Wildfire Risk to Rural Infrastructure: Locating the Highest-Risk to Infrastructure Clusters in the Western United States

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May 7th, 2023

Capstone Statement

Wildfires are a necessary component of a healthy ecosystem, but pose an extreme risk to lives and infrastructure, especially in the Western United States. The risk of destructive wildfire is higher than it has ever been due to ecological changes, past firefighting policy, and climate change. This project aims to assess the current wildfire risk to clusters of infrastructure outside of heavily urbanized areas based on landscape ecology and local climate in the Western United States, then investigate the effects of predicted climate change on future wildfire risk.

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Introduction & Background

The Western United States – Washington, Idaho, Montana, Oregon, Wyoming, California, Nevada, Utah, Colorado, Arizona, and New Mexico – shown in figure 1, are threatened by a variety of natural disasters, from earthquakes to tornados to volcanos, however, the most ubiquitous threat is wildfire.

***Figure 1** – Western United States*

Wildfire in the Western United States is part of the natural cycle that has sustained ecosystems spanning from the deserts and xeric shrublands of the Southwest to the temperate rain forests of the Pacific Northwest. Wildfire clears dead and overgrown vegetation, kills pests and diseases, and allows resinous trees to reseed. Without fire, ecosystems that depend on it are overtaken and eliminated, forever changing the ecology of a region [39].

While necessary for the natural cycle, wildfire is also one of the greatest natural threats to communities in the Western United States. Wildfire burns homes and businesses, disrupts all forms of transportation, destroys electrical generation and transportation facilities, and threatens the production of fossil fuels. These fires have far-reaching impacts, from the loss of homes, lives, and livelihoods to disruptions in supply systems affecting the entire World.

The threat of wildfire is currently greater than it ever has been in the history of the United States. An ongoing infestation of Western Pine Beetle, 10 times vaster than any seen before, has left huge swathes of pine forest dead, resulting in a massive fuel surplus in unburned areas [40]. Firefighting policy prior to the 1970's focused on fighting and extinguishing all fires, stifling the natural fire cycle, resulting in additional surpluses of fuel in areas that typically burn more frequently [41]. Finally, climate change has shifted the climate of many areas to a hotter, drier fire season, increasing the likelihood of fire ignition and enhancing propagation once burning [42]. These factors combined have increased the likelihood of large, dangerous fires that once started, burn uncontrollably through anything in their path.

Large wildfires typically burn uncultivated grasslands, shrublands, and forests and once burning, can be almost impossible to put out. Wildfires ordinarily happen between the months of May and November and are usually started by intentional or unintentional human interaction but can also be caused by lightning strikes. Contemporary fire-fighting policy is to allow fires to burn naturally under observation until they threaten lives and infrastructure. This allows the natural cycle to continue, however, fires have recently become so large and out of control that mandatory evacuation is the only option to save lives, even at significant economic loss to economies that depend on at-risk forests [43].

Beyond the obvious threat wildfire poses to large urban areas, the topography of the West creates natural clusters where roads, railroad tracks, power lines, and fuel pipelines are funneled through mountain passes or natural corridors (cluster examples in Appendix C). These clusters create a significant vulnerability as these routes and the infrastructure that use them are often the only access to certain areas without substantial workarounds.

This project will identify these infrastructure clusters in the Western United States by analyzing the proximity of the transportation network, electrical grid, and petroleum processing chain to find areas where components of these systems are in proximity. In addition, past wildfire activity, current ecological status, and recent and future climate factors are combined into overall current and future wildfire risk assessments for the Western United States. These analyses are combined to find where clusters are located in high wildfire risk areas, implying a weakness in the infrastructure system if threatened by wildfire.

Literature Review & Methodology

Wildfire Risk

Overall wildfire risk assessment considers many distinct factors, and much time and effort has been put into modeling wildfire genesis and propagation on a hyper-local scale. However, there are several important but easily measured variables that play a significant role in predicting overall fire risk for a larger area. On the simplest level, they can be broken down into the basic fire triangle – Oxygen, heat, and fuel [1].

For fire to start and continue burning, the three elements of the fire triangle must be present: Oxygen, heat, and fuel. In a wildfire, Oxygen is supplied by the atmosphere and is always available, however, oxygen inflow can be increased by strong winds [2]. Heat for the wildfire is provided initially by an ignition source and once burning, the fire itself generates more than enough heat to maintain combustion [3]. After ignition, fire is spread via contact and proximity heat transfer or via lofted embers that typically travel less than two kilometers from the fire igniting spot fires ahead of the main fire. In certain conditions, fires with extremely strong convective updrafts and very high winds, embers can travel as far as 9 kilometers or more from a fire, igniting flammable structures far from the fire front [4][24]. Most wildfires in the United States start by human interaction, either intentionally or unintentionally. Less commonly, wildfires are naturally ignited by lightning striking dry fuel sources [5]. Finally, fuel for wildfires is vegetation, alive or dead, present in the environment. While dead vegetation is typically drier and combusts more easily, living, and damp vegetation will readily burn at high enough temperatures [6]. Once a fire has taken hold, anything in its path becomes fuel.

For this analysis, wildfire risk for a region is assessed using fuel availability and climatic heat sources and suppression. The fuel sources considered are based on landcover and are classified into four categories, evergreen forests, deciduous forests, shrublands, and grasslands. Most forests of the Western United States are evergreen forests, with some areas of deciduous forest in the southern and eastern portions of the area [7]. Evergreen forests will typically burn more readily than deciduous forests due to their resinous wood, however, deciduous forests still pose a significant wildfire risk due to the availability of fuel [8]. Shrublands usually contain smaller, more spread-out trees and bushes, separated by grassy areas. While not as significant as the risk of forest fire, wildfires in shrublands can still become very large and destructive under hot, dry, and windy conditions. Grasslands also present a risk of destructive wildfire, but due to the lack of large fuel sources and significant vegetation, wildfires in grasslands tend to be less intense and destructive than wildfires in forests or shrublands [9].

Another variable in the fuel availability equation is the amount of dead timber in an area, measured as metric tons of Above Ground Carbon (AGC). Forests typically contain trees that have died naturally from age, storms, fire, or disease; however, the current Western Pine Beetle epidemic has created a large surplus in the amount of dead timber in affected forests

[10]. The beetles infest trees and kill them, spreading through forests relatively quickly, stopped only by wildfire burning the trees they live in. Past firefighting policy limiting the spread of wildfire has allowed the population of these beetles to explode, killing far more trees than usual and adding to the flammable fuel available in an area [11].

The final element considered in the fuel equation for this analysis is past fire activity. Because wildfire is a natural process, it generally follows a regular cycle. In the evergreen forests of the West, trees typically take 20-30 years to mature, allowing enough time to produce resinous cones that are then opened by fire, reseeding the forest on a regular basis. The firefighting policy of the past inhibited this cycle, leading to an abundance of old, dead trees and limited the reseeding of forests [12]. Fires in shrublands and grasslands occur far more frequently as the grasses that constitute their main fuel source regrow each year.

On the heat side of the fire triangle, climatic factors that affect the amount of moisture present in the environment are the primary considerations for wildfire risk [13]. Water in the ground, on vegetation, and in the atmosphere works to cool temperatures and help inhibit quick heat transfer over large areas. When enough moisture is present in the air as water vapor, it condenses and falls as precipitation, helping to put out small fires and limit the spread of large fires. Winter precipitation adds to the snowpack in an area and as the snow melts in the spring, it keeps the soil and vegetation wet, greatly reducing the chance of ignition [14]. Lower humidity levels imply dry atmospheric conditions and increase the amount of moisture lost to evaporation from fuel sources, increasing fire risk with decreasing humidity. High temperatures also dry out and preheat fuel sources, making them even more prone to ignition

[15]. Because of this, areas with high temperatures, low humidity, low summer precipitation, and low winter snowpack are more at risk for wildfire.

