

Project Title: Optimizing Spatial and Temporal Treatments to Maintain Effective Fire and Non-fire Fuels Treatments at Landscape Scales

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Project Website:

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I. Abstract

There is a recognized need to apply and maintain fuel treatments to reduce catastrophic wildland fires. A number of models and decision support systems have been developed for addressing different aspects of fuel treatments while considering other important resource management issues and constraints. Although these models address diverse aspects of the fuel treatment-planning problem, no one model adequately handles the strategic maintenance scheduling of fuel treatments while considering 1) the spatial and temporal changes of fuel treatment effects on a landscape, and 2) the economics of maintenance fuel treatments plus other operational constraints.

The objective of this project was to integrate existing fire behavior, vegetation simulation, and land management planning tools into a system that supports long-term fuel management decisions. The system was to build on the existing land management optimization tool MAGIS, while incorporating the Forest Vegetation Simulator and the Fire and Fuels Extension (FVS-FFE) to project vegetation change over planning periods and predict the resulting fuel parameters for fire behavior modeling, and FlamMap to model fire behavior in each planning period. The system was to include automated data transfer interfaces between the models to offer an easier way to use multiple sophisticated models for analyzing alternative fuel management schedules.

The project developed OptFuels, a GIS-based modeling system for spatially scheduling forest fuel treatments over multiple planning periods in the presence of budget and other constraints. OptFuels utilizes FVS-FFE to project stands into the future both with and without fuel treatments and compute the fuel parameters needed for fire behavior modeling in FlamMap, which is conducted for each planning period in each iteration of the OptFuels solver. The OptFuels solver spatially schedules fuel treatments over multiple planning periods (1 – 5 user-defined periods) to minimize the expected loss from potential future wildland fire.

OptFuels has been tested on two fuel treatment planning areas on the Bitterroot National Forest, the 34,000-acre Trapper-Bunkhouse area, and the 103,689-acre Willow-Gird area. Fuel treatment scenarios scheduled over two planning periods were able to substantially reduce the fire arrival time in the wildland urban interface portion of the Trapper-Bunkhouse area, thereby reducing the expected loss from future fires. Smaller reductions in expected loss were found in the Willow-Gird area. Although increases in arrival time were created by the scheduled fuel treatments, these treatments did not increase the arrival times sufficiently in the areas on the landscape having the highest expected loss, such as the wildland urban interface. This occurred primarily because of the relatively close proximity of the ignition points in the wildland urban interface simulating human ignited fires.

II. Background and Purpose

There is a recognized need to apply and maintain fuel treatments to reduce catastrophic wildland fires. The Healthy Forests Restoration Act of 2003 mandates actions to identify and inventory priority areas. Treating all of the 81 million hectares of federal land in the USA considered at risk from fire (Schmidt et al. 2002) would be costly and impractical. Forest managers faced with limited budgets, narrow burning windows, air quality issues, and effects on other critical forest resources must establish priorities for where, when, and how to apply new and maintenance fuel

treatments. Science-based yet field applicable guidelines to strategically maintain fuel treatments on landscapes should be incorporated into treatment design to reduce catastrophic fire and restore ecosystem health over time. Therefore, decision support systems that can predict the outcomes of fuel treatments are valuable information tools for fuel management decisions. There is a need for the use of such models to be utilized at a national level.

A number of models and decision support systems have been developed for addressing different aspects of fuel treatments while considering other important resource management issues and constraints. These models operate on a variety of geographic scales, varying from an individual stand to an entire landscape comprised of many individual stands. Some models operate only on current conditions, while others span over multiple decades.

A. Fire behavior and fuel hazard modeling

The FARSITE Fire Area Simulator (Finney 1998) was designed to model continuous fire behavior over multiple burning periods at a 30-meter resolution. FARSITE is able to compare the effectiveness of different suppression strategies and treatments for containing fire under varying weather conditions. FARSITE evaluations are based on simulating fires starting at various locations and spreading under varying fuel and weather conditions. There is, however, no temporal component to these analyses that reflects how the effectiveness of treatments changes over time with vegetative growth.

