Designing Regional Fuel Breaks to Protect Large Remnant Tracts of Greater Sage-Grouse Habitat in Parts of Idaho, Nevada, Oregon, and Utah

Final Report

Prepared by The Nature Conservancy
for the
Western Association of Fish & Wildlife Agencies
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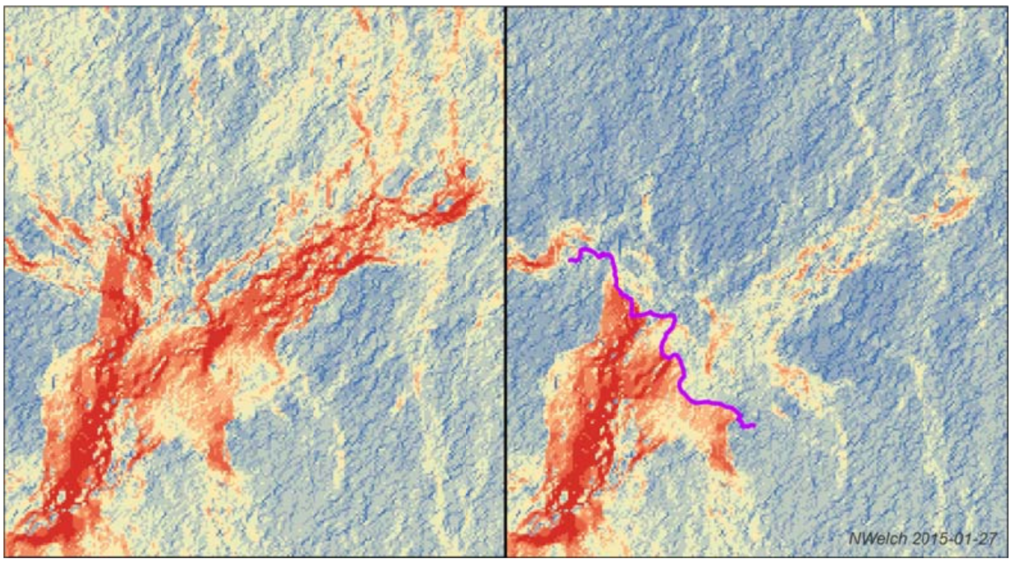

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Introduction

Since the U.S. Fish & Wildlife Service (2010) ruled that the Greater Sage-Grouse (GSG; *Centrocercus urophasianus*) is warranted for listing under the Endangered Species Act, but precluded at this time by other priority listing actions, western land managers have been scrambling to improve the condition of the species' sagebrush-steppe habitat. The loss of sagebrush-steppe habitat to uncharacteristically large and frequent wildfires has been identified as the primary threat to GSG populations in the western portion of the species' range (USFWS 2013). Despite regional coordination of suppression resources among federal and state agencies, there have been few successes in preventing or minimizing large wildfires. Policy documents regularly identify the need for landscape-scale approaches to design and implement fuel treatments (e.g., fuel breaks) to prevent loss of GSG habitat (e.g., BLM and Forest Service 2013; Jewell 2015).

In an effort to help federal and state agencies reduce the impact of large wildfires, we developed a GIS protocol for identifying strategic locations for fuel breaks and simulating potential fuel breaks to protect remaining large patches of important GSG habitat. As a demonstration, we applied our protocol to a 27 million acre (110,000 km^2) region that includes parts of Idaho, Nevada, Oregon, and Utah; and devised general recommendations for a regional network of fuel breaks. The Project Area (**Figure 1**) includes the Northern Great Basin (26a) and Box Elder (26b) GSG populations designated by the U.S. Fish & Wildlife Service. For our analyses, the Project Area is surrounded by a 30-km buffer. This buffered landscape totals 41 million acres (164,000 km^2). **Figure 2** shows an overlay of GSG Breeding Density Areas (Doherty et al. 2010) and Priority Areas for Conservation identified by the Fish & Wildlife Service (2013) in the Project Area. We used such classifications to identify important GSG habitat in the Project Area.

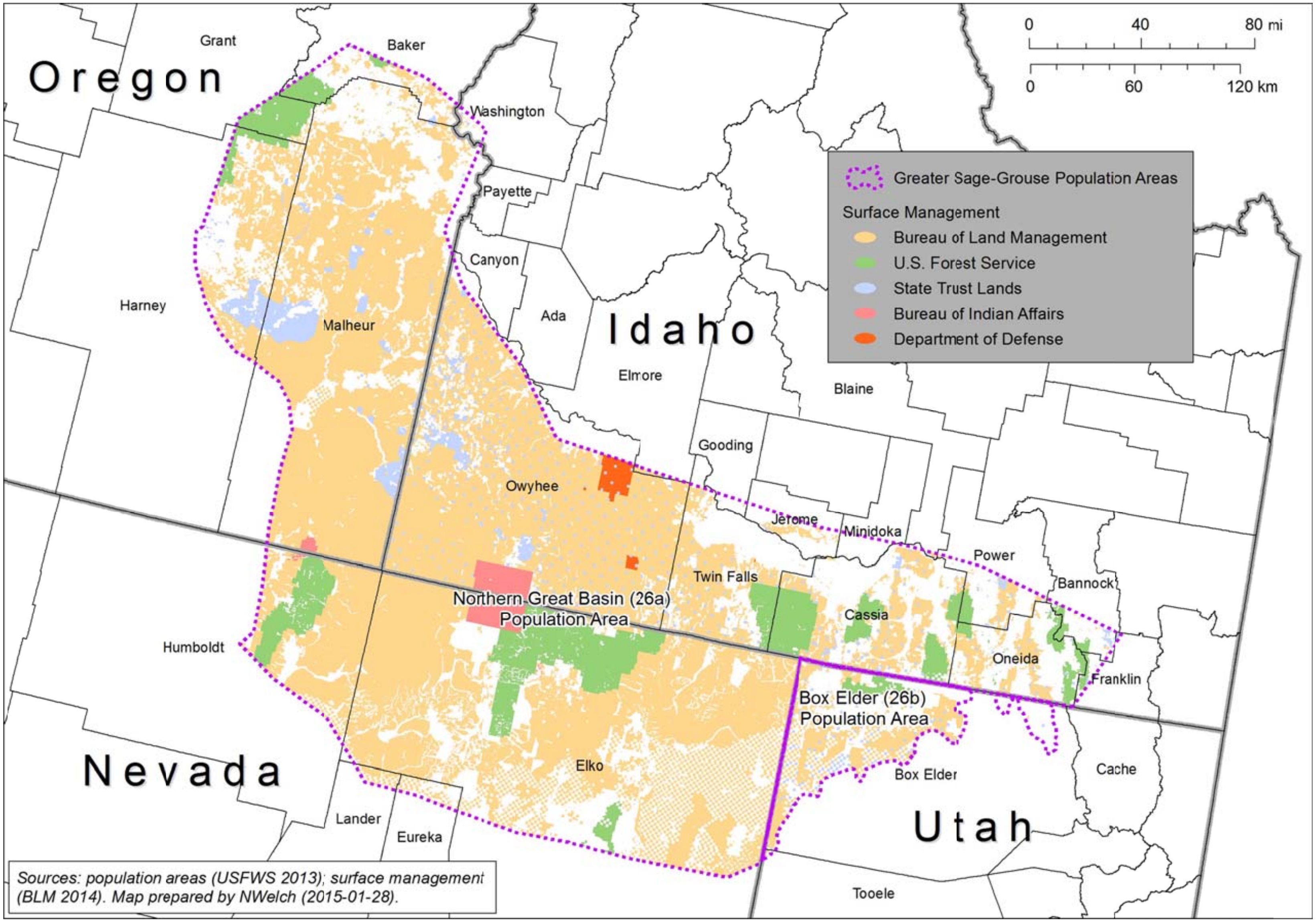

Figure 1. Project Area.

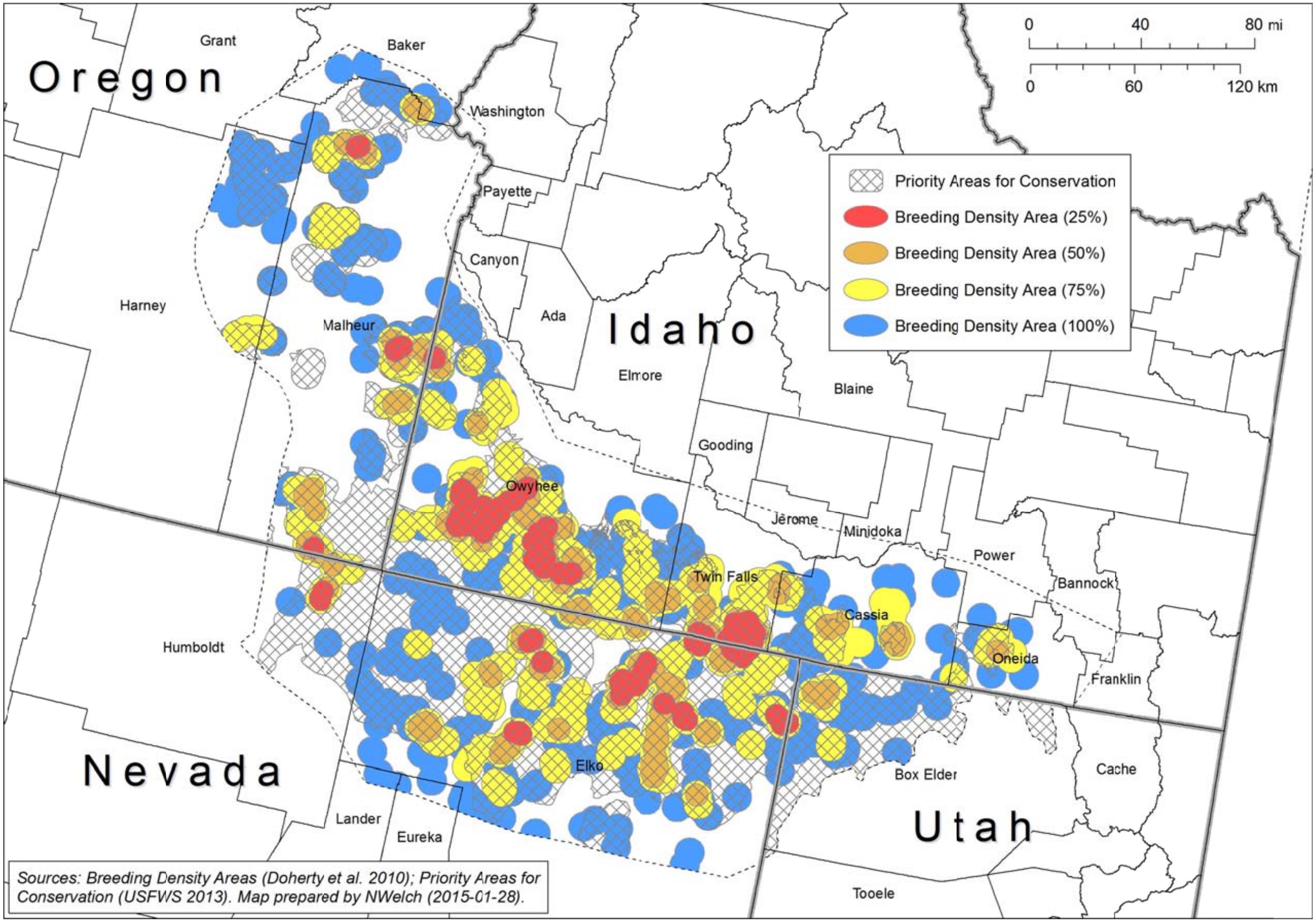

Figure 2. Examples of important-habitat classifications for Greater Sage-Grouse in the Project Area.

Rather than applying traditional fire behavior models, we took a phenomenological approach to wildfire modeling where different spatial data are related to each other in ways that are consistent with fundamental theories about wildfire, but are not directly derived from these theories. Consequently, we can investigate general questions about wildfire across regional landscapes with existing datasets that would overwhelm traditional fire behavior models that require many large datasets and intensive computer resources. Moreover, we attempted to keep our methodology simple and reproducible so others can design fuel breaks within this Project Area or explore fuel break placement in new areas.

We intend our findings to be used to help identify general locations where fuel breaks might be an appropriate and efficient tool for protecting important GSG habitat from wildfire. We are not recommending the exact location, configuration, or composition of fuel breaks. These details must be determined using local information and expertise. In preparing our general recommendations and sample artificial fuel breaks, we are striving to make use of and augment existing fire-resistant features (e.g., roads and other highly-disturbed areas) and avoid sensitive or protected areas.

This final report includes a full description of our methods, maps illustrating model inputs and outputs, and general recommendations for developing a regional network of strategically-located fuel breaks. The report is accompanied by a collection of GIS data in a compressed file geodatabase (FuelBreakDesignData_TNC_20150130.zip). The file geodatabase (.gdb) includes the vector and raster data shown in the report. Contact the authors to download a copy of the data.

Methods

We used Circuitscape, a free, open-source software program (http://www.circuitscape.org), to model wildfire and simulate fuel breaks. Circuitscape was originally developed for modeling habitat connectivity for wildlife (McRae et al. 2008; McRae et al. 2013). However, it is now being applied to other ecological topics, including wildfire (Gray 2013; Gray and Dickson *In press*). The software is based on electrical circuit theory and represents landscapes as conductive surfaces and maps the flow of electrical current across them. Resistance is the inverse quantity of conductance and is the concept we used. The inputs for the model are *sources* where electrical current enters the system, *grounds* where current departs the system, and a *resistance surface* across which the current will flow between sources and grounds. The Circuitscape program generates a map of current flow or density, which we interpret as *wildfire transmission* and *fuel break potential*.

Circuit models can be related to ecological processes via connections between circuit and random walk theories (McRae et al. 2008). In particular, circuit models are useful in identifying “pinch points”, or areas where movement, or flow, is concentrated because there are few alternative routes available. Pinch points have high current flow or density in a Circuitscape model output. Such pinch points have been prioritized in the past for maintaining landscape connectivity for wildlife, because their loss could disproportionately disrupt *animal movement*. For our purposes, these pinch points provide connections between areas with high flammability, but where adjacent areas with low flammability could constrict wildfire movement. We interpreted these pinch points, or *areas with high wildfire transmission*, as opportunities for installation of fuel breaks, because of their potential for disproportionately disrupting *wildfire movement*. Areas with high wildfire transmission would have high fuel break potential.

Sources

For our purposes, a source represents the location of a wildfire ignition. Our source raster is created by randomly selecting 10,000 ignition locations throughout the Study Area (the Project Area and a 30-km buffer) (**Figure 3**). In the model, 1 Amp of electrical current is injected at each of these locations simultaneously. We simulated fuel breaks on the landscape by modifying the sources raster to include negative current sources that remove fire from the system. The process of delineating and modeling fuel breaks is described in the "Fuel Breaks" section below.

