Oregon Connectivity Assessment and Mapping Project

Implementation Plan

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Abstract

There is a pressing need to initiate development of connectivity maps for a broad array of Oregon's terrestrial wildlife species. Many species rely on the ability to move throughout the landscape to fulfill their daily and seasonal needs for access to food, shelter, and opportunities to reproduce. Anthropogenic landscape change can restrict the ability of wildlife to move across the landscape by adding barriers, instigating behavioral changes, impacting critical stopover sites, and increasing habitat fragmentation. To date, efforts to map connected habitat corridors in Oregon have been based primarily on expert opinion, and have proven to be insufficient in making decisions related to maintaining species' ability to move across the landscape. Improvements in the availability and resolution of spatial data, as well as new and more robust statistical modeling techniques, have made fine-resolution, landscape-scale habitat connectivity modeling feasible. This implementation plan was co-developed with state, federal, and NGO partners and represents the current best practices in landscape-scale connectivity assessment and mapping for movement and migration corridors. The fine resolution connectivity maps produced using these guidelines will provide utility to a wide diversity of partners, aiding in statewide planning and prioritization for strategic conservation investment, protection measures, siting for land use changes and development, mitigating barriers to animal movement, targeted restoration efforts, and transportation improvements, among many other uses.

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Cover—Threats to wildlife connectivity may include land clearing (photo courtesy Sam Beebe), urban development (photo courtesy Bob Rost/OSU), fencing and other physical barriers (photo courtesy Dale Dombrowski/NPS), energy development (photo courtesy Dsink000, Wikimedia Commons), and roads (photo courtesy Mike Kaplan/USAFA). All wildlife taxa, including mammals, birds (photo courtesy Lee Karney/USFWS), reptiles, and amphibians (photo courtesy John Battaso/USFWS) should be considered as part of terrestrial connectivity planning efforts.

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Introduction

In 2016, a diverse group of stakeholders convened the Oregon Habitat Connectivity Consortium (OHCC), a group formed to promote functional natural landscape connectivity and to mitigate barriers to wildlife movement at multiple scales throughout Oregon and the surrounding region. Members of the OHCC include the Oregon Department of Fish and Wildlife (ODFW), Portland State University, the Oregon Department of Transportation, the US Fish and Wildlife Service, the US Forest Service, The Nature Conservancy, Oregon Wildlife Foundation, and Samara Group. The OHCC, led by ODFW, has developed this Oregon Connectivity Assessment and Mapping Project Implementation Plan (Implementation Plan) for how best to assess and map habitat connectivity for terrestrial wildlife throughout Oregon. This document was co-developed with state, federal, and non-governmental organization (NGO) partners and represents current best practices in landscape-scale connectivity assessment and mapping.

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.

Further, ODFW consistently receives requests from federal and state agencies, city and county planners, energy development companies, private consulting firms, conservation organizations, and the general public for information regarding key wildlife habitat linkages across Oregon. Entities require the information to inform land use development, including expansion of urban growth boundaries (city planners), permitting for renewable energy development (Oregon Department of Energy), mitigating for wildlife-vehicle collisions (Oregon Department of Transportation), and informing development of sensitive habitats (Department of State Lands).

Organizations are also keenly interested in wildlife movement pathways in order to inform long-term planning documents for managed lands (Bureau of Land Management, US Forest Service, Oregon Department of Forestry), guide granting efforts (Oregon Watershed Enhancement Board), and direct on-the-ground acquisition, restoration, and conservation of habitat for fish and wildlife (Defenders of Wildlife, The Nature Conservancy, Coalition of Oregon Land Trusts, US Fish and Wildlife Service).

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 analytical procedures outlined in this document draw on techniques developed and 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 to the Pacific Northwest (Buttrick et al. 2015; McRae et al. 2016). In using these previous projects to inform the Implementation Plan, 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 Plan also represents a standard protocol with clear procedures that can be easily shared with partner groups, helping to advance a cohesive vision for connectivity assessment and mapping throughout the Northwest.

Approach

The overall project goal is to advance priority conservation planning aimed at understanding and mitigating barriers to wildlife movement in Oregon. Our approach is to fill critical knowledge gaps by completing connectivity assessment and mapping at fine resolutions across Oregon, conduct extensive outreach to encourage a diverse group of partners to utilize and implement the results from the assessment, and to make all data and results from our analyses easy to find, view, and understand.

Priority conservation areas for maintaining landscape connectivity are best identified by generating maps using geospatial models (Baldwin et al. 2010, Spencer et al. 2010, WHCWG 2012, McRae et al. 2012). We will produce connectivity maps for up to 60 species across their respective ranges in Oregon, representing different taxa, habitat associations, life history strategies, and dispersal capabilities. Each species' range will be buffered by a significant margin, based on the scale of the species' movement and extending into neighboring land in

Washington, Idaho, Nevada, and California when applicable to a) reduce the likelihood that the effects of the artificial limitations of map edges will obscure important linkages (Koen et al. 2010), b) better understand cross-boundary connectivity in cases where species ranges extend beyond Oregon's borders, c) allow for maps produced for separate species to be composited into multi-species maps, and d) allow for better understanding of potential climate-driven range shifts.