FlamMap (<http://fire.org/>) is a spatial fire area potential calculator for assessing fuel hazard in terms of fire behavior. The purpose of FlamMap is to generate fire behavior data that are comparable across a landscape for a given set of weather and/or fuel moisture data inputs. The fire behavior models in FlamMap are used to make calculations for all cells of a raster landscape, independently of one another (there is no contagious process that accounts for fire movement across the landscape or among adjacent cells). FlamMap calculates the instantaneous behavior of a fire occurring at each pixel in the analysis area based on the same local weather inputs. In this way FlamMap compares potential fire behavior across a landscape by distinguishing different hazardous fuel and topographic combinations.

FlamMap contains an option called Minimum Travel Time (MTT) (Finney 2002) which is a fire growth simulator that uses minimum travel time methods to simulate how fast one fire or a band of multiple fires are expected to move across a landscape. It is used to identify the routes where fire is expected to travel most quickly. Like the main component of FlamMap, these simulations are based on the current fuels, specific locations for fire starts, and weather conditions. If one accepts that fuel treatments should be prioritized on the basis of juxtaposition of high values to hazardous fuels, this program begins to give us the ability to develop a biophysical definition of wildland urban interface based on the distance fire can travel under specified conditions. It does not include endogenous scheduling of treatments, and like the other fire behavior-based models, works only with the current fuels.

The Treatment Optimization Model (TOM) (Finney 2006) is another option on the FlamMap menu. It uses minimum travel time logic to determine effective locations for fuel treatments on a landscape. The treatment locations are based on the fire behavior expected from the current fuels present on the landscape, specific locations for fire starts, and weather conditions. The solutions suggest location, sizes, and orientations of fuel treatments that are efficient and effective at changing large fire growth by reducing the fire spread rate. The treatment locations are selected

to reduce the rates of fire spread across the landscape, and are not designed to protect specific locations on a landscape, such as designated wildland urban interface. Also, the placement of treatments does not consider feasibility factors associated with location or shape, nor do they address resource effects, or management limitations such as budget. Finally, there is no temporal aspect to TOM, so it cannot analyze alternative timings of fuel maintenance treatments on a landscape.

The Fire and Fuels Extension to the Forest Vegetation Simulator (FVS-FFE) evaluates the effectiveness of proposed fuel treatments in the context of potential fire effects on short- and long-term stand dynamics (Reinhardt and Crookston 2003). In contrast to other fire behavior fuel hazard models, the FVS-FFE has the ability to simulate the dynamics of vegetation, snags, and surface fuels, and the appropriate interactions between these processes at a stand level (Kurz and Beukema 1999). In combination with the Parallel Processing Extension (PPE; Crookston and Stage 1991) the FVS-FFE can be used to simulate the dynamics of landscapes containing several hundred to a few thousand stands. The FVS-FFE does not simulate fire spread between stands, but it has the ability to provide inputs to FARSITE and FlamMap (Hayes and others 2004).

Other fire models include 1) the First Order Fire Effects Model (FOFEM) which models duff and woody fuel consumption, mineral soil exposure, soil heating, smoke production, and tree mortality (Reinhardt and others 1997), 2) FIREHARM which can be used to calculate fire behavior and effects potentials for varying weather percentiles used in fire management planning, and 3) NEXUS (Scott and Reinhardt 2001) which is an Excel(tm) spreadsheet linking surface and crown fire prediction models. All these fire models, however, do not include treatment scheduling or address temporal aspects of fuels management.

B. Landscape simulation and treatment scheduling modeling

SIMPPLLE is a stochastic simulation model for projecting vegetation spatially in the presence of disturbances such as insects, disease, and wildland fire (Chew 1997, Chew and others 2004). Simulations can be made with or without fire suppression, with or without fuel treatments, and under average or extreme fire conditions. Spread logic is included for wildland fire and other disturbance processes. The location and frequencies of disturbance processes quantified from multiple stochastic simulations provide estimates of the location and probabilities of future disturbance processes. These provide a basis for identifying “problem areas,” as well as estimating costs and effects associated with disturbances processes.

