# Lake County Fuel Treatment Prioritization

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The Colorado Forest Restoration Institute at Colorado State University receives financial support under the Southwest Forest Health and Wildfire Prevention Act provided through the U.S. Forest Service, Department of Agriculture.


**CSU Land Acknowledgment:** Colorado State University acknowledges, with respect, that the land we are on today is the traditional and ancestral homelands of the Arapaho, Cheyenne, and Ute Nations and peoples. This was also a site of trade, gathering, and healing for numerous other Native tribes. We recognize the Indigenous peoples as original stewards of this land and all the relatives within it. As these words of acknowledgment are spoken and heard, the ties Nations have to their traditional homelands are renewed and reaffirmed. CSU is founded as a land-grant institution, and we accept that our mission must encompass access to education and inclusion. And, significantly, that our founding came at a dire cost to Native Nations and peoples whose land this University was built upon. This acknowledgment is the education and inclusion we must practice in recognizing our institutional history, responsibility, and commitment.

**Document Development:** This technical report was developed using the collaborative Risk Assessment and Decision Support (RADS) framework developed by CFRI based on the Scott et al (2013) risk assessment process. Our aim was to help apply the latest science within local decision-making context to empower science-informed, actionable knowledge. We received critical input from the Lake County Forest Health Council as well as a smaller team of technical experts and local leadership composed of staff from Lake County government including a County Commissioner, Office of Emergency Management, and Fire Chief, US Forest Service Leadville District Ranger, the Friends of Twin Lakes President, Envision Chaffee County co-lead, and Smoyer and Associates facilitation. The tech and leads team met bi-weekly throughout the year-long planning process to incorporate feedback from the larger Forest Health Council and provide input on key decisions. This report documents the collaborative decision-making process, technical details, and final products of the Lake County Wildfire Risk Assessment to inform the Lake County Community Wildfire Protection Plan.

**Acknowledgements:** First, we would like to extend sincere thanks to Benjamin Gannon and Brett Wolk for technical model development and creating the template of the collaborative RADS process. Allie Rhea and Scott Ritter conducted the technical modeling and wrote the technical report. Brett Wolk and Stephanie Mueller mentored both Allie and Scott in the analysis methods, were critical participants throughout the stakeholder engagement process, and provided helpful edits to both technical reports. Jackie Edinger supported the data collection, modeling, and community meeting. Document editing and layout by Angela Hollingsworth. We thank Kim Smoyer and Cindy Williams for expert facilitation which kept the process fun and productive, and the Lake County Forest Health Council for thoughtful engagement in input.

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## Purpose and Scope

The purpose of this fuel treatment prioritization is to inform a revision of the Lake County Community Wildfire Protection Plan (CWPP). The focus of the prioritization is identifying cost-effective treatment opportunities at the county scale using the results of the Lake County Wildfire Risk Assessment and available spatial data on treatment constraints.

## Methods

The Colorado Forest Restoration Institute's Risk Assessment and Decision Support (RADS) model was used to prioritize fuel treatment type and location considering constraints on treatment feasibility and cost. RADS uses a generalized form of the linear programming optimization model described in Gannon *et al.* (2019) and Figure 1 to select treatment locations and types that maximize risk reduction for the available budget. Spatial treatment units are defined by the user at an appropriate scale for decision-making. Each treatment unit is attributed with the area feasible for treatment and the average risk reduction and treatment cost for each treatment type. Linear optimization is then used to identify the optimal treatment plan for the available budget (see Appendix I – Model formulation). The resulting treatment plan represents the most cost-effective means to reduce wildfire risk given the specified constraints.

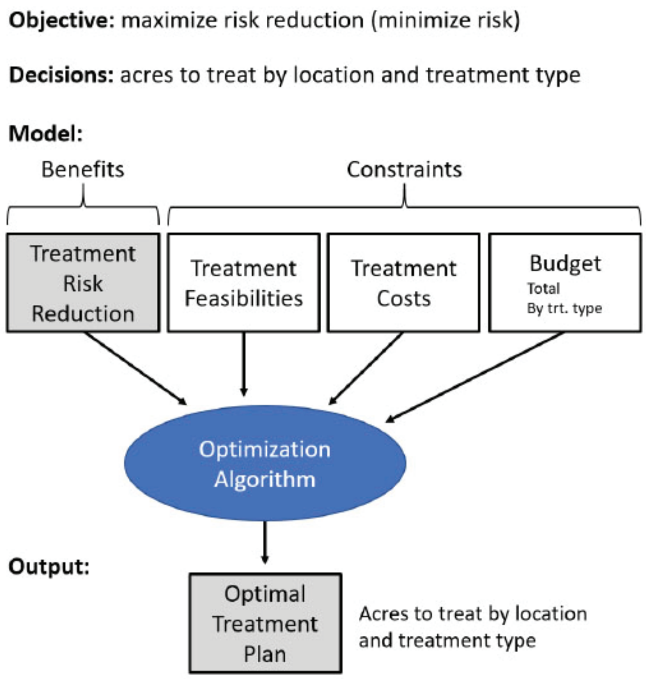


*Figure 1: Conceptual diagram of the Risk Assessment and Decision Support (RADS) fuel treatment optimization model. Fuel treatment benefits and constraints are summarized for the feasible treatment area in each treatment unit. Linear optimization is then used to maximize risk reduction for the available budget. Budget is manipulated by the user to focus or expand priorities.*

## Treatment units

The technical team selected National Hydrography Dataset Plus (NHDPlus) catchments as treatment units for the prioritization (USEPA and USGS 2012). There are 265 catchments in Lake County. The median and mean catchment sizes are 243 and 927 acres respectively.

## Treatment types

This prioritization considered four treatment types: 1) thin only, 2) prescribed fire only, 3) complete (thin followed by prescribed fire), and 4) patch cut.

Treatments are simulated in the baseline fuels data from LANDFIRE (2016) by changing surface and canopy fuel attributes by the mean effect sizes for hazardous fuels reduction and forest restoration projects in the western U.S. (Stephens and Moghaddas 2005; Stephens *et al*. 2009; Fulé *et al*. 2012; Ziegler *et al*. 2017). Treatment effects on canopy attributes are applied as proportional adjustments to the pre-treatment data (Table 1). Treatment effects on surface fuels are represented by changing the fire behavior fuel model (Table 2, Scott and Burgan 2005). For this assessment, it was assumed that the thin only treatment would not alter the fire behavior fuel model, prescribed fire would shift the fire behavior fuel model to the least intense model in the same category, and the complete treatment of thinning followed by prescribed fire would achieve the same effects as prescribed fire. It was assumed that patch cut would not alter grass fuel models, but would shift all other fuel types to the lowest grass shrub model. The dominant non-forested fuel model represented by LANDFIRE in Lake County is the grass-shrub model. Therefore, it was assumed that patch cut treatments were not targeting shrub removal, were not followed by broadcast burning that would alter shrub cover, and thus would revert all forested areas to the lowest grass shrub model.

*Table 1: Fuel reduction treatments are simulated with proportional adjustments to baseline canopy attributes using mean effect sizes from fuels reduction and forest restoration projects in the western U.S. (Stephens and Moghaddas 2005; Stephens* et al. *2009; Fulé* et al. *2012; Ziegler* et al. *2017). We assumed patch cut treatments would lead to complete canopy removal forcing all canopy metrics to zero.*

| Parameter | Thin Only | Rx Fire Only | Complete | Patch Cut |
|---|---|---|---|---|
| Canopy base height | 1.20 | 1.09 | 1.20 | 0 |
| Canopy height | 1.20 | 1.13 | 1.20 | 0 |
| Canopy cover | 0.70 | 0.95 | 0.75 | 0 |
| Canopy bulk density | 0.60 | 0.92 | 0.50 | 0 |

*Table 2: The categorical fire behavior fuel model was not modified for the thin treatment. The surface fuel reductions from prescribed fire and complete treatments are represented by transitioning fire behavior fuel models to the least intense fire behavior fuel model in the same category (Scott and Burgan [2005]). Patch cut changes all fuel types, with the exception of grass, to a grass shrub model. Changes are highlighted with red text.*

| Category | Code | Baseline | Thin | Prescribed Fire | Complete | Patch Cut |
|---|---|---|---|---|---|---|
| Grass | GR1 | 101 | 101 | 101 | 101 | 101 |
| | GR2 | 102 | 102 | 101 | 101 | 102 |
| | GR3 | 103 | 103 | 101 | 101 | 103 |
| | GR4 | 104 | 104 | 101 | 101 | 104 |
| | GR5 | 105 | 105 | 101 | 101 | 105 |
| | GR6 | 106 | 106 | 101 | 101 | 106 |
| | GR7 | 107 | 107 | 101 | 101 | 107 |
| | GR8 | 108 | 108 | 101 | 101 | 108 |
| | GR9 | 109 | 109 | 101 | 101 | 109 |
| Grass Shrub | GS1 | 121 | 121 | 121 | 121 | 121 |
| | GS2 | 122 | 122 | 121 | 121 | 121 |
| | GS3 | 123 | 123 | 121 | 121 | 121 |
| | GS4 | 124 | 124 | 121 | 121 | 121 |
| Shrub | SH1 | 141 | 141 | 141 | 141 | 121 |
| | SH2 | 142 | 142 | 141 | 141 | 121 |
| | SH3 | 143 | 143 | 141 | 141 | 121 |
| | SH4 | 144 | 144 | 141 | 141 | 121 |
| | SH5 | 145 | 145 | 141 | 141 | 121 |
| | SH6 | 146 | 146 | 141 | 141 | 121 |
| | SH7 | 147 | 147 | 141 | 141 | 121 |
| | SH8 | 148 | 148 | 141 | 141 | 121 |
| | SH9 | 149 | 149 | 141 | 141 | 121 |
| Timber Understory | TU1 | 161 | 161 | 161 | 161 | 121 |
| | TU2 | 162 | 162 | 161 | 161 | 121 |
| | TU3 | 163 | 163 | 161 | 161 | 121 |
| | TU4 | 164 | 164 | 161 | 161 | 121 |
| | TU5 | 165 | 165 | 161 | 161 | 121 |
| Timber Litter | TL1 | 181 | 181 | 181 | 181 | 121 |
| | TL2 | 182 | 182 | 181 | 181 | 121 |
| | TL3 | 183 | 183 | 181 | 181 | 121 |
| | TL4 | 184 | 184 | 181 | 181 | 121 |
| | TL5 | 185 | 185 | 181 | 181 | 121 |
| | TL6 | 186 | 186 | 181 | 181 | 121 |
| | TL7 | 187 | 187 | 181 | 181 | 121 |
| | TL8 | 188 | 188 | 181 | 181 | 121 |
| | TL9 | 189 | 189 | 181 | 181 | 121 |
| Slash Blowdown | SB1 | 201 | 201 | 201 | 201 | 121 |
| | SB2 | 202 | 202 | 201 | 201 | 121 |
| | SB3 | 203 | 203 | 201 | 201 | 121 |
| | SB4 | 204 | 204 | 201 | 201 | 121 |

## Treatment feasibility

Hard constraints are captured in binary rasters representing whether each pixel is feasible (1) or infeasible (0) for the target treatment type. Economic constraints are instead captured with variable treatment costs described in the Treatment cost section.

Feasible locations for the **thin only** treatment were defined by the following constraints:

- Must be forested (LANDFIRE canopy cover ≥ 10%)
- No treatment in wilderness or upper tier roadless

Given these constraints, 100,714 acres, or 41% of Lake County, are considered feasible for the thin only treatment (Figure 2).