The analytical steps involved in connectivity assessment and mapping are intensive and include: 1) selecting representative species for evaluation of connectivity; 2) selecting the appropriate method for analyzing species' connectivity; 3) building and validating models to assess areas that facilitate or impede each species' movements across the landscape; 4) using model output to identify, map, and prioritize linkages and pinchpoints; and 5) combining individual species' models to represent connectivity for terrestrial wildlife in Oregon as a whole. Beyond the analytical approach to connectivity mapping, there are several steps to ensure that products provide utility to practitioners, are made widely available and easy to access, and remain relevant into the future: 6) development of partnerships, outreach, and engagement; 7) development of web tools to facilitate sharing of models and support product use; and 8) consideration of long-term needs for model validation, refinement, and updating.

1) 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) — typically large-bodied, highly-mobile generalist species with low sensitivity to barriers and habitat types. 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).

Species will be selected on an ecoregion-by-ecoregion basis, using input from a variety of biologists, conservation planners, species experts, and potential end-users of the connectivity maps. For each of Oregon's eight terrestrial ecoregions (Coast Range, Willamette Valley, Klamath Mountains, East Cascades, West Cascades, Columbia Plateau, Blue Mountains and Northern Basin and Range), we will begin species selection by identifying the habitat types present in the ecoregion, as well as species-habitat associations (Johnson and O'Neil 2001). We will then utilize hierarchical clustering analysis (Glenn 2002) to group species based on habitat associations for each of our target ecoregions, to ensure that surrogate species adequately represent diverse habitat needs. This initial list of candidates for each ecoregion will be filtered based on the following criteria:

- Species must be native and noninvasive
- Species should have close associations with (most often found in or obligate to) habitats of interest
- Species' ranges should occur primarily within the ecoregion under consideration
- Species should be neither very rare nor overly common

Following initial filtering, a group of biologists, species experts, and other practitioners from the ecoregion will be asked to score candidate species on a variety of criteria, evaluating mobility, susceptibility to barriers, availability of data on species presence and distribution, and sensitivity to anthropogenic disturbance. While hierarchical clustering and grouping based on close habitat associations will help identify surrogate species representing diverse habitat needs, we recognize that many highly-mobile species, generalist species, and species of particular conservation or socioeconomic concern will be lost during this process, and that consideration of connectivity for these species remains important. Accordingly, scoring participants will also be asked to add "focal" species — species such as burrowing owl (*Athene cunicularia hypugaea*; a species of greatest conservation need in Oregon) or Rocky Mountain elk (*Cervus elaphus nelsoni*; a big game species important to Oregon's economy) — to the candidate list.

A webinar will be held in advance of scoring to ensure that all participants understand the goals of the exercise, scoring criteria, and what the overall group of species selected for an ecoregion is intended to represent. The group of species selected for each ecoregion should represent a diversity of:

- the different ecoregional habitat types
- taxa (mammals, birds, amphibians, reptiles, invertebrates)
- mobility and dispersal capabilities
- susceptibility to barriers
- different life history strategies

- different habitat structural components (these will be ecoregion-specific; seral stages, canopy layers, etc.)
- different threats to persistence (also ecoregion-specific; land clearing/vegetation removal, development, roads/traffic, people/domestic animals, energy development/transmission lines, fire impacts, etc.)

For each ecoregion, after scoring is completed, species will be ranked and a workshop will be held during which interested parties will convene to evaluate the species' rankings and finalize species selection for that ecoregion. To best represent the movement needs of diverse taxa, we will select a range of surrogate species and at least one focal species for each ecoregion. The use of surrogate species, combined with select focal species, will allow us to effectively represent the connectivity needs of the widest possible diversity of species in Oregon, meaning that our final products will be relevant to species beyond those directly addressed in the assessment. We expect to select approximately 8-16 species to represent each of Oregon's eight terrestrial ecoregions, depending on the complexity and distribution of habitat types within a given ecoregion as well as the ecoregion's size. Overlap of species chosen to represent different ecoregions is expected; we will ultimately assess connectivity for up to 60 species across the state as whole.

2) Methodological Approach

There remains a lack of consensus about how connectivity should be quantified and modeled (Beier et al. 2008; Sawyer et al. 2011; Zeller et al. 2012; Zeller et al. 2018). As such, there are a wide variety of tools and software programs available to facilitate connectivity mapping, each with varying advantages, disadvantages, and assumptions. Currently, the four most common approaches to connectivity assessment draw on cost distance (LaRue and Nielsen 2008; Richard and Armstrong 2010), resistant kernel (Compton et al. 2007; Wasserman et al. 2012), current flow (Koen et al. 2014; Pelletier et al. 2014), and network flow (Carroll et al. 2011) approaches.