Vulnerable Infrastructure

The primary goal of current Department of the Interior's firefighting policy is to allow wildfires to burn under supervision, constantly evaluating and predicting the movement and growth of the fire with the protection of human life as the single, overriding priority. After that, priorities include protecting communities, community infrastructure, other property and improvements, and natural and cultural resources [16]. Locations where transportation, electrical, and fuels infrastructure is clustered are particularly vulnerable, especially in areas of high fire risk.

Roads and Railroads are the major form of transportation of goods through the supply chain. The disruption of this chain has far reached impacts. In certain areas, a single road is often the only access rural communities have to food or medical care and may be the only option for evacuation if needed. Wildfire burning over a road or railroad can significantly damage them, making them unusable until extensive repairs can be made [17].

Airports and ports are also vulnerable to wildfire. Airports are often a major hub for the transportation of goods and people and a disruption at a single airport can ripple through the entire air traffic system, causing delays and cancellations [18]. Ports have a highly demanding schedule to maintain, so any disruption or destruction of a port requires ships to travel to different ports, backing up the supply chain and causing widespread interruptions [19].

Electrical generation facilities can sustain considerable damage from wildfires. Beyond the destruction of buildings associated with traditionally fueled power plants, wildfire can significantly damage wind turbines and solar fields. Additionally, overhead transmission lines can be damaged in intense wildfires, cutting off the power supply to large areas and even becoming additional sources of ignition when damaged [20].

Both above ground and buried fossil fuel transport pipelines can be damaged by wildfire, disrupting the flow of fuel to all types of users. Additionally, the refineries, processing plants, and mines that supply the fuel used daily are in danger in high fire risk areas [21].

The relationships of these variables and their sources can be found in the conceptualization diagram in Appendix A. These risks to infrastructure are significant threats to daily life on their own, but when clustered together in areas where wildfire risk is high, present a unique danger to the normalcy of daily lives both in the Western United States and around the World.

Two important additional variables in wildfire propagation that were not considered are topography and prevailing winds. Fire propagation is significantly affected by topography, with fire propagating quickly uphill and slowly downhill. Also, the primary driver of fire propagation direction is the prevailing wind direction. Embers and heated air are pushed downwind from fires, spreading the fire with the wind [27]. When considering fire propagation, areas that are upslope and downwind of those areas identified as high risk for wildfire ignition are at greater risk than those areas downslope and upwind of risk areas. These variables were not considered as the primary focus of this study was the initial ignition risk of fires and propagation is highly dependent on conditions at the time of a fire.

Methodology

For the analysis of infrastructure clusters and the associated wildfire risk, the infrastructure clusters were identified, then wildfire risk based on current climate and future climate predictions was calculated for the entire Western United States. These layers were then overlaid and combined to determine the fire risk to individual clusters [28]. Infrastructure is broken down into four subcategories: urban areas, transportation infrastructure, electrical infrastructure, and fossil/biofuel infrastructure. Fire risk is broken into two categories: fuel availability and climate factors (both current and future) [29]. All infrastructure data was in vector form and fuel and climate data was in raster form except for past fire activity, which was initially in vector form then rasterized.

Urban areas are defined as census blocks with population densities of at least 500 people per square mile and adjacent blocks that encompass a population of at least 2,500 people [22]. Protecting lives and communities is the first goal in firefighting policy and infrastructure is highly clustered in and around urban areas so any wildfire nearby urban areas is dangerous and a priority when planning where to concentrate firefighting efforts [16]. Because of this, urban areas, and a buffer area of 9 kilometers around urban areas are excluded from the analysis. The buffer distance is derived from typical wildfire propagation rates (10% of wind speed) under average wind conditions (15 kph wind) in a 6-hour period [23]. This buffer distance also includes the travel distance of lofted embers ahead of the fire front [4][24].

Transportation factors considered include roads, railroads, airports, and maritime ports [25]. Roads included almost 7,000 numbered highways and roads in the Western United States. Paved roads are typically not damaged by wildfire, however, if burning vegetation falls on the road surface, certain pavements can melt, buckle, or crack [26]. Railroads included all in-use railroad lines in the Western United States and are at risk due to the use of wood timbers in railroad ties and for support in critical, vulnerable bridges. Both roads and railroads are unusable and at risk when in proximity to a wildfire, so a 2-kilometer buffer around all roads and railroads was used [17][30]. Airports and ports are at risk due to their sprawling footprint. Both include paved areas and buildings at risk from ember induced ignition, so again, a 9-kilometer buffer was used around all airports and ports [19].

Electrical infrastructure includes power generation facilities and the transmission lines that carry electric energy from one point to another. For this analysis, all overhead lines carrying over 69 kV or more are considered. Because they are at relatively little threat from ember induced ignition, a 2-kilometer buffer around each line was used [20] [31]. Also considered are all types of electrical generation facilities, including fossil fuel and nuclear power plants, hydroelectric dams, solar fields, and wind farms. These facilities are under threat from wildfire embers and contain flammable buildings and equipment, so the larger 9-kilometer buffer was used for these facilities [20] [31].

Fuel production and transportation facilities were also considered in the analysis due to the impact fuel shortages can have on the entire country and the threat posed to them by wildfire. Natural gas wells and oil wells were aggregated by field and plotted with a 9-kilometer buffer around them due to threat of hot embers igniting flammable materials near them [32]. Coal mines, fossil fuel refineries, and biofuel processing plants were also considered with a 9-kilometer buffer as they all have significant build-up that would be threatened by embers as well [21]. Pipelines are often buried, however, they have above-ground exposed valve assemblies every few miles and at junctions and are often transporting highly pressurized, flammable fluids that pose an extreme fire risk if the line is damaged or heated beyond its structural capacity. For these reasons, a 2-kilometer buffer was used around all above- and below-ground oil and gas pipelines [33].

After generating these buffers, a simple polygon count was used to determine the areas where many buffers overlay each other and those areas with the highest polygon count were classified as clusters. A simple count is used instead of a weighted analysis as each layer of infrastructure is important in some way and none presents a significantly greater value over another - the loss of any single piece of infrastructure will have far-reached effects [34].

Wildfire fuel availability was calculated using Landsat 30m resolution Land Cover data current as of 2020, provided by USGS and classified using the United Nations Land Cover Classification System. Nineteen classifications are present, but only ten classifications of four general types were considered wildfire fuel for this analysis: evergreen/needleleaf forests, deciduous/mixed forests, shrublands, and grasslands [7][8][9]. In addition to land cover, measurements of Above Ground Carbon (AGC) due to Western Pine Beetle kill were added to the raster scoring, with four classifications: 0 Mg per square kilometer, 0.1 – 999.9 Mg per square kilometer, 1,000 – 1,999.9 Mg per square kilometer, to 2,000+ Mg per square kilometer [10]. Additionally, past fire data was filtered to single out fires from the last 25 years in forested areas as these areas are not fully mature yet and are typically less prone to significantly large forest fires [12]. This data was rasterized, and a raster sum was calculated using the three fuel variables to produce an overall wildfire fuel availability score [35]. The sum of fuel scores ranges from 0 to 17 and individual scores are shown in table 1.

Fuel Variable	**Score**
Land Cover	Not Applicable – ***0***, Grassland / Shrubland - ***6***, Deciduous Forest – ***9***, Evergreen Forest - ***12***
AGC	0 Mg/km^2 – ***0***, 0.1 to 999.9 Mg/km^2 - ***1***, 1,000 to 1,999.9 Mg/km^2 – ***2***, 2,000+ Mg/km^2 - ***3***
Fire History	Fire within 25 years – ***0***, No fires within 25 years – ***2***

Table 1 – Wildfire fuel variable scoring.

Climate scoring was based on historical climate data from 1991 – 2020 and future predictions for the period of 2081 – 2100 at 1 kilometer resolution, provided by the AdaptWest Climate Adaptation Conservation Planning Database derived from an ensemble of 13 climate models. For each period, May – September precipitation totals, summer (May – July) mean temperatures, autumn (August – October) mean temperatures, mean yearly humidity, yearly total snowfall, and a Climate Moisture Index (CMI – measure of precipitation and evaporation) were combined to generate a climate score [13][14]. Each variable was classified into four categories based on their range and scored from 0 to 3. Increasing precipitation, humidity, and snowfall totals and lower temperatures, and CMI imply less wildfire risk and are scored accordingly. The current and future climate scoring are shown in table 2 and table 3.

