Final Grant Report - Oregon Watershed Enhancement Board Award #218-8390-16725

Ashland Forest All Lands Restoration Initiative: tactical fire management opportunities analysis

2.28.21

John D. Bailey, PhD
College of Forestry
Oregon State University
John.bailey@oregonstate.edu

Christopher J. Dunn, PHD
College of Forestry
Oregon State University
chris.dunn@oregonstate.edu

OREGON STATE UNIVERSITY

Project Background

Wildfire risk to communities continues to increase because of rapid climate change, historical fire and forest management, and an increasing wildland urban interface. The western US is one of the most fire-prone regions globally, and northern California and southern Oregon are wildfire hot-spots in the United States. In response, public and private lands managers, in collaboration with non-governmental organizations (NGOs) and university researchers are actively pursuing strategies to mitigate risk to highly valued resources and assets, including strategies to manage wildfire for resource objectives, increase the use of prescribed fire, and continue to restore forest conditions to be more resilient to wildfire and climate change.

The Ashland Forest All-lands Restoration (AFR) project has a multi-decadal long history of treatments across federal, City of Ashland, and private lands to mitigate fire risk. New methodologies and data have been produced in recent years to help pre-plan for wildfires. This grant facilitated the production of these datasets for application in the AFR landscape. This spatial fire planning process included working directly with local stakeholders and collaborators to define and delineate fire management features so treatments may better align with fire management needs. Concurrently, we were able to evaluate historical treatment benefits on suppression capabilities and reduction in wildfire effects through a series of spatial modeling exercises.

This work was initially envisioned with much shorter timelines and less robust analysis and reporting, and with no contract funding to Oregon State University. As the project has matured, however, the opportunity has emerged to shift funding from TNC staff to contract with OSU to develop wildfire risk analytics to improve that dimension of the ultimate product. Local partners, particularly Ashland Fire and Rescue, are eager to utilize these analytical results to guide investments in wildfire mitigation actions cohesively across City and USFS lands and to prepare for future wildfire response.

Project Objectives

The spatial fire planning process directly engages with local fire managers to understand fire management options in the AFAR landscape. This required a series of workshops guided by data from the Pacific Northwest Quantitative Risk Assessment (PNW QRA) (http://oregonexplorer.info/content/pacific-northwest-quantitative-wildfire-risk-assessment), and derived indices (Suppression Difficulty Index and Potential Control Locations). Specifically we identified Potential Wildfire Operational Delineations (POD) boundaries, and then vetted and refined them with local fire managers to facilitate preparation for future fire suppression response and informed decision making about managing fire across the spectrum of potential outcomes. Subsequently, we used these delineations along with local available data to prioritize allocation of treatments across a network of Strategic Containment Units (SCUs) and all stands for future use by the City of Ashland, US Forest Service, and other collaborators. This process identified post-treatment tactical fire management opportunities and demonstrate the utility of emerging data sets that quantify wildfire risk, Suppression Difficulty Index and Potential Control Locations.

The following specific objectives were achieved. All data layers and prioritization metrics are subject to change pending peer-review which will be underway by May 2021 but is beyond the scope of this agreement yet important to its overall intended outcome and use.

1) Evaluated and updated existing data quality and structure, including identification of missing treatment units.

2) Characterized changes in fuel characteristics due to ecological thinning and prescribed fire in the AFARI landscape. Leveraged existing monitoring data to infer fuel model, canopy base height, and canopy bulk density for activities and disturbances not previously monitored. This also included 1-week of field tours and sampling to confirm monitoring data and applicability across treatments not previously monitored.

3) Developed Suppression Difficulty Index (SDI) and Potential Control Location Atlas (PCLs), as well as fire behavior estimates for pretreatment and posttreatment landscapes.

4) Collaboratively developed and vet nested, hierarchical PODs (e.g., planning PODs and response PODs) based on existing collaborative PODs, fire suppression and risk metrics, and ongoing feedback

5) Engaged in co-learning with AFR stakeholders regarding use and application of fuel treatments and PODs for fuels mitigation and wildfire response activities

6) Identified priorities for future investments in fuel treatments, both mechanical and prescribed fire, for the AFR project area

7) Produce draft manuscripts and public reports that will increase the impact of this work.

Objective 1: ***Updating topology and fuel treatments layers***

Upon initial evaluation of the AFR spatial datasets for surface and ladder (SL), density management (DM), and underburn (UB) units, it was clear that the topology within and among the datasets needed to be corrected. As far as I could discern, these issues arose from the following:

1. There is no base layer of stands or treatment units to pull from in the GIS, and layout in the field. Instead, it appears field units are delineated and the boundaries likely derived from GPS and then added to the spatial dataset. While this is not inherently wrong, it does open up the GIS database to topology issues as they are added and not corrected at that time.
2. I suspect many different people have walked the various boundaries with GPS over the years and have slightly different methodologies, as well as collecting data under different satellite

configurations. This can lead to the GSP collecting more or less points, as well as varying resolutions and accuracy with respect to the unit boundary in the field. When added to the spatial dataset, this can result in overlapping polygons or missed areas.

3. It doesn't appear users maintained consistent coordinate systems when creating polygons in GIS or transferring from WGS84 (GPS coordinate system) to the spatial dataset.

I had to adjust nearly every polygon, all by minor amounts, to get them aligned. In general, I went thru the SL, DM, and UB datasets to fix the topology to address:

1. Misaligned polygons amongst the SL and DM datasets. UB was evaluated, and adjusted to a much lesser extent given advice that they did not necessarily match the other treatment boundaries.
2. To align the SL and DM polygons to the roads, trails and tax lot spatial datasets. It was obvious in many cases that these were intended boundaries but that they were off by a few meters here and there, or random points showed up because the GPS temporarily lost good satellite configuration.

Additional Adjustments

I changed Hoff001SL18 to Hoff001SL13 because this unit was treated in 2013, not 2018, although it was revisited in 2018 for maintenance (HoffLitSL18, plus some other larger units that overlapped).

I changed Epst002SL19 to Epst002SL14, added SPER 2, 2014 SL to comments as per conversation with Kerry Metlen, PhD.

Added additional datasets in the landscape surrounding the original AFR landscape from US Forest Service databases to capture changes not directly associated with AFR treatments. https://data.fs.usda.gov/geodata/edw/datasets.php

Identified treatments not present in TNC shared databases for AFR landscape, all implemented in 2020, to update data layers to match our current use.

Data sharing

Data bases have been produced and have been shared upon request. We have agreed to wait on final delivery of geodatabase until manuscripts have been peer-reviewed in the event changes are required. The hope is to prevent too many versions that result in confusion on which is best to use moving forward. However, data is being shared as needed with all stakeholders to meet presentation and prioritization needs, primarily in the form of map packages via ArcGIS.

Objective 2: ***Characterize changes in fuel structure***

I cross-walked monitoring treatment data to those units that did not have monitoring plots installed. This was dominantly based on treatment type and stratification of forest cover type. Treatment types includes surface and ladder treatments, density management treatments, and underburning. We assumed all hand-piles were burned for this exercise, given the successful track record in completing these burns in a timely manner. There were enough monitoring plots to make this successful crosswalk, with field observations to confirm the efficacy of this effort.

I spent the week of October 19, 2020 in the field within the AFR landscape. This field work allowed for sampling and confirmation that the crosswalk of monitoring data successfully captured fuel and forest conditions across this landscape. One notable adjustment was made to an unit where the burned piles crept in between them and consumed more fuel than other units. This was noted and included in the fuel adjustments made to the post-treatment (current) landscape.

Objective 3: ***Create suppression-oriented wildfire risk analytics***

Multiple data analytics were created for the AFR and expanded area (see below for further details on delineation of expanded area) landscape to inform spatial fire planning, and as independent metrics used in prioritizing maintenance and future treatments across this area. These include estimates of fire behavior, suppression difficulty index, and potential control locations.

<u>Fire behavior modeling</u>

Methods

I used FlamMap 6 (https://www.firelab.org/project/flammap) for all fire behavior calculations across this landscape. The only exception were the fire behavior metrics used within the PNW QRA that uses the FSim model to derive burn probability and fire intensity metrics used to estimate conditional and expected net value change to highly valued resources and assets. Fire weather modeling parameters are provided in Table 1, which were based on conditions across multiple local Remote Automated Weather Stations.

Table 1: Fire weather and fuel moisture parameters used in fire behavior modeling.

Percentile Conditions	1-hr fuel moisture	10-hr fuel moisture	100-hr fuel moisture	Live herbaceous moisture	Live woody fuel moisture	Windspeed (mph)	Wind direction (azimuth)
90th	6	6	8	40	75	10	315
97th	4	5	7	33	60	10	315

The fuelscape (spatially defined fuel models necessary for fire behavior modeling), and broader landscape file, were obtained from the Rogue Basin QRA that covered the expanded focal area. These layers were initially built from the Landfire 2012 data layers, with signficant local adjustments to account on local experiential knowledge that is often lost in national-scale products. These fuel models were also confirmed during my site visit, and adjustments to this data layer followed the procedure described previously when crosswalking monitoring data.

