 118: 884–907.

Stralberg, D., C. Carroll, J. H. Pedlar, C. B. Wilsey, D. W. Mckenney, and S. E. Nielsen. 2018. Macrorefugia for North American trees and songbirds: climatic limiting factors and multi-scale topographic influences. Global Ecology and Biogeography 27:690–703.

Chapter 19: Environmental diversity datasets for North America

Authors:

Julia Michalak (School of Environmental and Forest Sciences, University of Washington)
Jennifer Cartwright (U.S. Geological Survey)

1. Dataset overview

This dataset includes several data layers that represent, in various ways, the diversity of environmental conditions across a landscape. These data layers include two metrics of topographic diversity: elevational diversity and **heat-load index (HLI)** diversity (see chapter glossary for definitions of terms). **Land-facet diversity** (figure 19.1) represents the variety of land-facet types, which are landscape areas classified according to **landform**, elevation, HLI, and soil order. **Ecotypic diversity** measures the variety of Ecological Land Units as defined by Sayre *et al*. (2014). Ecological Land Units represent unique combinations of landform, growing degree days, an aridity index, lithology (soil parent material), and land cover. The study that produced these data layers also evaluated current climate diversity and climate velocity, however, these data layers are not described in detail in this chapter.

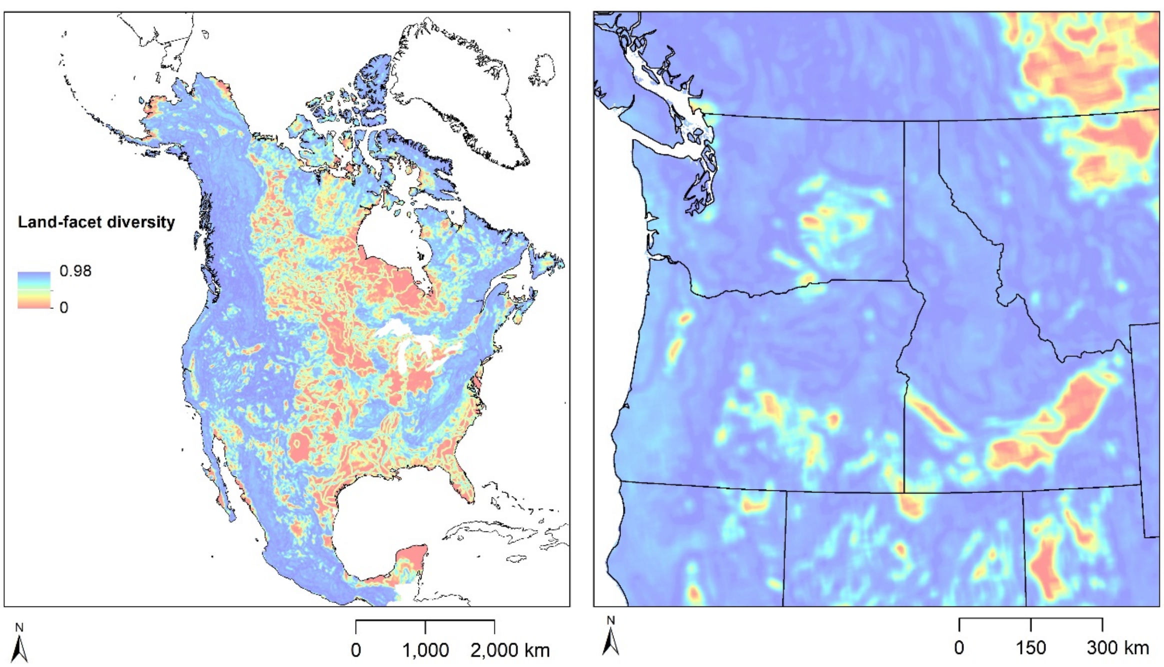

Figure 19.1. Diversity of land facets, which are areas of the landscape with similar soil order, elevation, landform, and heat-load index. Higher values indicate areas with a greater local variety of land facets, whereas lower values indicate areas with relatively few distinct land facets. The left panel shows the entire extent of the dataset; the right panel shows land-facet diversity for the Pacific Northwest.

Glossary

Heat-load index (HLI): an index based on topography of how much solar warming a site receives by virtue of its latitude, slope, and aspect (the direction a slope is facing); see McCune and Keon (2002).

Topographic position index (TPI): the difference in elevation between a focal pixel and the mean elevation of the pixels surrounding it at a given radius; see Jenness (2006).

Landform: a classification of the landscape based on topography, namely slope and TPI.

Land-facet diversity: a measure of the variety of land facets (i.e., locations with unique landform, HLI, elevation, and soil order characteristics) within a given spatial neighborhood.

Ecotypic diversity: diversity of ecotypes (i.e., locations with unique climatic, landform, lithology, and land cover characteristics, see Sayre *et al*. (2014)) within a given spatial neighborhood.

Refugia: locations to which components of biodiversity can retreat and in which they can persist despite regional declines in climatic and/or habitat suitability.

For detailed information about these terms, please consult the dataset citation in section 2.

2. Data access information

Dataset citation:

Carroll, C., T. Wang, D. R. Roberts, J. L. Michalak, J. J. Lawler, S. E. Nielsen, D. Stralberg, A. Hamann, and B. H. McRae. 2017. Scale-dependent complementarity of climatic velocity and environmental diversity for identifying priority areas for conservation under climate change. Global Change Biology 23:4508–4520.

Dataset documentation link:

https://doi.org/10.1111/gcb.13679
(open access)

Data access:

The dataset can be downloaded from:
https://adaptwest.databasin.org/pages/environmental-diversity-north-america

The dataset is not available for interactive online map viewing.

Metadata access:

Formal metadata is not available for this dataset.

Dataset corresponding author:

Carlos Carroll
Klamath Center for Conservation Research
carlos@klamathconservation.org

3. Conceptual information

Data type category (as defined in the Introduction to this guidebook):

Topoedaphic

Species or ecosystems represented:

This dataset does not represent any individual species or ecosystems.

Units of mapped values:

Elevational diversity: meters (m)
HLI diversity: unitless
Land-facet diversity: unitless; represents the Gini-Simpson diversity index
Ecotypic diversity: unitless; represents the Gini-Simpson diversity index

Range of mapped values:

Elevational diversity: 0 to 1,286.54
HLI diversity: 0 to 0.07087
Land-facet diversity: 0 to 0.97828
Ecotypic diversity: 0 to 0.99402

4. Spatial information

Spatial data type: a raster dataset (grid)

Data file format(s): ASCII (.asc)

Spatial resolution: 1 km

Geographic coordinate system:

World Geodetic System (WGS) 1984

Projected coordinate system:

World Geodetic System (WGS) 1984 Lambert Azimuthal Equal Area

Spatial extent:

Continental (North America) excluding Central America and the Caribbean islands

Dataset truncation:

The dataset is truncated along the border separating Mexico from Guatemala and Belize.

5. Temporal information

Time period represented: Static (relatively unchanging over time)

6. Methods information

Methods overview:

Elevation, slope, HLI, and **topographic position index** (TPI) were obtained from a digital elevation model (DEM) at 100-m resolution. Calculation of HLI is explained in McCune and Keon (2002); calculation of TPI is explained in Jenness (2006). Diversity of HLI and elevation were calculated by comparing all pairs of pixels within a 27-km moving window (spatial neighborhood around the pixel of interest). Landforms were classified based on categories of slope (flat, gentle, and steep) and TPI. Land-facet categories were derived from classifications of elevation (10 bins), HLI (warm, neutral, and cool), landforms, and 38 soil orders. Ecotypes--also known as ecological land units--were obtained from Sayre *et al*. (2014) and represent landscape categories based on climate, landform, lithology, and land-cover type. Diversity of land-facets and of ecotypes was calculated using the Gini-Simpson diversity index and a 27-km moving window. For more information, please consult the dataset citation listed in section 2 of this chapter.

This dataset relied on the following general types of models:

Terrain or geomorphology models

Major input data sources for this dataset included:

Historical climate observations or models, digital elevation models (DEMs) or topography, soil characteristics, lithology

7. Guidelines for interpretation

The mapped values of the dataset may be interpreted as follows:

Elevational diversity: higher values indicate a greater diversity of nearby elevations and are generally associated with complex, rugged terrain; lower values are associated with flatter terrain.

HLI diversity: higher values indicate a greater diversity of nearby microclimates (e.g., cooler north-facing slopes, warmer south-facing slopes) and are generally found in rugged terrain; lower values indicate less microclimate diversity and are generally found in flatter terrain.

Land-facet diversity: higher values indicate a greater nearby variety of land facets (combinations of elevation, HLI, landforms, and soil orders).

Ecotypic diversity: higher values indicate a greater nearby variety of ecotypes (combinations of climate, landform, lithology, and land-cover type).

Representations of key concepts in climate-change ecology:

This dataset relates to species' adaptive capacities, specifically the ability of species to access newly suitable climates in areas within or nearby their historical ranges. Given comparable levels of climate-change exposure, areas with greater environmental diversity (as represented by the data layers in this dataset) are generally expected to have reduced vulnerability (due to greater adaptive capacity) for two main reasons. First, locations with high geophysical diversity are generally correlated with higher levels of biodiversity. Second, a high diversity of topographic conditions increases the likelihood that a variety of microclimatic conditions are present that could serve as **refugia** (Beier *et al*., 2015). In other words, areas with diverse environmental conditions are expected to increase the likelihood that species will be able to find and access newly suitable habitats as climate conditions change (Carroll *et al*., 2017).

These concepts illustrate the conservation idea known as "conserving the stage" or "conserving nature's stage" (Beier *et al*., 2015). This approach to conservation in the face of climate change suggests that conserving a diverse set of physical environmental conditions (the "stage") can be an effective "coarse-filter" approach to conserving many individual species (the "actors"). This approach is commonly juxtaposed with other "fine-filter" approaches that focus on individual species. The diversity of physical environmental conditions in an area has been quantified in different ways by different research teams, but generally incorporates information on landscape topography (e.g., shaded slopes versus sunny slopes), soil types, and geology.

8. Uncertainties

This dataset involves the following assumptions, simplifications, and caveats:

Topographic data layers derived from DEMs (such as slope, TPI, and HLI) are sensitive to the spatial resolution of the input DEM. This study used a 100-m DEM as input, therefore finer-resolution topographic features could not be discerned and small-scale (e.g., 10-m or 30-m) topographic diversity was not accounted for, although it might be important to certain species' responses to climate change. Furthermore, complex patterns of microclimate and diversity of microclimates can arise from factors not included in these datasets. Such considerations include latitude, season, disturbance patterns and succession, formations of fog, dew, and frost, wind patterns and their potential to redistribute precipitation, and biological feedbacks that affect soil characteristics.

Quantification of uncertainty:

Uncertainty was not quantified for the individual data layers in this environmental-diversity dataset. Sources of uncertainty associated with these datasets include mapping accuracy of soils and lithology datasets, the definition and classification of landforms, and whether, in general, the quantified topoedaphic variables appropriately capture features important to biodiversity and climatic resilience. The study that produced these datasets did include a comparison among the different data layers, informed by: correlations among data layers, relationships to elevation, and the spatial conservation priorities that would be derived from each data layer. The study that produced these datasets also examined climate velocity (not covered in this guidebook chapter) and did quantify uncertainty for this velocity data layer regarding variability across climate models and greenhouse-gas scenarios.

Field verification:

Creation of this dataset did not involve any field verification of the mapped values.

9. Peer review

Prior to dataset publication, peer review was conducted by external review (at least two anonymous reviewers, each from a different institution).

10. Conservation applications

Potential conservation applications of this dataset could include the following:

This dataset has potential to help inform an evaluation of existing networks of protected areas and provide information relevant to decision-making for acquisition of new protected areas. For example, the study that produced these datasets (Carroll *et al*., 2017) found that the existing network of protected areas across North America was more effective in capturing diversity of elevation and HLI and somewhat less effective in capturing diversity of ecotypes and land facets. This was linked to the tendency for mountainous areas to be over-represented in protected area networks relative to lower-elevation plains. Also, this study found that the various environmental diversity data layers (diversity of elevation, HLI, ecotypes, and land-facets) produced noticeably different outcomes when they were used as inputs to identify optimal networks of protected areas. This implies that, from a conservation perspective, a variety of strategies for considering environmental diversity may need to be considered and conservation practitioners should not assume that one type of environmental diversity is necessarily representative of other types of environmental diversity.

Applicable scales for detailed spatial assessments:

For conservation applications requiring detailed assessment of spatial variation of the dataset within a geographic boundary (such as a protected area), the following geographic scales may be most appropriate (see appendix 3 for more information).

At the scale of: a Bureau of Land Management (BLM) district, a river watershed (8-digit hydrologic unit code [HUC-8]), an individual county, a national forest, a level-3 ecoregion (e.g., the North Cascades), a single state (Washington, Oregon, or Idaho), a region (multiple states in the Pacific Northwest or in western North America), the continental United States, the North American continent.

Applicable scales for assessing general patterns:

Due to spatial resolution, the dataset may not show detailed spatial variation at the following geographic scales, however, the dataset may be useful to assess general patterns or for comparison to other locations (see appendix 3 for more information).

At the scale of: a small (< 1 km^2) nature preserve, a state park or state wildlife area, a local watershed (12-digit hydrologic unit code [HUC-12]).

Use of the dataset in conservation applications may be limited by the following considerations:

In the decision-making process leading up to the designation of new protected areas, many practical considerations (e.g., social, economic, administrative) are involved that this dataset does not address. Furthermore, this dataset fundamentally represents a "coarse-filter" approach, meaning that it does not represent any individual species and uses no species-specific information. Managers may wish to combine information from this dataset and similar datasets on environmental diversity with species-specific information where available, e.g., species range maps or habitat suitability assessments. Conservation decision-making may also be informed by ecological information and management priorities related to disturbance (e.g., fires or droughts), ecological restoration, and specialized or sensitive habitats (e.g., wetlands or riparian environments) that are not represented in these data layers.

Past or current conservation applications:

The dataset has not yet been used in any on-the-ground conservation applications to the knowledge of the authors of this chapter.

References cited

Beier, P., M. L. Hunter, and M. Anderson. 2015. Special section: conserving nature's stage. Conservation Biology 29:613–617.

Carroll, C., T. Wang, D. R. Roberts, J. L. Michalak, J. J. Lawler, S. E. Nielsen, D. Stralberg, A. Hamann, and B. H. McRae. 2017. Scale-dependent complementarity of climatic velocity and environmental diversity for identifying priority areas for conservation under climate change. Global Change Biology 23:4508–4520.

Jenness, J. 2006. Topographic position index (tip_jen.avx) extension for ArcView 3.x.