Climate Variable	**Score**
Precipitation	0-125mm – ***3***, 125-250mm – ***2***, 250-375mm – ***1***, 375-500+ mm - ***0***
Summer Temp	-15.8 to 10°C – ***0***, 10 to 17°C – ***1***, 17 to 24°C – ***2***, 24 to 37.3°C – ***3***
Autumn Temp	-27.1 to 10°C – ***0***, 0 to 17°C – ***1***, 17 to 24°C – ***2***, 24 to 30.3°C – ***3***
Humidity	36 to 47% - ***3***, 47 to 55% - ***2***, 55 to 63% - ***1***, 63 to 96% - ***0***
Snowfall	0-50mm – ***3***, 50-300mm – ***2***, 300-550mm – ***1***, 550+ mm - ***0***
CMI	0-250 – ***0***, 250-700 – ***1***, 700-1,150 – ***2***, 1,150-2,185 – ***3***

Table 2 – Current Climate Variable scoring.

Climate Variable	Score
Precipitation	0-125mm – ***3***, 125-250mm – ***2***, 250-375mm – ***1***, 375-500+ mm - ***0***
Summer Temp	-10.4 to 10°C – ***0***, 10 to 17°C – ***1***, 17 to 24°C – ***2***, 24 to 42.9°C – ***3***
Autumn Temp	-16.6 to 10°C – ***0***, 0 to 17°C – ***1***, 17 to 24°C – ***2***, 24 to 34.3°C – ***3***
Humidity	36 to 47% - ***3***, 47 to 55% - ***2***, 55 to 63% - ***1***, 63 to 96% - ***0***
Snowfall	0-50mm – ***3***, 50-300mm – ***2***, 300-550mm – ***1***, 550+ mm - ***0***
CMI	0-250 – ***0***, 250-700 – ***1***, 700-1,150 – ***2***, 1,150-2,545 – ***3***

Table 3 – Future Climate Variable scoring.

The variables used and their relationships and derivations can be visualized using the implementation diagram in Appendix B. The derived scores are then combined to create a fire risk on a scale of 0 – 35, with zero having no fuel and no climate factors that would suggest significant wildfire risk and 35 having extreme wildfire risk. This also allows the current and future climate data to be scored on the same scale. The fire risk will then be classified into seven categories: Very Low – 0 - 5 points, Low – 6 - 10 points, Moderate-Low – 11-15 points, Moderate – 16-20 points, Moderate-High – 21-25 points, High – 26-30 points , and Extreme – 31-35 points [36].

To find the relationship between infrastructure clusters and fire risk areas, the derived cluster polygons were overlaid on the fire-risk score raster and the intersecting fire risk score was assigned to the cluster polygon [37]. To find the most at-risk areas, a query of the top pixel-counts of extreme and high scores in a single cluster polygon was run and the resulting areas were those with the most extreme pixels within the polygon [35][38]. Additionally, areas within one day of a fire were plotted around each infrastructure cluster using a 36-kilometer buffer based on a 15 kph wind and the 10% propagation rate estimate and overlaid on the high and extreme fire risk polygons. The resulting overlay will indicate areas where if a fire starts, it is within one day of threatening an associated infrastructure cluster [39]. The derived areas were then plotted on a map of the Western United States.

Results, Analysis, and Discussion

The primary output of the analysis is represented in two forms. First, shown in figure 2, is a map of the infrastructure clusters identified as extreme risk and high risk. The extreme-risk clusters are clusters of ten or more units of infrastructure in areas identified as extreme fire risk areas. The high-risk clusters are clusters of five or more units of infrastructure in extreme fire risk areas. There were two clusters identified as extreme risk clusters based on current climate data; a powerplant in northern California and a major interstate intersection with nearby railroad tracks, powerlines, and fuel pipelines in central Utah. There were also 17 clusters

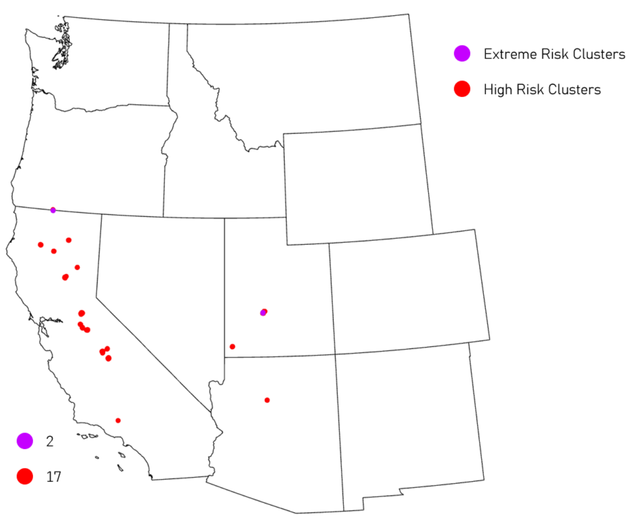

***Figure 2** – Current At-Risk Clusters*

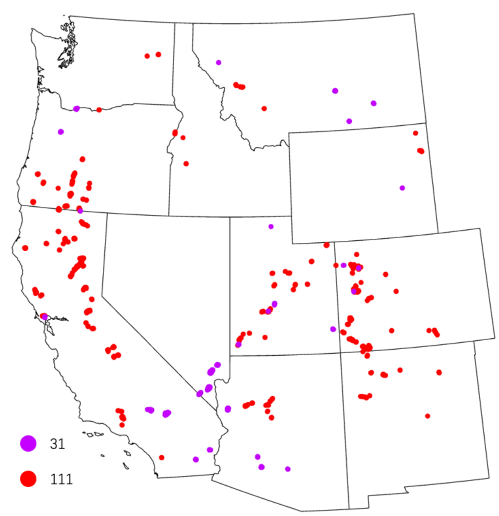

***Figure 3** – Future At-Risk Clusters*

identified as high-risk clusters, primarily in California. Figure 3 shows the same infrastructure data as figure 2, but with the risk analysis based on the future climate predictions. A significant change in the number high and extreme risk clusters can be seen with many still in California, but others spread primarily across Utah, Arizona, Colorado, and New Mexico with several others in the rest of the region.

Also derived from this data is a map of areas where fire is within one day of affecting an infrastructure cluster. Figure 4 shows the current fire risk areas based on high and extreme fire risk to small (5-9 units of infrastructure) and large (10+ units of infrastructure) clusters. Figure 5 shows the same fire risk areas derived from the future climate data. The current risk is primarily