Most applications of cost distance and resistant kernel methods, while frequently utilized, suffer from several shortcomings. Both resistant kernel and cost distance approaches assume that organisms have perfect knowledge of the landscape and move with the intent to minimize travel costs, assumptions which are likely not representative of natural systems for most species. For example, dispersing individuals would not have had any exposure to the landscape outside their natal area, and some migrating ungulates move not to minimize travel costs, but to maximize energy intake (Bischof et al. 2011).

Many of the existing approaches to connectivity analysis, including cost distance, resistant kernel, and network flow models, assess connectivity between discrete patches, in the form of terminals or core area polygons. Patch selection, however, can strongly influence connectivity modeling results (Baldwin et al. 2010, Perkl et al. 2016). Decisions about how patches are

defined (e.g. minimum size requirements for core areas), as well as placement, directly impact the spatial outputs of the connectivity assessment. Without a complete understanding of the effects of patch selection within a study area, any given set of patches may lead to erroneous conclusions about connectivity that translate into negative consequences for subsequent management. One application of current flow (Circuitscape) also relies on patch selection, and is susceptible to similar issues. Further, relying on connections between discrete patches can also obscure important connectivity routes within patches. Cost distance approaches and Circuitscape do not model connectivity within core areas, meaning that assessment of connectivity within such patches cannot be made.

Our analyses will primarily utilize current flow in a wall-to-wall framework using the Omniscape algorithm. 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. Second, the current flow approach of Omniscape simultaneously evaluates the contribution of multiple movement pathways, rather than identifying a single least-cost corridor. 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 initial conservation, mitigation, or restoration investment.

Omniscape 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 areas, each pixel on the landscape is assessed independently. This process requires two primary inputs: a surface describing suitable habitat for a species (the source weight layer, identifying where movement is likely to originate) and a surface describing barriers or impediments to movement for a species (the resistance layer). The algorithm passes a moving window throughout the study area (in this case, the state of Oregon and adjacent lands in neighboring states) centered on a single pixel and determines first if that pixel is a habitat pixel. If the pixel is identified as habitat, the model uses that pixel as a "ground". It then "injects" a current into all habitat pixels (sources) within the radius of the moving window, with source pixels that represent better habitat receiving stronger current. The injected currents flow toward the target ground pixel, moving around barriers identified in the resistance layer. The model then moves the window one pixel and repeats the process; if the target pixel is not habitat then the model moves on to the next pixel and no data are recorded. Each model run is ultimately summed to create a cumulative current

flow map that highlights the pixels across the landscape that are the most likely to facilitate animal movement.

3) Model Building and Validation

Individual species habitat models are the primary data sources used to model habitat connectivity and barriers to animal movement. Using available habitat models, published literature, and expert opinion of a particular species' needs (e.g. the animal requires wetland habitat, will not travel further than 500 meters from a water source, etc.) we will determine the salient habitat needs of an animal to develop habitat layers. In addition, we will use empirical data, published literature, and expert knowledge to define the landscape features that act as barriers or impediments to animal movement, such as roads, density of human development, or canopy gaps beyond a certain size. These surfaces are modeled using available spatial data in the form of GIS layers. These layers might include, among others: NLCD land cover data; LEMMA GNN data; the National Hydrology Dataset; the National Wetlands Inventory; NRCS SSURGO soil data; the National Elevation Dataset (in order to model elevation, slope, and aspect); PRISM climate data; TIGER road data; Oregon Transportation Network data; Oregon Railroads data; HIFLD electric power transmission and natural gas pipeline datasets; and The U.S. Wind Turbine Database.

Omniscape is parameterized using: (1) a resistance surface; (2) habitat (as expressed by the "source strength" of current flow injected into the source cells within the moving window), and (3) the size of the moving window. These habitat/source weight models and resistance surfaces will be developed as raster layers with a minimum pixel size of 30 meters, with relative resistance values assigned to different landscape features. For example, a pixel representing a barrier for a given species would be assigned a relatively high resistance value and low source weight, whereas a pixel representing the species' ideal habitat would be assigned a relatively low resistance value and high source weight.

The species habitat and resistance models will be validated against species occurrence data where available and peer reviewed by experts when empirical data are not available. The validation process consists of fitting and cross-validating species distribution models with widely used methods (e.g., Boosted Regression Trees, Generalized Linear Models, MaxEnt, or Marked Point Pattern analysis), to presence data using the habitat model output as the single predictor. The suitability of the habitat models is assessed by the quality of the model fit and out-of-sample (cross-validation) predictive performance. Subsequent to validation, the models will be edited and updated as necessary.

Once resistance and source weight models are built for a given species, the Omniscape algorithm is run, resulting in output of a continuous surface highlighting where on the landscape species movement is most likely to occur. Omniscape models are (as are all resistance-based

connectivity models) more mechanistic than statistical, and thus, until validated, models should be viewed as hypotheses regarding where on the landscape we expect animal movement to be facilitated or impeded. For some species, high-quality, independent telemetry and/or observational datasets already exist in Oregon that will allow for assessment of the degree to which our connectivity models accurately represent patterns of use and movement trajectories of a focal or surrogate species. To validate the connectivity model for a particular species, we will develop predictive statistical models that link species landscape use data (as the response) with the measure produced by the Omniscape model (as its sole predictor).

