Risk Assessment and Decision Support (RADS) Technical User Guide

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This document provides technical details on the Colorado Forest Restoration Institute Risk Assessment and Decision Support (RADS) Tool.

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INTRODUCTION

The Risk Assessment and Decision Support (RADS) Tool is a modular wildfire risk assessment and fuels reduction prioritization system. The core functions are aimed at quantifying wildfire risk to multiple highly valued resources and assets (HVRAs) and prioritizing the locations and type of fuels reduction treatments to minimize risk.

RADS assesses wildfire risk using common methods for multi-resource wildfire risk assessment that conceive of risk as the product of fire likelihood and fire consequences (Finney 2005; Scott et al. 2013; Figure 1). Fire consequences are quantified in this framework using a combination of fire modeling to characterize fire intensity with exposure and effects analyses to translate fire intensity into ecological, social, or economic net value change. Throughout the user guide and associated products, we make use of the terms *conditional* and *expected* net value change. Expected Net Value Change (eNVC) is a whole actuarial measure of risk incorporating the probability of fire occurrence. Conditional Net Value Change (cNVC) refers to the predicted change in value conditional on (or *given*) fire occurrence. It is often useful to consider both conditional and expected metrics to understand the relative contributions of likelihood and consequences to risk.

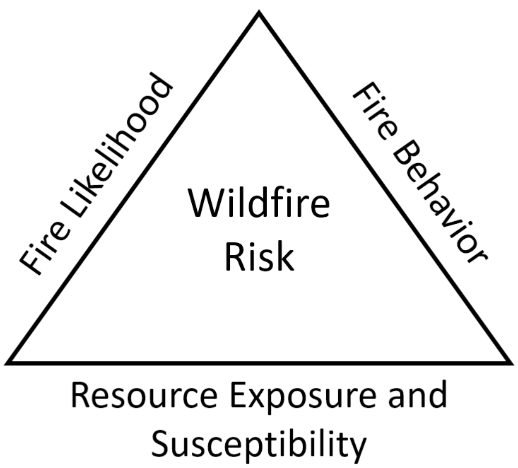


Figure 1: Wildfire risk triangle adapted from Scott et al. (2013).

Use of wildfire risk assessments in land and watershed management is now commonplace, but it is rare that these assessments go beyond characterizing baseline conditions to plan efficient mitigation programs with analysis of fuel treatment effectiveness, opportunities, and costs (but see Gannon et al. 2019 and Kreitler et al. 2020). Risk mitigation is quantified in RADS by modeling the primary effects of fuel treatments on the input fuels data to the risk assessment and differencing pre- and post-treatment estimates of risk. This approach can be used to compare the effectiveness of alternative treatment types (e.g., thinning versus prescribed fire) and to understand how treatment effectiveness differs across the landscape due to variation in biophysical conditions. Major fuel treatment constraints are quantified with spatial models of fuel treatment feasibility and cost. RADS combines spatially explicit measures of fuel treatment risk mitigation, feasibility, and cost to optimize the location and type of treatment to minimize risk using an adaptation of the model presented in Gannon et al. (2019) (Figure 2). This approach is equivalent to the recently proposed cost-effectiveness framework from Kreitler et al. (2020).

Objective: maximize risk reduction (minimize risk)

Decisions: acres to treat by location and treatment type

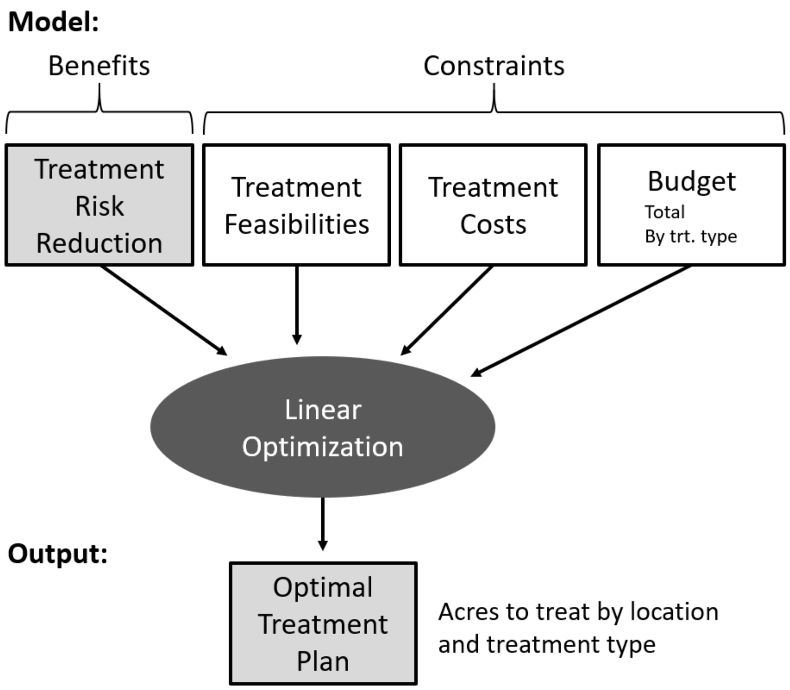


Figure 2: Conceptual diagram of RADS prioritization model.

RADS is a set of modular scripts written in the R language for statistical computing and graphics (R Core Team 2019) to progress through the wildfire risk assessment and fuel treatment planning. A very basic graphical user interface is provided to guide a user through the workflows. In combination, the system is somewhere between a script and full software. It is expected that the user will provide the required wildfire hazard components (burn probability, flame length, and crown fire activity predictions), but the RADS model also includes template scripts to update fuels treatment data and batch fire behavior predictions with FlamMap 5.0 (Finney et al. 2015) for those users able to work in R. See Appendix I for installation instructions and use limitations.

The following sections detail the use of the RADS model for wildfire risk assessment and fuel treatment planning.

RISK ASSESSMENT

RADS uses an adaptation of the wildfire risk model from the Colorado Wildfire Risk Assessment (Technosylva 2018) (Figure 3). Fire intensity is represented with two metrics modeled with FlamMap (Finney et al. 2015): flame length, which is directly related fire intensity (Byram 1959), and crown fire activity (Scott and Reinhardt 2001), which is often used as a proxy for burn severity in watershed effects analyses (e.g., Gannon et al. 2019). Variability in fire weather is incorporated by modeling fire behavior for low, moderate, high, and extreme levels of fuel moisture and wind speed. The RADS effects analysis uses common flame length-based response function methods (Scott et al. 2013; Technosylva 2018) to translate modeled flame length into cNVC within the extent of each HVRA. It also accommodates integration of alternative effects analyses if the outputs can be communicated as raster surfaces of cNVC. cNVC measures by HVRA and weather scenario are then combined with weighted averaging based on their probabilities of occurrence. The final measure of eNVC, or risk, is computed using stakeholder-defined relative importance weights by HVRA to create a composite measure of cNVC that incorporates community values (Scott et al. 2013) multiplied by a modeled surface of burn probability to represent the likelihood of encountering wildfire.

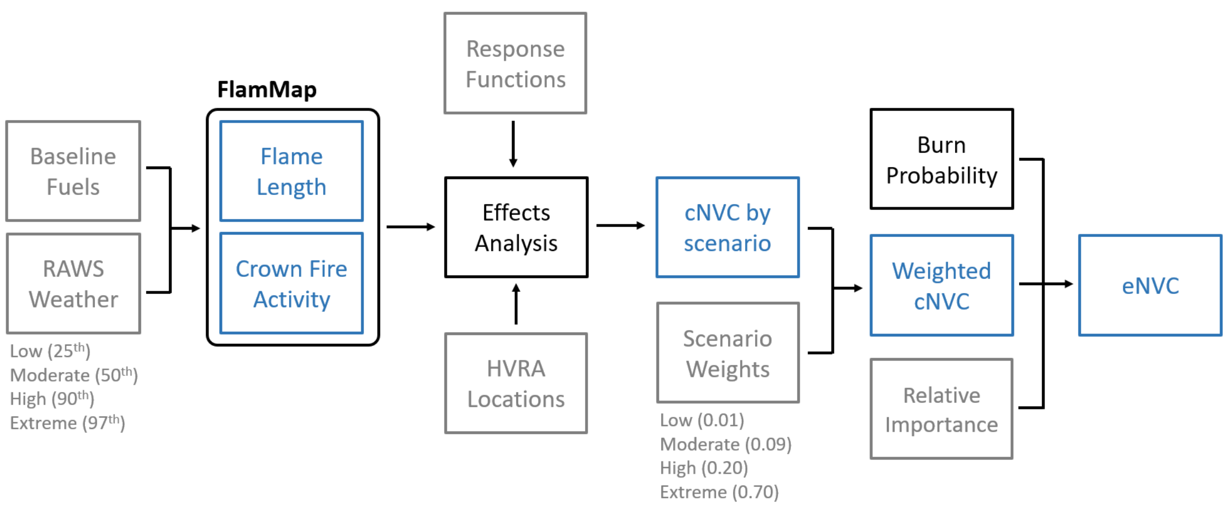


Figure 3: RADS wildfire risk assessment model.

Data preparation

The primary data inputs (Table 1) to the risk assessment portion of RADS can be separated into four categories: 1) reference spatial data, 2) fire hazard rasters, 3) HVRA spatial data, and 4) tables of response functions and relative importance weights. A file map is provided with RADS to document what the inputs should be named and how they should be placed within the file directory.

Table 1: Risk analysis input data. All spatial data should use the same coordinate reference system. All vector data should be stored in an ESRI file geodatabase named VECTOR_INPUT.gdb unless otherwise noted. All raster data should have the same spatial resolution and be snapped to a common alignment (base fuels data from LANDFIRE is a good choice).