McCune, B., and D. Keon. 2002. Equations for potential annual direct incident radiation and heat load. Journal of Vegetation Science 13:603–606.

Sayre, R., J. Dangermond, C. Frye, R. Vaughan, P. Aniello, and others. 2014. A new map of global ecological land units — an ecophysiographic stratification approach. Association of American Geographers, Washington, DC.

Chapter 20: Landforms and physiographic diversity of the United States

Authors:
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Jennifer Cartwright (U.S. Geological Survey)

1. Dataset overview

This dataset contains a set of seven data layers that depict the spatial patterns in physical features of the landscape that support ecosystems and evolutionary processes. These include **landforms**, continuous **heat-load index**, multi-scale **topographic position index**, **lithology**, **physiography**, physiographic diversity (figure 20.1), and topographic diversity (see chapter glossary for definitions of terms). One of the central layers is landscape physiography that is represented as a combination of landforms (e.g., mountains, slopes, valleys) and lithology. A total of 269 "physiographic units" were mapped for the continental United States by overlaying landforms and lithology and were used to map the overall diversity of physiographic units at a variety of spatial scales, ranging from >100-km radius to approximately a 1-km radius. This metric of physiographic diversity essentially represents how varied or how uniform the physical landscape is for locations throughout the United States. Mountainous areas

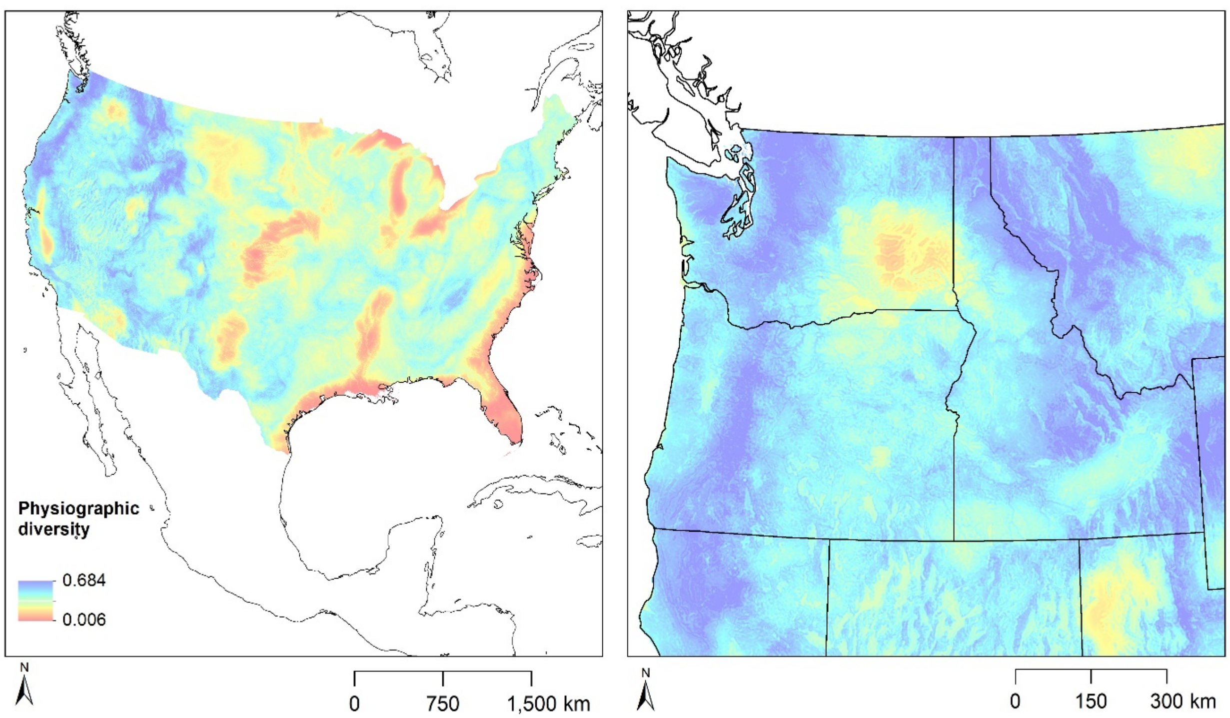

Figure 20.1. Physiographic diversity values. High values represent areas with a rich diversity of landforms (physical landscape features) and soil parent material types. Lower values represent areas with less diversity of landforms and more homogenous soil parent material. The left panel shows the entire extent of the dataset; the right panel shows physiographic diversity for the Pacific Northwest.

generally have much higher physiographic diversity than flat plains, and thus may provide a greater diversity of environmental conditions for plants and animals.

Glossary

Heat-load index (HLI): an index based on topography of how much solar warming a site receives by virtue of its latitude, slope, and aspect (i.e., the direction a slope is facing); see McCune and Keon (2002).

Landforms: physical landscape features such as peaks, ridges, cliffs, slopes, and valleys, differentiated by warm, neutral, and cool heat load.

Lithology: surficial geology that provides parent material for soil formation, including sediment deposits and areas of exposed bedrock.

Physiography: landscape patterns that combine landforms and lithology.

Topographic position index (TPI): the difference in elevation between a focal pixel and the mean elevation of the pixels surrounding it at a given radius; see Jenness (2006).

For detailed information about these terms, please consult the dataset citation in section 2.

2. Data access information

Dataset citation:

Theobald, D. M., D. Harrison-Atlas, and W. B. Monahan. 2015. Ecologically-relevant maps of landforms and physiographic diversity for climate adaptation planning. PLoS One 10:e0143619.

Dataset documentation link:

https://doi.org/10.1371/journal.pone.0143619
(open access)

Data access:

Landform maps are available in the public data catalog associated with Google Earth Engine and may be downloaded from:
https://www.sciencebase.gov/catalog/item/564b4bb0e4b0ebfbef0d31d2

Physiographic diversity maps are not available for interactive online map viewing and may be obtained by contacting the corresponding author.

Metadata access:

Formal metadata is available from:
https://www.sciencebase.gov/catalog/item/564b4bb0e4b0ebfbef0d31d2

Dataset corresponding author:

David Theobald
Conservation Science Partners
davet@csp-inc.org

3. Conceptual information

Data type category (as defined in the Introduction to this guidebook):

Topoedaphic

Species or ecosystems represented:

This dataset does not represent any individual species or ecosystems.

Units of mapped values:

unitless; represents Shannon-Weaver diversity index

Range of mapped values:

Physiographic diversity values range conceptually from 0 to 1, in practice they range from 0.006 to 0.684.

4. Spatial information

Spatial data type: a raster dataset (grid)

Data file format(s): GeoTiff (.tif)

Spatial resolution:

For landform maps: ~30 m (0.00026949459 decimal seconds)
For physiographic diversity: ~270 m

Geographic coordinate system:

For landform maps: World Geodetic System (WGS) 1984
For physiographic diversity: North American Datum of 1983

Projected coordinate system:

For landform maps: World Geodetic System (WGS) 1984
For physiographic diversity: North American Datum of 1983 Albers

Spatial extent:

Conterminous United States

Dataset truncation: The dataset is truncated along the United States borders with Canada and Mexico.

5. Temporal information

Time period represented: Static (relatively unchanging over time)

6. Methods information

Methods overview:

First, landforms were mapped using the TPI. Highly positive TPI values are associated with peaks and ridges, while highly negative TPI values are associated with valley bottoms. Landforms were further classified as "warm", "neutral", or "cool" based on a topographic metric that approximates incoming solar radiation. A national-scale dataset on lithology (Soller *et al*., 2009) was used to represent soil parent material and was overlaid on the landform maps to generate physiographic units. For example, areas that were classified as the "warm upper slope" landform and as "carbonate" lithology became a physiographic unit of "warm upper slope, carbonate". This overlay of landforms and lithology resulted in 269 physiographic units. Finally, the Shannon-Weaver diversity index (an index commonly used to quantify diversity of species in an area) was calculated to represent the diversity of physiographic units within an area of a given size (radius). This was done for seven radii ranging from 1.2 km to 115.8 km (Theobald *et al*., 2015).

This dataset relied on the following general types of models:

Terrain or geomorphology models

This dataset employed the following specific models:

Topographic position index (TPI)
Modified version of the topographic heat-load index (McCune and Keon 2002)

Major input data sources for this dataset included:

Digital elevation models (DEMs) or topography, lithology (surficial materials) representing soil parent material

7. Guidelines for interpretation

The mapped values of the dataset may be interpreted as follows:

For landform maps: values are categorical and represent various landform classes.

For physiographic diversity: values are continuous and unitless and represent the degree to which a given area has a strong diversity of landforms and soil parent material types. Low values for physiographic diversity are more common in flat plains or areas of homogenous lithology. High values for physiographic diversity are more common in rugged mountains or areas of highly varied lithology.

Representations of key concepts in climate-change ecology:

Landscape areas with relatively high physiographic diversity may exhibit higher adaptive capacity in the face of climate change than other areas because the diversity of nearby microclimates may enable species to seek refugia or shift their habitats to take advantage of locally favorable conditions. This increased adaptive capacity could result in reduced climate vulnerability in areas of high physiographic diversity. Note that this dataset does not represent climate exposure in that no future climate projections were used.

As described in chapter 19, conservation of areas with relatively high physiographic diversity may be part of a "coarse-filter" approach to biodiversity conservation under climate change, consistent with the idea of "conserving nature's stage" (Beier *et al*., 2015). This approach can be combined with more "fine-filter" approaches that also incorporate information about individual species or groups of species.

8. Uncertainties

This dataset involves the following assumptions, simplifications, and caveats:

Although physiographic diversity was calculated at a range of scales, very fine-scale (e.g., meter-scale or sub-meter-scale) diversity of microclimates was not captured. Inputs to this analysis were topographic and lithologic. Thus, physiographic diversity does not incorporate other possible physical features and processes that could affect ecosystems, such as groundwater expression (e.g., in springs or seeps) and orographic effects (e.g., rain shadows). The model of continuous HLI assumes insolation reflecting the sun at noon on the equinox.

Quantification of uncertainty:

This dataset does not include any quantification of uncertainty relating to the mapped values.

Field verification:

Field verification of this dataset was not performed, however, classification of certain landforms (cliffs and flats) was checked against geomorphological types from the Soil Survey Geographic Database (SSURGO) (Natural Resource Conservation Service, 2014).

9. Peer review

Prior to dataset publication, peer review was conducted by external review (at least two anonymous reviewers, each from a different institution).

10. Conservation applications

Potential conservation applications of this dataset could include the following:

A primary application of this dataset is to guide "coarse-filter" approaches to conservation, which focus more on conserving a variety of physical features of the landscape rather than on individual species or ecosystems. Physiographic diversity was positively correlated with vertebrate species richness (Pearson correlation ~ 0.45) supporting the idea that physiographic diversity promotes biodiversity (Theobald *et al*., 2015). In some cases, the dataset could be adapted for "fine-filter" conservation approaches focused on individual species, e.g., by locating areas of greatest physiographic diversity within a species' range. The study that produced these datasets (Theobald *et al*., 2015) included a gap analysis component in which the level of land protection was assessed for each landform class. In general, landforms associated with more rugged, mountainous areas were better protected (e.g., peaks and cliffs) and lower-elevation areas were less protected (e.g., flat slopes and valley bottoms). This may point to a need to better protect some of these lower-elevation landforms in order to conserve overall landform diversity.

Applicable scales for detailed spatial assessments:

For conservation applications requiring detailed assessment of spatial variation of the dataset within a geographic boundary (such as a protected area), the following geographic scales may be most appropriate (see appendix 3 for more information).

At the scale of: a local watershed (12-digit hydrologic unit code [HUC-12]), a Bureau of Land Management (BLM) district, a river watershed (8-digit hydrologic unit code [HUC-8]), an individual county, a national forest, a level-3 ecoregion (e.g., the North Cascades), a single state (Washington, Oregon, or Idaho), a region (multiple states in the Pacific Northwest or in western North America), the continental United States.

Applicable scales for assessing general patterns:

Due to spatial resolution, the dataset may not show detailed spatial variation at the following geographic scales, however, the dataset may be useful to assess general patterns or for comparison to other locations (see appendix 3 for more information).

At the scale of: a small (< 1 km^2) nature preserve, a state park or state wildlife area.

Use of the dataset in conservation applications may be limited by the following considerations:

Because this dataset represents an abiotic "coarse-filter" approach to providing information for conservation decision-making, it focuses on the physical attributes of the landscape (the conservation "stage") rather than species (the "actors"). This dataset would likely be combined with other sources of information to enable assessment of individual species, ecosystems, or biological processes. Conservation decision-making is commonly informed by a range of considerations other than physiography, including ecological issues (e.g., endangered species, disturbances, and sensitive habitats) and pragmatic considerations (e.g., social, economic, and administrative issues).

Past or current conservation applications:

Conservation case study

This dataset has been used at the landscape scale by a number of Federal agencies, including the USDA Forest Service, the National Park Service, and U.S. Fish and Wildlife Service, over medium (5 to 10 years) to long-range (decades) conservation planning timeframes. For example, these data were used to refine a map of resistance and resilience of sagebrush ecosystems to inform restoration activities on BLM lands in the Green River Basin in Wyoming.

For more information on this conservation case study, please contact the corresponding author listed in section 2.

References cited

Beier, P., M. L. Hunter, and M. Anderson. 2015. Special section: conserving nature's stage. Conservation Biology 29:613–617.

Jenness, J. 2006. Topographic position index (tip_jen.avx) extension for ArcView 3.x.

McCune, B., and D. Keon. 2002. Equations for potential annual direct incident radiation and heat load. Journal of Vegetation Science 13:603–606.

Natural Resource Conservation Service. 2014. Soil Survey Geographic (SSURGO) Database. http://sdmdataaccess.nrcs.usda.gov/.

Soller, D., M. Reheis, C. Garrity, and D. Van Sistine. 2009. Map database for surficial materials in the conterminous United States. U.S. Geological Survey Data Series 425.

Theobald, D. M., D. Harrison-atlas, and W. B. Monahan. 2015. Ecologically-relevant maps of landforms and physiographic diversity for climate adaptation planning. PLoS One 10:e0143619.

Chapter 21: Topoclimate diversity of the Pacific Northwest

Authors:
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Ken Popper† (The Nature Conservancy in Oregon)
Jennifer Cartwright (U.S. Geological Survey)

† through February 2019

1. Dataset overview

This dataset represents the local diversity of **topoclimates** within an area (figure 21.1; see chapter glossary for definitions of terms). North-facing slopes are topographically shaded and thus provide cooler local temperatures than nearby south-facing slopes, which receive greater sunlight. Therefore, a given area that includes a diversity of sunny and shaded slopes provides greater diversity of local temperatures relative to another area the same size that includes only flat land with neither sunny nor shaded slopes. As another example, ridgetops may be well-drained whereas local depressions and valley bottoms accumulate runoff into streams. Therefore, an area with both ridgetops and valley bottoms might provide greater diversity of moisture conditions than an area that contains only one or the other type of landform.