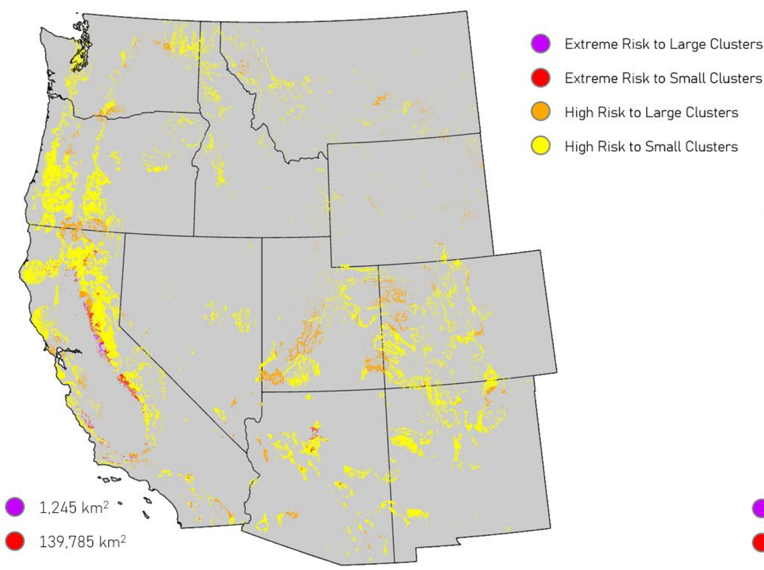

Figure 4 *– Current Infrastructure Risk Areas*

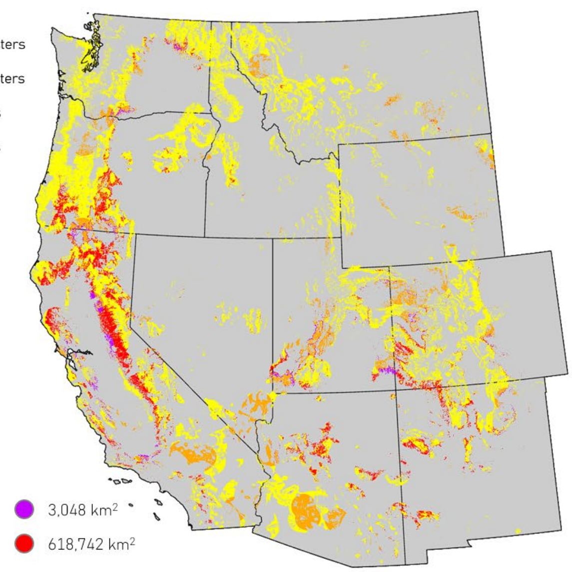

Figure 5 *– Future Infrastructure Risk Areas*

to small clusters in northern California and southern Oregon, with other risk areas spread sparsely throughout the region. The future risk shows significantly higher risk to the areas currently threatened, particularly in norther California and southern Oregon, with additional risk areas widely spread throughout the region.

To arrive at these data sets, the infrastructure, fuel, and climate data was processed per the implementation diagram in Appendix B and detailed in the Methodology section. The infrastructure used is plotted on the map in figure 6, and clusters were derived from the polygon count of the overlaid buffers for each unit of infrastructure. Examples of the clusters

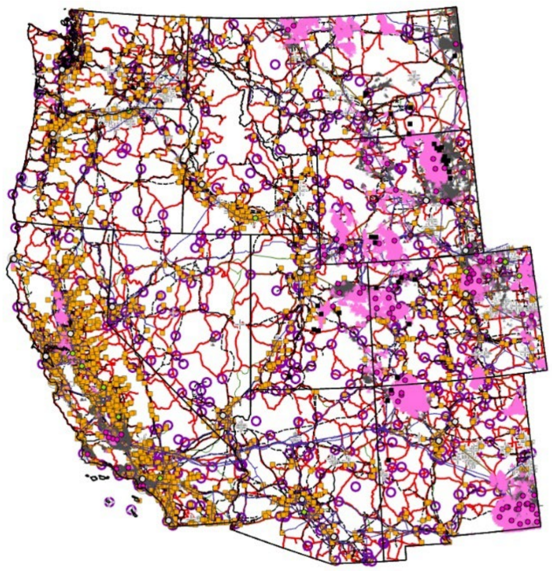

Figure 6 *– All Infrastructure Considered in Analysis*

are shown in Appendix C. Finally, all the identified clusters are shown on the map in figure 7. The results show large areas of risk through central California, Utah, Colorado, and Wyoming, with clusters of infrastructure spread throughout the entire region. Investigating the largest clusters showed that the clusters of ten or more units of infrastructure were very often centered on fossil fuel powerplants due to the abundance of roads, railroads, and fuel pipelines at each plant in addition to the clustering of powerlines originating at the powerplant.

The fuel score was derived from landcover data, above ground carbon data, and the past fire history of the region. The individual layers and scoring are shown in Appendix D and the fuel composite score is shown in figure 8. The fuel map shows an abundance of available fuel in the Cascade Mountains, the Sierra Nevada Mountains, the Rocky Mountains of northern Idaho and Montana as well as the forested regions of Utah, Colorado, New Mexico, and Arizona.

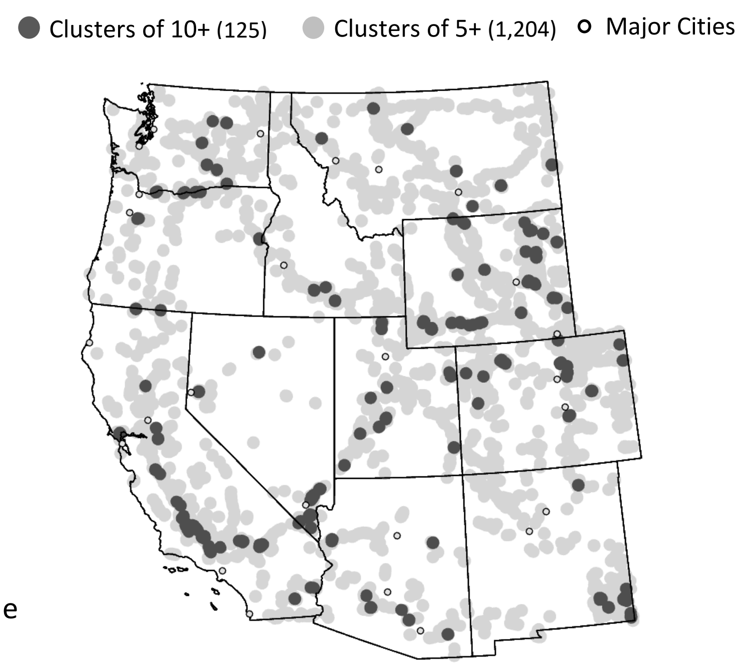

Figure 7 *– Infrastructure Clusters*

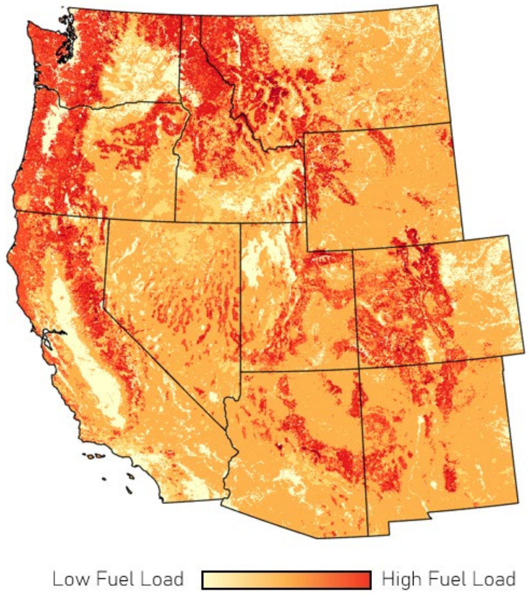

***Figure 8** – Calculated Fuel Load*

Finally, climate risks were calculated from six climate parameters: total yearly snowfall, average yearly relative humidity, average summer temperatures (May-July), average autumn temperatures (August-October), yearly Climate Moisture Index (CMI), and summer (May-September) precipitation totals. These parameters were combined for both current (1991-2020) and future (2081-2100) predicted climate composite scores. The current climate composite score is shown in figure 9 and the future score is shown in figure 10. The change in each climate parameter and the overall composite was calculated to