Data type	Descriptions
Reference spatial data	Polygon feature classes of risk_analysis_extent and mapping_extent Rasters of ra_extent.tif and ma_extent.tif (inside = 1, outside = NA) Polyline feature classes of Major_roads, Major_streams, and Major_contours hillcl.tif hillshade raster clipped to the mapping extent
Fire hazard rasters	baseline_[FW SCENARIO - either 25, 50, 90, or 97]_FLAMELENGTH.tif baseline_[FW SCENARIO - either 25, 50, 90, or 97]_CROWNSTATE.tif BURNPROBABILITY.tif
HVRA spatial data	Point, polyline, or polygon feature classes in VECTOR_INPUT.gdb GeoTIFF rasters of HVRA extent ([HVRA NAME].tif) (presence = 1, absence = NA) GeoTIFF rasters of cNVC ([HVRA NAME].tif for baseline and [TREATMENT SHORT NAME]_[HVRA NAME].tif for post-treatment; note that cNVC analyses should use the same fire scenarios and weights as RADS but are not required to)
Response function and relative importance tables	HVRA_settings.csv relative_importance.csv

Reference spatial data

RADS uses several reference spatial data layers (Table 1) to communicate the risk analysis and mapping extents and to provide context to the automated maps. The risk analysis extent is used to define the area that is being planned for – only this area will be used when calculating the relative extent of HVRAs for the importance weighting (Scott et al. 2013). The mapping extent can be larger to provide context to the planning area; for example, if the analysis area is a county, it may be helpful to define the mapping extent as the county plus a 5 km buffer. Most of the risk analysis processes in RADS utilize raster calculations, so it speeds up many processes to generate raster layers of the risk analysis and mapping extents in a Geographic Information System (GIS). Raster extent inputs should be coded as 1 for within extent and NA for outside extent. Make sure your GIS codes NULL values as 0 (Some ArcGIS processes use 128 by default). RADS produces many maps to communicate intermediate results of the risk assessment process. Major road, stream, and contour layers should be provided to add context to these maps.

Fire hazard rasters

The risk assessment requires flame length rasters (in meters) for each fire scenario to complete the response function-based effects assessments (Scott et al. 2013; Technosylva 2018). Crown fire activity should also be modeled if conducting a watershed or water supply effects analysis like Gannon et al. (2019). This manual is not meant to provide training to a novice on how to assemble, critique, and summarize the required fuels and weather data for fire modeling and to critique the output. Hence, only a high-level description is provided of the recommended steps. RADS includes several pre-processing scripts to help an experienced risk analyst update fuels data to reflect recent fuel treatments, assemble fuels data into fire modeling fuelscapes, and batch FlamMap runs (see Appendix II). Additionally, RADS requires a raster surface of burn probability. None of the core processes in RADS require this to be an absolute estimate of annual burn probability, but the analyst should know that any supplementary analyses of expected area burned will be meaningless if a relative burn probability raster is provided.

For flame length and crown fire activity modeling, the recommended steps are:

1) Acquire up-to-date raster fuels and topography data from a source like LANDFIRE including elevation, slope, aspect, canopy cover, canopy height, canopy base height, canopy bulk density, and fire behavior fuel model (Scott and Burgan 2005).
2) If meaningful change has occurred on the landscape since the last fuels update, update the fuels to reflect current conditions. The provided code (Appendix II) demonstrates how to accomplish this in R. Alternatively, fuels can be updated manually with the FlamMap graphical user interface (Finney et al. 2015) or with the ArcFuels Toolbar.
3) Develop the four required fire weather scenarios using representative Remote Automated Weather Stations (RAWS) and the FireFamilyPlus software. The scenarios should include low (25^{th} percentile), moderate (50^{th}), high (90^{th}), and extreme (97^{th}) fire season fuel moisture and wind speed conditions. The necessary fuel moisture information includes the 1-hr, 10-hr, 100-hr, herbaceous, and woody fuel moistures rounded to the closest percent. A wind speed (in mph @ 20-ft) must also be specified for each scenario. The analyst can choose whether to model fire behavior using a worst-case scenario of wind blowing uphill or to specify a single wind direction with or without modeling terrain influenced winds.
4) Use FlamMap to calculate flame length (and crown fire activity if required) with the basic fire behavior module. The provided code (described further in Appendix II) demonstrates how to batch this process for any number of fuelscapes and weather scenarios. The baseline modeling for the risk assessment should be labeled as “baseline” underscore “percentile” underscore “fire behavior type” with options of “FLAMELENGTH” or “CROWNSTATE” (e.g., “baseline_25_FLAMELENGTH.tif”).

Burn probability modeling can be accomplished with a variety of simulation tools. See Miller and Ager (2013) and Parisien et al. (2019) for a review of common processes and discussion of model limitations. If custom burn probability modeling is beyond the scope of the assessment, it may be possible to use the national burn probability product from FSim (Finney et al. 2011; Short et al. 2020) or from a state wildfire risk assessment portal (e.g., CO-WRAP). Take care to critique these products, modify them as necessary, and resample them to match the extent, cell size, and alignment of the other fire behavior products.

HVRA spatial data

There are three ways to input spatial data into RADS: 1) vector feature classes of points, polylines, or polygons, 2) binary HVRA extent rasters, and 3) modeled cNVC rasters.

Vector features classes can be named and organized as desired within the VECTOR_INPUT.gdb located in scripts/INPUT/Spatial. The feature classes should use the same coordinate system and spatial projection as the reference data and fire modeling. The feature classes can be organized in feature datasets if desired. The names will be specified in a later table. The spatial packages in R are based on open-source GIS tools that have stricter vector geometry rules than are enforced by ESRI GIS products. This occasionally leads to issues when loading in data. Common solutions for errors include:

1) Using the "repair geometry" tool in ArcGIS on the offending feature class.
2) Buffering the offending feature class by a small distance (e.g., 0.1-m).
3) Converting multi-part features to single-part features.

If these solutions fail, you can convert the feature class into a binary raster surface.

The second option is to provide the HVRA extent as a binary raster. Raster values should be coded as 1 for the HVRA extent and NA for outside the HVRA extent. Make sure your GIS codes NULL values as 0 (Some ArcGIS processes use 128 by default). The extent, cell size, and alignment should match the fire behavior rasters.

The final option is to provide a cNVC raster in place of an HVRA extent. This option allows the analyst to use an alternative effects analysis (e.g., a quantitative model in place of the flame length-based response function). Keep in mind that that alternative cNVC modeling should adhere to several standards for proper integration with the other HVRAs:

1) Values should range from -100 for total loss to +100 for radical gain.
2) The model should ideally be run for each of the four fire weather scenarios and combined through weighted averaging (Figure 3). If it is not practical to run the model at each level, choose the high or extreme scenario, because these are assigned the highest weights to reflect that most area burns under these conditions.
3) Areas outside the extent of the HVRA should be assigned a NULL value.
4) As with other raster inputs, the extent, cell size, and alignment should match the fire behavior rasters.
5) The baseline name is specified in the HVRA settings table ([HVRA_name].tif). If using RADS for treatment prioritization, the post-treatment cNVC estimates must share the same name, but with the treatment name as a prefix ([TREATMENT SHORT NAME]_[HVRA NAME].tif). The treatment short name should match the FB_Code field in Table 7.

The HVRAs to consider in the assessment are communicated to RADS in a settings table, a portion of which is shown in Table 2. Each HVRA is described with a row in the table. The layer field is a numerical code for labeling intermediate products. HVRA contains the name for use in output maps and tables. Each HVRA is assigned to a category. Relative importance values are assigned by HVRA category in a later table. In this table, the RI_HVRA field is used to designate the relative importance of each HVRA to the category. For example, low and high density WUI are both assigned 50% of the category importance. This value should sum to 100% for each category. The name of the input feature class or raster is specified in the FeatureClass field. Include file extensions for rasters. Data type is communicated in the Type field; acceptable values include "Point", "Polyline", "Polygon", and "Raster". All the HVRAs in the example represent HVRA locations ("Location"), but this field should be set to "cNVC" when using a cNVC raster from an external analysis. A buffer distance in meters must be specified for point and polyline feature classes to represent the zone of fire influence (Buffer_m field) and it is optional for polygon feature classes. The Include field is used as a switch to include (1) or exclude (0) an HVRA from the assessment without deleting its data from the table.

Table 2: HVRA specifications portion of the HVRA_settings.csv table.

Layer	HVRA	Category	RI_HVRA	FeatureClass	Type	Represents	Buffer_m	Include
1	Low density WUI	WUI	50	WUI_low_density.tif	Raster	Location	0	1
2	High density WUI	WUI	50	WUI_high_density.tif	Raster	Location	0	1
3	Power transmission	Infrastructure	50	Electric_Power_Transmission_Lines	Polyline	Location	200	1
4	Communication	Infrastructure	50	Communication_points	Point	Location	200	1

Response function and relative importance tables

To calculate cNVC, each HVRA represented by an extent feature class or binary extent raster needs a quantitative response function translating flame length into net value change (Scott et al. 2013; Technosylva 2018). The convention in RADS is to code a total loss as -100, no impact as 0, and a radical improvement as +100. Any continuous value between -100 and +100 is acceptable, although it rarely makes sense to assign cNVC in increments of less than 5 or 10 units. Example response functions for four HVRAs are presented in Table 3.

Table 3: Response function portion of the HVRA_settings.csv table. Fire intensity levels are as described in Scott et al. (2013): FIL1 = 0-2 ft, FIL2 = 2-4 ft, FIL3 = 2-6 ft, FIL4 = 6-8 ft, FIL5 = 8-12 ft, FIL6 = > 12 ft.