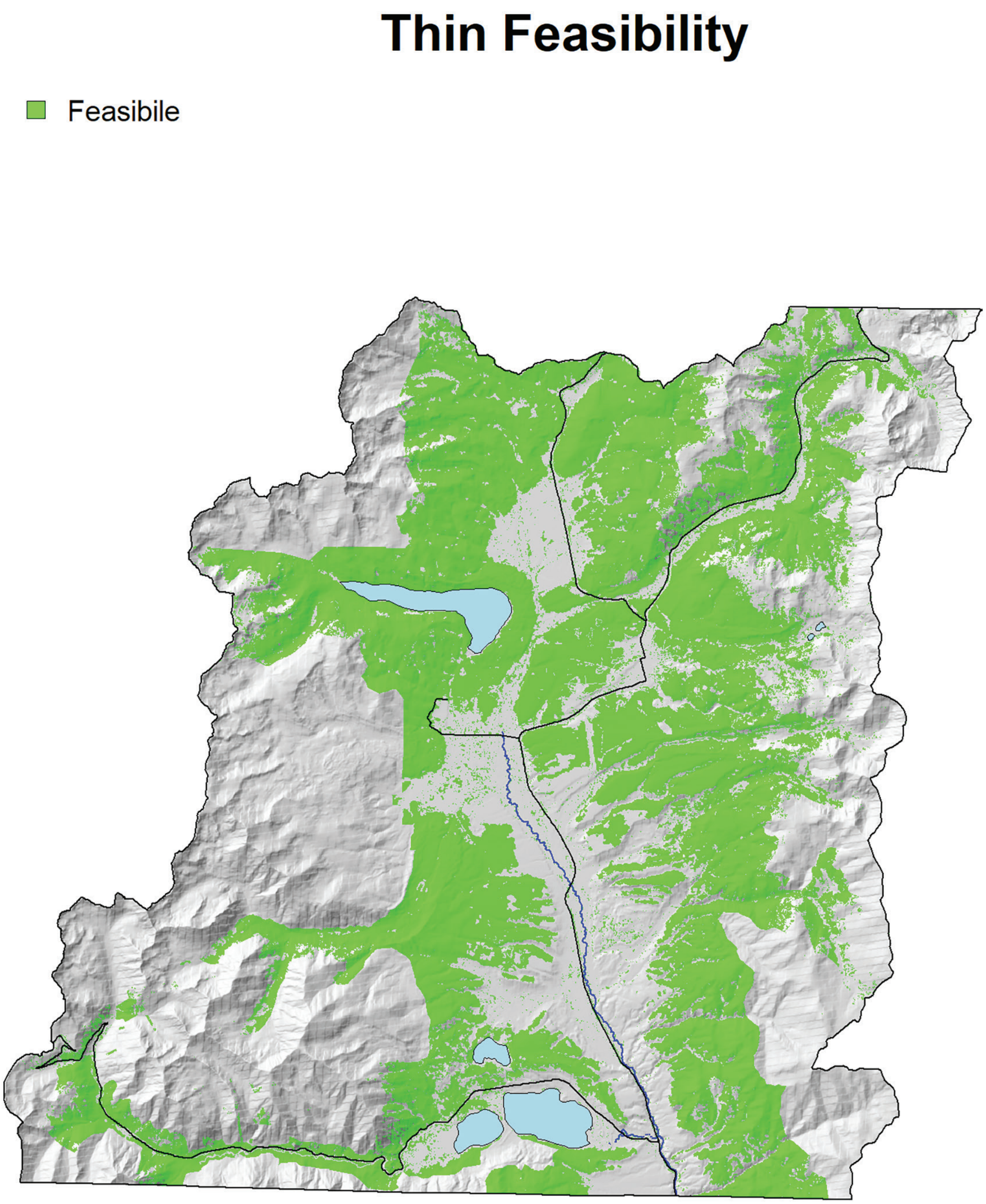


*Figure 2: Feasible locations for the thin only treatment in Lake County.*

Feasible locations for the **prescribed fire** only treatment were defined by the following constraints:

Must be forested (LANDFIRE canopy cover ≥ 10%)

No treatment in wilderness or upper tier roadless

Limited to "frequent" fire forest types that can be burned with broadcast prescribed fire as a first entry treatment (i.e., no high elevation forest types like lodgepole or spruce-fir)

Given these constraints, 14,558 acres, or 6% of Lake County, are considered feasible for the prescribed fire only treatment (Figure 3).

Additionally, stakeholders expressed that prescribed fire use is constrained by the availability of personnel and to some degree smoke permitting and hunting impacts. To capture that it is unrealistic to drastically increase prescribed fire use in the short-term, an additional constraint was created to limit spending on prescribed fire to 30% of the total budget.

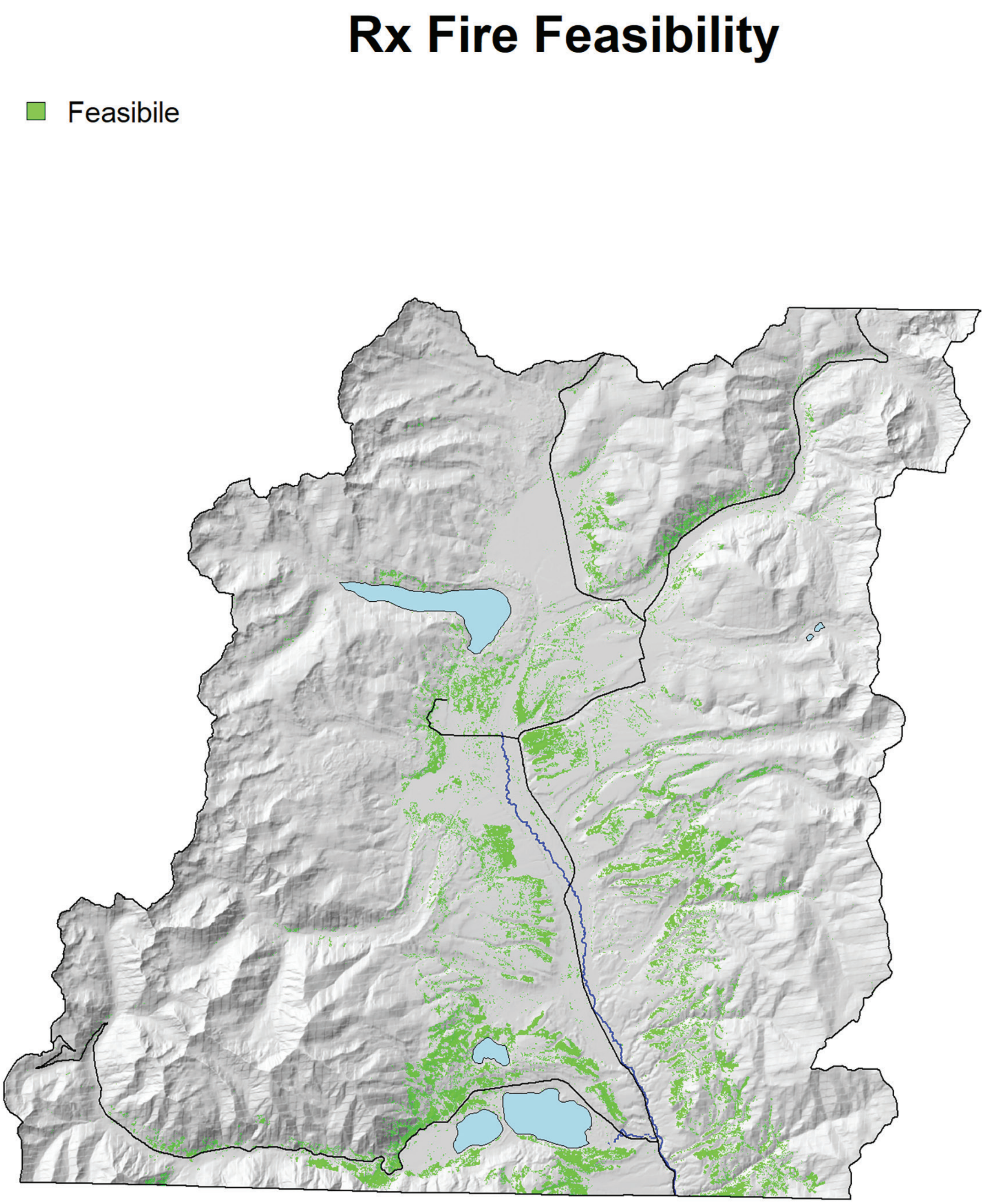


*Figure 3: Feasible locations for the prescribed fire treatment in Lake County.*

Feasible locations for the **complete** treatment were assumed to be the same as the prescribed fire only treatment:

Must be forested (LANDFIRE canopy cover ≥ 10%)

No treatment in wilderness or upper tier roadless

Limited to "frequent" fire forest types that can be burned with broadcast prescribed fire (i.e., no high elevation forest types like lodgepole or spruce-fir)

Given these constraints, 14,558 acres, or 6% of Lake County, are considered feasible for the complete treatment (Figure 4).

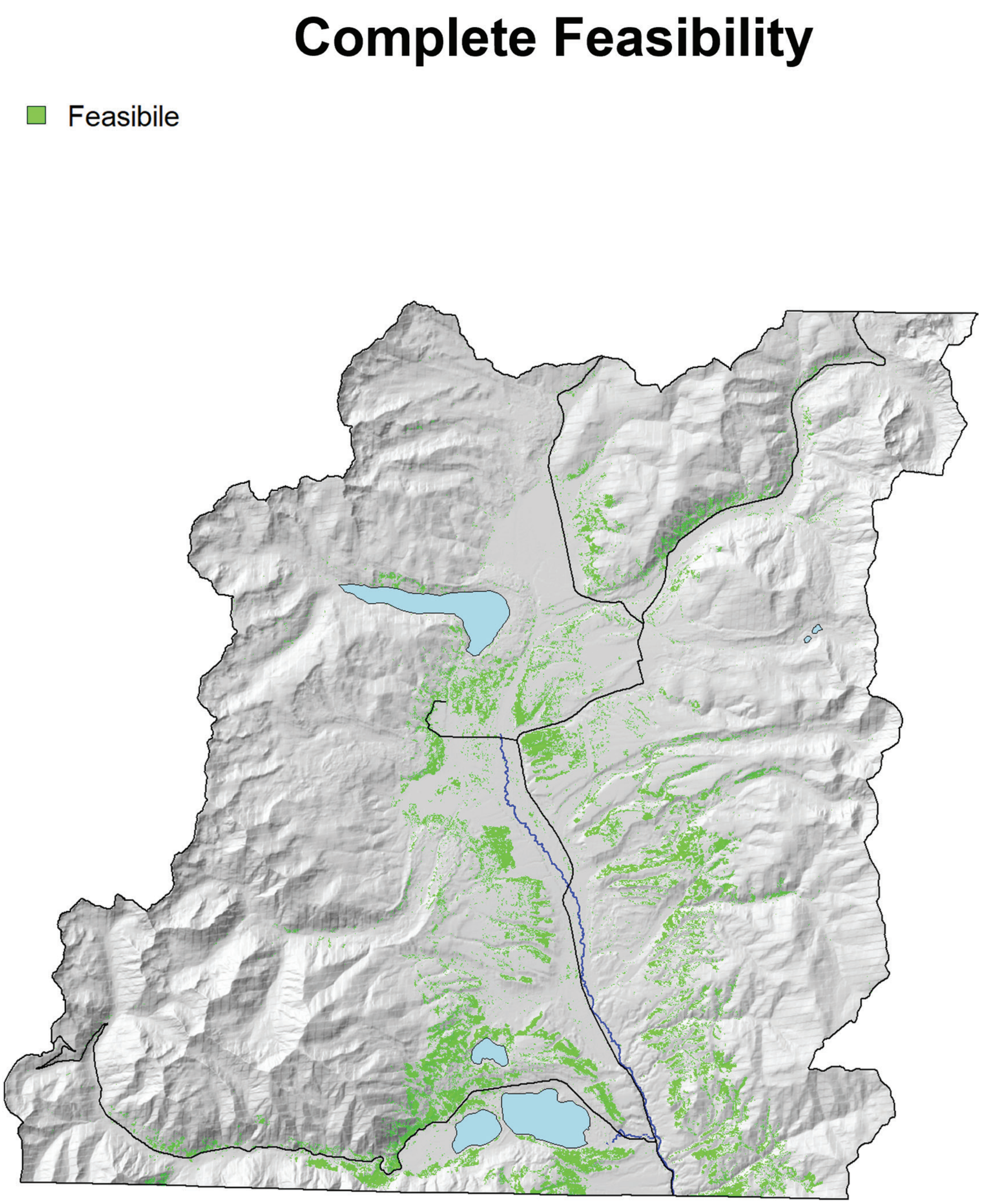


*Figure 4: Feasible locations for the complete treatment (i.e., thin followed by prescribed fire) in Lake County.*

Feasible locations for the **patch cut** treatment were defined by the following constraints:

Must be forested (LANDFIRE canopy cover ≥ 10%)

No treatment in wilderness or upper tier roadless

Limited to Lodgepole and aspen stands based on ecological compatibility

Given these constraints, 34,627 acres or 14% of Lake County are considered feasible for the patch cut treatment (Figure 5).

