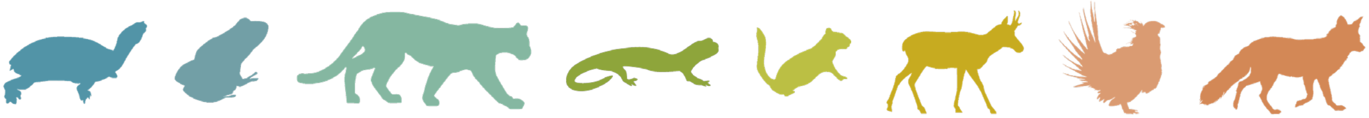
Oregon Connectivity Assessment and Mapping Project



Technical Report

OREGON
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Oregon Connectivity Assessment and Mapping Project (OCAMP)

Technical Report

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Table of Contents

Introduction

Habitat loss and fragmentation represent the single greatest threat to biodiversity worldwide (Beier and Noss 1998, Heller and Zavaleta 2009, Hilty et al. 2012). The intensification of human development is so severe that planning for connecting species and processes between natural habitats has become a conservation imperative (Worboys 2010). Connectivity aids species in fulfilling their daily, seasonal, and life history needs (Noss 1991), allows for dispersal (Hanski 1998), helps maintain genetic diversity (Watts et al. 2015), and promotes population viability and persistence in increasingly fragmented landscapes. Further, maintaining and restoring landscape connectivity is the most frequently proposed strategy to aid wildlife in adapting to changing climates (Heller and Zavaleta 2009).

“Barriers to Animal Movement” is one of seven Key Conservation Issues (KCIs) outlined within Oregon’s State Wildlife Action Plan, the Oregon Conservation Strategy, which is the overarching state strategy for conserving Oregon's fish and wildlife species. The importance of species and habitat connectivity is identified under Goal 2 of the Barriers to Animal Movement KCI: ‘Provide connectivity of habitat for the broad array of wildlife species throughout Oregon.’ The need for developing connectivity maps is identified under Action 2.2: ‘Continue to collect terrestrial wildlife movement data and refine maps and models to better identify and prioritize wildlife movement corridors.’ Connectivity is also a vital component of the Climate Change KCI, Land Use Changes KCI, and Water Quality and Quantity KCI.

In 2016, the revision of the Oregon Conservation Strategy identified a need for a statewide analysis of existing wildlife habitat connectivity. Planning for wildlife connectivity is an intensive process that includes considerations of large expanses of geographic space that cross political jurisdictions. Connectivity models provide practical, much-needed tools for developing mitigation, restoration, avoidance, and/or conservation responses to habitat conversion and fragmentation; in order to be useful to practitioners, however, models in adjacent regions must be comparable and cohesive. Thus, connectivity assessments undertaken across political boundaries using a unified framework are critical for planning for connected landscapes at large scales.

The Oregon Department of Fish and Wildlife (ODFW), together with contributions from its partners, developed the Oregon Connectivity Assessment and Mapping

Project (OCAMP) to map connectivity for wildlife throughout the entirety of Oregon. The project was initiated in 2019 and completed in 2022, with analyses based on current best practices in landscape-scale connectivity modeling and executed by a partnership between ODFW, Portland State University, and Samara Group, and with input from experts in other state and federal agencies, as well as universities, Tribes, non-profits, consulting groups, and other NGOs.

Products developed through OCAMP are intended to aid in statewide planning and prioritization efforts to maintain structural and functional habitat connectivity, help direct on-the-ground efforts for acquisition, restoration, and conservation of habitat for fish and wildlife, inform long-term planning documents for managed lands, guide granting efforts, inform land use development, including expansion of urban growth boundaries, permitting for renewable energy development, and development of sensitive habitats, and aid in mitigating transportation issues, including identification of areas where wildlife passage structures could best reduce wildlife-vehicle collisions.

The analytical procedures developed for OCAMP draw on techniques utilized in connectivity projects in neighboring states, including the California Essential Habitat Connectivity Project (Spencer et al. 2010) and the Washington Connected Landscapes Project (WWHCWG 2012), as well as newer methods developed by The Nature Conservancy and applied more broadly to the Pacific Northwest (Buttrick et al. 2015; McRae et al. 2016; Schloss et al. 2021). In using these previous projects to inform the connectivity models developed here, we ensure that data produced for Oregon will be comparable to existing connectivity data for Washington and California and will help fill in data gaps in the greater Pacific Northwest region.

This report is intended for those seeking a detailed understanding of the development and interpretation of OCAMP products, including the rationale behind the selected methodologies, the statistical approaches used in validating model output, and project limitations. For those seeking a more generalized overview of project methods, we recommend visiting the Priority Wildlife Connectivity Areas page within the Oregon Conservation Strategy website or reading through the project's Executive Summary.

Methods

The analytical steps involved in the landscape resistance-based connectivity assessment and mapping for this project included: 1) selecting representative species for evaluation of connectivity; 2) extensive literature review to identify species habitat requirements, drivers of movement, and tolerance of unsuitable habitat conditions and/or anthropogenic features; 3) building habitat models to represent the permeability of different habitat types and landscape features for each species; 4) offering species experts an opportunity to review draft maps to provide feedback on literature and interpretation of habitat requirements, data sources, model parameterization, and model outcomes; 5) validating habitat models using empirical occurrence datasets to ensure modeled permeability properly aligns with species habitat use and avoidance; 6) connectivity modeling to identify expected movement pathways based on habitat permeability; 7) spatial conservation prioritization of species-specific connectivity maps; and 8) composition of species-specific priorities to identify the highest-value areas of the landscape for supporting wildlife movement.

Species Selection

Given limited resources and data availability, it is infeasible to model connectivity for all species of concern, and for many species connectivity maps may be desired but data limitations preclude assessment. As a result, planning efforts are restricted to modeling connectivity networks for a subset of species. Common approaches to species selection rely on umbrella species (Lambeck 1997). Umbrella species selected for connectivity modeling are typically large-bodied, highly mobile generalist species with low sensitivity to barriers. Recent research suggests that despite being area-demanding, umbrella species function as poor representatives and do not encompass the connectivity needs of a diversity of species. Instead, surrogate species, selected based on diverse habitat needs, are thought to be most effective (Meurant et al. 2018).

Surrogate species are species that are representative of larger suites of species, habitat characteristics, and/or ecological processes (Beier et al. 2008). Analysis and mapping for these surrogate species is representative of connectivity not just for the species themselves, but also for a suite of other species with similar habitat associations and movement capabilities. For example, the beaver (*Castor canadensis*) is a riparian-obligate ecological engineer and is a widely studied species with well-known habitat requirements and needs for travel and dispersal pathways. As such, beaver can act as an effective surrogate for other riparian-obligate species, including a variety of other mammals, reptiles, birds, and invertebrates, which have similar habitat requirements but might lack sufficient information for effective connectivity modeling (Stoffyn-Egli and Willison 2011).

We utilized a Goals-Based Species Selection process (GBSS) to select surrogate species for connectivity mapping. This process includes six major steps:

1. Clarifying and articulating project goals
2. Data acquisition to prepare for analysis
3. Hierarchical cluster analysis
4. Interpretation and refinement of clusters
5. Evaluation of remaining candidate species in context of project goals
6. Final species selections

Species selection took place in April and May of 2019 and from February to June in 2020. To ensure that we captured regional habitat variation and reached experts working throughout Oregon, we broke the state into its respective ecoregions (Coast Range, Willamette Valley, Klamath Mountains, West Cascades, East Cascades, Columbia Plateau, Blue Mountains, and Northern Basin and Range) and executed the GBSS process separately for each ecoregion.

The first step in GBSS is a clear articulation of project goals. The ultimate goal of OCAMP was to advance priority conservation planning aimed at preventing and mitigating barriers to wildlife movement in Oregon by identifying an interconnected network of Priority Wildlife Connectivity Areas—the parts of the landscape with the highest overall value for facilitating wildlife movement. For each ecoregion, we intended to select between five and 12 surrogate species from the ecoregion for connectivity modeling, based on the size of the region and the diversity of habitat types therein. The desired outcome was to apply limited resources while still representing connectivity needs of the broader wildlife community. To best represent Oregon's native species, we required that:

- Species have close year-round or seasonal associations with (most often found in or obligate to) habitats of interest. Consideration should be given to representation of breeding and/or migratory habitats if applicable.
- Species are neither very rare nor overly common in the area of interest
- Species must be native and noninvasive

At the project level, we also wanted to ensure that species represented a diversity of:

- Taxa (mammals, birds, amphibians, reptiles, invertebrates)
- Mobility and dispersal capabilities
- Responses to landscape elements that are potential barriers due to a behavioral response (i.e., avoidance of roads, anthropogenic sources of noise, artificial light, presence of people and/or domestic animals)
- Life history strategies
- Association with different habitat structural components (seral stage, canopy layers, etc.)
- Susceptibility to different threats to persistence (such as land clearing/vegetation removal, development, climate change, road mortality, fence entanglement, energy development, invasive species, fire impacts, etc.).

The second step in GBSS is to acquire the necessary data to determine an appropriate pool of candidate species. We developed a list of candidate species and species-habitat associations using data provided by *Wildlife-Habitat Relationships in Oregon and Washington* (Johnson and O'Neil, 2001), filtered to include only those species associated with habitat types found in the Oregon. Johnson and O'Neil (2001) include the strength of association for each habitat/species relationship, as well as the confidence level of that association. We ultimately considered only those species categorized as "highly associated with high confidence" with a given habitat type, resulting in an initial list of 271 mammal, bird, reptile, and amphibian candidates. Notably, this approach favors habitat specialists, which we address in step four.

The third step in the GBSS process is a hierarchical clustering analysis to group the initial candidate list into clusters based on similarities in habitat associations. We varied the number of clusters used for each ecoregion, based on the size of the ecoregion, the number of habitats occurring within the ecoregion, and the number of candidate species within the ecoregion. We used as few as four clusters for ecoregions with lower habitat diversity (e.g., Columbia Plateau), and as many as eight clusters for ecoregions with many different habitat types (e.g., Klamath Mountains).

The fourth step in GBSS includes additional filtering, interpretation, and refinement of the cluster results. We further refined our list of potential surrogate species at this stage by removing from consideration non-native species, marine mammals, and migratory birds that do not breed in Oregon. The type of landscape resistance-based connectivity modeling applied in OCAMP is not the most suitable method for mapping connectivity for long-distance migratory birds. For that reason, we chose to focus on mapping connectivity of breeding habitat for bird species in this project and removed migratory birds that do not breed in Oregon from consideration. We then reviewed species distribution maps for all candidate species within each ecoregion to ensure selected surrogate species were representative primarily of the target ecoregion, rather than of similar habitats elsewhere in the state (Csuti et al. 2001). Species with range boundaries that had limited or no overlap with the target ecoregion were removed. At this stage we also added generalist and/or focal species to the candidate list. Given that our initial clustering method focused on species closely associated with particular habitat types, this approach favors habitat specialists rather than generalists. However, generalist and focal species can play an important role in representing connectivity among disparate habitat types, or in fulfilling needs for connectivity analysis for species of particular sociopolitical interest. The final candidate list included 162 species, representing a diversity of mammals, birds, amphibians, and reptiles, as well as several invertebrates.

The fifth step in GBSS is to evaluate the remaining candidate species in the context of the project goals. For each ecoregion, we developed a scoring worksheet to aid in compiling and comparing species' qualities and sensitivities. Worksheets were organized by species habitat association, with rows for each candidate species. Columns represented project goals, such as adequate representation of landscape features, sensitivity to anthropogenic threats, and movement capabilities; ecoregional goals, such as representation of specific structural habitat characteristics (e.g., seral stages, canopy layers, snags, sagebrush height); and additional considerations, including general understanding of species habitat requirements and data availability. The scoring process was designed to be sensitive to limited availability and time constraints of participating scorers to reduce barriers to participation.

We solicited participation in the scoring process through presentations to relevant groups, direct emails to species experts in state and federal agencies, universities, non-profit organizations, and consulting groups throughout Oregon, and distribution to relevant email lists for species working groups around the state. We asked participants to add information to the worksheet for species within their expertise, scoring candidates within each field. We provided a webinar to species experts with the background and goals of the project and instructions for scoring and encouraged experts to share the webinar and worksheet with colleagues. We also directed participants to include additional species for consideration if they felt a particular feature or taxon was not adequately represented in the original list.

Of 162 total candidate species, 142 species (88%) were scored by participants. The 20 species that were not scored were all small mammals: shrews, moles, mice, voles, and pocket gophers. Of the 142 species that received scores, 68% were evaluated by more than one participant. Fourteen species were scored by at least five individuals, and 30 species were scored by four or more participants. In addition to the 162 proposed candidates, 47 additional species were suggested by reviewers and scored.

The sixth and final step in the GBSS process is to make final species selections. We used the scoring worksheets completed by species experts to rank potential surrogates and developed a list of proposed final species selections for each ecoregion. We then held a series of ecoregion-specific workshops to continue discussion and provide a platform for further debate on the suitability of the proposed surrogates to represent each ecoregion's habitats and landscape features, as well as overall project goals. Following completion of the workshops, we closely evaluated the feedback and recommendations received and finalized the species list for the project. We ultimately selected 54 species (Table 1): 23 mammals, 16 birds, 8 amphibians, 4 reptiles, and 3 invertebrates.