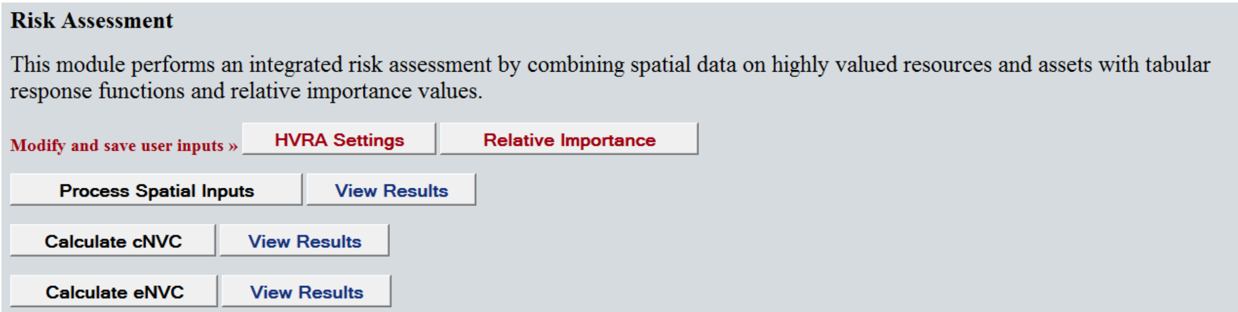
HVRA	FIL1	FIL2	FIL3	FIL4	FIL5	FIL6
Low density WUI	-20	-40	-80	-100	-100	-100
High density WUI	-40	-80	-100	-100	-100	-100
Power transmission	0	0	0	-30	-40	-40
Communication	0	0	0	-30	-100	-100

As previously mentioned, there are two layers of relative importance weights in RADS. The first, apportions a value of 100% among the HVRAs in a category (Table 2). The second, assigns a weight to each category for the final composite (Table 4). Any positive value is accepted, but it is suggested to assign a score of 100 to the most important category and then to assign weights to the remaining categories based on their relative importance to the most important category.

Table 4: Relative importance table (relative_importance.csv).

Category	RI
WUI	100
Infrastructure	80

Running the model



After inputs are assembled, the model is run in three phases: 1) process spatial inputs, 2) calculate cNVC, and 3) calculate eNVC.

The ***Process Spatial Inputs*** module reads in the vector and raster data specified in the HVRA settings table and creates a standardized binary extent raster for each HVRA regardless of input data type. During this process, the model will also calculate the area of the HVRA for later use in the eNVC weighting. As previously mentioned, there is potential for errors in this phase if vector input data do not meet open source GIS data standards. If an error is encountered, try the troubleshooting tips presented in the previous section. The module also creates a simple map book (in PDF format) so the analyst can confirm that input data are correct (Figure 4). It may also be helpful to share with stakeholders who do not have GIS skills or software. The view results button can be used to access the HVRA extent rasters for viewing in GIS.

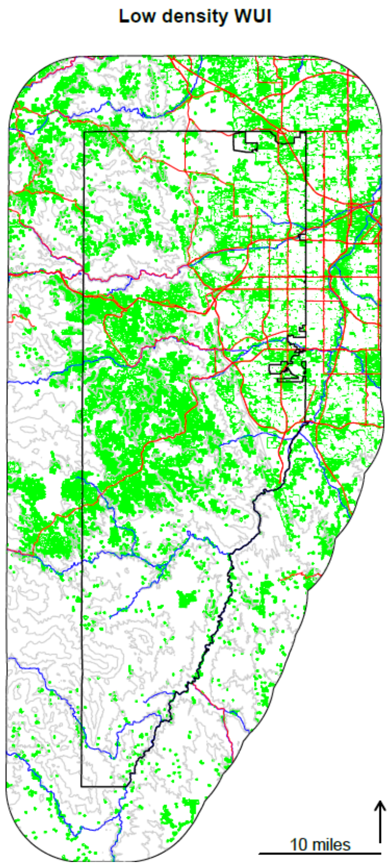


Figure 4: Example of HVRA extent map for low density WUI (green) with roads (red), streams (blue), contours (grey), and the risk analysis extent (black).

The ***Calculate cNVC*** module applies the response functions from the HVRA settings table (Table 3) to the predicted flame lengths, within the extent of each HVRA, by fire weather scenario, and then outputs the weighted average cNVC. Alternatively, it will simply copy the provided cNVC raster when using the represents "cNVC" option. A basic map will be created for each HVRA to facilitate the critique of outputs (Figure 5). It will display the quantitative response function only if that method is used.

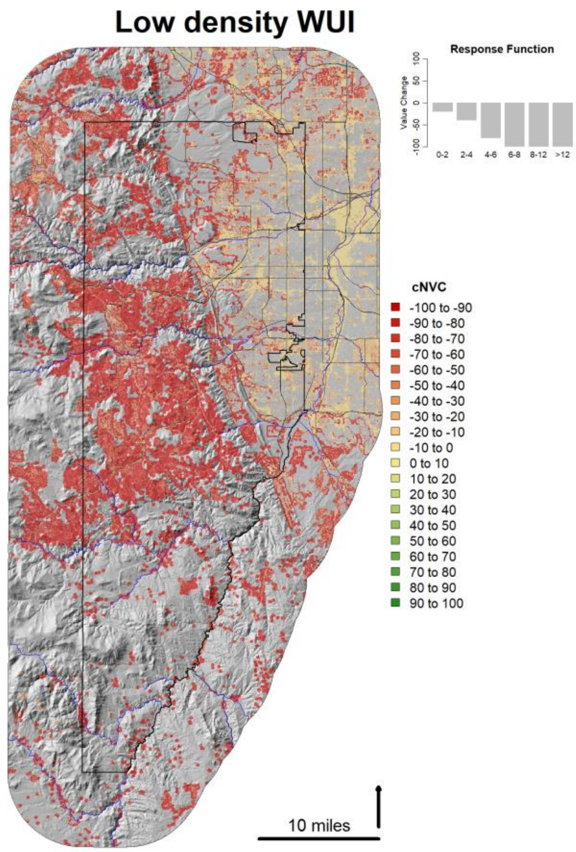


Figure 5: Example of cNVC map for the low density WUI HVRA.

The ***Calculate eNVC*** module composites the HVRA level cNVC rasters and then multiplies by burn probability to calculate eNVC. This is accomplished in three stages. In the first stage, the HVRA and category relative importance weights are combined. Table 5 presents an example to complement the following text. The HVRA relative importance weights are normalized to sum to one by category and then the category relative importance weights are normalized to sum to one. The HVRA and category relative importance weights are multiplied together to calculate the combined relative importance for each HVRA, which can range between zero and one. Then, the combined relative importance is divided by the HVRA relative extent (area of HVRA divided by total area of all HVRAs) for the final weighting to composite cNVC. This weighting scheme controls for the area of the HVRA, so as not to let extensive but low importance HVRA dominate the risk assessment (Scott et al. 2013). In the second stage, the cNVC rasters are then composited, first by category, and then across categories. The composite cNVC raster is output for comparing with eNVC. In the third stage, the category and composite cNVC rasters are multiplied by burn probability to calculate eNVC. Category and composite eNVC rasters are output for subsequent analyses. Basic maps will be created to facilitate the critique of the composite cNVC, composite eNVC, and eNVC by category (Figure 6).

Table 5: Example relative importance (RI) and relative extent (RE) calculations for the eNVC weighting.

HVRA	Category	HVRA RI	Category RI	Combined RI	Area (ac)	RE	RI/RE
Low density WUI	WUI	0.5	0.56	0.28	186,139	0.701	0.1947
High density WUI	WUI	0.5	0.56	0.28	50,877	0.192	0.0532
Power transmission	Infrastructure	0.5	0.44	0.22	23,779	0.090	0.0199
Communication	Infrastructure	0.5	0.44	0.22	4,736	0.018	0.0040

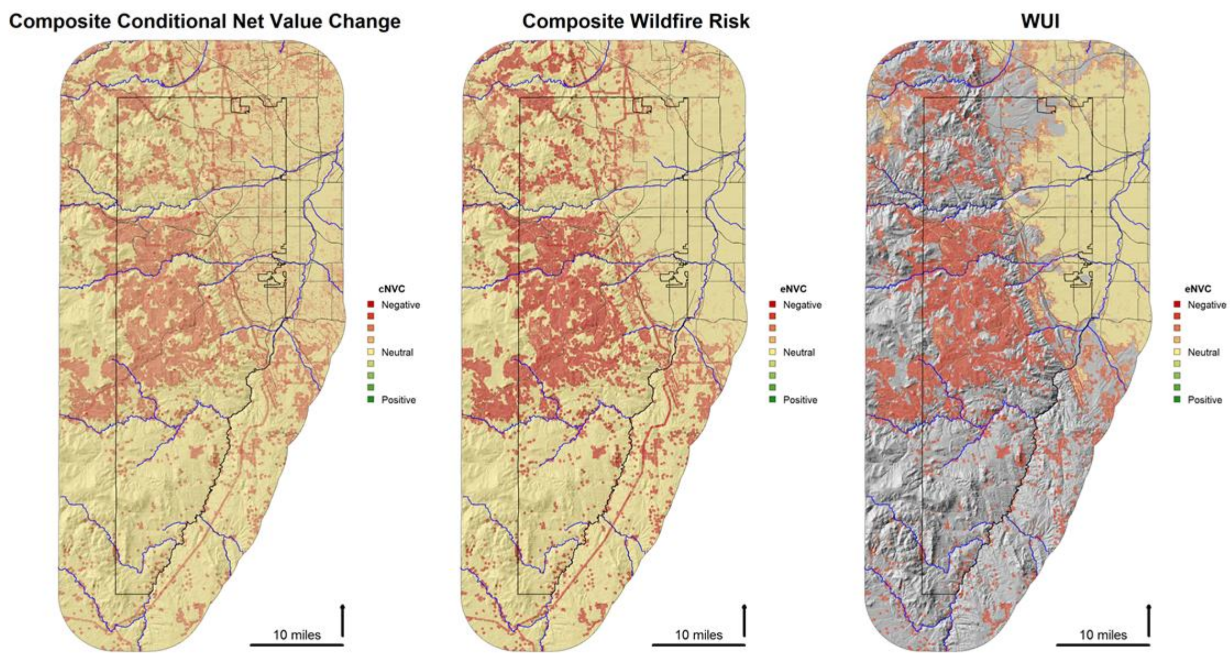


Figure 6: Examples of composite cNVC (left), composite eNVC (center), and a category eNVC (right). Note that category-level eNVC will only display a value where there is an HVRA present.