Suppression Difficulty Index

Methods

The Suppression Difficulty Index (SDI) is a spatially explicit quantification of the wildfire operational environment (Rodriguez y Silva et al., 2020; Rodríguez y Silva et al. 2014), and weighs fire behavior against road and trail access/egress, including topographic impediments to mobility, in an expert weighted system, to map a relative measure of responder exposure to wildfire.

I produced SDI for pre- and post-treatment landscapes using the 2020 methodology identified in Rodriguez y Silva et al. (2020). Fire behavior inputs were derived from FlamMap 6, as previously described. These data layers were produced for the pre- and post-treatment landscapes.

Mapped Results

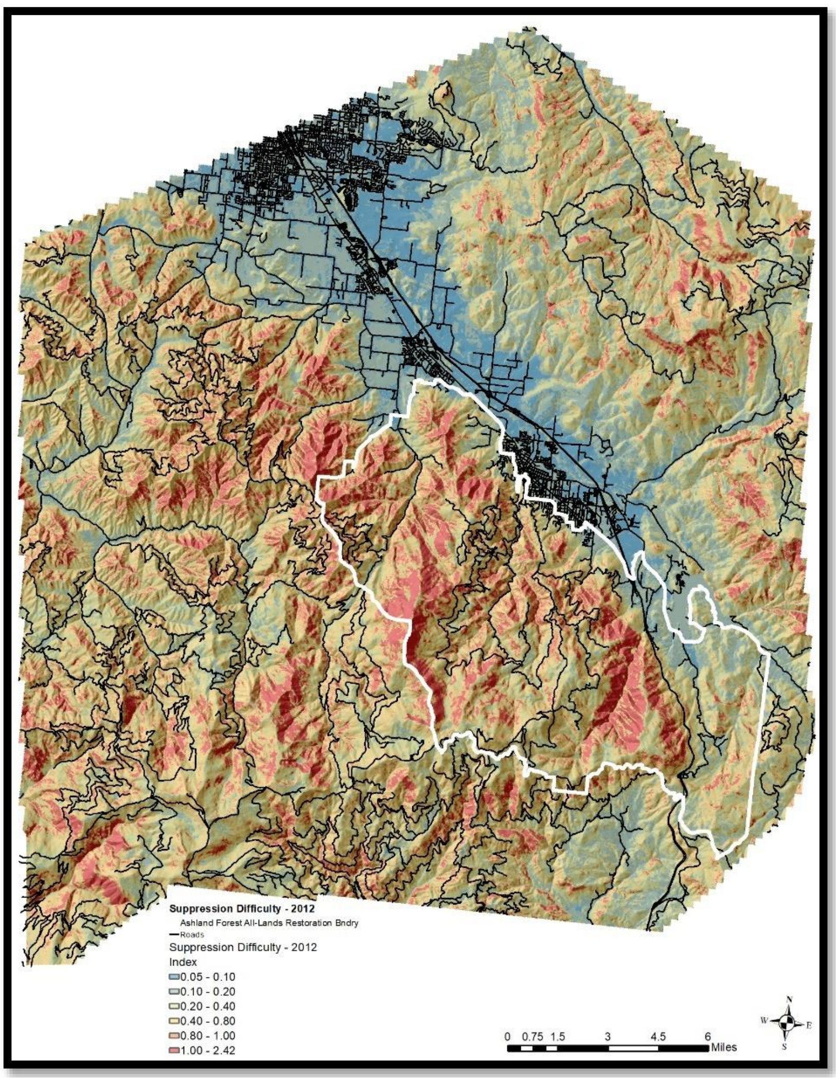

Figure 1: Suppression Difficulty Index is a spatially explicit quantification of the wildfire operational environment. This image depicts the condition of the AFR and extended landscape area prior to major treatment investment within the project area.

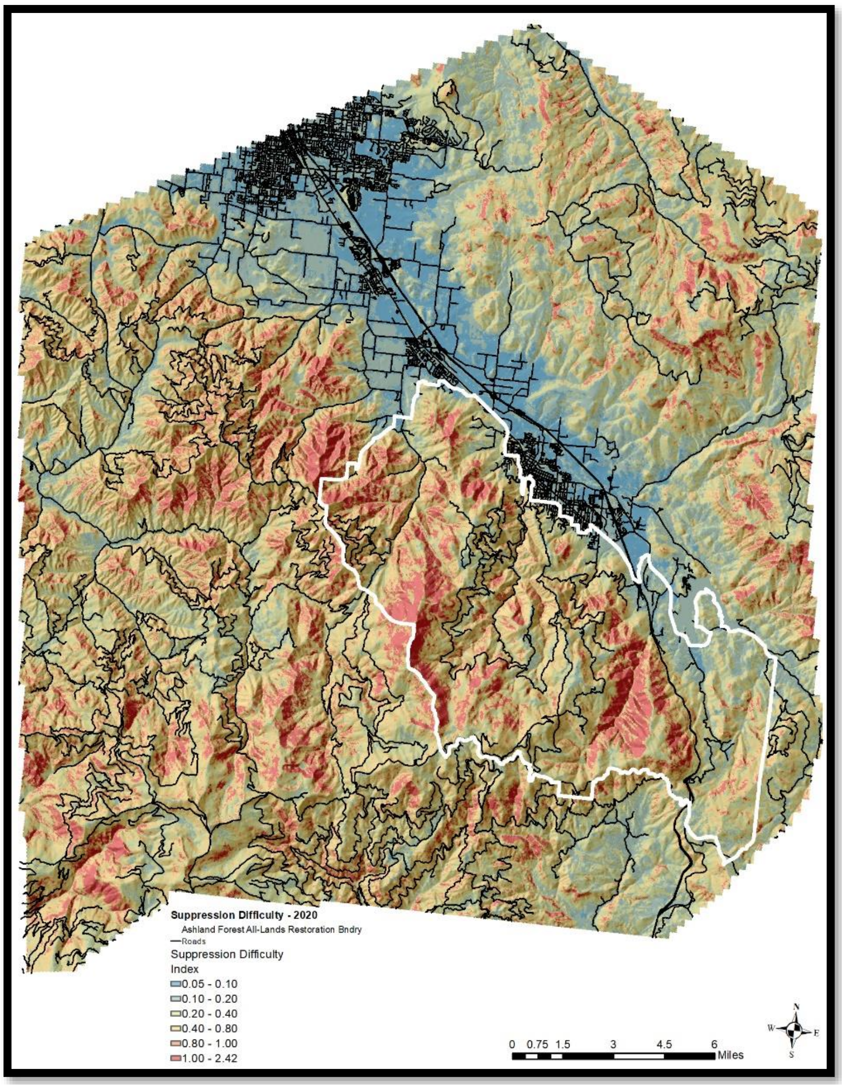

Figure 2: Suppression Difficulty Index is a spatially explicit quantification of the wildfire operational environment. This image depicts the condition of the AFR and extended landscape area after major treatment investment, beginning in 2012, within the project area.

<u>Potential Control Locations Atlas</u>

Methods

The second wildfire management analytical product I provided was an atlas of potential control locations (PCLs), which identify areas on the landscape where fires are likely to be contained, and which can support development of safe and effective response strategies (Dunn et al. 2017; Wei et al. 2019). Here, we build off recent analytical methodologies using machine learning algorithms to quantify the relationship between final containment lines for large fires (>200 ha) and nine predictor variables indicative of the complex factors evaluated by fire managers during large fire containment (O'Connor et al., 2017; Dunn et al., 2020).