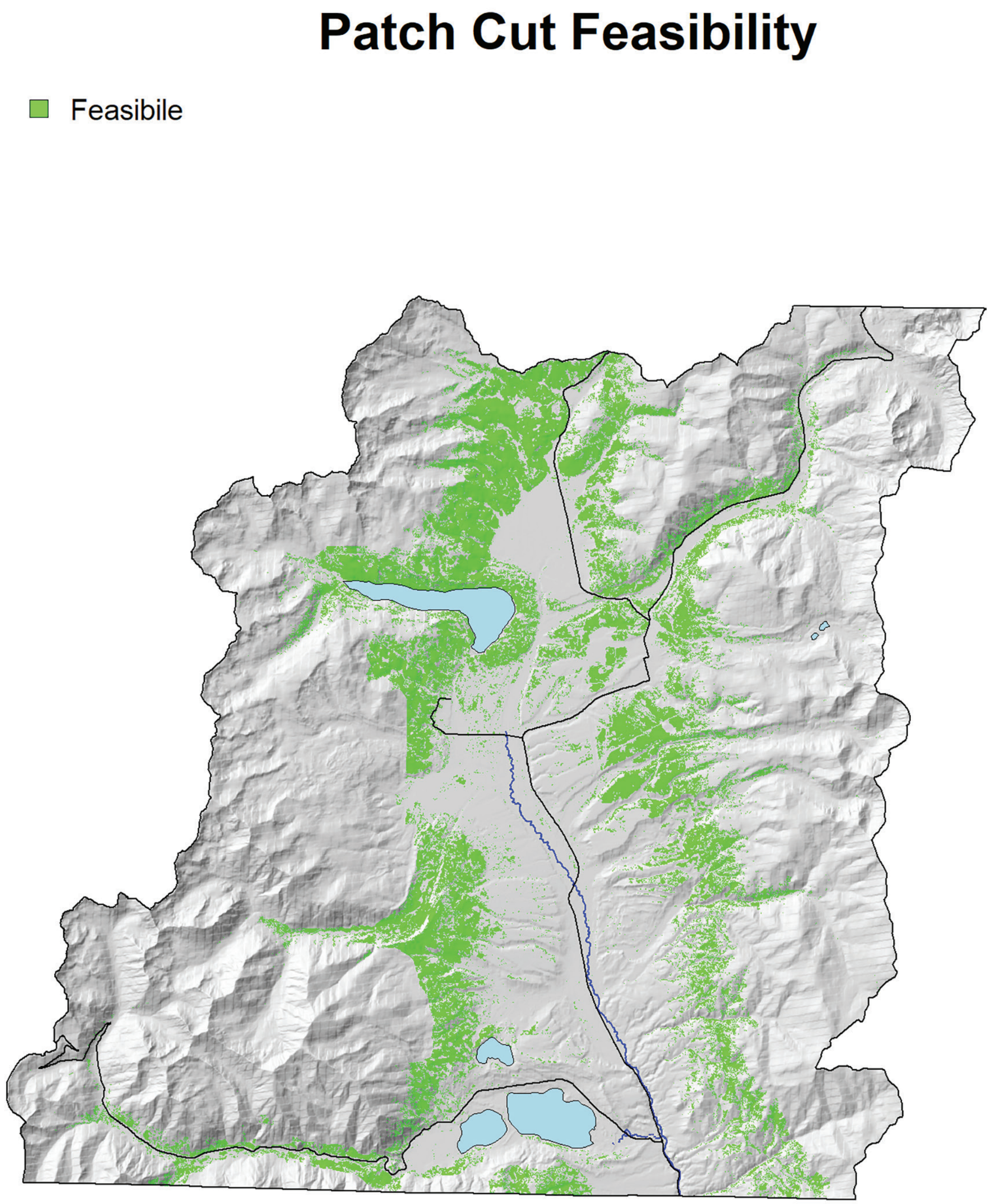


*Figure 5: Feasible locations for the patch cut treatment in Lake County.*

## Risk reduction

The risk reduction benefit of treatment is assessed on a per-pixel basis as the difference between current risk using the Lake County Wildfire Risk Assessment and simulated post-treatment risk. The benefit of fuel treatment is only represented as changing fire behavior (flame lengths, crown fire activity) as modeled with FlamMap 5 (Finney *et al.* 2015), not burn probability. This approach is consistent with the primary objectives of fuel treatments (Reinhardt *et al.* 2008), but it could underestimate fuel treatment benefits where they are expected to reduce area burned (Thompson *et al.* 2013). Risk reduction estimates are mapped for each treatment type in Figure 6 through Figure 9.