MAGIS is an optimization model for spatially scheduling treatments that effectively meet resource and management objectives while satisfying user-imposed resource and operational constraints (Zuuring and others 1995). MAGIS accommodates a wide variety of land management treatment types, and associated costs, revenues, and effects. MAGIS also contains a road-network component for analyzing road construction, re-construction, and closure. The combination of the land management and road-network components provides the capability to include the limitations (for example sediment production) and costs associated with vegetation treatments as well as access and roads in spatially analyzing maintenance of fuel treatments.

SIMPPLLE and MAGIS have been used in a process for spatially scheduling treatments and analyzing the effectiveness of those treatments (Jones and Chew 1999, Chew and others 2003, Jones and others 2004). In this process, SIMPPLLE is used first to run stochastic simulations for the “no action” management alternative. From these simulations the frequency of natural

disturbances is recorded for each polygon in the landscape, representing the risk of these natural processes occurring over a period of time. These risks are then incorporated into MAGIS and combined with resource and operational objectives and constraints to develop an alternative spatial treatment schedule. These treatments schedules are then simulated in SIMPPLLE and the results compared with the results of the “no action” simulations to measure the effectiveness of the fuel treatment scenario. Key questions, however, remain in the SIMPPLLE/MAGIS approach involving computation of the risk index and the treatment patterns resulting from it, among others.

A past Joint Fire Science project, A Risk-Based Comparison of Potential Fuel Treatment Trade-off Models, compared the SIMPPLLE/MAGIS approach with two non-spatial models FETM (CH2M Hill 1998) and VDDT (Beukema and Kurz 1998) on eight areas representative of major fuel types. The focus was on modeling fuel treatment trade-offs for use in strategic planning. The comparison found significant differences in how information is assembled and used in the models. SIMPPLLE and MAGIS were sensitive to the spatial arrangement of vegetation and treatments, making the data requirements somewhat more stringent, but they also provide as output the spatial arrangement of proposed treatments. Non-spatial solutions may not be either optimal or even operationally feasible.

C. The need for integrating types of models

Although these models address diverse aspects of the fuel treatment-planning problem, no one model adequately handles the strategic maintenance scheduling of fuel treatments while considering 1) the spatial and temporal changes of fuel treatment effects on a landscape, and 2) the economics of maintenance fuel treatments plus other operational constraints. For example, FARSITE and FlamMap are able to compute fire behavior characteristics at a landscape scale, but neither maintenance scheduling nor temporal effects of treatments are included in either model. FVS-FFE has the ability to model stand-level fuel and vegetation dynamics, but it does not simulate the spread of fires between stands. On the contrary, MAGIS has the ability to spatially schedule fire and non-fire maintenance treatments that effectively meet resource and management objectives, but no fire spread logic exists in the system. Fire managers have to use these multiple systems in order to analyze spatial and temporal effects of maintenance fuel treatments, but lack of time and resources to maintain and operate these sophisticated systems has been a hurdle. Consequently, there is a critical need to merge these systems into one easy-to-use decision support system that 1) facilitates automatic linkages among the existing models, 2) streamlines analyses for identifying where, when, and how to treat in order to achieve and maintain desired fuel reduction goals, and 3) bridges the fire sciences and management gap by incorporating given resource and operational constraints (e.g. budgets, treatment acres, and operational feasibility of treatments) into decision-making process.

D. Project objectives

The main objective of this project was to integrate existing fire behavior, vegetation simulation, and land management planning tools into a system that supports long-term fuel management decisions. The system was to build on the existing land management optimization tool MAGIS, while incorporating FVS-FFE to project vegetation change over planning periods and predict the resulting fuel parameters for fire behavior modeling, and FlamMap to model fire behavior in each planning period. The system was to include automated data transfer interfaces between the

models to offer an easier way to use multiple sophisticated models for analyzing alternative fuel management schedules. The system was to be validated on two landscapes.

III. Study Description and Location

This project developed OptFuels, a GIS-based modeling system for spatially scheduling forest fuel treatments over multiple planning periods in the presence of budget and other constraints. OptFuels utilizes the Forest Vegetation Simulator and the Fire and Fuels Extension (FVS-FFE) to project stands into the future both with and without fuel treatments and compute the fuel parameters needed for fire behavior modeling in FlamMap, which is conducted for each planning period in each iteration of the OptFuels solver. The OptFuels solver spatially schedules fuel treatments over multiple planning periods (1 – 5 user-defined periods) to minimize the expected loss from potential future wildland fire.