Grounds

We placed grounds along the northeast edge of the Study Area. We selected the northeast edge because prevailing winds in this region blow from southwest to northeast and we assumed large fires generally move with prevailing winds. Electrical current injected at sources will generally flow toward the grounds and ultimately leave the landscape there. The ground raster was created by placing a continuous line of pixels along the northeast edge of the landscape, each connected to ground with a resistance of 1 Ohm (**Figure 3**).

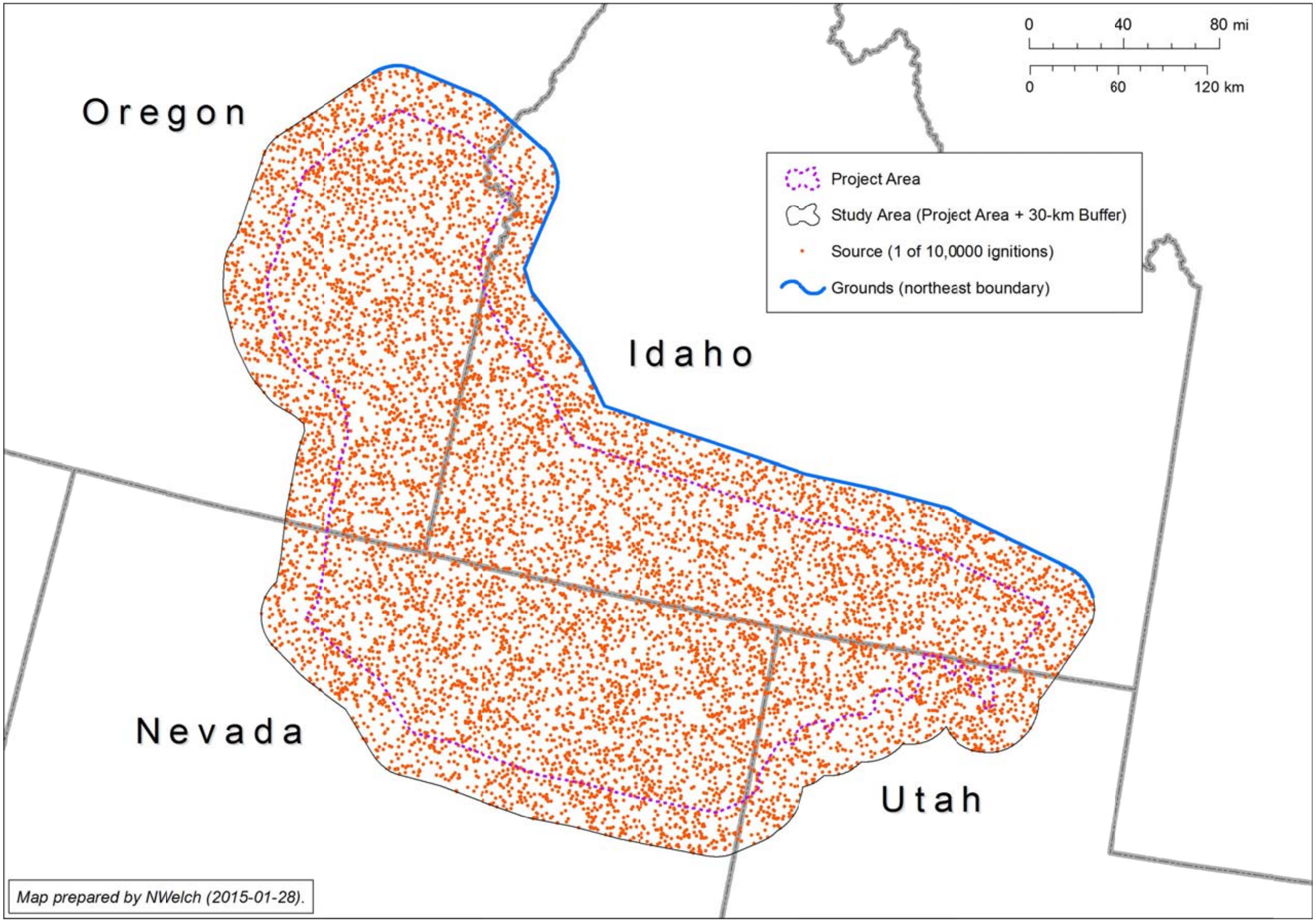

Figure 3. Sources and grounds.

Resistance Surface

For this study, a resistance surface is a landscape grid or raster made up of pixels (e.g., 90 m x 90 m grid cells), where each pixel is assigned an index value of flammability. Pixels with high resistance values represented locations on the landscape with low flammability and vice versa.

We calculated flammability using published fire return intervals (York et al. 2008; Provencher et al. 2013) and spatial information about vegetation (LANDFIRE 2010; http://www.landfire.gov), recent fires (GeoMAC & Monitoring Trends in Burn Severity; http://www.geomac.gov and http://www.mtbs.gov), cheatgrass abundance (Boyte et al. 2013), and heat load index (Evans et al. 2014). Heat load index is a relative estimate of solar radiation that accounts for slope and aspect (McCune & Keon 2002) and correlates with fuel moisture. **Figures 4–9** show a complete resistance/flammability raster and several of the rasters used to estimate flammability.

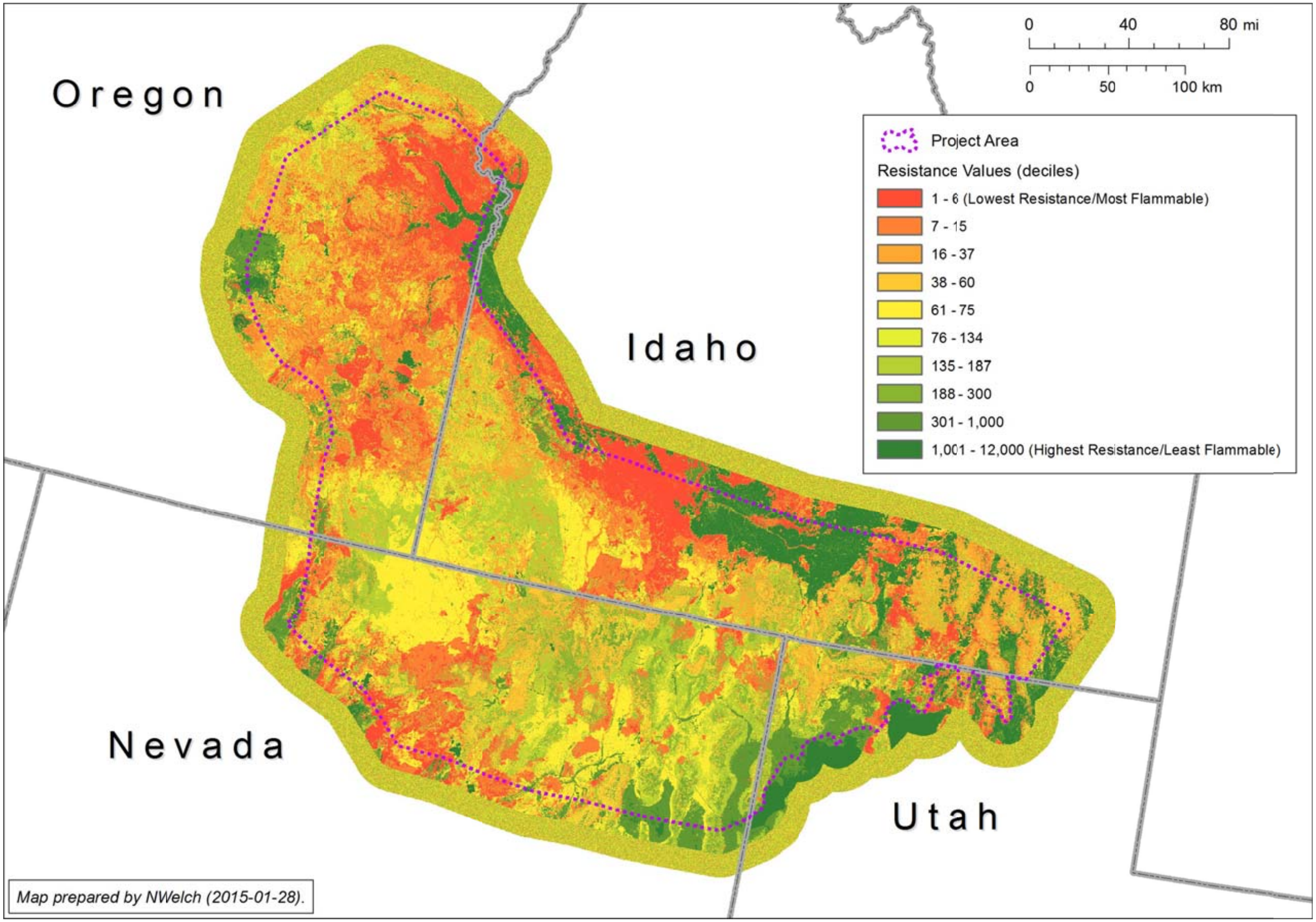

Figure 4. Resistance/flammability raster.

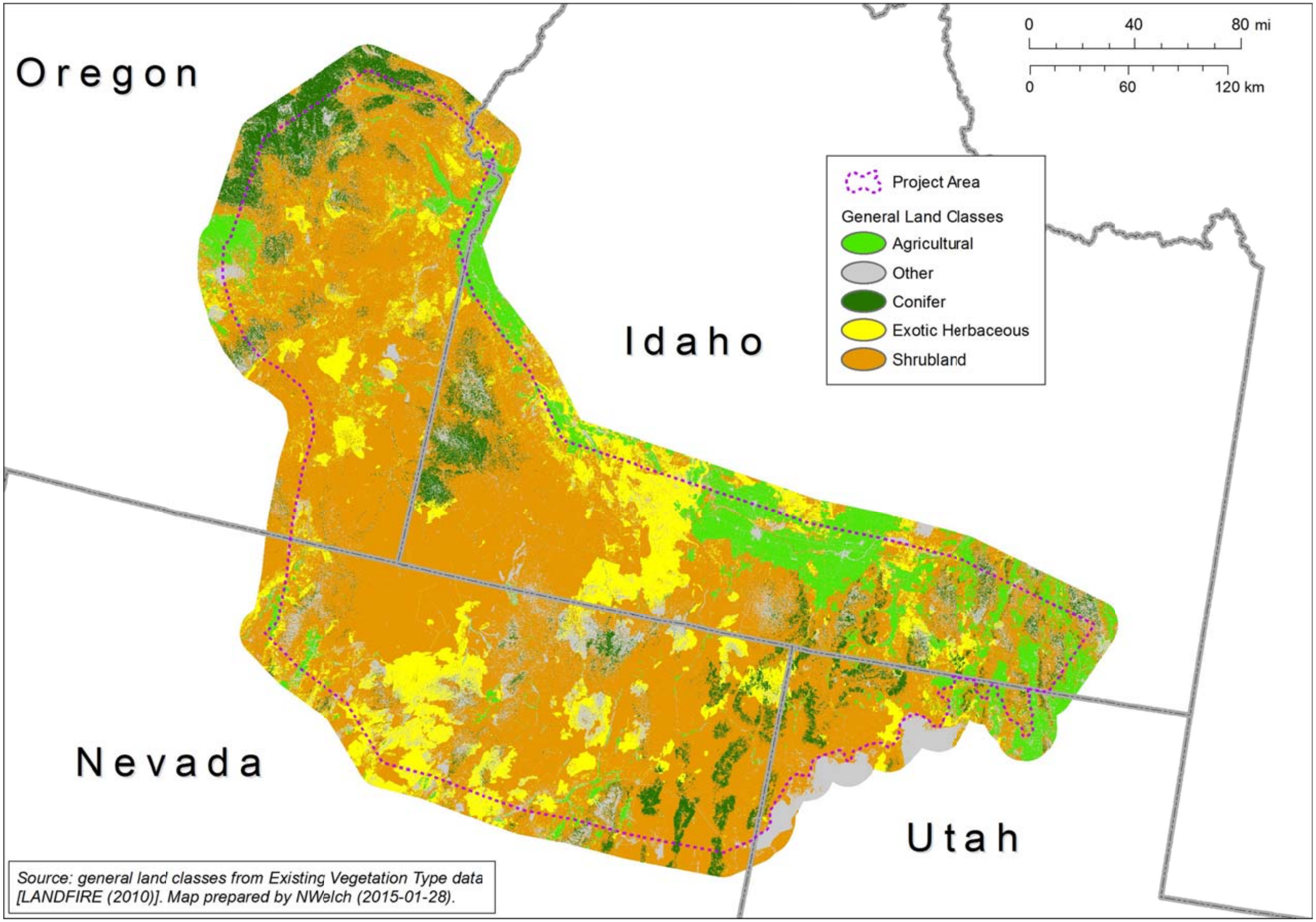

Figure 5. Existing Vegetation Types is one of the LANDFIRE (2010) datasets used to calculate resistance. This map shows general land classes and is intended for general reference only.

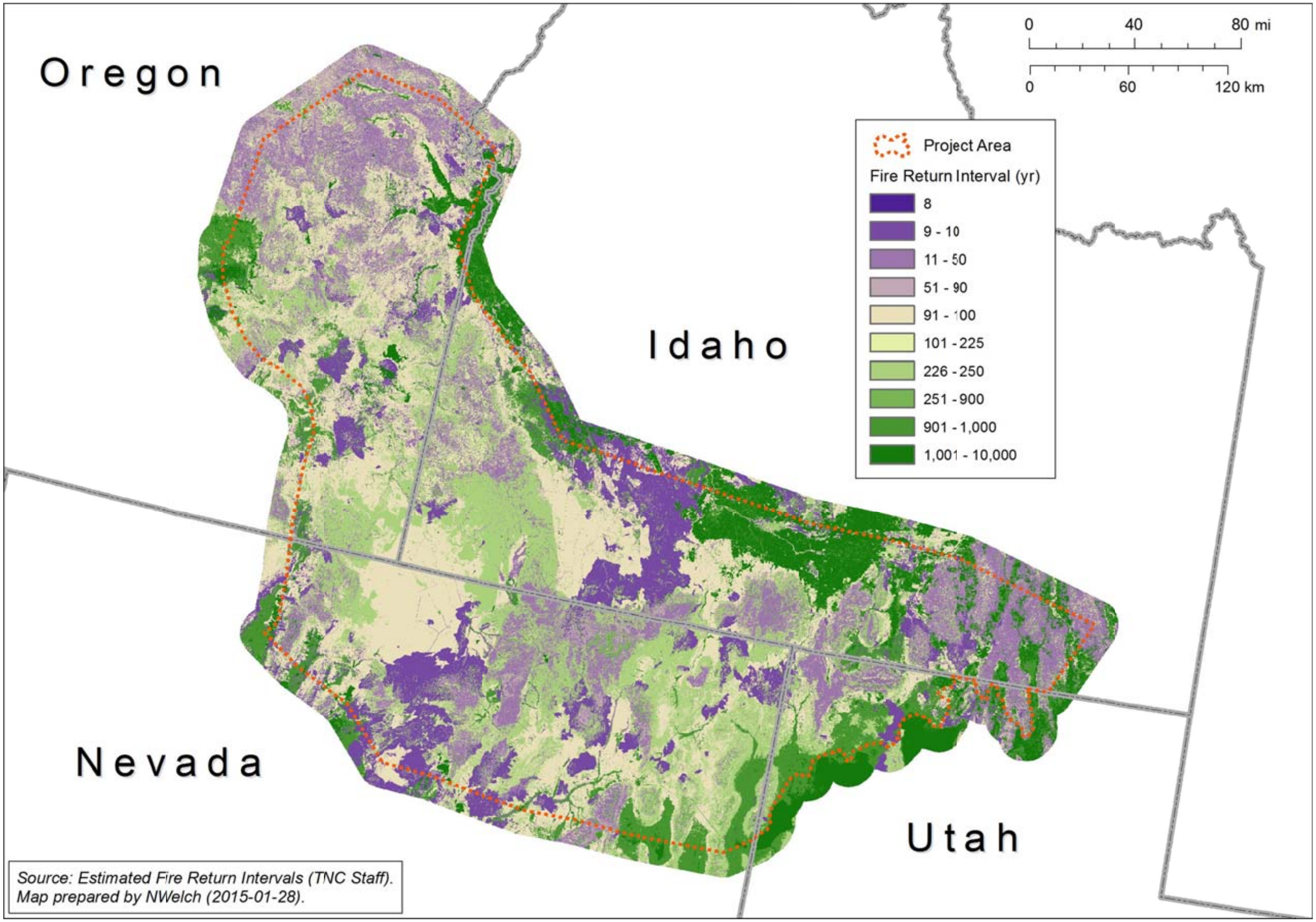

Figure 6. Fire Return Interval (FRI) values assigned by The Nature Conservancy (TNC) Staff using LANDFIRE (2010) and TNC project data (York et al. 2008; Provencher et al. 2013).