Table 1: Selected species and habitat representations by ecoregion

Ecoregion	Species common name	Selected to represent
Blue Mountains	Bighorn Sheep	Dwarf Shrub-steppe: Alpine meadows and rocky slopes
	Black-tailed Jackrabbit	Shrub-steppe: sagebrush, shadscale, greasewood, chaparral thickets and forest edges
	Lewis's Woodpecker	Westside Oak and Dry Douglas-fir Forest and Woodlands: High density of snags
	Long-toed Salamander	Herbaceous Wetlands: Dense cover such as leaf litter/down wood
	Mountain Goat	Alpine Grasslands and Shrublands/Subalpine Parkland
	Cougar	Habitat Generalist: Focal species
	Red-naped Sapsucker	Upland Aspen Forest
	Rocky Mountain Elk	Habitat Generalist: Focal species
	Western Rattlesnake	Westside Lowlands Conifer-Hardwood Forest: South-facing rocky outcroppings
Cascades	American Pika	Alpine Grasslands and Shrublands/Subalpine Parkland: Associated with talus slopes
	Cascades Frog	Alpine Grasslands and Shrublands/Subalpine Parkland: Permanent lentic waterbodies
	Coastal Tailed Frog	Conifer hardwood forests: Headwater streams

	Great Gray Owl	Eastside (Interior) Mixed Conifer Forest/Ponderosa Pine Forest and Woodlands: Montane meadows
	Hoary Bat	Westside Lowlands Conifer-Hardwood Forest: Mature stands
	Pacific Marten	Montane Mixed Conifer Forest: Mid/late seral, multi-layered canopy
	Mule Deer	Habitat Generalist: Focal species
	Oregon Slender Salamander	Westside Riparian Wetlands, Late Seral Stage Douglas-fir Forests
	Pileated Woodpecker	Mixed Conifer Woodlands: Snags in valley bottoms
	Sierra Nevada Red Fox	Alpine Grasslands and Shrublands/Subalpine Parkland
	Western Bumble Bee	Mixed Conifer Woodlands: Floral resources
	Western Toad	Montane Coniferous Wetlands
Coast Range	American Beaver	Open Water/Riparian & Herbaceous Wetlands
	Northern Flying Squirrel	Conifer Hardwood Forests: Mid/late seral, interconnected conifer canopies
	Northern Red-legged Frog	Conifer Hardwood Forests: Mid/late seral, aquatic-terrestrial linkage/pond associated
	Pacific-slope Flycatcher	Conifer Hardwood Forests: Old growth/mature stands, multiple canopy layers
	Snowy Plover	Coastal Dunes & Desert Playa and Salt Scrub Shrublands: associated with dry salt flats and salt-evaporated waterbodies
	Townsend's Chipmunk	Conifer Hardwood Forests: Early seral stage and clearings
	Wrentit	Dense shrub layers, also associated with oak woodlands
Columbia Plateau	Burrowing Owl	Shrub-Steppe: Open, treeless areas with low sparse vegetation
	Ord's Kangaroo Rat	Shrub-steppe: Associated with open areas and sandy substrates
	Vesper Sparrow	Shrub-steppe: Associated with open areas and short, sparse grass and scattered shrubs
Klamath Mountains	Black-tailed Deer	Habitat Generalist: Focal species
	Pacific Fisher	Montane Mixed Conifer Forest, Eastside (Interior) Mixed Conifer Forest, Westside Riparian-Wetlands, and Westside Lowlands Conifer-Hardwood Forest
	Foothill Yellow-legged Frog	Southwest Oregon Mixed Conifer-Hardwood Forest: Streams, riparian edges, & gravel bars
	Hermit Thrush	Southwest Oregon Mixed Conifer-Hardwood Forest: Dense shrub layers
	Little Brown Myotis	Ponderosa Pine Forest and Woodlands: Forest areas associated with pond, lakes or streams
	Northern Alligator Lizard	Conifer hardwood forests: Meadow edges and riparian zones
	Roosevelt Elk	Habitat Generalist

	Western Pond Turtle	Open Water: Lakes, rivers and streams
Northern Basin and Range	Columbia Spotted Frog	Open Water/Riparian & Herbaceous Wetlands
	Ferruginous Hawk	Shrub-Steppe/Dwarf Shrub-Steppe: Cliffs, outcrops and tree groves
	Lazuli Bunting	Eastside Riparian Wetlands: Open woodlands with dense shrub cover
	Long-nosed Leopard Lizard	Desert Playa and Salt Scrub Shrublands: Scattered low plants with sandy/gravel substrates
	Morrison's Bumble Bee	Shrub-steppe: flowering plants
	Porcupine	Upland Aspen Forest
	Pronghorn	Shrub-Steppe: Open, expansive terrain
	Pygmy Rabbit	Shrub-Steppe: Areas with tall, dense shrub cover
	Greater Sage-grouse	Shrub-Steppe: Focal species
	Western Meadowlark	Eastside Grasslands: Associated with open grasslands, prairies, and meadows
Willamette Valley	Bushy-tailed Woodrat	Montane Mixed Conifer Forest: Early/mid seral, open and/or rocky habitats
	Fender's Blue Butterfly	Grasslands/Prairie: Early seral
	Purple Martin	Westside Lowlands Conifer-Hardwood Forest: Early seral, associated with snags
	Western Gray Squirrel	Westside Lowlands Conifer-Hardwood/ Dry Doug Fir-Oak: Mid/late seral
	White-breasted Nuthatch	Oak woodlands: Mid/late seral

Literature Review

We conducted extensive literature reviews to determine each species' habitat requirements and preferences, movement capabilities, behavioral drivers of movement (if known), and tolerance for moving through unsuitable habitats. Particular attention was given to any natural or anthropogenic features or land cover types which may present a barrier to movement. We restricted our literature sources to include only peer-reviewed publications in scientific journals or conservation and management plans developed by federal or state governments. We focused primarily on research completed within the state of Oregon, although information from surrounding states was utilized when necessary. We prioritized literature published within the last 10 years over older publications. We compiled relevant information and citations for each species corresponding to each landscape feature or characteristic of interest.

Habitat Permeability Modeling

The first step in landscape resistance-based connectivity modeling is construction of a resistance layer, used to represent how easy or difficult the landscape is expected to be for a given species to move through. For our resistance layers, we began by constructing species-specific Habitat Permeability Models (HPMs), using pertinent information compiled from the literature review to assign permeability values to different habitat components using readily available spatial data. Permeability is defined by the habitat component's or landscape feature's influence on species movement, either facilitating or impeding movement. Each component of the HPMs was developed as a raster layer at a resolution of 30 m.

Species Groups

We divided species into 12 groups (Table 2) to better facilitate model building and processing. Groups focused on broad habitat associations with the understanding that species within a given group were likely to share similar component layers, allowing for more efficient data sourcing and organization. Development of models, as well as model review and validation, progressed sequentially through groups.

Table 2: Species Groups

Group/Association	Species common name
Group 1: Mixed conifer-hardwood forests associates	Northern red-legged frog Pacific marten Pacific-slope flycatcher
Group 2: Sage-steppe associates	Pronghorn Greater sage-grouse Columbia spotted frog Western rattlesnake
Group 3: Generalists	Mule deer Black-tailed deer Rocky Mountain elk Roosevelt elk Cougar

Group 4: Oak associates	Lewis's woodpecker Western gray squirrel White-breasted nuthatch Wrentit
Group 5: Open water and riparian associates	American beaver Cascades frog Lazuli bunting Long-toed salamander Snowy plover Western toad Western pond turtle
Group 6: Meadow and grassland associates	Fender's blue butterfly Great gray owl Northern alligator lizard Vesper sparrow Western meadowlark
Group 7: Old-growth associates	Pacific fisher Northern flying squirrel Oregon slender salamander Hoary bat
Group 8: Unique/limited habitat associates	Coastal tailed frog Long-nosed leopard lizard North American porcupine Red-naped sapsucker
Group 9: Alpine associates	American pika Bighorn sheep Mountain goat Sierra Nevada red fox
Group 10: Mixed conifer hardwood associates	Foothill yellow-legged frog Hermit thrush Little brown myotis Pileated woodpecker Western bumble bee
Group 11: Sage-steppe associates	Black-tailed jackrabbit Burrowing owl Ferruginous hawk Morrison's bumble bee Ord's kangaroo rat Pygmy rabbit

Group 12: Early seral associates	Bushy-tailed woodrat Townsend's chipmunk Western purple martin

Dataset parameterization

We parameterized relevant spatial datasets for each species individually by assigning integer permeability values between +3 and -3 to each category (for categorical data) or numerical threshold (for continuous data), identified using information from the literature review. On a biological or behavioral level, positive permeability values represent a landscape feature or habitat component which provides positive value to the species or represents a feature or habitat type that is expected to facilitate species movement. A zero value represents a feature or habitat component which is expected to neither facilitate nor impede species movement. Negative values represent features or habitat components that are expected to impede species movement, with a parameterization of -3 indicating a highly unsuitable habitat feature or area of the landscape expected to be highly resistant to species movement. If a landscape feature or habitat type exists that is considered to be entirely impermeable for a given species, that feature was parameterized using a value of 999 and was treated as an impassable barrier in the connectivity model.

The HPMs developed for OCAMP are not traditional species distribution or habitat suitability models; rather, they illustrate how easy or difficult it will be for a species to move across each 30m cell. HPMs are built specifically for assessing connectivity and thus evaluate the landscape through the lens of species movement. These models are typically less restrictive than species distribution or habitat suitability models, recognizing that species will often move through less suitable or unsuitable habitat in order to access key resources.

While subspecies and subpopulations of species are common among the species selected for OCAMP, and may have minor regional differences in habitat use, in most cases we elected to model habitat permeability for the parent species in the state. However, substantial evidence exists to indicate that different subspecies of elk, deer, and Pacific marten utilize and move through habitats differently within Oregon, enough so to warrant separate HPMs. As a result, we developed HPMs individually for mule deer (*Odocoileus hemionus hemionus*) and black-tailed deer (*O. hemionus columbianus*); for Rocky Mountain elk (*Cervus canadensis nelsoni*) and Roosevelt elk

(*C. canadensis roosevelti*); and for the coastal (*Martes caurina humboldtensis*) and inland (*M. caurina caurina*) subspecies of Pacific marten. Additionally, we found evidence to support the development of individual HPMs representing the Coast Range versus the Cascades populations of Roosevelt elk, due to variation in home range size, movement, and habitat use between these subpopulations.

Guidelines for Permeability Values

3 = Considered optimal component/feature where species movement is expected to be facilitated
2 = Suitable component/feature that may not meet all life history needs, but that is expected to generally facilitate species movement
1 = Component/feature that does not meet species life history needs, but the species might still choose to move through if motivated (during dispersal or migration, when seeking reproductive opportunities, etc.)
0 values= Considered neutral permeability. Expected to neither facilitate nor impede species movement.
-1 = Unsuitable habitat component/feature, expected to impede species movement
-2 = Impediment to species movement is more severe
-3 = Considered highly unsuitable component/feature, severely impeding species movement
999 = Barrier. Species are not expected to be able to inhabit, move through, or cross the habitat or landscape feature.
NODATA (no permeability value applied, not representative of species usage)

Multiple parameters with assigned permeability scores from the literature review are housed within individual data layers (components) that target a group of landscape features. For example, the forest layer may be parameterized using percent canopy cover thresholds or other structural components such as number of understory layers or basal area of trees. For each species we developed and parameterized many component layers pertaining to a variety of landscape features or habitat types, including things like vegetation cover or density, water seasonality, road attributes, infrastructure, topography, non-vegetated gaps in the landscape, and more.

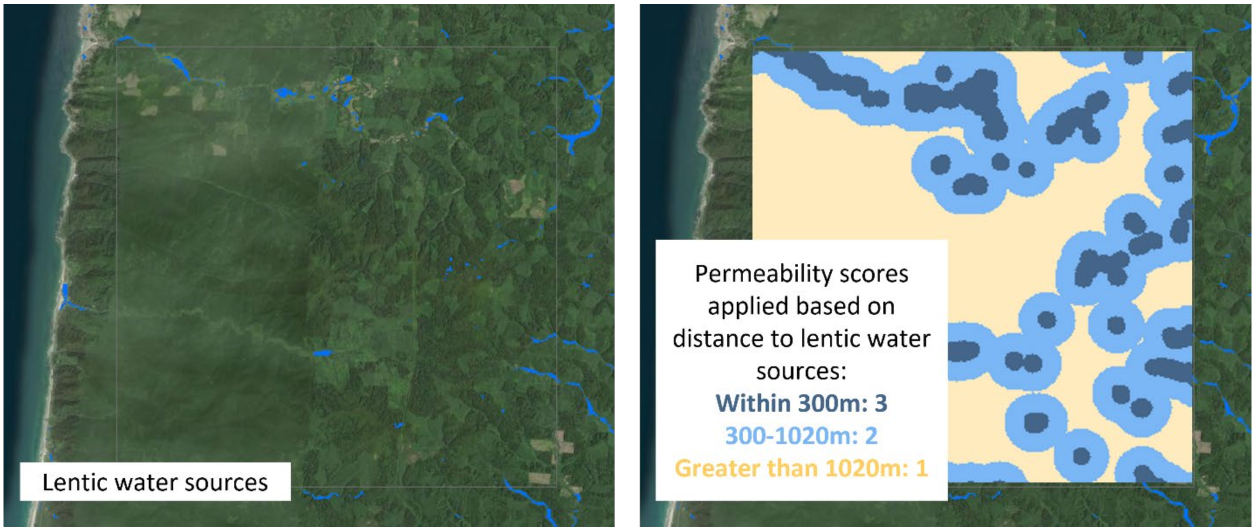
We provide two conceptual examples below. The first illustrates numerical thresholds and parameterization for a forest cover component, represented using percent canopy cover from GNN LEMMA data, for a terrestrial species that is dependent upon dense canopies (Figure 1). The second provides a visual representation of the application of permeability scores to spatial data, applied using distance to lentic water sources for a species closely associated with riparian zones (Figure 2).

Figure 1: Conceptual example of numerical thresholds and parameterization applied to represent permeability of a forest cover component for a terrestrial species that is dependent upon dense canopies.

Forest Cover: Percent Canopy Cover

Threshold	Permeability Value
<10%	999 (barrier)
10-19%	-2
20-29%	-1
30-49%	0 (neutral)
50-59%	1
60-89%	2
>90%	3

Figure 2: Visual representation of the application of permeability scores to spatial data, applied using distance to lentic water sources for a species closely associated with riparian zones. The left-hand map illustrates the locations of lentic water sources on the landscape, in blue. The right-hand map illustrates the application of permeability scores to those areas based on distance from the lentic water source, with distance thresholds identified from published research on the species' habitat use.