Working with GIS data

The outputs all share a similar structure with any graphical or tabular output stored in parent directory and any GIS files stored in the GIS sub-folder (Figure 7). You can either click on the "View Results" link or navigate to the appropriate output directory. All raster output is in GeoTIFF format with the same spatial reference and projection as the input data. GIS files will be named only with the layer number from the HVRA settings table (Table 2).

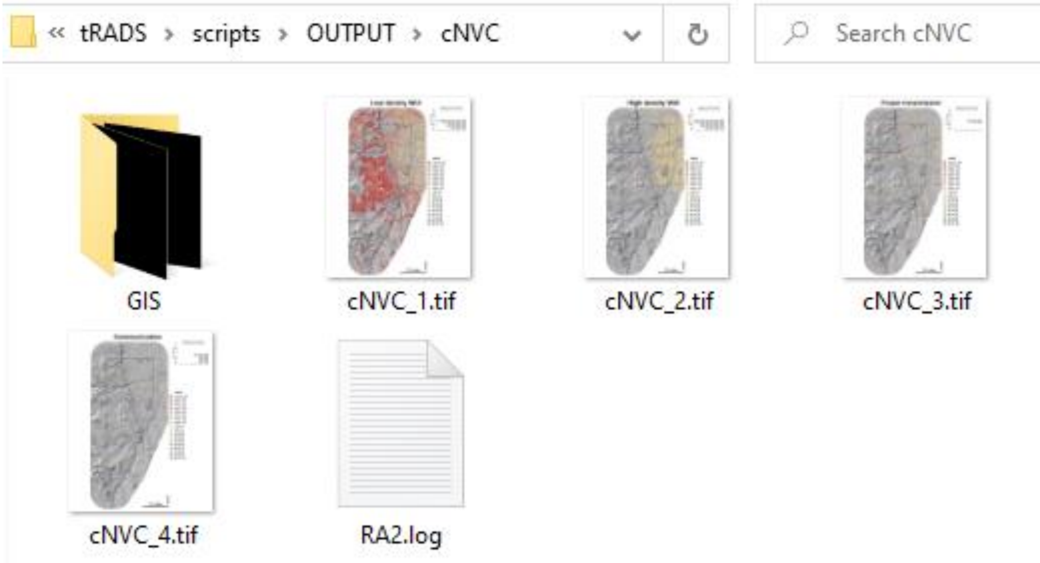


Figure 7: Example output directory structure showing map and log files in the parent and GIS data files in the GIS sub-directory.

FUEL TREATMENT PLANNING

The fuel treatment planning capabilities of RADS are aimed at informing near-term decisions about fuel treatment type and location across large landscapes based on cost-effectiveness. A simplified diagram of the workflow is provided in Figure 8. Effectiveness is evaluated in terms of risk reduction by differencing baseline risk and simulated post-treatment risk for each candidate treatment. Risk reduction will vary across treatment types due to differences in their effects on fuels and it will vary spatially due to differences in baseline fuel conditions and topography. Cost is provided to the model as a raster surface that can be as simple or complicated as the analyst desires. Treatment feasibility is provided to the model as a binary raster surface developed by the analyst. The structure of RADS assumes that treatment feasibility can vary across treatment types and within treatment units. Within each treatment unit, only the feasible area for treatment will be used to estimate the average risk reduction and treatment cost. The model allows multiple treatment types to be assigned to the same treatment unit so long as they do not overlap. The treatment type and unit options are sorted with a linear optimization to identify the most cost-effective treatment plan for a specified budget.

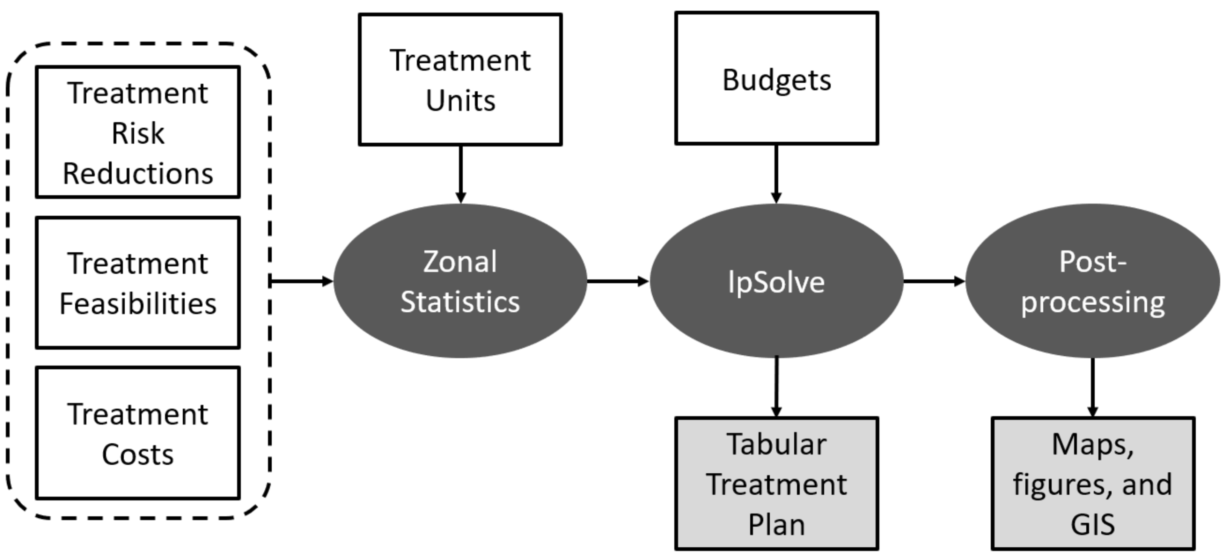


Figure 8: Simplified workflow of the RADS fuel treatment planning module. Input rasters on treatment risk reduction, feasibility, and cost are combined with spatial treatment unit and budget information to summarize the cost effectiveness of each treatment type in each unit. This information is then used to parameterize and solve a linear optimization model with lpSolve for the provided budget to identify the optimal area to treat in each location with each treatment type. The treatment plan and several intermediate products of the analysis are then post-processed to communicate treatment priorities and benefits.

Linear Optimization Model

Objective function:

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

Constraints:

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

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

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

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

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

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 (USD)

$RR_{i,t}$ is the risk reduction (USD ac^{-1}) for 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 (USD ac^{-1}) of applying treatment *t* in treatment unit *i*

Budget is the funding available for fuel treatment (USD)

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.

Data Preparation

Fuel treatment planning requires that a baseline risk assessment has been run using RADS, so all data detailed in Table 1 is assumed present. The additional data needed to run the fuel treatment planning model is presented in Table 6.

Table 6: Additional input data required for fuel treatment planning. All raster data should have the same spatial resolution and be snapped to a common alignment (base fuels data from LANDFIRE is a good choice).

Data type	Descriptions
Treatment units	Polygon shapefile of treatment_units.shp with integer unique identifier field (UID) Raster of raster_treatment_units.shp (inside = UID, outside = NA)
Post-treatment fire hazard rasters	[TRT CODE]_[FW SCENARIO - either 25, 50, 90, or 97]_FLAMELENGTH.tif [TRT CODE]_[FW SCENARIO - either 25, 50, 90, or 97]_CROWNSTATE.tif
Risk rasters	Total_eNVC.tif (generated by Wildfire Risk Assessment) [TRT CODE]_eNVC.tif (generated in the first step of Fuel Treatment Planning
Cost rasters	GeoTIFF rasters of cost ([ANY NAME].tif) (units of USD per ac)
Feasibility rasters	GeoTIFF rasters of feasibility ([ANY NAME].tif) (feasible = 1, infeasible = 0)

Treatment units

The size and spatial configuration of the candidate treatment units are up to the analyst, but it is recommended that the treatment units are at minimum 10 ha in size and no less than 60-m wide to make robust estimates of treatment benefits and constraints. Treatment units are communicated to the model in shapefile and raster formats as described in Table 6. The shapefile must have an integer unique identifier field (UID). The analyst should convert the treatment units into GeoTIFF raster format using their GIS program of choice, taking care to make sure the spatial coordinate system, resolution, and alignment matches the rest of the input data.

Post-treatment fire hazard rasters

To estimate change in risk with treatment, the first step in fuel treatment planning is to estimate post-treatment risk. The analyst is responsible for modeling post-treatment flame length and crown fire activity for each candidate treatment and fire weather scenario (Table 6). Each raster should be tagged with its treatment type using a short code. This short code will be specified in a table and used to tag treatment specific outputs. R code to automate the fuels adjustments, assemble the fire modeling fuelscapes, and run FlamMap for each scenario is described further in Appendix II. The most important choices in this process are how to simulate treatment effects on the baseline fuels to accurately portray the subsequent effects on fire hazard components and risk. This manual is not meant to serve as a reference on fuel treatment effects, but Appendix II describes the technical process of simulating thinning, prescribed fire, and combined treatments in forests of Colorado that may be relevant for other geographies.

Risk rasters

The final composite eNVC raster from the risk assessment is carried forward into fuel treatment planning as the baseline measure of risk. The first step of fuel treatment planning will be to re-run the risk assessment for each candidate fuel treatment. The post-treatment risk is subtracted from the baseline risk to estimate risk reduction in the model (see Figure 9 for an example).

Cost rasters

It is recommended that the analyst represent how treatment cost varies across the landscape due to controls like accessibility, operability, and need for biomass removal (see Figure 9 for an example). This manual is not meant to serve as a reference on fuel treatment costs, but Appendix II describes one way to estimate thinning costs as a function of accessibility and operability that is roughly calibrated to treatment costs in Northern Colorado. The analyst can provide a spatially uniform cost raster, if desired. The units must be USD per ac.

