



XyloPlan

Fire Pathways™ Risk Assessment And Optimized Vegetation Treatment Plan Recommendations

Prepared for:

City of Paradise

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October 2024

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Executive Summary

The 2018 Camp Fire was the deadliest and most destructive fire in California's history, resulting in 85 fatalities and the loss of more than 18,800 structures over about 153,000 acres. In an effort to enable the people of Paradise and the surrounding communities to return to rebuild the area as a fire adapted community, a project was defined to assess the use of Wildland Risk Reduction Buffers (WRRBs) between the urban area and the wildlands. The Conservation Biology Institute (CBI) issued findings and defined the WRRBs outside of the population centers, which encompassed about 35,000 acres of buffer. While effective at mitigating wildfire risk, the total area of mitigation was too large to implement for a community the size of Paradise.

XyloPlan offers a different approach to wildfire risk mitigation that is data-driven and provides the optimum vegetation mitigation recommendations for an area given constrained vegetation management resources. To provide effective treatment mitigation recommendations at a smaller acreage, XyloPlan conducted a wildfire risk analysis for Paradise, Magalia, and Concow, using speed-based Fire Pathways to identify areas with the highest risk for future catastrophic community losses from wildfire. Fire weather, topography, and fuel type/loading were considered in the analysis to derive maps of areas likely to undergo rapid fire spread and to identify areas of transition where vegetative fire is most likely to encounter high-density values-at-risk.

Vegetation treatment locations were identified and evaluated for their contribution to disrupting fire spread and increasing fire arrival time to the built environment. Reducing the fuel load and continuity along the Fire Pathways in the recommended areas is projected to substantially slow fire growth, benefit community safety, and reduce average annual loss (AAL) by providing additional time for resident egress and the firefighting response.

Fire Pathways Methodology

1. The Paradise Technical Advisory Committee (TAC) provided the study area structure information as the values-at-risk for the Fire Pathways analysis. These structures are in areas of high density, with low structure separation distance, putting them at risk for urban conflagration.
2. The LANDFIRE dataset was used to provide spatial information on fuel type and topography for the study area. XyloPlan updated this fuel dataset with information about non-burnable features from the OpenStreetMap (OSM) dataset.

3. Two extreme fire weather scenarios were modeled to simulate Fire Pathways from opposite sides of the study area. The Camp Fire (dry northeast wind) weather data was used for the first scenario, and a simulated southwest wind event was used for the second. For each scenario, reference data from the Cohasset RAWS weather station was used to derive wind, relative humidity, and fuel moisture parameters.
4. From archetypal fire ignition lines located several kilometers upwind of the study area values-at-risk, fire spread analyses were used to model the Fire Pathways, which delineate the corridors where fuel, terrain, and wind align to support rapid fire growth.
5. Machine learning optimization methods were used to identify high-impact recommended vegetation treatment areas in locations with a high suitability index, which weights inputs, including slope, accessibility, and fire spread reduction potential.

Modeling Outputs

Outputs from the Fire Pathways wildfire simulation include:

1. Fire Pathways, which identify the contiguous portions of the landscape where fuels, topography, and wind align to produce rapid fire growth.
2. 3,701 acres of Recommended vegetative treatment areas, which are optimized for treatability and fire spread reduction potential. For the study area, grazing buffers are additionally outlined around the primary treatment areas, to bolster the treatment effectiveness.
3. A treatment effectiveness arrival time layer that shows the difference between the untreated and treated fire arrival times, highlighting the arrival time improvement attributed to the vegetative treatments.

Background

Throughout the United States, 44.8 million housing units are in the Wildland Urban Interface with exposure to wildfire.¹ As seen with the 2018 Camp Fire, the spread of wildfire from vegetation to structures can cause devastating impacts on human lives and critical infrastructure, when the arrival of fire to the built environment outpaces the fire fighting response. The rate at which wildfires spread into the community is a critical factor in the extent of damage within the community, and it is possible to mitigate the rate of spread through vegetation management, home hardening, defensible space, and the fire fighting response. The Fire Pathways analysis described here identifies the landscape features likely to produce the fastest fire spread toward community values-at-risk and provides data-driven recommendations for interrupting the spread of fire.

Fire Pathways are the routes formed by the combination of topography, weather, and vegetative fuel that bring wildfire to values-at-risk, including structures and critical infrastructure, during a fast-moving, wind-driven fire event. XyloPlan enhances a community's wildfire resiliency and ability to disrupt Fire Pathways by creating data-driven, optimized vegetation fuel management plans, which balance cost-benefit and are designed to slow the rate of spread of fire. By implementing treatments that delay the arrival of fast-moving wildfire to values-at-risk, communities can gain time for the aggregation of an effective firefighting response and an organized evacuation of residents.

XyloPlan's goal is to provide a framework to create and maintain fire adapted communities through high-value, prioritized mitigations, which slow wildfire spread into critical areas. With an understanding of where Fire Pathways intersect values-at-risk, firefighting agencies can strategically assess the ability, capacity, and arrival times of firefighting resources to control fast-moving, wind-driven fires. With a data-driven, shared view of wildfire risk, agencies can also better communicate wildfire risk to stakeholders and prioritize effective outreach, education, incentives, and enforcement of home hardening and defensible space measures at the entry points to conflagration zones where Fire Pathways intersect the community. By evaluating vegetation management, the firefighting response, and home hardening and defensible space within the same Fire Pathways framework, communities can prioritize mitigations and efficiently work to encounter wildfire without sustaining catastrophic damage.

¹ Radeloff, V.C.; Hammer, R.B.; Stewart, S.I.; Fried, J.S.; Holcomb, S.S.; McKeefry, J.F. 2005. The wildland-urban interface in the United States. *Ecological Applications* 15(3):799-805

Attachment A: Study Area



Study Area: Paradise, Concow, and Magalia

The values-at-risk for the analysis were identified by the Paradise TAC, and the project area discussed in this report includes the communities of Paradise, Concow, and Magalia.

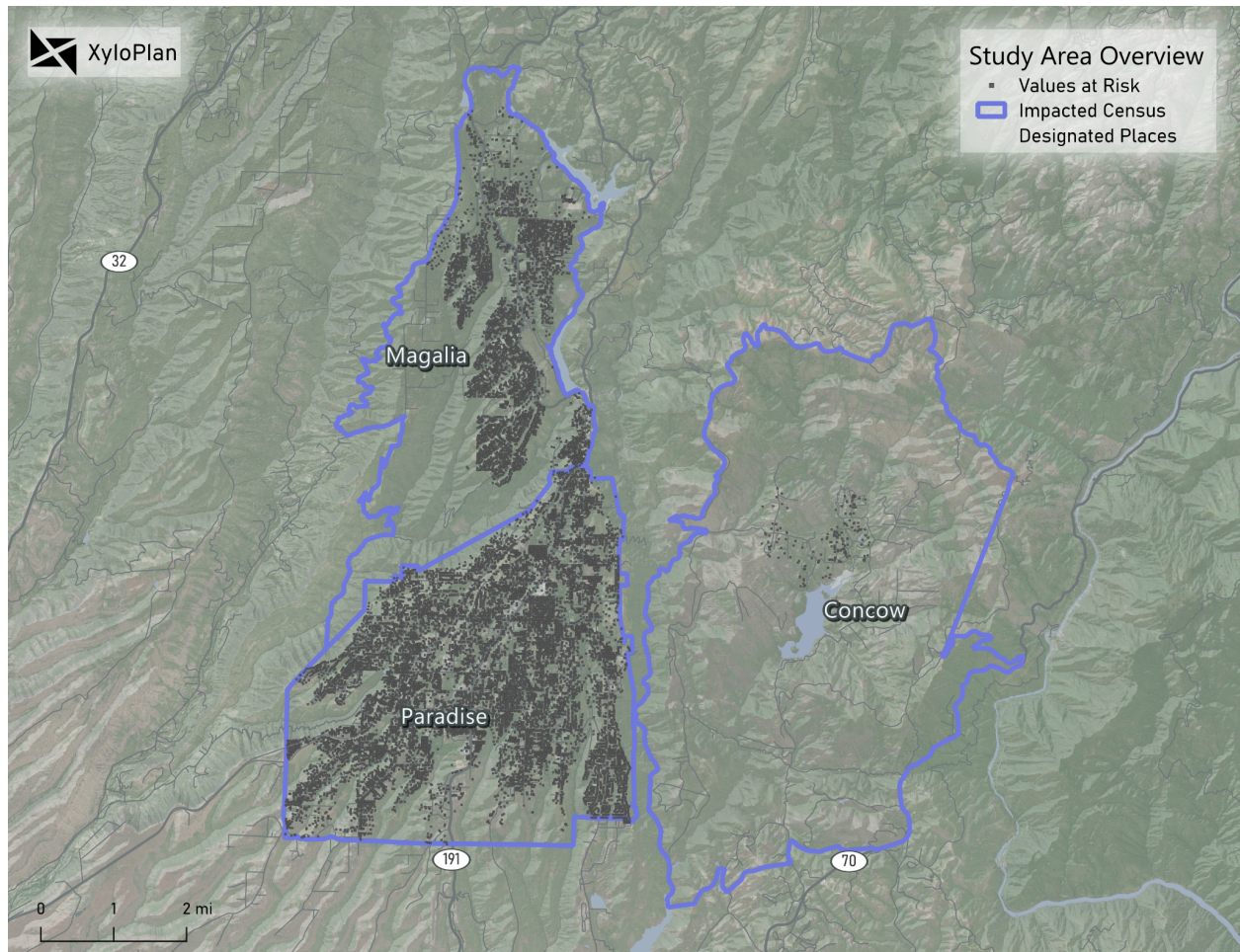


Figure 1.1: The Fire Pathways study area identified by the Paradise values-at-risk, including the communities of Paradise, Concow, and Magalia.

