Habitat Connectivity for Fishers and Martens
in the Klamath Basin Region of California and Oregon

Conservation Biology Institute

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Introduction

This report identifies important landscape connectivity areas in the mid-Klamath Basin of northern California and southern Oregon for two forest species of conservation concern: Pacific marten (*Martes caurina*) and Pacific fisher (*Pekania pennanti*). It assesses current connectivity status and identifies where connectivity could be improved through restoration or other actions. Results for the current condition could serve as a baseline against which to compare potential future conditions due to the effects of land management, climate change, fire, or other factors.

Conservation Biology Institute performed the analyses in partnership with the U.S. Fish and Wildlife Service Yreka Office and the Klamath Basin Strategic Habitat Conservation (SHC) Demonstration Project. Staff from these organizations and several other species experts formed the Core Team for the project, which was led by Michelle Reilly (USFWS) and included Greg Schrott, Joel Shinn, Daryl Van Dyke, Jenny Ericson, Gregory Schmidt, Laura Finley, and Gina Glenne (also all USFWS); Katie Moriarty (USFS, Pacific Northwest Research Station), Keith Slauson (USFS Pacific Southwest Research Station), and William Zielinski (PSW, Emeritus).

The project was intended to assess connectivity needs for species of pre-listing conservation interest in the Klamath region, as well as to inform decisions for the Klamath Strategic Habitat Conservation Terrestrial Project. The project Core Team determined that connectivity modeling would focus on fisher and marten. Other species considered but not included for various reasons (such as insufficient data, lower level of conservation concern, or marginal contribution of the Klamath Region to their conservation) included porcupine (*Erethizon dorsatum)*, salamanders (*Plethodon* spp.), ringtail (*Bassariscus astutus*), and western yellow cedar (*Cupressus nootkatensis*).

Key Take-aways

The project team used habitat suitability models (also known as species distribution models, or SDM) to define habitat core areas for martens and fishers, and least-cost corridor models to delineate and prioritize connecting habitats (or linkages) between cores. In concert with other information sources, the resulting models and maps (see links below) provide important information to consider in conservation planning and forest management decisions.

Fisher

Results suggest that fisher habitat in the region is relatively abundant and widespread, but also highly convoluted and edge affected (Figure 1). Many core area polygons are no more than one or two female home ranges wide, and habitat value often does not vary dramatically between modeled core versus linkage areas. This makes distinctions between core (or "live-in") habitat and connecting (or "inter-core movement") habitat relatively subtle and uncertain in many locations. Moreover, fisher habitats in the region are highly dynamic due to fires, forest management, climate change, and vegetation succession. These observations suggest that it may be best to view the fisher "core and linkage" map (Figure 1) as a snapshot of a dynamic complex of habitats that facilitate fisher metapopulation functions over time, rather than static, black-and-white depictions of different habitat categories (e.g., cores versus linkages versus non-habitat). We therefore find it helpful to view the underlying, continuous maps of fisher habitat value and resistance to movement in concert with the modeled cores and linkage to better understand landscape context (see maps on Data Basin, linked below).

This network of convoluted fisher habitat areas is at risk of further fragmentation by severe fires, forest management, and other factors, which could disrupt metapopulation dynamics and further threaten the species' resilience in the region. Management actions should prioritize strategically located forest restoration projects to sustain, expand, and improve habitat conditions within existing core habitat areas while also protecting critical "pinchpoints" in the linkages between them. Opportunities for improving habitat values, regardless of "core" versus "linkage" status, should also be continually assessed, especially in light of changes due to climate, fires, and other factors. Some areas of high priority or great uncertainty are identified in maps linked below.

Figure 1. Pacific Fisher Connectivity Map showing habitat cores and least-cost corridors. A dynamic version of this map is available in the species gallery: Pacific Fisher Klamath Connectivity Gallery.
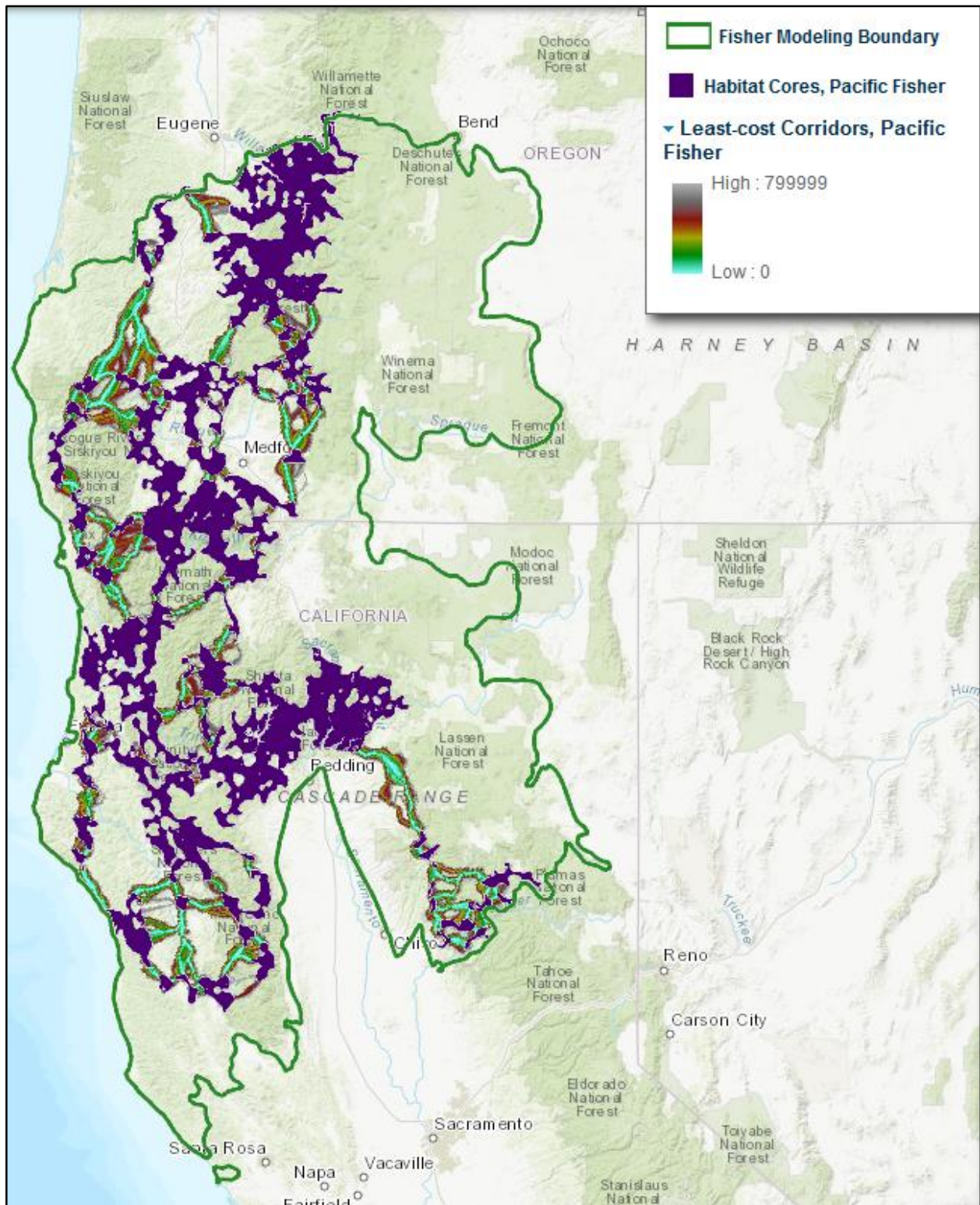
Marten

Core and linkage areas are somewhat more distinct for martens than for fishers, in part because martens live and breed in higher elevation conifer forests that are more limited in the region than the lower-elevation forests preferred by fishers. Marten cores are therefore generally more discrete and widely separated than fisher cores, often with long linkages that must cross lower-elevation habitats, which are unlikely to be suitable as live-in habitat and risky for inter-core movements (Figure 2). Managing to maintain or increase forest cover in these linkage areas may help maintain marten metapopulation function, but may also conflict with some forest management actions intended to reduce wildfire risks and increase forest resilience (e.g., forest thinning). A population genetic study in this region would be useful for identifying which subpopulations may be genetically connected or isolated to help identify where management interventions may be most beneficial. In general, marten core habitats are probably less threatened by forest management (e.g., timber harvest) and fires than is fisher habitat, but strategic habitat restoration projects may nevertheless increase marten population resilience.

Figure 2. Pacific Marten Connectivity Map showing habitat cores and least-cost corridors. A dynamic version of this map is available in the species gallery: Pacific Marten Klamath Connectivity Gallery.

Results - Data Products

Results of this project are available as maps and data that can be viewed and downloaded from Data Basin. We recommend the user start with the "Connectivity Gallery" for the species of interest, or use the index below to access individual products.

Fisher Connectivity

Pacific Fisher Klamath Connectivity Gallery
1. Pacific Fisher Connectivity Map
2. Pacific Fisher Connectivity Conservation Priority Areas Map

Connectivity Model Outputs
1. Linkage Priority Value, Pacific Fisher
2. Pinchpoints, Pacific Fisher
3. Least-cost Corridors, Pacific Fisher
4. Connectivity Conservation Priority Areas, Pacific Fisher
5. Areas of Uncertainty, Pacific Fisher

Input Data for Connectivity Model
1. Habitat Cores, Pacific Fisher
2. Enhanced Resistance Surface, Pacific Fisher

Input Data for Resistance Surface
1. Habitat Suitability, Pacific Fisher
2. Processed and Weighted Roads Data Layer
3. Clearcuts
4. High Burn Severity Fire
5. Water Bodies

Input Data for Fisher Habitat Suitability
1. Fisher Detections Used in USFWS Fisher Model
2. Model Regions for First Generation Fisher PPO for the West Coast DPS
3. Percent Slope, 10km-2 moving window, 90m
4. Latitude-adjusted Elevation, 10km-2 moving window, 90m
5. Tasseled Cap Wetness, 2000, 10km-2 moving window, 90m
6. Proportion Conifer Forest, 2008, 10km-2 moving window, 90m
7. Biomass, 2000, 10km-2 moving window, 90m
8. Mean Temperature Coldest Quarter, 1960-1990, 10km-2 moving window, 90m
9. Isothermality, 1960-1990, 10km-2 moving window, 90m
10. Maximum Temperature Warmest Month, 1960-1990, 10km-2 moving window, 90m