Feasibility rasters

Hard constraints on treatment are communicated with binary feasibility rasters (1 = feasible, 0 = infeasible) by treatment type to mask out areas of the landscape that are not amenable to treatment (see Figure 9 for an example). Generally, hard constraints should capture restrictions on treatment due to land designations (wilderness, roadless, etc.) and whether there are fuels that can be treated with a given treatment type. Constraints related to cost should ideally be incorporated into the cost rasters to reflect that treatment is still possible but more expensive. Code described in Appendix II is provided as a template for mapping feasibility.

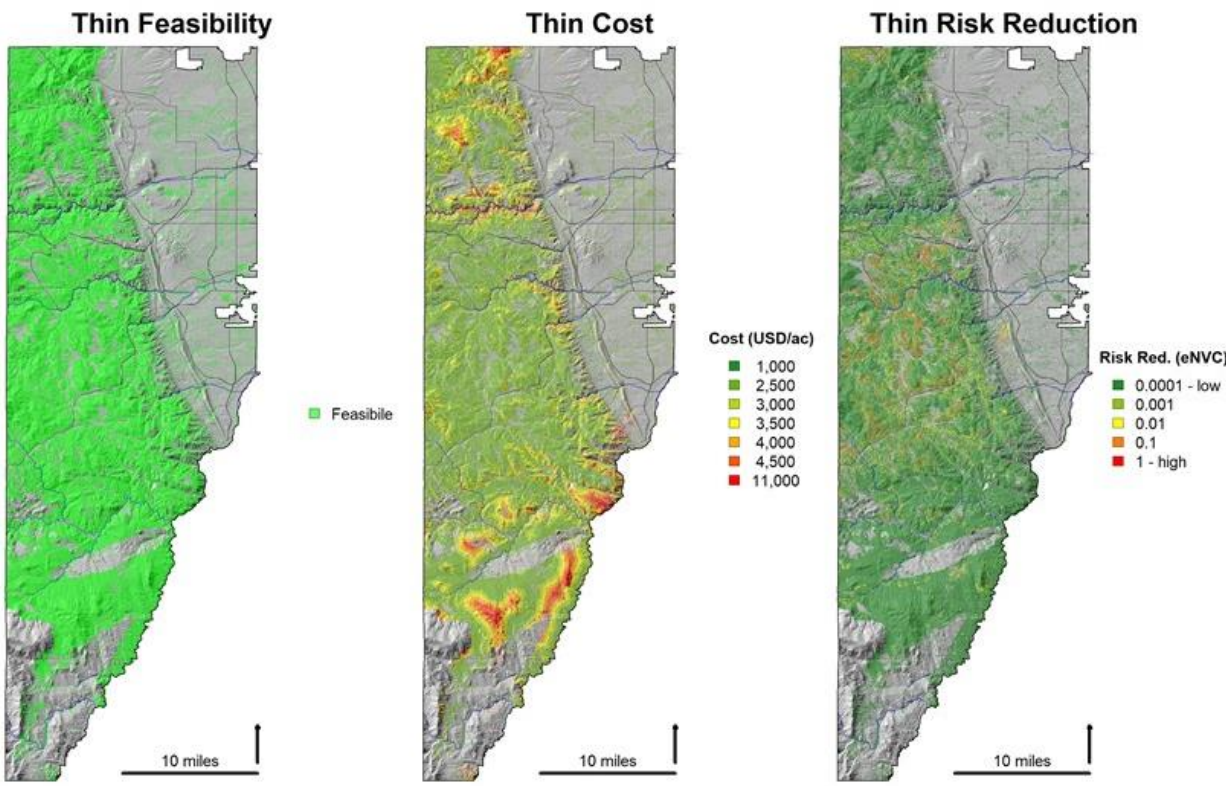
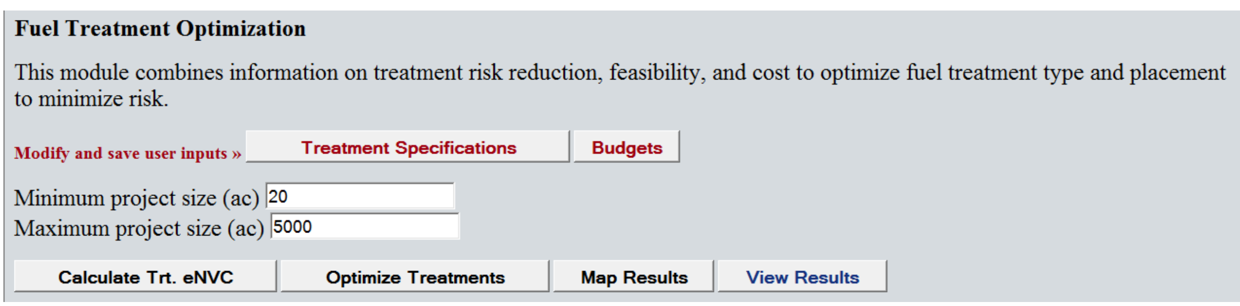


Figure 9: Example feasibility, cost, and risk reduction rasters for a thinning treatment across a diverse landscape.

Running the model



After inputs are assembled, the model is run in three phases: 1) calculate post-treatment eNVC, 2) optimize treatments, and 3) optional mapping of results.

Beyond assembling the required raster inputs (Table 6), the only controls to the model are treatment specifications and budget tables and minimum and maximum project size constraints. The treatment specifications table (Table 7) is used to describe the relevant data for each treatment type in the model. Rows can be added or subtracted to accommodate different treatments. The columns are used to specify the relevant input data related to fire hazard components (FB_Code), cost estimates (T_Cost), and feasibility (T_Feas). The maximum budget proportion field is used to constrain how much of the budget is spent on a treatment type to temper unrealistic plans. Minimum and maximum treatment unit project size constraints are entered in the graphical user interface. The default values are 20 and 5,000 acres. The budgets table (Table 8) is used to communicate the budget(s) to run the model at, which are translated into qualitative priority levels.

Table 7: The treatment specifications table is used to describe the input data for each treatment type. Treatment = name of treatment. FB_Code = short name for treatment used to tag fire hazard raster inputs and eNVC outputs. T_Cost = name of treatment cost raster. T_Feas = name of treatment feasibility raster. MaxBudgetProp = optional constraint on how much of the budget can be allocated to a given treatment (in proportion).

Treatment	FB_Code	T_Cost	T_Feas	MaxBudgetProp
Thin	thin	mocost.tif	mofeas.tif	1
Rx fire	RxFire	Rxcost.tif	Rxfeas.tif	1
Complete	comp	mRxcost.tif	mofeas.tif	1

Table 8: The budgets table is used to communicate the budget(s) to run the model at. For prioritization, it is recommended to use multiple budgets and assign them qualitative names. Lower budget = higher priority.

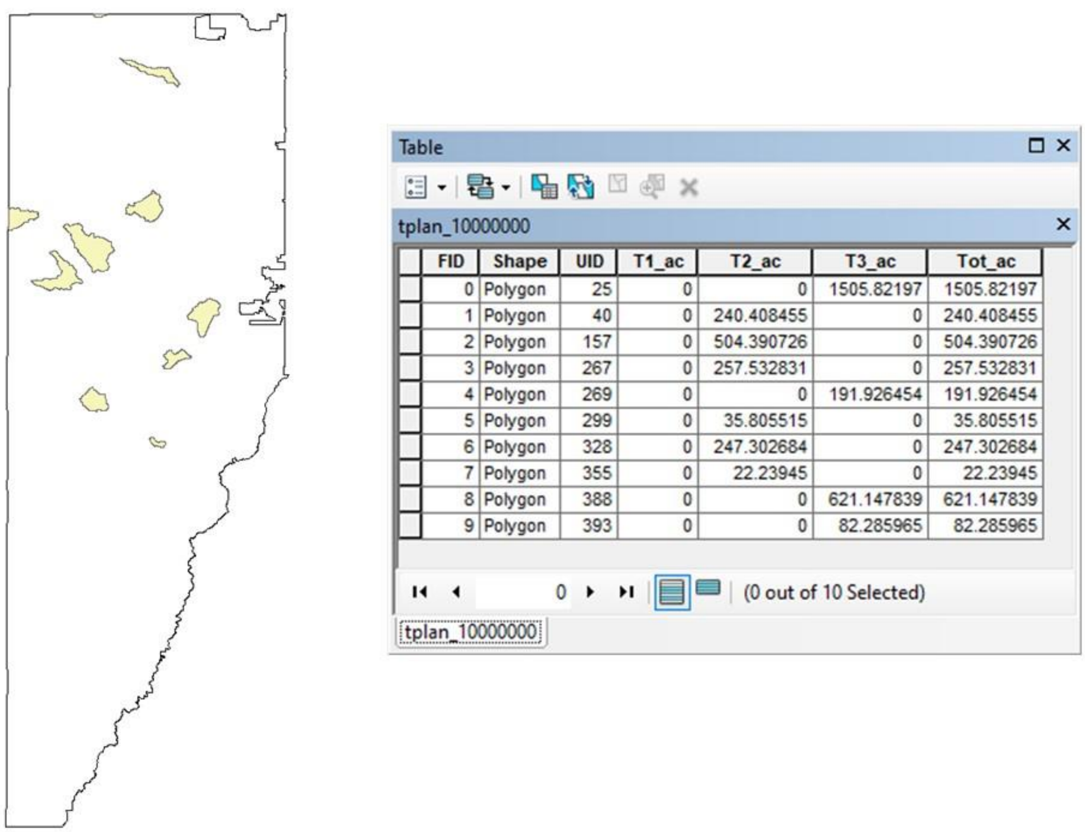
Budget	Priority
10000000	Highest
50000000	Higher
100000000	High

The ***Calculate Trt. eNVC*** module repeats the risk assessment for each treatment type described in the treatment specifications table (Table 7). No maps are produced during this process, but the output rasters are available for viewing in scripts/OUTPUT/PT_eNVC directory. The treatments are labeled with the same short code used to tag the fire hazard component inputs (Table 7).