When movement data are available for a species we can model the probabilities for the observed trajectories for individuals' relocations conditioned on the outputs from the Omniscape model with, for example, particle trajectory modeling methods. Given that movement data most accurately represent how a species uses the landscape, model validation should ideally be based upon these data. However, movement data over the spatial domain of interest are currently available for only a few species. Where movement data are not available, presence data and observation data can also be used for validation as imperfectly observed partial proxies for movement. If using presence data, the probability of the species occupying/using a particular pixel given the outputs from the connectivity model would be calculated with a marked point pattern model or a similar approach.

With observed data, the validation consists of assessing model suitability, which can be ascertained by considering both traditional goodness-of-fit statistics, as well as out-of-sample predictive measures obtained either through cross-validation, or, with sufficiently large datasets, by partitioning them into a training dataset used for model building and a validation dataset with which prediction is performed. That is, the validation process attempts to determine if the connectivity model is able to accurately explain the positions of individuals. If the probability of many observed presence locations are low (i.e., large fitting errors), this would be an indication that the connectivity model is neglecting something. An additional metric would involve testing for departures from the connectivity model, by, for example including a spatial random effect; if this spatial random effect turns out to be meaningful it would provide an indication that other factors not considered by the connectivity model are driving the location.

4) Prioritization of Movement Pathways
The output of a statewide connectivity analysis is expected to be extensive; even smaller-bodied species obligate to specific habitat types will likely have a number of potential linkages highlighted on the landscape. These data will ideally be used to inform conservation, transportation, and land use planning, but funds are often limited for such actions, so there will be a need to prioritize linkages across the state. Potential variables that could be used for prioritization include quality of habitat for a given species, how a particular pixel connects to other pixels in the network of the species' movements, the potential barriers to movement within

each species' range, and even ratios depicting connectivity improvement for a species if a given barrier was removed. We expect that additional prioritization will take into account areas where linkages for multiple species overlap, existing or forecasted development pressures, and intersection with existing Oregon Conservation Strategy Conservation Opportunity Areas (http://oregonconservationstrategy.org/conservation-opportunity-areas/) or GAP 1 and 2 protection status (https://gapanalysis.usgs.gov/) lands, among others. Additionally, prioritization efforts will need to address climate change and road mitigation.

Consideration of climate change
While habitat loss and fragmentation are the primary causes of decline in biodiversity (Fahrig 2003), climate change is predicted to interact with and intensify the effects of these issues. Preservation, enhancement, and restoration of landscape connectivity have been identified as key conservation strategies that may provide protection for species by enabling them to move with shifting climates (Krosby et al. 2010; Littlefield et al. 2017; Carroll et al. 2018; Schloss et al. *in prep*). As such, while the primary intention of this project is to assess and map existing connectivity for terrestrial wildlife in Oregon, there is also a need to evaluate potential future connectivity, particularly for species with narrow climate envelopes, such as American pika (*Ochotona princeps*) and wolverine (*Gulo gulo*).

For these climate-sensitive species, resistance and source weight surfaces can be constructed with consideration of future habitat suitability under changing climates. This species-specific approach is data and labor intensive and would necessitate consideration of a range of possible climate futures based on available climate models and downscaled climate data. An alternative approach would be to identify areas of existing connectivity that will likely facilitate future range shifts for wildlife in a way that is robust to uncertainties in how climate change will play out on the landscape (Lawler et al. 2015). The Nature Conservancy's "Conserving Nature's Stage" project used such an approach to identify terrestrial landscape resilience to climate change (Buttrick et al. 2015) and connectivity for climate resilient landscapes (McRae et al. 2016) in the Pacific Northwest. By overlapping existing connectivity identified in this project for focal and surrogate species in Oregon with the climate resilient areas identified by The Nature Conservancy, we will highlight those movement pathways on the landscape that are important for facilitating the ecological reorganization expected from climate change. This type of inventory of existing climate resilient pathways, while not specifically evaluating species' range shifts under various potential climate futures, will allow for strategic conservation investment in areas that will likely best maintain ecological processes and biodiversity despite changing climates.

Road mitigation
Roadways represent one of the most visible and persistent threats to wildlife connectivity. Animals are frequently struck and killed attempting to cross roads, and wildlife are exposed to

continually increasing risks as human populations expand, traffic volumes rise, and roadways are widened. Since wildlife mortalities on roads are often associated with a threat to human health and safety from vehicular collisions with large-bodied animals, the incentives to mitigate road crossings for wildlife are generally high.