Marten Connectivity

Pacific Marten Klamath Connectivity Gallery
1. Pacific Marten Connectivity Map
2. Pacific Marten Connectivity Conservation Priority Areas Map

Connectivity Model Outputs
1. Linkage Priority Value, Pacific Marten
2. Pinchpoints, Pacific Marten
3. Least-cost Corridors, Pacific Marten
4. Connectivity Conservation Priority Areas, Pacific Marten

Input Data for Connectivity Model
1. Habitat Cores, Pacific Marten
2. Resistance Surface, Pacific Marten

Input Data for Resistance Surface
1. Habitat Suitability, Pacific Marten
2. Processed and Weighted Roads Data Layer
3. Clearcuts
4. High Burn Severity Fire
5. Water bodies

Input Data for Marten Habitat Suitability
1. Pacific Marten Detections, Klamath Region, OR and CA
2. Extents for Klamath Marten Habitat Suitability Model
3. Proportion Forest, 2012, 5km-2 moving window, 90m
4. Mean Annual Temperature, 1981-2010
5. Old-growth Structure Index, 2012, 5km-2 moving window, 90m
6. Slope, 0.64km-2 moving window, 90m
7. Slope, 2km-2 moving window, 90m
8. Marten SDM Input: 30-yr Normal Precipitation
9. Proportion Forest (v2), 2012, 5km-2 moving window, 90m
10. Forest Patch Density, 2012, 2km-2 moving window, 90m
11. Stand Age, 2012, 0.64km-2 moving window, 90m

How to Use The Data Products

Accessing the Data

The gallery for each species opens with two primary maps, followed by folders containing supporting data and intermediate results. We recommend that users first become familiar with these two primary result maps and then investigate them in more detail (e.g., by turning on and off various layers or changing their order or transparency) to better understand the results.

1. Connectivity Map (Figures 1 and 2 above). This shows the "basic" core and linkage (least-cost corridor) model outputs, along with some important input layers to aid in their interpretation.
2. Connectivity Conservation Priority Areas. This shows the connectivity outputs prioritized using various linkage prioritization metrics, again with some important input layers to aid interpretation.

Additional maps are also provided in folders below the primary maps for each species, to show model input data and intermediate model results that may be useful in interpreting the final results.

Uncertainties

These models and maps are offered as information to consider in conservation planning and management decisions. Because all models are simplifications limited by available data, they contain uncertainties and should be interpreted and applied with appropriate caution. The results are not presented as infallible truth about field conditions, but rather as hypotheses about geographic locations that are likely important to maintaining demographic and genetic integrity of populations or metapopulations in the planning region based on the criteria, data, and assumptions that went into model creation. It is critical that additional information, including expert opinion, field verification, and changing conditions be considered in applying the results to planning and management.

Considering these cautions, we have identified the following specific "Known Areas of Uncertainty" where we suspect data limitations, model assumptions, changing conditions, or other factors warrant extra caution in interpreting model results. These uncertainties should be carefully weighed when considering the results and where additional analyses may be helpful.

Fisher Occupied Areas Not Identified as Cores or Otherwise Potentially Important

● *Letts Creek and other Occupied Habitat in the Southern Coast Ranges*. The Letts Creek watershed area represents the southernmost habitat area in the Coast Ranges having recent fisher detections. Fishers in this and other southern Coast-Range subpopulations *may* have some genotypes valuable for fisher adaptation to climate change. A

population genetic study in the Coast Ranges might be valuable for informing management actions.

- *Lassen NF Green Mountain Area*. Fishers have recently re-occupied this isolated portion of Lassen NF (which is surrounded by private timber lands) southwest of Burney. Increasing habitat value in this area due to forest succession may be increasing its potential as a fisher core area and is likely to alter the location of a modeled least-cost corridor across Highway 299 and the Pit River watershed. Additional monitoring and analyses are needed to determine the importance of this subpopulation and potential linkages in the area.
- *South Shore of Lake Shasta.* Fishers have recently been observed in this area, which did not qualify as core habitat based on habitat modeling. Potential importance of this area to overall metapopulation integrity deserves more attention.
- *Old Baldy Research Natural Area west of Klamath.* Although the habitat model did not show this as a potential core area, recent fisher detection data suggest it may support a subpopulation of fisher (K. Moriarty, personal communication. Further monitoring is warranted.

Potential Fisher Linkages not Identified by Models

- *West Fork Salt Creek and Vicinity[1]*. No linkages were modeled in this area about 30-40 km south of Hayfork due to how model algorithms handle very large, convoluted cores close to one another: The single least-cost path between two cores is preferentially selected and used to model an inter-core linkage, even if alternative paths may also be functional and important to metapopulation connectivity. In this case, given the long and highly convoluted nature of the cores, alternatives farther south of the selected least-cost path (where the two cores come very close to one another near Hayfork) may also be functional and important. Further analyses of potential alternative linkages between these two cores are warranted east of the South Fork Trinity River between State Route 36 and Black Rock Mountain.
- *Red Mountain.* This area south of the Smith River (near Redwood State Park) and the Klamath River (near the Yurok Reservation) was not modeled as a linkage, but it may be functioning as one based on the density and linearity of fisher observations in the area (although this could be biased by heavy sampling intensity here). A north-south linkage here would complement the modeled linkage about 10 km farther inland near the Siskiyou Mountains). A more coastal linkage might improve population resilience in this region by adding a redundant, functional linkage.

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[1] We originally labeled this area as West Fork Salt Creek, but it includes a larger region east of the South Fork Trinity River, roughly between State Route 36 and Black Rock Mountain, about 30-40 km south of Hayfork.

- *Marten Locality Data.* Some marten locality points (e.g., on Mt. Shasta) were observations of martens at campsites or other high-elevation sites likely to have supplemental human foods that attract martens. This may add spatial bias to the model and possibly de-emphasize the importance of dense conifer forests at slightly lower elevations to marten habitat.
- *Potential Impacts of Recent Wind Energy Developments.* There are wind turbines and an associated road near Burney paralleling and partly within an important marten linkage that available landcover input layers did not reflect. Future modeling should consider these data (https://eerscmap.usgs.gov/uswtdb/), and field assessment of marten habitat in the vicinity may be warranted.

Methods

Decisions about species to include and modeling approaches were made collaboratively with the project partners as represented by the Core Team. CBI developed a draft analytical framework, tested and prototyped it, and presented interim results with key decisions for the Core Team to discuss in several review meetings. Meetings were held by conference line and screen share on January 26 2018, March 6 2018, and June 8 2018, March 21 2019, and a final review in January 2019. This report presents the final agreed-upon methods.

Project Region and Modeling Extents

This project was intended to inform conservation planning decisions in the Klamath Strategic Habitat Conservation Terrestrial Project area (Figure 3) as well as pre-listing decisions for two forest carnivores of conservation concern (fisher and marten) in a broader portion of northwestern California and southwestern Oregon. We therefore established fairly broad modeling boundaries to include areas occupied by the species that may contribute to overall species' metapopulation function in the region, as well as to put connectivity concerns within the Strategic Habitat Conservation planning area into a broader bio-functional context. Because habitat and connectivity modeling for the Humboldt marten (*M. c. humboldtensis*) was being performed separately by the Humboldt Marten Conservation Group (Slauson et al. 2019), and because connecting habitats for this coastal subspecies with more inland martens (*M. c. caurina* and *M.c. sierrae*) was not considered by experts to be feasible or genetically desirable, we excluded the geographic range of the Humboldt marten from these analyses (habitats west of the pink line in Figure 3).

Figure 3. Sub-regions and overall Modeling Boundary. [Link to map in Data Basin](#).

Overall Modeling Approach

We developed least-cost corridor models using the Linkage Mapper Toolbox. Least-cost corridor models require two inputs: core habitat areas to be connected and a resistance surface reflecting the costs or risks of animal movements between cores. The basic modeling process was similar for both species, but species-specific details are described following the general methods described here that were common to both species.

Habitat Value and Core Delineation

Habitat values were calculated and mapped using MaxEnt (Phillips et al. 2006), available GIS environmental variables, and species detection points. MaxEnt compares species detection points with a sample of background points to create a prediction of relative habitat suitability based on environmental variables in those locations and their interactions. For fisher, we used the composited regional models developed in concert with USFWS for the 2016 Fisher West Coast Distinct Population Segment status report (Fitzerald et al. 2013, USFWS 2016). For marten, we developed a new habitat suitability model for this report (see species-specific details below). For both species, MaxEnt models were run using 10-fold cross-validated replication using MaxEnt default parameters (with a few exceptions where alternatives were more defensible; see species details below) .

Resulting habitat suitability values were converted to 0 in areas of recent high severity fires and clearcuts (to account for vegetation changes later than the GIS vegetation data used in the models) and then smoothed by averaging values over a moving window that approximates each species' home range size (for comparability with other variables in the MaxEnt models). To define habitat cores, the resulting continuous suitability values were thresholded to create binary, suitable-unsuitable habitat polygons, and suitable patches > ~ 5 female home ranges were delineated as habitat cores.

Connectivity Modeling

Resistance surfaces were created at 90-m resolution by first transforming the continuous MaxEnt suitability values into resistance values using a negative exponential function:

$$R = 100 - 99 \left(\frac{1 - exp(-c \cdot H)}{(1 - exp(-c))} \right)$$

where R = Resistance, H is suitability, and c determines the shape of the curves (Keeley et al. 2016). Figure 4 shows example curves resulting from this transformation equation. We used c = 2 for fisher and c = 8 for marten based on expert opinion (see species-specific details, below)[2]; and instead of scaling resistance from 0 to 100 as in Figure 4, we scaled it from 1 to 1000 to accentuate resistance discrimination, based on expert opinion from previous projects and the literature (McRae and Kavanagh, 2011).

These initial habitat-based resistance values were further modified at finer (30-m) resolution based on expert opinion to account for factors that may affect movement costs or risks that are not adequately reflected in the habitat suitability outputs, such as recent high-severity fires and clearcuts, roads, and open water that may serve as barriers or filters to movement. For least-cost corridor modeling, it is important that potential influences on an animal's on-ground, fine-scale movement decisions (e.g., avoiding barriers), are reflected at the finest resolution available, whereas habitat models generally average variables at coarser resolution to account for differences amongst input variable resolutions (varying from 30 to 270-m for variables used in our models) and to reflect resolutions at which animals integrate habitat information when selecting habitat areas and establishing home ranges.