Barriers

Barriers are impassable landscape features; the likelihood of an individual attempting to move through an area denoted as a barrier is exceedingly unlikely. The barrier feature is essentially a complete block of movement, either through physical impediment to movement or high likelihood of mortality. Barriers are attributed a 999 in the HPMs and, as a result, prohibit or block the flow of current in the connectivity model. It is possible for many habitat types or landscape features to impede movement. Features that strongly inhibit movement of the species but do not create a complete barrier, or areas considered highly unsuitable habitat, are attributed a low permeability score and impede movement in the model, but do not block it. Barriers are applied conservatively for most species. For example, while building footprints and high traffic roads are both unsuitable habitats, buildings would be treated as a barrier to movement while high traffic roads would be assigned a negative permeability score, impeding rather than blocking species movement. Barriers may be anthropogenic (e.g., buildings, solar facilities), topographic (e.g., slope, elevation), or distance-based metrics (e.g., distance to water for aquatic species).

Model Development/Processing

Map projection/coordinate system

The Oregon Lambert Conformal Conic projection (WKID: 2992) is the standard format for Oregon government data. The North American Datum (NAD 83), measured in feet, is the associated coordinate system. We applied this standard to all OCAMP products including habitat permeability and connectivity models.

Model processing extent

Our goal was to capture each species' full range in Oregon, extending into neighboring states to a) reduce the likelihood that the effects of the artificial limitations of map edges will obscure important linkages (Koen et al. 2010), and b) better understand cross-boundary connectivity in cases where species ranges extend beyond Oregon's borders. We used the State of Oregon boundary buffered by 100 km for the overall model processing extent. For each species, we then clipped models to 125% of the known or estimated species range.

Species range extent

The OCAMP species ranges were created using predictive/modeled maps from ORBIC (updated as recently as 2020 for birds) and GAP species data/USGS CONUS maps (U.S. Geological Survey Gap Analysis Project 2018). These sources represent coarse predicted occupancy of the species by watershed hydrologic unit (HUC). The ORBIC and GAP/CONUS range maps were combined to represent the broadest geographic limits of a species' currently known or predicted presence that can be digitally mapped in Oregon. This range was updated for later drafts of the HPMs, taking into consideration feedback from species experts and species occurrence data to refine range boundaries prior to connectivity modeling.

Other data processing information

The unit area of the data is 98.42 feet/30-meter cells. All processing applied nearest neighbor interpolation so that data sources were transformed or translated to fit uniformly into this format. Additional processing options which helped standardize and produce consistency in the output data layers included setting the projection/extent to the buffered Oregon state boundary, assigning cell alignment, and snapping to the output. Data outputs were stored as either a GRID/TIFF format for intermediate processing or 16-bit TIFF format for sharing products outside of the GIS environment, such as work done for model validation in program R.

Data sources

We utilized a variety of data sources for building the individual component layers of the habitat permeability models; many datasets were relevant to multiple species (Table 3). The habitat permeability model layers, data source tables, GIS parameter tables, and data layer metadata were compiled from the best available, finest resolution, and most recently available information within the last ~10 years.

The criteria we used when selecting data sources are as follows:

1. Information collected or processed within a decade of the OCAMP start date (approximately 2010-2020).
2. Information originating from trusted sources, with good documentation, that is routinely reviewed, updated, and maintained for data accuracy.
3. Relatively good continuous coverage for the species' range within Oregon or with Oregon-specific accuracy assessments/plot validation.
4. Finest resolution available without sacrificing data accuracy or integrity (30-m resolution preferred).
5. Contained coded values that could be used to parameterize information or reclassify codes to meaningful permeability values.
6. Fit within the list of broad features/characteristics pertaining to the species' permeability or movement capabilities.

Table 3: Parameters identified in the literature review process common across project species and the associated metrics used to model habitat features.

Parameter (Feature/Characteristic)	Metric
Proximity to water source- any here or type (below):	Distance, meters
Water- Lentic	Presence, Type/Cowardin Classification (i.e., estuarine or deep water or saline/alkaline etc.), Seasonality, Speed (fast or slow)
Water- Lotic	Presence, Seasonality, Speed (fast or slow), Stream Order
Density of Open Water habitat	Percent, %
Density of Wetland habitat	Percent, %
Importance of Riparian area/woody veg	Presence or proximity to
Forest density any here or type (below)/Cover Percent:	Percent, %, Proximity (meters)
Forest Conifer: Cover or Composition	Percent, %
Forest Deciduous: Cover or Composition	Percent, %
Max canopy gap (trees)	Area, meters, or edge
Importance of shrub layer density/Cover Percent	Percent, % or type
Density of desert scrub/sagebrush habitat	Percent, % or type

Density of grassland habitat	Percent, %, type, and proximity (meters)
Natural disturbance response or adaptation (fire regime/intensity/frequency, thinning, vegetation removal, flooding, drought…)	Presence i.e., Fire perimeter, clearcut
Substrate preferences	Presence, Soil or ground substrate type
Max ground cover gap (with no veg) of type: Bare ground	Area, meters
Max ground cover gap (with no veg) of type: Open Water	Area, meters
Max ground cover gap (with no veg) of type: Developed	Area, meters
Response to agricultural land use	Presence, type i.e., crops
Density of structures (i.e., buildings, airports, fencing, solar facilities, wind turbines)	Percent, %, proximity (meters), or type
Impact of road presence: (Substrate such as: Gravel/dirt, asphalt) (Road types including: Footway/pedestrian/path/trails, Residential/local, Service/arterial, Highway)	Presence, or type
Vehicle speed (mph)	Presence, or type
Road width (number of lanes)	Presence, or type
Impact of traffic volume (AADT): Low (<500) Moderate (500-5,000) High (5,000-10,000) Very High (10,000-35,000) Extreme (>35,000)	Presence, or type

Ability to use existing culverts: (Include information on material if relevant such as: Metal, concrete, and structure type such as: Bridged, box, pipe, and passage conditions such as dry, wet, or both)	Presence, or type
Topography (elevation, slope, Aspect, insolation):	Elevation- meters Slope- % grade Aspect- degrees of circle Solar irradiance/Insolation- % Proximity to Slope (Escape Terrain) - meters
Minimum width of suitable habitat area (i.e., corridor type)	Not used in HPM, Considered for Connectivity output, Distance (metric varies)
Minimum patch size of suitable habitat area (i.e., steppingstone type)	Used for Species Range extent buffer- Area or converted distance (metric varies)
Migratory Movements	Not used in HPM, Considered for Connectivity output, Distance (metric varies)

Data manipulation

A single data source may be used to develop multiple components for the HPMs. Each component layer contained parameterized values based on species-specific movement abilities and habitat use, which was scored as a permeability value (-3 to +3, or 999 barrier, see above). Up to 30 component layers were developed for each species based on the availability of literature and GIS data that matches features/characteristics at the scale required for the project. Any data sources that were not matched to the correct data format of our models may have been converted from shapefile features to a raster grid, converted into density, expanded or buffered in extent, or be subjected to other processing methods in order to parameterize the data correctly. Examples of such transformed data include proximity distances to water, gap sizes of non-vegetated bare ground, and densities of building footprints. If a GIS data source was not available or could not be matched to literature review/species expert information, we denoted the parameter as N/A or Not Available at the time the draft HPM was built.

Additionally, in order to match the literature review parameters to a compatible data resolution and create a uniform combined output of different data sources, some sources required upsampling. Each unit area at 30 meters resolution received a permeability score. For thresholds determined at a scale less than 30 m, we upsampled to 30 m for uniformity in HPM output. For example, the literature review may suggest that canopy gaps over 17 m in size for a given species are preferable and should be given a higher permeability score. In the GIS model, this greater-than-17 m threshold value is translated as greater than 30 m, due to the minimum 30 m resolution of our model building environment. Although this literature-to-GIS conversion process may broaden and potentially over- or under-estimate some areas of permeability for the species, through this process we ensure 1) all input parameters to the draft HPM can be traced to parameters derived from published scientific research and 2) component layers are uniform in resolution and can be combined.

There are instances where limited literature pertaining to Oregon-specific details or lack of spatial data availability within the species range resulted in missing layers for features/characteristics applicable to the species. Any areas without information (NODATA) or no designated permeability value automatically receive a neutral 0 permeability score. In these instances, we have added notes to the species' parameter table to flag for future revision of the HPM if representative data become available.

Model summation and post-processing

After translating the features/characteristics influencing species movement and permeability from the literature review to the GIS parameter tables and constructing and parameterizing each component layer accordingly, we summed across all component layers using a cell statistics operation to obtain a final permeability score for each 30 m cell. For some species, open water, bridges, wildlife crossing structures, and complete barriers to species movement were then "burned into" the draft model, replacing the summed values. This step ensured that the flow of current in the connectivity model would pass as intended through crossing structures or be minimized or halted by barrier features.

This draft HPM was based on our current understanding of species habitat needs and drivers of movement, with parameterization based on species-specific research drawn from published literature and using the best-available spatial data. HPMs represent static landscapes, or a snapshot in time; finer details such as individual trees or small streams may not be represented due to limitations in the data sources and the 30-m resolution of the models, but the draft HPM should illustrate the overall landscape for each species at a regional/statewide scale. Habitat permeability models are not intended to represent connectivity, species movement, or habitat permeability over time. A useful way to interpret HPMs is to think of each HPM as a hypothesized representation of the likelihood of the species being able to pass through or occupy each unit area at any point in time, defined by a permeability score. The connectivity model takes into account both the HPM as the basis for landscape resistance, as well as additional factors such as ease of movement between unit areas at greater movement distances relative to home range size/dispersal abilities. While the HPM illustrates how each individual cell on the landscape is expected to facilitate or impede species movement, the connectivity model illustrates the likelihood of movement across cells and predicted connections across the species' range (see Omniscape methods, below).

Species Expert Review

For the review process, we reached out to a wide variety of professionals in Oregon expected to have familiarity with project species. We began by contacting individuals who helped score candidate species during the species selection process, as well as ODFW staff that work with any of the project species. We then broadened our outreach to encompass biologists, researchers, and practitioners working in Oregon at academic institutions, state and federal agencies, non-profits, and NGOs, and made additional contact through referrals made by colleagues and invited participants. We typically reached out to between four and eight potential reviewers for each species, with the goal of securing participation of a minimum of three experts per species.

We designed a process to solicit feedback on draft HPMs from species experts using web-accessible maps. Once the initial drafts of HPMs were completed for a Species Group, we uploaded maps to ArcGIS Online, hosted through ODFW's Representational State Transfer Service. The ArcGIS Online web application included: a map legend for color gradients and symbols on the map; a layer list to display or hide layers; measuring tools; a tool for uploading additional spatial data; a search engine for locations by address or site name; an access directory of public data layers, such as basemaps and reference layers; bookmarks to save locations of interest; and editing tools to add and revise comments. Reviewers also had access to the parameter tables outlining habitat requirements identified by the literature review, the spatial dataset(s) used to represent each requirement, and how we elected to parameterize each dataset. Additionally, we provided reviewers with a technical/troubleshooting guide, available in both written and audio-video format.

Maps were available for a two- to four-week period, allowing reviewers to view maps and utilize ArcGIS Map Tools to draw polygons and add comments directly on top of the HPMs. We asked reviewers to provide their name and organization and contribute feedback on the species' parameter table (including the values drawn from the literature review, the spatial data layers selected to represent habitat needs, and the parameter values), a symbolized, color-graded map of the draft HPM, a separate layer representing barriers to the species' movement, and the species' draft range boundaries. Reviewers were able to provide attachments, such as links to research articles, species distribution or habitat suitability models, or species occupancy data. We recorded all reviewer comments, including spatially explicit information added directly to the maps, as well as reviewer's comments on the parameter tables. We stored any additional materials provided by reviewers alongside reviewer feedback. In the instances where reviewers shared sensitive information, we stored data according to individual data sharing agreements. When necessary, we followed up with reviewers after the review period to ensure accurate interpretation of their feedback.

We stored all feedback from species experts in geodatabase format as well as in a .csv table in order to easily access, review, and display the information for model revision. We also compiled feedback into a table outlining reviewer comments, as well as any action taken to incorporate comments into changes made to the HPMs. In general, reviewers provided thorough, high-quality comments that aided in improving overall HPMs prior to formal validation. Any changes proposed by reviewers were evaluated by the OCAMP core team prior to incorporation into the HPMs. We addressed all reviewer comments but were selective in how we made changes to the overall models. In some cases, reviewer comments did not align with project goals (e.g., suggestions to incorporate time-series data); in others, suggestions were justified but we lacked appropriate spatial data to address the need.

Following the end of review for each species, once the review period window had closed and we compiled and processed all feedback, we distributed a final email to reviewers thanking them for their participation and summarizing the review feedback we received. We also provided reviewers with information on the changes we made to the HPMs based on reviewer feedback, or, if changes were requested by reviewers but were not made, justification as to why.

In pilot testing project methods with the early species groups, we initially assigned barrier values to many habitat types that were expected to have limited permeability value for the species in question. Following review, with comments indicating species presence was possible within areas designated as strict barriers to movement, we relaxed the strict barrier designation for many of these habitat types and instead applied low permeability values. Due to the model processing workflow and project time constraints, these new lower permeability values were not integrated into the sum of all components but were instead assigned a value at least one integer below the lowest sum value. This removed the barrier to movement but retained high resistance for these areas. Subsequently, these "ranked" high resistance areas were processed differently during validation. In later species groups, we were more conservative with our designation of strict barriers and these high resistance areas were integrated into the overall HPM sum.

As noted above, we created our initial species range maps using the union of ORBIC occupied watersheds and USGS CONUS data. We used this early version of the range map to clip the draft HPMs for the review process. During the review process, we asked reviewers to provide comments on range boundaries and to indicate adjustments or missing portions of the range. We then revised our species range boundaries, adding additional occupied watersheds (HUC 6) based both on reviewer feedback and on the species occurrence dataset compiled for validation. This process was intended to represent the broadest range possible in the state the species has been known to occupy. Both ORBIC occupied watersheds and USGS CONUS data may rely on historic occupancy, and for some species, robust occurrence data across the full range in the state does not exist. As a result, final species range boundaries may over- or under-estimate where the species is likely to occur.