The main spatial component of an OptFuels model is a GIS stand polygon coverage. For simplicity, these stand polygons double as treatment unit polygons, thereby avoiding the necessity for a separate treatment unit polygon coverage at this stage in the planning process. Management regimes comprised of one or more treatment activities are assigned to the polygons based on user-specified rules that are tied to spatial zones and stand characteristics. Each management regime is comprised of a sequence of treatment activities that may extend over multiple planning periods to represent scheduled retreatment of the same location, or represent a one-time treatment occurring in a single planning period. Costs for activities are entered as table lookups, allowing costs to vary by conditions where appropriate, while at the same time accommodating a simple average treatment activity cost.

After the management regimes have been assigned to the polygons, OptFuels runs FVS-FFE to simulate the no action landscape. Then treatment options are assigned to the polygons based on the no action output and geographically defined management zones. These treatment options are then simulated with FVS-FFE for the sequence of treatments specified in the management regimes. In this process, FVS-FFE is used to project both treated and untreated stands and compute the resulting fuel parameters for each planning period. Timber and non-merchantable material amounts can be recorded and used for developing recourse management scenarios.

Once an OptFuels model is built, the solver develops alternative treatment schedules for user-specified scenarios. Users specify the fire scenario including the wind direction and speed, the fuel moisture conditions, and ignition points, assign one or more optional constraints on such things as acres to treat, or treatment budget. The OptFuels solver then determines the location and timing of treatment activities to minimize the expected loss from future fire across the planning area.

An OptFuels solution consists of the schedule of treatments selected by the solver, the associated expected loss value, the amounts computed for the constraints, the FlamMap fire behavior summary reports for both the untreated and treated landscapes, and FlamMap-ready landscape files for both the untreated and treated landscapes. These files are useful for additional FlamMap analyses that could be run on the solution results.

A. System design

Input Data and Model Building Process

Figure 1 presents a flow diagram of the OptFuels data input and model building process. This process can be divided into four components: Framework data, Planning area, Model build, and Fuel treatment scenario specifications.

Framework data – These data are not specific to a fuel treatment planning area, they are expected to apply to multiple planning areas that have similar conditions. The Framework data includes:

- Master list of variables, which become GIS attributes that are used to categorize information in the Framework data. These variables (GIS attributes) include the treatment zones used in assigning management regime options to polygons, the value-at-risk categories present on a polygon, and attributes used in cost table lookups.
- Fuel treatments are defined using FVS keywords for mechanical treatments (such as THINBBA), and prescribed fire. Additional keywords can be used to control fuel calculations (FIRECALC, FUELCALC, and FUELMODL) in FVS. Activity-costs can also be entered to account for administrative and other costs. Costs can be entered as a simple average, or in a table lookup where costs vary by user-defined attributes, such as slope or aspect.