The ***Optimize Treatments*** module performs the bulk of the analysis. It reads in all the raster input on post-treatment risk, treatment cost, and treatment feasibility. It then calculates risk reduction for each treatment type. Zonal statistics are then used to summarize the mean risk reduction and mean treatment cost within the feasible area for each treatment type and treatment unit combination. The linear program is then defined and parameterized for solving with the *lpSolveAPI* package (lp_solve and Kjell Konis 2016). The program is solved to identify the optimal treatment type area by location for each provided budget level. The results are output as a tabular treatment plan for each budget level (Table 9), a shapefile treatment plan for each budget (Figure 10), and a summary table reporting the total risk reduction and treatment area by type for each budget (Table 10). To provide the user with a sense of how the provided budget levels compare to the full range of possible options, the model is run at 100 budget levels incremented between zero and the cost of treating the full feasible area with the most expensive treatment type. The avoided risk and treatment area allocation by type are graphed as a function of budget (Figure 11). A shapefile summarizing treatment priority is also created by tagging each selected unit for treatment with the lowest budget level it was selected at (Figure 12).

Table 9: Example treatment plan table for a specific budget filtered to the treatment unit and type combinations selected for treatment. UID = treatment unit unique identifier. TotFeasAcre = total feasible acres for treatment in unit with any treatment type. FeasAcre = feasible acres for the selected treatment type in the unit. RedPerAcre = mean risk reduction (eNVC per acre) within the feasible area for that treatment type. CostPerAcre = mean treatment cost (USD per acre) within the feasible area for that treatment type. TrtType = numerical treatment code corresponding to the row number in Table 7. Acres = selected area for treatment.

UID	TotFeasAcre	FeasAcre	RedPerAcre	CostPerAcre	TrtType	Acres
40	929	240	0.031	1,000	2	240
157	2,728	504	0.029	1,000	2	504
267	364	258	0.022	1,000	2	258
299	241	36	0.018	1,000	2	36
328	990	247	0.019	1,000	2	247
355	51	22	0.040	1,000	2	22
25	1,648	1,644	0.063	3,534	3	1,506
269	192	192	0.198	3,516	3	192
388	657	621	0.114	3,614	3	621
393	83	82	0.101	5,486	3	82



FID	Shape	UID	T1_ac	T2_ac	T3_ac	Tot_ac
0	Polygon	25	0	0	1505.82197	1505.82197
1	Polygon	40	0	240.408455	0	240.408455
2	Polygon	157	0	504.390726	0	504.390726
3	Polygon	267	0	257.532831	0	257.532831
4	Polygon	269	0	0	191.926454	191.926454
5	Polygon	299	0	35.805515	0	35.805515
6	Polygon	328	0	247.302684	0	247.302684
7	Polygon	355	0	22.23945	0	22.23945
8	Polygon	388	0	0	621.147839	621.147839
9	Polygon	393	0	0	82.285965	82.285965

Figure 10: Example treatment plan shapefile for a specific budget. UID = treatment unit unique identifier. T[X]_ac = allocated acres to treatment type X. Tot_ac = combined acres treated in unit across treatment types.

Table 10: Example budget summary table. Budget = input budget in USD. ObjVal = total risk reduction (eNVC) for optimal treatment plan. T[X]_acres = acres allocated to treatment type X. T[X]_USD = budget (USD) allocated to treatment type X. PerRR = percent risk reduction calculated compared to the total risk.

Budget	ObjVal	T1_acres	T1_USD	T2_acres	T2_USD	T3_acres	T3_USD	PerRR
10000000	245	0	0	1,308	1,307,680	2,401	8,692,320	0.44
50000000	820	0	0	2,820	2,819,962	13,272	47,180,038	1.49
100000000	1,348	0	0	4,912	4,911,583	26,702	95,080,856	2.44

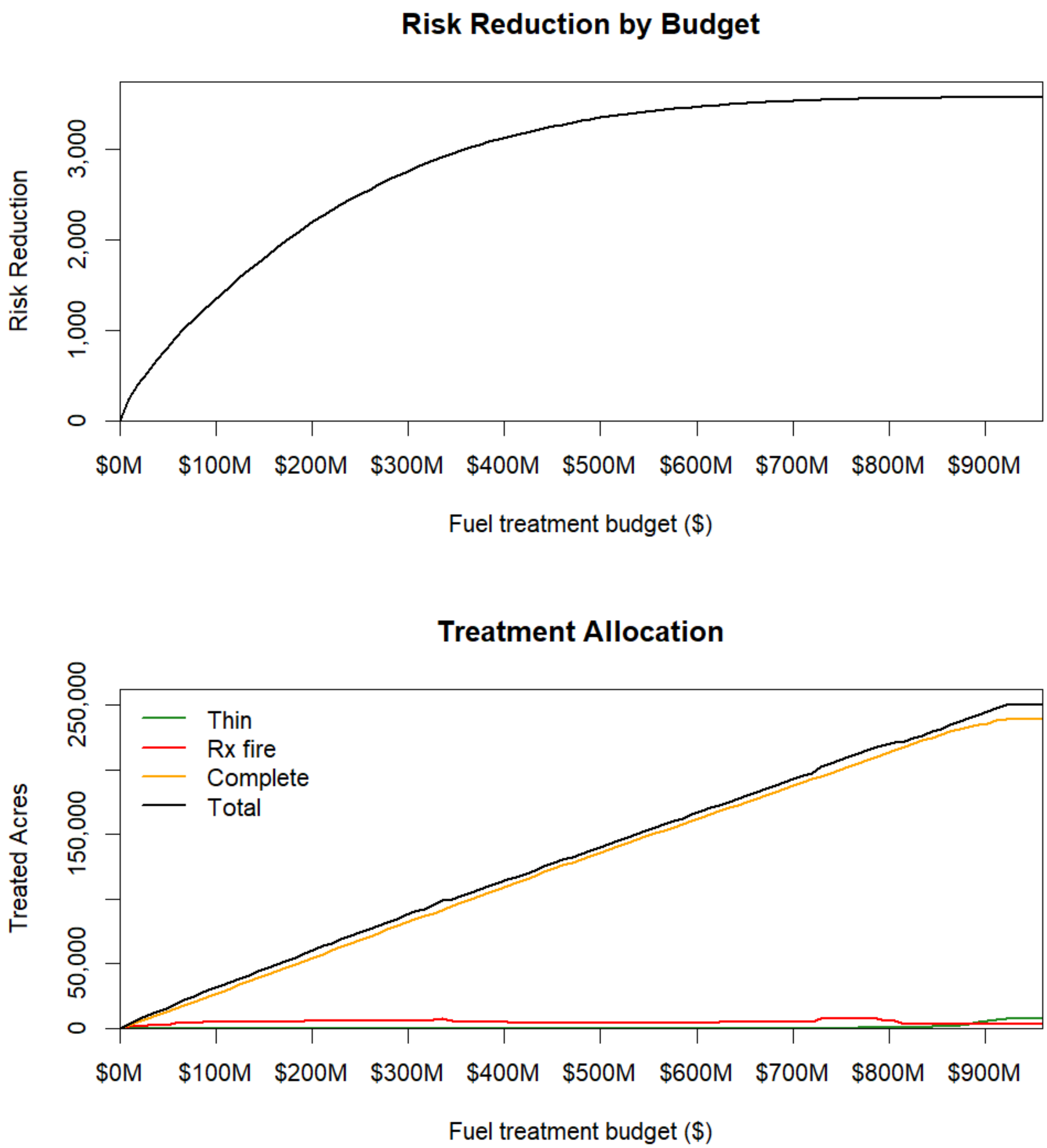
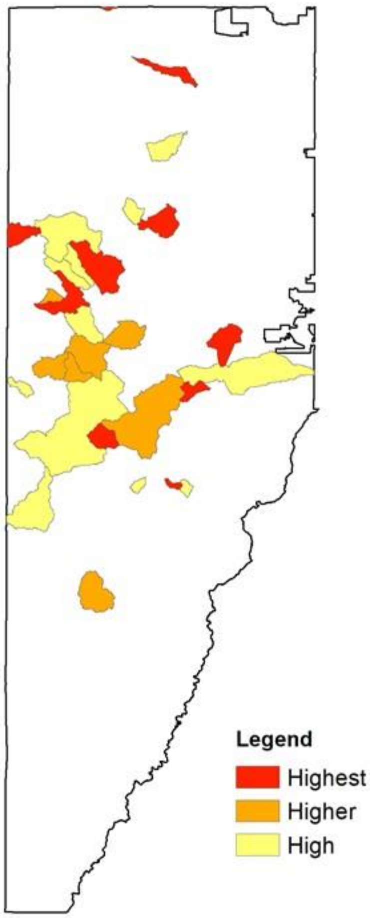


Figure 11: Example avoided impact analysis showing how much risk reduction can be achieved across the possible range of budgets (top panel) and how the treatment is allocated across treatment types (bottom panel).