Mapped Results

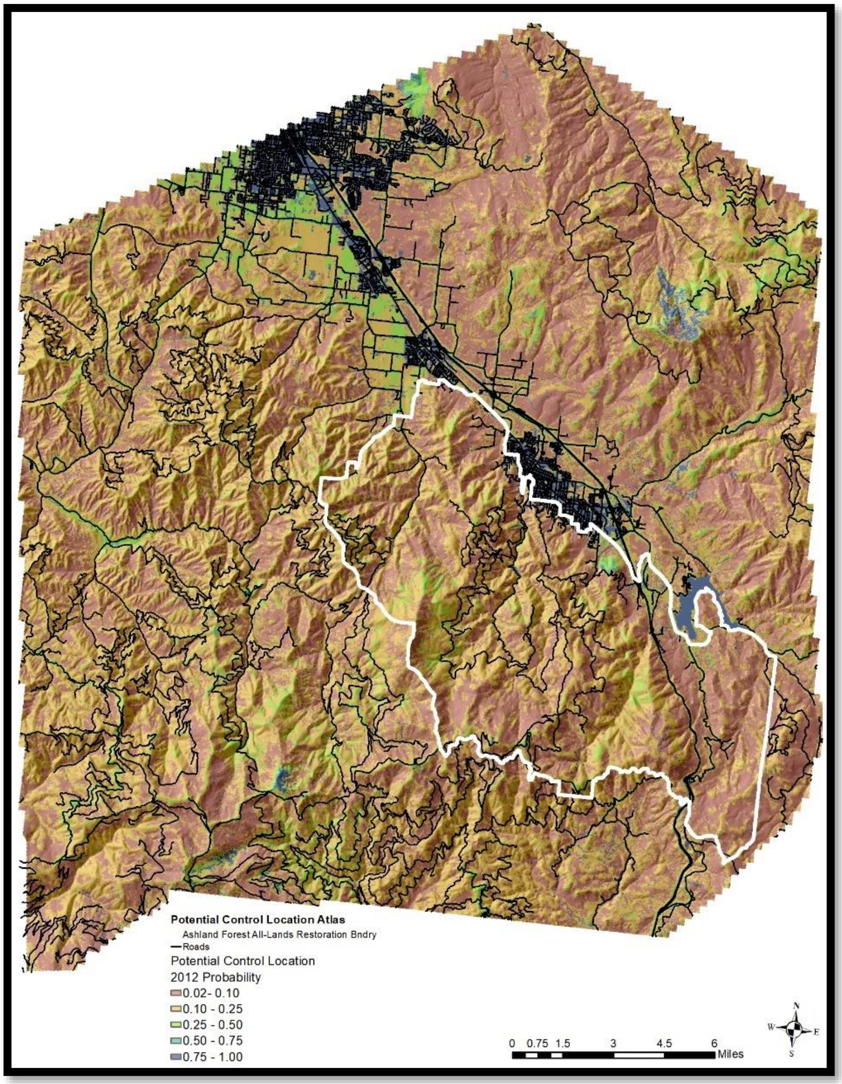

Figure 3: Potential Control Location Atlas for the AFR and expanded area landscape prior to major treatment investment. This is representative of the landscape in 2012. Warmer colors indicate lower probability of being successfully used to contain a large wildfire.

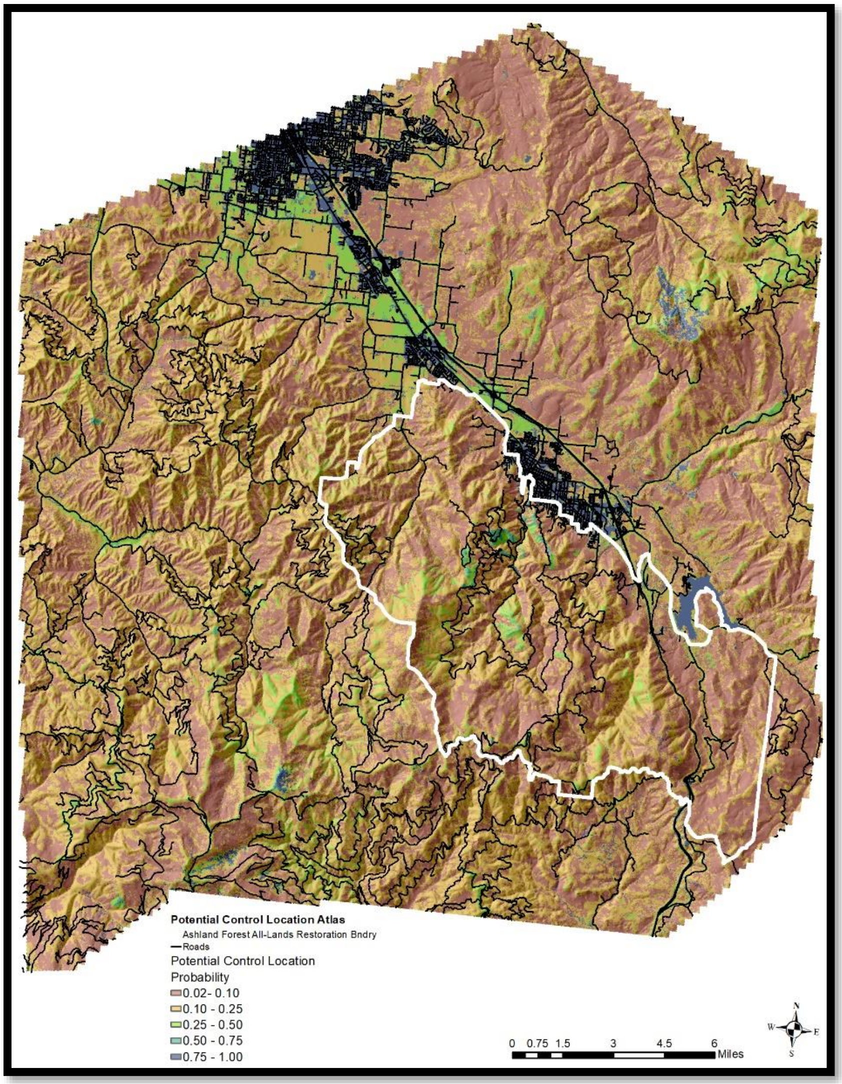

Figure 4: Potential Control Location Atlas for the AFR and expanded area landscape following major treatment investment in mitigation activities. This is representative of the landscape in 2020. Warmer colors indicate lower probability of being successfully used to contain a large wildfire. Note the increase in potential control location probability following prescribed burning within the primary AFR landscape.

Objective 4 and 5: ***Collaboratively Develop Potential Wildfire Operational Delineations (PODs)***

Potential wildland fire operations delineations (PODs) are polygons whose boundary features are relevant to fire control operations (e.g., roads, ridgetops, and water bodies). PODs are created by local fire experts with the help of analytical tools that highlight landscape features with control potential and provide information on their likely effectiveness. PODs are useful for summarizing wildfire risk and planning strategic response to unplanned ignitions accordingly. In an operational response context, POD boundaries can be used to guide and communicate choices of where to construct or hold fire line as well as where to conduct burnout operations. PODs may also prove useful for strategic fuels planning, with potential applications for designing controlled burn units, reinforcing existing POD boundaries, or prioritizing treatment opportunities within PODs. Vetting and mapping POD boundaries essentially formalizes and institutionalizes the knowledge of fire management experts. The basic idea of delineating "boxes" within which to manage fire has long been around; the POD concept uses risk-based analytics, ground-truthing, and expert consensus to take that concept much farther, and moves it into the pre-fire planning world to buy more time.

In collaboration with The Nature Conservancy, City of Ashland, US Forest Service and other stakeholders we developed PODs for the expanded area around the AFR landscape through a series of virtual workshops that took place across from December (2019) to February (2020). This series of meetings took redefined POD boundaries specific to this area, from previously delineated PODs created in 2019 in other collaborative meetings. Each of these PODs meetings continued to refine PODs to appropriate scales and along boundaries with the greatest control opportunity.