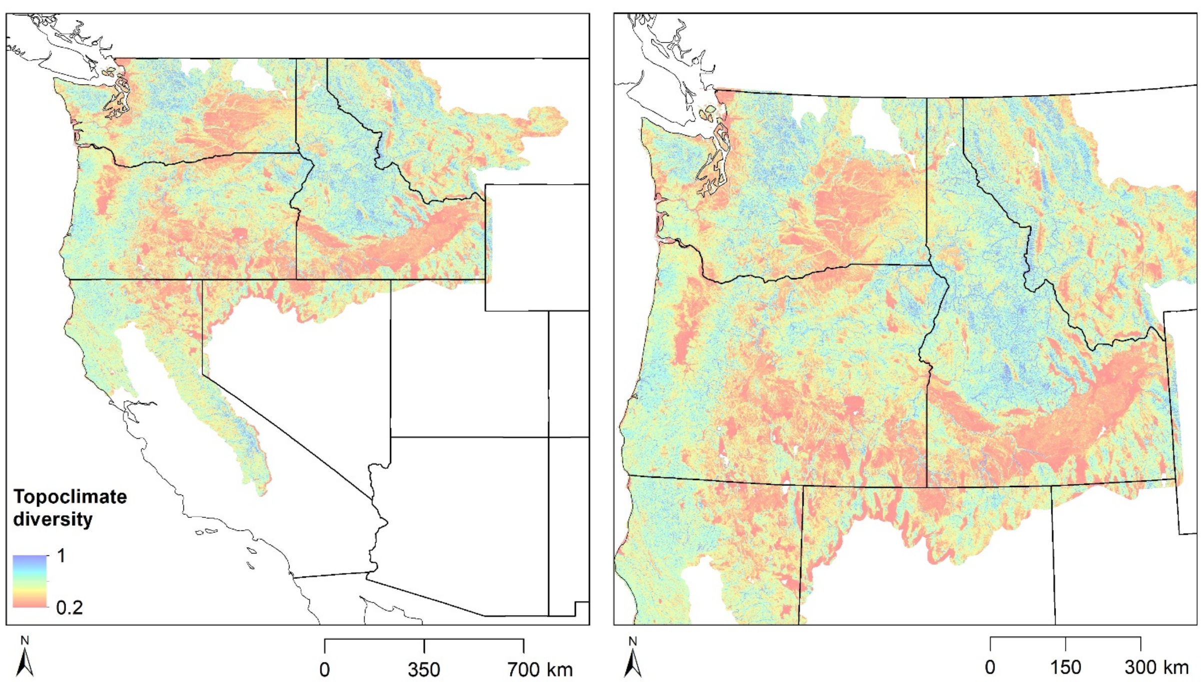

Figure 21.1. Diversity of topoclimate conditions in the Pacific Northwest. High values indicate areas with a wide variety of local temperature and moisture conditions as determined by topography. Low values indicate areas with topography that suggests little spatial variation in temperature and moisture conditions. The left panel shows the entire extent of the dataset; the right panel shows topoclimate diversity for the Pacific Northwest. White areas are not included in the dataset.

Glossary

Compound topographic index (CTI): “a metric of potential ground wetness” that “models water flow accumulation as a function of upstream contributing area and slope.” “Smallest CTI values are typically found along ridgelines and largest values in valley bottoms” (Buttrick *et al.*, 2015).

Heat-load index (HLI): “an approximation of relative, local temperature” (Buttrick *et al.*, 2015) in which southwest-facing slopes have the highest values and northeast-facing slopes have the lowest values.

Topoclimates: “local climate conditions as influenced by topography” (Buttrick *et al.*, 2015).

Resilience: “a measure of the degree of opportunities provided for species within an area to respond to changes in temperature and moisture (changes in climate). A resilient system is one that allows adaptive responses by species and is less likely to change its species composition” (Buttrick *et al*. 2015). For the study that produced this dataset, resilience to climate change was calculated by multiplying topoclimate diversity and local permeability, and then the results were attributed to land facets within each ecoregion.

For detailed information about these terms, please consult the dataset citation in section 2.

2. Data access information

Dataset citation:

Buttrick, S., K. Popper, M. Schindel, B. McRae, B. Unnasch, A. Jones, and J. Platt. 2015. Conserving nature’s stage: identifying resilient terrestrial landscapes in the Pacific Northwest. The Nature Conservancy, Portland, Oregon, USA.

Dataset documentation link:

http://nature.org/resilienceNW
(open access)

Data access:

The dataset can be downloaded from https://s3-us-west-1.amazonaws.com/orfo/resilience/PNW_Topoclimate_Data.zip

The zipped folder linked above contains the following files in a geodatabase: CTI_ALL_ECOREG, CTI_FOCAL_NRM, HLI_ALL_ECOREG, HLI_FOCAL_NRM, TOPOCLIMATE_ALL_ECOREG. Topoclimate diversity is represented by the data layer TOPOCLIMATE_ALL_ECOREG. Please consult the dataset citation for explanations for each file.

The dataset available for interactive online map viewing at:
https://databasin.org/galleries/e41a3ea84e78463bbf9f03ce2f8e9205

Metadata access:

Formal metadata files are included with the datasets available from:
https://s3-us-west-1.amazonaws.com/orfo/resilience/PNW_Topoclimate_Data.zip

Dataset corresponding authors:

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Ken Popper
self-employed; formerly with The Nature Conservancy in Oregon
kjpopper@yahoo.com

3. Conceptual information

Data type category (as defined in the Introduction to this guidebook):

Topoedaphic

Species or ecosystems represented:

This dataset does not represent any individual species or ecosystems.

Units of mapped values:

unitless

Range of mapped values:

0.2 to 1.0

4. Spatial information

Spatial data type: a raster dataset (grid)

Data file format(s): GeoTiff (.tif)

Spatial resolution: 90 m

Geographic coordinate system:

North American Datum of 1983

Projected coordinate system:

USA Contiguous Albers Equal Area Conic

Spatial extent:

Regional (Pacific Northwest of the United States)

Dataset truncation:

The dataset is truncated at non-ecological borders along the northern edge at the United States border with Canada.

5. Temporal information

Time period represented: Static (relatively unchanging over time)

6. Methods information

Methods overview:

The only input dataset was a 30-m digital elevation model (DEM) from the National Elevation Dataset (U.S. Geological Survey, 2009). The Geomorphometric and Gradient Metrics Toolbox (Evans, 2011) was used to calculate **heat-load index (HLI)** and **compound topographic index (CTI)**. Then, ranges of HLI and CTI were calculated using a 450-m moving window approach. The results were standardized from 0 to 1 and multiplied to create a topoclimate diversity value. For more information, please consult the dataset citation listed in section 2 of this chapter.

This dataset relied on the following general types of models:

Terrain or geomorphology models

This dataset employed the following specific models:

Geomorphometric and Gradient Metrics Toolbox (Evans, 2011)

Major input data sources for this dataset included:

Digital elevation models (DEMs) or topography

7. Guidelines for interpretation

The mapped values of the dataset may be interpreted as follows:

High values of topoclimate diversity indicate areas with a wide variety of local temperature and moisture conditions as determined by topography. Low values indicate areas where, based on topography, there is little spatial variation in temperature and moisture conditions.

Representations of key concepts in climate-change ecology:

This dataset primarily represents climate-change adaptive capacity, in that it represents the availability of microclimates that could facilitate species migration and refugia in which species could persist in place. The dataset does not represent climate-change exposure, meaning that it does not represent the direction or magnitude of projected climate change. This dataset may represent climate-change sensitivity to the degree that, for example, areas without topographic shading are more sensitive to regional climate warming (showing a greater local increase in temperature) than are areas with more topographic shading.

As described in chapter 19, topoclimate diversity is a metric that may be useful as part of a “coarse-filter” approach to conserving biodiversity because areas with high topoclimate diversity may represent areas best able to support climate adaptation for a variety of species, consistent with the idea of “conserving nature’s stage” (Beier *et al*. 2015). Information about individual species may also be considered (as a “fine-filter” approach) to enhance assessments of climate vulnerability and species conservation options.

8. Uncertainties

This dataset involves the following assumptions, simplifications, and caveats:

Because this dataset represents only topographic controls on climate, it provides a simplified depiction of microclimate diversity. In real ecosystems, microclimate conditions (local temperature and moisture) are influenced by many factors and processes other than topography. These include soil drainage characteristics, vegetation (e.g., use of water by plants and shading provided by tree canopies), groundwater discharge from springs and seeps, temperature inversions from cold-air pooling, and effects from disturbances. The input dataset (a DEM) was at 30-m resolution. Therefore, finer-scale topoclimate diversity (i.e., diversity of topoclimate conditions within a single 30-m pixel) is not represented although it may be ecologically important to some species. The dataset represents topoclimate only for terrestrial areas and should not be used to evaluate aquatic ecosystems (streams or lakes), marine areas, or estuaries.

Quantification of uncertainty:

This dataset does not include any quantification of uncertainty relating to the mapped values.

Field verification:

Although topoclimate diversity itself was not field-verified by the dataset authors, the intermediate variables CTI and HLI were compared to field measurements by McCune and Keon (2002). The HLI calculations in McCune and Keon (2002) were calibrated based on field measurements of direct solar radiation on various combinations of slope, aspect, and latitude.

9. Peer review

Prior to dataset publication, peer review was conducted by internal review (reviewers were from the same institution).

10. Conservation applications

Potential conservation applications of this dataset could include the following:

This dataset could be used to identify priority areas for conservation (areas with high topoclimate diversity) based on the idea that these areas may help sustain native biodiversity as climate conditions change. Like other datasets described in chapters 19 and 20 of this guidebook, this dataset represents physical features of the landscape rather than representing any individual species or ecosystem. However, a primary reason for examining topoclimates is their importance to species habitat. Species that are shifting their distributions in response to climate change may be able to access suitable microclimates in areas with high enough topoclimate diversity. Also, high topoclimate diversity may provide more habitat niches to a greater number of species, thereby promoting biodiversity.

This information could guide conservation investments including land acquisition for protected areas, ecosystem restoration initiatives, and biodiversity monitoring programs. Stratifying the data by habitats or land types (land facets in Buttrick *et al*. 2015) is useful so that comparisons are made between areas with similar habitats or facets that may nonetheless differ in topoclimate diversity and thus in their **resilience** to climate change.

Applicable scales for detailed spatial assessments:

For conservation applications requiring detailed assessment of spatial variation of the dataset within a geographic boundary (such as a protected area), the following geographic scales may be most appropriate (see appendix 3 for more information).

At the scale of: a local watershed (12-digit hydrologic unit code [HUC-12]), a Bureau of Land Management (BLM) district, a river watershed (8-digit hydrologic unit code [HUC-8]), an individual county, a national forest, a level-3 ecoregion (e.g. the North Cascades), a single state (Washington, Oregon, or Idaho), a region (multiple states in the Pacific Northwest).

Applicable scales for assessing general patterns:

Due to spatial resolution, the dataset may not show detailed spatial variation at the following geographic scales, however, the dataset may be useful to assess general patterns or for comparison to other locations (see appendix 3 for more information).

At the scale of: a small (< 1 km^2) nature preserve, a state park or state wildlife area.

Use of the dataset in conservation applications may be limited by the following considerations:

It should be noted that this data layer does not explicitly represent current or future biodiversity and has not been tested for the strength of its association with biodiversity. Different species may respond differently to topoclimate diversity within their ranges, so managers may wish to combine this dataset with existing knowledge about microhabitats for particular species of conservation concern. Some areas of high topoclimate diversity may not represent viable habitat for particular species, so it is advisable to consult a variety of other datasets in conjunction (for example, land use, land ownership, species ranges, climate projections) for conservation planning purposes. Also, very small areas of topoclimate diversity may be ecologically important for conservation but not show up in this dataset due to its scale and resolution (90 m).

Conservation case study

This dataset has been used in conservation planning by The Nature Conservancy, Idaho Department of Fish and Game, Oregon Department of Fish and Wildlife, and multiple land trusts in the Pacific Northwest of the United States.

For example, The Nature Conservancy (TNC) is managing a $6 million grant program from the Doris Duke Charitable Foundation (DDCF) for land trusts in Oregon, Washington and Idaho to protect areas that are more likely to be resilient to climate change, defined by topoclimate diversity, local permeability, and regional connectivity (Buttrick *et al*., 2015). Similar information and investments are being made in the eastern United States through a TNC-DDCF-Open Space Institute grant program. Also, in Oregon and Idaho, topoclimate diversity data are being incorporated into updates of State Wildlife Action Plans, and multiple land trusts in the Pacific Northwest of the United States are using this dataset along with others described in Buttrick *et al*. (2015) to update their conservation priorities.

For more information on this conservation case study, please contact the corresponding authors listed in section 2.

References cited

Beier, P., M. L. Hunter, and M. Anderson. 2015. Special section: conserving nature’s stage. Conservation Biology 29:613–617.

Buttrick, S., K. Popper, M. Schindel, B. McRae, B. Unnasch, A. Jones, and J. Platt. 2015. Conserving nature’s stage: identifying resilient terrestrial landscapes in the Pacific Northwest. The Nature Conservancy, Portland, Oregon, USA.

Evans, J. 2011. Geomorphometric and Gradients Metrics Toolbox (version 1.0). GIS software. https://github.com/jeffreyevans/GradientMetrics.

McCune, B., and D. Keon. 2002. Equations for potential annual direct incident radiation and heat load. Journal of Vegetation Science 13:603–606.

U.S. Geological Survey. 2009. National Elevation Dataset (NED). https://lta.cr.usgs.gov/NED.

Chapter 22: Soil sensitivity index for western Washington, Oregon, and California

Authors:

Wendy Peterman (USDA Forest Service)
Jennifer Cartwright (U.S. Geological Survey)

1. Dataset overview

Land degradation, through processes such as vegetation loss and soil erosion, is a concern globally and regionally in the context of climate change. This dataset consists of a map of **soil sensitivity** (figure 22.1), conceptualized as a soil's ability to recover from disturbance (see chapter glossary for definitions of terms). Specifically, the study that produced this dataset examined the implications of a drying climate and spatial patterns in soil characteristics that could make soils more (or less) sensitive to drying, which in turn could make them more (or less) sensitive to disturbances such as fire, insects and disease.