Validation

As noted above, each Habitat Permeability Model serves as the basis for a resistance layer, the primary input for landscape resistance-based connectivity modeling. Having built HPMs based on values translated from published literature, the derived HPMs yield only an indication of potential for habitat use, and as such, remain hypotheses about where we expect species permeability to be facilitated or impeded. Thus, the HPM layer used to inform resistance in our connectivity model needed to be validated to determine if empirical observations of species presence lend support to the hypothesis these models represent. Considering this, we built models linking species presence-only data with each HPM and its component layers. The suitability of these layers can be ascertained by considering both traditional goodness-of-fit statistics as well as out-of-sample predictive metrics obtained from cross-validation. Given that movement data most accurately represents how a species uses and connects the landscape, ideally validation models should be solely based upon these data.

However, telemetry data is costly to acquire and is typically only available at fine temporal scales for larger-bodied animals. Because of this, the validation process must be a long-term and ongoing process, advancing as data become available for species and areas where it is currently lacking.

Data Gathering and Preprocessing

We sourced data from a wide variety of organizations, including state and federal agencies, universities, non-profits, NGOs, consulting firms, private businesses, and community science platforms. We conducted outreach between fall 2019 and summer 2021 to ODFW staff, individuals who had participated in the OCAMP species selection process, wildlife groups (e.g., the Oregon chapter of The Wildlife Society, the Forest Carnivore Working Group, Northwest Partners in Amphibian and Reptile Conservation, etc.), OCAMP listservs, and university natural resource and wildlife programs inquiring about species occurrence data for OCAMP species and encouraging broader distribution of the data request.

Our minimum requirements for presence data were attributes for species, location, and date. Observations were required to be identified to the species level. Coordinates were requested in either WGS84 Lat/Long or Oregon State Lambert, International Feet, although we considered for inclusion any location collected by GPS or through documentation of specific coordinates. We did not accept points collected at coarser precisions (e.g., Township/Range/Section). Observations were required to include at minimum the year in which the species was observed, although year, month, and day were preferable. In addition to these minimum requirements, we also requested additional information, if available, on locational accuracy, the total number of individuals observed, sex, age class, and the methodology used in collecting locations (e.g., targeted survey of a species, incidental observation, camera trap, line transect, etc.). During the data outreach process, we provided files outlining data requirements as well as information on how data might be used. In some cases, we established data sharing agreements with data providers to protect sensitive data.

The principal data sources for most species included ODFW Scientific Take Permit Reports, the BLM Geographic Biotic Observations database, the USFS Natural Resource Manager database, the ORBIC Point Observation Database, iNaturalist, ODFW survey/monitoring data, and, for birds, eBird. All told, we collected 687,532 observation points across the 54 project species, ranging from a minimum of 59 (Morrison’s bumble bee) to a maximum of 95,458 (western meadowlark). However, not all collected data points were used in validation.

Prior to making use of our compiled data, we curated points in order to 1) remove redundancies, including duplicate entries within a single database or points recorded in multiple datasets (for example, a location may have been reported in both a Scientific Take Permit Report and on iNaturalist); 2) remove older data that are likely less reflective of current habitat conditions; and 3) to identify and potentially correct obvious sampling biases. The observations we retained for analysis were recorded no earlier than 1990, fell within the species range, and were not spatiotemporal duplicates with any other observations. In some cases, eBird data were removed from consideration due to obvious spatial misalignment between the location of the observer and the species under observation (see 'Measurement error', below). Once data were filtered, we overlayed all remaining observation points on our HPMs and matched each observation with a habitat permeability score.

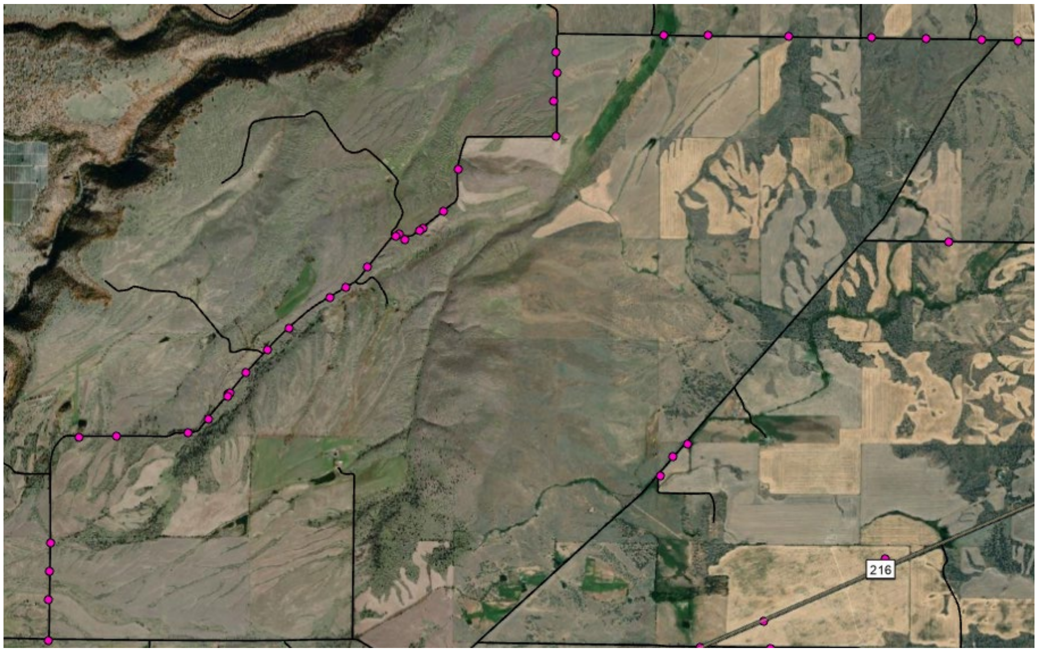
Measurement error

Wildlife occurrence data are often susceptible to measurement error, wherein an animal's physical location is obscured. For observations where individuals are identified visually, recorded near or at the precise location the animal was sighted, and using a GPS unit with high spatial accuracy to obtain coordinates, measurement errors are generally negligible. Some wildlife species, however, can be difficult to locate visually, and/or are observed at a distance. In these cases, measurement error becomes a significant concern because the recorded location, usually the location of the observer, is not reflective of where the animal was actually using the landscape.

Given that our validation process is intended to test the assumption that species are more likely to be located in habitat that has more permeable features, occurrence data with significant measurement error cannot be used, as the recorded locations align not with where the species was using habitat, but where the observer was located. For most species, data have been collected from aerial surveys, motion-detecting cameras, capture-recapture efforts, DNA sampling, or other survey methods for which measurement error is minimized. For birds, however, measurement error is often more prevalent (Simons et al. 2009). Many bird observations are recorded aurally based on distinct calls and songs that, depending on the surrounding vegetation and topography, can be heard from several hundred meters from the bird's true location, or visually using binoculars or spotting scopes at a distance. This can result in misalignment between the recorded location and the habitat the species was actually using.

For many of the bird species selected for the project, the bulk of our occurrence data originated from the community science platform eBird. While eBird data may provide tens of thousands of locations for a given species, often the majority of these observations are recorded along linear features such as roadways (Figure 3), indicating that observations were recorded at the location of the observer rather than the location of the animal. Further, eBird observations do not include any supplemental information on general spatial accuracy, or the direction or distance from which a bird was observed, making it impossible to correct for these measurement errors. We found measurement error to be a significant factor for ten of our 16 bird species (ferruginous hawk, hermit thrush, lazuli bunting, Lewis's woodpecker, Pacific-slope flycatcher, pileated woodpecker, vesper sparrow, western meadowlark, white-breasted nuthatch, and wrentit), and were unable to leverage eBird data for validation of these species' HPMs.

Figure 3: Spatial locations of observations of western meadowlark (*Sturnella neglecta*; magenta points) retrieved from eBird. Note the close association between the observation points and roadways (black lines), indicating spatial misalignment between the recorded observation and the actual location of the animal.



Insufficient occurrence data

We made every attempt to gather adequate occurrence data for each species to permit HPM validation. Unfortunately, for five of our 54 project species, we were unable to source enough data meeting the data standards of the project (i.e., documented with coordinates, species ID, and year, collected after 1990, etc.) to make a robust statistical evaluation of HPM against species presence feasible. These species included two of our three invertebrate pollinators (Fender's blue butterfly and Morrison's bumble bee), one small mammal (Ord's kangaroo rat), and two birds, for which we could not leverage eBird data due to the measurement error described above (Pacific-slope flycatcher, Lewis's woodpecker). As a result, we were unable to identify underperforming component layers for these species, and their respective HPMs were not revised beyond the species expert review process.

Habitat Permeability Model Validation

The primary assumption underlying the HPM validation process is that species are more likely to use locations that have more permeable habitat, which can be interpreted as a positive correlation between the habitat permeability scores and species presence. This provides a clear strategy to validate the suitability of the HPM scores through regression. However, given that most wildlife observation data are presence-only, working with these data brings additional modeling challenges.

Through the validation we aimed to estimate the regression function described by the probability of presence given environmental conditions, which corresponds to

$$P(x) = \frac{f(x|Y=1)P(Y=1)}{f(x)}$$

where Y denotes the random variable that measures species presence (Y=1) or absence (Y=0), x is a vector of variables that characterize environmental conditions, $f(x|Y=1)$ is the density of the environmental variables over the presence sites, and

$$f(x) = f(x|Y=0)P(Y=0) + f(x|Y=1)P(Y=1)$$

is the (marginal) density of the environmental variables x without conditioning on the presence/absence status of the species.

Given that wildlife data are almost exclusively presence-only, only the density for the presence sites $f(x|Y=1)$ can be estimated directly, and additional steps are required to deal with the fact that no absences are available in the data. The typical approach to work with presence-only data involves the use of background samples (also called pseudo-absences), which are usually drawn by randomly choosing locations in the region of interest where the predictors (e.g., environmental features) are known and treating them as absences. Having augmented the dataset with pseudo-absences, one may proceed using standard analysis methods for presence-absence data (Elith et al., 2011).

Using background samples enables approximating $f(x)$. However, because the prevalence of the species in the region (described by $P(Y = 1)$) remains unknown, the number of background samples to be drawn (which depends on $P(Y = 0) = 1 - P(Y = 1)$) may be somewhat arbitrary. As such, results from a model including background samples can only be interpreted on a relative scale.

Background sampling

Given the importance of background samples to validation using presence-only data, care is needed to ensure that samples are drawn far enough from the observed presences to allow the environmental conditions to vary from those found at the presence locations (and enable separation) but not so far that extrapolation becomes excessive. We designed a background sampling domain determined by inner and outer boundaries around each presence location based on average minimum patch size, or, in cases in which information could not be found in the literature on average minimum patch size for a given species, average home range size.

The inner boundary at a particular presence location is a circular buffer around the location with an area equal to the average minimum patch size for the species. The union of all inner boundaries is computed and clipped to the species range. The outer boundary at a particular presence location is a buffer created around each point from the union of all watersheds that intersect a circle with area equal to three times the average minimum patch size for the species. This approach is applied to all project species with the exception of migratory species like deer and elk, which require a larger background domain due to their high mobility during migration. For these species, we calculated the average migratory distance across sexes, and then used an outer boundary of a circle with area $3Q$, where $Q = \pi r^2$ and r is the average migratory distance.

The resulting background sampling domain is the set of watersheds given by the union of all outer boundaries but excluding the union of all inner boundaries. We sampled background points uniformly at random from the background sampling domain, and we drew the same number of background points as the number of presence locations for each species.

Habitat score modeling

After drawing the background samples, we proceeded by using standard analysis methods for binary response data. In fitting these models, we used 10-fold cross-validation, where each fold was assigned approximately the same number of background and presence locations. Each of the approaches we used to validate the HPMs take the binary presence indicator as the response variable and the HPM scores as the sole predictor.

We fitted models using Generalized Additive Models (GAM), MaxEnt, and Random Forests. All of these methods are capable of describing both linear and non-linear relationships between the HPM score and the probability of presence. We took advantage of this feature to determine if the relationship between the HPM score and the presence probability conforms to our hypothesized expectation of a positive relationship between the two. After fitting models through cross-validation, we obtained the out-of-sample predicted probabilities of presence at the locations in each of the 10 folds. This process helps identify concentrations of presence locations with unusually low probabilities, which might warrant further exploration. The idea behind this strategy is to use these “hotspots” of low habitat scores to attempt to identify relevant environmental conditions absent from the habitat permeability scores.

Component analysis

We utilized a second type of analysis for validation of the HPMs to evaluate and make adjustments to the individual component layers used in determining the overall the HPM scores. We expect each of the individual component scores to be positively correlated with the probability of presence. We first extracted the values for each of the components at every presence and background location. We only included components that take on two or more values at the locations included in the analysis (e.g., if no presences or background samples occur on roads, the “roads” score is 0 at all locations, thus the “roads” component is not included. This does not indicate that the component itself is not useful, but rather that we cannot validate it). We then transformed component scores into ordered categorical predictors and included these predictors in a binary regression model, with the presence-(pseudo)absence indicator as the response. Including the components as ordered categorical predictors enables us to evaluate 1) if the relationship between each component and the probability of presence is monotonic and positive, and 2) if the magnitudes of the different values used for the component score are appropriate for producing linear relationships with probability of presence.

In this regression model, a well-behaved component is expected to have a positive trend in regression coefficients when the coefficients are ordered according to the component parameters. If the component suitably discriminates the different levels of the environmental feature, separation should occur between the coefficients of varying levels within the same component (e.g., the coefficient for level "1" should be significantly greater than the coefficient for "0").

After fitting the model for a given species, we identified underperforming components as candidates for recategorization. For these components we extracted, for all locations considered, the raw values used in the construction of the component scores, which are typically continuous. The idea of this step is to identify the relationship between the underlying (continuous) raw variable (that the component represents) and the probability of presence, given the presence information available. With this in mind, we replaced the ordered categorical variables used to represent the problematic components in the initial model by a smooth of the raw version of the component and fit the model again using a GAM. Using a GAM enables us to estimate the empirical functional relationship between the raw component and the probability of presence, which can then be used to reevaluate how to assign permeability scores for the component.