Attachment B: Fire Weather Scenarios

Paradise Wind Scenarios

Local weather data informed the inputs to the Fire Pathways simulations, creating realistic scenarios to model fire on the landscape. Two critical fire weather scenarios were developed to represent potentially catastrophic fire conditions in the study area.

For the first weather scenario, the weather parameters for the Camp Fire were used. Strong, dry northeasterly winds with low humidity were modeled with an average wind speed of 24mph. This scenario is characteristic of a downslope wind event, descending from the western slopes of the Sierra Nevada.

The second weather scenario for the study was chosen from a direction to complement the Camp Fire scenario. A dry, southwest wind scenario was simulated, modeling Fire Pathways on the opposite side of the study area. The same parameters for 100hr fuel moisture were modeled in both scenarios, reflecting cured live fuel from several months without significant rain.

	Scenario 1: Northeast	Scenario 2: Southwest
100hr Fuel Moisture	Dry - 6%	Dry - 6%
Wind Speed	24 mph	18 mph
Wind Direction	Northeast (82 degrees)	Southwest (208 degrees)
RAWS Reference Station	Cohasset	Cohasset
Description	Weather data from the Camp Fire on 10/08/2018.	Dry South/Southwest wind

Table 2.1: Selected weather parameters for the two fire weather scenarios.

Attachment C: Fire Pathways Modeling



Fire Pathways

Using the fire weather scenarios described in Attachment B, Fire Pathways were modeled by extending the work of and graph-based modeling algorithms of Mark Finney and the Missoula Fire Sciences Laboratory². The Fire Pathways highlight the contiguous portions of the landscape where fuels, topography, and wind align to produce rapid fire growth. As shown in Figure 3.1 below, the Fire Pathways display the projected minimum travel time of a fire from the given ignition for the selected weather scenarios.

Fuel Model

One of the primary inputs to the Fire Pathways model is the fuel model. The LANDFIRE 2020 dataset was used for this study and reflects the vegetative disturbances to the landscape from the Camp Fire. However, in many cases, the LANDFIRE wildfire fuel model maps do not capture the role of golf courses, orchards, vineyards, farmland, and other developed vegetative areas as non-burnable fuel breaks, so to reflect the role these areas play in slowing, or in some cases stopping, wildfire growth, this analysis uses data from a variety of open data sources, including OpenStreetMap, to correct the standard fuels datasets.

Fire Pathways Ignition Line

The precise location of fire ignition is highly stochastic and cannot be predicted accurately enough to effectively model risk for an entire community. Unpredictable human and natural ignition events interact with various landscape factors (including slope, aspect, fuel conditions, and roadway design) and transient weather conditions (such as wind speed, wind direction, and relative humidity) to develop an ignition into an uncontrolled wildfire. While probabilistic modeling can estimate the outcomes of different ignition scenarios, the probability of occurrence itself has limited value because a single fire, regardless of the likelihood of its ignition point, can have catastrophic consequences.

Rather than attempting to predict unpredictable ignition factors, the Fire Pathways analysis utilizes an illustrative ignition line that assumes the presence of an unsuppressed fire aligned with the wind. This archetypal ignition line is positioned several kilometers upwind of a community's values-at-risk, and Fire Pathways are modeled along the entire length of the ignition line. This modeling approach reveals the areas where wildfire will pose a threat to a community's values-at-risk via Fire Pathways. Research on the Fire Pathways algorithm has shown that regardless of the exact ignition location, fire has a

² Finney, Mark. (2002). Fire growth using minimum travel time methods. Canadian Journal of Forest Research-revue Canadienne De Recherche Forestiere - CAN J FOREST RES. 32. 1420-1424. 10.1139/x02-068.

high tendency to travel along the same minimum travel time trajectories, supporting the choice to avoid making assumptions about the exact location of ignition sources and to use an ignition line to model community wildfire risk at scale.

Surface Fire Entry Points

Entry points are the areas where Fire Pathways intersect with values-at-risk and enter a community. Located at the termination of minimum travel time pathways, these areas are the first to experience surface fire exposure. As a result, they are most likely to encounter fire before firefighting resources can respond, facilitating the transition from vegetation to structure and subsequent structure-to-structure spread that can result in conflagration-level losses. It is most important to prioritize home hardening and defensible space education and enforcement measures in these areas.

Speed-based Fire Pathways identify **high-risk entry points** to the **built environment**

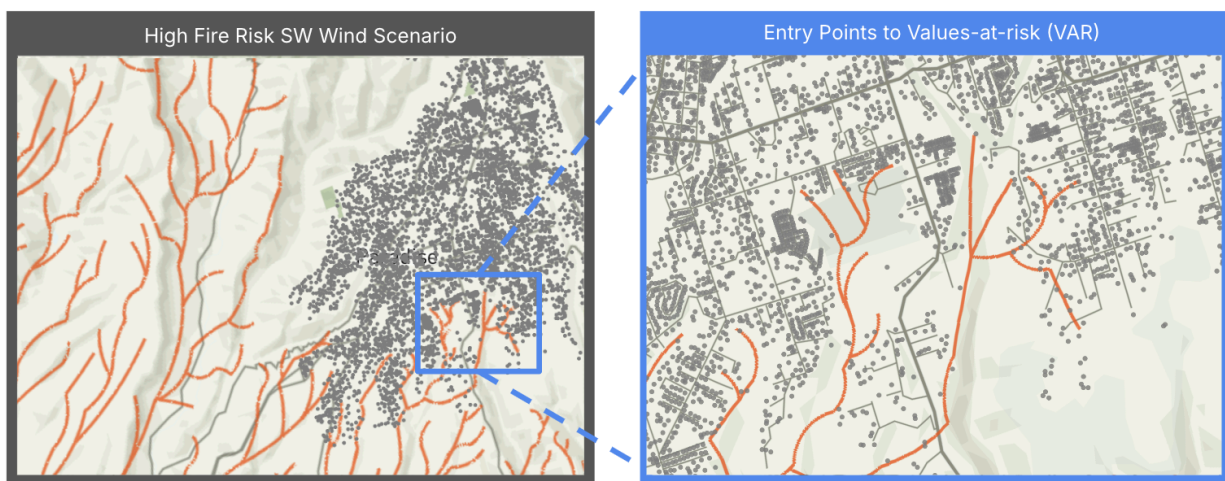


Figure 3.1: Fire Pathway Entry Points to values-at-risk in Paradise.