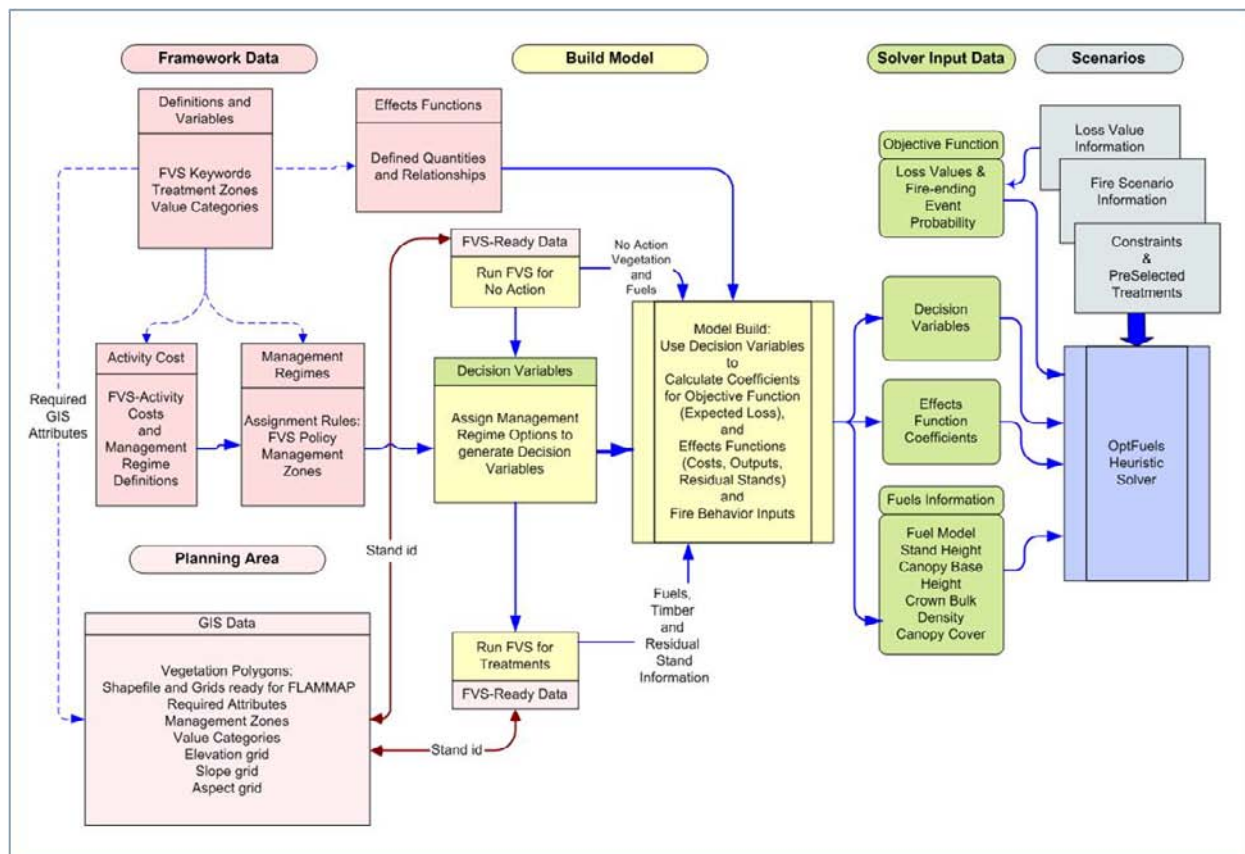


Figure 1. The OptFuels data input and model building process.

- Management regime definitions. Each management regime is comprised of one or more FVS and non-FVS activities as a sequence (for example: sale preparation cost, followed by mechanical thinning, followed by a broadcast burn) that occurs in a planning period. A given treatment unit polygon may have options for treatment in each planning period.
- Rules for assigning management regimes as options to the GIS polygons. These rules are based on the vegetation and fuel conditions present in the polygon as well as the management zone where the polygon resides. For example, management regimes with mechanical treatment can be limited to a zone where road access exists, or to specific stand conditions (or both). In the same manner, individual (or all) management regimes can be excluded as options in riparian areas or other restrictive land management zones.
- List of the value-at-risk categories for use in the expected loss calculation such as structures, critical wildlife habitat, and so on.

Planning area – These data are comprised of a GIS vegetation polygon coverage that includes the GIS attributes used in the framework data (attributes for management zone, value-at-risk categories and cost table lookups) and an identifier that associates each polygon to FVS-ready stand data. The GIS data goes through validity and completeness checks to ensure all necessary information is present prior to the model building process. The GIS data also include raster grids for elevation, slope, and aspect, and polygon (treatment unit) boundaries.

Model building process – This begins with an OptFuels interface running FVS-FFE for the no action alternative for each unique set of FVS-ready data. One set of FVS-ready data may apply to one or multiple GIS polygons. This design avoids having to run the same FVS-ready data for each polygon to which it applies. The FVS-FFE no action run projects the FVS-ready data through the planning periods (from 1 period to a maximum of 5 periods) and computes the fuels information needed for fire behavior modeling in each planning period.

The management regime assignment rules are applied using results of the no action FVS-FFE runs and the management zone information to assign the management regime options to the polygons. This process creates the decision variables for the OptFuels solver.