Mapped Results

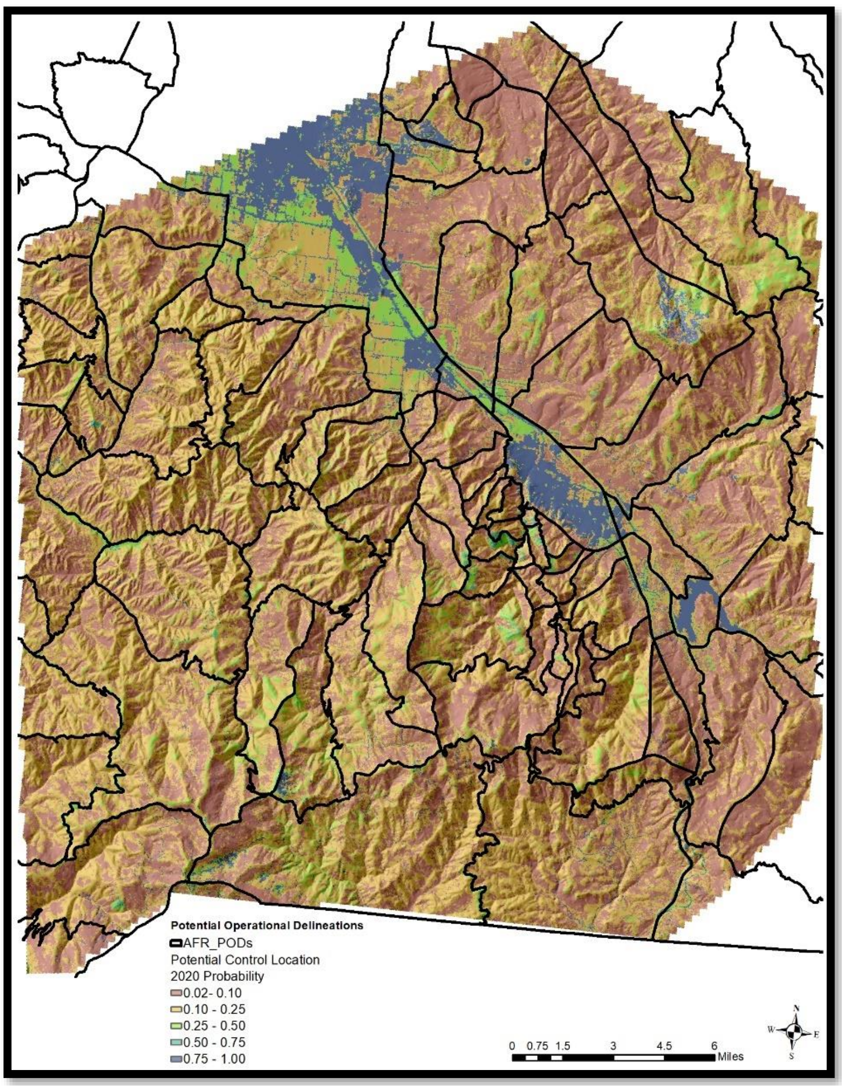

Figure 5: Potential Wildfire Operational Delineations (PODs) were delineated by local fire and forest managers, in collaboration with other stakeholders, across the AFR expanded landscape.

This process is often referred to as the "PODs process", or spatial fire planning. The intent of these workshops is to both obtain a POD network that can be used to identify best wildfire control opportunities, mitigation treatment needs, and educate important stakeholders on the challenges the fire management service faces in controlling fires across these landscapes. While virtual workshops are not ideal, these workshops did afford attendees the opportunity to look at the landscape from the perspective of fire management professionals. This affords transfer of knowledge and learning, which helps people understand the reasons mitigation treatments are done at the locations chosen. It also educates stakeholders on the decisions fire managers must make when responding to a fire, where protection of values and firefighter safety remain top objectives in all incidents.

Objective 6: ***Prioritization treatments across the AFR landscape***

The Nature Conservancy, City of Ashland and stakeholders were interested in two scenarios for prioritization mitigation treatments. The first scenario focused on enhancing containment of wildfires at a landscape scale, which is closer to the scale of the wildfire risk challenge. This required identification of Strategic Containment Units (SCUs) which are individual stands along locally defined POD boundaries that represent treatment units that would directly support large wildfire containment. These treatments units are similar to strategic fuel breaks or shaded fuel breaks, but their locations are determined by the collaboratively developed PODs network. SCUs are stands located along these POD boundaries. The second scenario evaluated all stands across the AFR landscape for treatment prioritization. Both scenarios addressed specific objectives, identified below, with some overlap. The results are decision support tools aiding local managers and decision makers in their effort to mitigate wildfire risk to a multitude of values.

Actual treatment type should be determined based on observed field conditions, but my recommendation is that the treatments are designed to restore pre-EuroAmerican colonization estimates of stand structure and composition and reintroduce low-moderate severity fire. Doing so should be sufficient for meeting fire response containment line standards used during indirect attack, with the exception of a bare mineral soil fireline unless located on a road.

<u>Managing wildfire for resource objectives</u>

Managing wildfires for resource objectives are important for increasing the pace and scale of mechanical or prescribed fire mitigation treatments. To determine opportunities to manage fires for resource objectives, we defined strategic response zones (SRZs) based on wildfire risk summaries and PODs following methods described in Thompson et al., 2016 and Dunn et al., 2020. SRZs establish broad response objectives to aid decisions in advance of an ignition, based on cNVC from the PNW QRA. Summarizing wildfire risk at this operationally relevant scale frames the fire management objectives and strategies around likely positive or negative consequences from fire. Aligning POD boundaries with high probability PCLs increases decision makers' confidence, likelihood of successful containment, and ability to respond effectively in accordance with values at risk. I summarized wildfire risk to resources and assets within PODs using the following rubric:

1. I summarized values at risk (cNVC) within each POD delineation (*In situ* risk) based on data from the PNW QRA.
2. I summarized values at risk (cNVC) within each simulated burn perimeter, and then attributed that value back to the ignition point and the POD it started in, to assess the potential for a fire to

occur in a location and negatively impact values at risk elsewhere (source risk). I summed these values for all ignitions within each POD.

3. I integrated *in situ* and source risk together (based on the sign (i.e. positive or negative) to determine the appropriate strategic response zone, where:

    +/+ = maintain, or default strategy is to manage fire for resource objectives.

    +/- = restore, or default strategy is to manage fire for resource objectives when conditions are appropriate to do so.

    -/- = protect, or fire should be aggressively suppressed to protect values at risk.

Figures 6 – 8 depict the outcomes of this analysis, ultimately identifying the appropriate response to wildfires based on values at risk.

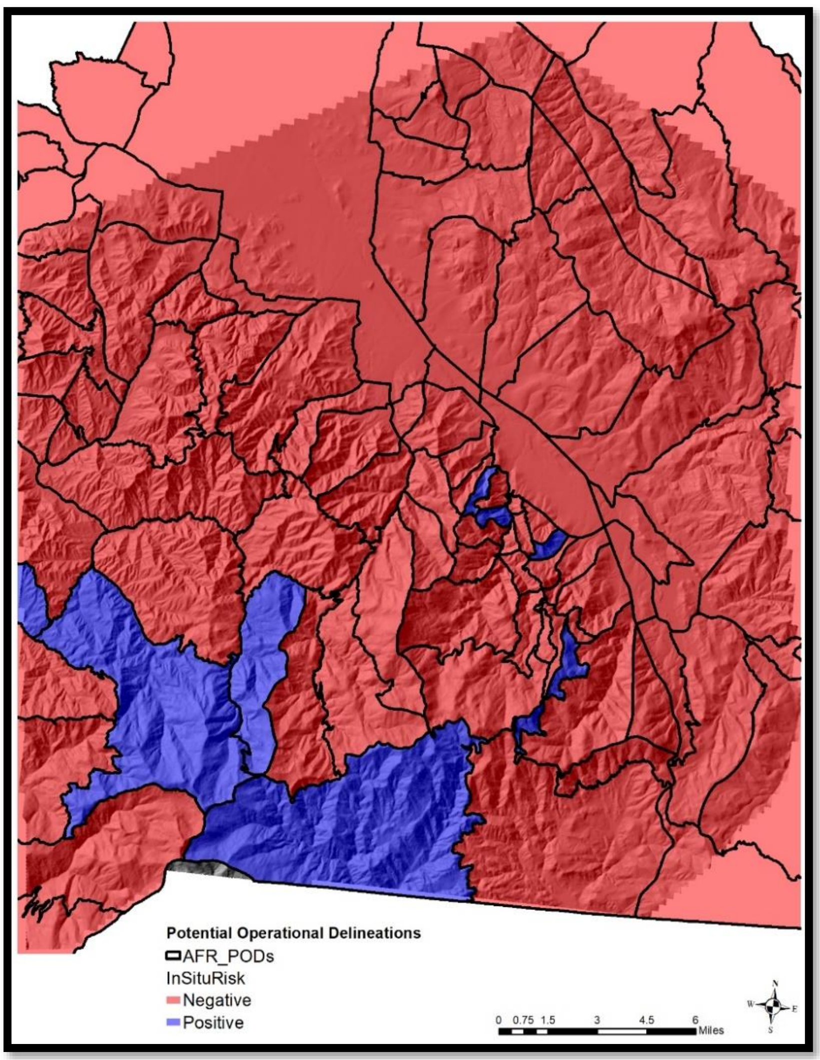

Figure 6: *In situ* wildfire risk for each POD across the AFR expanded landscape. I summed conditional net value change within each POD, and then distinguished the positive and negative outcomes should a wildfire occur within that POD.