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[2] We use c = 8 for marten and c = 2 for fisher. C = 2 for fisher reflects that fishers, especially females, rarely disperse outside high-quality live-in habitat (dense, mature forest); and results with this parameter fit expert opinion about fisher movements. In contrast, marten appear to be more adventurous than fisher in passing through marginal habitats during dispersal (W. Spencer and K. Moriarty, expert opinion and J. Tucker genetic data) and the marten resistance surface has much less variance than the fisher surface, resulting in some unrealistic straight-line linkages with C < 8. We examined outputs with c = 2, c = 4, and c = 8, and determined that c = 8 best represented how marten likely move through the landscape.

Figure 4. Inverse exponential curves for converting habitat suitability values to movement resistance values. We used c = 2 for fisher and c = 8 for marten based on the animals' movement responses to habitat quality, and scaled the Y-axis from 0 to 1,000 to accentuate resistance (see text).
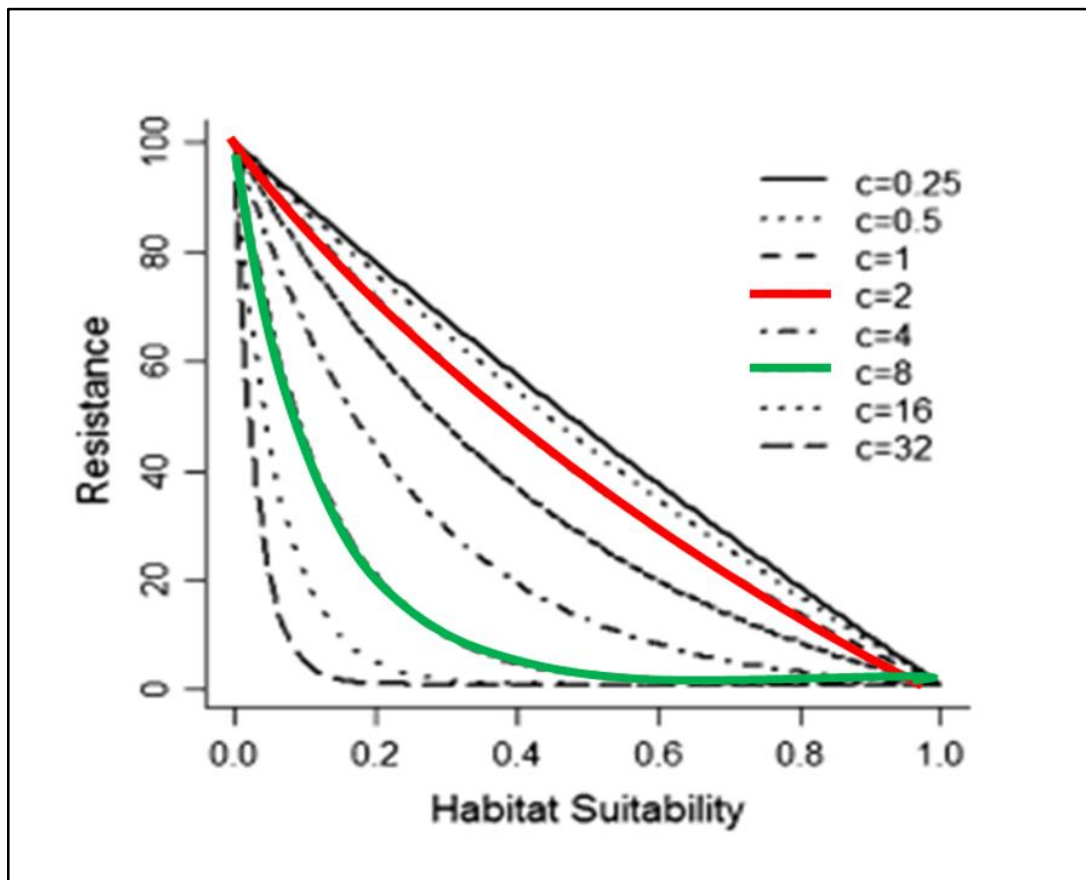
We then used the resulting "enhanced" resistance surface and the cores map layer as inputs to the Linkage Mapper software, which contains several tools:

1. We ran the Linkage Pathways tool to calculate least-cost corridors between core areas.
2. We ran the Linkage Priorities tool, which considers a suite of criteria, including the Centrality Mapper Tool results, to map the relative priority of each linkage *relative to other linkages* (described in further detail in the fisher section below).
3. We ran Pinchpoint Mapper, which uses Circuitscape software based on Circuit Theory to assign relative connectivity priority values *within* each linkage.
4. We then synthesized these products into a single layer, yielding two final products, a Connectivity Map (showing the least-cost corridors output) and a Connectivity Conservation Priority map (showing the synthesis and providing the user the ability to investigate the various prioritization schemes).

Fisher-specific Details

Habitat Value and Core Delineation

Pacific fisher core use areas in the Klamath region of California and Oregon were derived from the CBI MaxEnt relative habitat suitability model created in 2013 (Fitzgerald et al. 2013) for the USFWS listing evaluation (USFWS 2016). That effort, which covered the entire west coast fisher Distinct Population Segment (DPS) from California to British Columbia, subdivided the geographic range into 3 fisher-occupied regions and 3 non-occupied regions, and projected MaxEnt models from occupied onto unoccupied regions (Figure 5) with the exception of Region 5, for which an expert-opinion model was developed by USFWS. The regional models were combined in areas of overlap (between Regions 2 and 3, and between 4 and 5; Figure 5) using distance-weighted averaging, and then mosaicked together.

The final model for region 2 included the following 4 environmental predictors in order of mean permutation importance: Tassel-cap wetness, proportion conifer forest, latitude-adjusted elevation, and percent slope. The final model for region 3 included the following 5 environmental predictors in order of mean permutation importance: biomass, mean temperature of the coldest quarter, isothermality, maximum temperature of the coldest month, and percent slope. (See Fitzgerald et al. 2013 for details of the modeling methods and results.)

Our Klamath modeling extent encompasses large portions of occupied Regions 2 and 3, and small portions of unoccupied Regions 4 and 5 (Figure 5). For the current analysis, we projected the MaxEnt results for Regions 4 and 5 over the Klamath modeling extent as the basis for delineating potential core habitat areas. To update the 2013 habitat model to reflect vegetation changes due to more recent fire and management effects, areas with high burn severity (2000-2015, MTBS) and clearcuts (2000-2014, LANDFIRE) were converted to a suitability value of 0 and the habitat model re-run at the home-range scale. We thresholded the resulting continuous habitat value outputs using MaxEnt's equal training sensitivity and specificity threshold (which balances errors of omission and commission). Suitable habitat polygons > ~5 female core breeding ranges ($38.75km^2$ based on Spencer et al. 2015) were delineated as potential habitat cores.[3]

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[3] Spencer et al. (2015) analyzed unpublished data provided by R. Sweitzer for home range characteristics of fishers on Sierra National Forest in the southern Sierra Nevada. They found that adult female fisher "core-use" areas of $7.78km2$ minimized intrasexual overlap and therefore best represented exclusive female breeding ranges for purposes of population analyses. We rounded this to $7.75km2$ and calculated that $38.75km2$ represented a minimum core size to support at least 5 breeding females.

Figure 5. Fisher model extents used by Fitzgerald et al. (2013) and reinterpreted for the Klamath region. Solid colors are fisher-occupied model calibration regions; hatched areas are unoccupied regions where models were projected (arrows); green boundary is the fisher modeling extent for this Klamath Region analysis.

Resistance Surface

We created the fisher movement resistance surface according to the logic model shown in Figure 6. The process started with converting the MaxEnt fisher habitat values using the negative exponential function (Figure 4) using c = 2. The low exponent, c = 2, for fisher reflects that fishers, especially females, rarely disperse outside high-quality live-in habitat (dense, mature forest; based on J Tucker, genetic analyses). Also, sensitivity testing results with this parameter fit expert opinion about fisher movements better than higher (c > 2) alternatives.

This habitat-based foundation for the resistance layer was then modified using recent (i.e., post habitat-modeling data) clearcuts and severe fires to reflect how these habitat features are likely to influence fisher movements, as described above (Steps 2 and 3 in Figure 6). The resistance layer produced in Step 2 of Figure 6 was combined with the fire weights using MEAN to create the Step 3 resistance[4]. The results were finally "enhanced" by considering how water bodies and roads may influence fisher movements, using a MAXIMUM barrier function, as shown in Figure 6.

For this final enhancement step, roads were classified into six classes using OpenStreetMap data, augmented with state and federal government data for quaternary and tertiary roads (Table 1). Resistance values were ranked by expert opinion, from a maximum resistance of 1000 for major freeways (not crossed by fishers unless there are adequate crossing structures), a high resistance (600-800) for other major highways, lower resistance (200-300) for minor paved roads, and lowest resistance (120) for miscellaneous unpaved or unimproved roads (Table 1). Informal sensitivity analyses (testing various weightings and visually evaluating mapped effects on resistance) were used to refine initial estimates based on expert opinion. We assigned quaternary roads (e.g., logging roads) a non-zero resistance (120 or 200) because they are likely to slightly increase mortality risks by facilitating predator (bobcat, coyote, mountain lion) access into fisher habitat, as well as human access for illegal marijuana grow-sites and their associated risks to fisher due to rodenticides and other hazards.

Pixels lacking any environmental attributes (mostly rivers and lakes) were converted to a value of 1000 (lakes) or 600 (rivers or other) based on expert opinion. This is roughly consistent with treating lakes as being as impermeable to fisher movement as major highways and rivers as impermeable as primary paved roads (Table 1).

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[4] We combined clearcuts and fires into the resistance surface using "mean" instead of "maximum" with the assumption that if these disturbances happen in high quality habitat, then vegetation recovery in these areas will provide better habitat for dispersal than in areas where the disturbance occurred in low quality habitat.