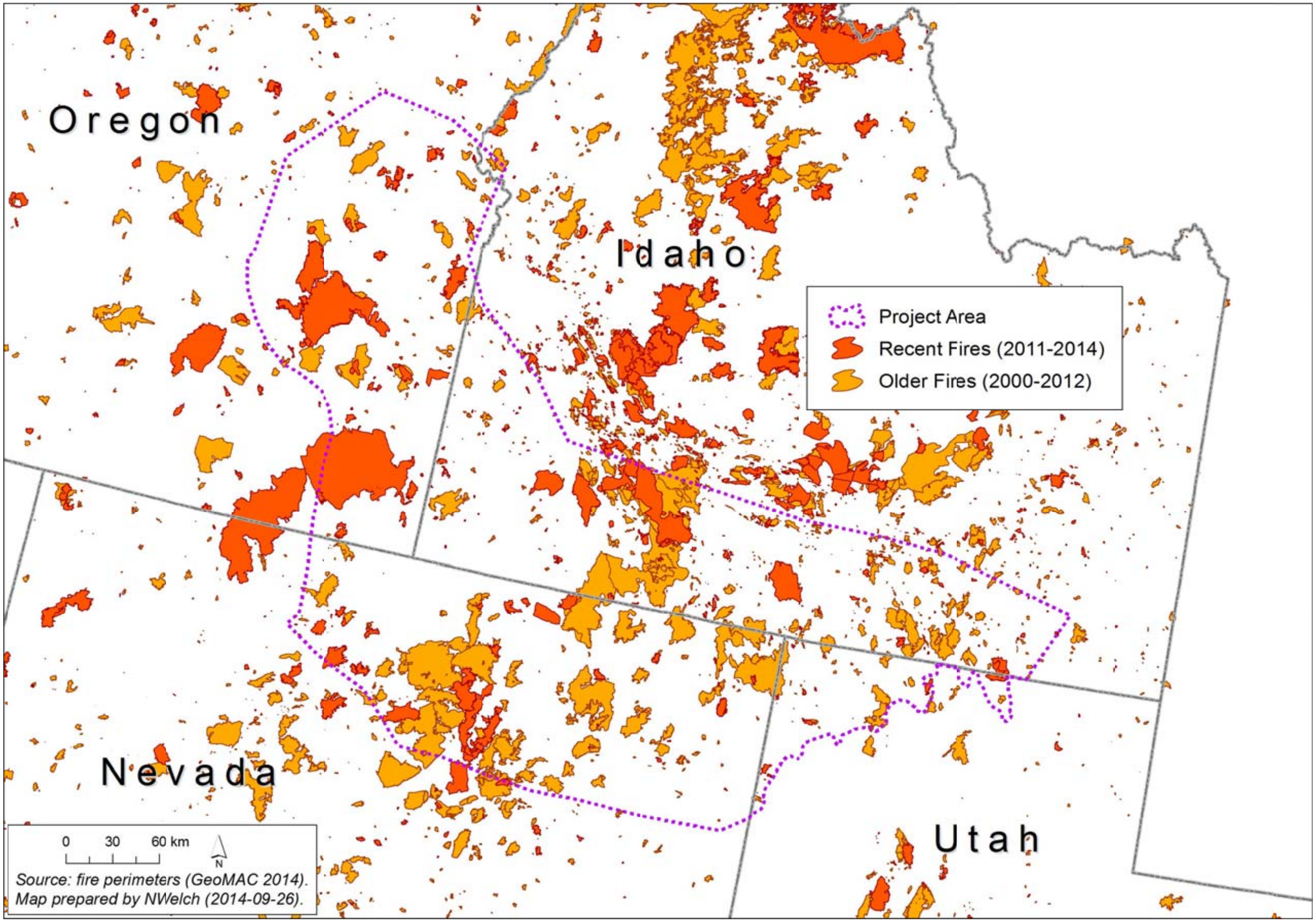

Figure 7. Fire perimeters (2000-2014).

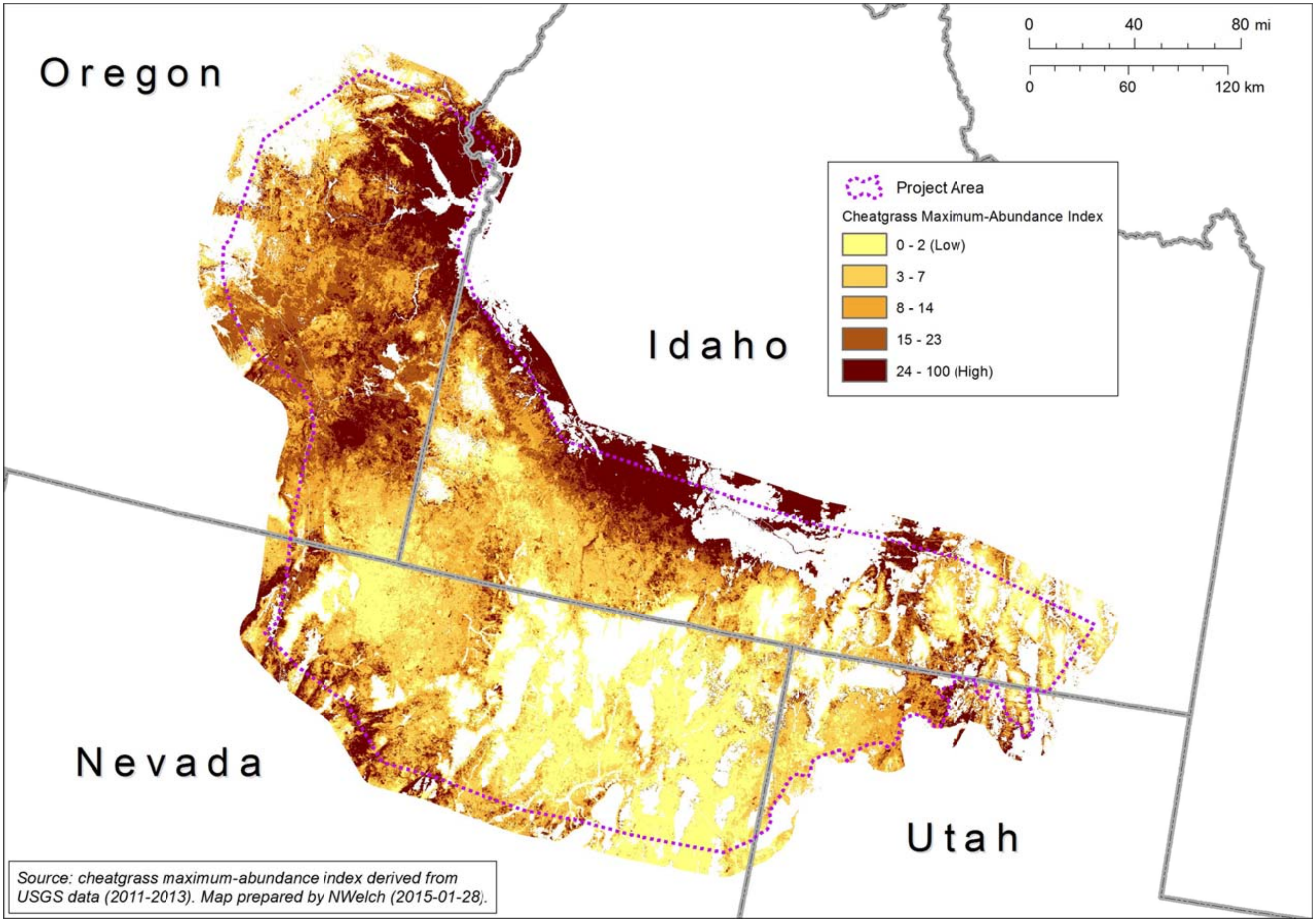

Figure 8. Cheatgrass maximum-abundance raster (2011-2013).

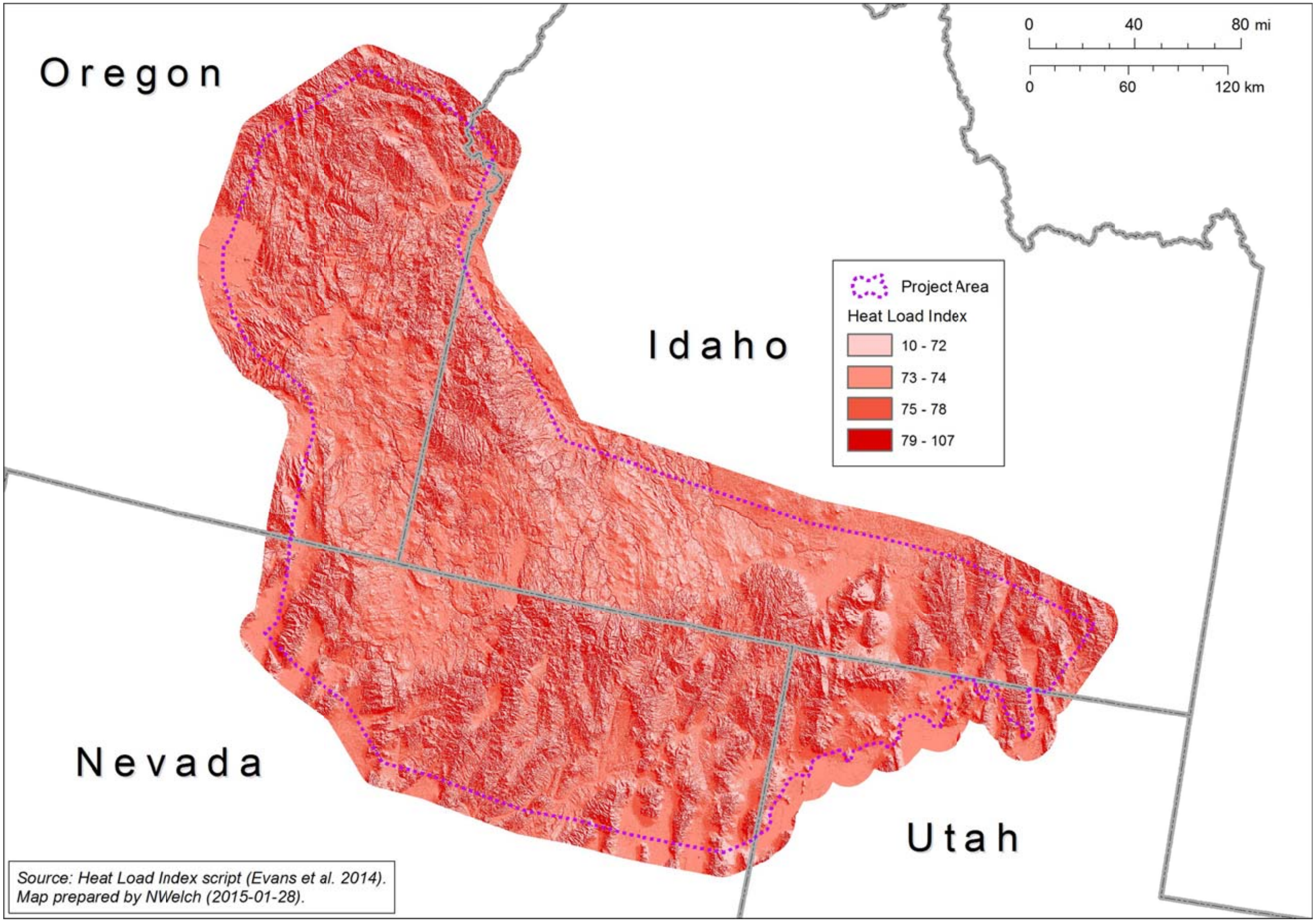

Figure 9. Heat load index raster.

Resistance Calculation

First, we identified ecological systems in the landscape by spatially combining LANDFIRE (2010, LF_1.2.0) rasters for Existing Vegetation Type, Biophysical Settings, and Succession Classes (LANDFIRE - http://www.landfire.gov) and assigned Fire Return Intervals (FRI's) to each combination. These FRI's ranged between 8 and 10,000 years. For example, an exotic annual grassland class of Wyoming big sagebrush was given a FRI of 10 years, whereas a late-succession reference class of Wyoming big sagebrush was given a FRI of 100 years.

Second, we assigned new FRI's to select shrubland types that burned in 2011-2014 (GeoMAC - http://www.geomac.gov/), since the release of LANDFIRE (2010). We assumed these shrubland types were likely converted to annual grasslands with shorter FRI's. This reflected how LANDFIRE might deal with fire in these systems.

Third, we modified all FRI's using multiplication factors based on the abundance of cheatgrass. We received cheatgrass abundance rasters (2011, 2012 & 2013) from the authors of a U.S. Geological Survey study that modeled annual cheatgrass abundance for our Project Area (Boyte et al. 2013). We combined these rasters by choosing the maximum cheatgrass abundance value for each pixel and creating a new maximum-abundance raster. Pixels with higher cheatgrass maximum-abundance were assigned smaller multiplication factors (e.g., 0.06, 0.15, or 0.45) and consequently the resistance of these pixels was reduced (i.e., its flammability increased). Pixels with lower cheatgrass maximum-abundance were assigned larger multiplication factors (e.g., 0.75 or 1.00). Each factor represented the average ratio of the new FRI of a class with additional cheatgrass divided by the FRI of the pixel before modification. After modifying our FRI raster with multiplication factors, we then referred to this raster strictly as a resistance or flammability raster.