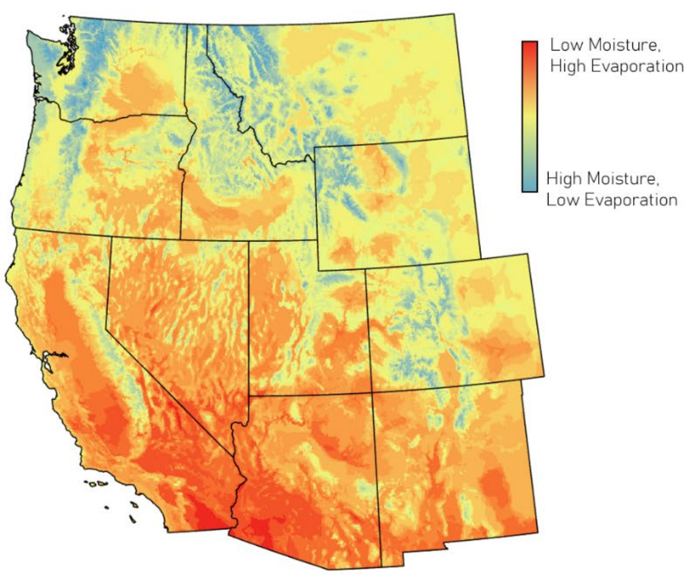

***Figure 9** – Current Climate Composite*

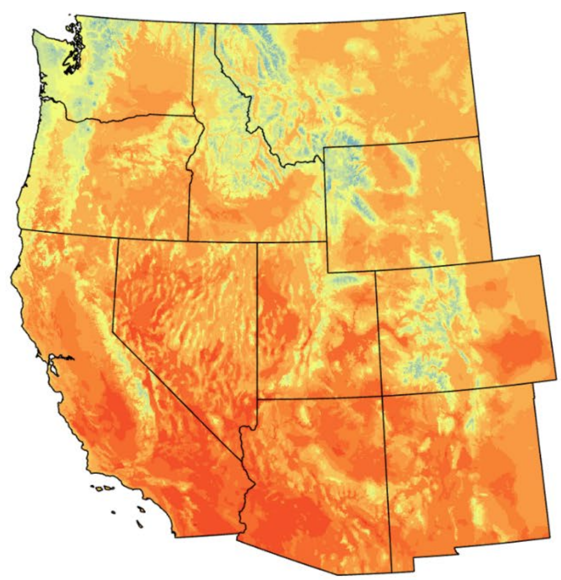

***Figure 10** – Future Climate Composite*

highlight changes in the climate data. The individual changes of each climate parameter are shown in Appendix E and the overall change in the climate composite score is shown in figure 11. The climate composites show that the desert southwest regions have the highest climate

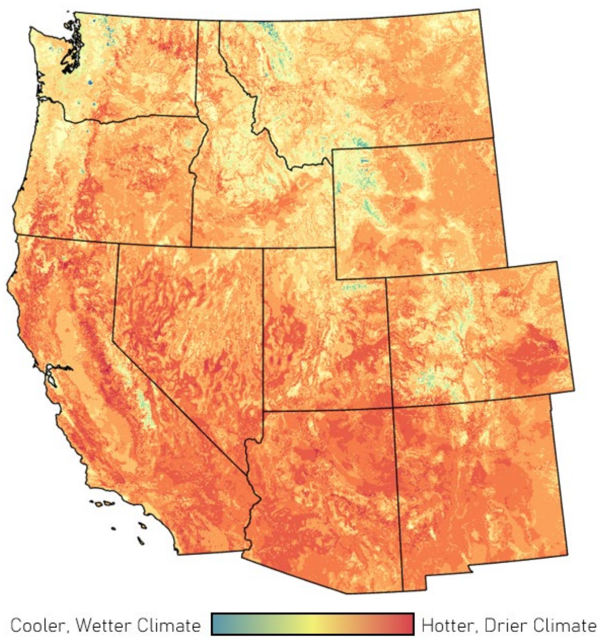

Figure 11 *– Change in Climate Composite score between the 1991-2020 period and the 2081-2100 period.*

risk score based on their high temperature and low moisture levels, meaning fuels in these areas will be dry and easily ignited with little moisture to limit the spread of wildfires. The change in the climate scores from the current data to the future data shows an overall increase in hot, dry weather for the entire region except for high-altitude mountainous areas.

The fuel score and climate composite scores were combined to determine a total fire risk score based on current and future climate factors and fuel availability. These fire risk score maps are shown in figures 12 and 13 respectively. The change in the fire risk from the current climate to the future climate is

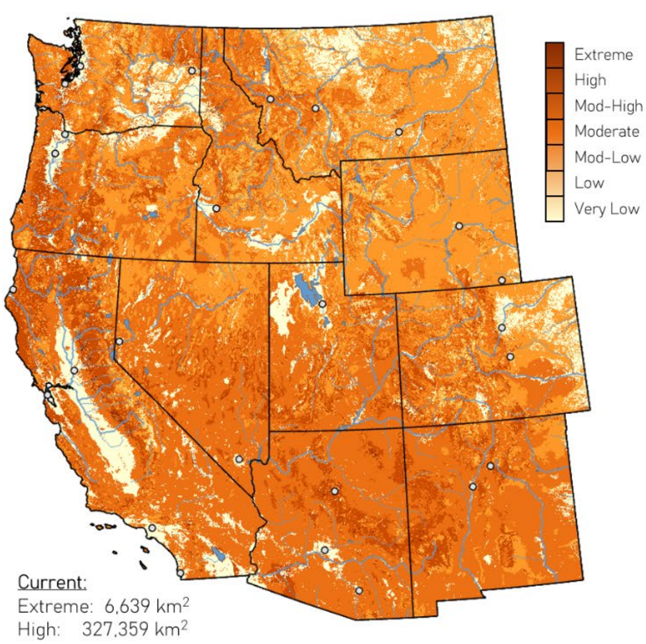

Figure 12 *– Current Fire Risk Composite*

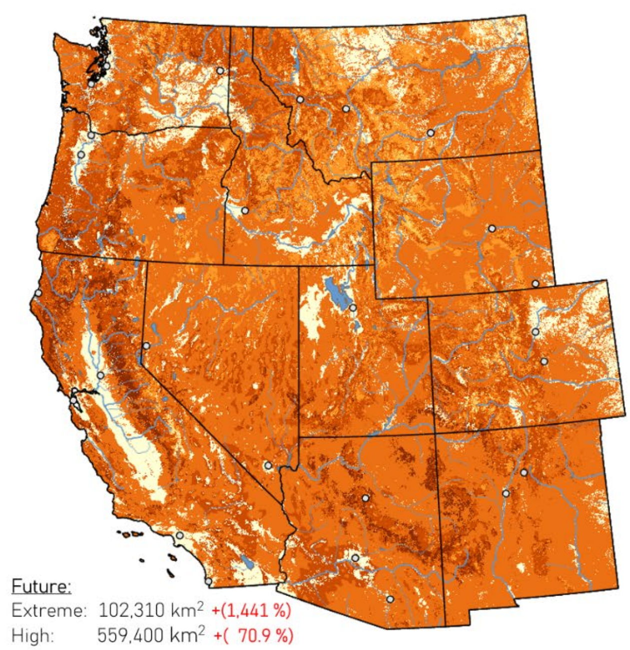

Figure 13 *– Future Fire Risk Composite*

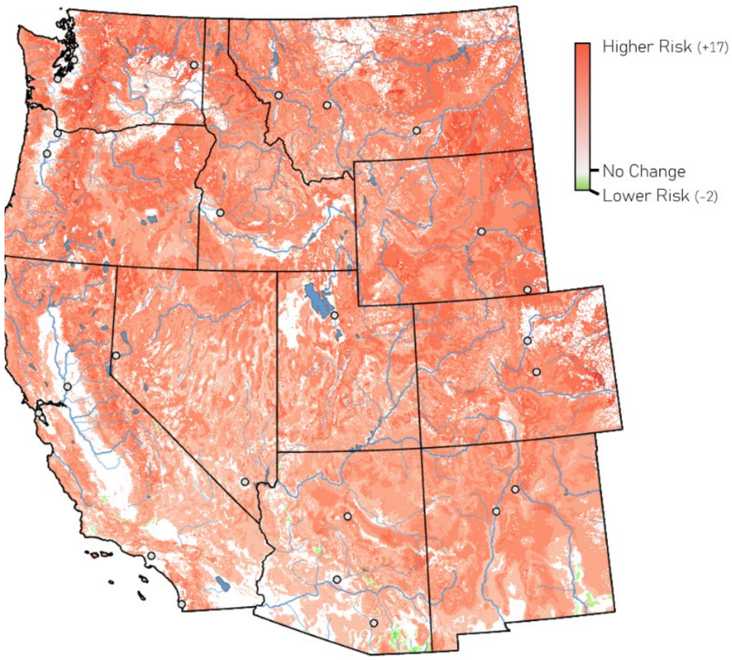

Figure 14 *– Change in Fire Risk Composite score between the 1991-2020 period and the 2081-2100 period.*

shown in figure 14. The fire risk scores show that the highest risk areas are those with the greatest fuel availability and those areas with the hotter, drier climates. The future score and the overall change show a shift in fire danger to the more northern areas of the region, with some small areas in the south showing a decrease in score due to additional precipitation in the area predicted in the future climate data.