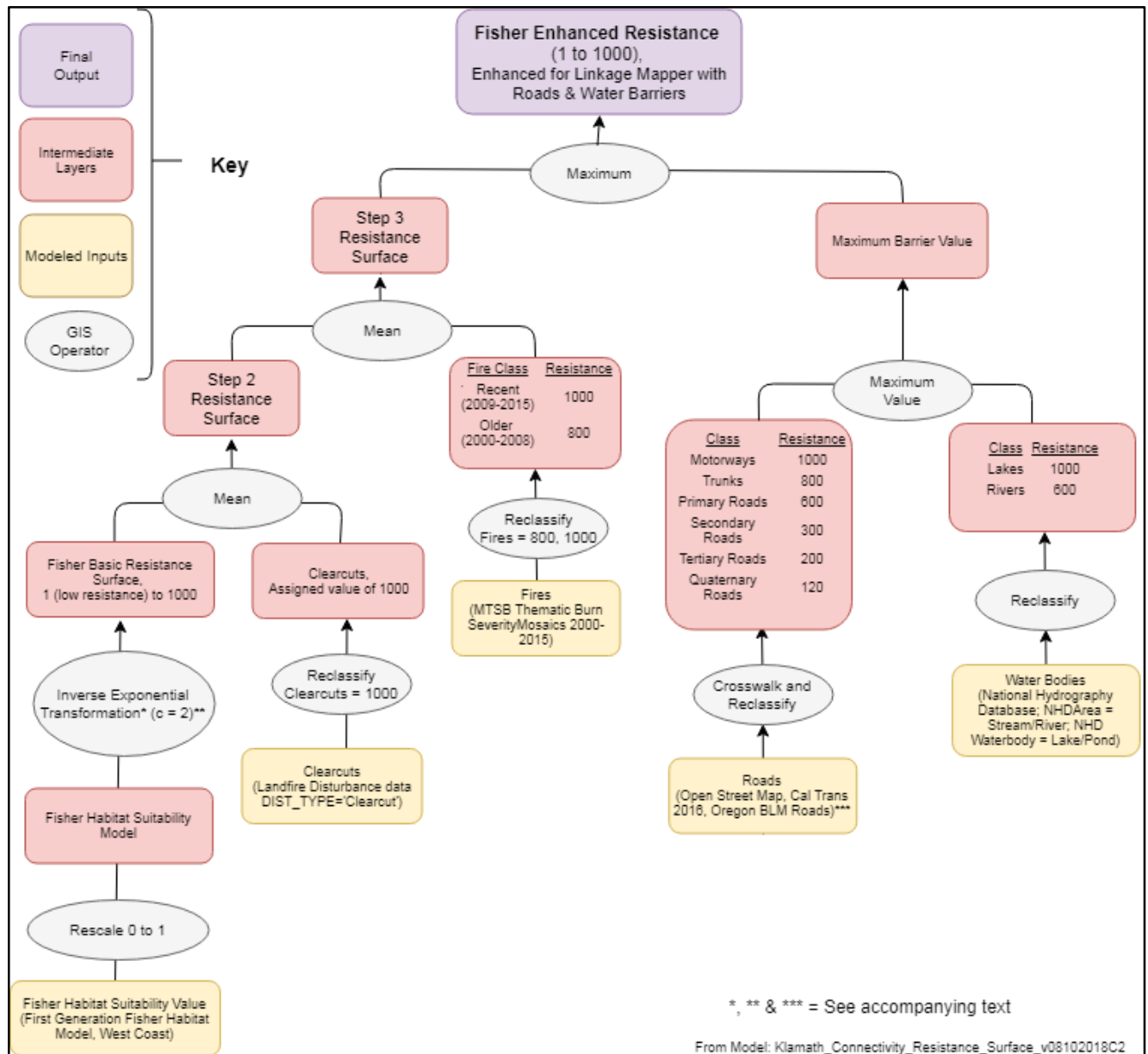**Figure 6.** The logic model for the fisher resistance surface.

Table 1. Road classes, their data sources, and resistance values assigned to them (see the roads layer in this [package of layers on Data Basin](#)).

Data Layer	Field(s)	Attribute(s)	Class	Class Name	Resistance
Open Street Map	Class Description	motorway	1	Motorway	1000
Open Street Map	Class Description	motorway_link	1	Motorway	1000
Open Street Map	Class Description	trunk	2	Trunk	800
Open Street Map	Class Description	trunk_link	2	Trunk	800
Open Street Map	Class Description	primary	3	Primary Road	600
Open Street Map	Class Description	primary_link	3	Primary Road	600
Open Street Map	Class Description	secondary	4	Secondary Road	300
Open Street Map	Class Description	secondary_link	4	Secondary Road	300
Open Street Map	Class Description	tertiary	5	Tertiary Road	200
Open Street Map	Class Description	tertiary_link	5	Tertiary Road	200
Open Street Map	Class Description	unclassified	6	Quaternary Road	120
CalTrans Roads, Combined with the above, using the max resistance value for a cell	mtfcc	S1100, S1200, S1400, S1630, S1640, S1730, S1740, OR S1750	N/A	N/A	120
Oregon_BLM Roads Combined with the above, using the max resistance value for a cell	SurfaceType	Hard Surface, Bituminous, OR Concrete	N/A	N/A	200
Oregon_BLM Roads Combined with the above, using the max resistance value for a cell	SurfaceType	Aggregate, Caliche, Crushed Sandstone, Grid Rolled, Natural Improved, Natural Unimproved, Not Known, Pit Run, OR Screened Base	N/A	N/A	120

Table 2. Roads data sources and processing.

Dataset	Source	Processing
OpenStreetMap data	https://download.geofabrik.de/north-america.html	Merged, projected and clipped to the study area (see Table 1 for types used)
BLM Oregon Roads data	https://www.blm.gov/or/gis/data-details.php?id=17	Converted to 90-m cell size and then reclassified as per the above table.
Caltrans data	ftp://svctftp.dot.ca.gov	Converted to a 90-m raster before being reclassified to the above resistance value (*Caltrans_quaternary_roads_120*)
Final Roads Output	New product	Created by combining the results of the previous processing using Cell Statistics using Maximum Resistance value to make sure that the highest weight is assigned to the cell in areas where there was overlap. These were then reclassified to remove values of 0 and assign those a NoData value to allow for proper integration into the fisher/marten resistance surfaces.

Table 3. Additional datasets and steps used to create the resistance layer.

Dataset	Source	Processing
Water Bodies	National Hydrography Dataset	Used feature classes NHDArea and NHDWaterbody to select out Streams/Rivers and Lakes/Ponds respectively. Streams/Rivers were weighted 600 and Lakes/Ponds were weighted 1000.
High Severity Fires	Monitoring Trends in Burn Severity (MTBS) Thematic Burn Severity mosaics (TIFFs) for Oregon and California years 2000-2015 (most recent available) were downloaded from MTBS on 2/2/18	The tiffs were converted to grids, reclassified (high burn severity, value = 4 was converted to 1, otherwise 0), and clipped to the Klamath model boundary. The Oregon and California yearly grids were mosaicked to new rasters using the "maximum" method. The yearly OR/CA grids were then combined to maintain yearly burn severity data (attributes HISEV_year where 1 indicates high burn severity during corresponding year). HISEV00_15 has value = 1 if high burn severity occurred any year from 2000-2015. We then weighted years 2000 to 2008 with a cost of 800 and years 2009 to 2015 with a cost of 1000.
Clearcuts	The most recent (2000-2014) disturbance data were downloaded from LANDFIRE on 6/25/18.	The yearly grids were reclassified (DIST_TYPE = 'Clearcut' was converted to 1, otherwise 0), and clipped to the Klamath model boundary. The grids were combined to maintain yearly clearcut data (attributes CCyear where 1 indicates clearcut during corresponding year). CC00_14 has value = 1 if clearcut occurred any year from 2000-2014. Clearcuts were assigned a weight of 1000 with the rationale that we used a MEAN to combine this layer with the inverse-exponentially-transformed Habitat Suitability layer, thereby reducing the high cost.

Create and Synthesize Connectivity Model Outputs

As described above, we used Linkage Mapper v2.1Beta5 to run Linkage Pathways, Pinchpoint Mapper, Centrality Mapper, and the Linkage Priority tool using the fisher cores and resistance layer as inputs. We used Linkage Pathways to make our Connectivity Map (Pacific Fisher Connectivity Map), and synthesized all the products to make our Connectivity Conservation Priorities Map (Pacific Fisher Connectivity Conservation Priority Areas Map).

Linkage Pathways Tool--We used an informal sensitivity analysis (visually evaluating mapped results using various parameter values) to establish a minimum linkage width of 800,000 cost-distance units for fisher. This correlated to about 2 km as the minimum linkage width for fisher, and roughly 1 km for higher-quality linkage value width. Since the linkages are mapped as a gradient (from green for more certain to brown for less certain on maps in Data Basin), this meant that the green (more certain) portions of the mapped linkage were about 1 km wide. The perception of fisher experts (W Spencer and C Thompson) is that 1 km is an appropriate minimum linkage width for fisher; and visualizing it this way, considering uncertainty, seemed appropriate and responsible. This tool yielded the least-cost corridor output, which is the standard connectivity output on our Connectivity Map. It also yields an auxiliary output that is useful for visualizing where individuals might feasibly explore for dispersal events, the cost-weighted distance layer.

Centrality Mapper and Linkage Priority Tools--We used the Centrality Mapper tool to determine the centrality of each core area, thereby indicating how important a linkage is for keeping the overall network connected (McRae 2012b). This tool uses Circuit Theory by calling upon Circuitscape algorithm from within the Linkage Mapper software. Then, for the Linkage Priority tool, we used mean permeability[5], and the average core area value of the two cores being connected. The core area value was an evenly weighted sum between the centrality, core habitat quality, and core shape (where rounder and bigger are better; see the bottom of Figure 6) (Gallo and Greene 2018). We used the default values for all other parameters.

Pinchpoint Mapper--We used the pinchpoint mapper tool of Linkage Mapper (McRae 2012a), which applies Circuit Theory to the landscape of cores and linkages, by calling upon Circuitscape software (McRae et al. 2008) to identify especially narrow or constrained portions of linkages. We used the "all pairs" evaluation rather than just adjacent pairs, and transformed the result to emphasize not only the pinchpoints region-wide, but to also shed light on the pinchpoints *within* each linkage. We did this by slicing the result into ten classes, and used the Jenks natural breaks function within ArcGIS, that achieves the normalization objective.

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[5] Mean permeability for this study was performed by (1) calculating the ratio of cost-weighted distance (CWD) of a linkage to the Euclidean distance of the path; (2) calculating an inverse score-range normalization of these values on the landscape, such that the linkage with the highest CWD to path length ratio becomes a zero, and the one with the lowest (the most permeable) becomes a 1, with all others scaled linearly between.