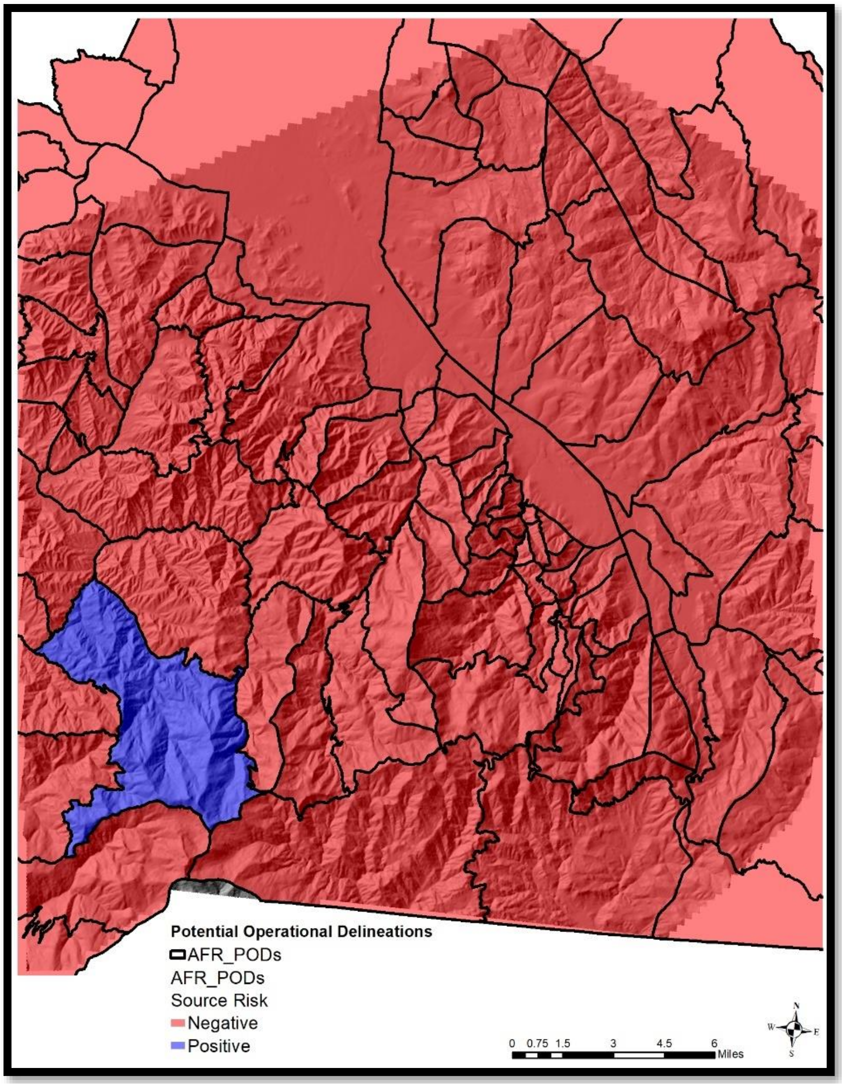

Figure 7: I calculated source risk for each POD across the AFR expanded landscape. I summed conditional net value change within each fire perimeter that ignited across this landscape, and then summed those values within each POD, to evaluate the potential for a POD to deliver a fire with negative consequences within this landscape.

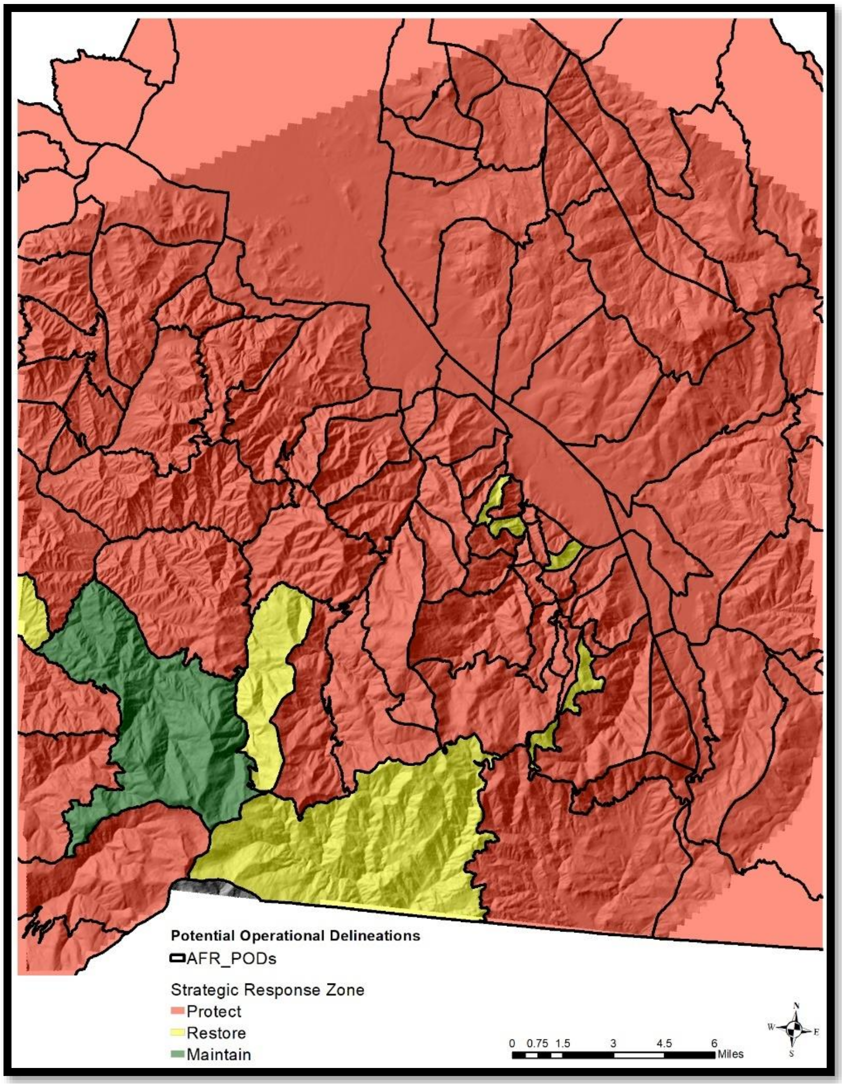

Figure 8: A depiction of strategic response zones across the AFR expanded landscape, depicting areas where fire should, could or should not be pursued as a strategy for mitigating risk.

Landscape-scale treatment prioritization: Strategic Containment Unit Prioritization

The following objectives were identified by the collaborative group when prioritizing strategic containment units:

1. Protect the Ashland Creek Watershed from unwanted large wildfires entering all or a portion of the watershed.
2. Protect communities and homes from the negative consequences of wildfire contact.
3. Protect values at risk to wildfire within or adjacent to each POD, by enhancing large fire containment opportunities.
4. Enhance the likelihood of containment success along POD boundaries to improve the likelihood of protection objectives.

Ashland Creek Watershed (ACW) Transmission Potential

I utilized simulated burn perimeters from the PNW QRA to define the area where wildfires could reach the Ashland Creek Watershed (ACW). This analysis began with selecting all simulated burn perimeters that intersected the ACW HUC 12. I then identified the ignition location of each of those perimeters and connected the ignition points furthest away from the ACW. This defined the expanded AFR landscape focal area that is depicted in each map provided in this report.

I then selected all simulated ignitions within this area and attributed each point with a yes or no dependent upon whether it intersected with the ACW HUC 12 boundary. Based on this data, I was able to estimate the probability of an ignition within a given portion of this expanded landscape to transmit across this area and impact the ACW. The resulting map in figure 9 represents a smoothed surface of the probability of an ignition to reach the watershed boundary (red area is the watershed boundary with decreasing likelihood as one moves further away).

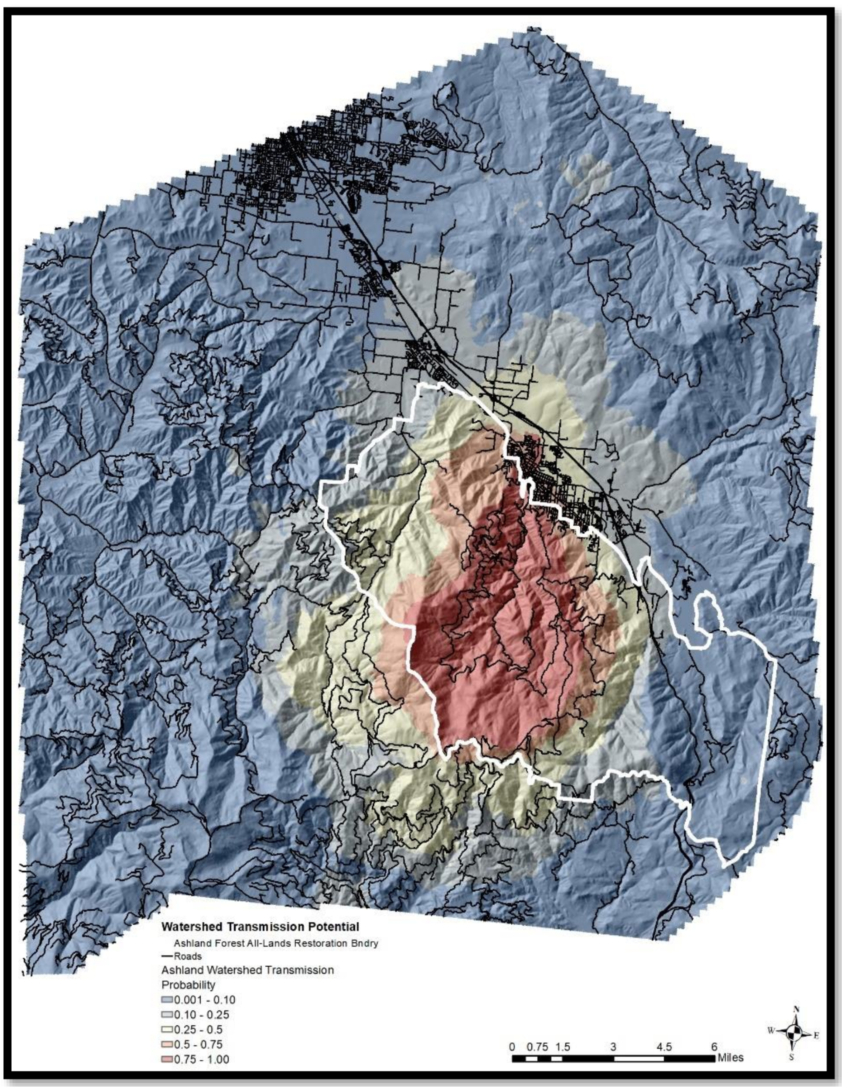

Figure 9: A measure of watershed transmission potential for the Ashland Creek Watershed.