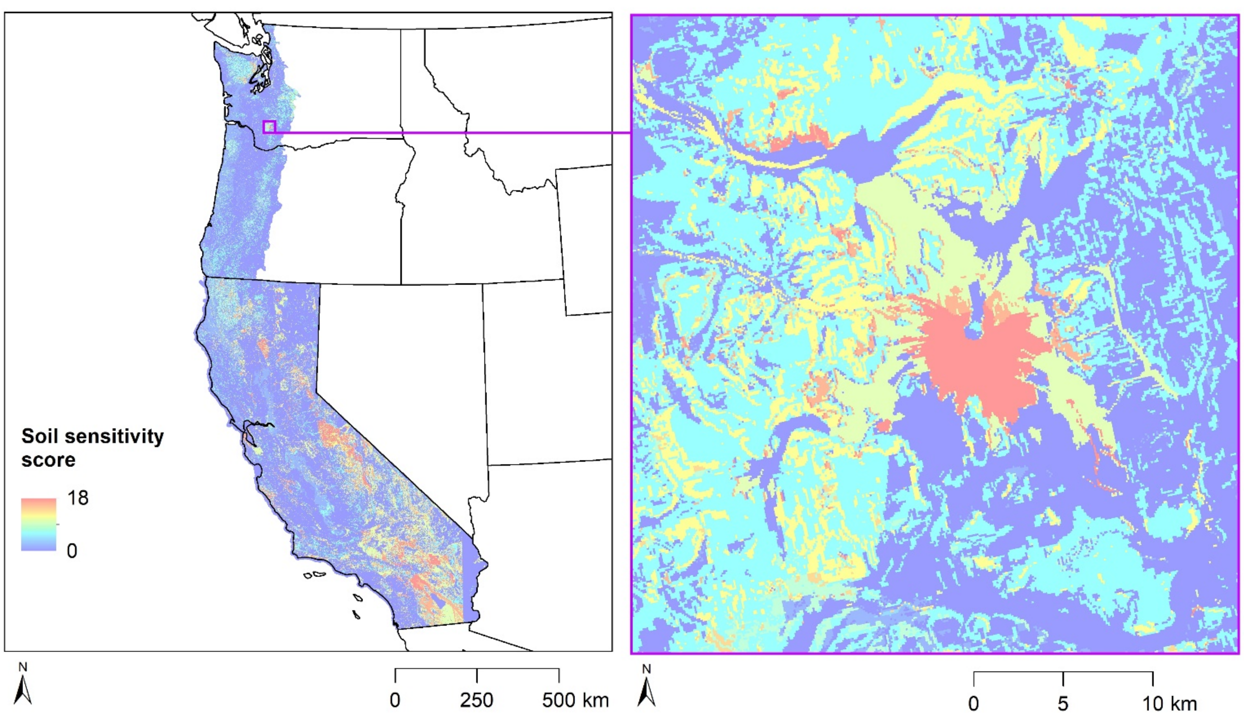

Figure 22.1. Soil sensitivity scores. Higher scores are associated with soils demonstrating properties—such as shallowness, erodibility, and drought susceptibility—that could exacerbate soil sensitivity to climate change, such as through aridification or soil disturbance. The left panel shows the entire extent of the dataset. The inset map on right (purple frame) shows a zoomed-in view of soil sensitivity scores.

Glossary

Soil sensitivity: in this dataset, soils are deemed "sensitive" if they have characteristics that may make them more susceptible to impacts from climate change, fire, or human disturbances.

For detailed information about these terms, please consult the dataset citation in section 2.

2. Data access information

Dataset citation:

Peterman, W. L., and K. Ferschweiler. 2015. A case study for evaluating potential soil sensitivity in aridland systems. Integrated Environmental Assessment and Management 12:388–396.

Note that this publication describes the methods used to produce this dataset but does not present the dataset itself. This publication presents a similar dataset produced using the same methods for a different geographic area (portions of Arizona, Colorado, New Mexico, Utah, Idaho, Wyoming, and Nevada).

Dataset documentation link:

https://doi.org/10.1002/ieam.1691
(subscription or fee required)

Data access:

The dataset can be viewed online and downloaded from:
https://databasin.org/datasets/093bdc4865d64540a6da54309b325136

Metadata access:

Formal metadata is available from:
https://databasin.org/datasets/093bdc4865d64540a6da54309b325136

Dataset corresponding author:

Wendy Peterman
USDA Forest Service
wpeterman@fs.fed.us

3. Conceptual information

Data type category (as defined in the Introduction to this guidebook):

Topoedaphic

Species or ecosystems represented:

This dataset represents the soil component of a variety of ecosystems within the study domain.

Units of mapped values:

unitless

Range of mapped values:

0 to 18

4. Spatial information

Spatial data type: a raster dataset (grid)

Data file format(s): GeoTiff (.tif)

Spatial resolution: Approximately 105 m

Geographic coordinate system:

North American Datum of 1983

Projected coordinate system:

USA Contiguous Albers Equal Area Conic

Spatial extent:

western Washington, western Oregon, entire State of California

Dataset truncation:

The dataset is truncated along the northern border of the State of Washington and the borders of the State of California.

5. Temporal information

Time period represented: Static (relatively unchanging over time)

6. Methods information

Methods overview:

Soil attributes were obtained from the Soil Survey Geographic (SSURGO) and State Soil Geographic (STATSGO) databases (Natural Resource Conservation Service, 2014a,b), and included indicators of soil depth, soil water storage, concentrations of calcium and gypsum, pH, particle size, temperature and moisture regime, and erodibility by wind and water. Soil horizons (vertical layers) were averaged together. In certain areas of the landscape, soil attributes from SSURGO were not available and so were modeled using a machine-learning approach based on available topographic, geologic, and climate datasets.

A set of rules was developed for all the soil attributes to identify soil sensitivity factors (Peterman and Ferschweiler, 2015). For each soil attribute, a threshold was identified beyond which the soil would be considered sensitive. For example, soils shallower than 10 cm were deemed sensitive based on soil depth and soils deeper than this threshold were deemed not sensitive. Finally, an overall soil sensitivity score was calculated by weighting the various soil sensitivity factors, which included (with weights in parentheses): droughtiness (5), shallowness (5), water erodibility (3), wind erodibility (3), gypsic (1), calcic (1), sodic (1), hydric (1), acidic (1), and alkaline (1). The weighted soil sensitivity factors were added together to produce an overall soil sensitivity score (Peterman, 2015). For more information, please consult the dataset citation listed in section 2 of this chapter.

Major input data sources for this dataset included:

Historical climate observations or models, digital elevation models (DEMs) or topography, soil characteristics

7. Guidelines for interpretation

The mapped values of the dataset may be interpreted as follows:

Areas with high soil sensitivity index values exhibited a range of characteristics (e.g., droughtiness, shallowness, erodibility) that could be associated with soil sensitivity to climate change, including aridification and soil disturbance. Areas with lower values were deemed less sensitive based on these soil characteristics.

Representations of key concepts in climate-change ecology:

This dataset primarily represents a component of climate-change sensitivity, specifically the sensitivity of certain soils to climate change and related disturbances such as droughts and fires. Soil sensitivity to changing climate conditions and changing disturbance patterns has potential influences for plant communities and, in turn, for whole ecosystems that depend on those plant communities. For example, soils that are most sensitive to drying and least capable of storing and delivering water to plants during droughts may be especially prone to vegetation loss and erosion, with consequences for terrestrial plant and animal communities and for streams that receive eroded sediment. Thus, this dataset helps illustrate the importance of soil characteristics in mediating ecosystem-level and species-level responses to climate change, including climate-driven shifts in drought patterns.

8. Uncertainties

This dataset involves the following assumptions, simplifications, and caveats:

A variety of factors could affect soil sensitivity to disturbance and climate change beyond those that were considered in creating this dataset. These include fine-scale effects of vegetation (e.g., soil stabilization, soil shading), history of disturbances such as recent fires and droughts, and various land-use practices (forest management practices, agricultural practices).

Quantification of uncertainty:

This dataset does not include any quantification of uncertainty relating to the mapped values.

Field verification:

Creation of this dataset did not involve any field verification of the mapped values.

9. Peer review

The methods used to produce the dataset are described in the publication cited in section 2, for which peer review was conducted by external review (at least two anonymous reviewers, each from a different institution).

10. Conservation applications

Potential conservation applications of this dataset could include the following:

Soils that have been identified as especially sensitive could be targeted for conservation practices aimed at mitigating soil erosion. These include practices to reduce disturbance (e.g., reducing vehicle traffic, using appropriate grazing practices) and to increase soil productivity through revegetation, including tree planting where appropriate and practicable. In some cases, erosion control practices may be considered to protect the soil surface.

Applicable scales for detailed spatial assessments:

For conservation applications requiring detailed assessment of spatial variation of the dataset within a geographic boundary (such as a protected area), the following geographic scales may be most appropriate (see appendix 3 for more information).

At the scale of: a local watershed (12-digit hydrologic unit code [HUC-12]), a Bureau of Land Management (BLM) district, a river watershed (8-digit hydrologic unit code [HUC-8]), an individual county, a national forest, a level-3 ecoregion (e.g., the North Cascades), a single state (California only), a region (California plus western Oregon and western Washington).

Applicable scales for assessing general patterns:

Due to spatial resolution, the dataset may not show detailed spatial variation at the following geographic scales, however, the dataset may be useful to assess general patterns or for comparison to other locations (see appendix 3 for more information).

At the scale of: a small (< 1 km^2) nature preserve, a state park or state wildlife area.

Use of the dataset in conservation applications may be limited by the following considerations:

This dataset represents soil conditions only based on existing soil attribute information from the SSURGO and STATSGO databases. Therefore, soil or vegetation information not represented in those databases is not reflected in this dataset. This includes information such as recent disturbance history, type and structure of vegetation, and history of management practices in a given area.

Past or current conservation applications:

Conservation case study

This dataset has been used by the BLM, the Desert Resource Conservation Group, and county governments in California for purposes of energy and agricultural conservation planning.

For more information on this conservation case study, please contact the corresponding author listed in section 2.

References cited

Peterman, W. 2015. Sensitive soil index for the North Pacific and California Landscape Conservation Cooperative. https://databasin.org/datasets/093bdc4865d64540a6da54309b325136.

Peterman, W. L., and K. Ferschweiler. 2015. A case study for evaluating potential soil sensitivity in aridland systems. Integrated Environmental Assessment and Management 12:388–396.

Natural Resource Conservation Service. 2014a. Soil Survey Geographic (SSURGO) Database. http://sdmdataaccess.nrcs.usda.gov/.

Natural Resource Conservation Service. 2014b. U.S. General Soil Map (STATSGO2) Database. http://sdmdataaccess.nrcs.usda.gov/.

Chapter 23: Soil drought probability for Pacific Northwest forests

Authors:
Chris Ringo (Oregon State University)
Karen Bennett (USDA Forest Service, Pacific Northwest Region)
Jennifer Cartwright (U.S. Geological Survey)

1. Dataset overview

This dataset represents the likelihood that forest soils experience prolonged summer drying. The dataset was developed using a model that incorporated variables including soil depth, **available water supply**, and evapotranspiration (see chapter glossary for definitions of terms). The model was calibrated using soil profiles and laboratory data for 25 sites from various forests in the Pacific Northwest to estimate the number of days per year on average that soil moisture drops below the permanent wilting point. The soil drought probability values (i.e., **droughty soil** index) in this dataset represent the degree to which a soil has chronically low seasonal moisture levels such that the soil would be particularly vulnerable to drought conditions during climatically dry periods (figure 23.1).

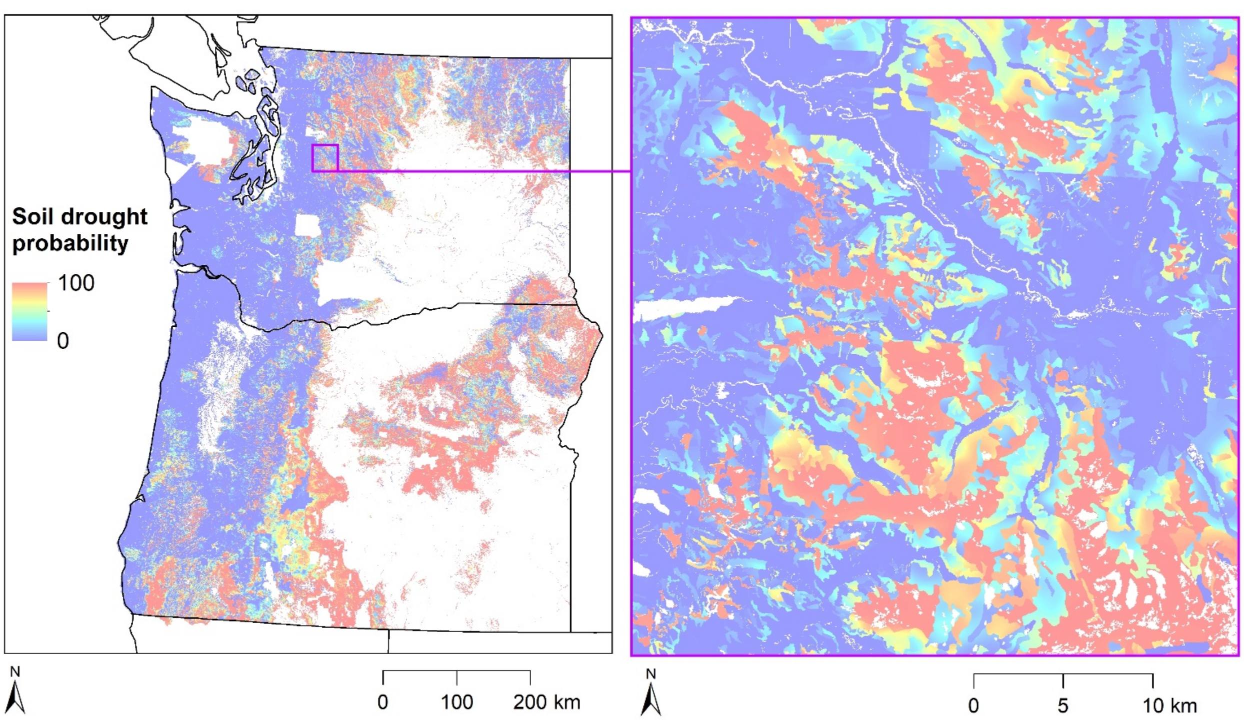

Figure 23.1. Soil drought probability for Pacific Northwest forest soils. Higher values indicate soils with greater likelihood of having soil moisture below the permanent wilting point for an average of at least 10 weeks per year. The inset map on the right (purple frame) shows a zoomed-in view of soil drought probability values.

Glossary

Actual evapotranspiration: the actual amount of moisture lost to the atmosphere from plant and soil surfaces.

Available water supply: a measure of how much plant-available moisture a soil is capable of holding at a given depth.