For a particular underperforming component, we assigned permeability values similar in magnitude to those in the original parameterization but used the functional relationship between the raw variable and probabilities of presence estimated from the model to determine new parameter thresholds. This process yielded suggested recategorization for the component, which was then evaluated in the context of the species biology and information obtained from the literature review and species experts prior to being incorporated into the final HPM.

Omniscape Modeling

Our analyses utilized landscape resistance-based connectivity modeling using Omniscape (McRae et al. 2016; Landau et al. 2021). Omniscape is an algorithm that utilizes circuit theory applied in a wall-to-wall framework to model habitat connectivity across a landscape. Landscapes are treated as resistance surfaces and the flow of electrical current across these resistance surfaces acts as a proxy for probable paths of animal movement. Highly resistant areas, such urban centers, will impede the flow of current, whereas less resistant areas, such as intact habitat, will facilitate current flow.

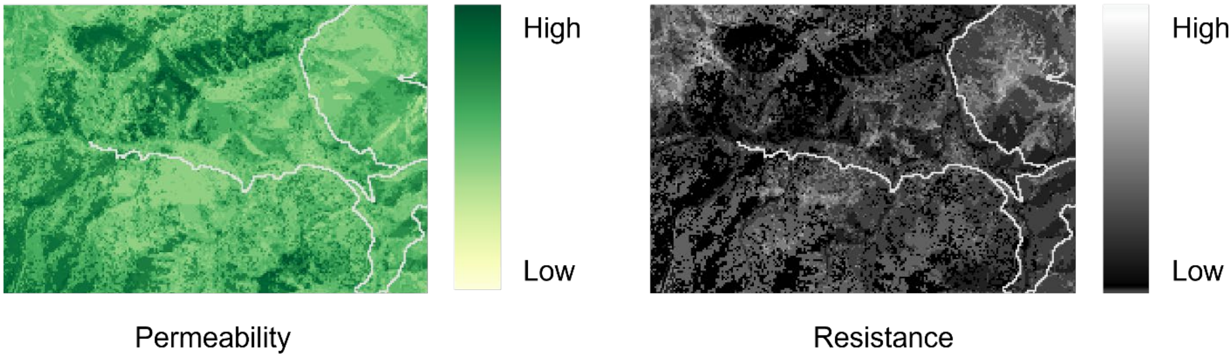
Using Omniscape to evaluate connectivity provides four primary benefits over alternative approaches. First, Omniscape does not rely on definition of core habitat patches; instead, connectivity is assessed continuously across the landscape. This is important because selection of core habitat patches, including location of core areas, shape, and minimum size requirements, strongly influence connectivity modeling results (Baldwin et al. 2010, Perkl et al. 2016). Without a complete understanding of the effects of patch selection within a study area, any given set of core areas may lead to erroneous conclusions about connectivity that translate into negative consequences for subsequent management. Second, the current flow approach of Omniscape simultaneously evaluates the contribution of multiple movement pathways, rather than identifying a single path. Representation of connectivity as a gradient more accurately represents natural systems—movement patterns found in nature are rarely restricted to single, discrete corridors, and sub-optimal paths likely still serve as functional connections for wildlife. Third, current flow models highlight areas of broadly connected natural lands where animal movement is unlikely to be impeded by barriers or otherwise constrained. These areas of diffuse flow are difficult to identify using other methods and maintaining areas of diffuse flow might be one of the most cost-efficient ways to maintain landscape function (McRae et al. 2016). Finally, one of the distinct advantages of current flow models such as Omniscape is the ability to easily identify "pinch points" where movement is restricted by landscape features, which can help prioritize areas for conservation, mitigation, or restoration investment.

The Omniscape algorithm models connectivity by assessing the flow of current across the landscape based on resistance to movement. Since Omniscape does not rely on the definition of core habitat patches, each cell on the landscape is assessed independently. Omniscape is parameterized using: 1) a resistance layer, describing resistance to movement for the species; 2) a source weight layer, identifying areas of suitable habitat for the species (from which movement is likely to originate); and 3) a moving window size, which can be based on biologically relevant parameters such as home range size or dispersal capabilities. The algorithm passes a moving window throughout the study area (in this case, a given species' range within the state of Oregon and adjacent lands in neighboring states) centered on a single cell and determines first if that cell represents habitat for the species. If the cell is identified as habitat, the model uses that cell as a "ground". It then "injects" a current into all habitat cells (sources) within the radius of the moving window, with source cells that represent better habitat receiving stronger current. The injected current flows toward the target ground cell, moving around barriers identified in the resistance layer. The model then moves the window one cell and repeats the process; if the target cell is not habitat, the model moves on to the next cell and no data are recorded. Each model run is ultimately summed to create a cumulative current flow model that highlights the areas of the landscape that are more or less likely to facilitate species movement.

Resistance raster

The peer reviewed, validated HPMs serve as the foundation for resistance rasters for each species. The habitat permeability score for each cell in the model, calculated by summing the permeability values attributed to each habitat component as described above, vary greatly between species but typically range between -5 (the lowest values representing the most unsuitable habitat expected to greatly impede species movement) and 30 (the highest values representing ideal habitat that is expected to facilitate species movement). To convert these HPMs to resistance layers for use in Omniscape, we reclassified absolute barriers (attributed a 999 in the HPMs) to NODATA values and linearly rescaled, from 1 to 100, all other values. Since Omniscape reads resistance rather than permeability, values are inverted during rescaling. High permeability scores result in low resistance values, whereas low permeability scores result in high resistance (Figure 4).

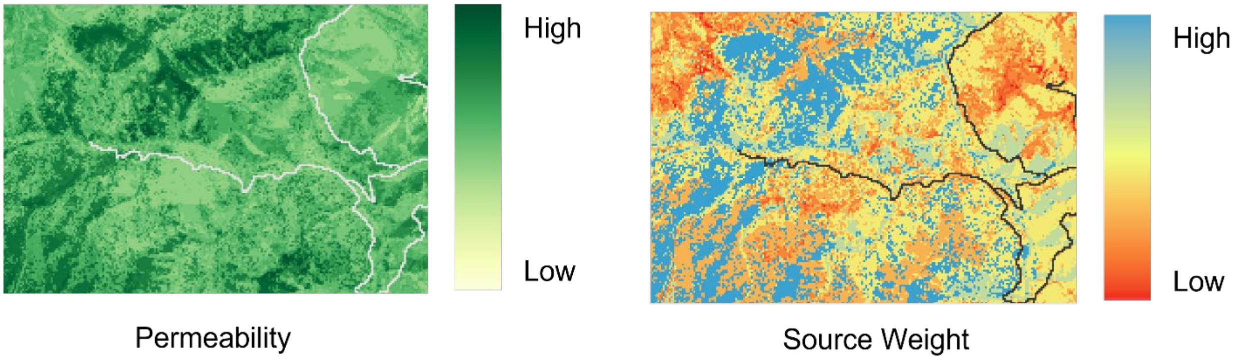
Figure 4: The relationship between the habitat permeability model (left) and the resistance layer developed for use in Omniscape (right). Areas of high permeability have low resistance, and vice versa.



Source raster

Source rasters used in Omniscape were also based on species HPMs (Figure 5). The source raster provides Omniscape with relative weighting that determines how much current will originate from each cell. Barriers (NODATA values in the connectivity model) are not considered sources–these are habitats or landscape features expected to block species movement from which individuals will not originate and to which individuals will not travel. Areas with negative permeability in the HPM, impeding species movement, are also not attributed a source weight. These are highly unsuitable habitats or areas of the landscape expected to deter species movement and are assigned a source value of 0; current will not originate from or flow to these areas as a source or ground, but current may pass through these areas based on their resistance value in the resistance layer. For the remaining (permeable) cells, we calculated source weights from the rescaled resistance values to equal 1/resistance. If an area is highly permeable, it will have low resistance (e.g., value = 1), and high source weight (e.g., value = 1). If an area is not very permeable, it will have a high resistance (e.g., value = 100), and low source weight (e.g., value = 0.01).

Figure 5: The relationship between the habitat permeability model (left) and the source weight layer (right). Higher permeability areas are assigned higher source weights.



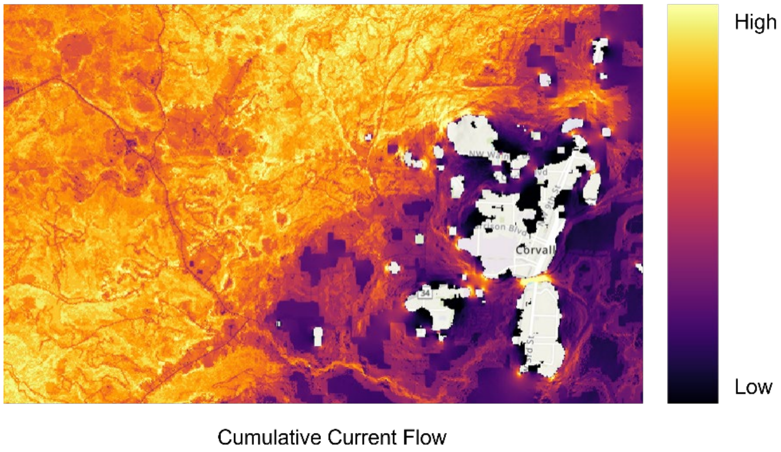
Moving window size

We assigned moving window size values to each species individually, based on the scale of species movement. For our moving windows we chose a value equal to 125% of average approximate minimum patch size for each species. If information on minimum patch size was not available, we used 125% of average approximate home range size.

Omniscape output

Three different output types can be produced by Omniscape: cumulative current flow, regional flow potential, and normalized cumulative current flow. Cumulative current flow is the default output and represents the sum of all current that flowed through each cell across all moving windows (Figure 6). Cells with the highest cumulative current flow repeatedly received more current than cells with lower cumulative current values.

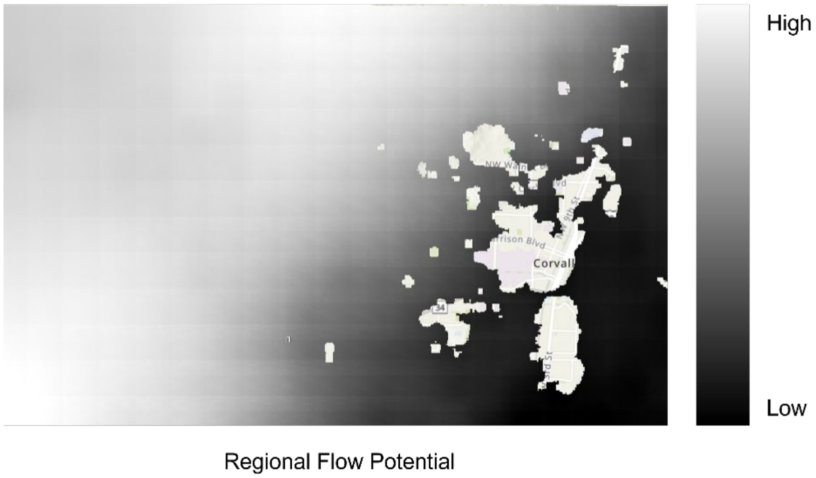
Figure 6: An example of cumulative current flow model output. Brighter areas represent locations that received high current flow across all moving windows; darker areas received less current flow. Areas that did not receive any current flow are barriers to species movement. In this case, dense urban development associated with the city of Corvallis blocked current flow for this species.



The flow through any given area depends on both the amount of suitable habitat to connect within the moving window as well as the configuration of permeable habitat between those suitable habitat areas. Areas of higher current flow represent locations of higher expected use, which could indicate higher quality, more permeable habitat, or could be a result of bottlenecking forcing current through a restricted pathway due to natural or artificial barriers. Low levels of flow may not necessarily indicate unsuitable habitat, as low current density can arise not only from impermeable habitat, but also from the diffuse spread of current across large areas of permeable habitat.

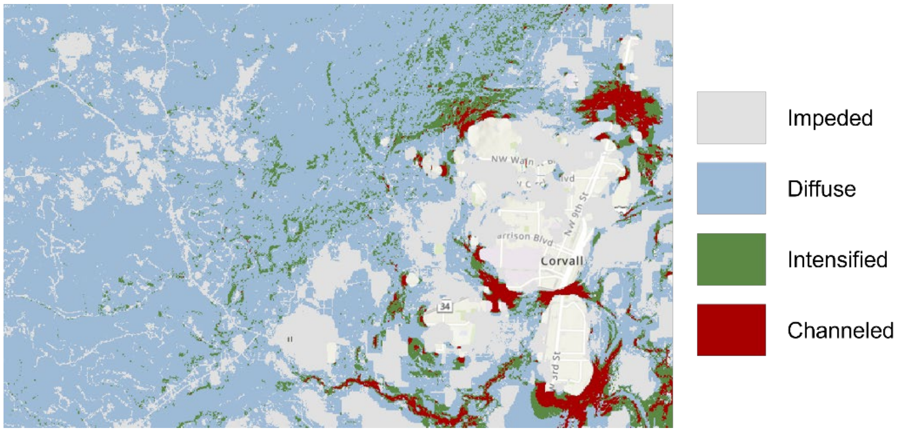
To help distinguish between areas of high-quality habitat and bottlenecks, and between areas of diffuse movement and poor-quality habitat, Omniscape can produce two additional connectivity models. The first is a model of regional flow potential, which illustrates, given the amount of suitable habitat to connect within the moving window and the configuration of permeable areas that link those suitable habitat areas, how much flow would be expected in the absence of barriers (Figure 7).

Figure 7: An example of regional flow potential model output. Brighter areas represent areas where we would expect more species movement if all resistance to movement was removed.



The second model output to help distinguish between areas of high-quality habitat and bottlenecks, and between areas of diffuse movement and poor-quality habitat, is normalized cumulative current, which compares cumulative current flow to regional flow potential, illustrating the degree to which a cell has more or less current than expected in the absence of any resistance to movement (Figure 8). Normalized cumulative current can help identify where barriers and resistance to movement are most impacting current flow on the landscape, as well as highlight large areas of diffuse movement. Normalized cumulative current must be interpreted in the context of the landscape in question, but a general rule of thumb is that values around 1 are areas where the cumulative current density is roughly equal to regional flow potential, indicating diffuse movement not impeded by barriers. Values above 1 indicate that flow is more channelized, highlighting bottlenecks or pinch points in current flow—pathways that may be important in connecting otherwise fragmented habitat. Values below 1 indicate flow is restricted, illustrating areas with poor or limited habitat for the species in question that are generally not conducive for movement.