Fourth, we modified the flammability raster using multiplication factors based on Heat Load Index (HLI) values for the landscape. Heat Load Index captures information about slope and aspect and is calculated using a Digital Elevation Model (DEM) and a central latitude. South-facing slopes with higher solar radiation have high HLI values and, as a result, lower soil & fuel moisture, while north-facing slopes with lower radiation and higher soil & fuel moisture have low HLI values. We calculated HLI using a Python script provided by Evans et al. (2014). Pixels with low, moderate, and high HLI values were arbitrarily assigned multiplication factors of 1.2, 1.0, and 0.8, respectively.

Fifth, to minimize edge effects in model results, we surrounded our calculated flammability raster with a 15-km wide buffer of randomly-generated resistance values following Koen et al. (2010). We generated these resistance values by sampling from a uniform distribution with values between 1 and 250. We selected this range because it captured the majority of values in the distribution of calculated resistance values. Model results for this buffer area were removed from final products.

Lastly, we averaged pixels to coarsen the resolution of the flammability raster from 30-m x 30-m pixels to 90-m x 90-m pixels. This enabled us to run the Circuitscape program for the entire landscape in a reasonable amount of time with available computing resources.

Circuitscape

We ran the Circuitscape program, using our source, ground, and resistance rasters as inputs, to generate maps of current flow or density. We interpreted the current density output as wildfire transmission (identifying areas of fuel break potential). We ran the program using both our calculated-resistance raster and a randomly-generated resistance raster (hereafter, random-resistance raster) for the entire landscape. Similar to the 15-km wide buffer of random resistance values described above, we created the random resistance raster for the landscape by sampling from a uniform distribution with values between 1 and 250.

Because of the configuration of our landscape, with current sources spread throughout the study area and grounds along one edge, current flow accumulates as the distance to ground decreases. We corrected for this effect by subtracting the current density output derived from the random-resistance raster (i.e., a null model) from the output from the calculated-resistance raster. This null model indicates how current is expected to accumulate moving southwest to northeast, and how it is affected by the shape of the northeast boundary, in the absence of effects of patterns of flammability on the landscape. Subtracting this null model result appears to reduce anomalies created by the irregular shape of the Project Area and reduces the accumulation of current on the northeast side of the landscape, regardless of resistance, caused by the even distribution of sources across the landscape in contrast to the placement of the ground on one edge. As mentioned above, we also removed the output for the buffer area surrounding the Project Area to reduce edge effects in the results.

We ran the Circuitscape program (version 4.0; “Advanced” mode; default settings) using the Circuitscape toolbox for ArcGIS (cs_arc.py version 2013-05-29), a Python script that calls the program from ArcMap (ESRI ArcGIS Desktop 10.2). The Circuitscape software, the toolbox, and documentation are available for download here: http://www.circuitscape.org/downloads. We ran Circuitscape on a Windows Server (2008 R2 Enterprise) with 128 GB of RAM. Runtime varied between 12 and 24 min for our 20-million-pixel landscape (at a 90-m resolution). (In early trials, runtime was less than 10 min for a 150-m resolution landscape using a laptop with 16 GB of RAM.)

Fuel Breaks

To simulate fuel breaks, we assigned negative current values to the pixels in the source raster that correspond to the pixels in a desired fuel break location. Originally, we experimented with creating fuel breaks by assigning high resistance/low flammability values to fuel break pixels in the resistance raster to selectively block current, but we found this approach simply routed current flows around breaks. We found better results by removing/absorbing current from the system with these negative current sources. The magnitude of the negative values determined the relative effectiveness or permeability of fuel breaks. If positive sources are analogous to wildfire ignitions, negative sources are analogous to wildfire extinguishers. We placed these extinguishers as needed, regulated their permeability (i.e., whether fire can jump fuel breaks), and quantified their relative effect on local wildfire likelihood.

We determined the negative current values for fuel breaks by running Circuitscape without breaks, evaluating the current density output and choosing an appropriate location for a fuel break, extracting the current density values from the output, multiplying extracted values by -1, multiplying those values by a scaling factor to set the permeability of the break, and then re-running Circuitscape with a new sources raster. This new sources raster included the original set of ignition points (i.e., 10,000 1-Amp sources) and the scaled negative source values representing fuel break pixels. We investigated scenarios with two classes of fuel breaks: major roads (existing) and artificial or simulated fuel breaks in addition to major roads.

Major Roads -

We incorporated the fuel-break effect of the existing network of major roads in the landscape (**Figure 10**) by treating these roads as weak breaks. Current values for these breaks were extracted from the current density output for a landscape without any major roads added. After multiplying these current values by -1, we applied multiplication factors of 0.10, 0.05, and 0.03, to interstates, U.S. & state highways, and major county roads, respectively. The range of factors was determined by testing different values to see what produced reasonable results, but scaled by our assumptions about the relative effectiveness of different road classes as breaks, e.g., an interstate with four lanes (factor = 0.10) is twice as effective as a state highway with two lanes (factor = 0.05). We ran Circuitscape with major roads as fuel breaks using our calculated-resistance raster and the random-resistance raster. We extracted current values for *simulated* fuel breaks from the current density output from the run using the calculated-resistance raster, the “Major Roads Scenario with Calculated Resistance Raster” (**Figure 11**). The difference between the current density output from the two runs, the “Final Major Roads Scenario” (**Figure 11**), was used to identify areas of high wildfire transmission/fuel break potential and place simulated fuel breaks.

Artificial or Simulated Fuel Breaks -

We placed artificial fuel breaks on the landscape in areas of highest wildfire transmission/fuel break potential to protect important “downstream” habitat for Greater Sage-Grouse (GSG). We informed our placement using a variety of data sources, including lek data (provided by Idaho Department of Fish & Game, Nevada Department of Wildlife, Oregon Department of Fish & Wildlife, and Utah Division of Wildlife Resources), breeding density areas (Doherty et al. 2010), existing vegetation types suitable for GSG (LANDFIRE 2010), and boundaries for Special Public Purpose Areas (e.g., Wilderness Areas). All artificial breaks were digitized along existing roads (U.S. Census Bureau 2014 TIGER/Line Shapefiles 2014). We tested a range of permeability levels using different multiplication factors, 0.10 (most permeable), 0.20, 0.30, 0.40, 0.50, and 0.80 (least permeable). We selected these values empirically, by testing different values to see what produced reasonable results. Scenarios are depicted in **Figure 11**.

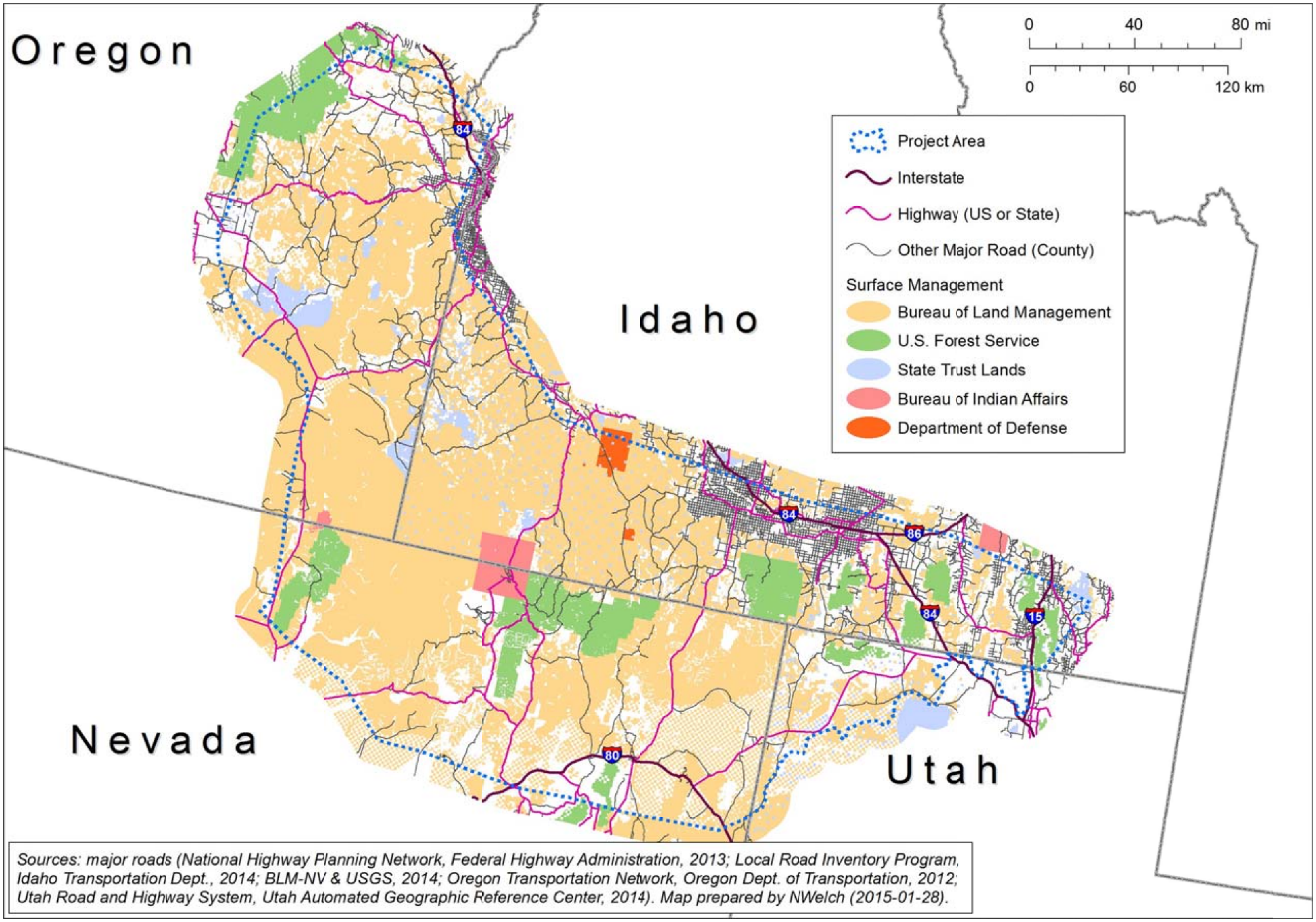

Figure 10. Major Roads.

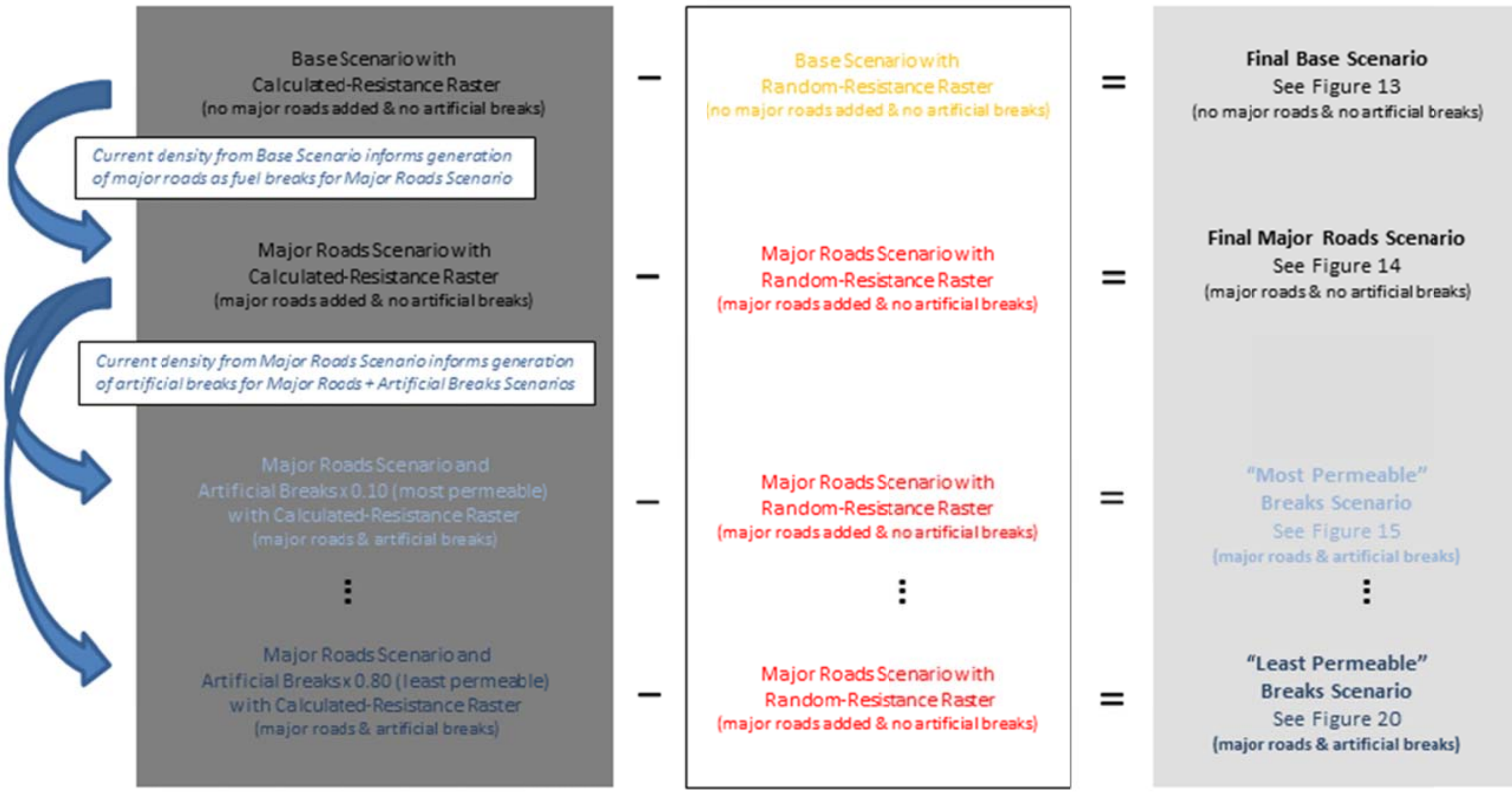

Figure 11. Model Scenarios.

Results

The Circuitscape program generates a map of current flow or density, which we interpreted as *wildfire transmission* informing *fuel break potential*. We interpreted areas of high current density (also known as pinch points) as areas with high wildfire transmission/fuel break potential. These are areas upwind and downwind of flammable features, but where non-flammable features channel wildfire transmission in such a way that a fuel break could disproportionately disrupt wildfire movement.

We simulated 13 sample fuel breaks (**Figure 12**). **Table 1** shows percent change in total current density downwind from each sample fuel break. The sum of current density is calculated for a semicircular area with a diameter equal to the distance between the start- and end-point of the respective break (**Figure 12**). The Final Major-Roads Scenario, lacking any artificial fuel breaks, was the basis for comparison.