Community Transmission

Community transmission is a measure of the housing unit density impacted by simulated fires igniting at that area within the landscape. The base data for housing unit density was developed by Pyrologix, Inc. from Microsoft Building Data and census information obtained from the American Community Survey. Individual homes are populated with the average number of persons per household.

Community transmission is then determined by summing the housing unit density (imputed to pixels where homes exist) within each simulated fire perimeter from the 2017 PNW QRA. The ignition point of each fire is then attributed with the summed housing unit density value. We then used inversed distance weighting in ArcMap 10.7.1, with a 3600 m search radius, to populate the raster datasets with a mean housing unit density value to depict variation in community impacts from large fires developing across different areas within the vicinity of Ashland, OR.

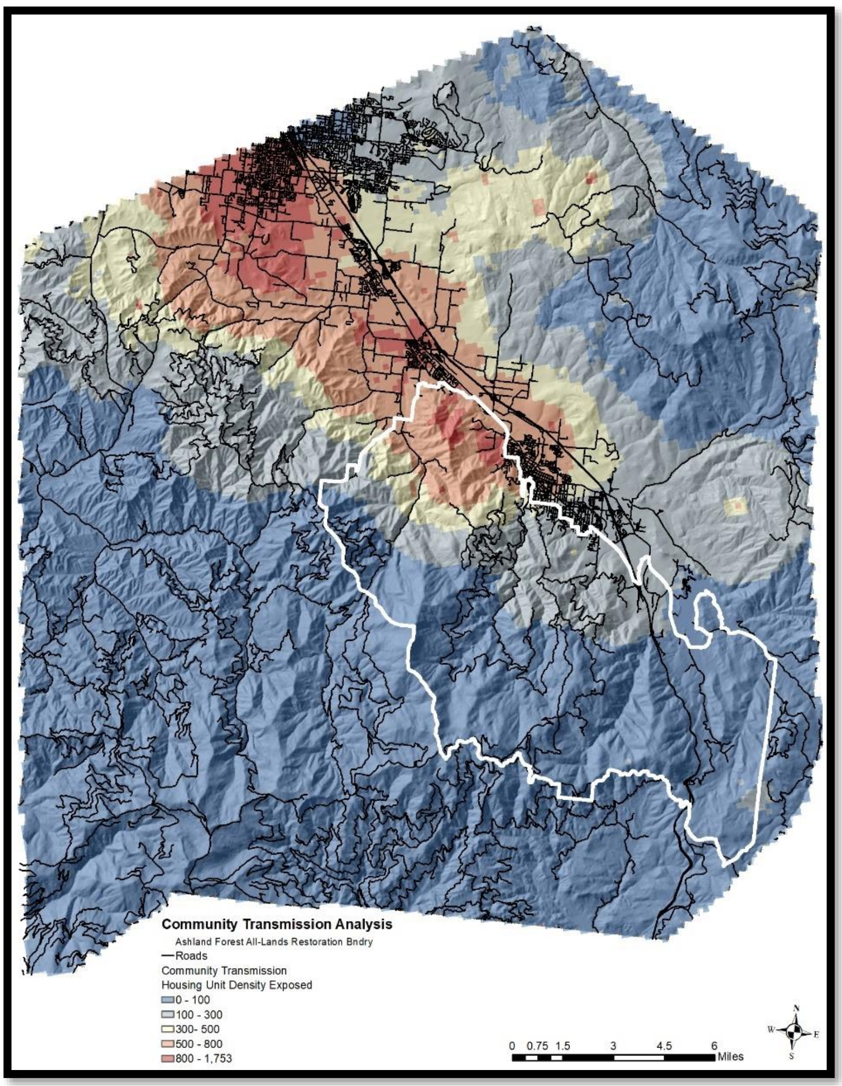

Figure 10: Community transmission across the expanded AFR focal area. Warmer colors suggest increased community exposure should a wildfire ignite within that landscape.

Values protected at strategic containment features

To address the objective of maximizing the values protected by enhancing fire responders success in containing a large fire, we summed expected net value change (eNVC) within each POD. This quantifies the total values protected by successfully implementing a strategic containment unit network that could facilitate wildfire response success. We included burn probability in this assessment to account for variation in the likelihood of fire occurrence across the expanded AFR focal area, and is presented in Figure 11.

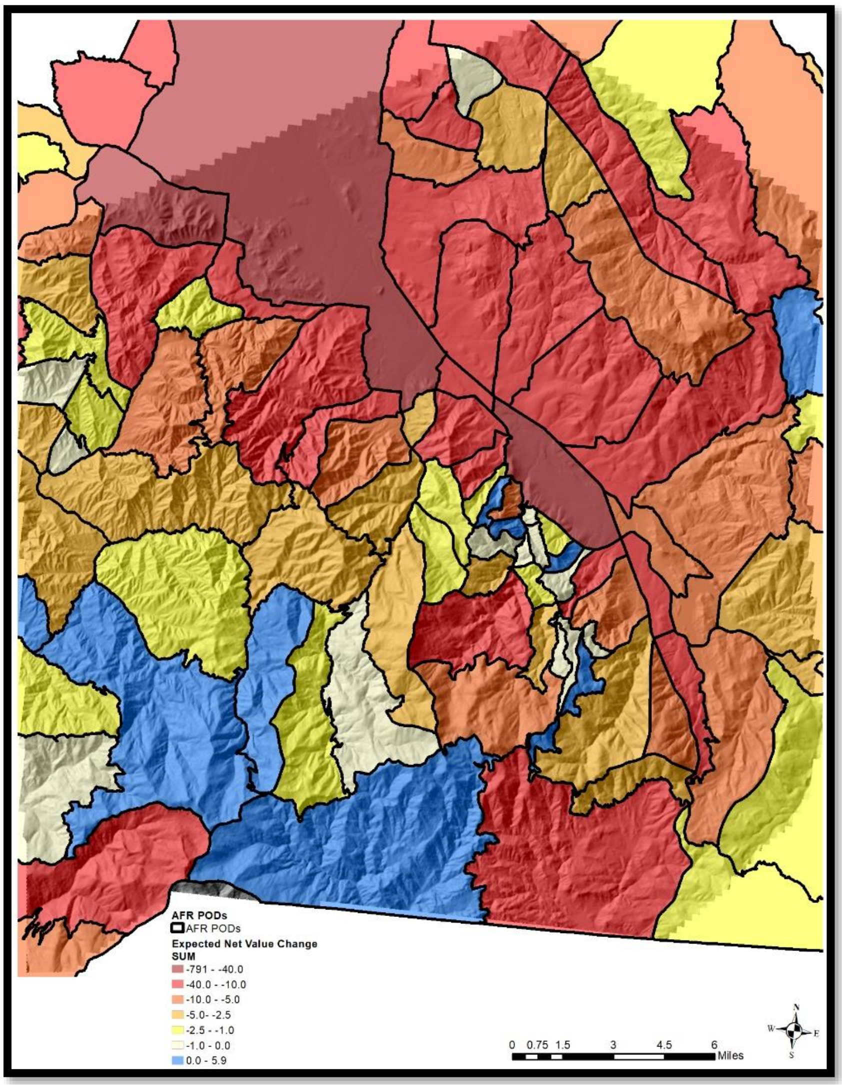

Figure 11: Variation in summed expected net value change at the POD scale across the expanded AFR focal area. Darker red colors have higher values at risk within the POD, and cooler colors have lower values at risk.

The final objectives for this prioritization effort is to target areas identified as preferred containment locations, but may not be currently in a condition that allows successful containment. I used the SDI and PCL data layers previously described to account for this need.