Fire Pathways Implications for Communities

Wildfire spread within the built environment is highly complex and poorly understood. Analysis of recent catastrophic wildfires (e.g, Lahaina, Marshall, Tubbs) has shown that vegetation-to-vegetation fire propagation plays only a minor role in the catastrophic loss of structures once the fire reaches the built environment, where dense structures are the fuel most likely to carry the fire. Fire spread within the built environment is currently poorly understood at a physical level and is highly sensitive to several variables including home hardening and defensible space attributes that modulate the behavior of structure-to-structure and vegetation-to-structure Fire Pathways. These effects are not modeled in this analysis; rather, **this analysis focuses on identifying the areas where rapid fast-moving vegetation-to-vegetation wildland fire spread may outpace the local firefighting response, resulting in a vegetative wildfire's arrival at values-at-risk.**

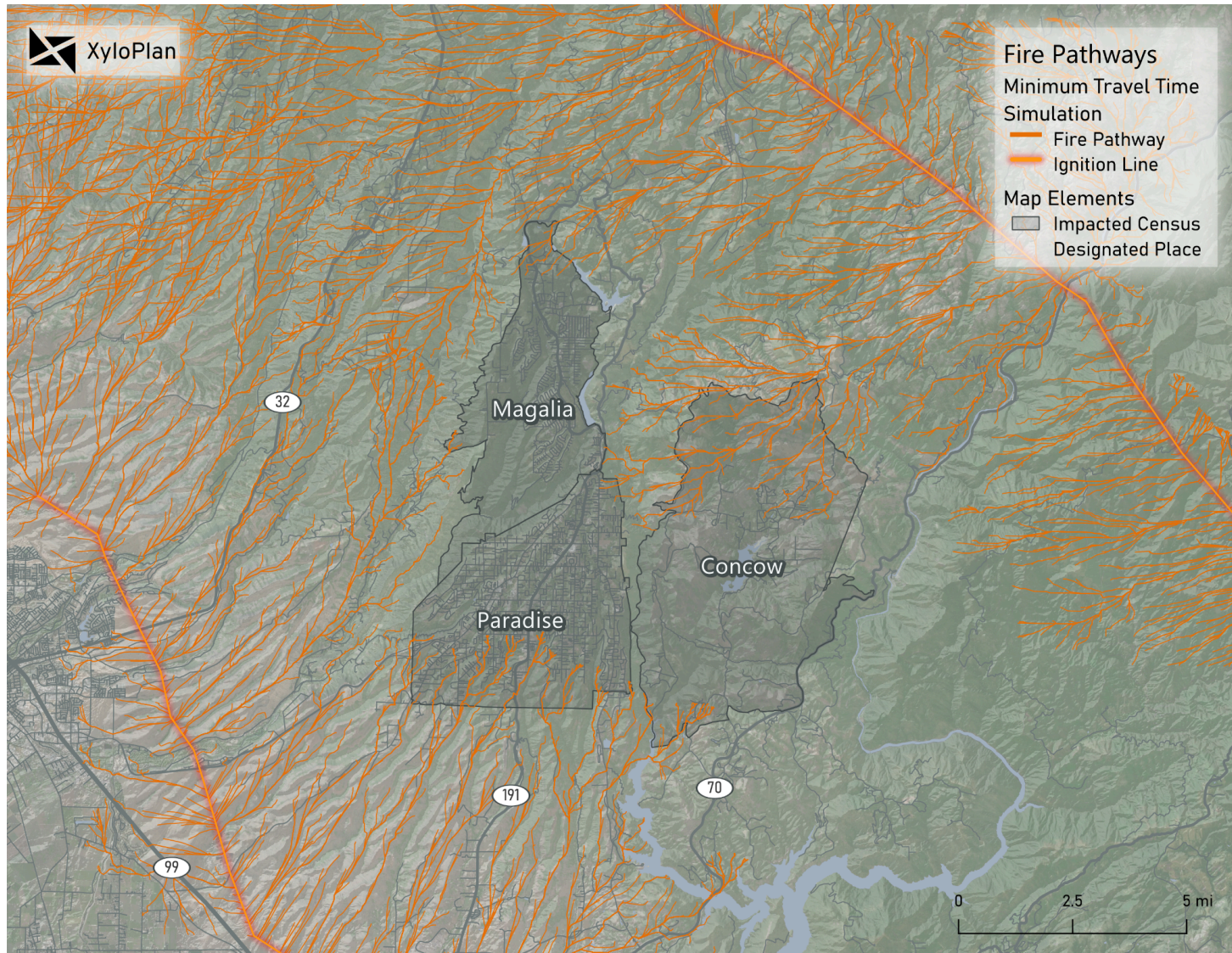


Figure 3.2: Ignition lines and Fire Pathways across the Study Area.

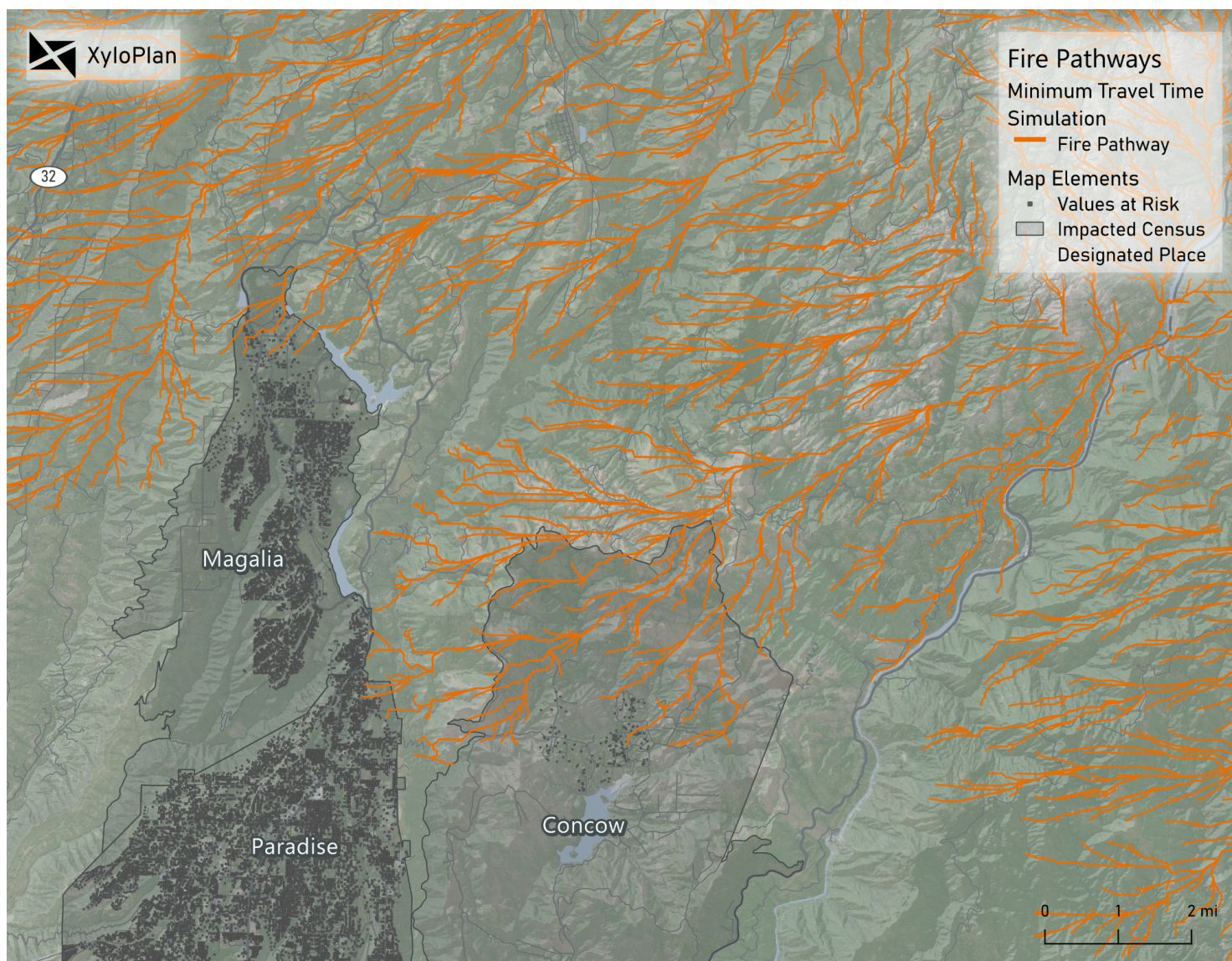


Figure 3.3: Fire Pathways driven by a northeast wind scenario.