Synthesis of Connectivity Priority Metrics--Similar to what we have done in five other regions, including three in California (Gallo et al. 2019), we combined the above intermediate datasets into a single synthesis layer, called Linkage Connectivity Value, using evenly weighted sums, as shown in Figure 4. Recognizing that some cores may be more important to population resilience than others and that movement *through* core areas may also be important (especially given the narrow, convoluted configuration and dynamic habitat values of fisher cores in the Klamath region), we included this information in the Conservation Priority Areas map layer. To do this, we rescaled core area value (a product of the Linkage Priority tool) to range from 0.25 to 0.5 instead of 0 to 1[6]. We also clipped the resistance surface to the core areas, inverted it, and made it range from 0 to 1. We then combined these two using an evenly weighted sum. This result, the estimated connectivity value within each core, was burned into the Linkage Connectivity Value map (see Figure 7) to yield the second final product: the Connectivity Conservation Priority Areas layer. Doing this gives a more refined picture of conservation priority areas than the traditional linkage least-cost corridor output, which is better for visualizing the ecological process of connectivity.

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[6] We used 0.25 to 0.5 for core area values for several reasons: (1) This range reasonably distinguished the "best" cores from more "marginal" cores, while still retaining marginal cores as potentially important; (2) cores rated as 0.5 (max), when combined with low resistance lands within them, resulted in an overall rating of 0.75 rather than 1, because overall ratings of 1 resulted in huge swaths of very high-priority areas, thereby swamping out potentially more valuable but smaller linkage areas.

Figure 7. The logic model for used to produce the Connectivity Conservation Priority Areas map.
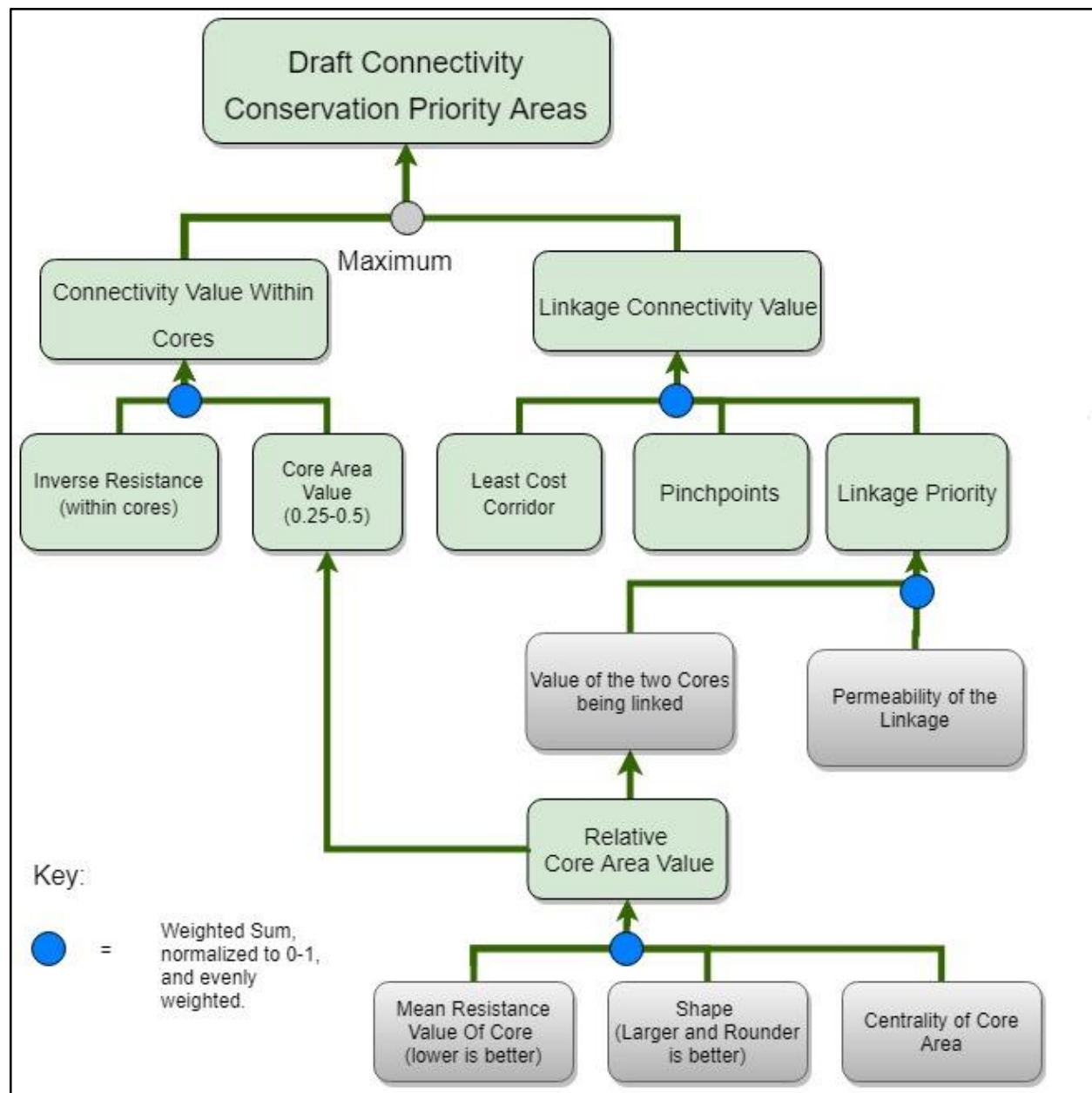
Marten-specific Details

Habitat Value and Core Delineation

Marten habitat cores were delineated from a MaxEnt habitat suitability modeling process using 10-fold cross-validation and three main steps: variable selection (testing predictors independently at multiple scales and evaluating predictor collinearity), multivariate model pruning, and model tuning. We usedMaxEnt default parameters except that we used linear, quadratic, and product feature types to produce smoother response curves (Santos et al. 2017) and because species response to ecological gradients are frequently nonlinear and interactions among predictors are common.

Model Extents--We delineated two model regions (north and south) within the larger Klamath study area (Figure 8) because previous model efforts suggested martens were selecting from different conditions in these regions. We clipped our model training extent to the Eastern and Western Cascades ecoregional sections to create the northern region and to the Southern Cascades and Sierra Nevada ecoregional sections for the southern region. Habitat suitability across the remaining larger study area was evaluated by projecting and averaging the models.

Detection and Background Data--Marten detection data from 1990 on were obtained from USFS NRIS (Natural Resource Information System) obtained from Region 5 (California) and Region 6 (Oregon); MSSC (California Mammal Species of Special Concern database), and CNDDB (California Natural Diversity Database, California Department of Fish and Wildlife, https://www.wildlife.ca.gov/Data/CNDDB). Detections obtained with visual, unknown, or aural methods and detections recorded by observers with limited or unknown experience were removed (n = 79). Detections (n = 31) overlaying developed open space, developed low intensity, or open water were also removed. To reduce sampling bias and improve model performance (Veloz 2009, Boria et al. 2014, Galante et al. 2017), remaining detections (n = 2899) were filtered to a minimum nearest neighbor distance of 977 m (approximate radius of female home range size, Moriarty et al. 2016), and divided into model training sets (n = 277: 114 north and 202 south) and testing sets (n = 69: 28 north and 51 south). We generated background points (n = 10,000) for each model region using the 'Create Random Points' tool in ArcMap (Version 9.3).

Figure 8. Marten detection data and model extents.
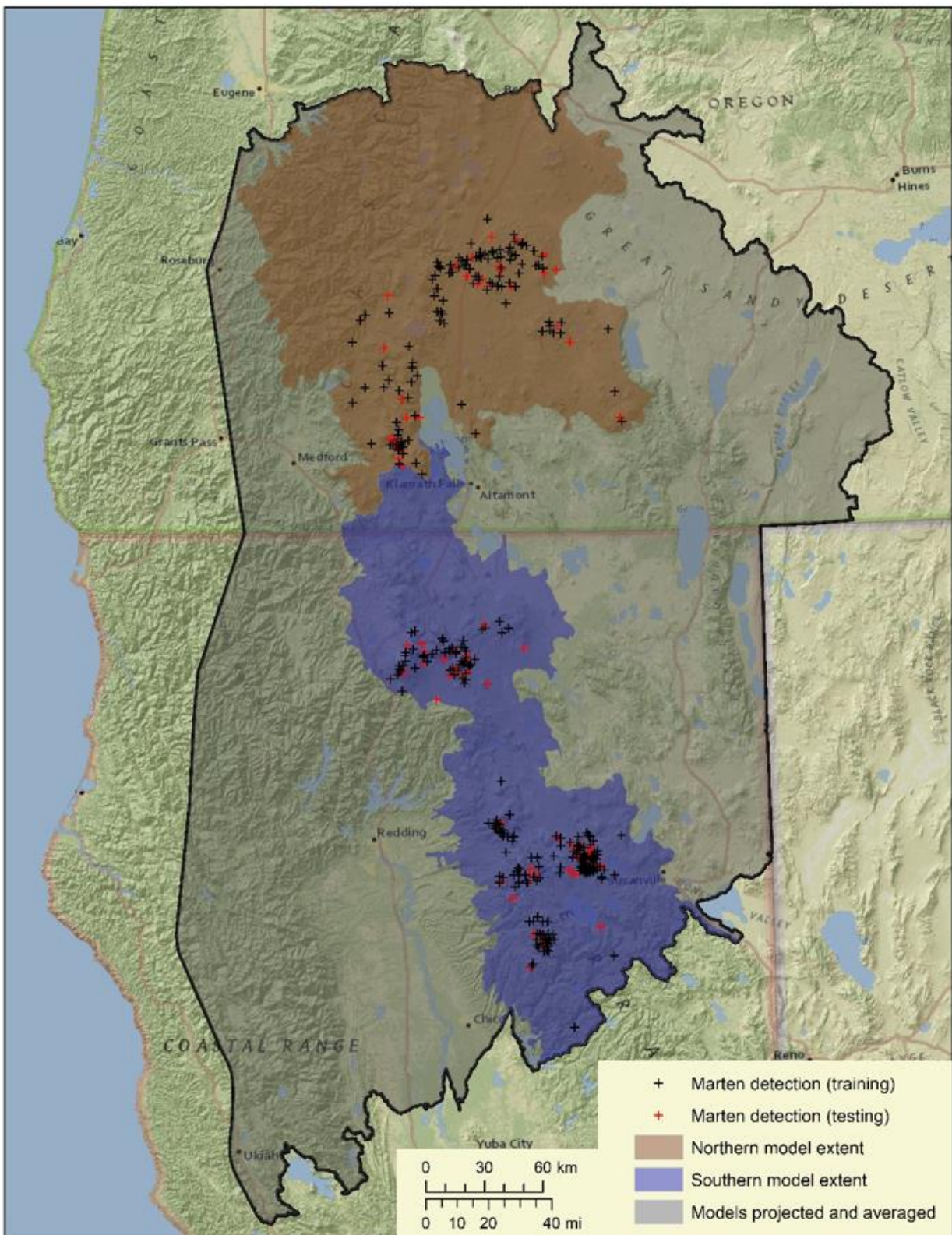
Variable Selection--We developed a set of 20 candidate environmental predictors considered important to marten habitat selection including climatic, topographic, and landscape composition and pattern variables at 90-m resolution (Table 4). Before using all candidate predictors in a 'full model', we conducted univariate analyses to determine the scales that best predict marten habitat selection in this region (Timm et al. 2016; Vergara et al. 2016). Univariate MaxEnt models were created using smoothed versions of our environmental predictors (not including climatic variables), derived at 3 circular moving window sizes (0.64, 2, and 5-km^2), selected to span a range of relevant scales, from sub-home range (0.64-km^2) to the home range scale (females 2.0-km^2 summer and 3.4-km^2 in winter, males 5.0-km^2 summer and 6.5-km^2 winter home range sizes, Moriarty et al. 2016). For each variable, we selected the moving window that produced the highest 10-fold cross-validated mean AUC (area under the receiver operating characteristic (ROC) curve, a threshold-independent assessment of model discriminatory ability, Fielding and Bell 1997) to carry forward for use in combination with climatic predictors in our multi-scale model. We next conducted a correlation analysis on the predictors using ENMTools (version 1.3, Warren et al. 2010). To create more parsimonious and interpretable results (Merow et al. 2013), we excluded correlated variables ($|r| > 0.7$), by selecting the one with the highest univariate 10-fold cross-validated mean AUC. Remaining predictors were carried forward to a multi-scale full model.