Droughty soil: a soil that has chronically low seasonal moisture and thus may be especially vulnerable to drought conditions during climatically dry periods.

Permanent wilting point: a theoretical lower limit of plant-available water, defined as the minimal amount of soil moisture below which a plant will wilt and then fail to recover when supplied with sufficient moisture.

Potential evapotranspiration: an estimate of the combined evaporation and transpiration that would theoretically occur if these processes were not limited by soil moisture availability.

Snow Telemetry (SNOTEL): a network of climate and weather stations (SNOTEL sites) administered by the U.S. Department of Agriculture Natural Resources Conservation Service in 11 states in the western U.S.

For detailed information about these terms, please consult the dataset citation in section 2.

2. Data access information

Dataset citation:

Ringo, C., K. Bennett, J. Noller, D. Jiang, and D. Moore. 2018. Modeling droughty soils at regional scales in Pacific Northwest Forests , USA. Forest Ecology and Management 424:121–135.

Dataset documentation link:

https://doi.org/10.1016/j.foreco.2018.04.019
(subscription or fee required)

Data access:

The dataset can be downloaded from:
https://ecoshare.info/soils/droughty-soils-model/

The dataset is not available for interactive online map viewing.

Metadata access:

Formal metadata is attached to the raster dataset and may be exported to XML format using Esri ArcCatalog.

Dataset corresponding author:

Chris Ringo
Oregon State University
Chris.Ringo@OregonState.edu

3. Conceptual information

Data type category (as defined in the Introduction to this guidebook):

Topoedaphic

Species or ecosystems represented:

This dataset represents the physical soil component of forest ecosystems.

Units of mapped values:

unitless

Range of mapped values:

0 to 100

The dataset values are depicted on a 0 to 100 scale in Ringo *et al*. (2018).

4. Spatial information

Spatial data type: a raster dataset (grid)

Data file format(s): File geodatabase raster

Spatial resolution: 30 m

Geographic coordinate system:

North American Datum of 1983

Projected coordinate system:

North American Datum of 1983 Oregon Washington Albers

Spatial extent:

Regional

Dataset truncation:

The dataset is truncated along the USDA Forest Service, Pacific Northwest Region boundary (States of Washington and Oregon, plus a small area in northern California).

5. Temporal information

Time period represented: Static (relatively unchanging over time)

6. Methods information

Methods overview:

A geospatial dataset was compiled representing available water supply to a depth of 150 cm or to a root-restricting layer (whichever was less). Several data sources were compiled to calculate available water supply, including from the Soil Survey Geographic (SSURGO) Database (Natural Resource Conservation Service, 2014a), provisional (unpublished) SSURGO data, State Soil Geographic (STATSGO) Database (Natural Resource Conservation Service, 2014b), and the USDA Forest Service's Soil Resource Inventory. With the exception of STATSGO, these datasets were also used to estimate soil depth. To represent climatic moisture limitation, the ratio of **actual evapotranspiration** (AET) to **potential evapotranspiration** (PET) was calculated using averages from July through September 2000 through 2014. A model representing soil moisture was constructed using soil depth, available water supply, and AET/PET ratio, and was calibrated using daily soil moisture observations from the network of **Snow Telemetry (SNOTEL)** sites in Oregon and Washington. For each SNOTEL site used for calibration, laboratory data were used to estimate the **permanent wilting point**, and the soil moisture data were used to calculate the average number of days per year that soil moisture dropped below the permanent wilting point. For more information, please consult the dataset citation listed in section 2 of this chapter.

Major input data sources for this dataset included:

Historical climate observations or models, soil characteristics

7. Guidelines for interpretation

The mapped values of the dataset may be interpreted as follows:

High values indicate forest soils that have a high probability of being "droughty," defined as having soil moisture below the permanent wilting point for an average of at least 10 weeks per year. Lower values indicate lower likelihood of a forest soil being "droughty" according to this definition.

Representations of key concepts in climate-change ecology:

This dataset represents a component of climate-change sensitivity, specifically the sensitivity of soils to drying during droughts. Forest ecosystems in drought-vulnerable soil areas may be especially vulnerable to drought intensification and long-term climatic drying. By contrast, less "droughty" soils may demonstrate greater resistance to droughts (maintaining greater soil moisture for vegetation) and may aid forest resilience in recovering from droughts. As described in chapter 22, soil properties that influence soil sensitivity to droughts and other disturbances have potentially important implications for terrestrial ecosystems and for aquatic ecosystems in streams that may receive sediment from eroding soils. Soil properties thus represent an important link between the meteorological effects of climate change (e.g., changes in timing and magnitude of precipitation) and the hydrologic and ecological effects experienced by natural communities.

8. Uncertainties

This dataset involves the following assumptions, simplifications, and caveats:

To represent climatic moisture limitation, the analysis that produced this dataset relied on fairly coarse-resolution (1-km) estimates of actual and potential evapotranspiration from a global model that may not accurately represent local climate conditions. Also, although soil depth can be an important constraint on availability of soil moisture for vegetation, some trees are able to access deep-water sources (e.g., deep soil layers, water tables, and weathered bedrock) that were not accounted for in this dataset. For the 25 SNOTEL sites used for calibration, most were predicted accurately by the model that produced this dataset, however, a few sites were not accurately modeled (e.g., a site in coarse volcanic soils and sites with local variation in canopy cover). In general, sites with coarse volcanic soils may be inaccurately represented by this dataset due to the difficulties in calibrating soil-moisture sensors in soils with high porosities.

Quantification of uncertainty:

In the study that produced this dataset, soil "droughtiness" was defined as a binary category (whether soil moisture falls below the permanent wilting point for more than 10 weeks per year on average). Uncertainty related to this classification is represented as a probability that a given site is "droughty".

Field verification:

The model that produced this dataset was calibrated using soil variables from 25 SNOTEL sites throughout the Pacific Northwest. However, the model was not independently validated because the number of available sites with soil variables in the study area did not allow for an independent dataset for model validation.

9. Peer review

Prior to dataset publication, peer review was conducted by external review (at least two anonymous reviewers, each from a different institution).

10. Conservation applications

Potential conservation applications of this dataset could include the following:

This dataset can provide important information to complement climate-based approaches to assessing drought vulnerability for Pacific Northwest forests. For example, forests with dry climate and deep soils with relatively large water-storage capacities may be less prone to drought stress than would be expected based on climate variables alone. Conversely, forests in climates without severe moisture limitation but with shallow soils that hold relatively little water might be more vulnerable to drought stress than would be predicted solely based on climate variables. Ringo *et al*. (2018) suggested that forest managers could use this dataset to prioritize forests for treatments such as thinning to reduce vegetation drought stress by reducing competition for soil moisture reserves. It could also be used to help improve wildfire prediction models by helping refine predictions of fuel moisture content.

Applicable scales for detailed spatial assessments:

For conservation applications requiring detailed assessment of spatial variation of the dataset within a geographic boundary (such as a protected area), the following geographic scales may be most appropriate (see appendix 3 for more information).

At the scale of: a state park or state wildlife area, a local watershed (12-digit hydrologic unit code [HUC-12]), a Bureau of Land Management (BLM) district, a river watershed (8-digit hydrologic unit code [HUC-8]), an individual county, a national forest, a level-3 ecoregion (e.g., the North Cascades), a single state (Washington or Oregon), a region (Washington and Oregon).

Applicable scales for assessing general patterns:

Due to spatial resolution, the dataset may not show detailed spatial variation at the following geographic scales, however, the dataset may be useful to assess general patterns or for comparison to other locations (see appendix 3 for more information).

At the scale of a small (< 1 km^2) nature preserve.

Use of the dataset in conservation applications may be limited by the following considerations:

Because this dataset primarily represents the soil component of forest ecosystems, there are other important factors influencing forest drought sensitivity that are not represented, including forest community composition (the mix of tree species present), demographics (size and age classes of trees), stand density, physiological adaptations to drought stress and chronic water limitation, and interactions between droughts and other disturbance dynamics such as fires and insect outbreaks. Also, in planning for climate-change impacts, regional variability in projected changes to temperature and precipitation patterns are important and not captured by this dataset. Therefore, forest managers should consult a variety of locally relevant information sources (e.g., climate projections and forest stand characteristics) in conjunction with the soil drought vulnerability information in this dataset.

Past or current conservation applications:

This dataset has not yet been used in any on-the-ground conservation applications to the knowledge of the authors of this chapter.

References cited

Natural Resource Conservation Service. 2014a. Soil Survey Geographic (SSURGO) Database. http://sdmdataaccess.nrcs.usda.gov/.

Natural Resource Conservation Service. 2014b. U.S. General Soil Map (STATSGO2) Database. http://sdmdataaccess.nrcs.usda.gov/.

Ringo, C., K. Bennett, J. Noller, D. Jiang, and D. Moore. 2018. Modeling droughty soils at regional scales in Pacific Northwest Forests , USA. Forest Ecology and Management 424:121–135.

Chapter 24: Sagebrush ecosystem resilience and resistance

Authors:
Jeanne Chambers (Rocky Mountain Research Station, USDA Forest Service)
Steve Campbell (USDA Natural Resources Conservation Service)
Jeremy Maestas (USDA Natural Resources Conservation Service)
Jennifer Cartwright (U.S. Geological Survey)

1. Dataset overview

Emerging applications of ecological resilience and resistance concepts in sagebrush ecosystems allow managers to better predict and mitigate impacts of wildfire, invasive annual grasses, and other disturbances. Soil temperature and moisture strongly influence the kind and amount of vegetation and are closely related to sagebrush ecological resilience to disturbance and resistance to invasive annual grasses (Chambers *et al*. 2007, 2014a, 2014b). Consequently, soil taxonomic temperature and

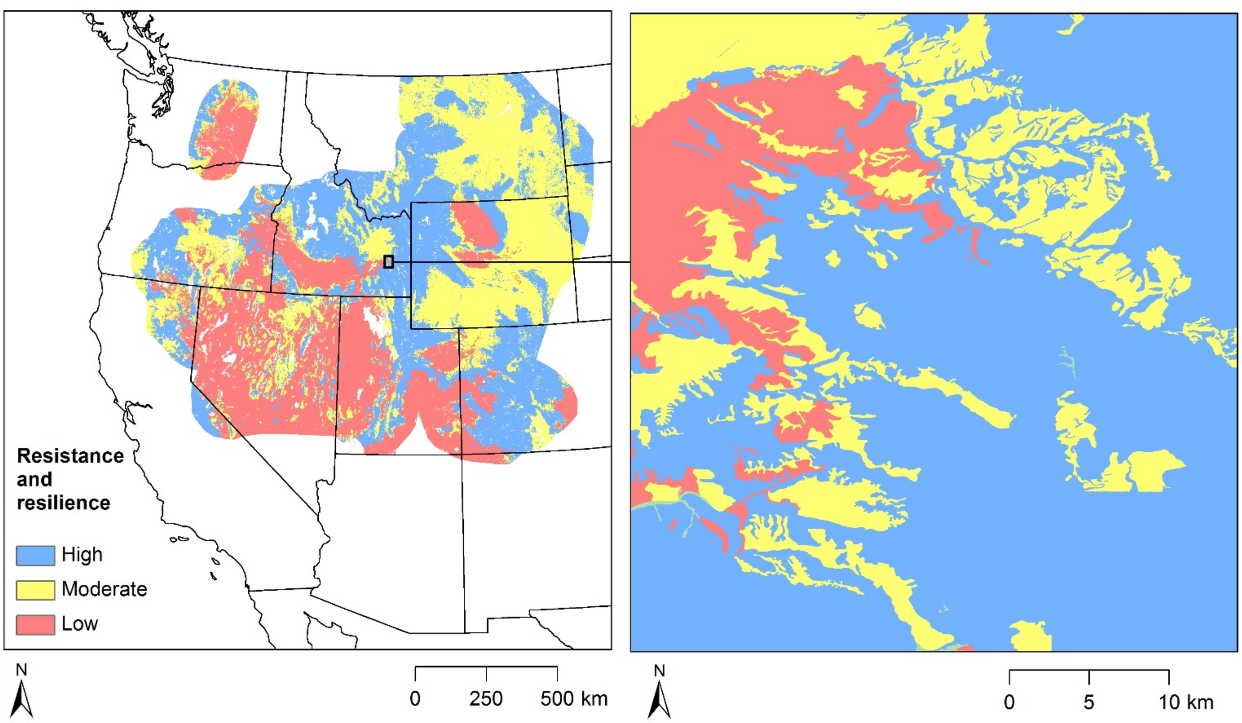

Figure 24.1. Categories of sagebrush ecological resilience to disturbance and resistance to invasive annual grasses based on soil temperatures and moisture regimes. Areas classified as "high" have soil characteristics conducive to ecosystem recovery after stressors and disturbances but not conducive to invasion by non-native annual grasses. Areas classified as "low" have soil characteristics less conducive to ecosystem recovery and may be at greater risk of invasion by annual grasses. The left panel shows the entire extent of the dataset; the right panel shows a zoomed-in view of resilience and resistance categories.

moisture regimes can be used as indicators of resilience and resistance at landscape scales to depict environmental gradients in sagebrush ecosystems that range from cold/cool-moist sites with relatively high resilience and resistance to warm-dry **ecological types** with relatively low resilience and resistance (see chapter glossary for definitions of terms).

To facilitate broad-scale analyses of resilience and resistance across the range of sage-grouse, the dominant ecological types in the sagebrush range were identified and their **soil temperature and moisture regimes** determined. Then resilience and resistance categories were assigned to each ecological type based on available ecological site descriptions and expert knowledge (figure 24.1). Soil survey spatial and tabular data were aggregated according to soil temperature and moisture regime and moisture subclass (Maestas *et al*., 2016). A simplified index of relative resilience and resistance was generated by assigning each soil temperature and moisture regime/moisture subclass to one of three categories (high, moderate, and low) based on the ecological site descriptions and expert input.

Soils data were derived from two primary sources available through the National Cooperative Soil Survey: (1) completed and interim soil surveys available through the Soil Survey Geographic Database (SSURGO) (Natural Resource Conservation Service, 2014a), and (2) the State Soils Geographic Database (STATSGO2) (Natural Resource Conservation Service, 2014b). The data product is a geodatabase with the dominant soil temperature regime, moisture regime, and moisture subclass of the soil map unit, and the corresponding resilience and resistance category across all sage-grouse Management Zones (Stiver *et al*., 2006). The geodatabase also includes the dominant ecological type assigned to each soil map unit. Users are encouraged to consider the spatial scale of analyses when using the dataset and to field verify soils when planning onsite projects.

Glossary

Ecological resilience: "the capacity of ecosystems to reorganize and regain their fundamental structure, processes, and functioning (i.e., to recover) when altered by stressors like drought and disturbances like inappropriate livestock grazing and altered fire regimes" (see dataset citation).