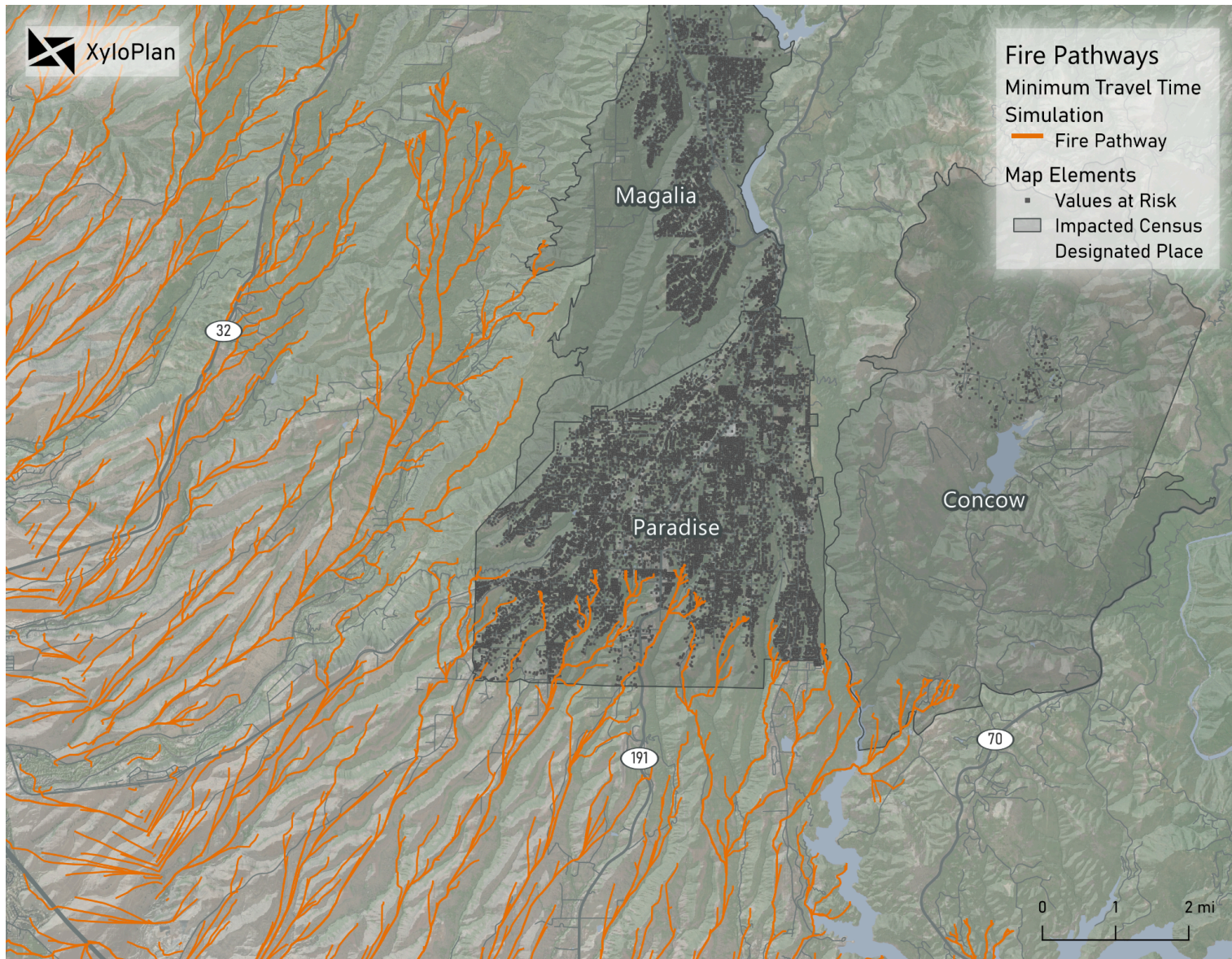


Figure 3.4: Fire Pathways driven by a southwest wind scenario.

Attachment D: Optimized Treatment Recommendations

Optimized Treatment Recommendations

After identifying the Fire Pathway entry points most likely to affect the values-at-risk within the study area, a treatment plan was developed to disrupt the Fire Pathways and decrease the rate of spread, supporting an effective firefighting response. The vegetation treatment plan consists of many small treatment areas called Strategically Placed Local Area Treatments (SPLATs). SPLATs were conceptualized by Mark Finney of the Missoula Fire Sciences Laboratory and are "patterns of disconnected fuel treatment patches that overlap in the heading fire spread direction are theoretically effective in changing forward fire spread rate."³ Figure 4.1 shows how the placement of SPLATs can slow the fire rate of spread.

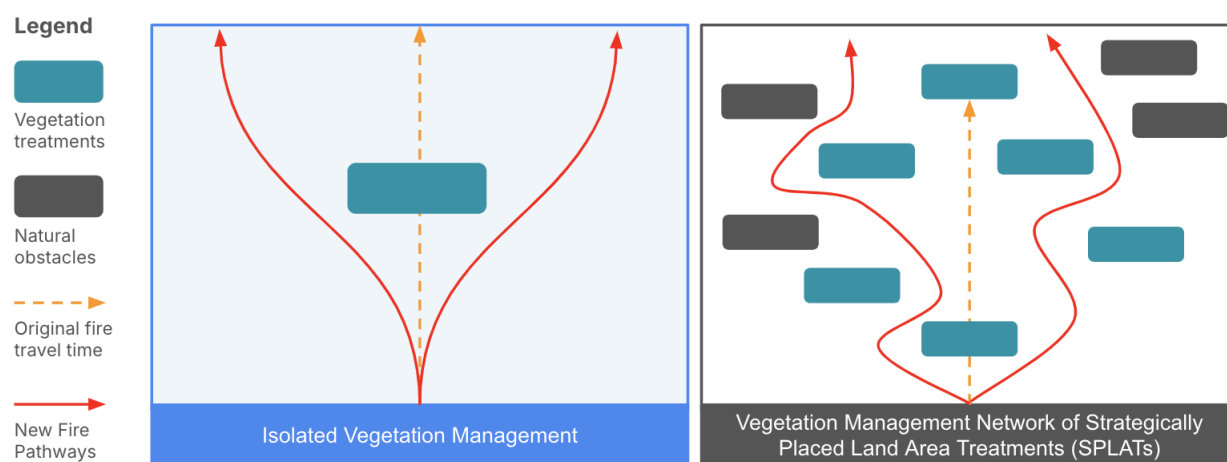


Figure 4.1: The effect of SPLATs on fire behavior and fire arrival time to values-at-risk.

Per Finney's work, "simulations suggested that these treatment patterns reduce the spread rate or fireline intensity over much of the area burned, even outside the treatment units where the fire was forced to flank."⁴

When modeling fuels for the SPLATs, modifications to the base fuel layer were made to represent characteristic fuel reduction activities. For example, in timber fuel models, activities such as thinning/removal and pile burning are represented by assuming a reduction in overall biomass, which is modeled by a change in the fuel load level. Similarly, shrub and grass fuel model reduction modifications can represent treatments such as mastication, mowing, broadcast burning, and grazing. The exact treatment that is selected for load reduction execution should be determined by local resources and their evaluation of the current climate and conditions on the ground.

³ Finney, M. A. (2001). *Design of regular landscape fuel treatment patterns for modifying fire growth and behavior*. Forest Science, 47(2), 219-228.

Figure 4.2 shows the results of the treatment plan for a portion of the study area. The blue SPLAT polygons are areas where vegetation management is recommended. The green areas are locations where fire arrival time is slowed by the recommended treatment locations. The darkest green areas may see arrival time increases of over 8 hours.

In total, 3,701 unique acres of treatment are recommended in the study area, with 2,190 acres recommended on the northeast side of Paradise and the remaining 1,511 acres recommended on the southwest side.