There were minor limitations and points of potential error in this study, in particular the clustering of electrical infrastructure influencing the analysis, the weighting and scoring of climate risk factors, and the effect of non-climate risk factors beyond land cover, beetle kill, and fire history on overall fire risk at a 1-kilometer resolution.

The clustering of electrical infrastructure resulted in several risk areas scoring very high due to the abundance of electrical transmission lines in an area, particularly near power plants, substations, and other non-transmission infrastructure. Future analysis could eliminate the power plant features from the analysis and remove a buffer area around them similar to the urban areas to exclude them from influencing the final outcome. For this study, they were left in as they were considered clusters of infrastructure outside of urban areas per the initial research question.

The climate risk factors were scored based on equal intervals within their range in the study area, resulting in an ordinal highest-to-lowest relationship between the most at-risk and least at-risk areas. Since certain parameters likely have more of a role in fire risk than others, further study into the actual role each climate factor has in assessing fire risk would lead to a more accurate evaluation of fire risk due to climate.

While land cover, beetle kill, and fire history are the primary factors in determining fuel availability, other factors influence it as well, like forest health, altitude, and natural and human-built fire breaks. Typically, healthy forests have less dead timber and retain more moisture than unhealthy forests, leading to healthy forests being less prone to fire than unhealthy forests [43]. Altitude also plays a role in fire risk; higher altitudes have less oxygen and therefore cannot burn as readily as areas at lower altitudes with higher levels of oxygen [44]. Also, fire breaks, or areas where fuel has either been naturally removed, like scree slides, stream cuts, or cliffs, or where fuel has been removed by people, like clearings for highways, railroads, and powerlines, require a large fire to jump, while smaller fires may be stopped [45]. These factors are difficult to model in the 1-kilometer resolution data, but higher resolution data may be able to better account for them.

Conclusions & Future Research

Overall, the analysis shows that infrastructure clusters at risk today are in areas that have hotter and drier climates and are close to areas of dense population, particularly on the western slopes of the Sierra Nevada mountains in central California. The northward shift of the hot, dry climate that currently dominates the south-western portion of the United States will increase the risk of fires in more northern areas that typically were not at a higher risk of wildfire in the past. The lower wildfire risk based on the current climate in the northern portion of the region has resulted in areas of high fuel availability and the shift to higher fire risk in these areas will lead for more frequent and larger wildfires in areas that have not seen them in the past. The possibility exists that with current firefighting policy allowing fires to burn naturally and as wildfire fuel in Oregon, Washington, Idaho, and Montana is expended, larger fires will become less frequent, but smaller fires will happen on a more regular, healthy basis.

Future research into wildfire risk and infrastructure clusters could help shed additional light on those areas at elevated risk and aid decision-making in where to build future infrastructure. Using higher resolution data to evaluate wildfire risk will provide detailed insights into areas that are at risk and could help focus fire prevention efforts. Using the data in this analysis to create an interactive map that allows real-time weather data (precipitation, wind speed and direction, etc.) in addition to fire propagation models could help fire fighters focus suppression efforts while still allowing fires to burn naturally. Additionally, this study shows the need to continue monitoring infrastructure growth and climate change as time goes on to ensure lives and infrastructure are protected in a region where wildfire risk is only going to increase.