Next, the OptFuels interface runs FVS-FFE for the treatments in the management regimes using the FVS-ready data. As with the no action FVS runs, only the unique combinations of management regimes and FVS-ready data are simulated by FVS-FFE. The FVS-FFE simulations project the stands that the FVS-ready data represent through the planning periods, applying the treatment sequences for the management regimes. These simulations compute the fuels information needed for fire behavior modeling in each planning period, as well as the wood product volumes removed by mechanical thinning and statistics describing the residual stands. The fuels data are stored for use by the OptFuels solver.

The last step in the model building process integrates the decision variable information, GIS data, framework data, and results from the FVS-FFE runs to compute the Effects Function Coefficients of each decision variable and stores these results for use by the OptFuels solver. The Effects Functions are computations of model quantities such as acres treated, costs, timber products, and non-monetary resource benefits and impacts as defined by the user. An Effects Function Coefficient measures the contribution of a specific decision variable to a specific Effects Function.

Fuel treatment scenario specifications – There are three components to specifying a scenario for the OptFuels solver: 1) Loss value information, 2) Fire scenario information, and 3) Constraints and preselected decision variables. The loss value information includes the items of information used in computed expected loss. Loss values for value-at-risk categories are entered by flame length. Following the approach of Calkin and others (2010) we recommend quantifying loss from wildland in terms of percentage loss relative to no fire occurring. This results in an index based on percentage loss that is used by the solver to schedule treatments (the objective is to schedule treatments in the way that minimizes this loss value index). Loss can instead be quantified in dollar terms at user discretion. Users have the ability to apply weights to the value-at-risk categories to reflect their relative importance for guiding fuel treatment decisions. The final item in the loss value information is a table of probabilities for fire duration. These fire duration probabilities could be developed by analyzing the duration of past fires, or through using historical weather data to estimate the probability of fire ending weather patterns at over various numbers of days. We recognize that MTT models fire spread assuming constant fire scenario conditions. However, in the real world, fire spreading weather is not continuous but rather occurs only in blocks of time. Days of fire duration in the real world can be converted to minutes of active fire spread in the fire behavior modeling by estimating the average number of active spread minutes in a 24-hour day.

The fire scenario information for OptFuels is the same information used for MTT. This includes fuel moisture files, custom (optional) fuel model file, fire weather information, and other fuels information (fuel moisture conditioning files, ground fuels etc.). The ignition points for the fire scenario are also specified. In addition, the number of fire spread minutes to run the MTT in the solving process must be specified. This value should be slightly larger than the estimated time needed to spread fire from the ignitions points across the planning area given the specified weather and fuel moisture information.

Constraints and preselected decision variables are optional. Constraints may be imposed on the solution by selecting an effects function and entering limits on its value. This is where limitations on budget, treatment acres, or other such effects function calculations can be specified. The user also has the option to set decision variables (a decision variable is a specific treatment on a specific polygon in a specific period) into the solution. Preselected decision variables occur in the solution schedule regardless of their effect on the objective function or constraints. Preselecting decision variables can be used to test the effects of specific treatments in specific locations, sets of treatments, or use sets of treatments in specific locations as the starting point for a new solution.

Heuristic Solver

The heuristic solver employed in OptFuels is designed to develop a number of alternative fuel treatment schedules (solutions), evaluate the cumulative effects of each alternative treatment schedule, and choose the best fuel treatment schedule that produces maximum treatment effects (minimize overall expected loss) over time while meeting given resource and operational constraints. The solver includes a subroutine to develop FlamMap landscape (LCP) files that represent vegetation and fuels attributes in each time period as treatment effects. Through dynamic link libraries (DLLs), the solver automatically runs the MTT algorithm on each LCP file and stores the outputs (i.e., flame length and fire arrival time in each pixel) for solution evaluation (Figure 2). Each solution is evaluated as the sum of expected loss value of a given

study landscape over time (Equation 1). Expected loss value in each pixel depends on user-defined relative value of the pixel and burn probability, and estimated flame length and fire arrival time retrieved from the MTT output.

$$\text{Minimize } \sum_{t \in T} \sum_{c \in C} \sum_{f \in F} \text{Loss}_{f,c,t} \times Y_{f,c,t} \times P_{c,t} \quad [\text{Eq.1}]$$

Where

f is an index of flame length category,

c is an index of grid cells (pixels),

t is a time period,

$\text{Loss}_{f,c,t}$ is an expected loss value of grid cell c at flame length category f in time period t ,

$Y_{f,c,t}$ is a binary variable indicating the flame length category of cell c in period t , and

$P_{c,t}$ is a probability of cell c being burn by given fire scenarios (fire ignition locations and durations) in time period t .