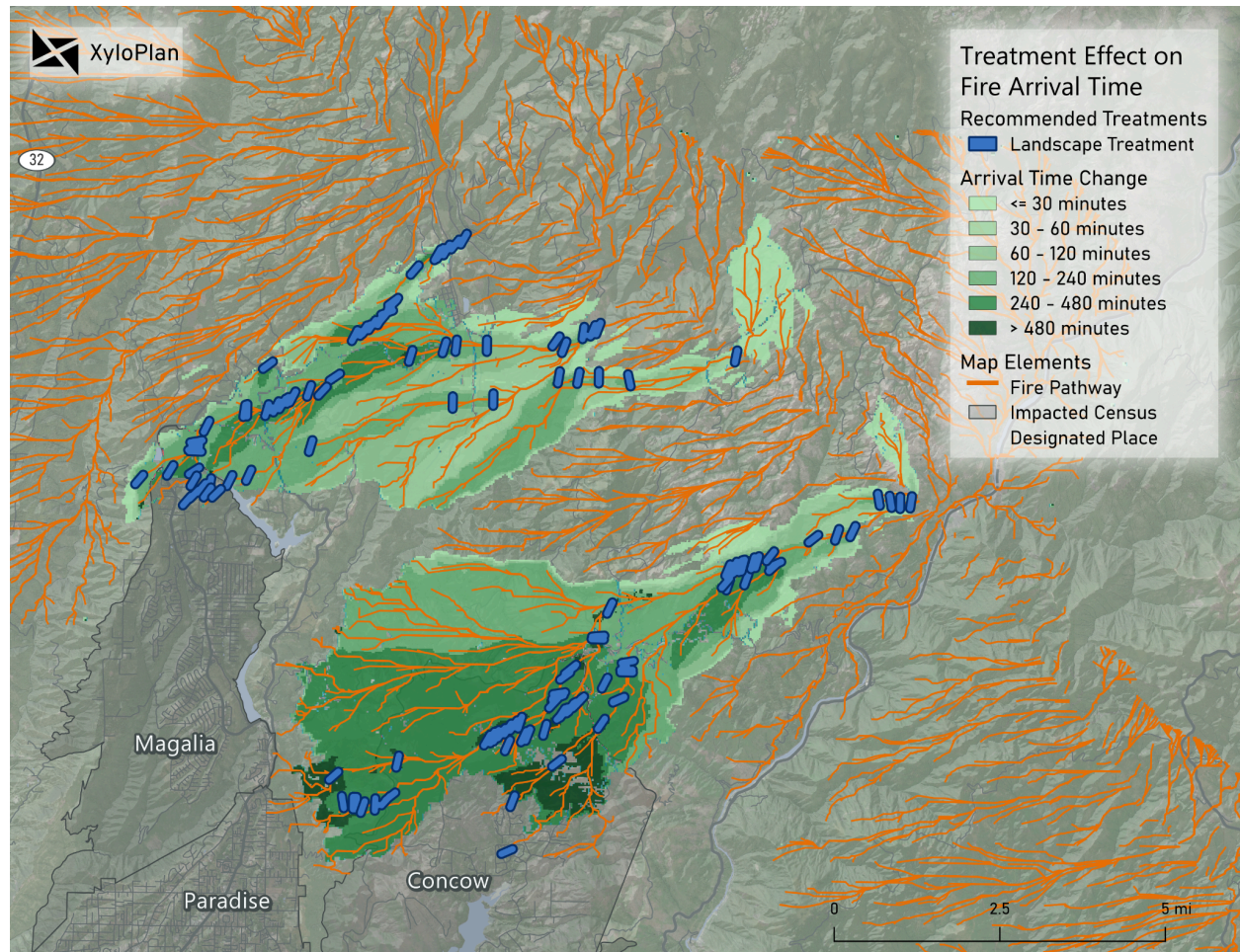


Figure 4.2: Arrival time changes as a result of the recommended vegetation treatment plan for the northeast wind fire scenario.

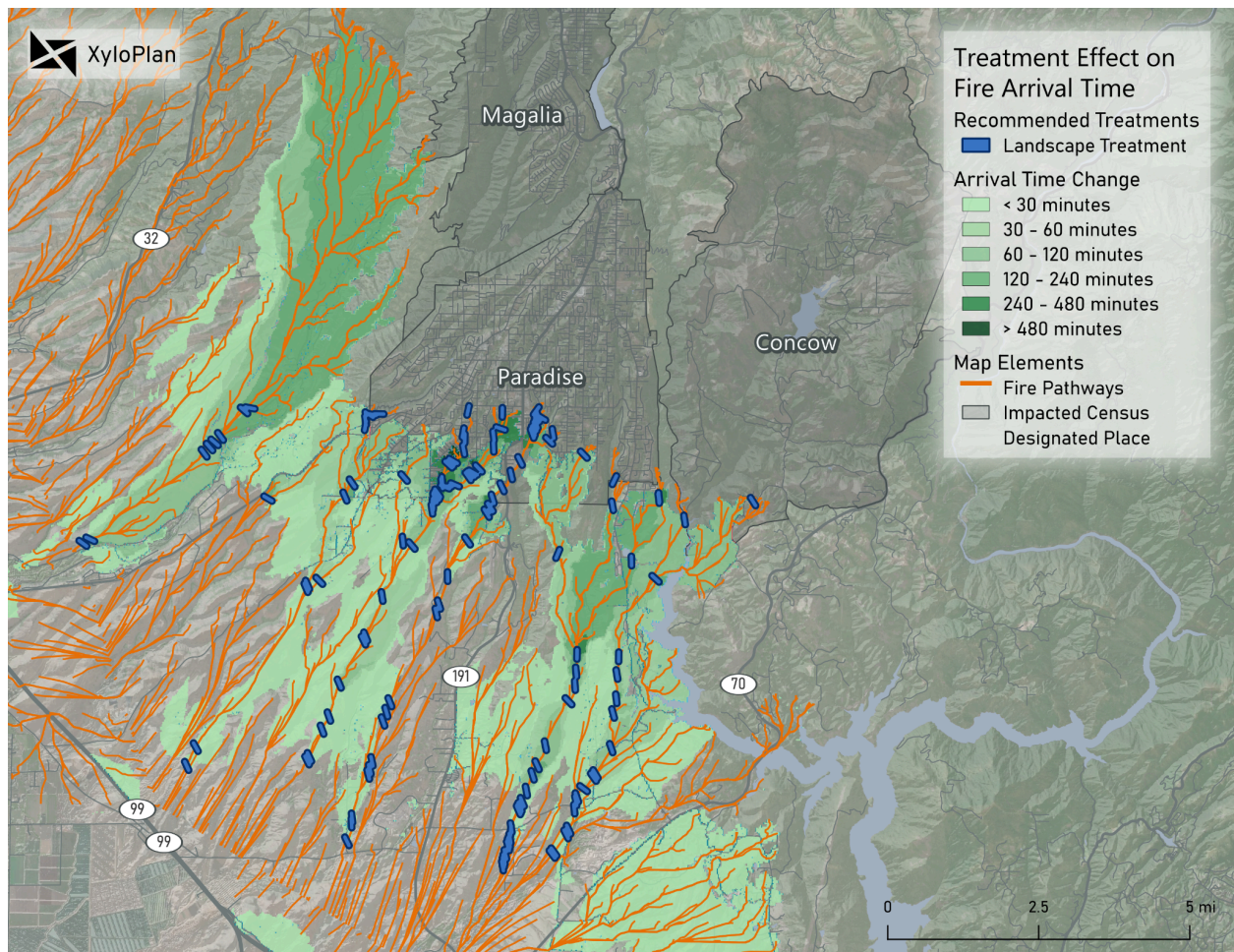


Figure 4.3: Arrival time changes as a result of the recommended vegetation treatment plan for the southwest wind fire scenario.

Once completely implemented, analysis suggests that the northeast treatment plan will provide an average benefit of 373 minutes, or 6.2 hours for the values-at-risk. The southwest treatment plan projects an average benefit of 140 minutes, or 2.3 hours for the values-at-risk.

Figures 4.4, 4.5, and 4.6 divide the northwest wind fire scenario's recommended treatments into three iterative treatment groups, called tranches. Each tranche is approximately 730 acres in area, and each tranche has a sequential priority, determined by treatment effectiveness. While all treatments from all tranches are recommended, the treatments in Tranche 1 will be most effective at delaying the arrival of wildfire to values-at-risk.