The Oregon Department of Transportation collects data on ungulate-vehicle collisions along all major roadways in the state. This information can be overlayed with the connectivity maps for ungulate species produced in this project to help determine if there are high-quality linkages near problem areas. Areas where roadkill "hotspots" overlap with wildlife linkages can help prioritize investment in wildlife passage structures and other road mitigation efforts, such as reduced speed limits and wildlife crossing signage.

Road mortality is also a persistent threat for smaller-bodied species, but since collisions with these species do not typically threaten human safety or damage vehicles, roadkill data are limited, and generating public support for mitigation efforts for these animals is often difficult. Prioritization for road mitigation areas for these species will likely rely on ground-truthing of connectivity model output.

5) Compositing Maps

The results of the analyses outlined within this Plan include up to 60 individual map layers, representing range-wide connectivity, movement pathway priorities, and potential barriers for each surrogate or focal species. Individually, these map layers will be of use to many constituencies interested in protecting or enhancing connectivity for a particular species, habitat, and/or area. However, a crucial aspect of this project is to develop layers useful for landscape-scale planning purposes, requiring these initial outputs to be composited into a state-wide map (or series of maps) to delineate features common to multiple species, such as important connectivity zones and barriers to movement. Composite maps provide multiple benefits to the end users of connectivity projects. They are more easily used and readily available than asking a practitioner to add ~60 individual layers to a map in order to determine a project's potential impact on all species' movement patterns. Composite maps increase the likelihood of the end products being used in site assessments, land development project reviews, and other planning purposes by practitioners across Oregon. Additionally, highlighting areas important to multiple species enhances conservation effectiveness through focusing partner funds and efforts into common areas with common goals.

There are no current best practices for combining species connectivity maps; accordingly, this will be an area of active research and evaluation to determine the optimal composite methodology. Map layers resulting from the analytical procedures outlined above will contain quantitative information on a suite of connectivity related variables at 30 m resolution across the state of Oregon. Complexity arises when considering how to composite individual species map

variables. Simply delineating "hotspots" of connectivity by summing or averaging the values representing permeability for multiple species masks the multitudinous ways in which different species perceive habitats. For example, a body of water might represent a barrier to movement for a small mammal, but facilitate movement for an amphibian, so a simple average of values would mask the impacts of the body of water on both species.

One compilation option could be to divide species into groups based on movement capabilities or habitat association and then combine results within groups. This strategy was utilized by the Washington Wildlife Habitat Connectivity Working Group, who identified three separate connectivity guilds and combined species' results accordingly (WWHCWG 2012). An additional approach may be to prioritize linkages for each species as discussed above and combine only the linkages representing the highest priorities for each species. Regardless of the approach ultimately developed for combining maps, the specific species information will be retained in related databases for those users who are interested in a particular species or identifying which species are contributing to each combined linkage.

6) Outreach and Engagement

To support creation of the best possible connectivity maps and encourage the adoption and use of the products of this analysis, we will work within existing landscape-scale partnerships, work to build new partnerships, and create opportunities for engagement with practitioners across the state. We will begin outreach by working with the members of the OHCC to compile a robust list of professionals that engage in wildlife biology, land use planning, restoration, and/or conservation, across the state of Oregon. We anticipate these individuals will range from biologists to city planners, from connectivity experts to transportation planners, from watershed council members to Tribal members, and everyone in between. These potential partners will then be invited to engage with and provide input on the project.

In order to ensure the modeling process and resulting maps are created using rigorous, science-based decision-making, we will also conduct outreach in order to develop a core science team of quantitative modeling and species experts from universities, NGOs, and state and federal agencies. This core team will provide input and review of species habitat models, source weights, and other model parameters, among others. Potential members will be contacted and invited to participate in regular meetings and engage with various aspects of the model development and validation processes.

Aside from the core science team, we will use outreach and engagement strategies to connect with partners through a series of workshops and feedback sessions that will be planned and delivered in several regions across the state. Partnerships will first be leveraged in the species selection process as outlined above. Interested participants will be asked to score candidate species based on a variety of criteria, after which a series of in-person workshops will be held to

discuss species ranking and finalize species selection for the connectivity assessment. Alongside these regional species selection workshops, we will hold feedback sessions to solicit interest and input from partners to discuss the usefulness and application of statewide connectivity maps. Information provided by participants during these sessions will be compiled into summary reports and used to provide structure and aid in decision-making while models and map products are being developed. We will continue to engage partners on important decision points based on their expertise and interest, and we will provide regular updates on the project to partners as modeling continues.

As we near completion of the modeling process, draft products will be shared with all partner groups, and feedback solicited, to ensure that products are easy to interpret and meet the needs of practitioners and those making decisions regarding land use change. A critical part of the process to composite maps, for example, will be to hold conversations and discussions with stakeholders, partners, and other end-users of these data to determine potential applications of the connectivity assessment output and common needs that will need to be addressed by the final products for this work. Results of these discussions will be used to focus on which variables should be used for combining maps and highlighting priority areas, as well as to guide decision-making regarding how maps and associated data should ultimately be accessed and displayed.