A simulated annealing (SA) algorithm is employed in the solver for the optimization engine. Simulated Annealing (SA) is a heuristic search technique that has been widely used to solve large combinatorial problems in various fields (Kirkpatrick and others 1983). The ideas that form the basis for SA were first published by Metropolis and others (1953) in an algorithm to simulate the cooling of materials in a heat bath - a process known as annealing. The approach is a Monte Carlo method that uses a local search in which a subset of solutions is explored by moving from one solution to a neighboring solution. To avoid becoming trapped in a local optimum, the procedure provides for an occasional acceptance of an inferior solution to allow it to move away from a local optimum. The SA algorithm employed in the heuristic solver is briefly explained below and illustrated in Figure 3. Any combinations of budget and acreage constraints can be considered during the optimization process.

Step 1. Develop and evaluate an initial solution. Store the solution as the current solution.

Step 2. Create a new solution by slightly modifying the current solution (randomly select a set of treatment polygons and assign new fuel treatment options including no action).

Step 3. Check the feasibility of the new solution. If the solution violates any of the constraints, discard the solution and go back to Step 2. Evaluate the new solution, otherwise.

Step 4. Accept or discard the new solution based on the SA solution acceptance rule.

Step 5. Go to Step 2 until predefined stopping criterion (i.e., ending temperature) is met.

In order to implement the SA search process, several control parameters need to be set by the user. These include beginning and ending temperatures, repetitions at each temperature level, and temperature cooling rate. The OptFuels interface provides four options for the user to choose from: low intensity, medium intensity, high intensity, and custom option. The higher

intensity option runs more iterations and thus can likely provide a better solution than the other two lower intensity search options, but requires a larger amount of computation time.

Test runs of the initial version of the solver indicated that the solver required a considerable amount of computation time due to the fire simulation process by MTT and the complexity of spatial and temporal scheduling problems. To improve the efficiency of the solution process, the current version of the heuristic solver was designed for multi-threading and multi-processing using OpenMP with Visual C++. As a result, the solver can now simultaneously run MTT for multiple time periods, and the computation time can be significantly reduced.

System Outputs

A tabular report is created for the schedule of treatments developed by the OptFuels solver. This report includes the expected loss value by planning period and the total expected loss across periods, the values computed for the effects functions, and a listing of the treatments selected by polygon. In addition there are options for spatially displaying various aspects of the treatment schedule solution. GIS maps can show the polygons treated by planning period. The expected loss values computed for the treatment schedule can be mapped for each planning period, showing where loss is expected to occur on the landscape. Finally, the contribution that each polygon makes to individual effects functions can be mapped. This could be used, for example, to see spatial distribution of costs or revenues across the planning area.

OptFuels also outputs selected landscape (LCP) files that were created by the solver to run MTT in the solution process. An LCP is the proprietary format for the fire behavior models FARSITE, FlamMap, and MTT and represents a multi-value spatial grid that includes slope, aspect, elevation, and five fuel characteristics. LCP files are output for each planning period for the treatment schedule developed by the solver and for no action. These LCP files can then be used in FlamMap to develop fire behavior information for the planning area both with and without treatment, including landscape raster grids of fire arrival time and flame length.

B. Test Areas and Test Runs

Trapper-Bunkhouse study area

This 34,000-acre study area is on the west side of the Bitterroot Valley west of Darby, Montana (Figure 4). Private property and state lands border the project area to the east and the Selway-Bitterroot Wilderness bounds the project area to the west. The wildland urban interface encompasses about 70% of the project area.