Figure 8: An example of normalized cumulative current model output. Areas where cumulative current density is roughly equal to regional flow potential indicate areas of diffuse movement, represented in blue. Grey areas are those where current flow is lower than expected given regional flow potential, indicating that barriers to movement are disrupting current flow. Green and red areas are those where current flow is higher than expected given regional flow potential, indicating intensification and channelization of current.



The three individual Omniscape outputs provide information on expected species movement, but interpretation can be difficult without considering all outputs together. For example, the highest current flow areas from the cumulative current flow model might represent high-quality habitat with high value for facilitating movement but could also instead represent an area of channeled flow where anthropogenic or natural barriers constrict species movement through a bottleneck. Similarly, an area of intermediate current flow in the cumulative current flow model might represent habitat of mediocre quality that is expected to be infrequently used, but could also instead represent a broad, intact area of high-quality habitat where a lack of human or natural barriers allows diffuse species movement across the landscape. In planning for conservation of habitat to facilitate wildlife movement, we must consider a range of needs—areas with channeled flow may be primary targets for protection, given that any land use change occurring within a bottleneck might sever the connection for wildlife entirely, but we do not want to discount the importance of areas of diffuse movement, as protecting broad, intact areas free of barriers may be one of the most cost-effective ways to maintain wildlife connectivity (McRae et al. 2016).

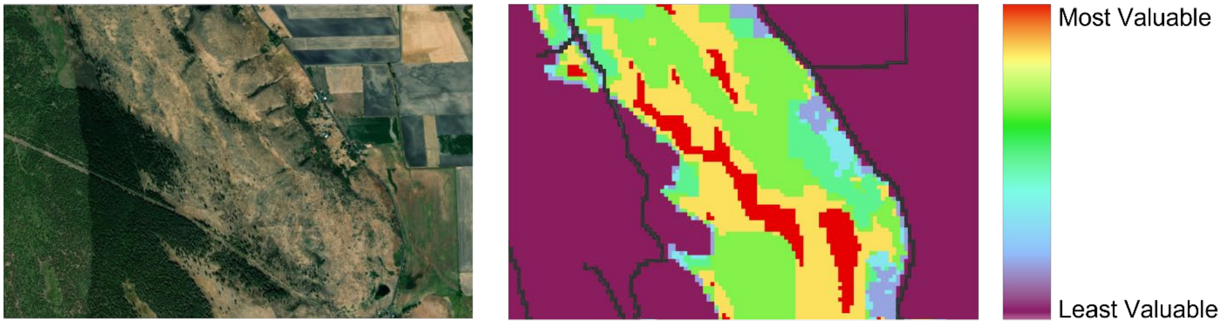
Prioritization

While the connectivity models produced by Omniscape provide information on current density and flow for each species, the ultimate goal of OCAMP was to identify the parts of the landscape that have the highest overall value for facilitating movement across all project species. We used spatial conservation prioritization (SCP) as a quantitative approach to identify priority areas for each species, with consideration of both high current flow and diffuse current flow areas as described above. Spatial conservation prioritization is a subset of systematic conservation planning. Fundamentally, SCP is a quantitative assessment of conservation value/potential, originally developed for reserve network design (Wilson et al. 2009). This approach translates well for OCAMP since the desired outcome is a network of priority movement areas across Oregon, similar to a network of conservation reserves. There are a number of decision-support software packages that have been developed to facilitate SCP, including Marxan, C-Plan, ConsNet, Conefor, and Zonation. We elected to use Zonation in our work as it: 1) produces a priority ranking for the landscape instead of a target-based solution (Moilanen et al. 2005; Lehtomäki and Moilanen 2013), 2) includes a number of approaches for maintaining connectedness among high-priority areas (Lehtomäki et al. 2009; Moilanen et al. 2014; Pouzols and Moilanen 2014) and 3) has already been applied to identify conservation priorities using input from omnidirectional circuit theory models (Linnell and Lesmeister 2019), similar to the output from Omniscape.

Zonation works by iteratively removing cells from the landscape, one-by-one, using minimization of marginal loss as the criterion to decide which cell is removed next (Moilanen et al. 2005). The core Zonation algorithm operates starting from the assumption that protecting the whole landscape would be best for conservation. Then, the algorithm successively discards the cell that leads to the smallest loss in conservation value aggregated across all inputs, thereby maximizing what remains. A balance between inputs is maintained by successive range-size normalization, i.e., the remaining fractions of the distributions of inputs occurring in the remaining cells are updated iteratively as cells are removed from the landscape. The algorithm is typically prioritized with input data such as species occurrence and habitat quality, but the approach can be extended to prioritize any feature of interest. In our case, the inputs are the connectivity models produced using Omniscape.

During iterative ranking, the first cells to be removed (lower rank values) include areas of the lowest current flow (e.g., developed areas and other unsuitable habitat; Figure 9). Then, iterative cell removal gradually “eats away” the entire landscape, with the last cells remaining having highest aggregate richness and rarity. The order of cell removal is retained, which produces a hierarchical and easily visualized prioritization from which it is possible to identify any desired top or bottom fraction of the landscape.

Figure 9: Example prioritization model output (right) when compared with the underlying satellite imagery of the habitat on the landscape (left) for a species that relies on open shrub-steppe for movement. For this species, agricultural areas and areas of dense tree cover had the lowest current flow, and were thus removed from the model first, retaining the open habitats as the most valuable to species movement.



Satellite Imagery

Prioritization

We developed four separate prioritization models for each species. The first, Protection, focused on identifying the top fraction of the landscape to target for protection of connectivity. The second, Maintenance, focused on the top fraction of the landscape with broader areas of intact habitat that facilitate diffuse movement. The third, Restoration Potential, focused on areas of the landscape where connectivity might be improved following habitat modifications. The final, Transportation Mitigation, focused on the barrier effect of major roadways in the state and locations where wildlife crossing structures might be most beneficial to maintaining or reestablishing connectivity. All prioritization models employed Core Area Zonation as the method of cell removal and implemented a boundary length penalty to induce cell aggregation and help maintain connectedness among higher-priority areas. Additionally, we used an analysis area mask in Protection and Maintenance models to exclude from consideration buildings, parking lots, roadways, lava, and built solar facilities.

Protection:

Areas of the landscape to protect should include both high-quality habitat for facilitating movement as well as areas where movement is intensified or channeled. Areas of channeled connectivity represent bottlenecks in movement where connectivity could be severed if habitat loss occurs. Prioritization models for each species targeting areas for protection leveraged the cumulative current density connectivity models, identifying high-quality habitat, as well as the normalized cumulative current density connectivity models, which place a greater emphasis on areas of diffuse and channelized current flow.

Maintenance:

Areas of the landscape to maintain wildlife connectivity should target broadly connected natural lands where animal movement is unlikely to be impeded by barriers or otherwise constrained. These larger contiguous areas of suitable habitat facilitate diffuse current flow—animal movement can generally occur freely throughout. For each species, we clipped the model boundaries to only those areas where cumulative current density was roughly equal to regional flow potential, indicating diffuse flow. We then ran the prioritization model using the cumulative current density model within these diffuse flow areas.

Restoration Potential:

In some areas, connectivity is impeded but could be improved if habitat restoration occurred. We identified locations for potential restoration by clipping model boundaries to areas with low cumulative current density but high regional flow potential, indicating flow is impeded by barriers or unsuitable habitat. We ran prioritization models using the cumulative current density models bounded within these low density/high potential areas.

Transportation Mitigation:

We ran a transportation-specific prioritization model for each species to identify locations where current would most likely flow across roadways if the barrier effect of the road was removed (de Rivera et al. 2022). To do so, we clipped each species' cumulative current density connectivity model to a 1 km buffer around all major roads in Oregon. We then removed the roadways, leaving a gap in the model, and interpolated across this gap using a moving window. The moving window fills in the area formerly occupied by the roadway by averaging across values on either side of the road. Prioritization proceeded using the cumulative current density values inside the buffered road corridor combined with these interpolated values.

Selection of Priority Wildlife Connectivity Areas

Priority Wildlife Connectivity Areas (PWCAs) are intended to represent the parts of the landscape that have the highest overall value for facilitating wildlife movement, across all species. Model output from the Zonation runs described above provide a hierarchical ranking of landscape value for protecting and maintaining connectivity for each species. As each project species was selected to represent a wide diversity of habitat associations and structural habitat characteristics, life history strategies, movement capabilities, and sensitivity to anthropogenic threats, combining priorities across all species should provide a comprehensive foundation of connectivity need for the state's wildlife.

The primary focus of Priority Wildlife Connectivity Areas is to direct conservation action to areas of the state that will have the greatest impact on wildlife connectivity. To this end, we began by extracting and combining top fractions of priority areas identified by the prioritization models targeting protection of connectivity for each species. We tested thresholds beginning at the top 15% of priority areas up to the top 0.5%. At thresholds of 2% or greater, combined species' priorities encompassed the majority of the state. Ultimately, we elected to focus on the top 1% of priority areas for each species.

While the boundary length penalty imposed by the prioritization modeling and overlap across species resulted in many aggregated groups of cells up to several hundreds of thousands of acres in size, in some locations the priority areas were small and isolated. We removed all priority areas of fewer than 250 acres in size outside of urban growth boundaries; we retained small patches within urban growth boundaries to allow for identification of smaller areas of remnant, intact habitat within cities.

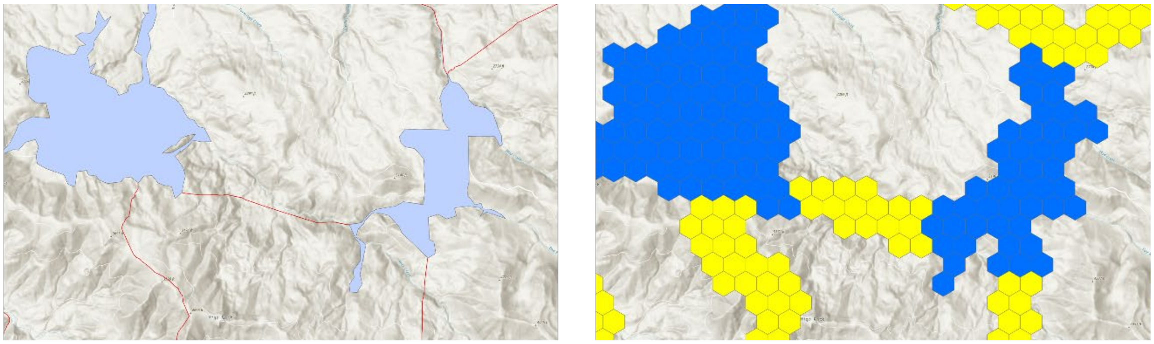
The remaining priority areas represented the top fraction of the landscape for protecting wildlife connectivity across all project species, but many of these areas were discontinuous. Although these habitat regions represent the parts of the landscape with the highest overall value for facilitating wildlife movement, without connections between regions, any development or land use change occurring around the periphery of a region risks a loss of functional connectivity if the region becomes isolated from its neighbors. To correct for this and create an interconnected network of priority areas, we executed a cost-connectivity network analysis to join each region to its neighbors, with optimal paths identified by least cost-distance.

We developed a cost surface favoring 1) the top 1% of priority areas fewer than 250 acres in size, 2) additional high priority areas for protecting wildlife connectivity (i.e., the top 2% of areas had a lower cost of movement than the top 3%, which had a lower cost of movement than the top 4%, etc.), and 3) high priority areas representing the top 2%, 5%, and 10% of the landscape identified by the prioritization models for maintenance of connectivity for each species. Additionally, we favored climate refugia (Michalak et al. 2018) and riparian corridors along waterways with a 70% or greater probability of streamflow permanence (Jaeger et al. 2018), as well as known mule deer migration corridors (ODFW, unpublished data).

After identifying optimal connections between all regions, we selected our final Priority Wildlife Connectivity Areas using a grid of 40-acre hexagons. While the underlying priorities are in raster format, the final dataset must be polygon data, to allow for naming, interfacing with other spatial data, inclusion of attributes, and selecting and export of subsets of the data. The use of hexagons reduces the sometimes-significant artefacts encountered when translating raster data to polygons and provides a consistent, minimum patch size and linkage width for PWCAs across the state. Additionally, the use of hexagons helps obscure potentially sensitive data encountered at smaller spatial scales and aligns with the format of other spatial products developed by ODFW, such as Conservation Opportunity Areas. We used 40-acre hexagons to balance connectivity needs across multiple spatial scales; at the statewide scale, groups of hexagons easily represent larger contiguous priority areas, whereas at the local scale, 40 acres represents a minimum functional patch size for habitat in fragmented areas (Hennings and Soll 2010).

To create the Priority Wildlife Connectivity Areas, we selected all hexagons in which priority regions occupied 10% or more of the area of the hexagon. We buffered optimal connections by 250 m and selected all hexagons intersecting these buffered connections (Figure 10).

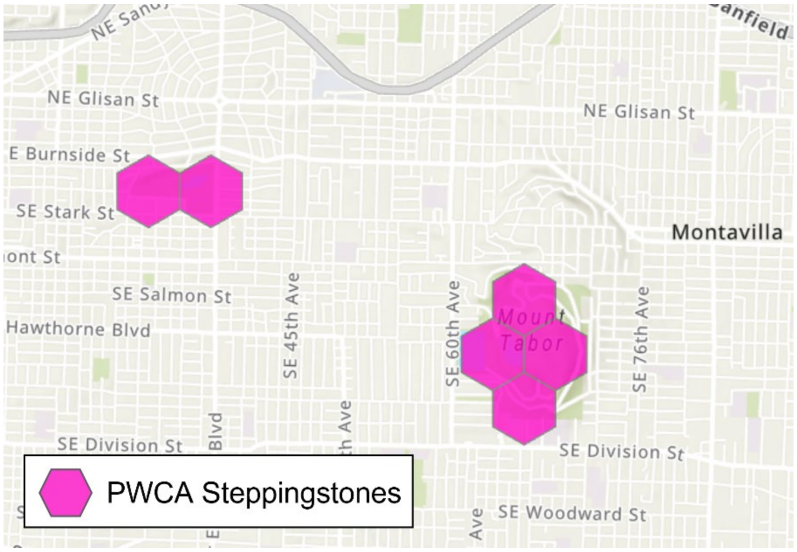
Figure 10: Relationship between the priority regions and optimal connections (left) and the final Priority Wildlife Connectivity Areas (right).