7) Product Access and Distribution

A critical component of succeeding in developing statewide connectivity maps is ensuring that the end products and information are not only easily available to partners and the general public, but also easy to use and understand. Providing map products within an interactive, online mapping application will allow users immediate access to the full suite of final mapping products and associated data, without requiring specialized software. Having the final reports, summaries, and other materials in a common website provides easy access for users to get as much detail as needed on the connectivity mapping process, and also serves as a convenient platform to post updates, publications, links to further research, and new applications as they are made available. This project will utilize existing resources for both the online mapping and informational websites to host the results of the project.

ODFW Compass (https://dfw.state.or.us/maps/compass/) serves as ODFW's online mapping tool for providing information to ODFW staff, partners, and the public on fish and wildlife species and habitats related to site assessments, project planning, and reviewing potential land management decisions. Compass was designed so that additional mapping layers can easily be added and maintained, and layers can be presented within the same data theme so that they are grouped together in a common location. Customized links can be built and provided so that any user visiting Compass specifically to access connectivity information will view the connectivity maps and associated data by default, ensuring that users will not have any trouble finding the appropriate map layers. Options within Compass layers provide several locations where spatial

data can link to project documents, metadata, and additional data source information so users will easily be able to find all necessary documentation on the data layers. Compass also includes a "Tools" section, where customized reporting tools can be developed to allow users to retrieve connectivity information for their project area or species or habitats of interest. All mapping data layers will be hosted within the ODFW GIS server infrastructure, which is accessible by the public and is already maintained by ODFW GIS and data management staff.

Final reports, documents, and other materials can be presented to the public on a project website within the Oregon Conservation Strategy site (https://oregonconservationstrategy.org/). ODFW actively maintains the Strategy site, and has the ability to add customized pages for projects that are specifically connected to Strategy components. In this case, the connectivity project will be hosted within the Barriers to Animal Movement Key Conservation Issue (http://oregonconservationstrategy.org/key-conservation-issue/barriers-to-animal-movement/).

Utilizing existing platforms for hosting project materials will reduce development and long-term management costs. All life phases of an application development plan will be considered, including designing customized tools, planning for ongoing maintenance, and documenting requirements for long-term management. Discussions with partners about user needs will be utilized to generate a list of requirements for tools, layer, and website development. The resulting websites and applications will provide the ability to connect to partner efforts, additional ODFW online tools and documents, and more detailed information, allowing users to further investigate additional aspects of connectivity and habitat management.

8) Long-Term Considerations

The collaborative analysis outlined here, produced using input from a range of state, federal, academic, NGO, and public partnerships, will highlight areas of the landscape that likely provide good, functional connectivity for terrestrial wildlife species in Oregon. While longer-term model refinement and updating is outside the scope of the current project, it is nevertheless important to consider here.

First, it is necessary to keep in mind that the output of resistance-based connectivity models provides an indication of potential connectivity. As such, the validity of these models has to be confronted against empirical observations of how species make use of the landscape. For many species, however, such data do not exist. Thus, a critical future step will be to collect data on species movements to validate connectivity models, as well as monitoring to evaluate the efficacy of identified linkages.

Second, the models and maps produced during this project will be based on current, existing connectivity in the state. They are in no way intended to be static, and will need to be updated and refined over time to remain relevant and useful, particularly as land use, disturbances (e.g.

fire, forest insect and disease outbreaks, etc.), population demographics, and climates change, and as statistical methods for modeling connectivity, and in measuring uncertainty in connectivity analyses, improve.

Though future work will be required to update and maintain connectivity maps under changing conditions, this analysis, encompassing the entire state of Oregon and adjacent lands in Washington, Idaho, Nevada, and California, will accomplish a critical first step in identifying regionally important connectivity areas. The results from this work will provide much-needed products and tools that will help to guide conservation investment, mitigation and restoration work, future research, and areas in need of finer-scale mapping approaches. Perhaps most importantly, these products, and the partnerships developed throughout the course of this project, will provide critical information on wildlife connectivity to aid wildlife managers, conservation practitioners, and land use planners and decision-makers that has thus far been lacking in Oregon.

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Appendix A: Estimated Project Costs

Task	Subtask	Description
I		**Species Selection**
	A	Hierarchical clustering of species habitat associations and initial filtering
	B	Prep for workshops
	C	Discussions with a core group to determine any ecoregion-specific criteria/considerations
	D	Development of species scoring workbooks
	E	Outreach to get biologists/experts/practitioners engaged and willing to participate in scoring
	F	Webinars to explain the process and how scoring should be done
	G	Scoring/Ranking
	H	Travel to workshops
	I	Facilitation of at least 5 workshops across state to discuss scores/ranking and come to a consensus on species selection for each ecoregion
	J	Summary reporting of workshop outcomes
	K	Expert opinion and peer review of model parameters
	L	Meeting to finalize surrogate & focal species for each ecoregion
	Estimated Costs	$73,698
II, III		**Model Building and Validation**
	A	Solicit expert opinion about species habitat requirements
	B	Literature review about species habitat needs
	C	Identify any existing telemetry data, presence data, or models on species movement/habitat needs
	D	Obtain relevant spatial data for species models
	E	Match salient habitat needs to existing GIS data for each species (e.g. buffer size around water); select spatial resolution of models.
	F	Build models (up to 60) and calculate resistance values and source weights
	G	Outreach to and engagement of science team members
	H	Facilitation of science team review of model parameters