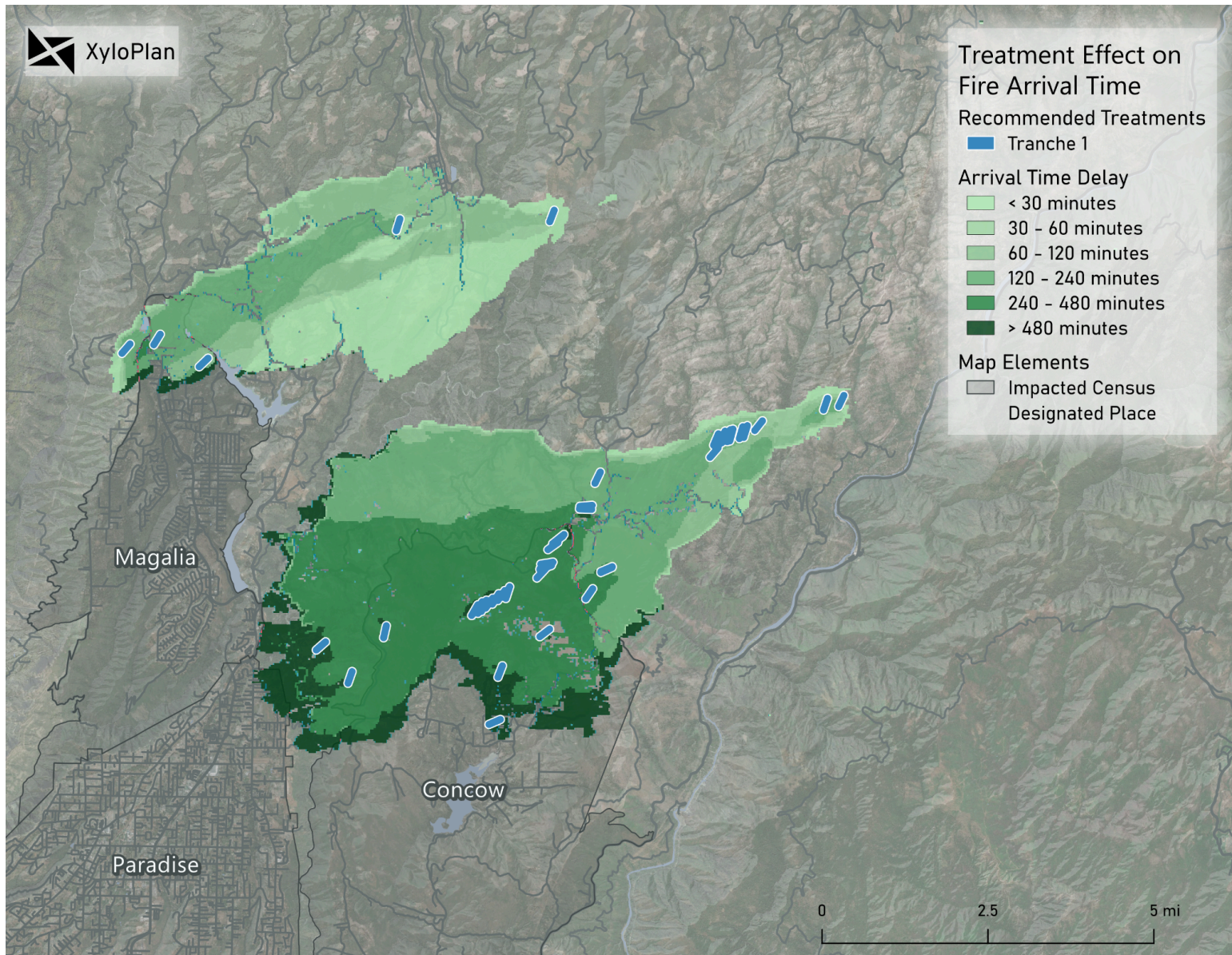


Figure 4.4: Tranche 1 arrival time delay on the northwest wind fire scenario arrival time in minutes.

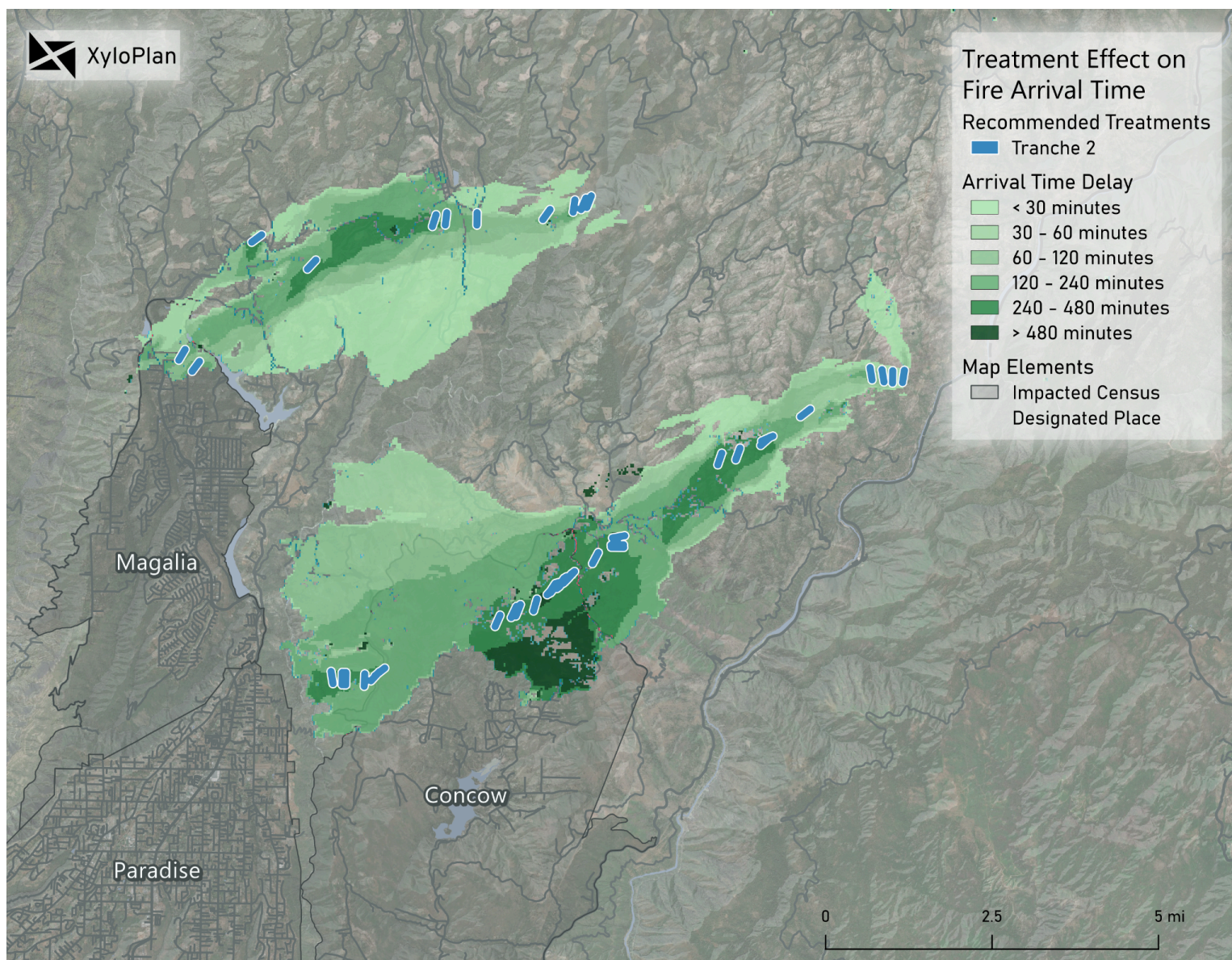


Figure 4.5: Tranche 2 additive arrival time delay on the northwest wind fire scenario arrival time in minutes.

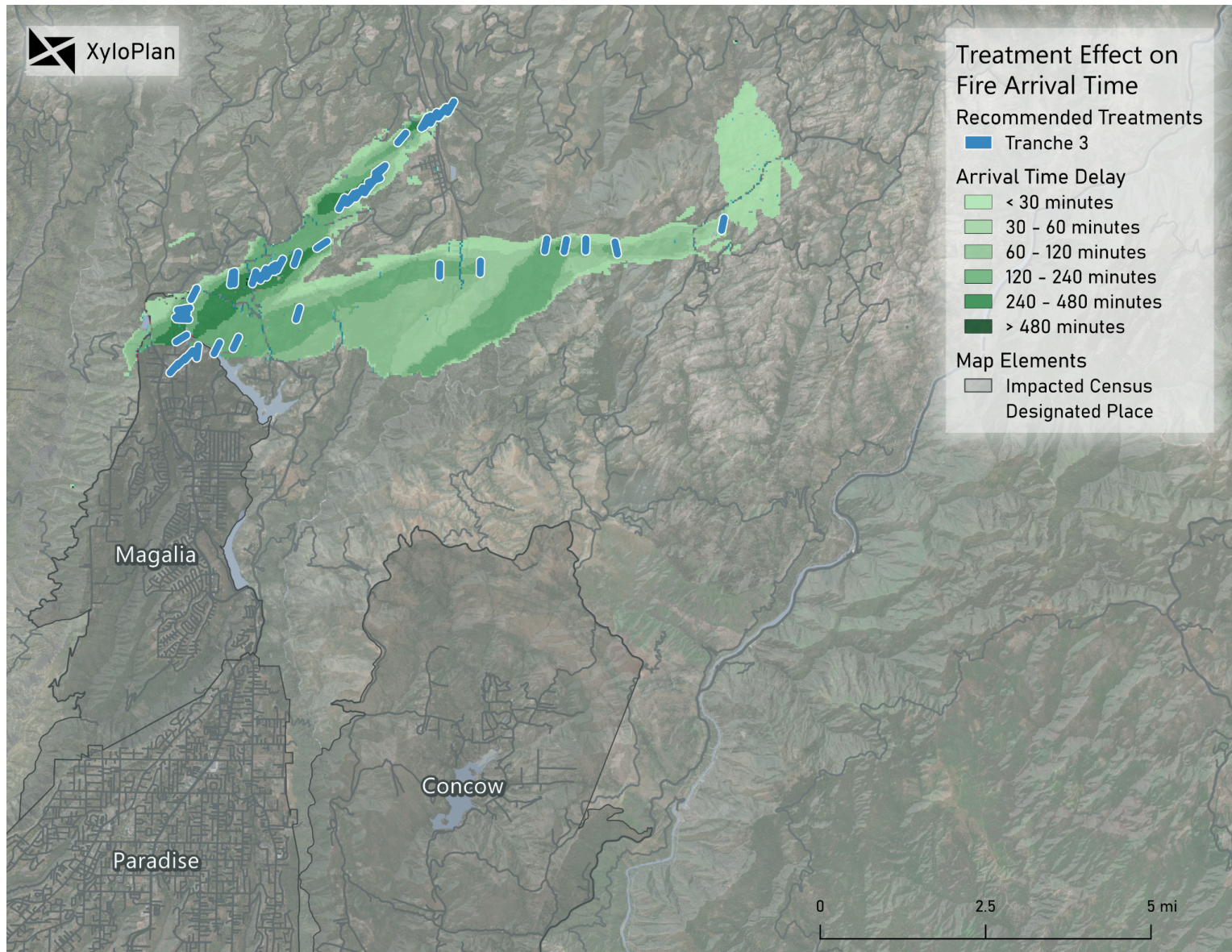


Figure 4.6: Tranche 3 additive arrival time delay on the northwest wind fire scenario arrival time in minutes.