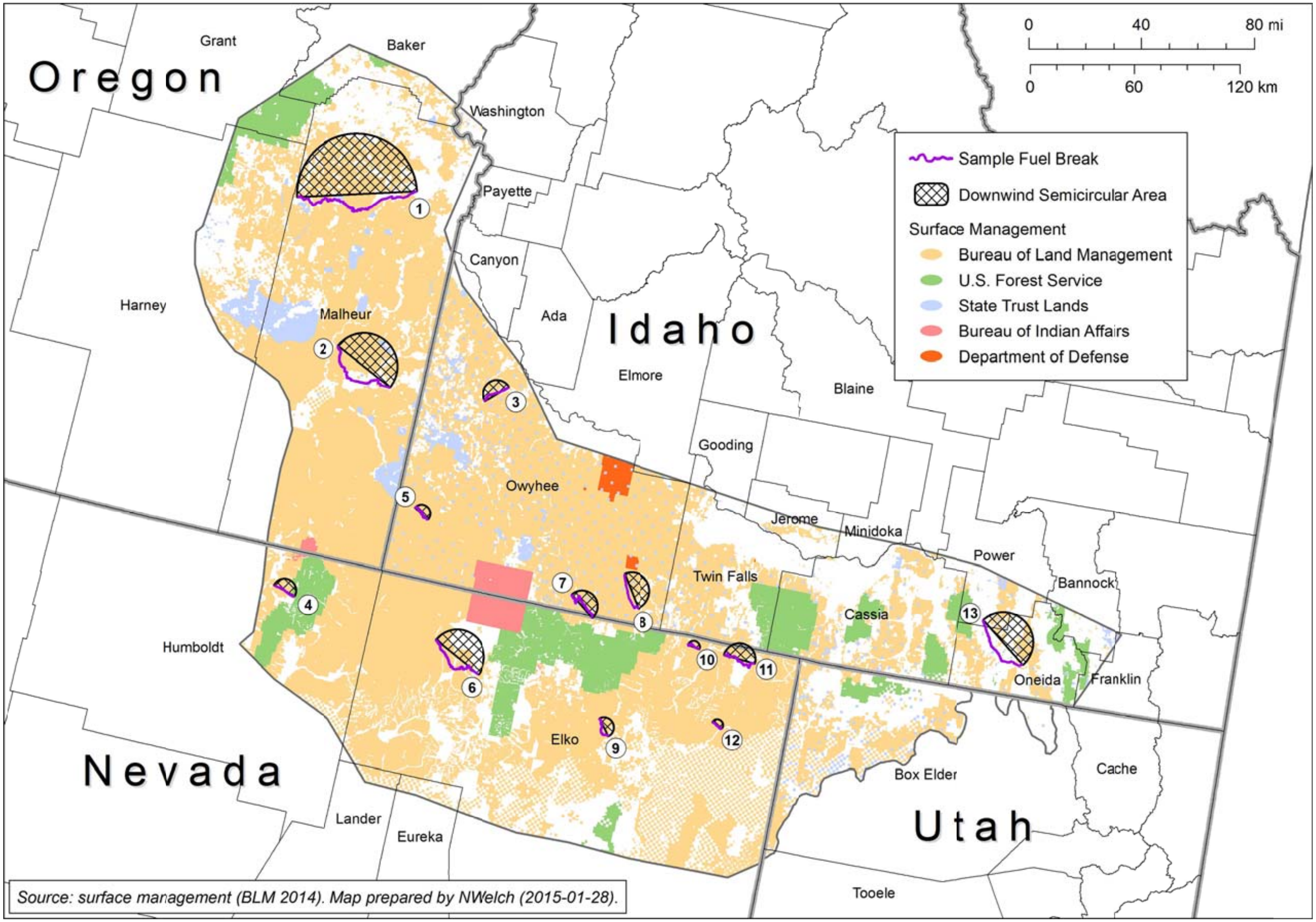

Figure 12. Sample fuel breaks (n=13) and downwind semicircular areas used to quantify fuel break effectiveness.

Table 1. Percent change in total current density/wildfire transmission downwind of each artificial fuel break.

Multiplication Factor or Permeability Level

Artificial Fuel Break ID	0.1 most	0.2 more	0.3 moderately	0.4 less	0.5 much less	0.8 least
#1	-16%	-37%	-58%	-79%	-98%	-111%
#2	-42%	-83%	-124%	-164%	-203%	-291%
#3	-27%	-55%	-82%	-107%	-123%	-94%
#4	-15%	-31%	-46%	-62%	-77%	-119%
#5	-24%	-47%	-69%	-88%	-103%	-94%
#6	-19%	-39%	-59%	-78%	-98%	-154%
#7	-28%	-55%	-81%	-101%	-110%	-40%
#8	-32%	-68%	-104%	-137%	-147%	-49%
#9	-17%	-32%	-45%	-55%	-62%	-54%
#10	-18%	-35%	-51%	-64%	-75%	-87%
#11	-26%	-49%	-69%	-83%	-88%	-46%
#12	-18%	-37%	-55%	-74%	-92%	-137%
#13	-22%	-51%	-80%	-108%	-135%	-178%

Note: 6 of 13 sample fuel breaks that behave like grounds when the multiplication is *too* large (i.e., 0.8) are highlighted.

Figures 13, 14, & 15–20 show current density (i.e., wildfire transmission) maps for the final scenarios for the 27 million acre (110,000 km^2) Project Area. These final scenarios represent the difference between Circuitscape outputs generated using the calculated-resistance raster and the random-resistance raster. We have used the same symbology (deciles) for all current density maps. The symbology is based on the range and classification of values from the Final Base Scenario (**Figure 13**), which had the widest range of values. Red areas indicate high wildfire transmission/fuel break potential, and blue areas indicate low wildfire transmission/fuel break potential.

Figure 14 (Final Major Roads Scenario) shows wildfire transmission/fuel break potential across the Project Area, including the effects of major roads as fuel breaks. Red areas represent possible opportunities for strategic placement of fuel breaks. We have included maps to illustrate the breeding density zones (Doherty et al. 2010), Priority Areas for Conservation (USFWS 2013), surface management, and Special Public Purpose Areas (BLM 2014), which also informed placement of artificial fuel breaks (**Figures 14a & 14b**).

Figures 15–20 ("Most Permeable" Breaks Scenario, …, "Least Permeable" Breaks Scenario) show the range of effects of 13 artificial fuel breaks installed in the Project Area with different levels of permeability. Note how effects are visible "downstream" from the fuel break, the direction closer to the northeast edge of the landscape where the grounds are located. Weak breaks with high permeability have a less pronounced cooling effect (e.g., dark red → light red) downstream from an artificial break, whereas strong breaks with high permeability have a more pronounced effect (e.g., red → blue).

Generally, the progression of Breaks Scenarios shows increasing effectiveness of artificial fuel breaks as the multiplication factor increases (see **Table 1** and **Figures 15-20**). Most fuel breaks are very effective with multiplication factors of 0.5 ("much less" permeable). The fuel break in western Elko County does not show effectiveness until the factor is 0.8 ("least" permeable). Because not all fuel breaks are equally effective for a given multiplication factor, we recommend custom factors for simulating future breaks. The need for a larger factor for an effective fuel break suggests a more robust break (e.g., wider break) or multiple downstream breaks might be needed on the ground; however, serial downstream breaks can be tricky to implement in Circuitscape due to spatial "electrical" interactions among fuel breaks, whereas this would not be a problem in the field.

In some cases, if an artificial break is too strong (i.e., multiplication factor is excessively large), the break starts to behave like a ground and increases current density (wildfire transmission) downstream. This happens because negative sources that are too strong can actually draw current from the downwind (northeastern) side of the fuel break. **Table 1** highlights (gray) 6 of 13 sample fuel breaks that behave like grounds when the multiplication is *too* large (i.e., 0.8). This ground behavior indicates an upper threshold on the multiplication factor, representing permeability, for a particular fuel break that the Circuitscape approach can reasonably simulate. **Figure 20** shows several fuel breaks behaving as grounds.

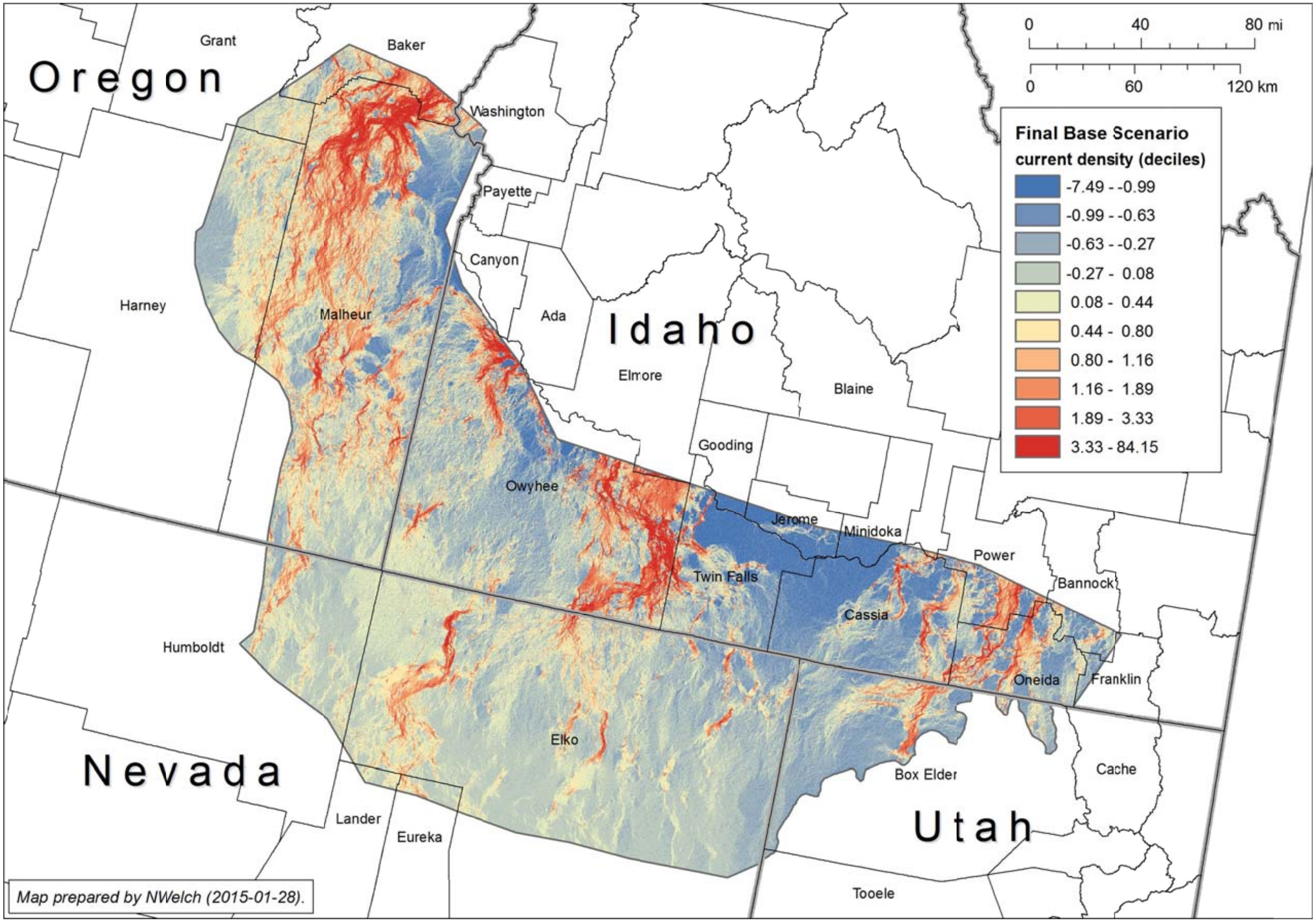

Figure 13. Final Base Scenario (no major roads & no artificial fuel breaks). Red areas have high current density values that represent high wildfire transmission, whereas blue areas have low current density values that represent low transmission.

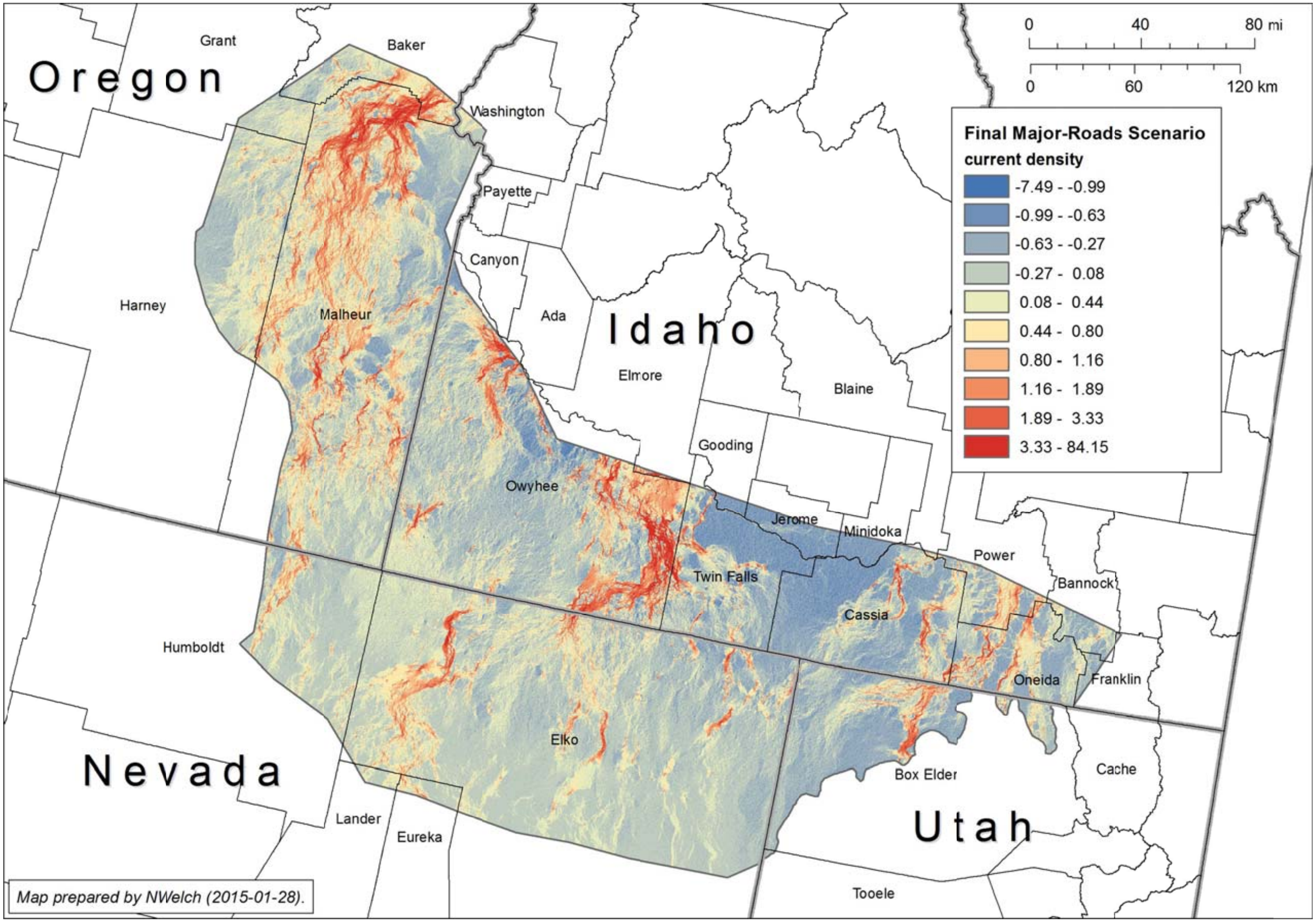

Figure 14. Final Major-Roads Scenario (major roads & no artificial fuel breaks). Red areas have high current density values that represent high wildfire transmission, whereas blue areas have low current density values that represent low transmission.