		I	Peer review of species habitat models
		J	Development of habitat model validation procedure
		J1	Species data collection and preprocessing
		J2	Develop habitat model validation R code
		J3	Perform habitat model validation
		J4	Report suggestions for improvement
		K	Update validated species models
		L	Rerun validation procedure
		M	Determine pixel size and moving window size for running models for each species
		N	Run three species as test models with Omniscape
		O	Assess model output and test aggregation
		P	Run all species models with Omniscape
		Q	Develop connectivity model validation procedure
		Q1	Species data collection and preprocessing
		Q2	Develop connectivity model validation R code
		Q3	Perform connectivity model validation
		Q4	Report suggestions for improvement
		R	Revise species connectivity models according to review and validation
		S	Rerun validation procedure
	Estimated Costs		$329,192
IV			**Prioritization of Movement Pathways**
		A	Core science team meeting to formulate key criteria for prioritizing corridors; decide cost/utility functions and weighting schemes across surrogate and focal species
		B	Assess overlap of high-flow movement areas with TNC's Conserving Nature's Stage climate resilient pathways
		C	Assess overlap of high-flow movement areas with ODOT roadkill dataset
		D	Additional development of prioritization methods based on feedback from engagement sessions, partner feedback, core science team meetings discussions, etc.

		E	Apply methods to prioritize corridors
	Estimated Costs		**$31,515.02**
V			**Compositing Maps**
		A	Core team meeting to discuss options for combining map output
		B	Develop weighting methodology for map aggregation that optimizes a given cost/utility function.
		C	Develop R code to estimate optimal weights surface
		D	Implement methodology to produce optimal weights surface for map aggregation
		E	Generate map with combined outputs
		F	Peer review; draft products shared with practitioners
		G	Revision post review
		H	Simplify model output, translating it from continuous current flow values into corridors (to help w/ communication and decision making about corridor management)
	Estimated Costs		**$85,754.46**
VI			**Outreach and Engagement**
		A	Development of potential partners list and invitations to participate. Updated as necessary.
		B	Facilitation of engagement workshops to determine user needs
		C	Engagement workshops summary report
		D	Workshops/webinars to share draft products with partner groups (V. F above)
		E	Workshop feedback discussion with core science team
	Estimated Costs		**$83,750.00**
VII			**Product Access and Distribution**
		A	Development of informational website
		B	Add data layers to ODFW Compass
		C	Develop customized tools for reporting, product use, etc. based on feedback from end users identified during engagement workshops and draft product sessions
	Estimated Costs		**$50,000.00**

			Reporting and Documentation
		A	Document all steps in process for repeatability
		B	Provide minutes after every core science team meeting, PSU/ODFW meeting, etc.
		C	Write progress/final report for each year and task
		D	Grant reporting, according to grant-specific requirements/deadlines
		E	Peer-reviewed publication (est. 3 pubs; open access)
	Estimated Costs		**$25,866.10**
			Other Budget Items
		A	Supercomputer use fee
		B	Travel to conferences/meetings (PSU)
		C	Tuition remission and fees for 3 PSU graduate students ($70,590)
		D	Indirect costs (PSU; $147,882)
		E	Materials
	Estimated Costs		**$244,416.00**

FUNDS NEEDED FOR REPTILES, AMPHIBIANS, AND INVERTEBRATES (up to 16 total species)			
			$246,758.99
FUNDS NEEDED FOR BIRDS AND MAMMALS (up to 44 total species)			
			$677,431.99
TOTAL ESTIMATED PROJECT COSTS			
			$924,190.98

Appendix B: Estimated Timeline for Implementation

Task	Subtask	Description	2019				2020				2021				2022			
I		**Species Selection**	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4
	A	Hierarchical clustering of species habitat associations and initial filtering	X	X														
	B	Prep for workshops			X	X	X											
	C	Discussions with a core group to determine any ecoregion-specific criteria/considerations			X	X	X											
	D	Development of species scoring workbooks	X	X	X													
	E	Outreach to get biologists/experts/practitioners engaged and willing to participate in scoring				X	X	X										
	F	Webinars to explain the process and how scoring should be done					X	X										
	G	Scoring/Ranking					X	X										
	H	Travel to workshops							X									
	I	Facilitation of at least 5 workshops across state to discuss scores/ranking and come to a consensus on species selection for each ecoregion					X	X	X									
	J	Summary reporting of workshop outcomes						X	X	X								
	K	Expert opinion and peer review of model parameters									X	X	X	X				
	L	Meeting to finalize surrogate & focal species for each ecoregion						X	X	X								
II, III		**Model Building and Validation**	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4
	A	Solicit and summarize expert opinion about species habitat requirements			X	X	X	X										
	B	Literature review about species habitat needs			X	X	X	X										
	C	Identify any existing telemetry data, presence data, or models on species movement/habitat needs			X	X	X	X										
	D	Obtain relevant spatial data for species models			X													
	E	Match habitat needs to existing GIS data for each species; select spatial resolution of models.			X		X	X	X	X	X	X						