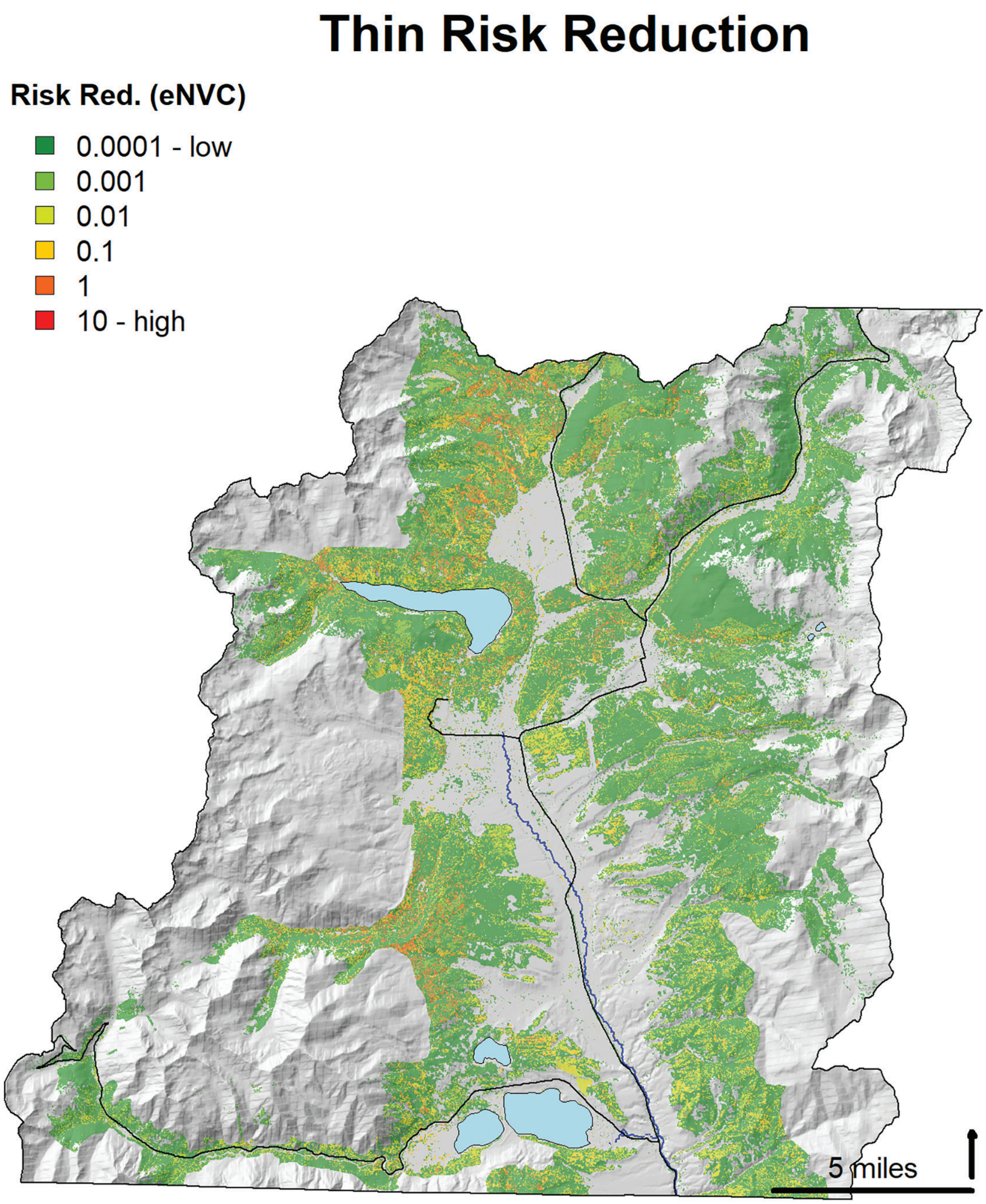


*Figure 6: Estimated risk reduction for the thin only treatment.*

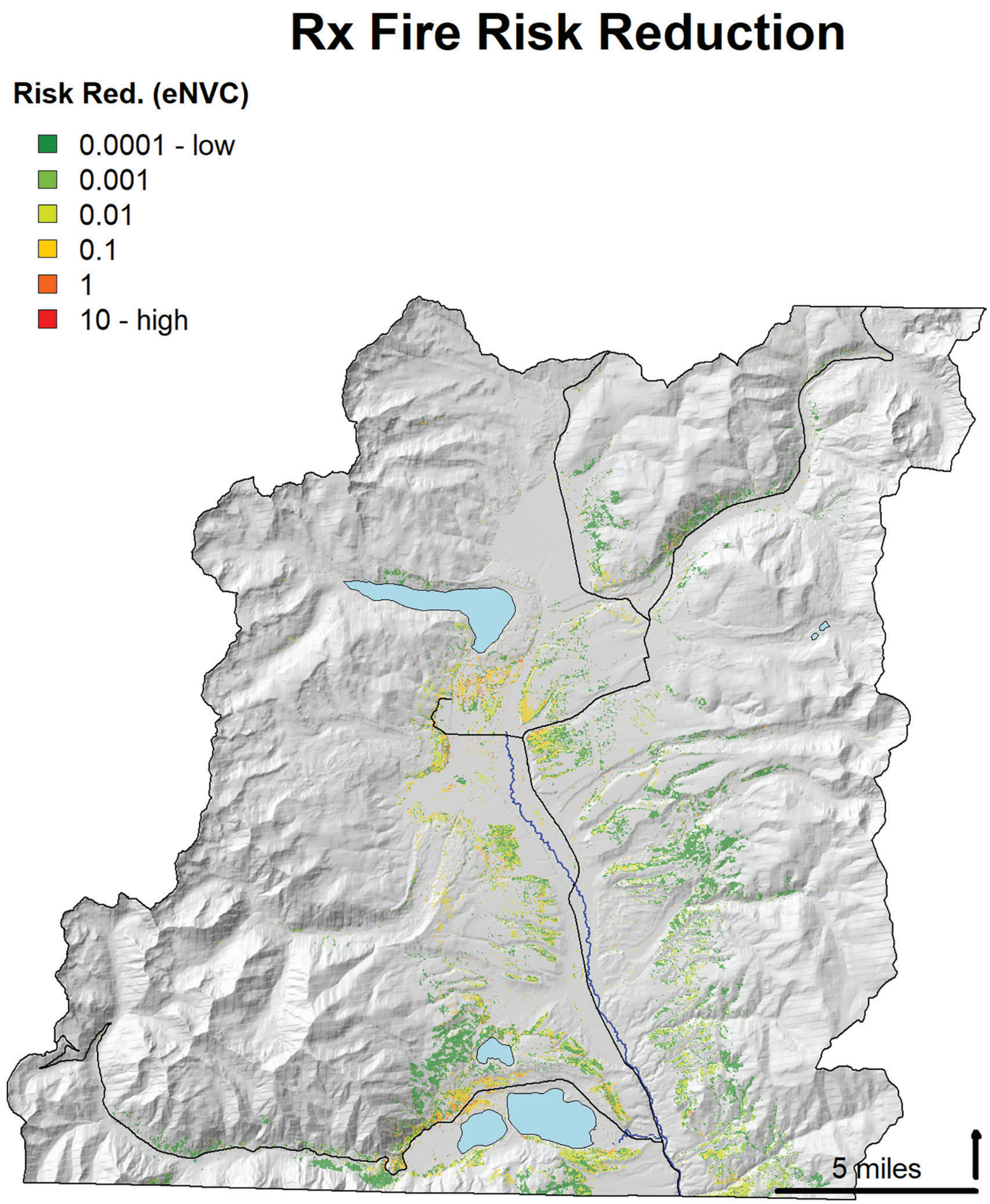


*Figure 7: Estimated risk reduction for the prescribed fire only treatment.*

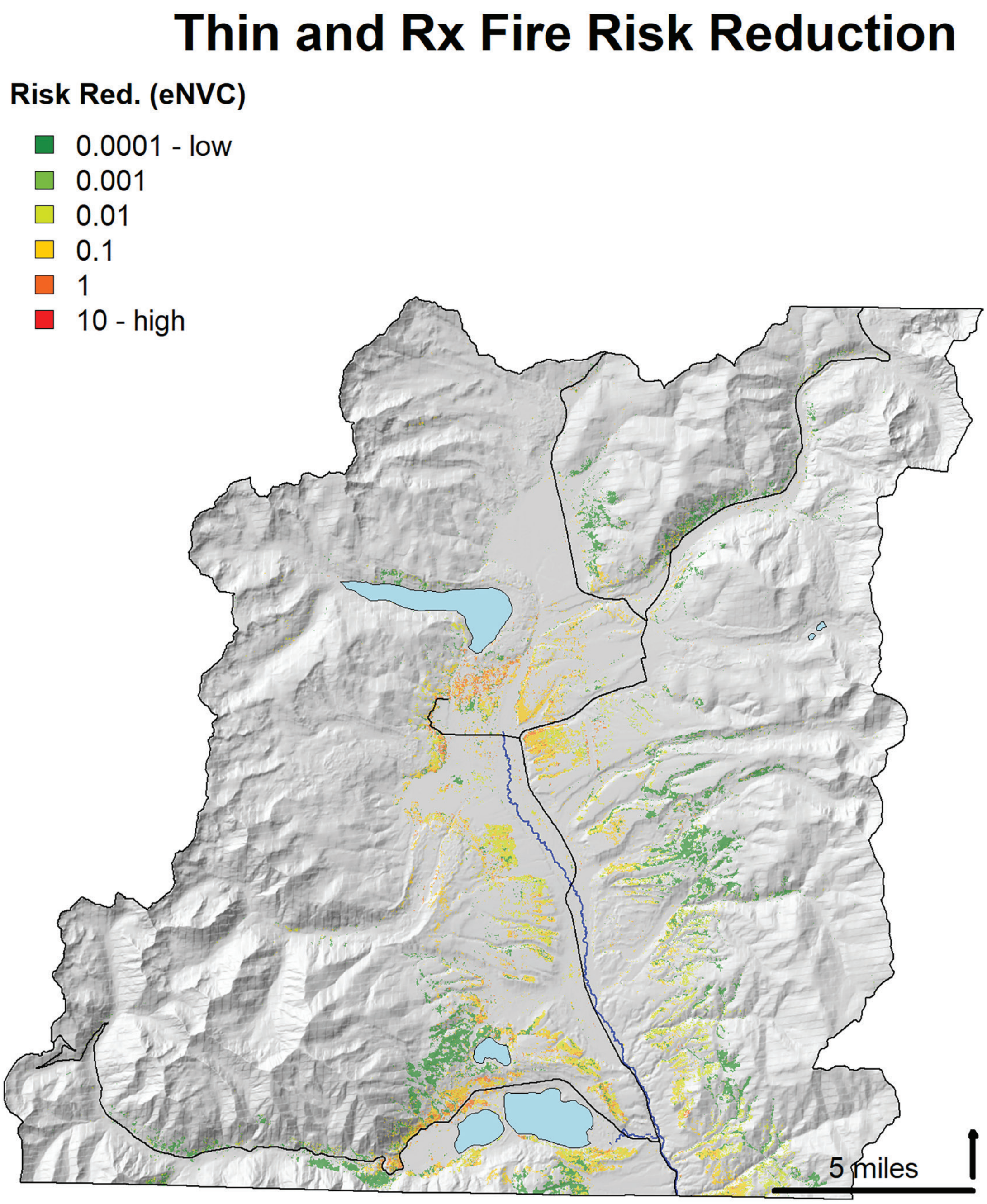


*Figure 8: Estimated risk reduction for the complete treatment (i.e., thin followed by prescribed fire).*

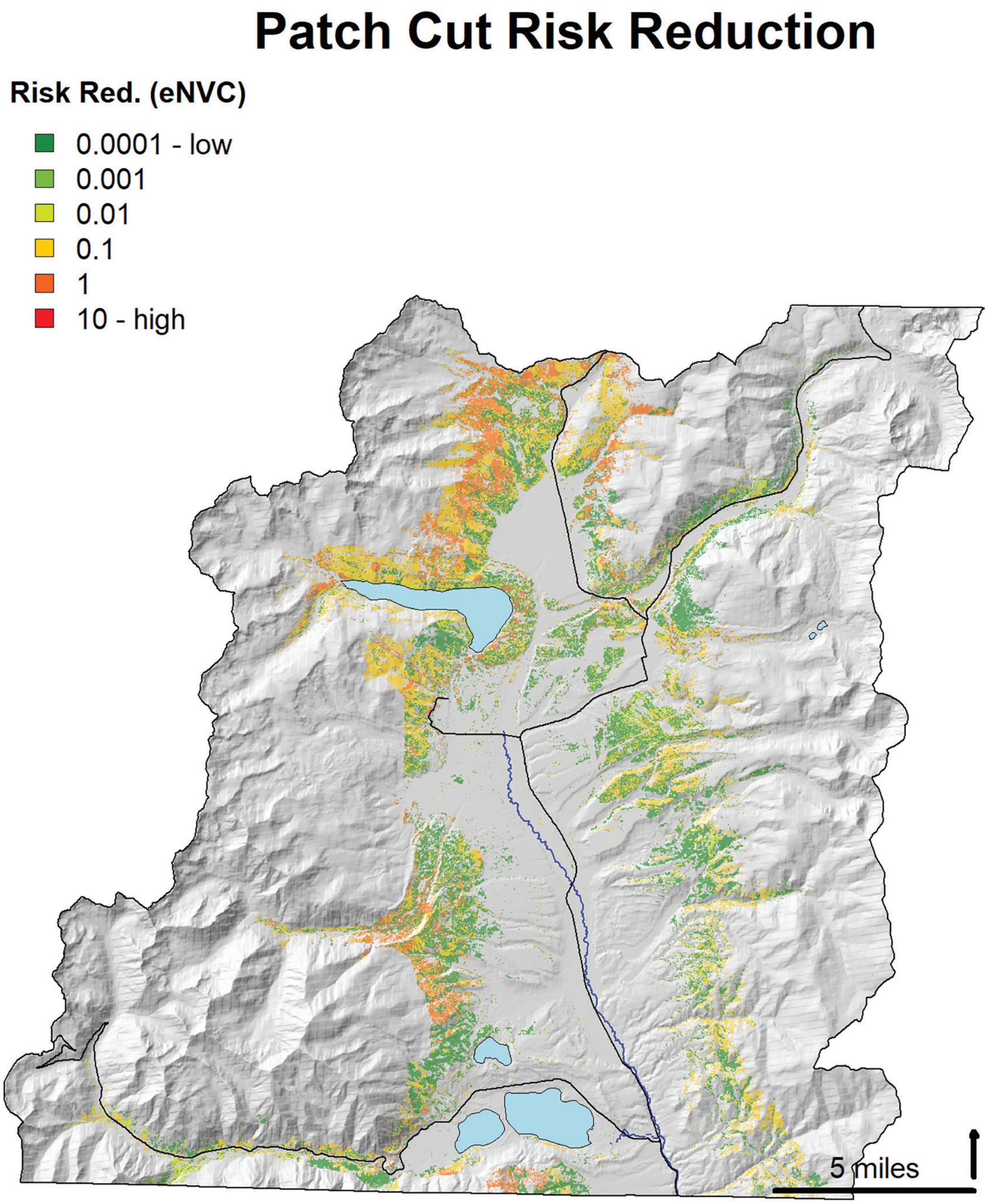


*Figure 9: Estimated risk reduction for the patch cut treatment.*

## Treatment cost

Treatment costs were based primarily on expert opinion because current treatment cost models either do not consider landscape-scale variation (Calkin and Gebert 2006) or require detailed data on stand conditions that are not available for most of the landscape (Fight *et al*. 2006).

Per acre cost for the **thin only** treatment is approximated by adapting an expert model developed in northern Colorado (Gannon *et al*. 2019) for use in Lake County. Cost is considered a function of base treatment cost under ideal conditions ($2,500/ac) with adjustments for distance from roads (Dcost) and slope steepness (Scost) in Equation 1.

$$Cost = 2{,}500 + Dcost + Scost \qquad \textbf{Equation 1}$$

Cost increases with distance from roads > 400 m as specified in Equation 2 such that the total cost of treatment increases to $10,000/ac at 5.2 miles from the nearest road.

$$Dcost(x) = \begin{cases} 0, & x < 400\ m \\ 1.25 * (x - 400), & x \geq 400\ m \end{cases} \qquad \textbf{Equation 2}$$

Cost increases with slope > 40% as specified in Equation 3 such that the total cost of treatment increases to $10,000/ac at 250% slope.

$$Scost(x) = \begin{cases} 0, & x < 40\ \% \\ 46.9 * (x - 40), & x \geq 40\ \% \end{cases} \qquad \textbf{Equation 3}$$

This formulation suggests the base cost applies anywhere within 400 m of roads and less than 40% slope. Total thinning costs were limited to a maximum of $10,000/ac if the combination of road distance and slope adjustments predicted costs in excess of $10,000/ac. The thin only treatment costs are shown in Figure 10.

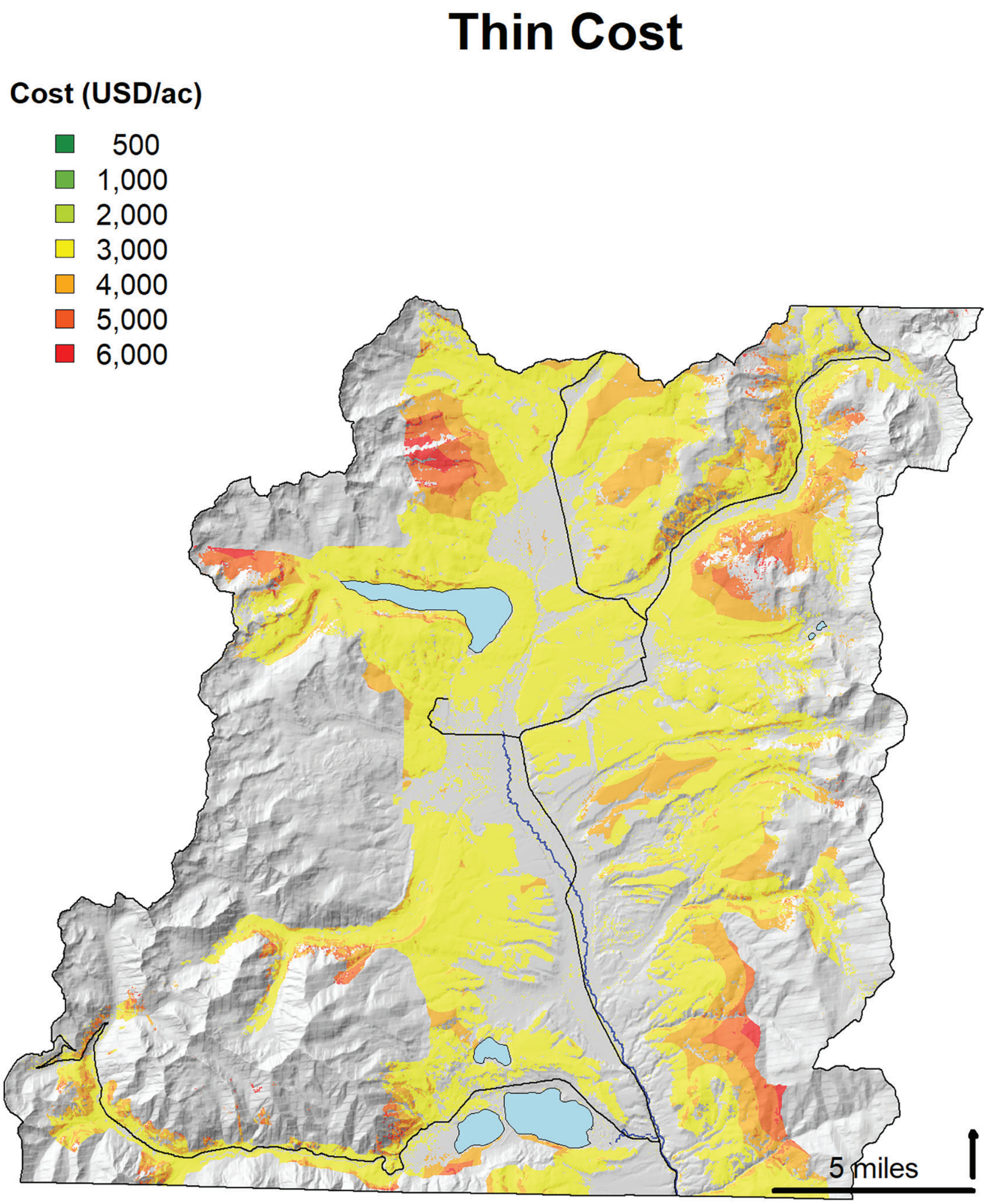


*Figure 10: Thin only treatment cost for Lake County estimated using distance from roads and slope steepness.*