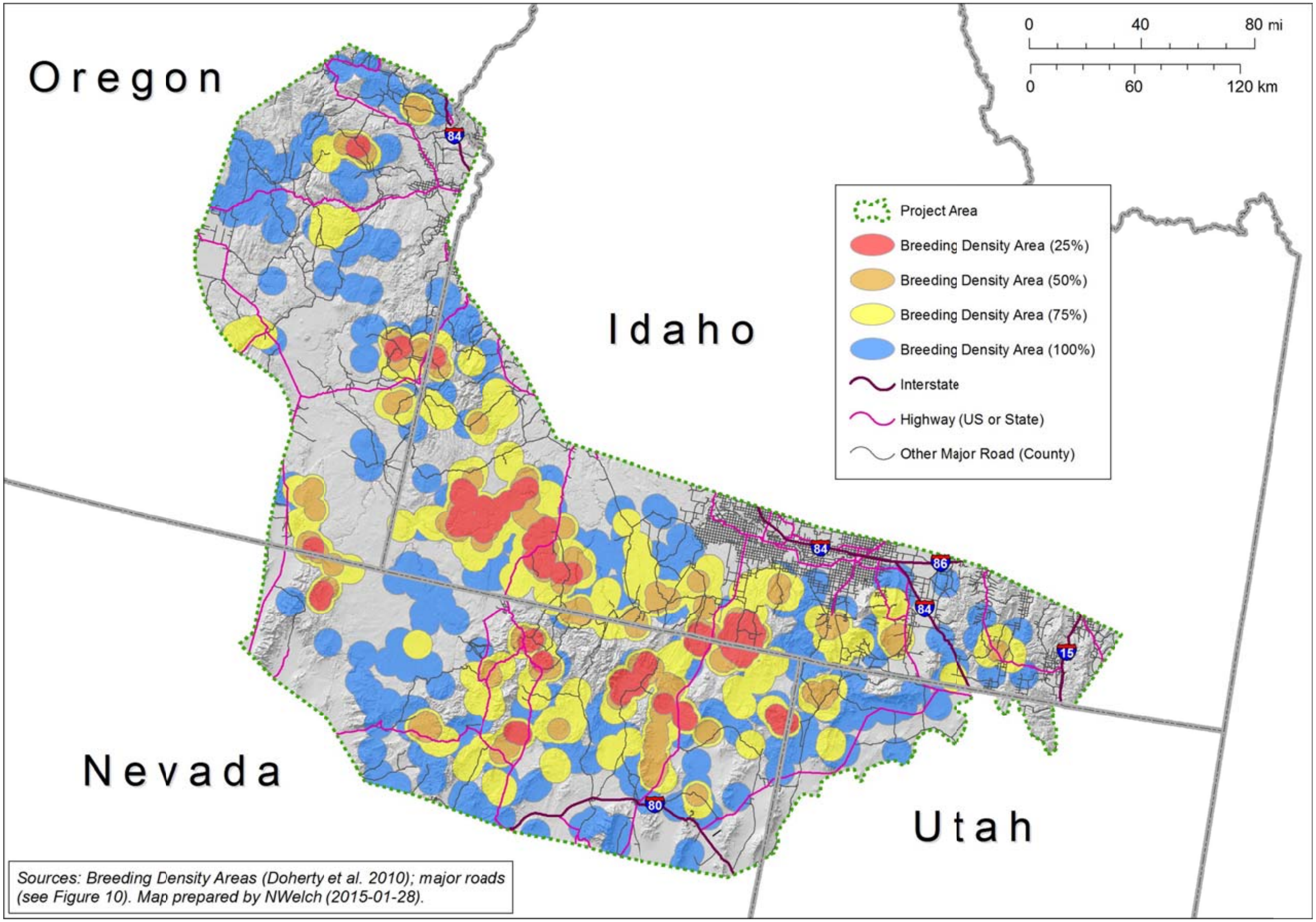

Figure 14a. Greater Sage-Grouse Breeding Density Areas and Priority Areas for Conservation.

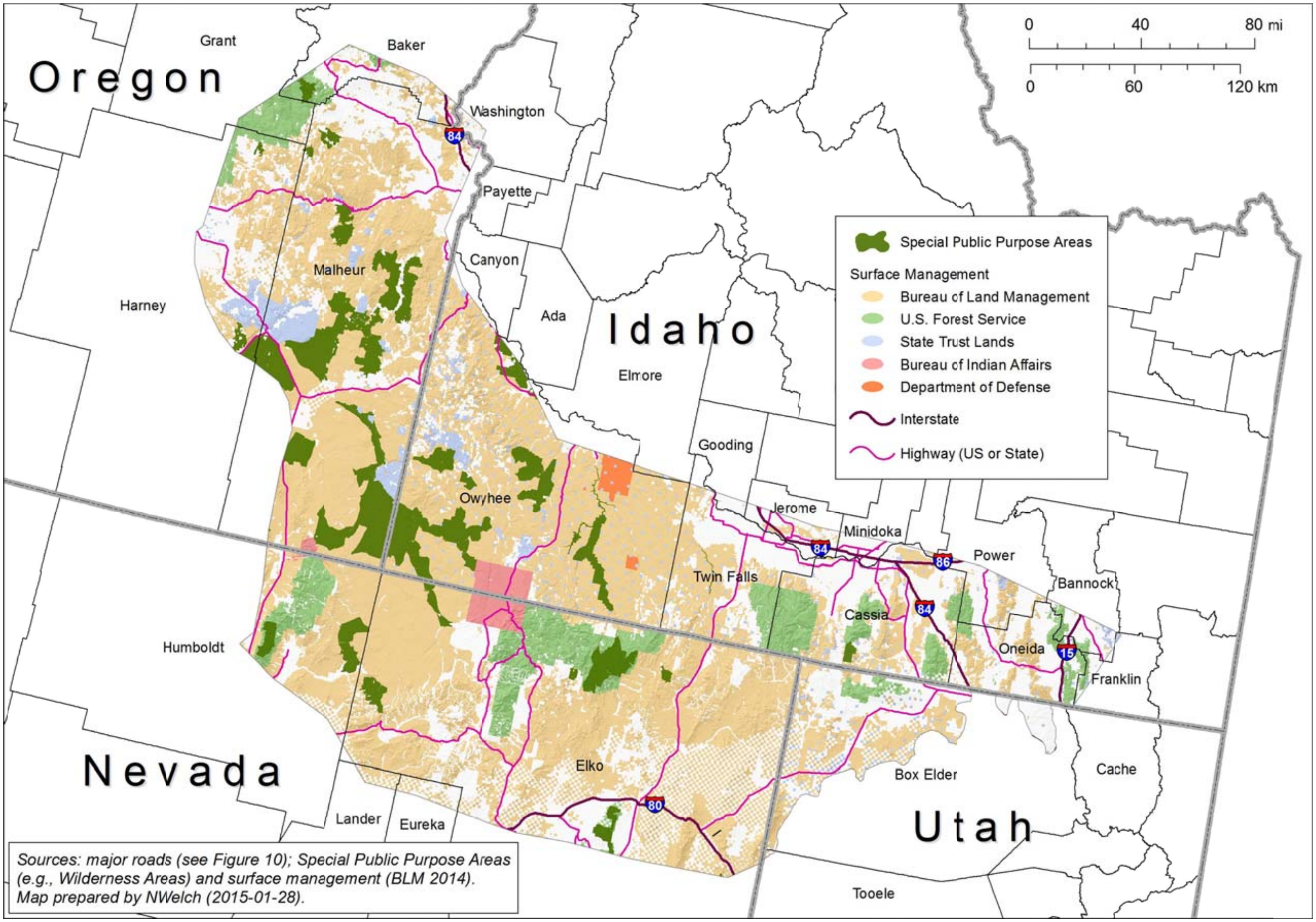

Figure 14b. Special Public Purpose Areas (e.g., Wilderness Areas & Wilderness Study Areas; BLM 2014).

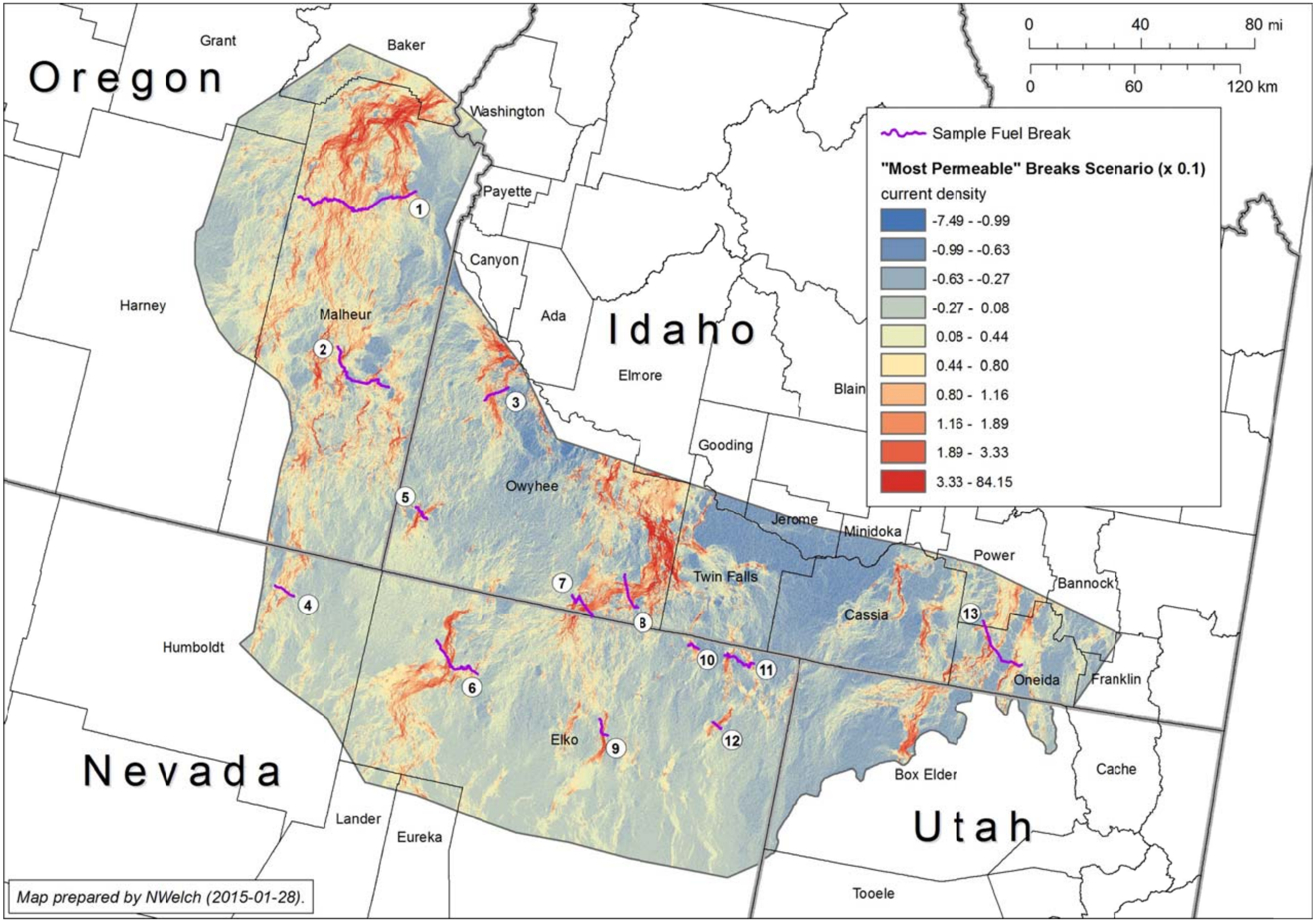

Figure 15. "Most Permeable" Breaks Scenario (major roads & artificial fuel breaks: x 0.10). Red areas have high current density values that represent high wildfire transmission, whereas blue areas have low current density values that represent low transmission.

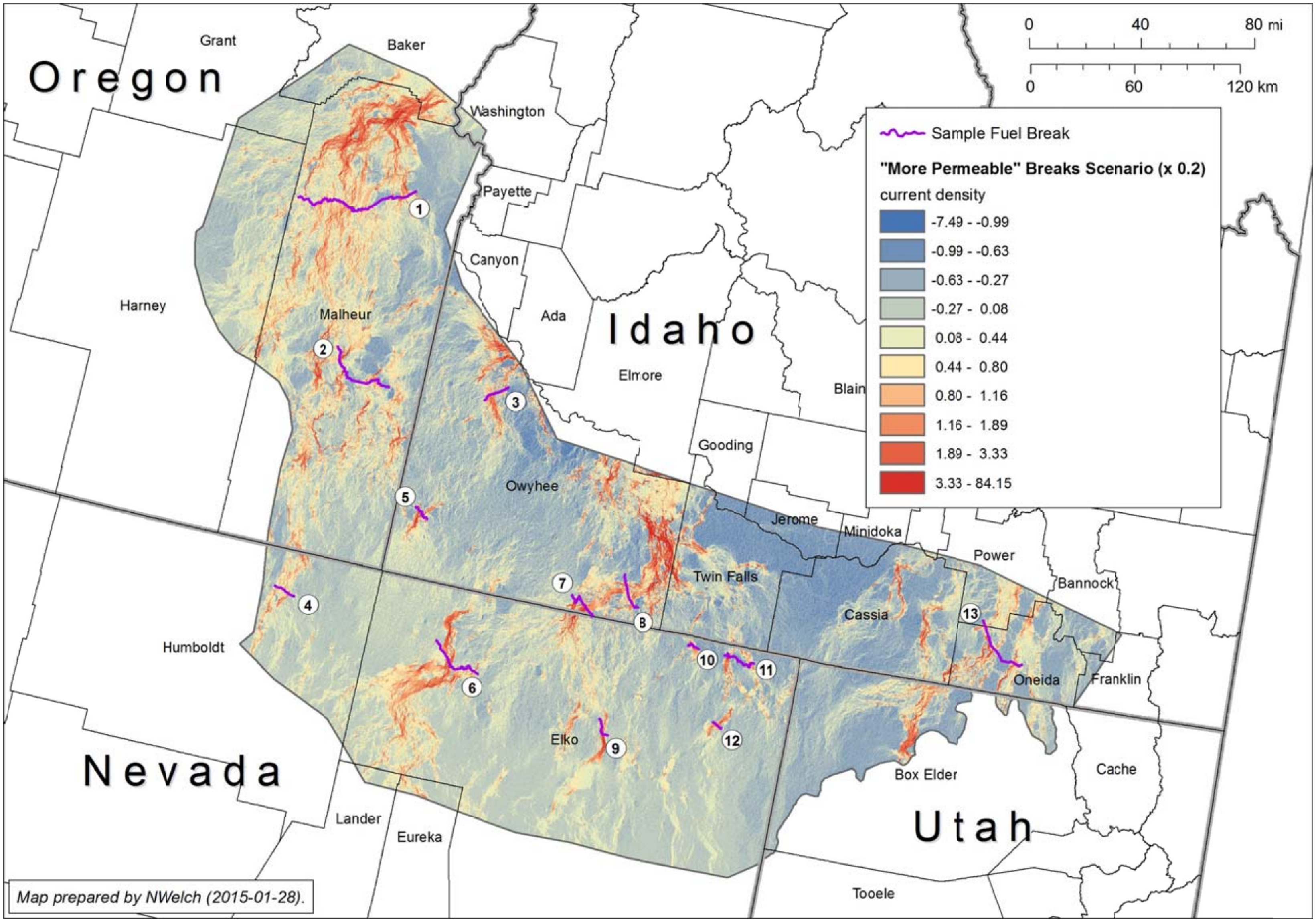

Figure 16. "More Permeable" Breaks Scenario (major roads & artificial fuel breaks: x 0.20). Red areas have high current density values that represent high wildfire transmission, whereas blue areas have low current density values that represent low transmission.