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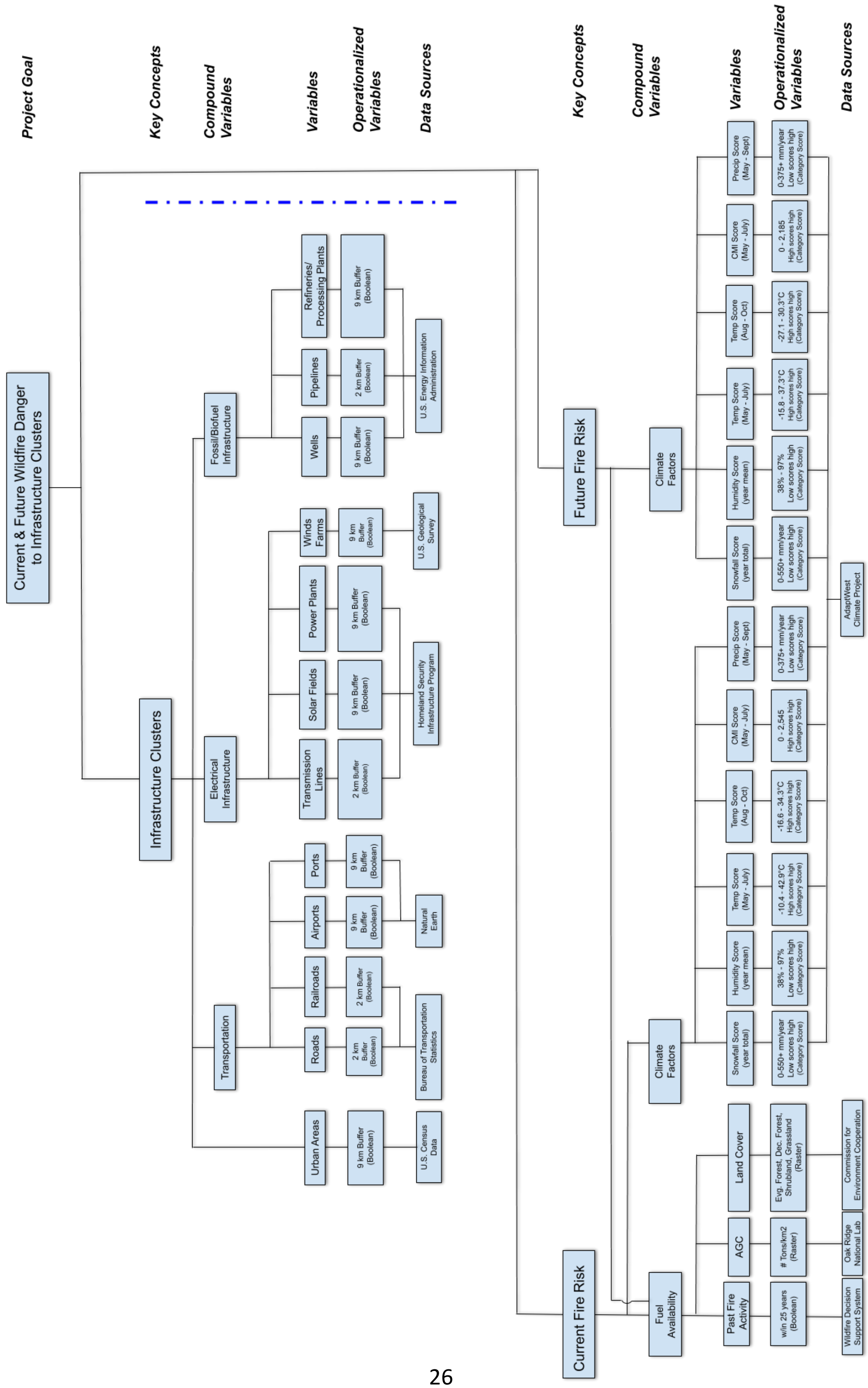
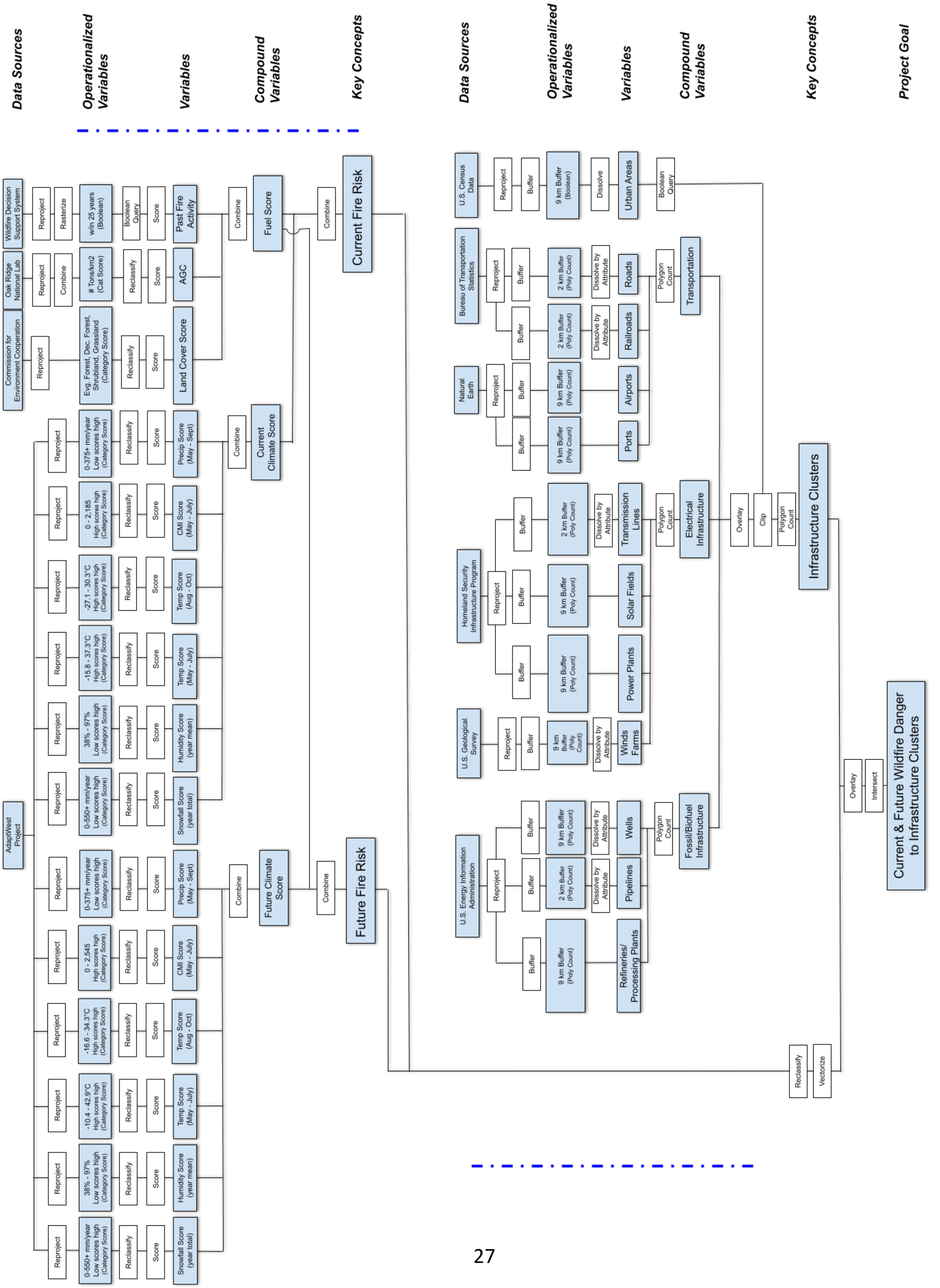
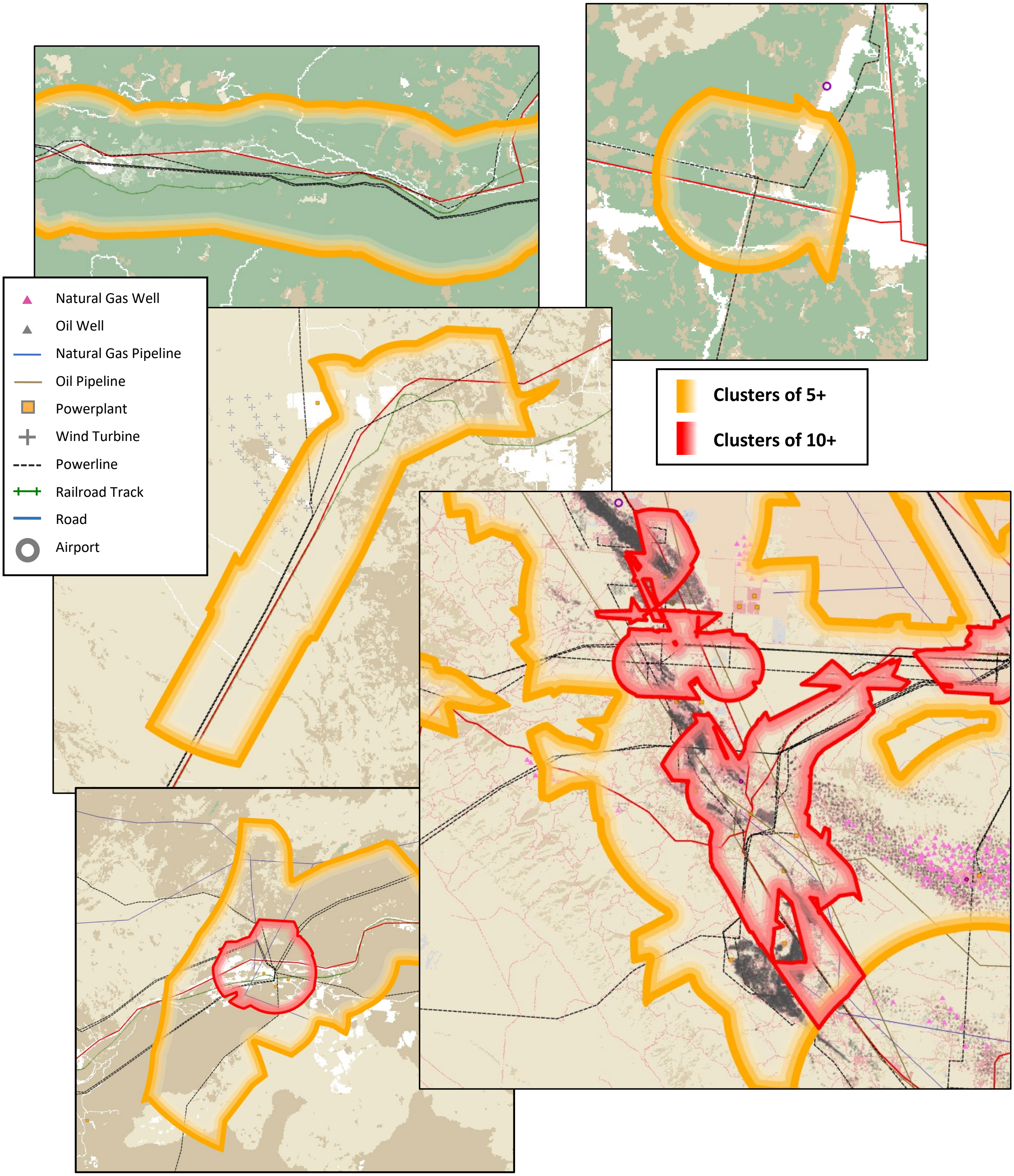
Appendix A – Conceptualization Diagram