Table 4. Descriptions, sources, and best scales of predictor variables used in marten habitat suitability model.

Predictor Variable	Source	Best Scale North	South
Proportion of tree species with plurality of basal area = lodgepole pine, grand fir, or noble fir, AND quadratic mean diameter >= 25 cm, AND canopy cover > 40%	GNN 2012, Forest Structure, Landscape Ecology, Modeling, Mapping, and Analysis, Oregon State University, https://lemma.forestry.oregonstate.edu/data/structure-maps	5-km^2	5-km^2
Proportion of tree species with plurality of basal area = lodgepole pine, grand fir, noble fir, or Jeffrey pine AND quadratic mean diameter >= 25 cm, AND canopy cover > 40%	GNN 2012, Forest Structure, Landscape Ecology, Modeling, Mapping, and Analysis, Oregon State University, https://lemma.forestry.oregonstate.edu/data/structure-maps	5-km^2	5-km^2
Largest patch index of tree species with plurality of basal area = lodgepole pine, grand fir, or noble fir, AND quadratic mean diameter >= 25 cm, AND canopy cover > 40%	GNN 2012, Forest Structure, Landscape Ecology, Modeling, Mapping, and Analysis, Oregon State University, https://lemma.forestry.oregonstate.edu/data/structure-maps	5-km^2	5-km^2
Percent of like adjacencies of tree species with plurality of basal area = lodgepole pine, grand fir, or noble fir, AND quadratic mean diameter >= 25 cm, AND canopy cover > 40%	GNN 2012, Forest Structure, Landscape Ecology, Modeling, Mapping, and Analysis, Oregon State University, https://lemma.forestry.oregonstate.edu/data/structure-maps	5-km^2	5-km^2
Patch density of tree species with plurality of basal area = lodgepole pine, grand fir, or noble fir, AND quadratic mean diameter >= 25 cm, AND canopy cover > 40%	GNN 2012, Forest Structure, Landscape Ecology, Modeling, Mapping, and Analysis, Oregon State University, https://lemma.forestry.oregonstate.edu/data/structure-maps	2-km^2	0.64-km^2
Mean basal area weighted stand age (years)	GNN 2012, Forest Structure, Landscape Ecology, Modeling, Mapping, and Analysis, Oregon State University, https://lemma.forestry.oregonstate.edu/data/structure-maps	0.64-km^2	5-km^2

Mean basal area of live trees >=2.5 cm dbh (m²/ha)	GNN 2012, Forest Structure, Landscape Ecology, Modeling, Mapping, and Analysis, Oregon State University, https://lemma.forestry.oregonstate.edu/data/structure-maps	0.64-km²	5-km²
Mean canopy cover of all live trees (%)	GNN 2012, Forest Structure, Landscape Ecology, Modeling, Mapping, and Analysis, Oregon State University, https://lemma.forestry.oregonstate.edu/data/structure-maps	5-km²	2-km²
Mean diameter diversity index	GNN 2012, Forest Structure, Landscape Ecology, Modeling, Mapping, and Analysis, Oregon State University, https://lemma.forestry.oregonstate.edu/data/structure-maps	0.64-km²	5-km²
Mean regionalized old-growth structure index (OGSI)	GNN 2012, Forest Structure, Landscape Ecology, Modeling, Mapping, and Analysis, Oregon State University, https://lemma.forestry.oregonstate.edu/data/structure-maps	5-km²	5-km²
Proportion OGSI > 80 year old stand	GNN 2012, Forest Structure, Landscape Ecology, Modeling, Mapping, and Analysis, Oregon State University, https://lemma.forestry.oregonstate.edu/data/structure-maps	5-km²	2-km²
Proportion Quadratic mean diameter >= 25 cm AND canopy cover > 40%	GNN 2012, Forest Structure, Landscape Ecology, Modeling, Mapping, and Analysis, Oregon State University, https://lemma.forestry.oregonstate.edu/data/structure-maps	5-km²	5-km²
Mean solar insolation index	LANDFIRE Topographic Data, Department of Interior, U.S. Geological Survey, http://landfire.cr.usgs.gov/viewer/	5-km²	5-km²
Mean topographic roughness	NatureServe	0.64-km²	0.64-km²
Mean slope (∘)	LANDFIRE Topographic Data, Department of Interior, U.S. Geological Survey, http://landfire.cr.usgs.gov/viewer/	0.64-km²	0.64-km²

Mean annual temperature (∘C), 1981-2010	PRISM Climate Group, Oregon State University, http://prism.oregonstate.edu	NA	
Mean annual minimum temperature (∘C), 1981-2010	PRISM Climate Group, Oregon State University, http://prism.oregonstate.edu	NA	
Mean annual maximum temperature (∘C), 1981-2010	PRISM Climate Group, Oregon State University, http://prism.oregonstate.edu	NA	
Mean annual precipitation (mm), 1981-2010	PRISM Climate Group, Oregon State University, http://prism.oregonstate.edu	NA	
Perennial stream density (m/m^2)	National Hydrography Dataset, U.S. Geological Survey, https://nhd.usgs.gov	5-km^2	5-km^2

Model Pruning and Tuning--Beginning with our multi-scale full models (7 variables north, 9 variables south), we pruned the models in a stepwise process by removing the variable contributing the least information to model fit (highest mean training gain without the variable) to decrease model complexity and increase performance (Warren et al. 2014, Yiwen et al. 2016)*. The model was run again with the remaining predictors. This was repeated until only one variable remained. We selected the model with the fewest predictors having a mean training gain not significantly different than the full model. Significance was defined as lack of overlap between 95% confidence intervals for training gain means (calculated in R version 3.5.1; R Core Team 2013).

To decrease model overfitting, we tuned our selected model by varying MaxEnt's regularization parameter to constrain model complexity (Anderson and Gonzalez 2011, Merow et al. 2013, Radosavljevic and Anderson 2014, Warren et al. 2014). We varied the parameter from 0 to 5 in increments of 0.5 (default = 1), and used ENMTools 'Model Selection' function to calculate AIC (Akaike information criterion) for each *(Warren and Seifert 2011)*. For this analysis, MaxEnt was run with the variables from the selected pruned model, but using the 'raw' output and no replicates (required for model selection with ENMTools). We selected as the best model the one with the lowest AIC score.