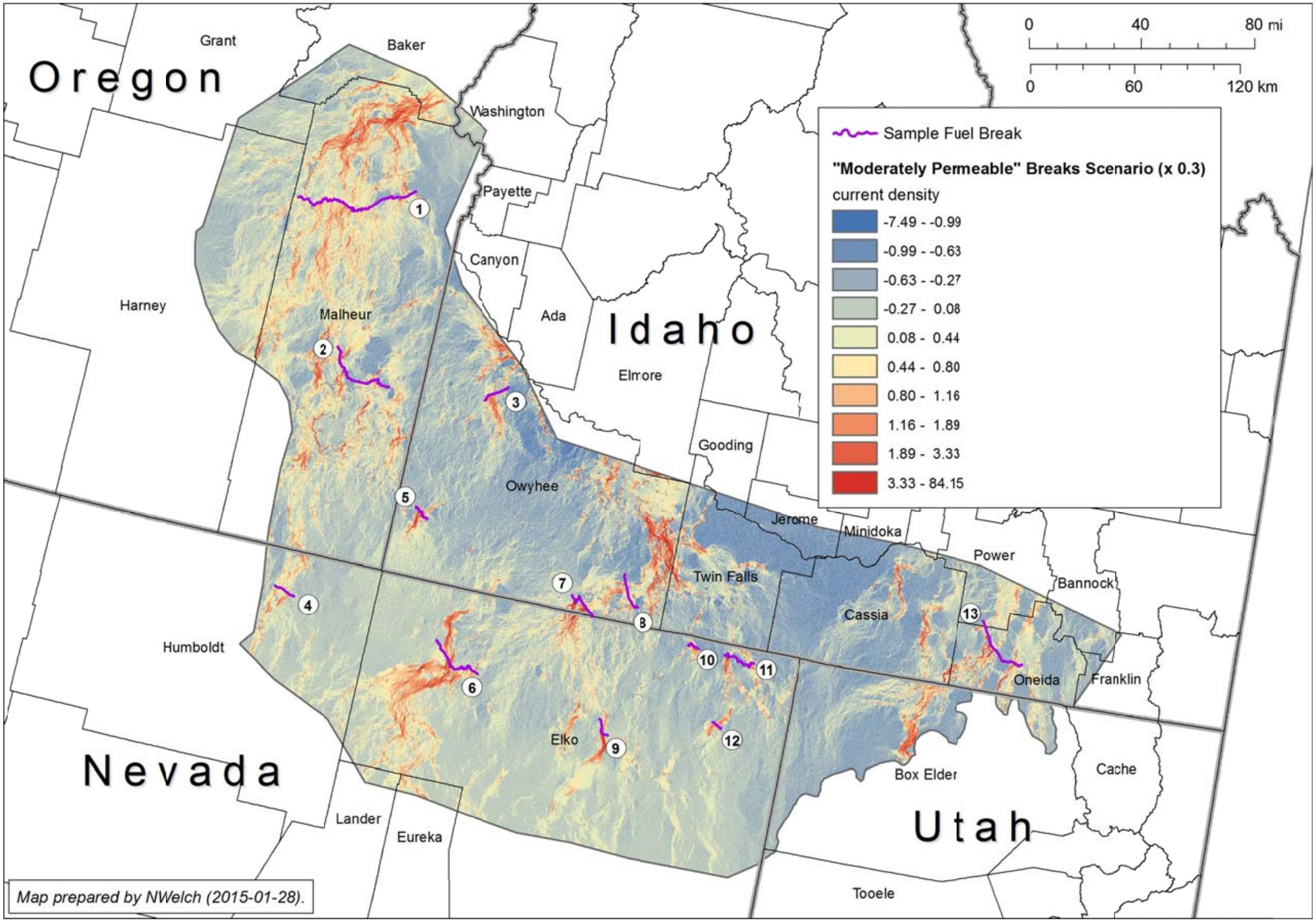

Figure 17. "Moderately Permeable" Breaks Scenario (major roads & artificial fuel breaks: x 0.30). Red areas have high current density values that represent high wildfire transmission, whereas blue areas have low current density values that represent low transmission.

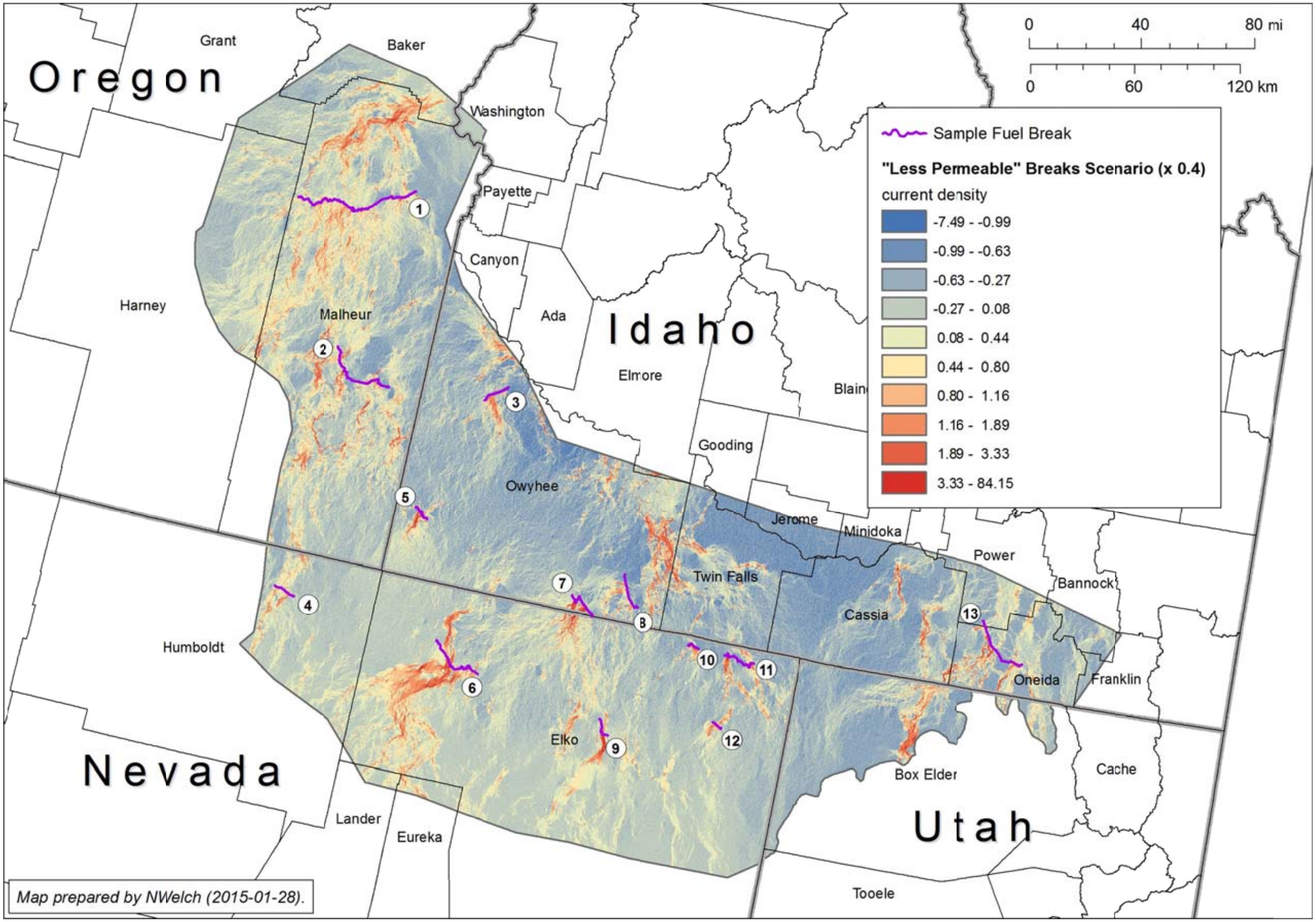

Figure 18. "Less Permeable" Breaks Scenario (major roads & artificial fuel breaks: x 0.40). Red areas have high current density values that represent high wildfire transmission, whereas blue areas have low current density values that represent low transmission.

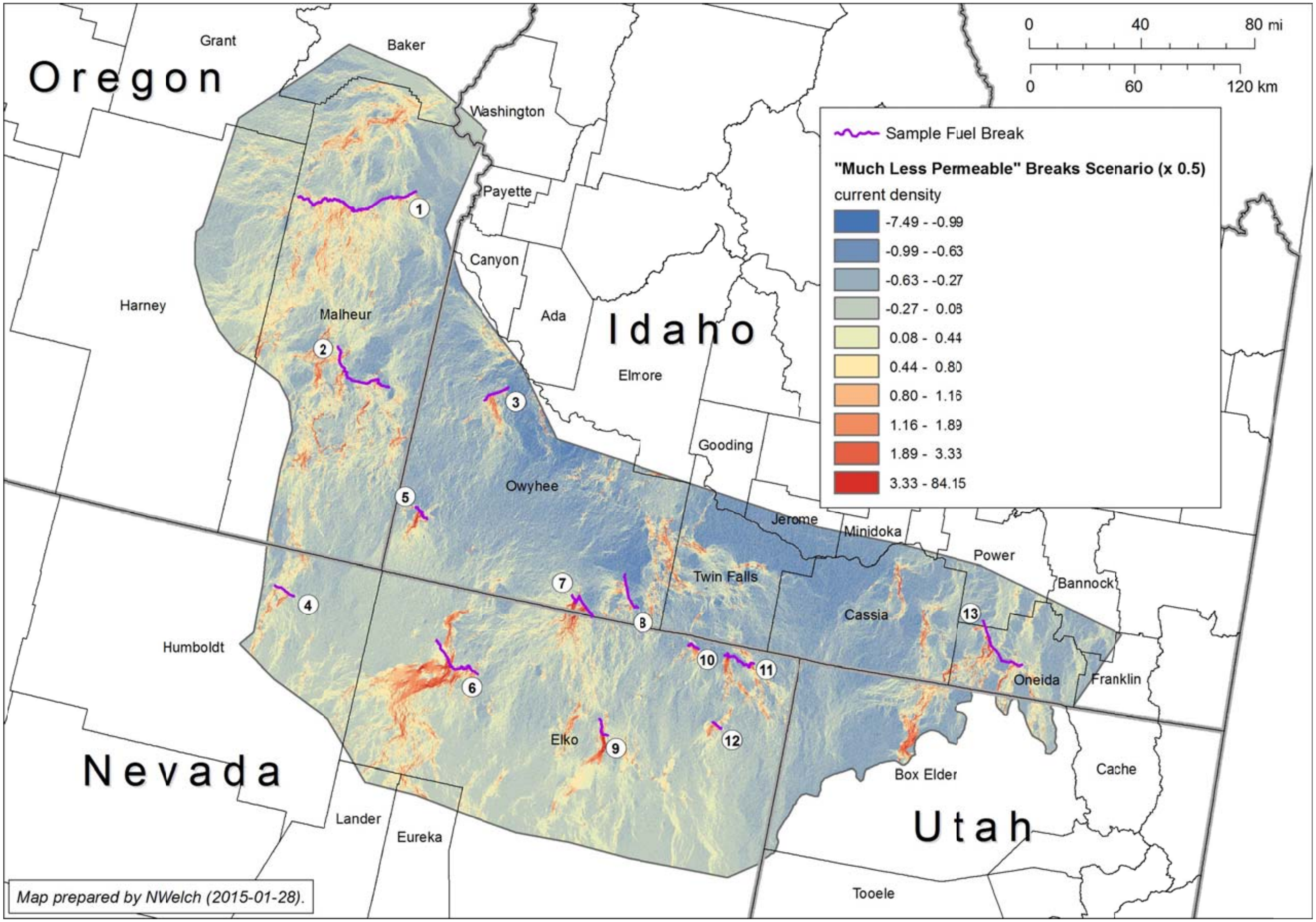

Figure 19. "Much Less Permeable" Breaks Scenario (major roads & artificial fuel breaks: x 0.50). Red areas have high current density values that represent high wildfire transmission, whereas blue areas have low current density values that represent low wildfire transmission.