Code	Task	Y1 Q1	Q2	Q3	Q4	Y2 Q1	Q2	Q3	Q4	Y3 Q1	Q2	Q3	Q4	Y4 Q1	Q2	Q3	Q4
F	Build models (up to 60) and calculate resistance values and source weights			▓	▓	▓	▓	▓	▓	▓	▓						
G	Outreach to and engagement of science team members			▓	▓	▓	▓	▓									
H	Facilitation of science team review of model parameters							▓	▓	▓	▓	▓					
I	Peer review of species habitat models			▓	▓	▓	▓	▓	▓	▓	▓	▓	▓	▓			
J	Development of habitat model validation procedure			▓	▓	▓											
J1	Species data collection and preprocessing				▓	▓	▓										
J2	Develop habitat model validation R code						▓	▓	▓								
J3	Perform habitat model validation								▓	▓	▓	▓					
J4	Report suggestions for improvement								▓	▓	▓	▓	▓	▓			
K	Update validated species models								▓	▓	▓	▓					
L	Rerun validation procedure								▓	▓	▓	▓	▓	▓			
M	Determine pixel size and moving window size for running models for each species			▓													
N	Run three species as test models with Omniscape			▓	▓												
O	Assess model output and test aggregation				▓										▓	▓	
P	Run all species models with Omniscape											▓	▓	▓	▓		
Q	Develop connectivity model validation procedure			▓	▓	▓	▓	▓									
Q1	Species data collection and preprocessing						▓	▓									
Q2	Develop connectivity model validation R code							▓	▓	▓							
Q3	Perform connectivity model validation								▓	▓	▓	▓					
Q4	Report suggestions for improvement									▓	▓	▓	▓	▓			
R	Revise species connectivity models according to review and validation													▓	▓	▓	
S	Rerun validation procedure								▓	▓	▓	▓	▓	▓			
IV	**Prioritization of Movement Pathways**	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4
A	Core science team meeting to formulate key criteria for prioritizing corridors				▓	▓											

			Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4
	B	Assess overlap of high-flow movement areas with TNC's climate resilient pathways					█	█	█	█	█	█	█	█	█	█	█	█				
	C	Assess overlap of high-flow movement areas with ODOT roadkill dataset					█	█	█	█	█	█	█	█	█	█	█	█				
	D	Additional development of prioritization methods based on partner feedback							█	█	█	█	█	█	█	█	█	█		█		
	E	Apply methods to prioritize corridors																		█		
V		**Compositing Maps**	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4
	A	Core team meeting to discuss options for combining map output				█	█	█	█													
	B	Develop weighting methodology for map aggregation that optimizes a given cost/utility function.								█	█	█	█	█	█							
	C	Develop R code to estimate optimal weights surface												█	█	█	█					
	D	Implement methodology to produce optimal weights surface for map aggregation															█	█				
	E	Generate map with combined outputs																█	█			
	F	Peer review; draft products shared with practitioners												█	█	█	█	█				
	G	Revision post review																		█	█	
	H	Simplify model output (to aid communication and decision making about corridor management)																		█	█	
VI		**Outreach and Engagement**	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4
	A	Development of potential partners list and invitations to participate. Updated as necessary.				█	█	█	█													
	B	Facilitation of engagement workshops to determine user needs															█	█	█	█	█	
	C	Engagement workshops summary report																		█	█	
	D	Workshops/webinars to share draft products with partner groups (V. F above)															█	█		█	█	
	E	Workshop feedback discussion with core science team																█				
VII		**Product Access and Distribution**	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4
	A	Development of informational website				█	█				█				█						█	█	
	B	Add data layers to ODFW Compass																		█	█	

			Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4
	C	Develop customized tools for reporting, product use, etc. based on feedback from end users													X	X	X	X
		Reporting and Documentation	**Q1**	**Q2**	**Q3**	**Q4**	**Q1**	**Q2**	**Q3**	**Q4**	**Q1**	**Q2**	**Q3**	**Q4**	**Q1**	**Q2**	**Q3**	**Q4**
	A	Document all steps in process for repeatability			X	X	X	X	X	X	X	X	X	X	X	X		
	B	Provide minutes after every core science team meeting, PSU/ODFW meeting, etc.			X	X	X	X	X	X	X	X	X	X	X	X		
	C	Write progress/final report for each year and task						X				X				X		
	D	Grant reporting, according to grant-specific requirements/deadlines						X				X				X		
	E	Peer-reviewed publication (est. 3 pubs; open access)								X	X	X	X	X	X	X		