Table

treatment_priority

FID	Shape	PCode	UID	Budget	Priority
0	Polygon	2	11	50000000	Higher
1	Polygon	2	15	50000000	Higher
2	Polygon	3	17	100000000	High
3	Polygon	1	25	10000000	Highest
4	Polygon	3	28	100000000	High
5	Polygon	3	29	100000000	High
6	Polygon	1	40	10000000	Highest
7	Polygon	3	49	100000000	High
8	Polygon	2	65	50000000	Higher
9	Polygon	2	69	50000000	Higher
10	Polygon	3	113	100000000	High
11	Polygon	3	115	100000000	High
12	Polygon	2	155	50000000	Higher
13	Polygon	3	156	100000000	High
14	Polygon	1	157	10000000	Highest
15	Polygon	3	174	100000000	High
16	Polygon	3	196	100000000	High
17	Polygon	2	209	50000000	Higher
18	Polygon	2	220	50000000	Higher
19	Polygon	1	267	10000000	Highest
20	Polygon	1	269	10000000	Highest
21	Polygon	1	299	10000000	Highest
22	Polygon	1	328	10000000	Highest
23	Polygon	3	332	100000000	High
24	Polygon	1	355	10000000	Highest
25	Polygon	3	360	100000000	High
26	Polygon	3	362	100000000	High
27	Polygon	1	388	10000000	Highest
28	Polygon	1	393	10000000	Highest

0 (0 out of 29 Selected)

treatment_priority

Figure 12: Example treatment priority shapefile. Each treatment unit is attributed with the lowest budget level it was selected at and the associated qualitative priority level.

The ***Map Results*** module creates optional map products to communicate the model process and results (Figure 12). This includes maps of treatment feasibility, cost, risk reduction, and cost-effectiveness (risk reduction/treatment cost) for each treatment type. Maps are also provided of the optimal treatment plans by budget level and the resulting treatment priority map. The components of a Google Earth kmz file are also provided (png and kml). To work in Google Earth, the analyst must manually zip the two component files and change the resulting zip file extension to kmz.

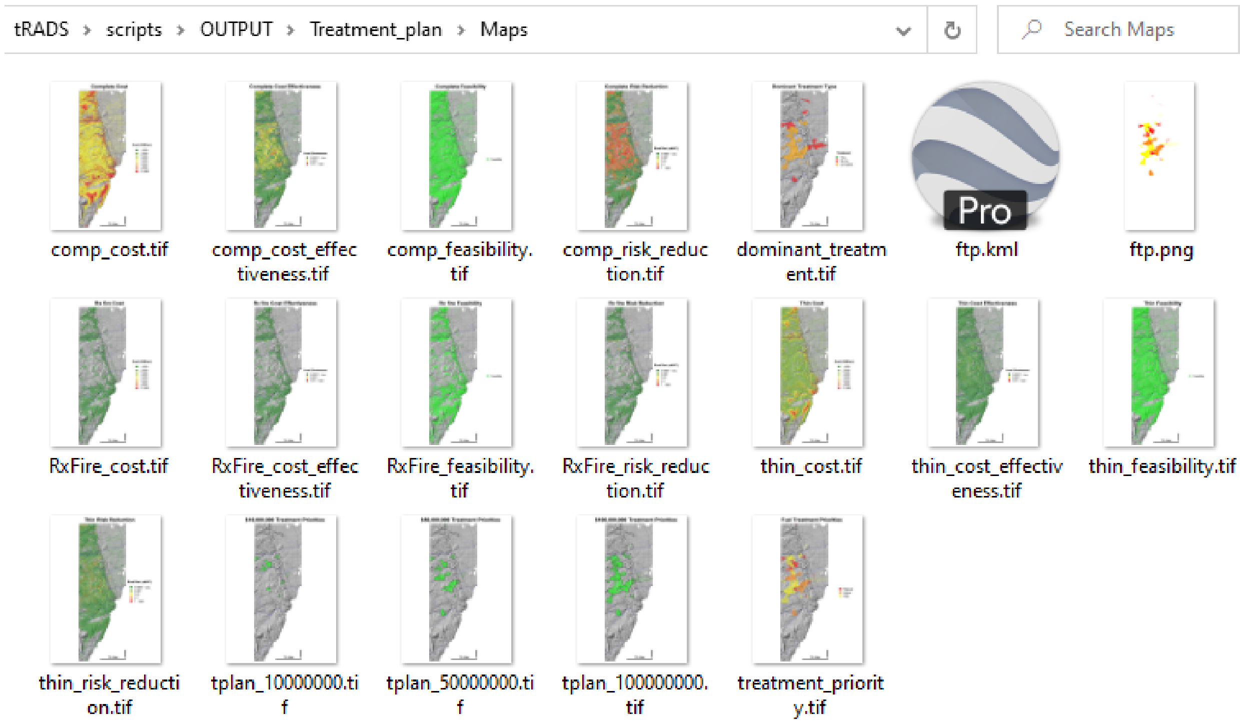


Figure 13: Optional map products from the Map Results module.

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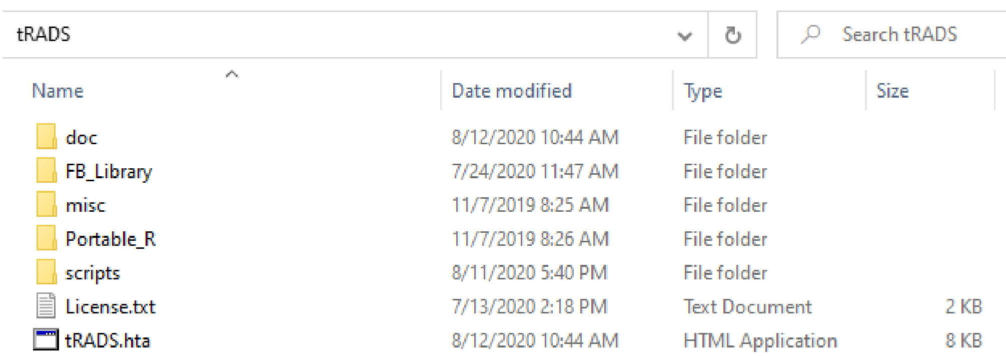
APPENDIX I – Installation instructions and use limitations

The Risk Assessment Decision Support Tool (RADS) was developed in R version 3.5.3 (R Core Team 2019). Given the nature of free and open source software to change over time, a distribution of this R version and all packages used in RADS are provided so it will continue to function as intended into the future. No support will be provided for RADS use on other versions of R or the dependent packages. A simple graphical user interface is provided in the form of an HTML application (.hta) to allow non-technical users to progress through the scripted workflow without any knowledge of R. The graphical user interface will only work on Windows 7 and 10 operating systems. Acceptable computing performance will be achieved on machines with at least 8 GB RAM and a Core i3 processor or higher.

RADS is distributed in zipped file folder. Unzip the contents to your preferred location on a real hard drive (e.g., the C drive on your computer, an external hard drive, or a network drive maintained by your organization). RADS will not function properly when stored and launched from a virtual drive (e.g., Box, Dropbox, OneDrive, Google Drive, etc.). RADS contains one HTML application and the supporting programs and files (Figure 14). Rearranging the contents of RADS or changing the names of the folders or files will cause it to malfunction. It is best for non-technical users to only operate RADS through the graphical user interface (tRADS.hta). This can be launched from its current location, or a shortcut can be created to launch it from the desktop or other location.



Name	Date modified	Type	Size
doc	8/12/2020 10:44 AM	File folder	
FB_Library	7/24/2020 11:47 AM	File folder	
misc	11/7/2019 8:25 AM	File folder	
Portable_R	11/7/2019 8:26 AM	File folder	
scripts	8/11/2020 5:40 PM	File folder	
License.txt	7/13/2020 2:18 PM	Text Document	2 KB
tRADS.hta	8/12/2020 10:44 AM	HTML Application	8 KB

Figure 14: Snapshot of the parent directory after unzipping. The tRADS.hta is the graphical user interface. Double click to launch from this location or create a shortcut for your desktop.

The graphical user interface (Figure 15) provides a web-like experience to progress through the sequential steps of performing a water supply risk assessment, optimizing fuel treatments to mitigate the risk, and evaluating the performance of a specific treatment plan. Inputs are flagged with green buttons and outputs are flagged with blue buttons. Grey buttons either open the reference materials provided at the top of the screen or they launch the R scripts that execute the analyses.