Prioritization schema

We used an existing polygon layer of square, 27-acre units as our representation of treatment units across the expanded AFR focal area. These units can be attributed with multiple variables to integrate into a prioritization ranking. Strategic containment units were selected by buffering POD boundaries by 100 ft, and then selected each square unit that intersected those lines. This results in at least 100 feet on either side of the desired containment location, but often longer given the size of the units. These units were then ranked based on the stated objectives, that were derived at two different scales as described below.

Landscape-scale estimates were used in this prioritization effort because SCUs would be leveraged to manage a landscape-scale fire, and therefore I needed metrics that accounted for that scale and potential outcome. I attributed the average value of ACW transmission potential, community transmission and values at risk (eNVC) at the POD scale to each SCUs. For watershed transmission potential and community transmission, higher values indicate a higher priority. These two metrics address the potential for fire to transmit beyond the POD boundary unless fire responders are successful. To account for values at risk within PODs abutting the strategic containment feature, we used summed eNVC and attributed SCUs with the lowest value intersected (lowest value indicates greatest loss) by the SCU from the POD-scale summaries.

Lastly, we took average values of SDI and PCL within each stand as a measure of the likelihood of success of containing a fire given the current conditions within each stand. Higher values of SDI indicate more difficulty to suppress, and lower value PCL indicate a lower rating of that feature for wildfire containment.

To integrate these metrics into a single prioritization metric, we first normalized the data on a scale from 0 – 1 based on the maximum and minimum values. I then took the geometric mean across all the metrics and rescaled that final metric to be between 0 – 1, using standard normalization equations. This process assumes each objective had equal weight but maintains the non-normal distribution of the underlying data. The final SCU prioritization ranking is provided in Figure 12.

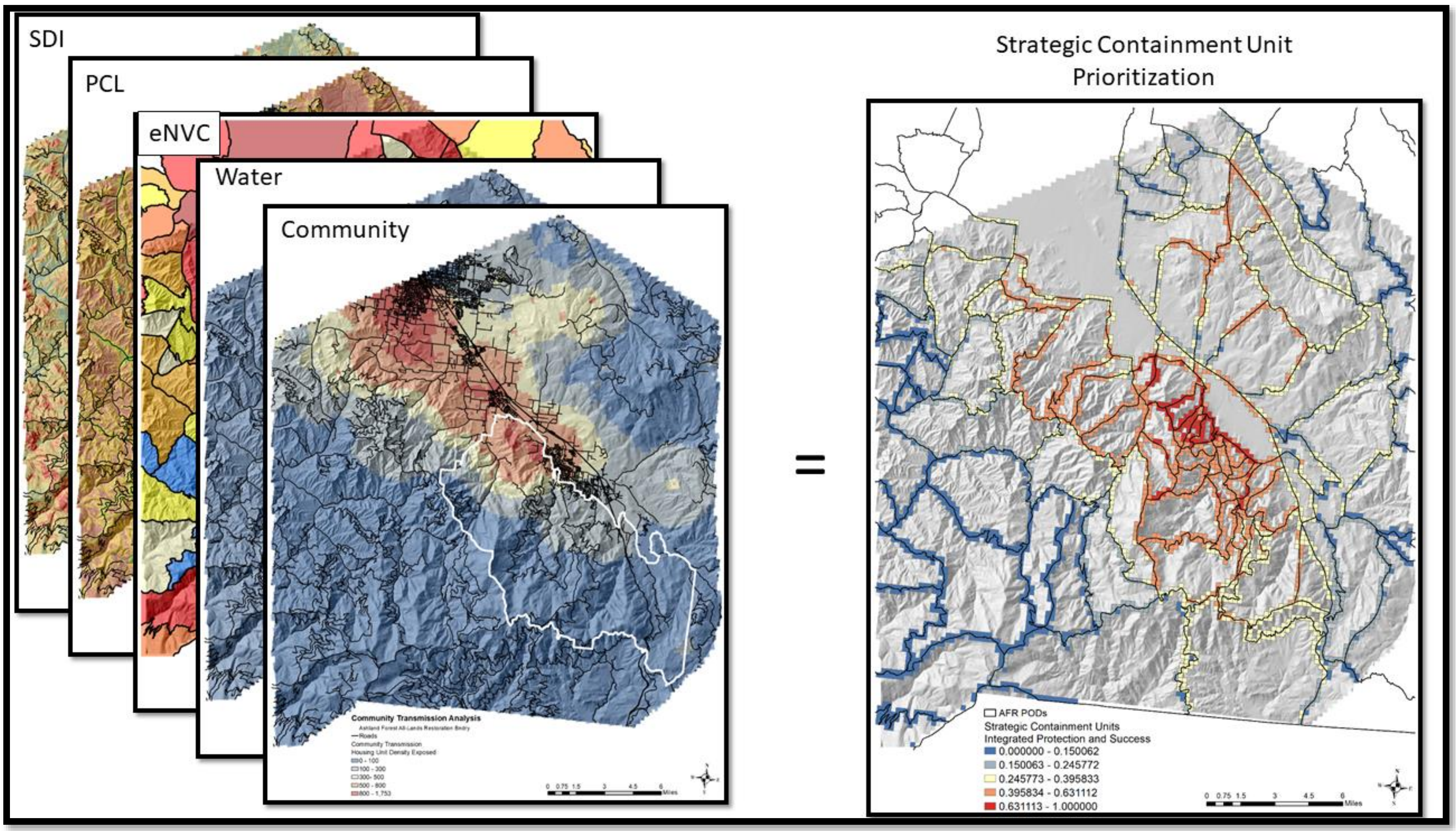

Figure 12: Integrated prioritization of strategic containment units across the expanded AFR focal area. Warmer colors indicate higher priority for treatments while cooler colors indicate lower priority.

Stand-scale treatment prioritization

The following objectives were identified by the collaborative group when prioritizing all treatment units across the AFR landscape:

1. Protect communities and homes from the negative consequences of wildfire contact.
2. Enhance climate resiliency of forest stands.
3. Restore the natural range of variability within stands to pre-EuroAmerican colonization conditions.
4. Protect Northern Spotted Owl core habitat.
5. Enhance the likelihood of containment success along POD boundaries to improve the likelihood of response success.
6. Reduce wildfire intensity to minimize consequences to valued resources and assets.

We leveraged existing datasets integrated into the Rogue Basin Cohesive Forest Restoration Strategy (https://www.conservationgateway.org/ConservationByGeography/NorthAmerica/UnitedStates/oregon/forests/Pages/Rogue_Basin_Restoration.aspx) as well as those created specifically for this project to meet these stated objectives. I do not describe these datasets in greater specificity as that information is available at the link provided above.

Prioritization schema

This prioritization schema followed the same procedures as described for strategic containment units except all summaries were done at the 27-acre stand-scale. The intent by the collaborative group is to enhance the ecological condition of the forest and other vegetation communities while reducing fire intensity and severity, protecting the community, and enhancing fire management opportunities.

To integrate these metrics into a single prioritization metric, we first normalized the data on a scale from 0 – 1 based on the maximum and minimum values. I then took the geometric mean across all the metrics and rescaled that final metric to be between 0 – 1, using standard normalization equations. This process assumes each objective had equal weight but maintains the non-normal distribution of the underlying data. The final prioritization ranking is provided in Figure 13 and 14.