Appendix B – Implementation Diagram



Appendix C – Examples of Infrastructure Clusters

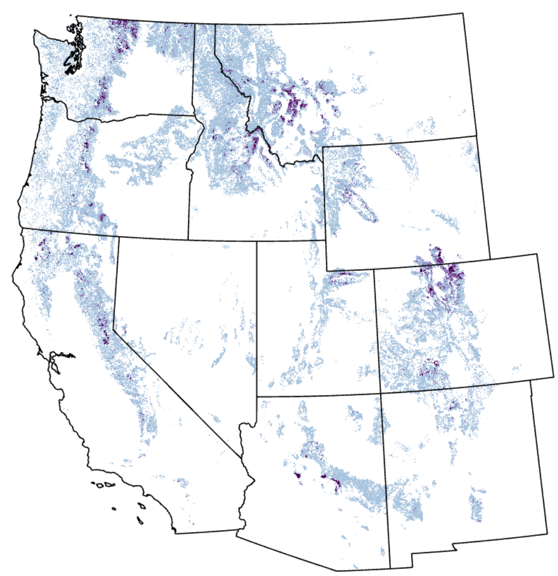


Appendix D – Fuel Variables & Scoring

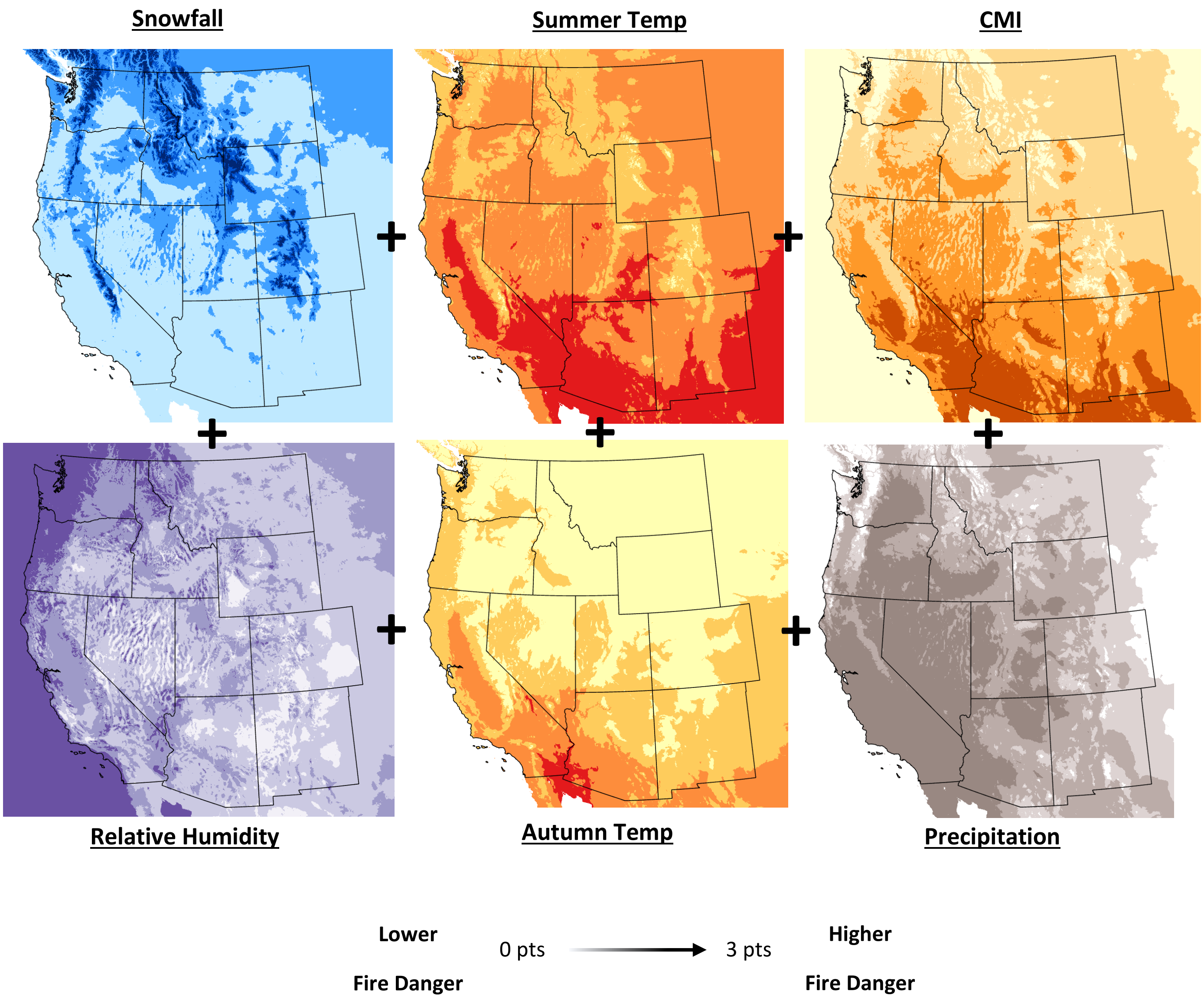
Land Cover

Fire History (25 years)

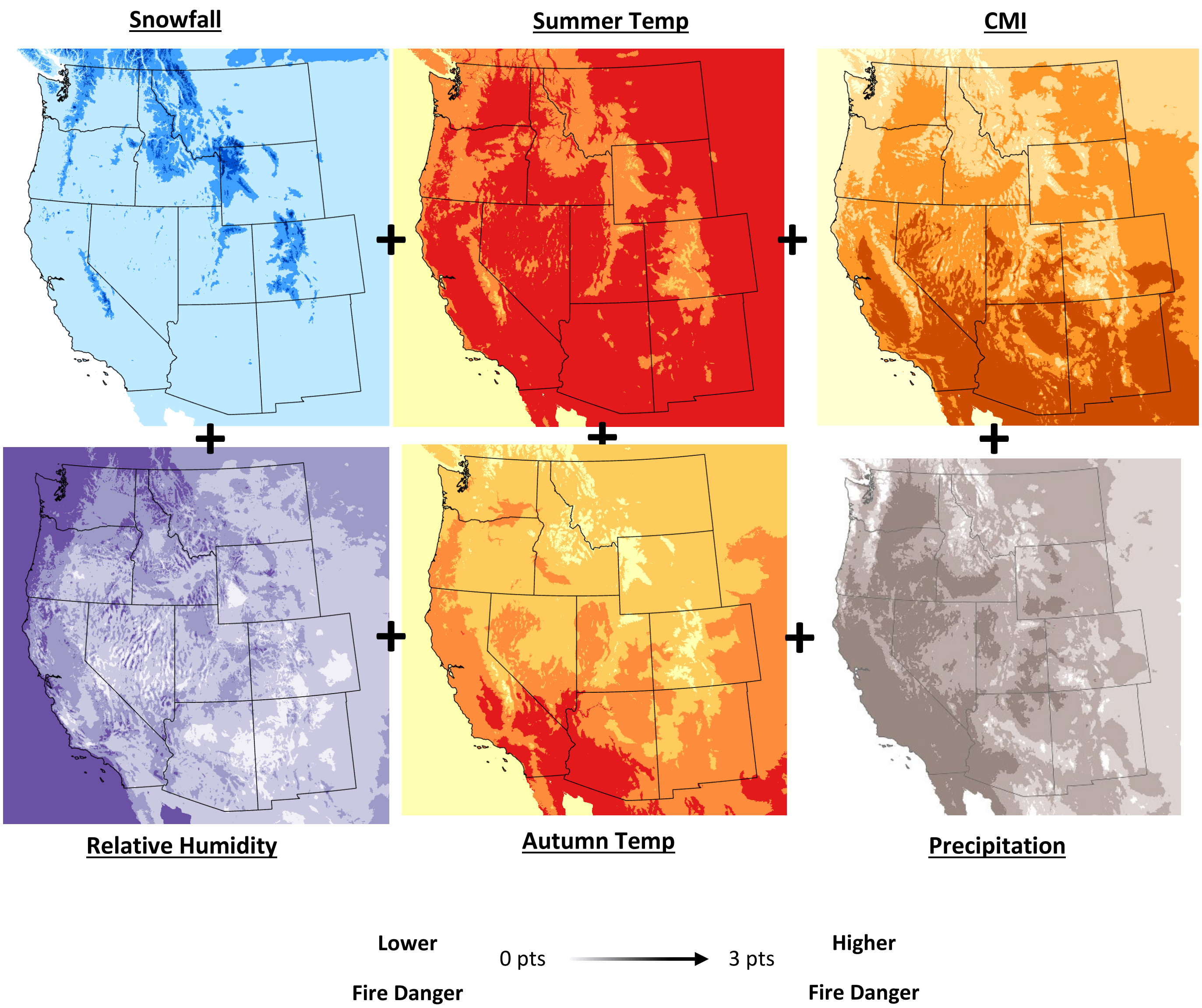
AGC (Beetle Kill)



Appendix E – Current Climate Variables



Appendix F – Future Climate Variables



Appendix G – Change in Climate Variables