Per acre cost for the **prescribed fire only** treatment is binary based on distance from structures in Equation 4. While prescribed fire costs vary widely, the causes of this variation are highly site and condition specific and therefore difficult to quantify with coarse spatial data. Prescribed fire costs are difficult to characterize in part because preparation costs are not consistently recorded. Based on limited information from other prescribed fires in Colorado and consultation with local fire professionals in Lake County, we assumed a flat rate of $1,000 per acre to cover both the preparation and day of costs. To account for the additional complexity, planning, communication, and staffing needed when burning closer to structures and communities, we assumed the cost of prescribed fire would double. Thus, base cost is assumed to be $1,000/acre when > 250 m of a structure and $2,000/acre when <250 m of a structure. The prescribed fire only treatment costs are shown in Figure 11.

$$Cost(x) = \begin{cases} 1{,}000\,, & x < 250\ m \\ 2{,}000\,, & x \geq 250\ m \end{cases} \qquad \textbf{Equation 4}$$

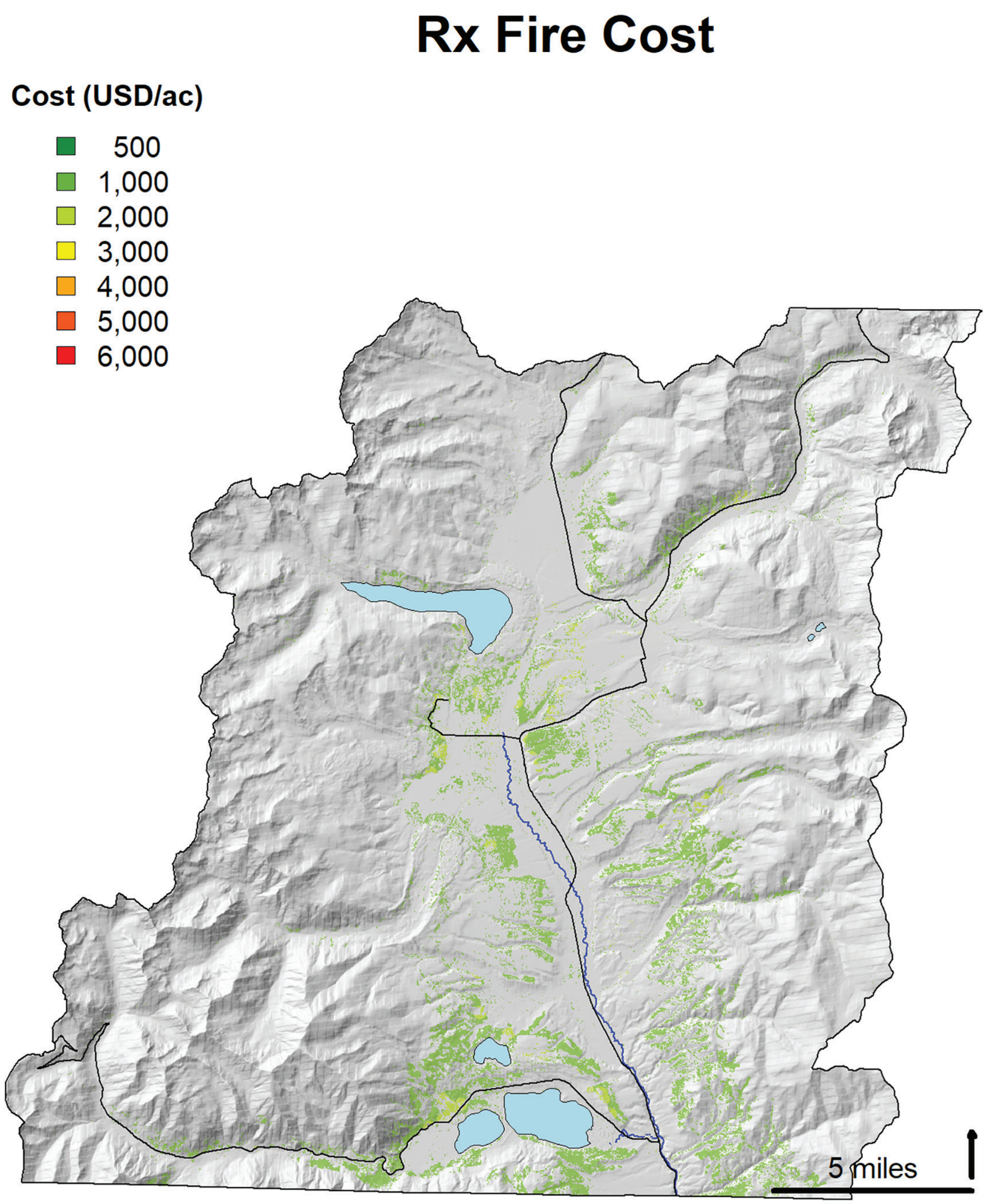


*Figure 11: Prescribed fire treatment cost for Lake County estimated as a binary value based on distance from structures.*

Per acre cost for the **complete** treatment is assumed to be the sum of the thinning and prescribed fire treatment costs. The technical team discussed whether the thinning treatment would reduce the prescribed fire costs by eliminating preparation work. Fire and fuels planners said that while thinning before prescribed fire often increases ability to both contain prescribed fire and implement fire in the unit to better achieve project objectives, the costs associated with planning, prepping, and staffing broadcast burning remain relatively similar. Previously thinned areas may require pile burns or other fuel manipulations before broadcast burning will achieve the desired effects. A similar effort is still required to prep control lines. The complete treatment costs are shown in Figure 12.

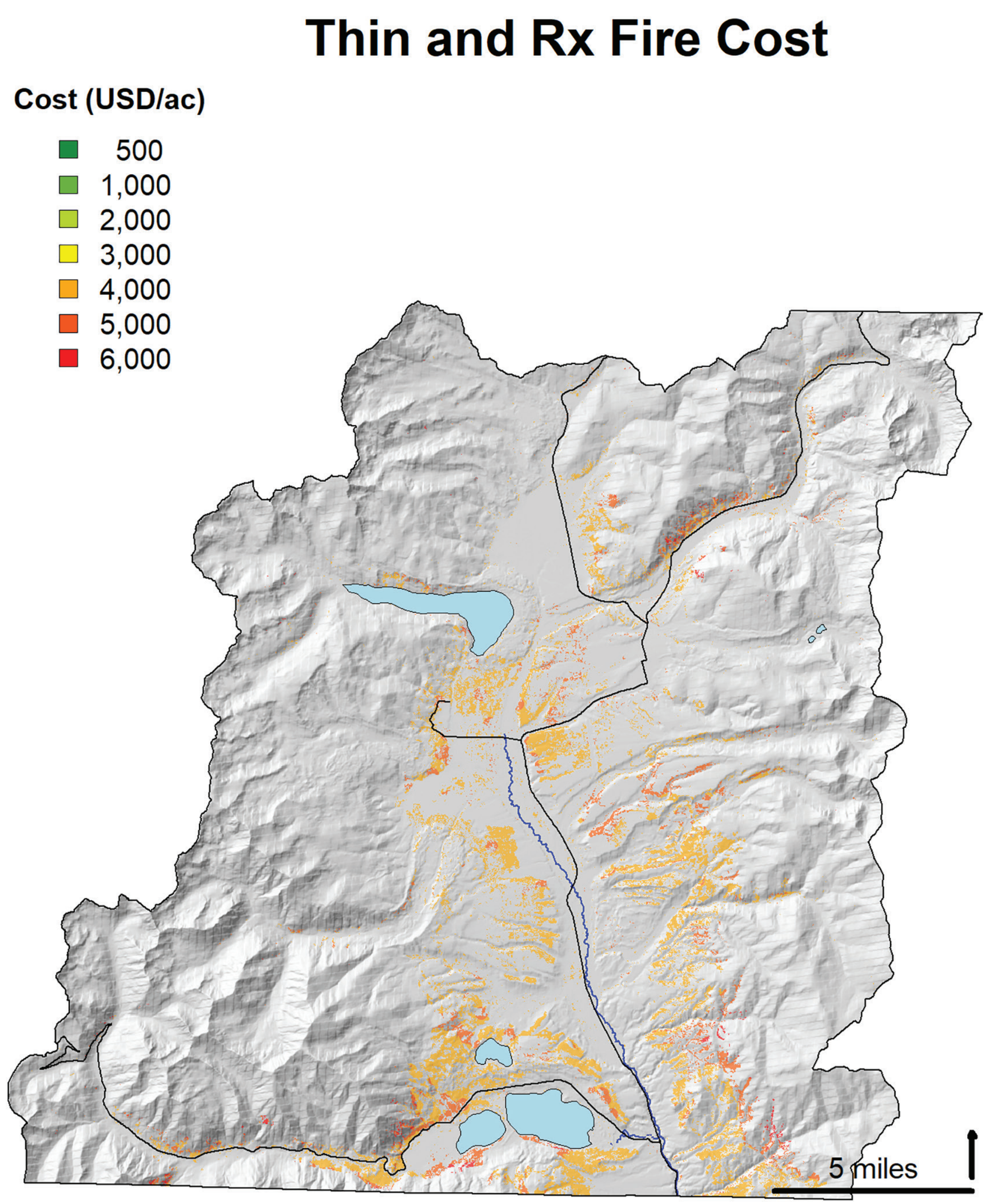


*Figure 12: Complete treatment cost for Lake County estimated as the sum of thinning and prescribed fire costs.*

Per acre cost for the **patch cut** treatment follows the same approach as thinning. Cost is considered a function of base treatment cost under ideal conditions ($2,000/ac) with the same adjustments for distance from roads (*Dcost*) and slope steepness (*Scost*) in Equation 5.

$$Cost = 2{,}000 + Dcost + Scost \qquad \textbf{Equation 5}$$

Where cost increases with distance from roads > 400 m as specified in Equation 2 and increases with slopes >40% as specified in Equation 3. This formulation suggests the base cost applies anywhere within 400 m of roads and less than 40% slope. Total patch cut costs were limited to a maximum of $10,000/ac if the combination of road distance and slope adjustments predicted costs in excess of $10,000/ac. The patch cut treatment costs are shown in Figure 13.

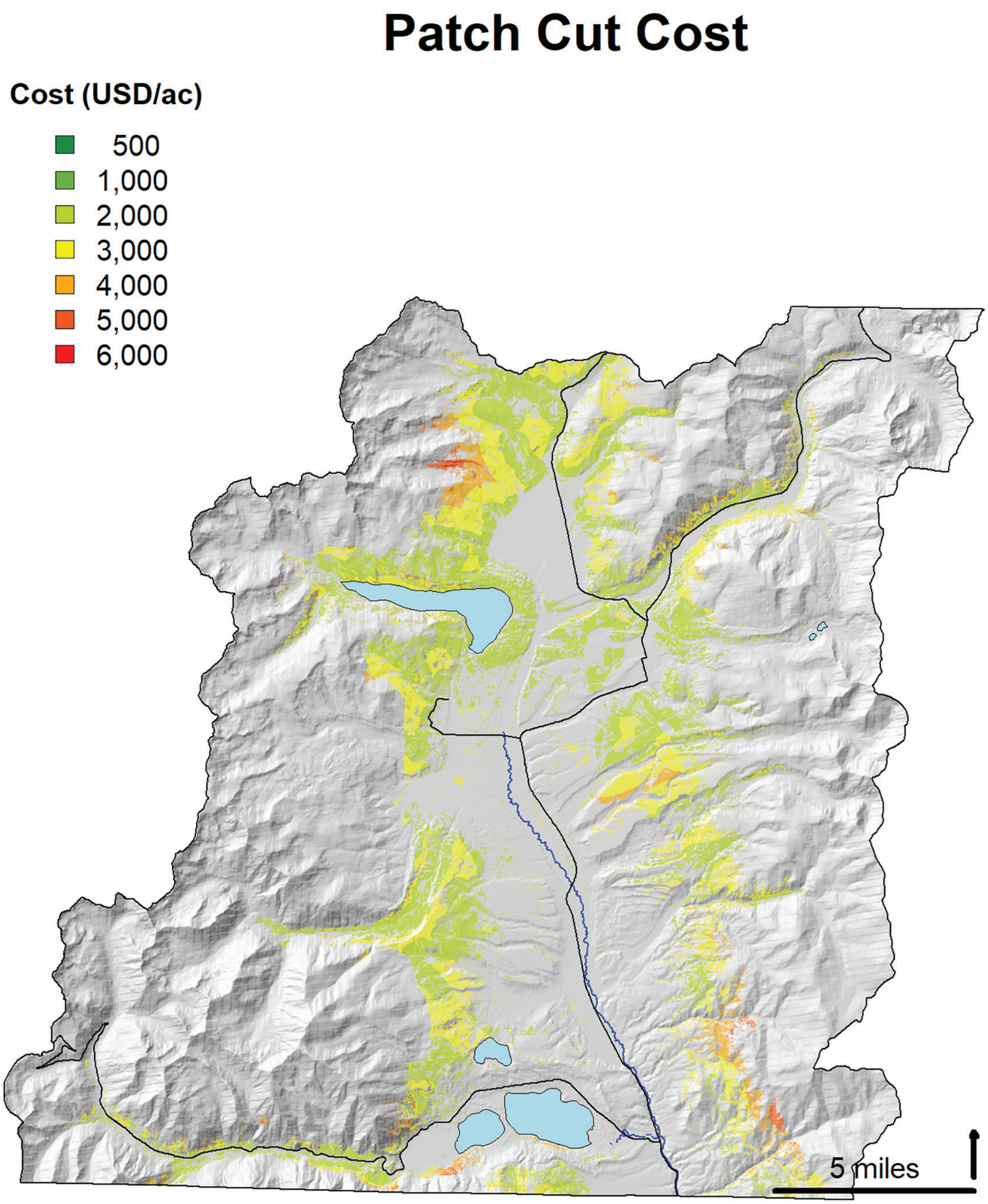


*Figure 13: Patch cut cost for Lake County estimated using distance from roads and slope steepness.*

### Prioritization

The RADS model prioritizes optimal treatment locations and types where risk reduction, measured by change in eNVC, is maximized relative to costs under any target budget level. Areas selected at lower budget levels are more cost effective to achieve desired outcomes than those selected at higher budget levels. The Lake County Forest Health Council selected budget levels of $10, $20, and $40 million as aspirational goals to achieve the highest bang for the buck that significantly reduces wildfire risk.