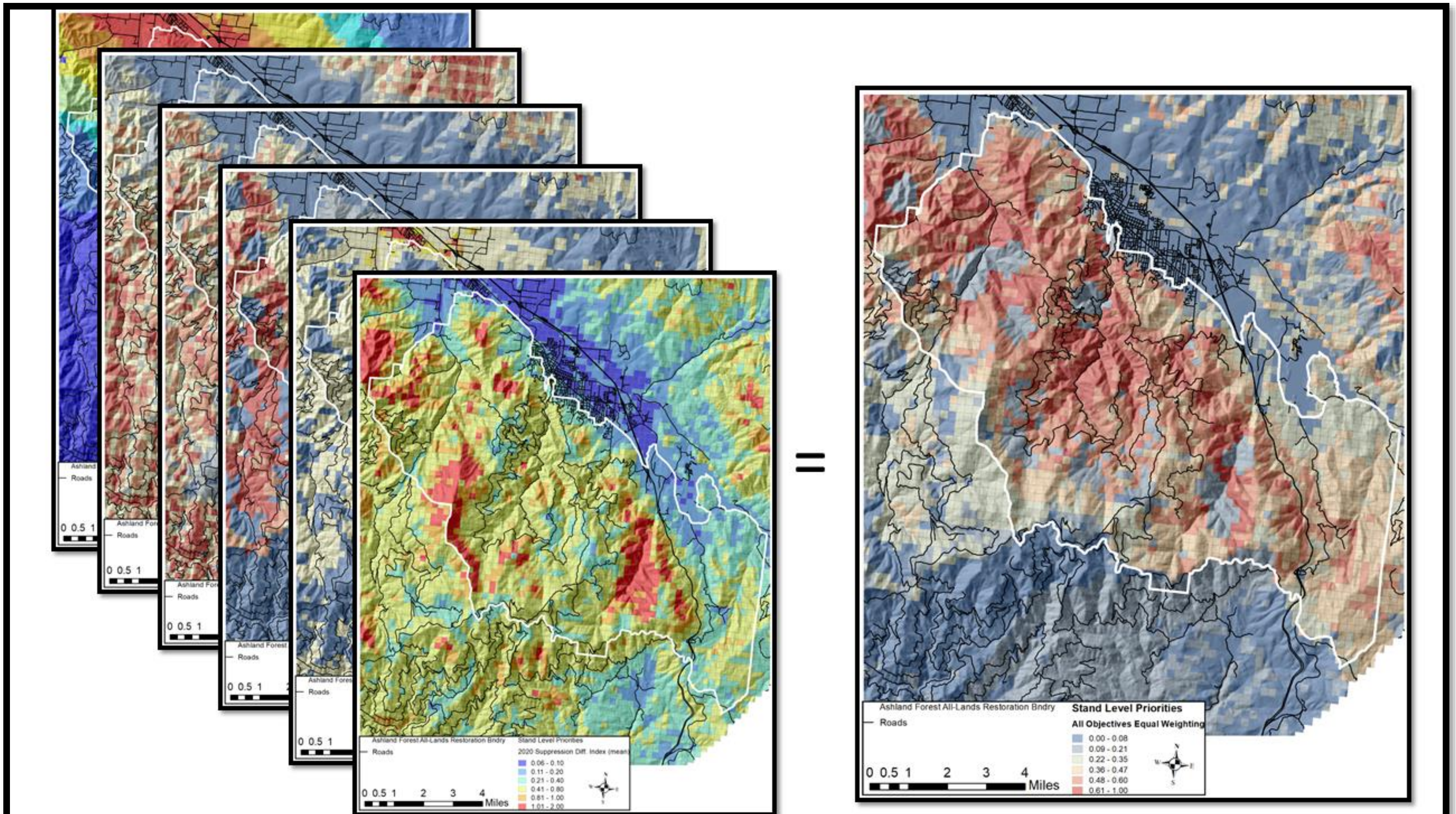

Figure 13: Depiction of the prioritization framework and outcome for stand-level treatments across the AFR landscape.

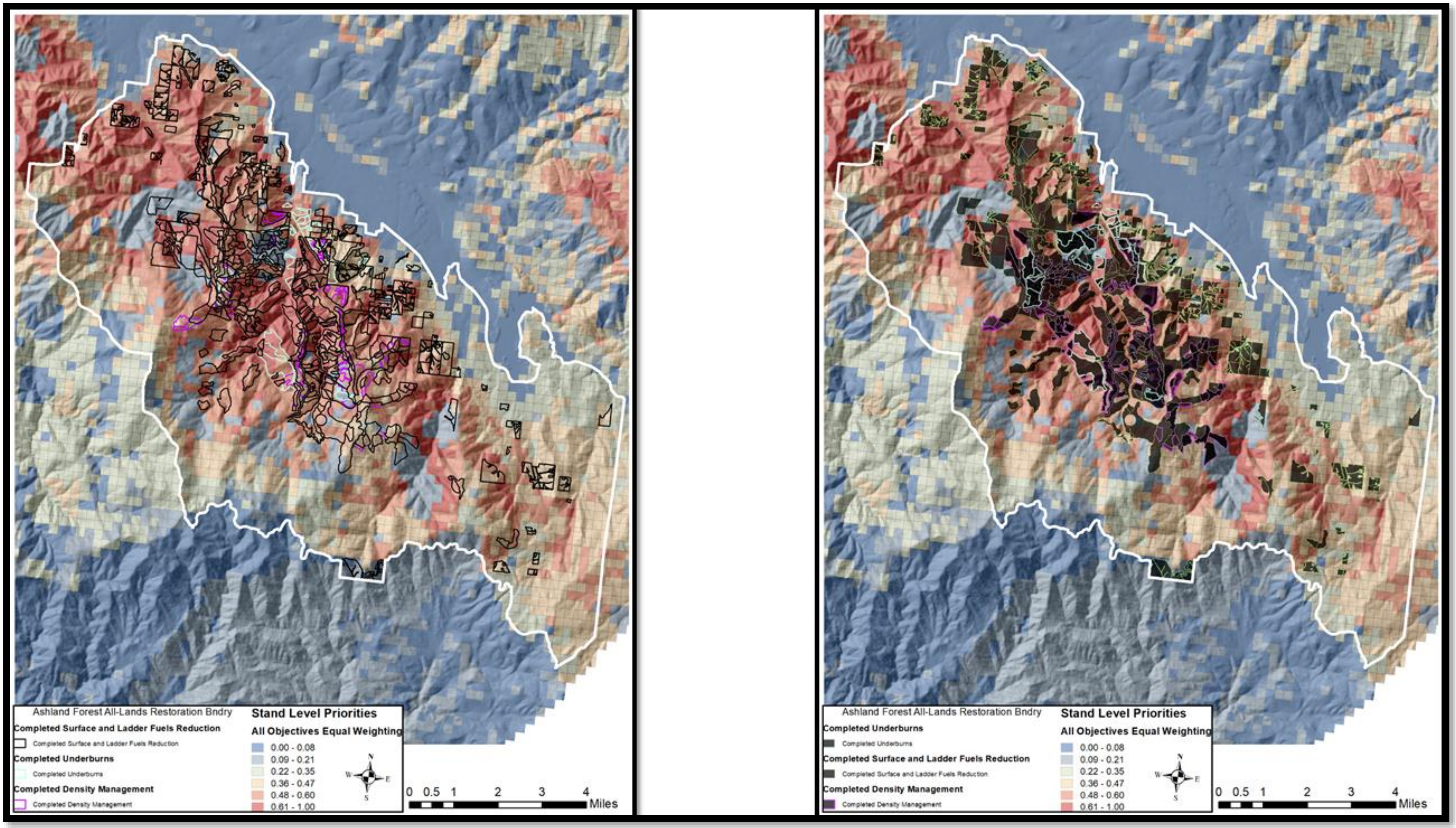

Figure 14: Depiction of stand-level prioritization and ranking with an overlay of recent mitigation treatments of varying types. Warmer colors warrant greater priority over cooler colors. Actual rankings and quantitative data are available for specific rankings.

Objective 7: Draft Manuscripts

I have developed a draft manuscript from this project. I intend to refine and submit for peer-reviewed publication in conjunction with members of The Nature Conservancy and local stakeholders by May 2021. I am also working on a white paper describing the outcome for a more lay audience, to reach a broader audience. In addition, the data has been and is continuing to be used in presentations at various meetings and workshops.

Literature Cited

Dunn, C. J., Thompson, M. P., & Calkin, D. E. 2017. A framework for developing safe and effective large-fire response in a new fire management paradigm. Forest ecology and management, 404, 184-196.

Dunn, CJ, O'Connor, CD, Abrams, J, Thompson, MP, Calkin, DE, Johnston, JD, Stratton, R, Gilbertson-Day, J. 2020. Wildfire risk science facilitates adaptation of fire-prone social-ecological systems to the new fire reality. Environmental Research Letters, https://doi.org/10.1088/1748-9326/ab6498

O'Connor, C.D., Calkin, D.E. and Thompson, M.P., 2017. An empirical machine learning method for predicting potential fire control locations for pre-fire planning and operational fire management. International journal of wildland fire, 26(7), pp.587-597.

Rodriguez y Silva, F , O'Connor, C. D., Thompson, M. P., Martínez, J. R. M., & Calkin, D. E. (2020). Modelling suppression difficulty: Current and future applications. International journal of wildland fire, 29(8), 739-751.

Rodriguez y Silva F, Martinez JRM, Gonzalez-Caban A. 2014. A methodology for determining operational priorities for prevention and suppression of wildland fires. *International Journal of Wildland Fire* **23(4)**, 544-554.

Thompson, M., Bowden, P., Brough, A., Scott, J., Gilbertson-Day, J., Taylor, A., Anderson, J. and Haas, J., 2016c. Application of wildfire risk assessment results to wildfire response planning in the southern Sierra Nevada, California, USA. Forests, 7(3), p.64.

Wei, Y., Thompson, M.P., Scott, J.H., O'Connor, C.D. and Dunn, C.J., 2019. Designing Operationally Relevant Daily Large Fire Containment Strategies Using Risk Assessment Results. Forests, 10(4), p.311.