Ecological type: “a category of land with a distinctive (i.e., mappable) combination of landscape elements, including climate, geology, geomorphology, soils, and potential natural vegetation. Ecological types differ from each other in their ability to produce vegetation and respond to management and natural disturbances” (see dataset citation).

Resistance to invasive annual grasses: “the capacity of ecosystems to limit the establishment and population growth of the invader” (see dataset citation).

Soil temperature and moisture regimes: “soil temperature regimes are defined by the mean annual soil temperature at a depth of 20 inches, and seasonal fluctuations from the mean. Soil moisture regimes are defined by the length of time plant-available moisture is present during the growing season” (see dataset citation).

For detailed information about these terms, please consult the dataset citation in section 2.

2. Data access information

Dataset citation:

Maestas, D., S. Campbell, J. C. Chambers, M. Pellant, and R. Miller. 2016. Tapping soil survey information for rapid assessment of sagebrush ecosystem resilience and resistance. Rangelands 38: 120-128.

Chambers, J. C., J. D. Maestas, D. A. Pyke, C. S. Boyd, J. C. Chambers, J. D. Maestas, D. A. Pyke, C. S. Boyd, M. Pellant, and A. Wuenschel. 2017. Using resilience and resistance concepts to manage persistent threats to sagebrush ecosystems and greater sage-grouse. Rangeland Ecology and Management 70:149–164.

Chambers, J.C., J.L. Beck, J.B. Bradford, J. Bybee, S. Campbell, J. Carlson, T.J. Christiansen, K.J. Clause, G. Collins, M.R. Crist, J.B. Dinkins, K.E. Doherty, F. Edwards, S. Espinosa, K.A. Griffin, P. Griffin, J.R. Haas, S.E. Hanser, D.W. Havlina, K.F. Henke, J.D. Hennig, L.A. Joyce, F.M. Kilkenny, S.M. Kulpa, L.L. Kurth, J.D. Maestas, M. Manning, K.E. Mayer, B.A. Mealor, C. McCarthy, M. Pellant, M.A. Perea, K.L. Prentice, D.A. Pyke, L.A. Wiechman, and A. Wuenschel. 2017. Science framework for conservation and restoration of the sagebrush biome: Linking the Department of the Interior's Integrated Rangeland Fire Management Strategy to long-term strategic conservation actions. Gen. Tech. Rep. RMRS-GTR-360. Fort Collins, CO: U.S Department of Agriculture, Forest Service, Rocky Mountain Research Station. 213 p.

Dataset documentation links:

https://doi.org/10.1016/j.rala.2016.02.002
(open access)

https://doi.org/10.1016/j.rama.2016.08.005
(subscription or fee required)

https://www.treesearch.fs.fed.us/pubs/53983
(open access)

Data access:

The dataset can be downloaded from:

https://www.sciencebase.gov/catalog/item/55229c34e4b027f0aee3cfa5

The dataset can be viewed online at:

https://map.sagegrouseinitiative.com/ecosystem/collapse?ll=43.4799,-110.7624&overlay=mesic_average&opacity=0.80&z=6&basemap=roadmap

Metadata access:

Metadata are available from:

https://www.sciencebase.gov/catalog/item/55229c34e4b027f0aee3cfa5?community=LC+MAP+-+Landscape+Conservation+Management+and+Analysis+Portal

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3. Conceptual information

Data type category (as defined in the Introduction to this guidebook):

Topoedaphic

Species or ecosystems represented:

This dataset represents sagebrush ecosystems and greater sage-grouse management zones (Stiver *et al*. 2006).

Units of mapped values:

categorical

Range of mapped values:

Ecological resilience and **resistance to invasive annual grass** values are classified as "high", "moderate", or "low".

4. Spatial information

Spatial data type: a raster dataset (grid)

Data file format(s): Esri file

Spatial resolution: 10 m

Geographic coordinate system:

North American Datum of 1983

Projected coordinate system:

North American Datum of 1983 USA Contiguous Albers Equal Area Conic

Spatial extent:

Regional

Dataset truncation:

The dataset is truncated along the border between the United States and Canada and the greater sage-grouse management zones for the United States (Stiver *et al*. 2006).

5. Temporal information

Time period represented: Static (relatively unchanging over time)

6. Methods information

Methods overview:

The data product is a geodatabase with the dominant soil temperature regime, moisture regime, and moisture subclass of the soil map unit (Campbell, 2016), and the corresponding resilience and resistance category, across all sage-grouse management zones (Stiver *et al*., 2006). The geodatabase also includes the dominant ecological type assigned to each soil map unit. Data on soil temperature and moisture regimes were derived from two sources: (1) completed and interim soil surveys available through the Soil Survey Geographic Database (SSURGO), and (2) the State Soils Geographic Database (STATSGO2) to fill gaps where SSURGO data were not available.

The dataset was produced by first identifying the dominant ecological types in the sagebrush range and then determining their soil temperature and moisture regime from the corresponding SSURGO and STATSGO2 soil map unit component data. In the western portion of the range (Columbia Plateau, Snake River Plain, Northern Basin and Range, Central Basin and Range), 12 ecological types were identified, and their soil temperature and moisture subclasses determined based on available ecological site descriptions, expert knowledge, and data from the USDA, Natural Resources and Conservation Service, National Soils Information System (NASIS; Maestas *et al*., 2016). In the eastern portion of the range (Northwestern Glaciated

Plains, Northwestern Great Plains, Wyoming Basin, Colorado Plateau, Southern Rockies) representative ecological site descriptions were organized by soil temperature and moisture subclasses and used to identify the dominant ecological types. Twenty ecological types were identified, and their soil temperature and moisture regime subclasses determined based on the ecological site descriptions, data from NASIS, and expert input (Chambers *et al*., 2017a). For both portions of the range, the ecological types and soil temperature and moisture regime subclasses were categorized according to their relative ecological resilience and resistance to invasive annual grasses based on recent research (Chambers *et al*., 2007, 2014a, 2014b) and expert knowledge.

To facilitate broad-scale analyses of resilience and resistance across the range of greater sage-grouse, simplified categories of relative resilience and resistance (high, moderate, and low) were assigned to each ecological type and their associated soil temperature and moisture regime. Data for soil map unit components were aggregated to identify the dominant soil temperature regime, moisture regime, and moisture subclass for each soil map unit. The soil map units were then assigned one of the three resilience and resistance categories. For regional analyses that consider the ecological types, a specific set of soil temperature and moisture regimes can be used (see table 6 in Chambers *et al*., 2017a). Soils with high water tables, wetlands, frequent ponding, or uncommon regimes that would not typically support sagebrush can be excluded from the dataset.

Major input data sources for this dataset included:

Soil characteristics

Specific input data sources were:

Soil Survey Geographic Data (SSURGO) (Natural Resource Conservation Service, 2014a)
State Soils Geographic Data (STATSGO2) (Natural Resource Conservation Service, 2014b)
Published Ecological Site Descriptions from the Ecological Site Information System (Natural Resources Conservation Service, 2012)
Unpublished Ecological Site Descriptions for the State of Nevada (Patti Novak, NRCS, personal communication)

7. Guidelines for interpretation

The mapped values of the dataset may be interpreted as follows:

Areas classified as "high resilience and resistance" in this dataset are considered to have soil characteristics (e.g., cool to cold and wet to moist soil conditions) that are conducive to ecosystem recovery after stressors and disturbances, but not conducive to invasion and population growth of invasive annual grasses. Stressors and disturbances include persistent ecosystem threats, such as nonnative plant invasions, altered fire regimes, conifer expansion, and climate change, and land use and development threats, such as energy development, conversion to cropland, livestock grazing, mining, and urban, suburban, and exurban development. Areas classified as "low resilience and resistance " are considered to have soil characteristics (e.g., warm and moist to dry) that are less conducive to ecosystem recovery after stressors and disturbances and may be at greater risk of conversion to alternative states (e.g., conversion of sagebrush-perennial grass systems to invasive annual grass systems).

Representations of key concepts in climate-change ecology:

This dataset uses soil temperature and moisture regimes as foundational layers for defining categories of ecological resilience to disturbance and resistance to invasion. Because soil temperature and moisture regimes are integrative indicators of long-term climatic conditions, they are increasingly used to assess ecological vulnerability and adaptive capacity. A process-based, ecosystem water-balance model was recently used to characterize current and future patterns in soil temperature and moisture conditions in dryland ecosystems across the western United States (Bradford *et al.*, 2019). Results indicate soil temperature increases in the 21st century that are substantial, relatively uniform geographically, and robust across climate models. Higher temperatures will expand the areas of warm and hot soil temperature regimes while decreasing the area of cold and cool temperature conditions. Despite large geographic variability in precipitation projections, and variation among climate models, future soil moisture conditions are relatively consistent across climate models. Many areas dominated by big sagebrush, particularly the Central and Northern Basin and Range and the Wyoming Basin ecoregions, have projections of increasing soil moisture. Also, many areas dominated by big sagebrush are expected to experience pronounced shifts toward cool season moisture, and thus more area with winter moist and less area with summer moist conditions. These results imply widespread geographic shifts in the distribution of resilience and resistance categories and provide a quantitative framework for assessing climate-change impacts on the responses of these ecosystems to stress and disturbance and the likelihood of invasion.

8. Uncertainties

This dataset involves the following assumptions, simplifications, and caveats:

This dataset represents soil conditions based on information from the SSURGO and STATSGO databases (Maestas *et al*., 2016). Although soil temperature and moisture regimes are closely aligned with the relative resilience and resistance of ecological types, other factors that may influence resilience and resistance, such as vegetation condition or presence of invasive plant species, are not represented.

These data are intended to be used at regional/landscape scales and other data and assessments are available for evaluating resilience and resistance at project and site scales. As with most large-scale mapping products, there are limitations in using Soil Survey information, including incongruities in soil regime classifications, especially along mapping boundaries, and variation in the level of survey detail available. Until improved products emerge, the Soil Survey still provides the most complete dataset to advance understanding of resilience and resistance.

Quantification of uncertainty:

This dataset does not include any quantification of uncertainty relating to the mapped values.

Field verification:

The dataset serves as one of the map layers for a Fire and Invasives Assessment Tool (FIAT), viewable at https://landscape.blm.gov/geoportal/catalog/FIAT/FIAT.page. FIAT was used successfully by the Bureau of Land Management (BLM) in the Snake River Plain, Northern Great Basin, and Central Great Basin to evaluate relative resilience and resistance as indicated by soil temperature and moisture regimes, habitat suitability for greater sage-grouse as indicated by land cover of sagebrush, and the primary threats (invasive annual grasses or conifer expansion depending on the area). The resilience-and-resistance layer was key to understanding potential for areas on the landscape to recover from wildfires and management treatments and prioritizing areas for conservation and restoration actions.

The dataset was also field tested in a series of field workshops sponsored by the Sage-Grouse Initiative and the Joint Fire Sciences Program, Fire Science Exchange. The map layers on relative resilience and resistance as indicated by soil temperature and moisture regimes helped to accurately identify the locations of different sagebrush ecological types. The map layers were also indicative of the capacity to resist invasive annual grasses and recover following wildfires.

9. Peer review

The National Cooperative Soil Survey has policy in place in the National Soil Survey Handbook (National Resources Conservation Service, 2019) for providing quality control and quality assurance for soil survey data products. See Part 609 of the National Soil Survey Handbook at the link below:
https://directives.sc.egov.usda.gov/OpenNonWebContent.aspx?content=41523.wba

All publications that describe the use of the dataset have received external peer review (at least three anonymous reviewers from different institutions).

10. Conservation applications

Potential conservation applications of this dataset could include the following:

Geospatial data on the resilience and resistance of ecosystems enables managers to: (1) evaluate differences in ecosystem responses to disturbance and their recovery potentials across landscapes; (2) identify locations where systems may exhibit critical transitions to alternative states in response to altered climate or other drivers; and (3) determine where conservation and restoration investments will have the greatest benefits. These data can be used in a risk-based framework along with data on high-value resources, such as greater sage-grouse populations (Doherty *et al*., 2016), and ecosystem threats, such as the probability of large wildfires (Short *et al*., 2016), to inform strategic management investments at regional scales and determine appropriate management strategies at local scales (Chambers *et al*., 2017a, 2019 a and b; Crist *et al*., 2019). For example, landscapes with relatively low resilience and resistance and high wildfire risk that support large populations of greater sage-grouse may be priorities for fuels reduction and fire suppression because these areas recover more slowly following disturbance and are less resistant to invasive annual grasses.

Applicable scales for detailed spatial assessments:

For conservation applications requiring detailed assessment of spatial variation of the dataset within a geographic boundary (such as a protected area), the following geographic scales may be most appropriate (see appendix 3 for more information).

The categorized dataset is intended for use at the scale of large landscapes, such as one or more Level III U.S. Environmental Protection Agency (EPA) ecoregions or Sage-grouse Management Zones (there are seven Management Zones across the western United States, each spanning the boundaries of two or more states). The dataset can also be used at the scale of a single state (Washington, Oregon, or Idaho) or at a regional scale (multiple states in the Pacific Northwest or in western North America). The entire dataset of soil temperature and moisture regimes provides greater detail, can be related to specific sets of ecological types, and can be used at smaller project scales (hundreds to thousands of hectares).

Use of the dataset in conservation applications may be limited by the following considerations:

This dataset represents resilience and resistance to invasive annual grasses based primarily on soil indicators and does not represent other potential factors influencing resilience and resistance, which could include disturbance history, vegetation cover and type, and projected changes in climate conditions. Thus, use of this dataset in conservation applications can be supplemented with additional datasets representing these other considerations.

Past or current conservation applications:

Conservation case study

U.S. Federal land management and natural resource agencies including the BLM and the USDA Forest Service are using the dataset in a risk-based framework for prioritizing sage-grouse conservation resources at national and regional scales and for developing more ecologically effective wildland fire operations, postfire rehabilitation, fuels management, and habitat restoration strategies (Chambers *et al*., 2017b). Recently, the risk-based framework has been used by the BLM to develop a multi-year program of work for conservation and restoration actions in the Great Basin (part or all of the Snake River Plain, Northern Great Basin, Central Great Basin).

The data have been used by the USDA Forest Service to develop their own risk assessment that evaluates key threats to all greater sage-grouse habitat in Forest Service Region 4, on lands managed by the Forest Service and for the region as a whole. The Forest Service is using this risk assessment to inform management decisions related to sagebrush ecosystems.

For more information on this conservation case study, please contact the corresponding author listed in section 2.