## Results

The RADS optimization model selected between 4,271 and 15,562 acres for treatment across the modeled budgets (Table 3). Budgets of $10M, $20M, and $40M correspond to selecting the top 5%, 10%, and 19% of treatment opportunities respectively. The draft fuel treatment priorities for Lake County are mapped in Figure 14.

*Table 3: Budget summary of risk reduction achieved and treatment allocation.*

| Priority | Budget | Risk Reduction (eNVC) | Thin (acres) | Rx fire (acres) | Complete (acres) | Patch Cut (acres) | Total (acres) |
|---|---|---|---|---|---|---|---|
| Tier 1 | $10M | 2,367 | 20 | 707 | 0 | 4,271 | 4,999 |
| Tier 2 | $20M | 3,972 | 20 | 1,509 | 628 | 7,527 | 9,684 |
| Tier 3 | $40M | 6,362 | 20 | 2,660 | 654 | 15,562 | 18,897 |

The model was also run across the full range of possible fuel treatment budgets to estimate the maximum potential of fuel treatments to reduce risk (Figure 15). Patch cut is the dominant treatment type across all priority budget levels (Table 3). The RADS model assigns <10% of the budget to prescribed fire treatments, never reaching the 30% cap, (Table 3; Figure 15) because the feasible extent is very limited for prescribed fire. Despite the cheaper cost of the thin only treatment, the model generally choses the more expensive complete treatment because there is substantial benefit to managing the surface fuels. The dominant treatment type assigned to each catchment is mapped in Figure 16 for the $40M treatment plan to provide a general indication of what treatment types are most appropriate in which areas. This map is not meant to be prescriptive or to replace the need for field assessment of current conditions to identify the appropriate treatment type. The RADS model can allocate multiple treatment types within large catchments, so the map should be interpreted with caution; however, only 4 treatment units were assigned multiple treatment types in Lake County. The map was generalized to represent the most common treatment at the highest budget level (i.e., $40M) to inform workforce development needs and future program planning. The spatial distribution of treatments is reflective of the current forest conditions and associated management practices: 1) patch cut is assigned exclusively within Lodgepole and aspen forests; 2) prescribed fire only and complete treatments are target ponderosa pine and dry mixed conifer zones; and 3) thin is the least restrictive, but least effective.

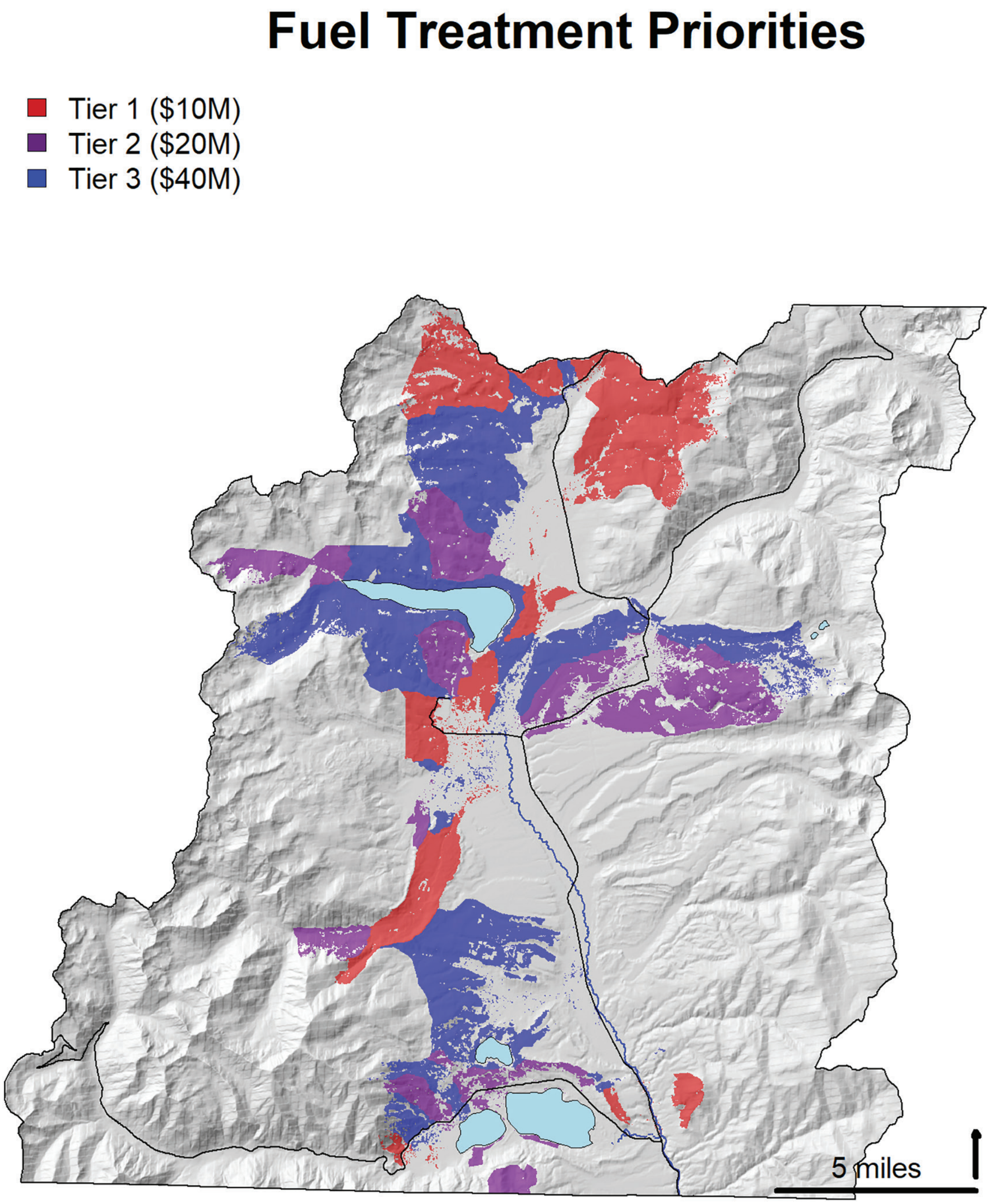


*Figure 14: Fuel treatment prioritization for Lake County's $10M, $20M, and $40M budgets.*

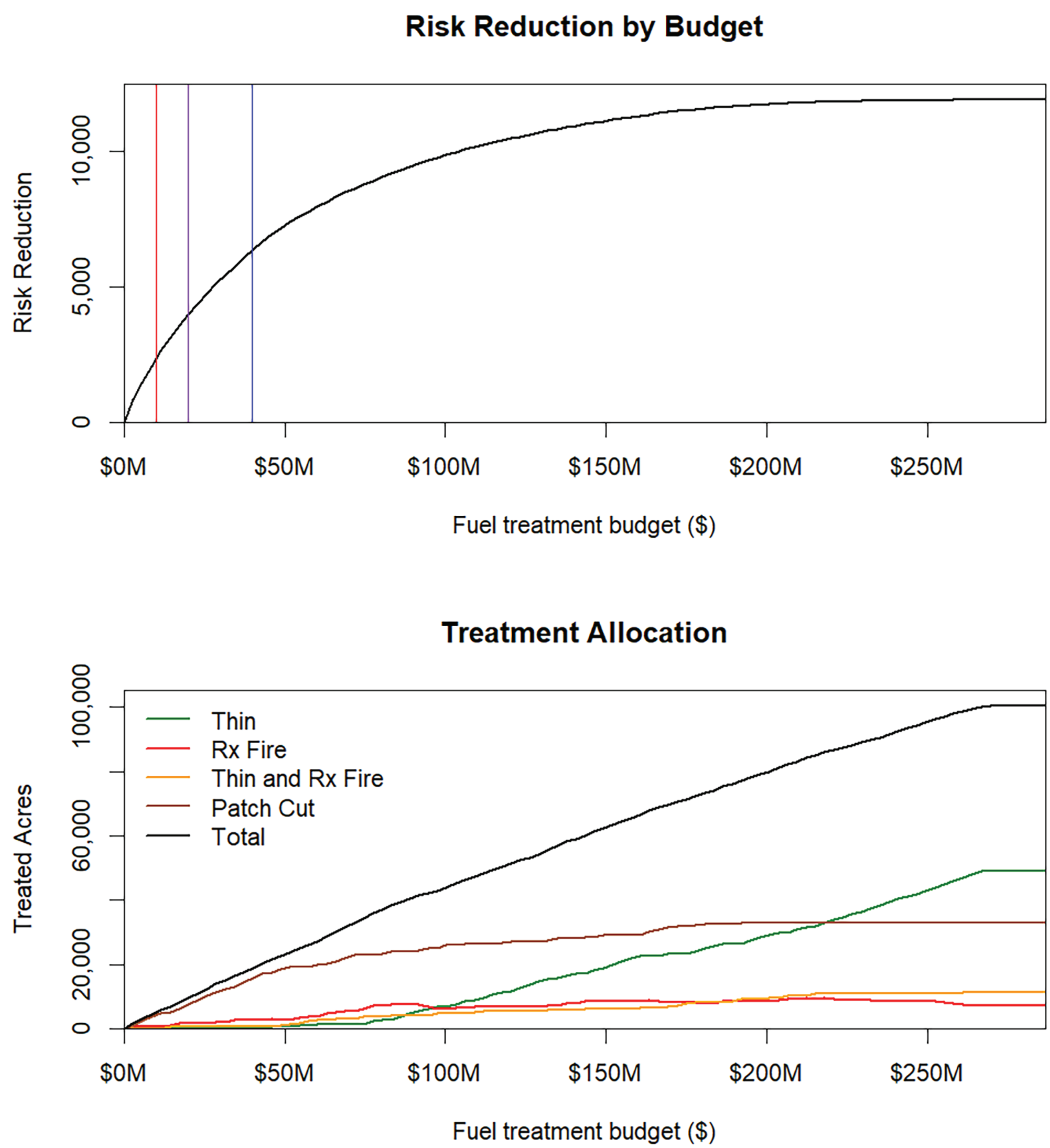


*Figure 15: The avoided risk curve shows the level of risk reduction achieved across a wide range of fuel treatment budgets in the top panel with the $10M, $20M, and $40M budgets marked by the red, purple, and blue vertical lines. Treatment type allocations are tracked by budget level in the lower panel. Risk is a unitless (or relative) measure of expected Net Value Change from the Lake County Wildfire Risk Assessment, and approximates 0% to 100% feasible risk reduction above $250 where the line flattens.*