Treatment Plan Development

XyloPlan's machine learning evolutionary progression algorithms were used to identify suitable areas for vegetation management along Fire Pathways, construct an optimized treatment plan, and evaluate the plan's effectiveness.

Treatment optimization occurred in the following phases:

1. **Pathway Prioritization:** Each Fire Pathway was divided into segments of uniform length and each segment was scored based on the number of values-at-risk it affects. Pathway weights were backpropagated, so that pathways with a high degree of centrality that affect many downstream areas were given higher priority than those segments that only affect a single downstream area. Pathways that do not intersect values-at-risk are discarded and are not eligible for treatment, because vegetation management work along these pathways is unlikely to translate into community safety benefits.
2. **Treatment Suitability Analysis:** Treatment opportunity polygons were created for each segment of the Fire Pathways that affect at least one value-at-risk. For each SPLAT polygon, a score was calculated reflecting the treatment suitability for that polygon, indicating both its capacity to interrupt fire spread towards values-at-risk and the technical feasibility of implementing treatment in that area. The layers used for the treatment suitability calculation are shown in Table 4.2. The weights for each layer are configurable and are used to further refine the selection criteria for the derived treatment plan.

Layer	Description	Weight
Pathway Weight	Number of affected assets at risk located along the pathway.	High
Pathway Branching Factor	Number of downstream branches along the pathway	Moderate
Unmitigated Rate of Spread	Average rate of spread within the treatment polygon with the current fuels	High
Mitigated Rate of Spread	Average rate of spread	Highest

	within the treatment polygon after vegetation management has been applied	
Slope	Average topographical slope within the treatment polygon, weighted such that high slopes are less desirable for treatment	Low
Accessibility	Average distance to the nearest public roadway, weighted such that areas located far from roads are less desirable for treatment.	Low
Community Tier	Average distance to community values-at-risk, weighted so that areas close to the community are more desirable for treatment	Moderate
Tendency to Make Hub	Average node centrality of pathway nodes within the treatment unit. High node centrality indicates nodes that have many edges, indicating the potential to spread fire in many directions.	Moderate
Ember Threat	Average ember threat to community for vegetation within the treatment unit, weighted so that areas likely to cast embers into the wildland urban interface (WUI) are prioritized for treatment.	Moderate

Table 4.1: Treatment suitability layers.

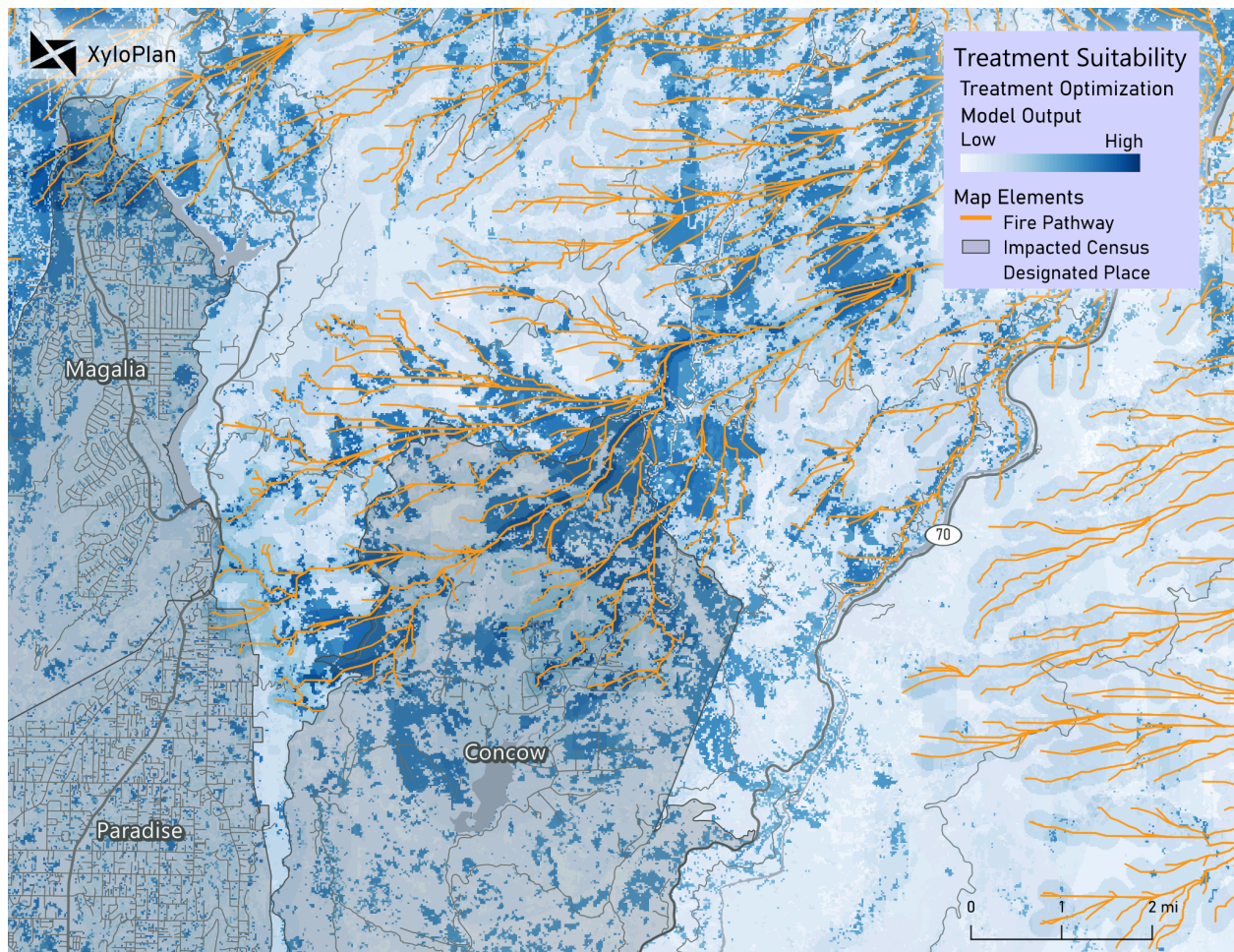


Figure 4.7: Example of the Treatment Suitability in the study area. Considerations such as the tendency for pathways to branch, likelihood of pathways intersecting values-at-risk, and the treatment effectiveness impact scoring.

3. **Iterative Core Opportunity Selection:** The treatment plan strategy for the northeast wind scenario was developed by iteratively selecting and evaluating potential combinations of treatment units. Guided by a unique learning algorithm, effective treatment plans are designed to make the most of constrained resources. Prioritization among the recommended treatment units is provided by sequentially building a treatment plan that iteratively interrupts Fire Pathways and adjusts to the emerging fire behavior as treatments are implemented. After each iteration, the potential value of the treatment plan as a whole is calculated by assessing the increase in fire arrival time at community values-at-risk. For the southwest scenario, XyloPlan recommends prioritizing treatments closest to the values-at-risk and then moving outwards with treatments towards the wildlands.
4. **Grazing Buffer Addition:** When applied in homogeneous areas of lighter fuels, like large expanses of contiguous grass and brush, isolated patches of vegetation management along pathways are often insufficient in slow fire growth enough to

be meaningful for community safety. In these cases, fire easily wraps around the proposed treatment units. Such areas are common in the south and west sides of the Paradise study area.

To mitigate fire moving quickly around a vegetation treatment, a “grazing buffer” is modeled to magnify the effect of the core treatment units. The grazing buffer is a 200m ring around the outside of a recommended unit that may be applied if some or most of the fuel in that ring is suitable for targeted herbivory, particularly grass. Grazing buffers are most applicable in this study's southwest scenario; however, some areas of the mountains to the northeast may also benefit from some grazing. Not all of the area in the buffer will be palatable for grazing, so additional local analysis should be performed to assess the suitability of grazing within a buffer unit depending on the type of grazing animal (cattle, goats, sheep, etc) and access to the treatment site. A commercial cattle or goat grazing program that focuses on the recommended buffers could generate revenue for the local community.