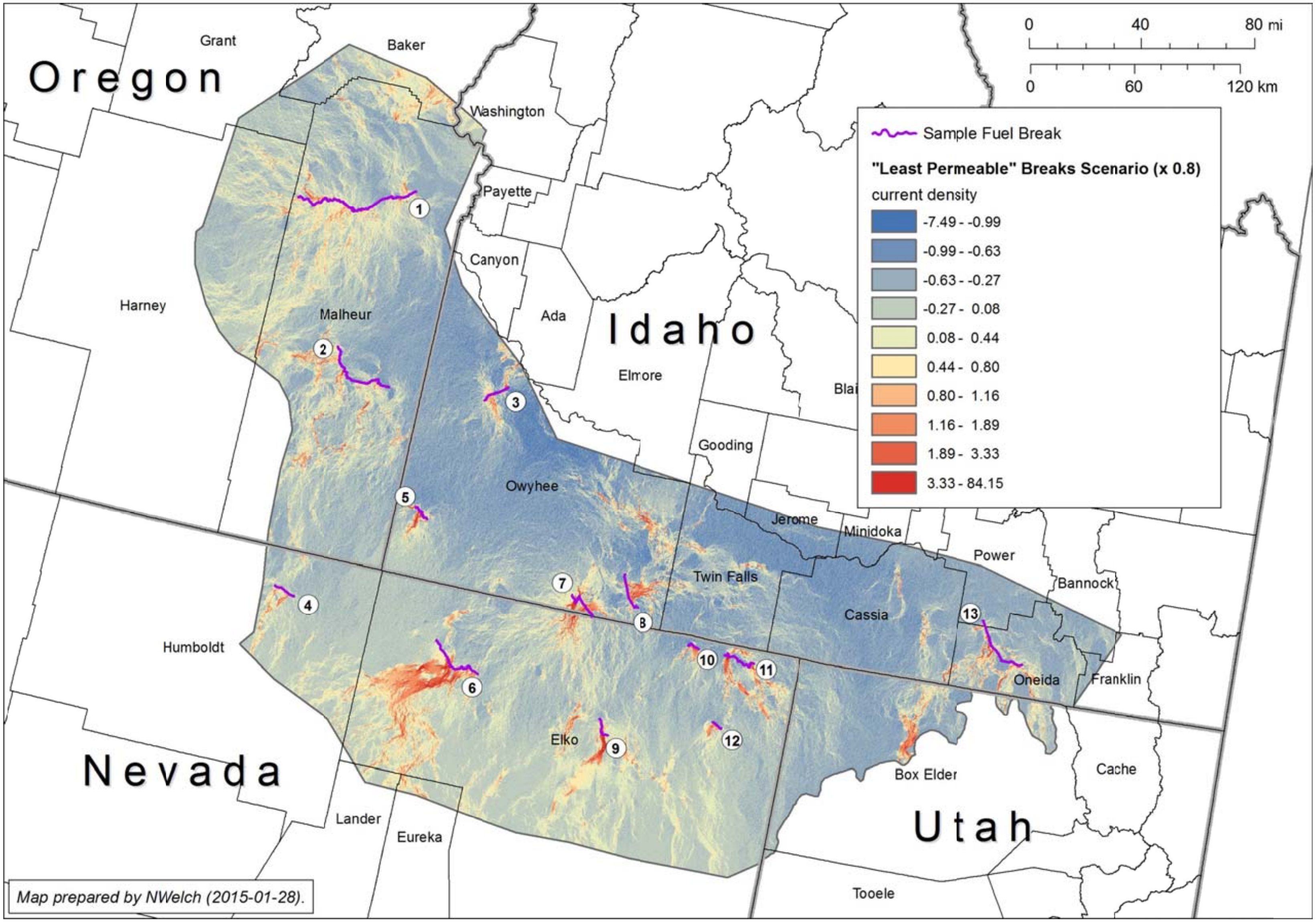

Figure 20. "Least Permeable" Breaks Scenario (major roads & artificial fuel breaks: x 0.80). Red areas have high current density values that represent high wildfire transmission, whereas blue areas have low current density values that represent low wildfire transmission.

Conclusions and Recommendations

Using Circuitscape, we have developed a process to identify strategic locations for fuel breaks and to simulate potential fuel breaks with different levels of effectiveness (i.e., permeability). Based on our wildfire transmission maps, we propose six focal geographies in our Project Area for further investigation for designing and implementing fuel breaks as a way to protect important GSG habitat (**Figure 21**). We also propose 13 more specific, sample locations where fuel breaks seem appropriate and seem generally effective for protecting critical GSG habitat within the focal geographies (**Figure 21**).

Our results show that simulated fuel breaks with low permeability (i.e., fires less likely to jump) can reduce wildfire transmission in and around important GSG habitat. For each sample fuel break, we could adjust the permeability level/multiplication factor to protect "downstream" habitat. In practice, fuel break permeability might translate into varying fuel break widths (e.g., less permeable breaks are wider), the number and spacing of parallel breaks, and plant composition (e.g., breaks occupied by less-flammable species or species more resistant to cheatgrass invasion might be less permeable).

Because so many existing wildfire modeling approaches use a coarse resolution (e.g., 270 m x 270 m grid cells), we tried to model using a resolution that better matched the width of real fuel breaks. A strength of our approach is the ability to run the model at a relatively fine resolution (90 m x 90 m grid cell) for a large region (~41 million acres) in a short amount of time (< 30 min). Even though the 90-m resolution we used would suggest moderately fat fuel breaks (90-m wide), our approach models electrical permeability, not pixel size or rows of pixels forming a fuel break; therefore, this approach can still be used to compare different fuel break locations, lengths, configurations, and combinations. Working at a smaller spatial extent would permit us to analyze the landscape at a finer resolution (e.g., from 90 m x 90 m → 30 m x 30 m grid cells).

From the beginning, we knew the detailed design and implementation of fuel breaks would require close collaboration with public land fire managers. We have discovered that even preliminary design of a network of fuel breaks will require close collaboration with local experts, especially BLM staff. The participation of local experts and their support of the design process will be critical for success. Besides encouraging others to use our Circuitscape approach for modeling fuel breaks, we intend to pursue a collaboration with fire managers in at least one of the focal geographies we identified.

From a modeling perspective, we see six major opportunities for additional work, ideally involving local knowledge and expertise:

1) simulating ignitions with different current source strengths, to reflect different probabilities of ignitions in different vegetation or land-use types,
2) refining the resistance/flammability raster or substituting resistance rasters from others,
3) delineating fuel breaks, including roads, artificial breaks (potential & existing), *and* natural features, with individuals more familiar with local landscapes,
4) setting locally appropriate multiplication factors/permeability levels for fuel breaks, including setting custom factors for individual breaks,

5) developing a procedure to simulate a set of parallel breaks, perhaps running Circuitscape iteratively to model serial breaks or scaling multiplication factors/permeability levels for downstream breaks appropriately, and
6) comparing and contrasting results with other modeling approaches.

As inspiration for the last opportunity, we have superimposed our recommended focal areas and sample fuel breaks on a Wildfire Hazard Potential (WHP) raster (Fire Modeling Institute 2014; **Figure 22**). Areas with higher WHP have a higher probability of experiencing extreme fire behavior (http://www.firelab.org/project/wildfire-hazard-potential). The WHP raster and our current density/wildfire transmission rasters are not independent, as both are informed by data from LANDFIRE (2010). Note that our focal areas and fuel breaks were designed to protect important GSG habitat. We did not try to eliminate all pinch points, areas with high wildfire transmission, from the landscape.

Given the importance of fuel breaks and the complexity of designing and implementing breaks, we encourage public land managers to use our Circuitscape approach for identifying strategic locations for fuel breaks and simulating the effectiveness of breaks in these locations. Our approach can be used to inform the placement and prioritization of fuel breaks on the ground to minimize large fires. We are also excited about the potential application of this experimental approach for modeling wildfire likelihood and fuel breaks in other large landscapes threatened by wildfire.

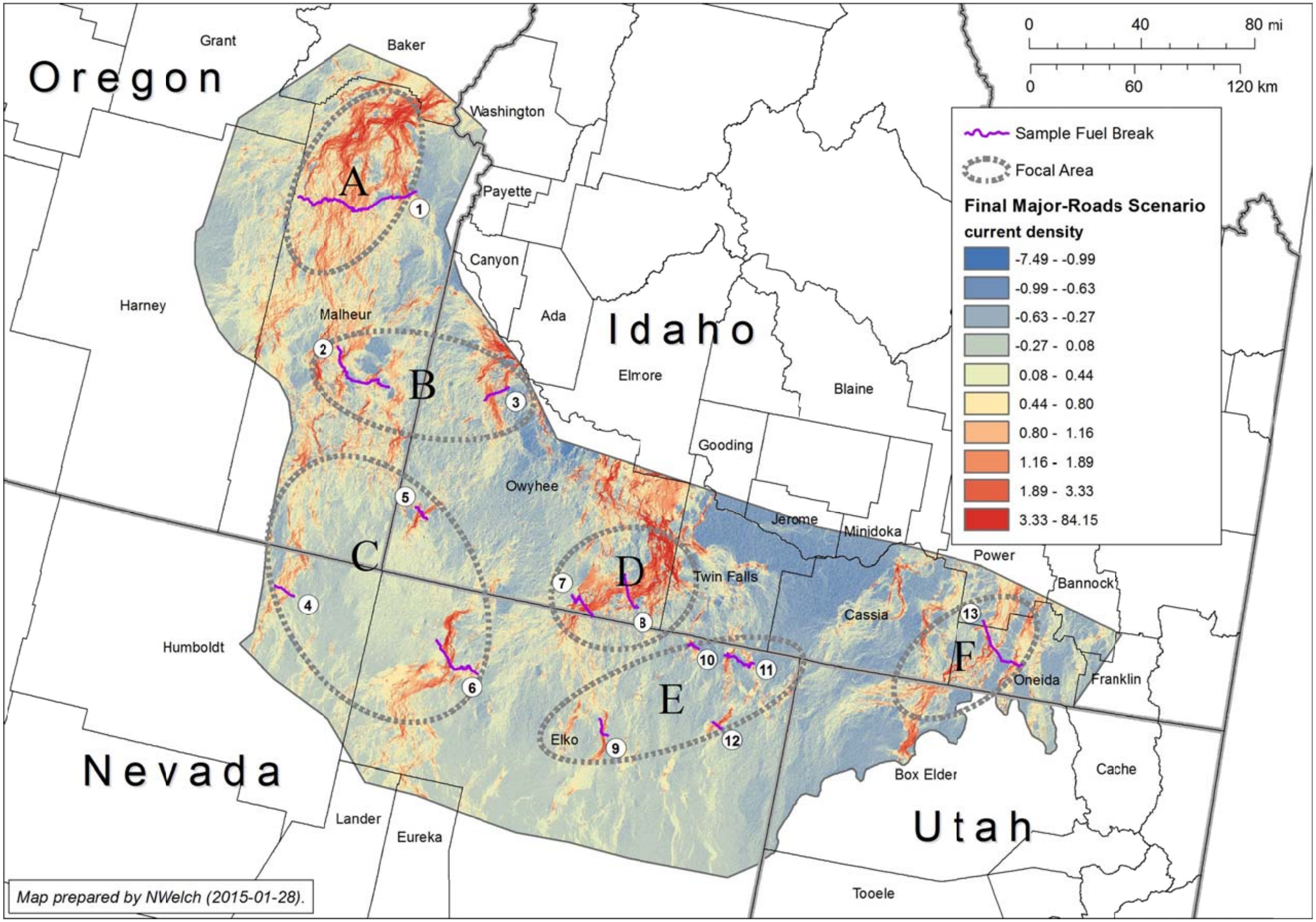

Figure 21. Recommended Focal Areas (A-F). Red areas have high current density values that represent high wildfire transmission/fuel break potential ("pinch points"), whereas blue areas have low current density values that represent low wildfire transmission. Samples breaks are NOT active.

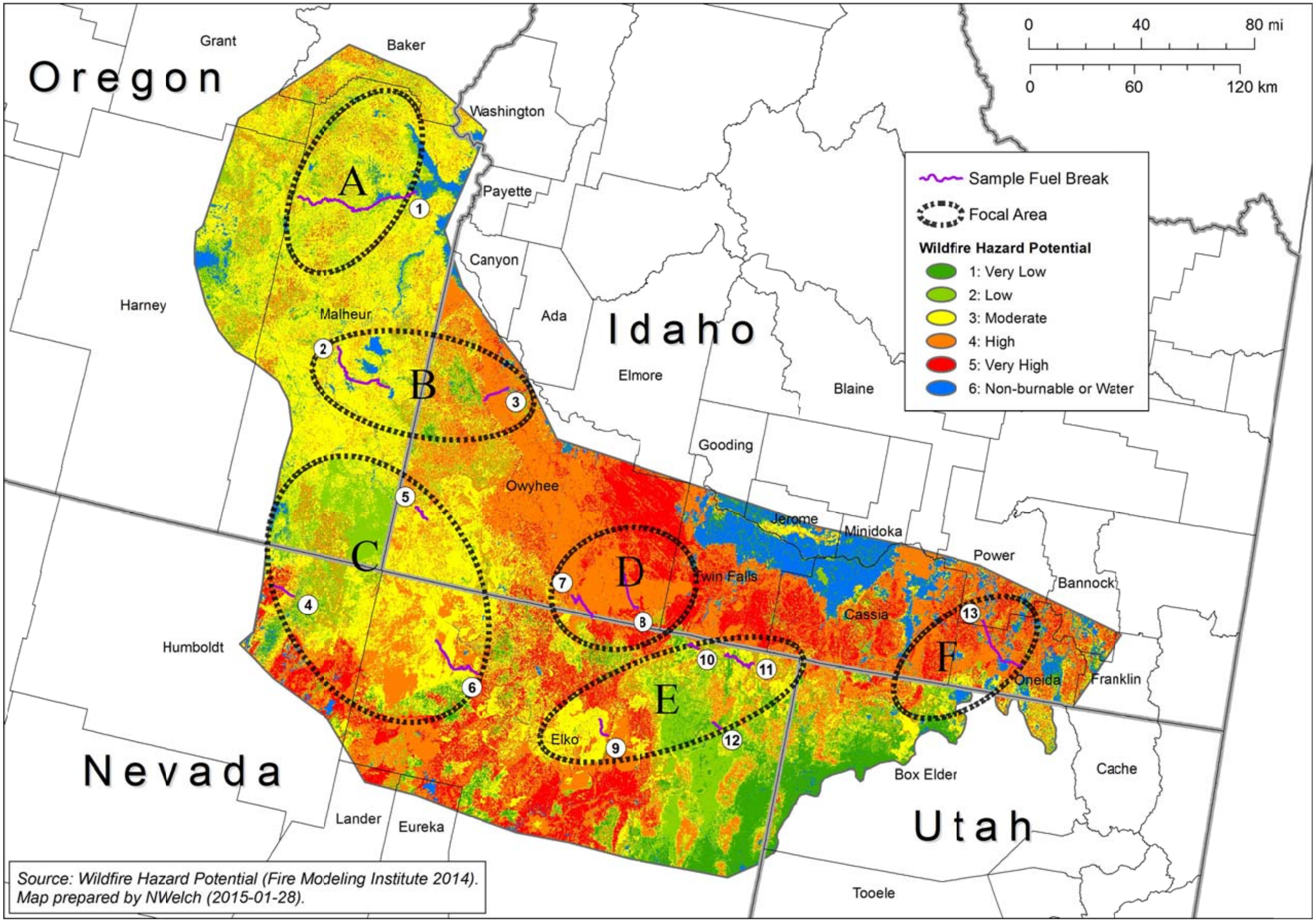

Figure 22. Wildfire Hazard Potential (WHP; Fire Modeling Institute 2014). WHP indicates the relative potential for wildfire that would be difficult for suppression resources to contain (http://www.firelab.org/project/wildfire-hazard-potential).

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