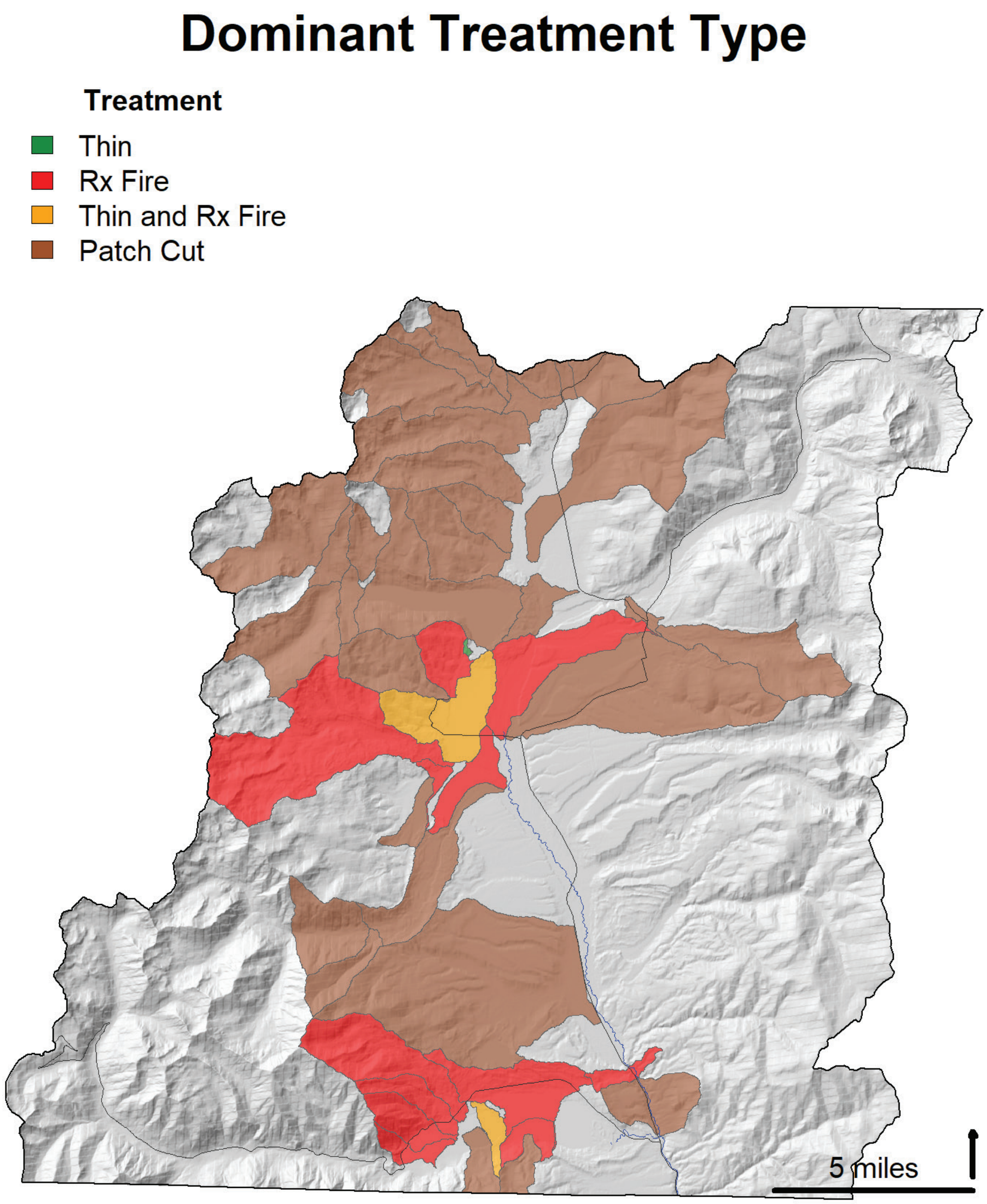


*Figure 16: This simplified map shows the dominant treatment type in each treatment unit based on the $40M treatment plan. It does not imply that the mapped treatment type should be applied across the entire treatment unit. Treatment-specific feasibility should be considered and multiple treatment types can be assigned to a treatment unit.*

# References


Calkin D, Gebert K (2006) Modeling fuel treatment costs on Forest Service Lands in the Western United States. Western Journal of Applied Forestry 21(4), 217-221.

Coop JD, Grant TA, Magee PA, Moore EA (2016) Mastication treatment effects on vegetation and fuels in piñon-juniper woodlands of central Colorado, USA. Forest Ecology and Management 396, 68-84. doi:10.1016/j.foreco.2017.04.007

Fight RD, Hartsough BR, Noordijk P (2006) Users guide for FRCS: fuel reduction cost simulator software. USDA Forest Service, Pacific Northwest Research Station General Technical Report PNW-GTR-668. 23 p (Portland, OR)

Finney MA, Brittain S, Seli RC, McHugh CW, Gangi L (2015) FlamMap: fire mapping and analysis system (version 5.0) [Software]. Available from http://www.firelab.org/document/flammap-software

Fulé PZ, Crouse JE, Roccaforte JP, Kalies EL (2012) Do thinning and/or burning treatments in the western USA ponderosa or Jeffrey pine-dominated forests help restore natural fire behavior? Forest Ecology and Management 269, 68–81. doi:10.1016/j.foreco.2011.12.025

Gannon BM, Wei Y, MacDonald LH, Kampf SK, Jones KW, Cannon JB, Wolk BH, Cheng AS, Addington RN, Thompson MP (2019) Prioritizing fuels reduction for water supply protection. International Journal of Wildland Fire 28(1), 785-803. doi:10.1071/WF18182

Heinsch FA, Sikkink PG, Smith HY, Retzlaff ML (2018) Characterizing fire behavior from laboratory burns of multi-aged, mixed-conifer masticated fuels in the western United States. USDA Forest Service, Rocky Mountain Research Station, Research Paper RMRS-RP-107. (Fort Collins, CO, USA)

Jain T, Sikkink P, Keefe R, Byrne J (2018) To masticate or not: useful tips for treating forest, woodland, and shrubland vegetation. USDA Forest Service Rocky Mountain Research Station General Technical Report RMRS-GTR-381. 55 p. (Fort Collins, CO)

LANDFIRE (2014) Fuel, topography, existing vegetation type, and fuel disturbance layers, LANDFIRE 1.4.0., U.S. Geological Survey. Available from http://landfire.cr.usgs.gov/viewer/

Reinhardt ED, Keane RE, Calkin DE, Cohen JD (2008) Objectives and considerations for wildland fuel treatment in forested ecosystems of the interior western United States. Forest Ecology and Management 256, 1997–2006. doi:10.1016/j.foreco.2008.09.016

Scott JH, Reinhardt ED (2001) Assessing crown fire potential by linking models of surface and crown fire behavior. USDA Forest Service, Rocky Mountain Research Station, General Technical Research Paper RMRS-RP-29. (Fort Collins, CO, USA)

Scott JH, Burgan RE (2005) Standard fire behavior fuel models: a comprehensive set for use with Rothermel's surface fire spread model. USDA Forest Service, Rocky Mountain Research Station, General Technical Report RMRS-GTR-153. (Fort Collins, CO, USA)

Stephens SL, Moghaddas JJ (2005) Experimental fuel treatment impacts on forest structure, potential fire behavior, and predicted tree mortality in a California mixed- conifer forest. Forest Ecology and Management 215, 21–36. doi:10.1016/j.foreco.2005.03.070

Stephens SL, Moghaddas JJ, Edminster C, Fielder CE, Haase S, Harrington M, Keeley JE, Knapp EE, McIver JD, Metlen K, Skinner CN, Youngblood A (2009) Fire treatment effects on vegetation structure, fuels, and potential fire severity in western U.S. forests. Ecological Applications 19, 305–320. doi:10.1890/07-1755.1

Technosylva (2018) 2017 Colorado Wildfire Risk Assessment Update. Report to the Colorado State Forest Service. (La Jolla, CA, USA)

Thompson MP, Vaillant NM, Haas JR, Gebert KM, Stockmann KD (2013) Quantifying the potential impacts of fuel treatments on wildfire suppression costs. Journal of Forestry 111, 49–58. doi:10.5849/jof.12-027

US Environmental Protection Agency (USEPA) and the US Geological Survey (USGS) (2012) National Hydrography Dataset Plus - NHDPlus. Version 2.1. Available online at: http://www.horizon-systems.com/NHDPlus/index.php

Ziegler JP, Hoffman C, Battaglia M, Mell W (2017) Spatially explicit measurements of forest structure and fire behavior following restoration treatments in dry forests. Forest Ecology and Management 386, 1-12. doi:10.1016/j.foreco.2016.12.002

# Appendix I – Model formulation

Linear program formulation

Objective function:

$$\max Z = \sum_{i=1}^{N}\sum_{t=1}^{P} RR_{i,t} * x_{i,t}$$

Constraints:

$$x_{i,t} \le F_{i,t} \qquad \forall\, i,t$$

$$\sum_{t=1}^{P} x_{i,t} \le tF_i \qquad \forall\, i$$

$$x_{i,t} \ge 0 \qquad \forall\, i,t$$

$$\sum_{i=1}^{N}\sum_{t=1}^{P} TC_{i,t} * x_{i,t} \le Budget * BP_t \qquad \forall\, i,t$$

$$\sum_{i=1}^{N}\sum_{t=1}^{P} TC_{i,t} * x_{i,t} \le Budget$$

Subscript notation:

*i* is used to index treatment units from 1 to *N*

*t* is used to index treatment types from 1 to *P*

Decision variables:

$x_{i,t}$ is the area (ac) of treatment *t* assigned to treatment unit *i*

Parameters:

*Z* is the total risk reduction (unitless)

$RR_i$,t is the risk reduction per acre of treatment *t* applied to treatment unit i

$F_{i,t}$ is the feasible area (ac) for treatment *t* in treatment unit *i*

$tF_i$ is the total feasible area (ac) for any treatment in treatment unit *i*

$TC_{i,t}$ is the cost ($/ac) of applying treatment *t* in treatment unit *i*

*Budget* is the funding available for fuel treatment ($)

$BP_t$ is the maximum budget proportion that can be allocated to treatment type *t*

Minimum and maximum treatment sizes (ac) are also imposed on the model by pre-processing decision units to eliminate those that fall under the minimum treatment size and by shrinking the feasible acres for those decision units that exceed the maximum treatment size. The min treatment size was 20 acres, max was 5,000 acres.

## Appendix II – Cost-effectiveness results

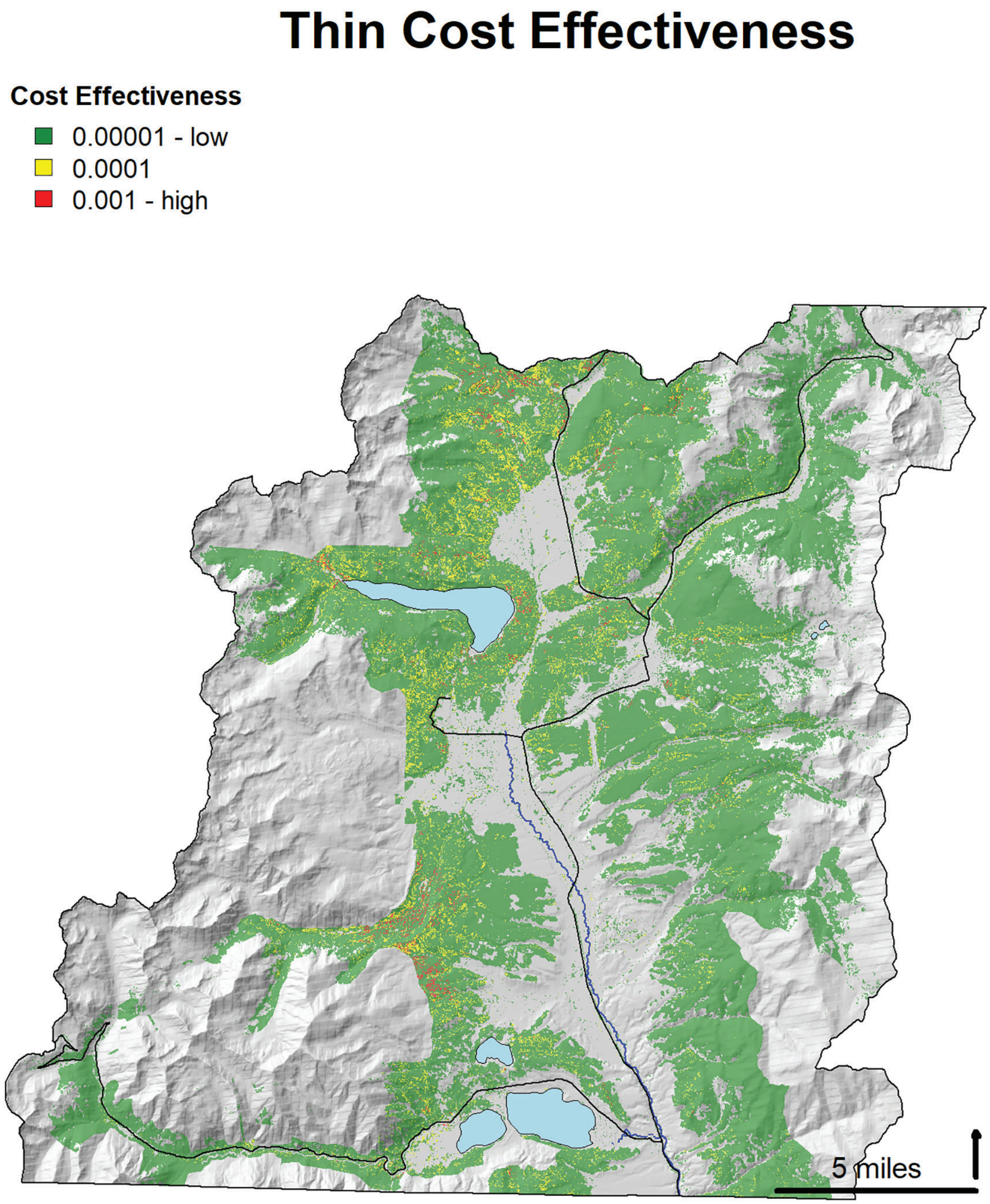


*Figure 17: Cost-effectiveness (risk reduction/treatment cost) of the thin only treatment.*