Grazing buffers are a way to further increase the efficacy of the core treatments designed in this study and can be undertaken optionally. Therefore, they are not included in the core treatment acreage figures.

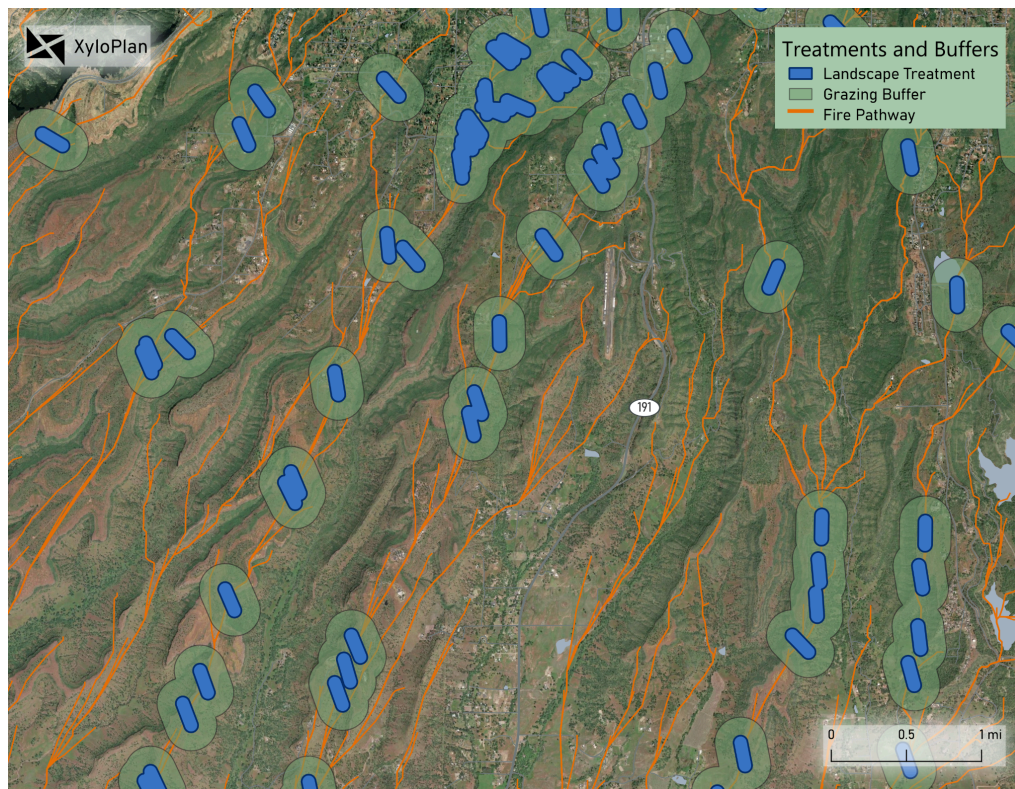


Figure 4.8: A subset of the grazing buffer dataset, including the Fire Pathways and Landscape Treatments for the southwest weather scenario.

- 5. Treatment Parcel Identification:** Treatments were designed, evaluated, and selected for recommendation based on ecological and fire behavior characteristics; they do not conform to parcel boundaries. A treatment overlapping a parcel does not imply that the entire parcel must be treated. Treatments should only be conducted in the portions of that parcel that play an important role in fire transmission.

To facilitate operationalizing the treatments, the recommended treatments were overlaid on a Butte County parcel map. The area and proportion of each parcel included in a recommended treatment polygon were summarized and provided as a key output.

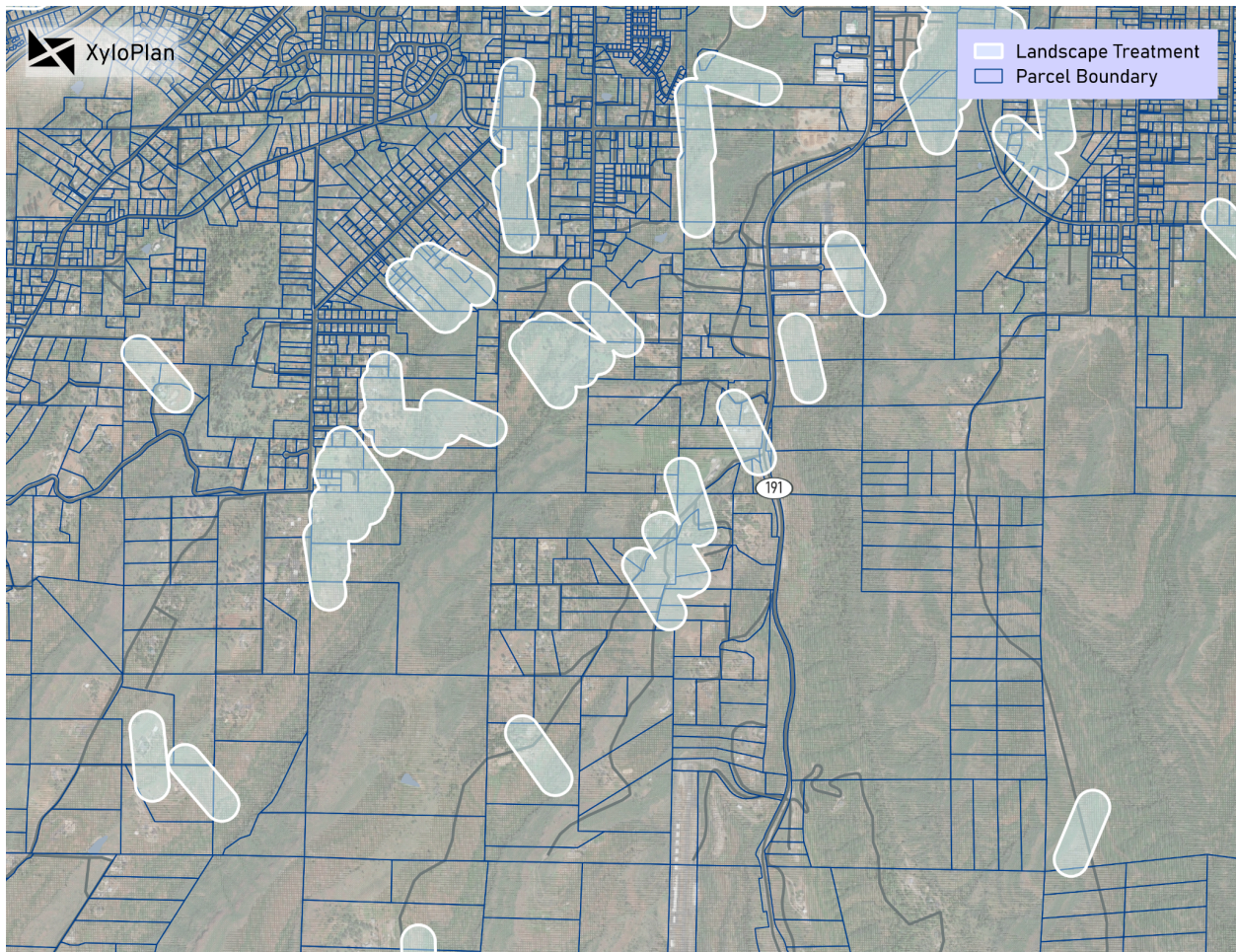


Figure 4.9: Treatments are agnostic of parcel boundaries, allowing for the most advantageous positioning along a Fire Pathway.

Treatment Plan Execution

XyloPlan's machine learning algorithms provide the locations to place SPLATs to most effectively slow down the rate of spread of fire. However, knowledge from the local vegetation management team will be required to review the recommendations and create the final treatment plan. For example, land ownership, vegetation type, environmental permitting, and the anchoring of treatments on non-burnable features to form PODs may be considered when translating the optimal treatment location recommendations into an executable treatment plan.

The treatment areas are provided as polygons, and the goal of the vegetation treatment plan should be to maximize fire behavior modification benefits within the polygon without transforming the area into a barren or non-burnable fuel model. The XyloPlan simulation measures the treatment benefits by simulating the effects of prescribed burning, mechanical and hand thinning, and mastication. Actual treatment activities will depend on local priorities, budget, and site-specific factors and must be designed by the local vegetation management team. To achieve maximum fire behavior modification benefits, it is recommended to:

1. Introduce prescribed fire as frequently as possible across the landscape, with an emphasis on areas with grass fuel models.
2. Introduce a grazing program that enhances the effectiveness of the core treatment units in light, flashy (grass) fuels.
3. Perform treatments within the recommended polygons, even though they may be located far from the built environment to generate a network effect of treatments.
4. Identify the appropriate treatment return interval per fuel type, to maintain each treatment into perpetuity.