Priority regions (blue) and optimal connections (red)   Final PWCA Regions (blue) and Connectors (yellow)

We also added individual or small groups of isolated hexagons in developed areas, selecting all hexagons overlapping smaller priority areas occupying at least 20% of the area of the hexagon within urban growth boundaries. Urban areas often do not have enough sufficient habitat to support a fully connected priority area. While these individual or small groups of hexagons are not linked to the network, remnant areas of intact habitat within otherwise developed landscapes still serve to facilitate wildlife movement through cities and are included as “steppingstones” of priority habitat (Figure 11).

Figure 11: Example of steppingstone PWCAs within a highly developed area. These small, isolated groups of hexagons highlight remnant areas of intact habitat that might aid wildlife in navigating cities.



We further refined Priority Wildlife Connectivity areas by:

- Filling in gaps of two or fewer hexagons within Regions
- Removing hexagons overlapping known airports, rail yards, landfills, feedlots, large industrial complexes, lumber mills, quarries, mines, and solar developments
- Removing hexagons overlapping known areas of recent change (e.g., new residential developments not reflected in the spatial data used during the modeling process)
- Ensuring, where intersection occurred, priority areas captured the entire periphery, but not the center, of large water bodies
- Reducing the width of connections within developed areas in instances where the underlying habitat was not likely to support wildlife movement

- Removing hexagons overlapping GAP Status 1 lands

GAP Status 1 lands, which include Designated Wilderness Areas and Crater Lake National Park, are under the highest level of protection possible in Oregon. Given that these areas are already protected, we include only the locations where Priority Wildlife Connectivity Areas enter or exit these sites.

The final Priority Wildlife Connectivity Area network occupies 25% of the state's area. A total of 53% of Priority Wildlife Connectivity Areas fall within lands managed by state or federal agencies. The remaining 47% of PWCAs fall within tribal lands, private lands, and industrial lands, as well as lands managed by cities, counties, universities, and other entities.

PWCA Attributes

Naming Conventions

There are three different types of PWCAs identified in the network: **Regions**, **Connectors**, and **Steppingstones**.

Regions were delineated from the combined top 1% of priorities across all 54 surrogate species, as described above. Regions are large, contiguous areas and represent the highest-value habitat for facilitating species movement throughout the state.

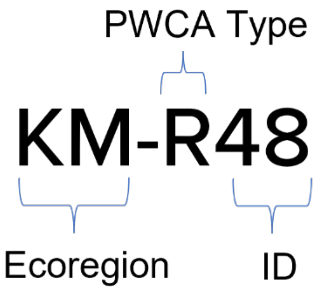
Connectors follow the optimal pathways between Regions. Connectors represent the best available habitat for facilitating movement from Region to Region. Connectors may pass through high-quality habitat in intact, relatively undisturbed parts of the landscape, as well as the best remaining marginal habitat in developed or degraded areas.

Steppingstones are individual or small groups of isolated hexagons within urban growth boundaries. Steppingstones represent remnant areas of intact habitat within otherwise developed landscapes that may help facilitate wildlife movement through urban areas.

Each PWCA has a unique name referencing its general location in the state (by ecoregion), the PWCA type, and a numeric identifier (Figure 12). Ecoregions include the Coast Range (CR), Willamette Valley (WV), Klamath Mountains (KM), West

Cascades (WC), East Cascades (EC), Columbia Plateau (CP), Blue Mountains (BM), and Northern Basin and Range (NBR). PWCAs that straddle or cross two ecoregions are named based on both (e.g., CR/WV). The three types of PWCAs include Regions (R), Connectors (C), and Steppingstones (S).

Figure 12: Each PWCA is named by its location within a given ecoregion, PWCA type, and numeric ID, as diagramed here for Klamath Mountains Region 48.



The hexagons within each PWCA contain additional information. Each individual hexagon has a unique name, which includes the PWCA name and is followed by a numeric identifier for that hexagon (e.g., KM-R48-H1 refers to hexagon 1 within Klamath Mountains Region 48). Hexagons also contain information on the general entity (or entities) responsible for managing the land within the hexagon, as well as recommendations for specific types of conservation action.

Land Management

We added attributes to each hexagon identifying general categories of ownership/management of lands within the hexagon. We began with a spatial dataset listing fee land title and land manager of lands located in Oregon and categorized parcels into general land management classes: Federal: USFS, Federal: BLM, Federal: USFWS, Federal: Other, State, City/County, Tribal, Private, or Other. The 'Private' class includes both private and private industrial lands. The class for 'Other' is comprised predominately of water, in addition to lands in neighboring states. We then intersected these categorized parcels with the PWCAs and calculated the percent area of each management class within each hexagon. We sorted and ranked land management classes within each hexagon to identify the predominant entity or entities responsible for managing lands within each hexagon. We identified both the majority land manager and secondary land manager for each 40-acre unit. For most of the PWCA network, land within each hexagon is managed by a single entity. In situations where land within a given hexagon is owned/managed by more than two entities, we include only the majority and secondary land managers.

Conservation Action Recommendations

Each 40-acre hexagon in the PWCA network has been attributed with both a Primary and Secondary Conservation Action Recommendation. These descriptors are intended to assist the user in determining what actions are needed within a given area to most benefit wildlife movement and conservation of wildlife connectivity in Oregon. Attributes for Conservation Action Recommendation were assigned using the underlying prioritization model data and, in some cases, additional spatial data layers. There are four categories for Conservation Action Recommendation: Protect, Restore, Transportation Mitigation, and Enhance/Maintain.

Areas attributed as 'Protect' were identified from the underlying modeling data, derived from the results of the prioritization models targeting areas for protection (see above). Any hexagons overlapping priority areas for protection as identified by the prioritization modeling were attributed with a Conservation Action Recommendation of 'Protect'. 'Protect' was typically assigned as the Primary Conservation Action Recommendation, with two exceptions. If we identified a need for transportation mitigation, or if greater than 50% of the area of the hexagon overlapped with habitat in need of restoration, then 'Protect' was assigned as the secondary, rather than primary, recommendation.

Restoration needs were identified using two approaches. First, we assessed overlap between hexagons and a disturbed lands dataset indicating areas of development, agriculture, and invasive vegetation. In priority areas for protection, hexagons where 50% or greater of the area of the hexagon overlapped with these disturbed lands were assigned a Primary Conservation Action Recommendation of 'Restore' and a secondary recommendation of 'Protect'. Outside of priority areas for protection, hexagons were assigned a Primary Conservation Action of 'Restore' when 25% or greater of the area of the hexagon overlapped with disturbed lands, and a secondary recommendation of 'Restore' when overlap was less than 25%. In addition to overlap with disturbed lands, we identified additional areas in need of restoration from the underlying modeling data, derived from the results of the prioritization models assessing restoration potential. We identified areas where multiple overlapping species had high restoration potential (high flow potential but low current flow, see above) and also attributed these hexagons with a primary recommendation of 'Restore'.

Areas in need of Transportation Mitigation were identified using two datasets: the transportation-specific prioritization models and information on roadkill collected by the Oregon Department of Transportation (ODOT). The transportation-specific prioritization models identified areas connectivity would be most improved if the barrier effect of the roadway was removed. We assessed potential for connectivity improvement by extracting the top 10% of priority areas from the transportation-specific models and identifying locations where multiple species' priorities overlapped. We then classified roadways segments based on the number of overlapping priorities, with classes for high overlap, intermediate overlap, and low/no overlap. The ODOT roadkill database identifies milepost locations associated with the carcasses of large-bodied wildlife (primarily deer and elk) removed from the highway following wildlife-vehicle collisions. We calculated the density of carcasses per mile and classified roadways into high-, intermediate-, and low-density sections.

To assign attributes to hexagons for transportation mitigation, we established thresholds for both potential for connectivity improvement and density of recorded collisions with large-bodied wildlife. Areas where PWCAs intersected with roadways and had high overlap with species priorities and/or high densities of recorded wildlife-vehicle collisions were assigned 'Transportation Mitigation' as the Primary Conservation Action Recommendation. Areas of intersection with intermediate overlap with species priorities and/or intermediate densities of recorded wildlife-vehicle collisions were assigned 'Transportation Mitigation' as the secondary recommendation.

Hexagons attributed as 'Enhance/Maintain' were identified based on underlying modeling data, derived from the results of the prioritization models targeting areas for maintenance. 'Enhance/Maintain' was also assigned in the absence of any other information. Priorities for 'Protect' and 'Transportation Mitigation' took precedence over 'Enhance/Maintain'. In situations where hexagons overlapped with both maintenance and restoration priorities, 'Enhance/Maintain' was assigned as the primary recommendation only when less than 25% of the area of the hexagon was comprised of disturbed lands.

Application

Interpreting and Using the Analysis

The Priority Wildlife Connectivity Areas identified by OCAMP represent the areas of the landscape with the highest overall value for facilitating wildlife movement. Focused investments in areas falling within PWCAs can increase the likelihood of long-term maintenance of wildlife connectivity in Oregon, maximize effectiveness over larger landscapes, improve funding efficiency, and promote cooperative efforts across ownership boundaries. The network of PWCAs serves as a science-based tool that can be used as a resource, in conjunction with other sources of information, to support habitat enhancement, restoration, and protection, transportation mitigation, and conservation planning efforts, as well as future research and monitoring. Priority Wildlife Connectivity Areas complement other landscape-scale conservation maps, such as Oregon's Conservation Opportunity Areas, indicating areas that are disproportionally important to wildlife connectivity, and can serve as a foundation for future analyses that address specific conservation challenges such as energy development, population growth, and climate change.

Recommendations for Conservation Actions

There are four broad categories of Conservation Action Recommendations: **Protect**, **Restore**, **Transportation Mitigation**, and **Enhance/Maintain**.

Protect: Permanently protecting habitat through acquisition, easement, or long-term management is the principal action needed to secure structural connectivity for wildlife. The single best conservation measure for maintaining wildlife connectivity in the state is to protect remaining undeveloped habitat. All hexagons within the PWCA network would benefit from protection measures, but those hexagons specifically attributed with a Conservation Action Recommendation of 'Protect' have been targeted for their value for facilitating wildlife movement. These hexagons represent both the highest-quality habitat available to facilitate movement, as well as bottlenecked areas of movement that risk loss of connectivity if land conversion were to occur. Hexagons attributed as 'Protect' would benefit from targeted measures to protect and preserve habitat, including land acquisition, execution of conservation easements, or specific habitat designation within policy. Some hexagons attributed as 'Protect' fall within public or other lands that are already under some level of protection from development. For these areas, efforts to 'Protect' habitat for wildlife connectivity may benefit from specific management actions, such as road closures, area closures, or other forms of recreation management, removal or modification of grazing leases, avoidance of habitat loss or disturbance from resource extraction activities such as logging or mining, and/or habitat modifications to reduce wildfire risk and remove invasive species.

Restore: In many areas of the state, habitat loss and modification due to development, agriculture, resource extraction, and the spread of invasive species impact functional connectivity for wildlife. While some species may still use these habitats to move, marginal-quality habitats impact the long-term value of the landscape in helping to facilitate species movement, may hinder the ability of wildlife to adapt to changing conditions, and may be more susceptible to catastrophic events such as wildfire and the spread of disease. As with the category for 'Protect', nearly all of the hexagons within the PWCA network would benefit from some level of habitat restoration or enhancement. Those hexagons attributed with a Conservation Action Recommendation of 'Restore', however, are those that have significant overlap with development, agriculture, and/or mapped areas of invasive vegetation. These hexagons in particular would benefit from measures to rehabilitate habitat damaged by human impacts, including actions to remove and prevent reestablishment of invasive species, remove or modify barriers to wildlife movement, and promote native ecological communities.

Transportation Mitigation: Roadways and vehicular traffic are a significant contributor to fragmentation of habitat and impacts to wildlife connectivity. Most species face at least some level of mortality risk associated with roadways, and many species display behavioral avoidance of the activity, noise, lights, vibrations, and smells associated with roads. Any location the PWCA network intersects with a roadway is a potential site for transportation mitigation. However, some roads pose a greater risk to wildlife connectivity than others, based on road width/number of lanes, traffic volumes, traffic speed, driver sightlines, and proximity to higher-quality habitats. Hexagons attributed with a Conservation Action Recommendation of 'Transportation Mitigation' are areas of the PWCA network that are particularly susceptible to fragmentation from roadways, as determined both by the value of the surrounding habitat for facilitating movement, as well as known areas of high densities of vehicle collisions with large-bodied wildlife. Areas designated as being in need of Transportation Mitigation would benefit from installation of wildlife crossing structures or autonomous animal detection systems that would improve wildlife passage across the road.

Enhance/Maintain: Some areas within the PWCA network 1) are at a lower risk of habitat loss due to conversion, 2) represent quality, but not necessarily the highest priority of, habitat available for facilitating wildlife movement, and 3) have limited overlap with development, agriculture, or invasive vegetation. These hexagons have been attributed with a Recommended Conservation Action of 'Enhance/Maintain'. As with the other hexagons in the network, these areas would benefit from protection measures, but specific actions associated with hexagons attributed as 'Enhance/Maintain' could include maintenance of existing conditions that are already favorable to an assemblage of species, avoidance or minimization of adverse impacts that would fragment habitat, removal, modification, or avoidance of the installation of barriers to wildlife movement, and minor habitat enhancements to ensure continued functionality, including prevention of the establishment of invasive species, wildfire risk minimization, and recreation management.