We then ran MaxEnt with the logistic output option and 10-fold cross validation with the selected regularization parameters to get final output grids of relative habitat suitability using our multi-scale multivariate tuned models projected across the entire larger Klamath study area. The final 'pruned and tuned' model for the northern region used a regularization parameter value of 0.5 and included the following 6 environmental predictors in order of mean permutation importance: mean precipitation (1981-2010), mean temperature (1981-2010), mean slope (over 2-km^2 circular moving window), mean basal area weighted stand age (over
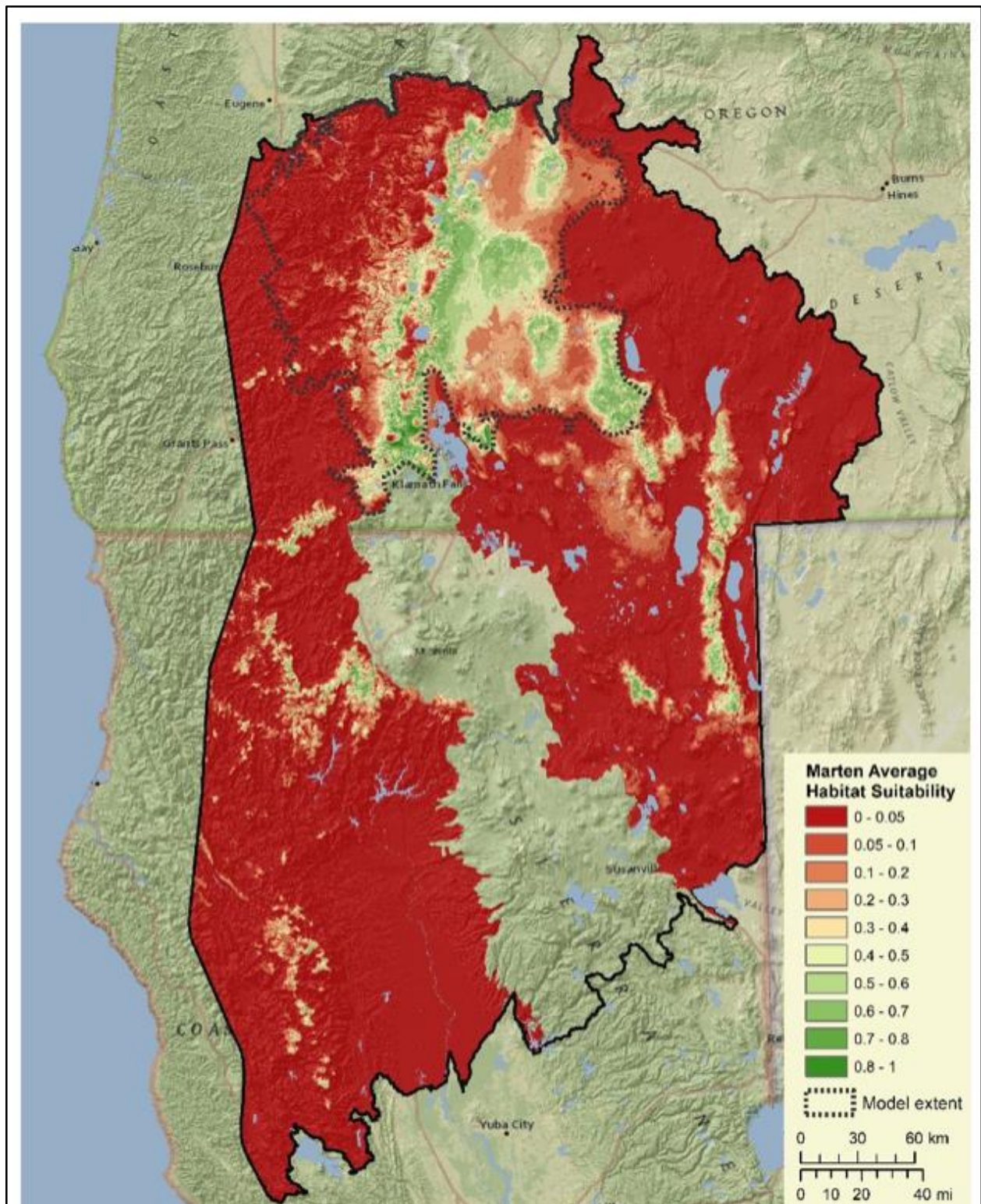
0.64-km^2 circular moving window), patch density of tree species with plurality of basal area as lodgepole pine, grand fir, or noble fir, AND quadratic mean diameter >= 25 cm, AND canopy cover > 40% (over 2-km^2 circular moving window), and proportion of tree species with plurality of basal area as lodgepole pine, grand fir, noble fir, and Jeffrey pine AND quadratic mean diameter >= 25 cm, AND canopy cover > 40% (over 2-km^2 circular moving window, Table 5, Figure 9).

This model has a mean 10-fold cross-validated test AUC score of 0.826 (standard deviation 0.044), mean 10% test omission of 0.148, mean difference between training and testing AUC of 0.047, and it correctly classified 60.7% of the reserved test occurrences using the equal training sensitivity and specificity threshold.

Table 5. Predictor permutation importance, northern region.

Predictor Variable	Full Model	Final Model
Mean annual temperature (◦C), 1981-2010	34.2	31.9
Mean annual precipitation (mm), 1981-2010	31.0	34.0
Mean slope (◦)	18.6	19.7
Mean basal area weighted stand age (years)	7.9	7.3
Patch density of tree species with plurality of basal area = lodgepole pine, grand fir, or noble fir, AND quadratic mean diameter >= 25 cm, AND canopy cover > 40%	4.9	4.9
Proportion of tree species with plurality of basal area = lodgepole pine, grand fir, noble fir, or Jeffrey pine AND quadratic mean diameter >= 25 cm, AND canopy cover > 40%	2.9	2.3
Mean solar insolation index	0.5	

Figure 9. Average relative habitat suitability for marten, northern model.

The final 'pruned and tuned' model for the southern region used a regularization parameter value of 1.0 and included the following 5 environmental predictors in order of mean permutation importance: proportion of tree species with plurality of basal area as lodgepole

pine, grand fir, and noble fir (over 5-km^2 circular moving window), mean temperature (1981-2010), mean precipitation (1981-2010), mean regionalized old-growth structure index (over 5-km^2 circular moving window), and mean slope (over 0.64-km^2 circular moving window, Table 6, Figure 10).

This model has a mean 10-fold cross-validated test AUC score of 0.899 (standard deviation 0.028), mean 10% test omission of 0.114, mean difference between training and testing AUC of 0.019, and correctly classified 82.4% of the reserved test occurrences using the equal training sensitivity and specificity threshold.

Table 6. Predictor permutation importance, southern region.

Predictor Variable	Full Model	Final Model
Proportion of tree species with plurality of basal area = lodgepole pine, grand fir, or noble fir AND quadratic mean diameter >= 25 cm, AND canopy cover > 40%	31.2	45.5
Mean annual temperature (◦C), 1981-2010	30.3	26.5
Mean annual precipitation (mm), 1981-2010	16.6	15.1
Mean slope (◦)	8.6	5.8
Mean regionalized old-growth structure index (OGSI)	6.4	7.2
Perennial stream density (m/m^2)	2.6	
Mean basal area of live trees >=2.5 cm dbh (m^2/ha)	2.4	
Patch density of tree species with plurality of basal area = lodgepole pine, grand fir, or noble fir, AND quadratic mean diameter >= 25 cm, AND canopy cover > 40%	1.8	
Mean solar insolation index	0.1	

**Figure 10.** Average relative habitat suitability for marten, southern model.
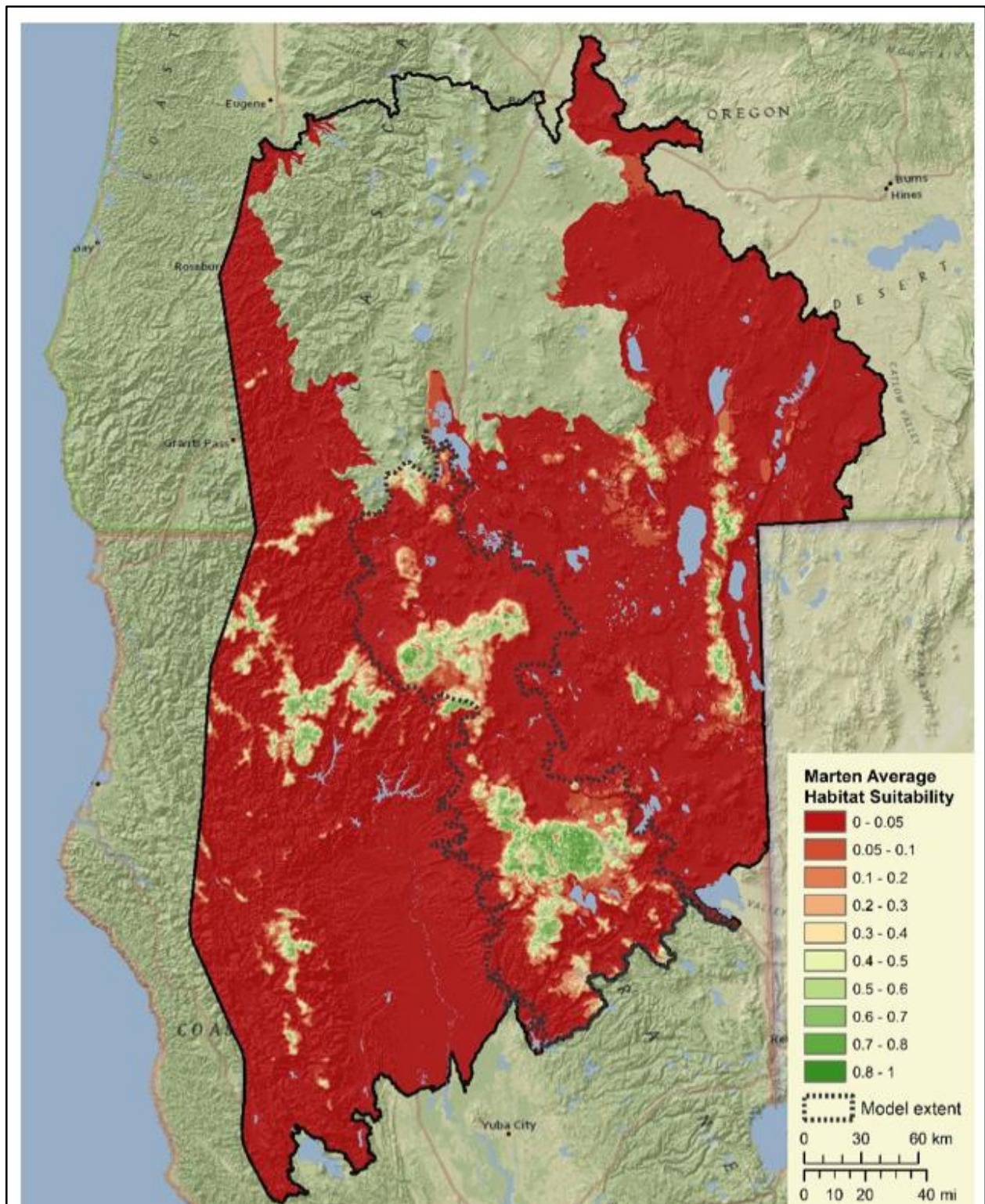
Habitat Core Area Delineation--Pacific marten core habitat areas were derived from the final models described above, defined as contiguous blocks of suitable habitat large enough to support at least five female home ranges. A mosaic of the model output grids was created, averaging outputs where both models were projected, outside the model calibration extents. Areas with high burn severity (2012-2015, MTBS) and clearcuts (2012-2014, LANDFIRE) post-model vegetation data (GNN 2012) were converted to a suitability value of 0 and then smoothed by calculating the focal mean using a 3-km^2 circular moving window (approximate female home range size, Moriarty et al. 2016).

While many thresholds are available to distinguish suitable from unsuitable habitat in MaxEnt models (Peterson et al. 2011), we often use the maximum sum of sensitivity and specificity (as we did above for model evaluation) which has been shown to be robust and consistent (Cao et al. 2013, Liu et al. 2013, Liu et al. 2016). However, we found that threshold to be too inclusive for core area delineation in this case, and instead opted to use the equal training sensitivity and specificity threshold, which has also been shown to be accurate (Cao et al. 2013).