References cited

Bradford, J.A., Shlaepfer, D.R., Lauenroth, W.K., Palmquist, K.A., Chambers, J.C., Maestas, J.D., Campbell, S.B. 2019. Climate-driven shifts in soil temperature and moisture regimes suggest opportunities to enhance assessments of dryland resilience and resistance. Frontiers in Ecology and Evolution. https://doi.org/10.3389/fevo.2019.00358.

Campbell, S. 2016. Soil temperature and moisture regimes across sage-grouse range. https://www.sciencebase.gov/catalog/item/538e5aa9e4b09202b547e56c. USDA Natural Resources Conservation Service, Portland, OR

Chambers, J.C, Allen, C.R., Cushman, S.A. 2019a. Operationalizing ecological resilience concepts for managing species and ecosystems at risk. Frontiers in Ecology and Evolution. *7:241.doi: 10.3389/fevo.2019.00241*

Chambers, J.C., Brooks, M.L., Germino, M.J., Maestas, J.D., Board, D.I., Jones, M.O., Allred, B.W. 2019b. Operationalizing resilience and resistance concepts to address invasive grass-fire cycles. Frontiers in Ecology and Evolution. 7:185. Online: doi: 10.3389/fevo.2019.00185.

Chambers, J.C., J.L. Beck, J.B. Bradford, J. Bybee, S. Campbell, J. Carlson, T.J. Christiansen, K.J. Clause, G. Collins, M.R. Crist, J.B. Dinkins, K.E. Doherty, F. Edwards, S. Espinosa, K.A. Griffin, P. Griffin, J.R. Haas, S.E. Hanser, D.W. Havlina, K.F. Henke, J.D. Hennig, L.A. Joyce, F.M. Kilkenny, S.M. Kulpa, L.L. Kurth, J.D. Maestas, M. Manning, K.E. Mayer, B.A. Mealor, C. McCarthy, M. Pellant, M.A. Perea, K.L. Prentice, D.A. Pyke, L.A. Wiechman, and A. Wuenschel. 2017a. Science framework for conservation and restoration of the sagebrush biome: Linking the Department of the Interior's Integrated Rangeland Fire Management Strategy to long-term strategic conservation actions. Gen. Tech. Rep. RMRS-GTR-360. Fort Collins, CO: U.S Department of Agriculture, Forest Service, Rocky Mountain Research Station. 213 p.

Chambers, J. C., J. D. Maestas, D. A. Pyke, C. S. Boyd, J. C. Chambers, J. D. Maestas, D. A. Pyke, C. S. Boyd, M. Pellant, and A. Wuenschel. 2017b. Using resilience and resistance concepts to manage persistent threats to sagebrush ecosystems and Greater Sage-grouse. Rangeland Ecology and Management 70:149–164.

Chambers, J. C., B. A. Bradley, C. S. Brown, C. D. Antonio, M. J. Germino, J. B. Grace, S. P. Hardegree, R. F. Miller, and D. A. Pyke. 2014a. Resilience to stress and disturbance, and resistance to Bromus tectorum L . invasion in cold desert shrublands of western North America. Ecosystems 17:360–375.

Chambers, J. C., R. F. Miller, D. I. Board, D. A. Pyke, B. A. Roundy, J. B. Grace, E. W. Schupp, and R. J. Tausch. 2014b. Resilience and resistance of sagebrush ecosystems: implications for state and transition models and management treatments. Rangeland Ecology and Management 67:440–454.

Chambers, J., B. Roundy, R. Blank, S. Meyer, and A. Whittaker. 2007. What makes Great Basin sagebrush ecosystems invasible by Bromus Tectorum? Ecological Monographs 77:117–145.

Crist, M.R, Chambers, J.C., Phillips, S.L., Prentice, K.L., Wiechman, L.A., eds. 2019. Science framework for conservation and restoration of the sagebrush biome: Linking the Department of the Interior's Integrated Rangeland Fire Management Strategy to long-term strategic conservation actions. Part 2. Management applications. Gen. Tech. Rep. RMRS-GTR-389. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 237 p.

Doherty, K. E., J. S. Evans, P. S. Coates, L. M. Juliusson, and B. C. Fedy. 2016. Importance of regional variation in conservation planning: a rangewide example of the Greater Sage-Grouse. Ecosphere 7:e01462.

Maestas, B. J. D., S. B. Campbell, J. C. Chambers, M. Pellant, and R. F. Miller. 2016. Tapping soil survey information for rapid assessment of sagebrush ecosystem resilience and resistance. Rangelands 38:120–128.

Natural Resources Conservation Service. 2012. Ecological Site Information System (ESIS). https://esis.sc.egov.usda.gov/About.aspx

Natural Resource Conservation Service. 2014a. Soil Survey Geographic (SSURGO) Database. http://sdmdataaccess.nrcs.usda.gov/

Natural Resource Conservation Service. 2014b. U.S. General Soil Map (STATSGO2) Database. http://sdmdataaccess.nrcs.usda.gov/

Natural Resources Conservation Service. 2019. National Soil Survey Handbook, Title 430-VI. http://www.nrcs.usda.gov/wps/portal/nrcs/detail/soils/ref/?cid=nrcs142p2_054242

Short, K. C., M. A. Finney, J. H. Scott, *et al*. 2016. Spatial dataset of probabilistic wildfire risk components for the conterminous United States. U.S. Department of Agriculture, USDA Forest Service Research Data Archive, Fort Collins, CO. https://doi.org/10.2737/RDS-2016-0034.

Stiver, S., A. Apa, J. Bohne, S. Bunnell, P. Deibert, S. Gardner, M. Hilliard, C. McCarthy, and M. Schroeder. 2006. Greater Sage-grouse comprehensive conservation strategy. Western Association of Fish and Wildlife Agencies, Cheyenne, WY.

Appendix 1: Climate models used by datasets in this guidebook

1. Introduction

Datasets that represent future projections under climate-change scenarios are typically created using general circulation models (GCMs) as inputs. A GCM is a type of mathematical climate model that simulates the circulation of oceans and the Earth's atmosphere (Randall *et al*., 2007; Rupp *et al*. 2013). Some climate models, known as Earth System Models (ESMs), also include carbon-cycle and ocean biogeochemical effects. Using future projections for greenhouse-gas emissions and sequestration (see appendix 2), GCMs can be used to generate future projections for climate variables such as temperature and precipitation.

GCMs differ in the ways in which they simulate ocean and atmospheric processes, including the equations and parameters they use and the horizontal and vertical spatial resolutions at which they operate. As a result, GCMs may differ in their sensitivities to climate forcing, such as how increased greenhouse gas concentrations influence global temperatures. Because the outputs of GCMs are often coarse in spatial resolution, downscaling methods are commonly employed to generate finer-resolution datasets. Downscaling methods are described in section 6 of each guidebook chapter for datasets that employed downscaled climate projections.

Table A1 presents a selection of GCMs that were used in the creation of datasets described in this guidebook. As GCMs are improved and updated, newer versions of GCMs are regularly published. Additional information on GCMs may be obtained by consulting the dataset citations in each chapter, and references therein. Detailed information about GCMs, including model evaluation and comparison among models, is available from Randall *et al*. (2007) and Rupp *et al.* (2013).

Table A1. Commonly used climate models as inputs to datasets in this guidebook

Model name	Model agency	Citation
ACCESS1.0	Commonwealth Scientific and Industrial Research Organization (CSIRO) and Bureau of Meteorology (BOM), Australia	Lewis and Karoly (2014)
BCC-CSM1-1	Beijing Climate Center, China Meteorological Administration, China	Wu (2012)
BNU-ESM	College of Global Change and Earth System Science, Beijing Normal University, China	Ji *et al*. (2014)
CanESM2	Canadian Centre for Climate Modeling and Analysis, Canada	Chylek *et al*. (2011)
CCSM4	National Center of Atmospheric Research, USA	Meehl *et al*. (2012, 2013)
CESM1-CAM5	National Center of Atmospheric Research, USA	Meehl *et al*. (2013)
CNRM-CM5	National Centre for Meteorological Research, France	Voldoire *et al*. (2013)
CSIRO-Mk3.6.0	Commonwealth Scientific and Industrial Research Organisation, Australia	Collier *et al*. (2011)
GFDL-CM3	National Oceanic and Atmospheric Administration (NOAA) Geophysical Fluid Dynamics Laboratory, USA	Griffies *et al*. (2011)
GISS-E2R	National Aeronautics and Space Administration, Goddard Institute for Space Studies, USA	Schmidt *et al*. (2014)
HadGEM2-ES, HadGEM2-CC	Met Office Hadley Center, UK	Collins *et al*. (2011), Jones *et*

		al. (2011), Martin *et al*. (2011)
INM-CM4	Institute for Numerical Mathematics, Russia	Diansky and Volodin (2002)
IPSL-CM5A-LR, IPSL-CM5A-MR, IPSL-CM5B-LR	Institut Pierre Simon Laplace, France	Dufresne *et al*. (2013)
MIROC5, MIROC-ESM	Atmosphere and Ocean Research Institute (The University of Tokyo), National Institute for Environmental Studies, and Japan Agency for Marine-Earth Science and Technology, Japan	Watanabe *et al*. (2010, 2011)
MPI-ECHAM5	Max Planck Institute for Meteorology, Germany	Roeckner *et al*. (2003)
MRI-CGCM3	Meteorological Research Institute, Japan	Yukimoto *et al*. (2012)
NorESM1-M	Norwegian Climate Center, Norway	Bentsen *et al*. (2013)

References

Bentsen, M., I. Bethke, J. Debernard, and T. Iversen. 2013. The Norwegian Earth system model, NorESM1-M - Part 1 : description and basic evaluation of the physical climate. Geoscientific Model Development 6:687–720.

Chylek, P., J. Li, M. K. Dubey, M. Wang, and G. Lesins. 2011. Observed and model simulated 20th century Arctic temperature variability: Canadian Earth System Model CanESM2. Atmospheric Chemistry and Physics Discussions 11:22893–22907.

Collier, M. A., S. J. Jeffrey, L. D. Rotstayn, S. M. Dravitzki, C. Moeseneder, C. Hamalainen, J. I. Syktus, R. Suppiah, J. Antony, A. El Zein, and M. Atif. 2011. The CSIRO-Mk3.6.0 atmosphere-ocean GCM: participation in CMIP5 and data publication. 19th International Congress on Modelling and Simulation, December 12-16 2011. Perth, Australia.

Collins, W. J., N. Bellouin, N. Gedney, P. Halloran, T. Hinton, J. Hughes, and C. D. Jones. 2011. Development and evaluation of an Earth-system model – HadGEM2. Geoscientific Model Development 4:1051–1075.

Diansky, N., and E. Volodin. 2002. Simulation of the present-day climate with a coupled atmosphere-ocean general circulation model. Izvestia, Atmospheric and Oceanic Physics 38:732–747.

Dufresne, J., M. Foujols, S. Denvil, A. Caubel, O. Marti, O. Aumont, Y. Balkanski, S. Bekki, H. Bellenger, R. Benshila, S. Bony, L. Bopp, P. Braconnot, P. Brockmann, P. Cadule, F. Cheruy, L. Fairhead, T. Fichefet, F. Codron, A. Cozic, D. Cugnet, N. De Noblet, C. Ethe, S. Flavoni, P. Friedlingstein, L. Guez, E. Guilyardi, D. Hauglustaine, F. Hourdin, A. Idelkadi, J. Ghattas, S. Joussaume, M. Kageyama, G. Krinner, S. Labetoulle, A. Lahellec, F. Lefevre, C. Levy, Z. X. Li, J. Lloyd, F. Lott, G. Madec, M. Mancip, M. Marchand, S. Masson, Y. Meurdesoif, J. Mignot, I. Musat, S. Parouty, J. Polcher, C. Rio, M. Schulz, D. Swingedouw, S. Szopa, C. Talandier, P. Terray, N. Viovy, and N. Vuichard. 2013. Climate change projections using the IPSL-CM5 Earth system model: from CMIP3 to CMIP5. Climate Dynamics 40:2123–2165.

Griffies, S., M. Winton, L. Donner, L. Horowitz, S. Downes, R. Farneti, A. Gnanadesikan, W. Hurlin, H.C. Lee, Z. Liang, J. B. Palter, B. L. Samuels, A.T. Wittenberg, B. L. Wyman, J. Yin, and N. Zadeh. 2011. The GFDL CM3 coupled climate model: characteristics of the ocean and sea ice simulations. Journal of Climate 24:3520–3544.

Ji, D., L. Wang, J. Feng, Q. Wu, H. Cheng, Q. Zhang, J. Yang, W. Dong, Y. Dai, D. Gong, and R. Zhang. 2014. Description and basic evaluation of Beijing Normal University Earth System Model (BNU-ESM) version 1. Geoscientific Model Development 7:2039–2064.

Jones, C. D., J. K. Hughes, N. Bellouin, S. C. Hardiman, G. S. Jones, J. Knight, S. Liddicoat, F. M. O. Connor, and I. P. Laplace. 2011. The HadGEM2-ES implementation of CMIP5 centennial simulations. Geoscientific Model Development 4:543–570.

Lewis, S., and D. Karoly. 2014. Assessment of forced responses of the Australian Community Climate and Earth System Simulator (ACCESS) 1.3 in CMIP5 historical detection and attribution experiments. Australian Meteorological and Oceanographic Journal 64:87–101.

Martin, G., N. Bellouin, W. J. Collins, I. D. Culverwell, and P. R. Halloran. 2011. The HadGEM2 family of Met Office Unified Model climate configurations. Geoscientific Model Development 4:723–757.

Meehl, G., W. Washington, J. Arblaster, A. Hu, H. Teng, J. Kay, A. Gettelman, D. Lawrence, B. Sanderson, and W. Strand. 2013. Climate change projections in CESM1 (CAM5) compared to CCSM4. Journal of Climate 26:6287–6308.

Meehl, G., W. Washington, J. Arblaster, A. Hu, H. Teng, and C. Tebaldi. 2012. Climate system response to external forcings and climate change projections in CCSM4. Journal of Climate 25:3661–3683.

Randall, D.A., R.A. Wood, S. Bony, R. Colman, T. Fichefet, J. Fyfe, V. Kattsov, A. Pitman, J. Shukla, J. Srinivasan, R.J. Stouffer, A. Sumi, and K.E. Taylor. 2007. Climate models and their evaluation. *in* S. Solomon, D. Qin, M. Manning, Z. Chen, M. Marquis, K. Averyt, M. Tignor, and H. Miller, editors. Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, New York, NY.

Roeckner, E., G. Bäuml, L. Bonaventura, R. Brokopf, M. Esch, M. Giorgetta, S. Hagemann, I. Kirchner, L. Kornblueh, E. Manzini, A. Rhodin, U. Schlese, U. Schulzweida, and A. Tompkins. 2003. The atmospheric general circulation model ECHAM5. Part I: model description. Report No. 349. Max Planck Institute for Meteorology, Hamburg, Germany.