Prioritizing PWCAs

There are many arenas in which information on PWCAs could help inform both on-the-ground conservation action and planning, including:

- Identification of priorities for land acquisition
- Identification of restoration priorities
- Identification of priorities for transportation mitigation, including siting of new wildlife crossing structures
- Land management plan revisions and decisions for habitat and recreation management for public lands
- Local and county government efforts to protect wildlife connectivity, including incorporation of PWCAs into county planning goals
- Investments through state and federal grant programs for conservation of habitat and working lands
- Informing renewable energy, land use, and waterway planning

The network of PWCAs within Oregon is extensive, and there may be a desire to further prioritize to identify the parts of the network most in need of conservation action. We anticipate that many entities will incorporate PWCAs into their respective planning and prioritization processes by combining overlap of PWCAs within their area of interest with other sources of information specific to their organizational mission, needs, and goals. In general, however, action within PWCAs may be particularly beneficial when:

- A PWCA supports priority wildlife species, such as Federally- or State-threatened or endangered species, at-risk species, or Conservation Strategy Species/Species of Greatest Conservation Need
- A PWCA is small and/or isolated (such as a steppingstone) or narrow/bottlenecked and may be at risk of loss or disconnection if any land use change occurs
- A PWCA contains unique features, such as rare or uncommon habitats
- A PWCA intersects with other conservation planning tools or habitat priorities (e.g., Conservation Opportunity Areas, aquatic habitat priorities, big game winter range, etc.)
- A PWCA is adjacent to ODFW Wildlife Areas, USFWS National Wildlife Refuges, Designated Wilderness Areas, or Crater Lake National Park
- Land within a PWCA is unprotected

Potential Misconceptions

Potential Misconception 1: Oregon Department of Fish and Wildlife developed Priority Wildlife Connectivity Areas without any external input.

The development of Priority Wildlife Connectivity Areas was a multi-year, cooperative effort among a wide diversity of project partners and stakeholders. The Oregon Department of Fish and Wildlife led this effort in close collaboration with Portland State University and Samara Group. The analyses associated with this project were not conducted in isolation, nor were analyses or products finalized without internal and external review. OCAMP has benefitted from contributions from more than 100 individuals across state and federal agencies, Tribes, universities, and NGOs (see Acknowledgements, below). Many individuals assisted with species selection and expert review of draft habitat models for each species, and/or provided occurrence data used in statistical validation of models to ensure that models accurately represented real-world species habitat use.

Potential Misconception 2: Habitat that is not part of the Priority Wildlife Connectivity Area network is not important for wildlife connectivity.

The Priority Wildlife Connectivity Areas identified by this project represent a landscape-scale tool to target conservation action in areas that will have the greatest overall value for facilitating wildlife movement. Accordingly, these areas capture only a fraction of the landscape representing the highest-priority areas across all project species. The final OCAMP product does not indicate that habitat falling outside of the Priority Wildlife Connectivity Area network is unimportant to facilitating wildlife movement or maintaining wildlife habitat connectivity. Areas falling outside of PWCAs may still have value for wildlife connectivity, may be important for local populations of wildlife species, and may still benefit from targeted conservation action to restore, enhance, or protect habitat.

Potential Misconception 3: Priority Wildlife Connectivity Areas should be the only factor in determining where conservation efforts take place.

While Priority Wildlife Connectivity Areas are a valuable tool for identifying the areas of Oregon’s landscape with the highest overall value for facilitating wildlife movement, users should leverage this information in conjunction with other relevant spatial data, conservation guidelines, and consideration of local/site-specific/project-specific needs. Other relevant factors may include land ownership, protected status, proximity to other habitats of interest, presence of species concern, or inclusion in other landscape-scale conservation planning tools, such as Conservation Opportunity Areas.

Potential Misconception 4: Priority Wildlife Connectivity Areas affect public and private land management.

Priority Wildlife Connectivity Areas are an informational tool to guide the work of all entities engaged in land, wildlife, and other natural resource management, including state, federal, county, and local governmental organizations, sportsmen’s organizations, conservation groups, NGOs, and private landowners interested in restoring, enhancing, and protecting habitat important for wildlife connectivity. Priority Wildlife Connectivity Areas are not regulatory and do not dictate land use for any public or private entity.

Potential Misconception 5: Priority Wildlife Connectivity Areas are permanent and will not be reevaluated.

The connectivity modeling completed for OCAMP and the PWCAs represent a snapshot of current landscape conditions, with analyses based on the best available information and spatial data at the time of the project. The OCAMP products do not consider future scenarios, including fluctuations in demographics or land management or anticipated shifts in connectivity due to changing climate conditions. Future changes, including rural, commercial, residential, energy, and agricultural development, spread of invasive species, wildfire, drought, and shifting communities due to climate change could affect species connectivity and the potential function of any given PWCA. As such, this analysis will need to be revised to incorporate new and better spatial data, to incorporate improved information on species habitat needs and drivers of movement, and to reflect changes to landscape conditions. This analysis and the associated PWCAs are not permanent and will undergo periodic review and updating.

Limitations

Throughout the project, every effort was made to use the best available data and model accurate, real-world conditions, but there may be instances where data limitations have influenced results. Some of these limitations have been presented above, including measurement error associated with eBird data and lack of sufficient occurrence data to permit Habitat Permeability Model validation for some species. We recommend careful consideration and evaluation of project and data limitations when interpreting and using project products.

In addition to limitations associated with occurrence data, products have been developed from *models* of species habitat use and movement, and models are only as strong as the data used in building them. In many cases, data sources will not accurately represent current-day landscape conditions because the data are based on information that can be several years old. For example, a primary data source for developing Habitat Permeability Models for all project species is the U.S. Geological Survey Earth Resources Observation and Science Center's National Landcover Database (NLCD). The most recent iteration of NLCD data was released in 2021 and provides remote sensing information on landcover only as recent as 2019. Any activity occurring between 2019 and present day drastically altering landcover, such as clear-cut logging, new development, or wildfire, will not be accurately represented. In some cases, manual review of the final PWCAs allowed removal of hexagons overlapping these recent changes, but generally, new features on the landscape will need to be considered separately in planning efforts.

Additionally, there may be variation in the quality of variables used in developing models. Our minimum data standards for inclusion of any spatial dataset in the project focused on information collected or processed within a decade of 2020, originating from trusted sources, with good documentation and routine review, updating, and maintenance for data accuracy. However, maps describing vegetative characteristics across the landscape (type, composition, structure, etc.) have been imputed from remote sensing data such as Landsat satellite imagery or LiDAR. While these models typically perform well at regional scales, characteristics of finer-scale habitat structural components, such as shrub composition or shrub height, or heterogeneity of characteristics occurring at finer spatial scales, may not be accurately represented.

While spatial data were available to represent many habitat components that are expected to facilitate or impede wildlife movement, we were not able to source adequate spatial data to represent every component identified as important during the literature review. Some features on the landscape that might influence movement have not been mapped (e.g., noise attenuation, light pollution), have been incompletely mapped (e.g., fences, solar facility footprints, logging access roads, fire severity, diversion channels, trails, soil types), or have not been mapped at a fine enough resolution (e.g., talus, colluvium, grassland cover/types, forb cover, stream morphology/flow/depth/substrate) to serve as a useful component of statewide species habitat models. Further, while our models leverage spatial data at a relatively fine resolution (30m), this scale does not capture all relevant landscape features that might influence wildlife movement, particularly for smaller-bodied and/or less-mobile species. Presence of specific graminoid, forb, or shrub species, snags, downed woody debris, rock outcroppings, or desirable microclimates may influence individual movement paths at smaller spatial scales.

The literature review process executed to identify each species' salient habitat needs was extensive and identified current best information on each species' habitat requirements and information on expected responses to different types of disturbance and barriers to movement. However, there will always be some uncertainty associated with determining how wildlife species perceive the landscape, as well as uncertainty in modeling how wildlife will respond to each of the individual components included in each species' Habitat Permeability Model. Many species lack research on habitat requirements, particularly regarding structural features that might influence movement. Many species in need of connectivity modeling were eliminated as candidates for this effort due to lack of available research. Some project species, such as Ord's kangaroo rat and Morrison's bumble bee, are not well-studied. Information on responses to disturbance and landscape features that most influence movement is limited, and models for these species should be interpreted with caution.

The overall project goals for OCAMP focused on identifying, to the greatest extent possible, current landscape connectivity for each project species. As such, we did not take into account any historic or projected future conditions that might impact wildlife habitat use. This snapshot approach may also miss important temporally variable drivers of movement, such as climate, weather, and availability of prey or presence of predators. For example, snowpack might affect the ability of a species to move through certain areas, but heterogeneity in snowpack levels is not well-documented at fine scales, and interannual variability in snowpack might mean that any given area is passable for a species one winter but not the next. To avoid this, our models did not include temporal factors, but they may warrant consideration in specific planning efforts.

The final PWCAs were developed from the top 1% of priority areas identified for each surrogate species. This focus necessarily limits the habitats and connections included in the final product, and not all important habitats for species will be represented. Species-specific information is available on a case-by-case basis for projects that would benefit from an understanding of species connectivity needs at thresholds beyond 1% (e.g., evaluation of critical habitat designations for listed species, development of species-specific management or conservation plans, etc.). While the 54 surrogate species selected for this effort were carefully chosen to represent a wide diversity of taxa, movement capabilities, sensitivity to anthropogenic threats, and specific habitat associations and/or structural habitat characteristics in Oregon, the resultant PWCAs do not, and cannot, represent the unique needs of every particular at-risk, threatened, or endangered species. Although surrogate species were selected to be broadly representative of larger suites of species, species with particularly low mobility, highly specific habitat needs, limited habitat, or site-specific threats may not be adequately represented by PWCAs and would benefit from individual assessment.

While the resistance layers that serve as the foundation for the species-specific connectivity models and, subsequently, priority areas, have undergone expert review and statistical validation, the final PWCAs have not been validated. Manual review of PWCAs removed overlap with obvious areas of non-habitat, as well as with areas of new development, wherever possible. However, without formal validation of PWCAs against independent occurrence and/or telemetry data, or ground-truthing to verify use, PWCAs should be viewed only as areas where movement is expected to occur.

Finally, in developing the network of PWCAs, connections were made between each priority region and all of its nearest neighbors. This process identified connections even in locations where habitat is not currently well-suited to facilitate wildlife movement. Examples of this effect can be seen with connections bisecting areas of center-pivot agriculture in the Columbia Plateau or passing through developed communities in the Willamette Valley. Connections target the best available habitat for facilitating wildlife movement, even in areas where the best available habitat for wildlife may be of low quality. Some of these connections may be impractical without extensive habitat restoration.

Future Work

As described in detail above, limitations exist in the ability of connectivity models to represent fine-scale patterns of wildlife movement. Spatial data required to accurately depict habitat quality are often inadequate or nonexistent, and many of Oregon's wildlife species have significant data gaps. These data gaps are present both in occurrence data identifying species presence on the landscape and in basic understanding of species life history processes, such as habitat requirements and drivers of movement, that allow for effective modeling and mapping of species connectivity. As a result, there will be a need for continuing study to better understand wildlife movement in Oregon, as well as periodic review and updating of the products associated with OCAMP, including PWCAs, to incorporate new information. In general, targets for future work fall into three categories: 1) additional validation of project models; 2) addressing data gaps; and 3) evaluation of the implementation of PWCAs.

Additional validation of project models

We elected to apply all of the available species occurrence data for our project species to validate Habitat Permeability Models, which serve as the foundation for all subsequent project products. Species connectivity models and the PWCAs have been manually reviewed but have not been statistically validated. Validation of these models would require extensive additional data (ideally movement data collected at fine temporal scales using GPS telemetry) that does not exist for most species. Telemetry data tracking individual animal movement is available for some species in Oregon, primarily ungulates, although most data have been collected at infrequent intervals (e.g., every 13 hours) which limits the utility of these data for assessing fine-scale movement. Future work should focus on development of statistical approaches to leverage presence-only data to evaluate connectivity model output, and/or in ground-truthing PWCAs with targeted field studies of PWCA use compared with use of habitat falling outside of PWCAs.

Addressing data gaps

The most significant project limitations for this effort arose from a lack of sufficient data—lack of research identifying species habitat requirements, lack of spatial data with the appropriate attributes, coverage, and/or resolution to model species habitat needs, and lack of occurrence and movement data to adequately validate all model output. Future iterations of species connectivity models and priorities would be improved by work done to address these data gaps. Research done to verify species habitat needs would improve models for many species, particularly smaller-bodied species such as Morrison's bumble bee, Ord's kangaroo rat, long-nosed leopard lizard, northern alligator lizard, and black-tailed jackrabbit.

Development of better, more accurate geospatial data layers would also benefit connectivity modeling, particularly for habitat components such as soil composition, shrub composition and shrub height, graminoid composition, and forb composition, as well as barriers to animal movement such as the location and type of fencing on the landscape. Collection of additional species location data, including movement data, would help to better refine maps and models and could be leveraged in validating model output. Availability of occurrence data from most sources was strongly biased towards species that are hunted or trapped, including deer, elk, pronghorn, bighorn sheep, cougar, beaver, and greater sage-grouse. Species with the fewest available occurrence points to use in validation for this effort included western rattlesnake, Fender's blue butterfly, northern alligator lizard, North American porcupine, long-nosed leopard lizard, Sierra Nevada red fox, western bumble bee, Morrison's bumble bee, black-tailed jackrabbit, Ord's kangaroo rat, and bushy-tailed woodrat.

Evaluation of the implementation of PWCAs

Across longer timeframes, it will be necessary to evaluate the implementation of conservation action taken to benefit wildlife connectivity in Oregon. In addition to assessing species use of Priority Wildlife Connectivity Areas, it will be important to measure the effectiveness of on-the-ground actions taken to enhance, restore, and/or protect habitat important to wildlife movement, as well as to evaluate the effectiveness of recommendations and best management practices developed to benefit wildlife connectivity. Critical evaluation of the success of conservation action and recommendations will allow for adaptive management to continually improve approaches to conservation of wildlife connectivity, helping ensure that species are able to respond to and persist in the face of infrastructure development, land use change, climate change, and other stressors.

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