Values in the smoothed layer greater than or equal to the equal training sensitivity and specificity threshold (0.466 for northern model, 0.383 for the southern model, the average of the two for areas outside model calibration regions) were extracted and areas of open water (NHD Waterbody, reservoir and perennial lake/ponds) were assigned a suitability value of 0. The resulting suitable habitat grid was then converted to polygon format. Polygons with area less than ~5 female home ranges (15-km^2, Moriarty et al. 2016) were removed, leaving 31 potential core use areas, ranging in size from 15 to 3897-km^2 (Figure 11).

**Figure 11.** Modeled marten core use areas.
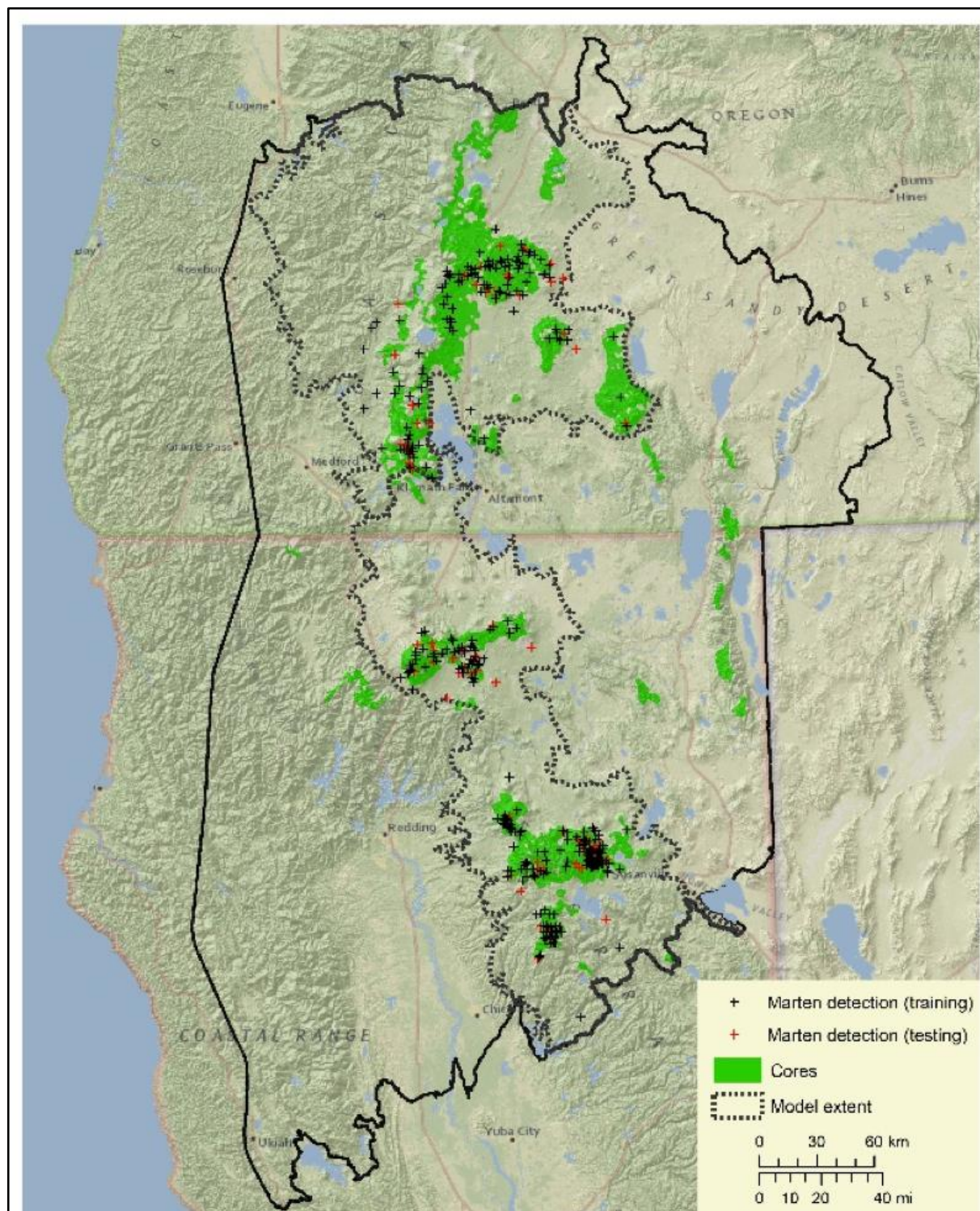
Resistance Surface

We used habitat values from the marten MaxEnt model, transformed with a negative exponential function, as a foundation for the resistance surface, and modified the results to account for movement influences not captured by the model. For marten, we used $c = 8$ in the negative exponential transformation (compared with $c = 2$ for fisher) based on expert opinion, sensitivity analysis, and literature suggesting that martens may be less discriminating of habitat value than female fishers when dispersing[7]. We also used slightly less resistance for marten than fisher for moving through fires and clearcuts based on expert opinion: 900 (recent) and 700 (older) instead of 1000 and 800 for fires; and 900 instead of 1000 for clearcuts. We used slightly different post-fire and post-clearcut resistances for martens (compared to fisher) because marten have been known (on Vancouver Island) to use young (<10 years) conifer forests following clearcutting and to use second growth (10-40 years) more than expected (Baker 1992). In these places, they use large stumps remaining from former harvest for resting (Baker 1992). We assumed that most clearcuts and fires mapped in the study area have such resting sites. All other methods used to create the marten resistance surface were the same as for fisher, as summarized in Figure 12.

Create and Synthesize Connectivity Model Outputs

We used the same methods for marten as for fisher to create and synthesize the connectivity model outputs, except for one parameter value: For marten, we set the maximum cost-weighted corridor distance to 40,000 cost-weighted km (rather than leaving it blank as for fisher). Otherwise, linkages would have been unrealistically mapped between the core at Manzanita Mountain (just west of the Warner Mountains) down through 60 km of mostly inhospitable, low and open habitat to Logan Mountain to the south, or Medicine Mountain to the west. This also removed an errant linkage from earlier runs that went from the Warner Mountains to Logan Mountain. All the other methods for creating and synthesizing intermediate layers were the same as for fisher.

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[7] Marten appear to be more adventurous than fisher in passing through marginal habitats during dispersal (W Spencer and K Moriarty, expert opinion and J. Tucker genetic data); and the marten resistance surface has much less variance than the fisher surface. We examined outputs with $c = 2$, 4, and 8, and determined that $c = 8$ best represented how marten likely move through the landscape. Using $c < 8$ resulted in unrealistically straight-line linkages where more sinuous movements, influenced by landcover, would be expected.

Figure 12. The logic model for the marten resistance surface.
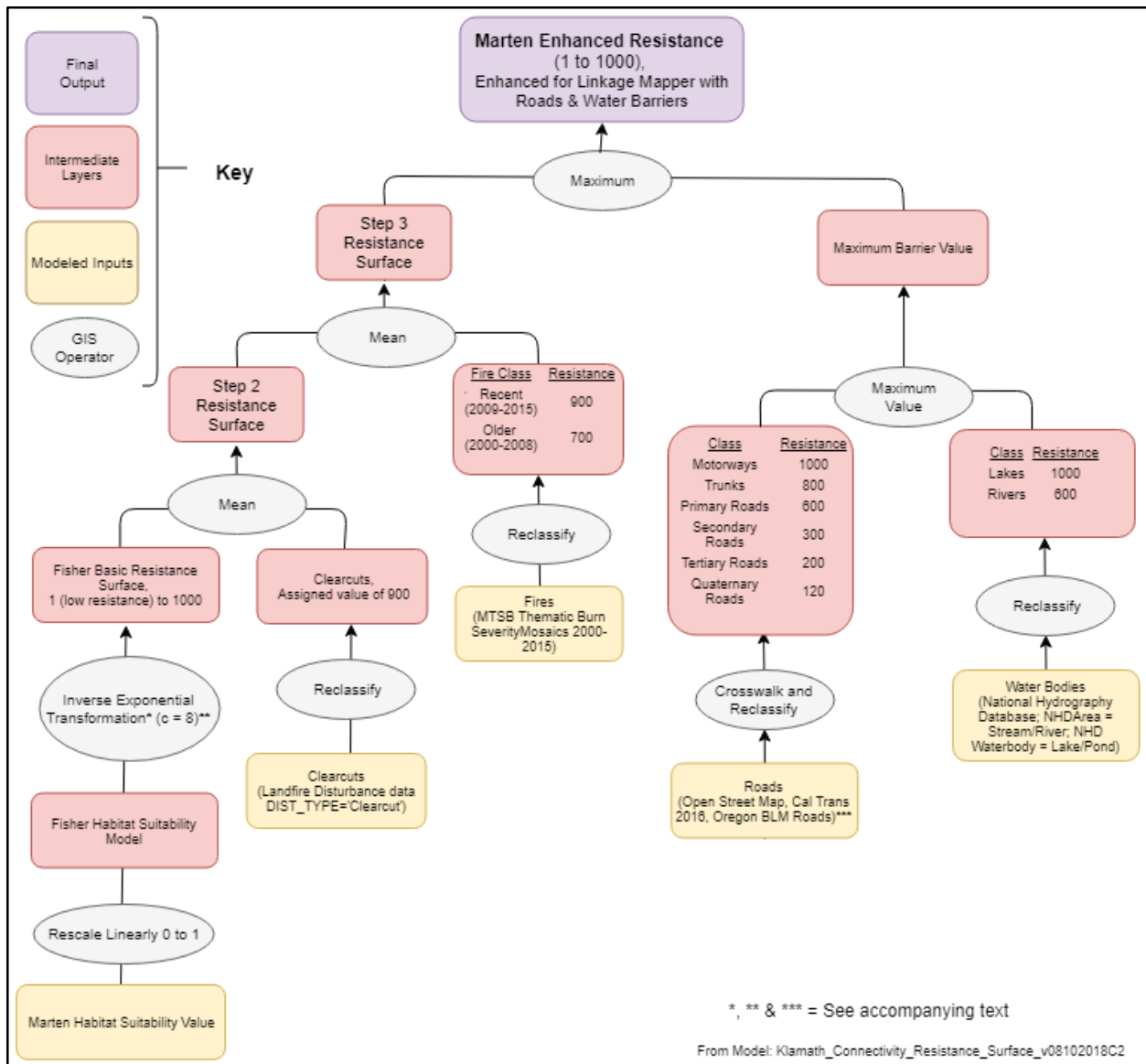
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