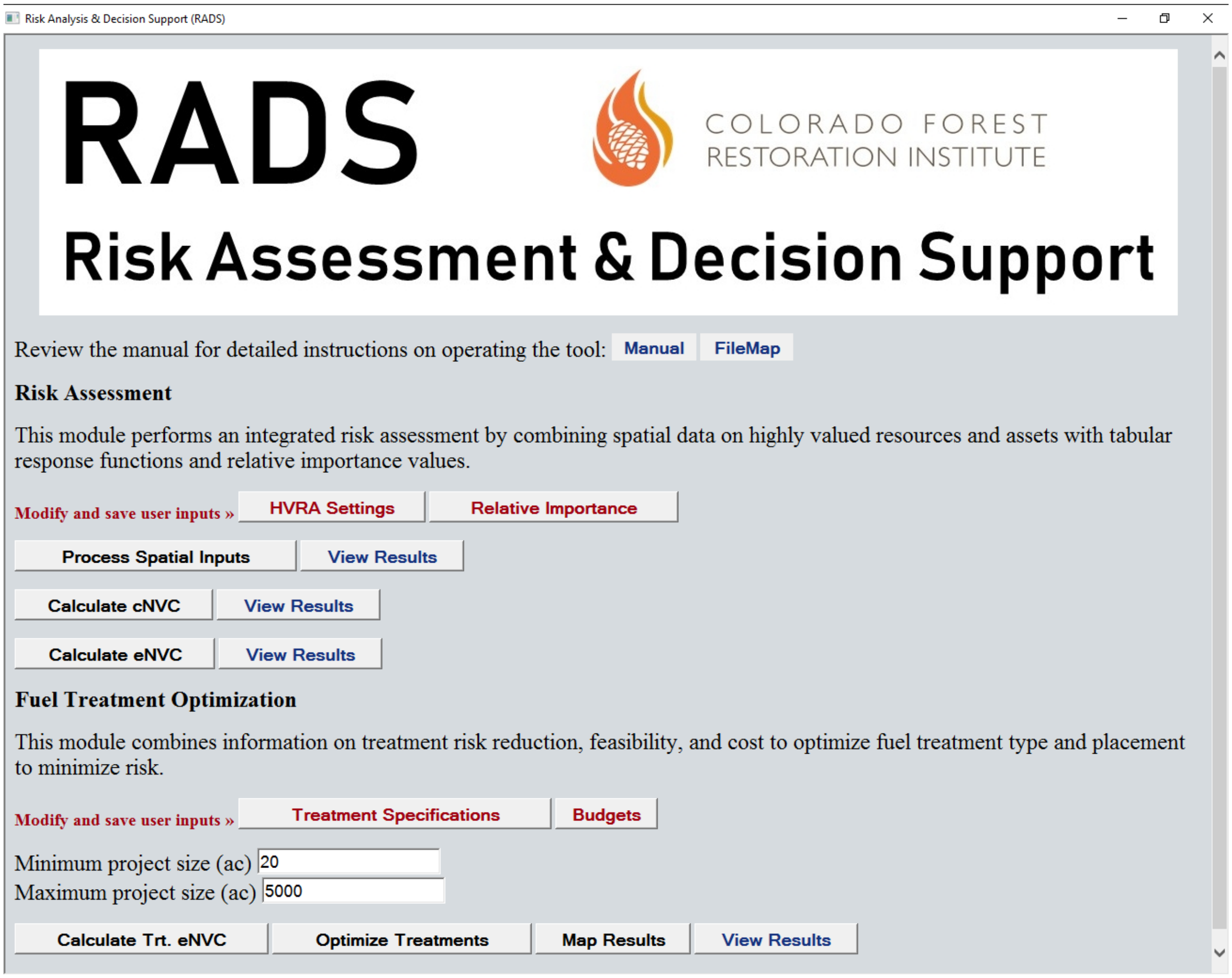


Figure 15: Graphical user interface for RADS.

All data requirements are documented within this manual, the file map, and the R scripts. The file map (File_map.xlsx) in the *doc* folder provides a full list of files in RADS and their functions. In addition to RADS, several pre-processing scripts are provided (tagged with "PP") to document the fuel treatment data processing, fuelscape generation, fire modeling, and constraint modeling. Additionally, several optional scripts are provided for supplementary analyses of the fire behavior and risk results (tagged with "O").

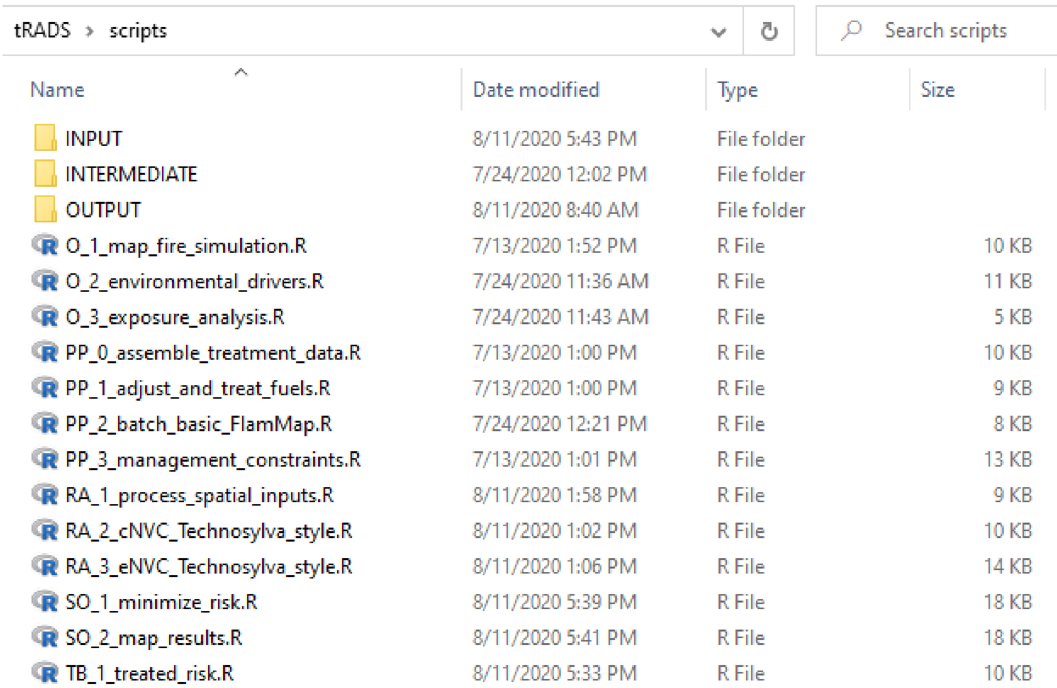


Figure 16: Scripts folder containing the R scripts and associated directory structure for the analysis inputs and outputs.

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APPENDIX II – Pre-processing utilities

As discussed previously, this manual is not meant to provide guidance on how to critique and update fuels, model fire behavior, complete a risk assessment, model fuel treatment effects, or model fuel treatment feasibility. However, to support efficient application of RADS to new landscapes, we have developed several preprocessing workflows in the R language for statistical computing and graphics (R Core Team 2019) to complete these tasks. This section will provide a brief overview of the included pre-processing scripts that may serve as useful templates to complete these tasks in future analyses. Providing access to these scripts should not be interpreted as endorsement of the models or default parameters for use in other landscapes.

PP_0_assemble_treatment_data.R

Fuels data often lags current conditions by 2-4 years, so a common task in risk assessment is updating the fire modeling fuelscape components to reflect current conditions before fire modeling. This script provides a template for combining national and local fuel treatment datasets, classifying them into canopy and surface fuel treatment categories, and simplifying their geometries. The canopy and surface fuel treatment categories should match the available treatment options described for the following script.

PP_1_adjust_and_treat_fuels.R

This script provides a template to update fuels to current conditions for the baseline risk assessment and to model the hypothetical fuel treatments used in the fuel treatment planning workflow. It requires fuels and topography rasters for fire modeling from LANDFIRE or a similar source and shapefiles of recent canopy and surface fuel treatments. The recent and hypothetical future fuel treatments are modeled using canopy adjustment factors (Table 11) and fire behavior fuel model reclassifications (Table 12). Fuel treatment effects will likely require modification for use in different environments. A fuel treatment can be added to the model by adding a row to the canopy adjustment factors table or a column to the fire behavior fuel model reclassifications and creating a new block of code to implement the treatment in the script. The code will generate updated fuels rasters and fire modeling fuelscapes in GeoTIFF format for each scenario.

Table 11: Example canopy adjustment factors for three treatment types. CBD = canopy bulk density. CBH = canopy base height. CC = canopy cover. CH = canopy height. Adjustment factors are applied with multiplication to adjust canopy attributes proportional to the starting conditions. For example, a canopy bulk density adjustment factor of 0.6 means reduce canopy bulk density 40%.

Treatment	cbd_AF	cbh_AF	cc_AF	ch_AF
Thin	0.6	1.2	0.7	1.2
RxFire	0.92	1.09	0.95	1.13
Complete	0.5	1.2	0.75	1.2

Table 12: Fire behavior fuel model reclassification table. The codes and FBFM40 numbers are from Scott and Burgan 2005. Changes from the baseline are noted in red for treatment types of manage (biomass removal, pile burning, etc.), broadcast prescribed fire, and rearrange (masticate and lop and scatter).

Code	FBFM40	Manage	RxFire	Rearrange
NB1	91	91	91	91
NB2	92	92	92	92
NB3	93	93	93	93
NB4	94	94	94	94
NB5	95	95	95	95
NB6	96	96	96	96
NB7	97	97	97	97
NB8	98	98	98	98
NB9	99	99	99	99
GR1	101	101	101	201
GR2	102	102	101	201
GR3	103	103	101	201
GR4	104	104	101	201
GR5	105	105	101	201
GR6	106	106	101	201
GR7	107	107	101	201
GR8	108	108	101	201
GR9	109	109	101	201
GS1	121	121	121	201
GS2	122	122	121	201
GS3	123	123	121	201
GS4	124	124	121	201
SH1	141	141	141	201
SH2	142	142	141	201
SH3	143	143	141	201
SH4	144	144	141	201
SH5	145	145	141	201
SH6	146	146	141	201
SH7	147	147	141	201
SH8	148	148	141	201
SH9	149	149	141	201
TU1	161	161	161	201
TU2	162	162	161	201
TU3	163	163	161	201
TU4	164	164	161	201
TU5	165	165	161	201
TL1	181	181	181	201
TL2	182	182	181	201
TL3	183	183	181	201
TL4	184	184	181	201
TL5	185	185	181	201
TL6	186	186	181	201
TL7	187	187	181	201
TL8	188	188	181	201
TL9	189	189	181	201
SB1	201	201	201	201
SB2	202	201	201	201
SB3	203	201	201	201
SB4	204	201	201	201

PP_2_batch_basic_FlamMap.R

This script automates FlamMap basic fire behavior runs for each fuel (baseline and treated) and fire weather scenario (low, moderate, high, and extreme). It uses a command line version of FlamMap (TestFlamMap developed Missoula Fire Sciences Laboratory, Missoula, MT) for the calculations. Once fuelscapes are generated to represent each scenario, the analyst should summarize the 1-hr, 10-hr, 100-hr, herbaceous, and woody fuel moistures and wind speed and direction for each scenario. This information will be entered into rows of the fire scenarios table. The table provides three options for winds: 1) specified wind direction, 2) winds blowing uphill (set wind direction to -1), and 3) gridded winds (requires wind direction and gridded wind resolution). The script will batch the calculations and output the requested fire behavior metrics tagged with the fire scenario name.

PP_3_management_constraints.R

This script provides template analyses to model fuel treatment cost and feasibility for each treatment type. It requires a local copy of GDAL to perform several operations (https://gdal.org/). Alternatively, these steps could be performed manually by the analyst using their GIS of choice. The cost model presented for forest thinning is roughly calibrated to treatment costs in Northern Colorado based on excerpt opinion of how costs vary as a function of distance from roads (accessibility) and slope steepness (operability).