Rupp, D. E., J. T. Abatzoglou, K. C. Hegewisch, and P. W. Mote. 2013. Evaluation of CMIP5 20th century climate simulations for the Pacific Northwest USA. Journal of Geophysical Research 118: 884–907.

Schmidt, G. A., M. Kelley, L. Nazarenko, R. Ruedy, G. L. Russell, I. Aleinov, M. Bauer, S. E. Bauer, M. K. Bhat, R. Bleck, V. Canuto, Y. Chen, Y. Cheng, T. L. Clune, A. Del Genio, R. De Fainchtein, G. Faluvegi, J. E. Hansen, R. J. Healy, N. Y. Kiang, D. Koch, A. A. Lacis, A. N. Legrande, J. Lerner, K. K. Lo, E. E. Matthews, S. Menon, R. L. Miller, V. Oinas, and A. O. Oloso. 2014. Configuration and assessment of the GISS ModelE2 contributions to the CMIP5 archive. Journal of Advances in Modeling Earth Systems 6:141–184.

Voldoire, A., E. Sanchez-Gomez, D. Salas y Melia, B. Decharme, C. Cassou, S. Senesi, S. Valcke, I. Beau, A. Alias, M. Chevallier, M. Déqué, J. Deshayes, H. Douville, E. Fernandez, G. Madec, E. Maisonnave, M.-P. Moine, S. Planton, D. Saint-Martin, S. Szopa, S. Tyteca, R. Alkama, S. Belamari, A. Braun, L. Coquart, and F. Chauvin. 2013. The CNRM-CM5.1 global climate model: description and basic evaluation. Climate Dynamics 40:2091–2121.

Watanabe, M., T. Suzuki, R. Oishi, Y. Komuro, S. Watanabe, S. Emori, T. Takemura, M. Chikira, T. Ogura, M. Sekiguchi, K. Takata, D. Yamazaki, T. Yokohata, T. Nozawa, H. Hasumi, H. Tatebe, and M. Kimoto. 2010. Improved climate simulation by MIROC5: mean states, variability, and climate sensitivity. Journal of Climate 23:6312–6335.

Watanabe, S., T. Hajima, K. Sudo, T. Nagashima, T. Takemura, H. Okajima, T. Nozawa, and H. Kawase. 2011. MIROC-ESM 2010: model description and basic results of CMIP5-20c3m experiments. Geoscientific Model Development 4:845–872.

Wu, T. 2012. A mass-flux cumulus parameterization scheme for large-scale models: description and test with observations. Climate Dynamics 38:725–744.

Yukimoto, S., Y. Adachi, M. Hosaka, and T. Sakami. 2012. A new global climate model of the meteorological research institute: MRI-CGCM3 — model description and basic performance. Journal of the Meteorological Society of Japan 90:23–64.

Appendix 2: Greenhouse-gas scenarios used in climate-change projections

Climate models, including general circulation models (GCMs), are produced by research institutions around the world (see appendix 1). The Coupled Model Intercomparison Project (CMIP) is a standardized framework for GCMs, which allows GCMs to be compared and their uncertainties to be studied (Knutti and Sedláček, 2013). CMIP Phase 5 (CMIP5) is a more recent effort that builds upon CMIP Phase 3 (CMIP3) and uses a different set of scenarios to represent future changes, such as greenhouse-gas emissions and sequestration, that may influence Earth's climate. Details and updates on the most recent CMIP Phase 6 (CMIP6) are available from the World Climate Research Programme (2019).

CMIP3 used a family of greenhouse-gas scenarios known as Special Report on Emissions Scenarios (SRES) scenarios A1, A2, B1, and B2, which were subdivided into groups of sub-scenarios (Intergovernmental Panel on Climate Change, 2000). Although greenhouse-gas scenarios are commonly referred to as "emissions scenarios", some scenarios also incorporate the effects of carbon sequestration in addition to emissions projections. Scenarios differ in how they represent future global conditions related to a range of factors that are expected to control greenhouse-gas emission and sequestration rates, including human population growth, geographic patterns of economic development, technological change, and patterns of natural-resource use (Intergovernmental Panel on Climate Change, 2000). Commonly used SRES scenarios include B1, A1B, and A2, listed in order of increasing predicted global surface warming by the year 2100 (Knutti and Sedláček, 2013). The B1, A1B, and A2 scenarios predict approximately 1.5°C, 2.5°C, and 3.5°C increases in global surface temperatures, respectively, between the mid-2000s and the year 2100 (see figure 1 in Knutti and Sedláček, 2013).

The newer CMIP5 uses representative concentration pathways (RCPs) as greenhouse-gas scenarios, including RCP 2.6, RCP 4.5, RCP 6.0, and RCP 8.5 (Meinshausen *et al*., 2011), again listed in order of increasing predicted global surface warming (Knutti and Sedláček, 2013). RCP 2.6, RCP 4.5, RCP 6.0, and RCP 8.5 predict approximately 1°C, 1.75°C, 2.5°C, and 4°C increases in global surface temperatures, respectively, between the mid-2000s and the year 2100 (see figure 1 in Knutti and Sedláček, 2013). While the CMIP3 and CMIP5 scenarios are not directly comparable because they include different assumptions related to environmental and socioeconomic forces that influence greenhouse-gas emissions and sequestration, Knutti and Sedláček (2013) provide a useful basis of comparison of the temperature and precipitation projections derived from the different sets of scenarios.

Some datasets described in this guidebook include future projections based on more than one scenario (e.g., A1B and A2, or RCP 4.5 and RCP 8.5). Natural-resource managers may wish to compare these projections to help address uncertainty about the magnitude and rate of future climate change. For example, future projections under the RCP 8.5 scenario represent conditions under more severe global climate change than projections under RCP 4.5. Additionally, managers may wish to compare future projections within a given greenhouse-gas scenario across future time periods, e.g., mid-21st-century compared to the end of the 21st century.

References

Intergovernmental Panel on Climate Change. 2000. Special Report on Emissions Scenarios. N. Nakićenović and R. Swart, Eds. Cambridge University Press, Cambridge, UK.

Knutti, R., and J. Sedláček. 2013. Robustness and uncertainties in the new CMIP5 climate model projections. Nature Climate Change 3:369–373.

Meinshausen, M., S. J. Smith, K. Calvin, J. S. Daniel, and M. L. T. Kainuma. 2011. The RCP greenhouse gas concentrations and their extensions from 1765 to 2300. Climate Change 109:213–241.

World Climate Research Programme. 2019. CMIP Phase 6 (CMIP6). https://www.wcrp-climate.org/wgcm-cmip/wgcm-cmip6.

Appendix 3: Spatial scale considerations for applying spatial datasets to management applications

1. Introduction

Spatial resolution is a key consideration in the selection of geospatial datasets for conservation and management purposes. Requirements for levels of spatial detail to inform decision-making may vary depending on management applications and conservation goals. Scale mismatches can occur when datasets are too coarse in resolution relative to the spatial scale and conservation purpose for which they are applied (Guerrero *et al*., 2013). For example, at a regional scale, a 1-km resolution dataset (meaning a gridded raster dataset with each square pixel having sides 1-km long) might be appropriate for a variety of conservation applications requiring detailed assessment of spatial variability. However, the same dataset might be too coarse for those applications at a local scale, such as a 5-km^2 protected area. In this example, the protected area would be covered by only five pixels of the dataset. At this scale, the dataset might help inform conservation in other ways that do not require detailed evaluation of spatial variability, for example to anticipate general changes over time for the entire protected area or to compare average dataset values for the projected area to average values for other locations in the region.

To help inform selection of datasets for appropriate conservation and management applications at a variety of spatial scales, tables A2 and A3 provide basic quantitative information on the dataset spatial resolutions needed to achieve specified numbers of pixels (100 and 1,000, respectively) within land-management units of varying sizes. Rows in tables A2 and A3 are in approximately increasing order by size. For each type of management unit, the tables list the median and 10^{th} percentile land areas based on distributions of management units (e.g., protected areas, watersheds, and counties) across the Pacific Northwest, along with approximations of the coarsest resolution of spatial data needed to ensure 100 and 1,000 pixels (for tables A2 and A3, respectively) within the median and 10^{th} percentile sizes of those management units. The choice of 100 and 1,000 pixels for calculations in these tables is arbitrary; however, the two tables can be compared to gain a sense of how spatial resolution needs change based on criteria for how many pixels are required within a given management unit. The median and 10^{th} percentile land areas in tables A2 and A3 could be used to perform similar calculations at other thresholds of number of pixels desired within management units.

Table A2. Area statistics for management units within the Pacific Northwest, along with dataset resolution needed to ensure 100 pixels within management units

Type of management unit	Median area (km^2)	10^{th} percentile area (km^2)	Approximate coarsest resolution to ensure 100 pixels within median area	Approximate coarsest resolution to ensure 100 pixels within 10^{th} percentile area
Non-profit nature preserves	0.2	0.02	48 m	14 m
State lands (e.g., state parks, wildlife areas, and conservation areas)	2.4	0.05	155 m	22 m
12-digit hydrologic unit watersheds (HUC-12s)	80.3	47.4	896 m	689 m
Bureau of Land Management (BLM) districts	1,756	522	4.2 km	2.3 km
8-digit hydrologic unit watersheds (HUC-8s)	2,886	1,582	5.4 km	4 km
Counties	4,523	1,562	6.7 km	4 km
National forests	6,969	3,147	8.3 km	5.6 km
Level 3 ecoregions	53,442	18,313	23.1 km	13.5 km

Table A3. Area statistics for management units within the Pacific Northwest, along with dataset resolution needed to ensure 1,000 pixels within management units

Type of management unit	Median area (km^2)	10^{th} percentile area (km^2)	Approximate coarsest resolution to ensure 1,000 pixels within median area	Approximate coarsest resolution to ensure 1,000 pixels within 10^{th} percentile area
Non-profit nature preserves	0.2	0.02	14 m	4 m
State lands (e.g., state parks, wildlife areas, and conservation areas)	2.4	0.05	49 m	7 m
12-digit hydrologic unit watersheds (HUC-12s)	80.3	47.4	283 m	217 m
Bureau of Land Management (BLM) districts	1,756	522	1.3 km	723 m
8-digit hydrologic unit watersheds (HUC-8s)	2,886	1,582	1.7 km	1.3 km
Counties	4,523	1,562	2.1 km	1.2 km
National forests	6,969	3,147	2.6 km	1.8 km
Level 3 ecoregions	53,442	18,313	7.3 km	4.3 km

2. Methods for assessing spatial resolution at different management scales

To create tables A2 and A3, polygons representing various management unit types were compiled from several sources. Polygons representing protected areas within Washington, Oregon, and Idaho were obtained from the Gap Analysis Program (GAP) Protected Areas Database (U.S. Geological Survey, 2016) and were subdivided by landowner and land manager using the “owner type” and “manager type” fields. Polygons representing state-owned lands were additionally screened to include only polygons with “manager name” as “State Dept Natural Resources,” “State Fish and Wildlife,” or “State Parks and Recreation” and having a “unit name” that included the search terms “natural”, “conservation”, “wildlife”, or “park.” This additional filtering was required to screen out very small localized areas such as gravesites, local greenways, and river access sites. Watershed polygons representing 8-digit and 12-digit hydrologic unit codes (HUC-8s and HUC-12s, respectively) were obtained from the National Hydrography Dataset (U.S. Geological Survey, 2013). Polygons representing U.S. Environmental Protection Agency Level 3 ecoregions were obtained from (Omernik and Griffith, 2014).

For each type of management unit in tables A2 and A3, the distribution of polygon areas was used to calculate the median area and 10^{th} percentile area. Although median area may be useful to consider for regional-scale conservation planning, managers may also wish to ensure that a dataset is of appropriate resolution even for relatively small management units within each type (represented by the

10th percentile area, such that approximately 90% of polygons of a given management unit type are equal to or larger than the listed area).

To calculate the coarsest resolution needed to ensure a minimum of *P* pixels within the median (and 10th percentile) of areas:

$$R = \sqrt{\frac{A}{P}}$$

where *R* is the coarsest resolution (linear distance along an edge of a square pixel) and *A* is the area in question (median or 10th percentile area). This equation can be used to modify the calculations in tables A2 and A3, by substituting other desired minimum number of pixels (*P*) instead of 100 and 1,000.

3. Scale considerations for applying datasets for management and conservation

Along with other considerations, tables A2 and A3 can be used to help guide selection of datasets for management and conservation applications at various spatial scales to avoid potential scale mismatches. Section 10 of each guidebook chapter ('Conservation applications') lists a series of geographic scales for which the dataset may be appropriate for conservation applications that require detailed assessment of spatial variation within a geographic boundary such as a protected area, informed by the analysis in table A3. This section also lists the finer geographic scales at which the dataset might be useful for other conservation purposes, such as to assess general patterns or for comparison to other locations.

It is important to note that these guidelines are based only on the resolution of datasets relative to the size distributions of management units and do not account for the local magnitude of variation for a given dataset at a given scale. Local variation in dataset values varies between datasets. For example, two datasets of the same resolution might differ in their usefulness for a given management purpose in a given protected area if one dataset shows a large amount of spatial variability within the protected area (allowing managers to discern which parts of the protected area have relatively high values and low values) and the other shows fairly homogenous values across the protected area. In addition to tables A2 and A3, managers may also wish to consider the nature of the information presented in each dataset because landscape characteristics and processes (e.g., climate variation, habitat availability, soil and geologic patterns, and species movements) operate across a broad range of scales (Carroll *et al*., 2017). In general, spatial resolution relative to management scale should be one of several considerations used in selecting datasets for conservation or management applications. Other important considerations are described in section 10 of each guidebook chapter.

References

Carroll, C., T. Wang, D. R. Roberts, J. L. Michalak, J. J. Lawler, S. E. Nielsen, D. Stralberg, A. Hamann, and B. H. McRae. 2017. Scale-dependent complementarity of climatic velocity and environmental diversity for identifying priority areas for conservation under climate change. Global Change Biology 23:4508–4520.

Guerrero, A. M., R. R. J. M. C. Allister, J. Corcoran, and K. A. Wilson. 2013. Scale mismatches , conservation planning , and the value of social-network analyses. Conservation Biology 27:35–44.

Omernik, J., and G. Griffith. 2014. Ecoregions of the conterminous United States: evolution of a hierarchical spatial framework. Environmental Management 54:1249–1266.

U.S. Geological Survey. 2013. The National Hydrography Dataset (NHD). https://nhd.usgs.gov/.

U.S. Geological Survey. 2016. National Gap Analysis Program, Protected Areas of the U.S. (PAD-US) dataset, version 1.4. https://gapanalysis.usgs.gov/padus/data/.