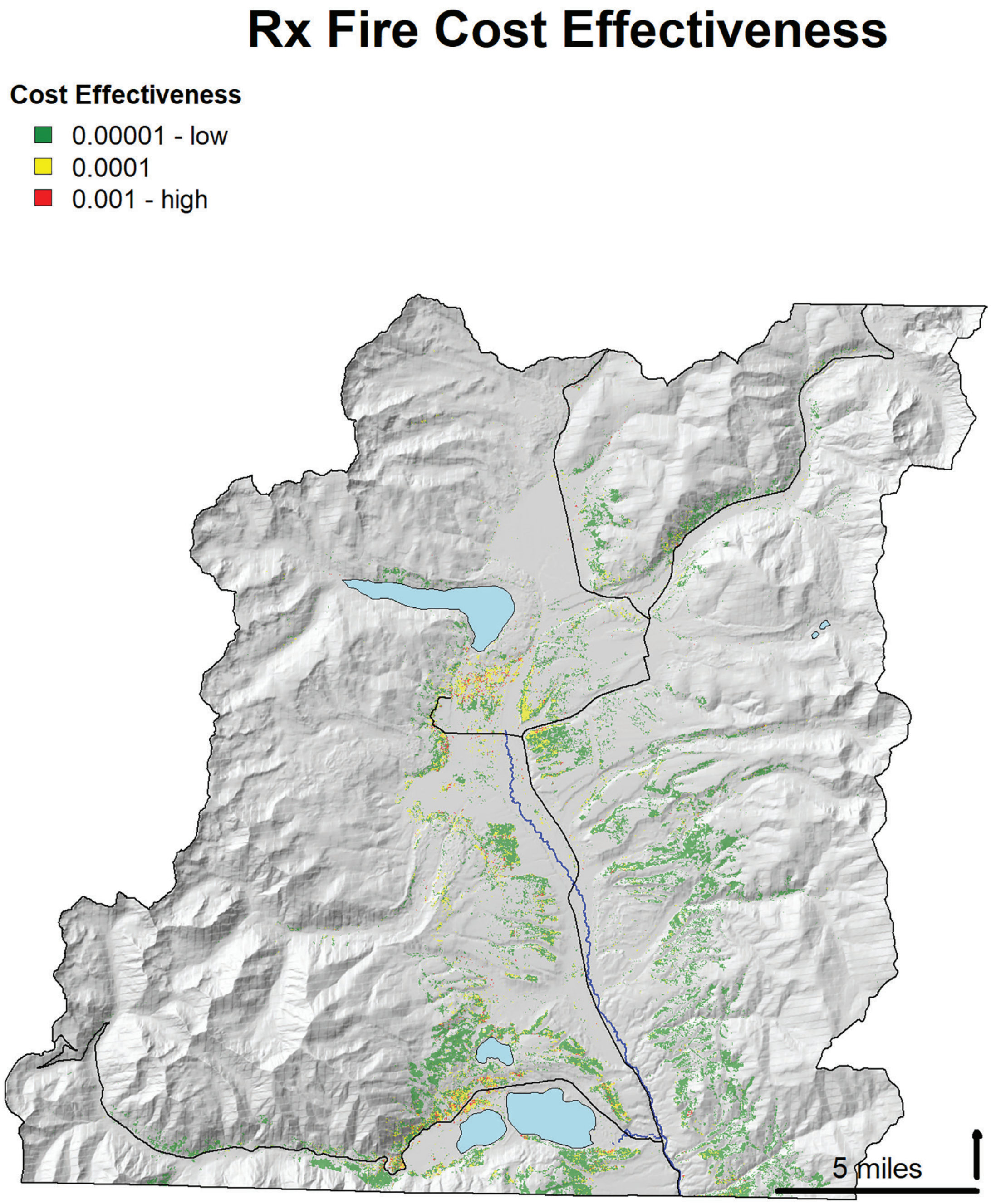


*Figure 18: Cost-effectiveness (risk reduction/treatment cost) of the prescribed fire only treatment.*

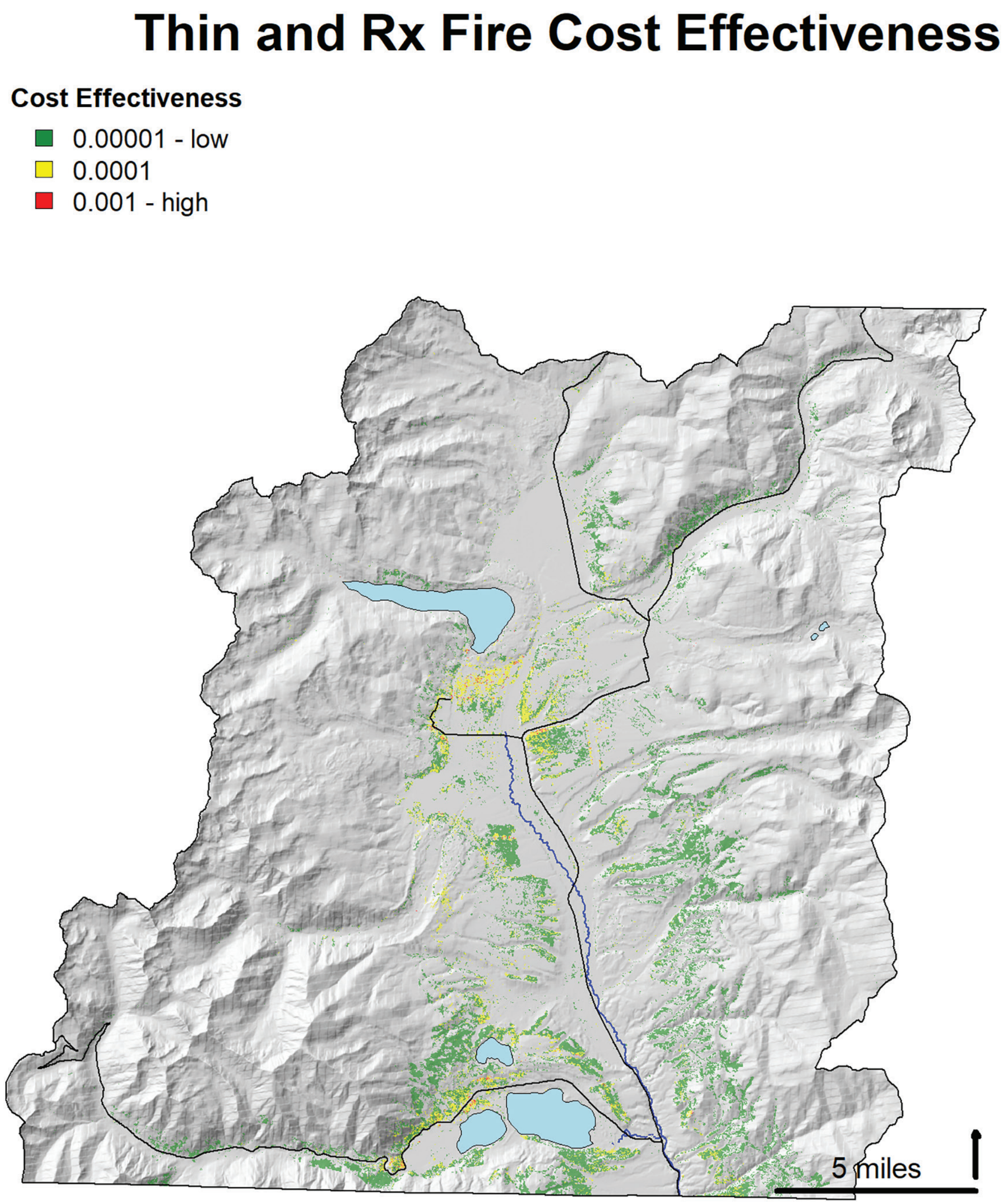


*Figure 19: Cost-effectiveness (risk reduction/treatment cost) of the complete treatment.*

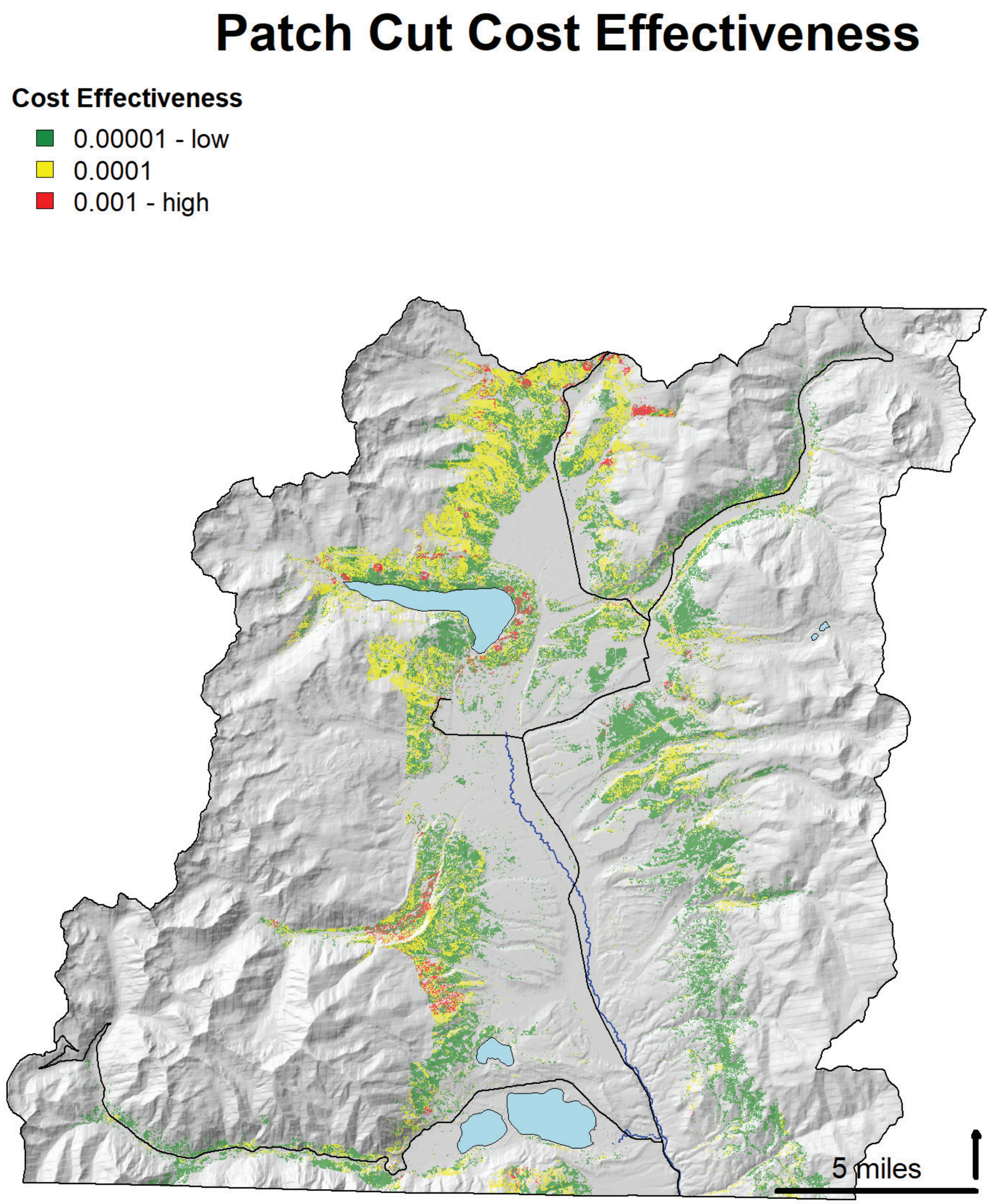


*Figure 20: Cost-effectiveness (risk reduction/treatment cost) of the patch cut treatment.*