Existing fuel loads (including live trees) pose a threat to the public, fire fighters and natural resources. Any large fire (>100 acres), or multiple ignitions in one day on the Bitterroot Face has the potential to overwhelm suppression forces and travel unimpeded to the Forest

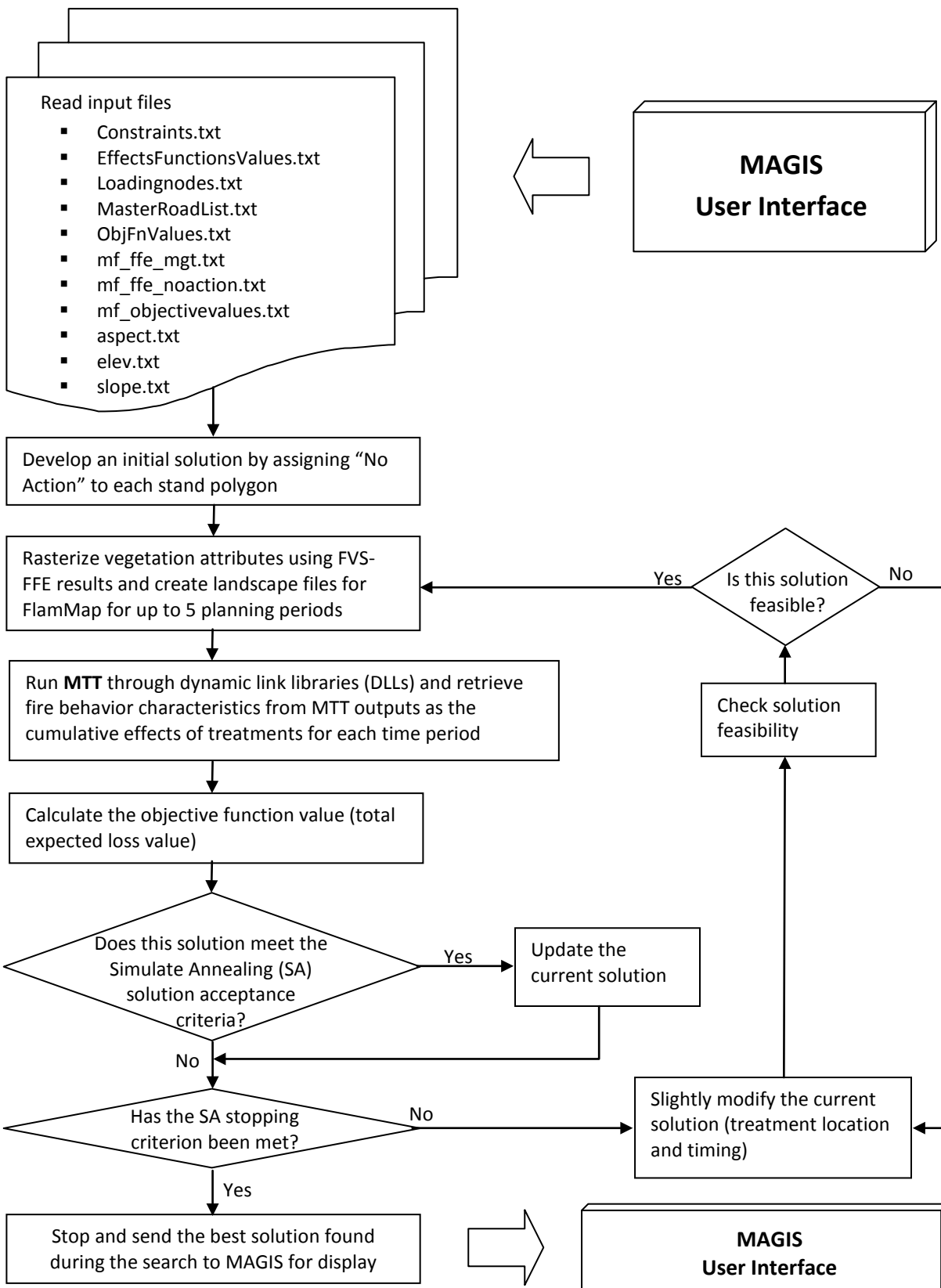


Figure 2. Data flow and analysis employed in the Heuristic Solver to optimize fuel treatment schedules.

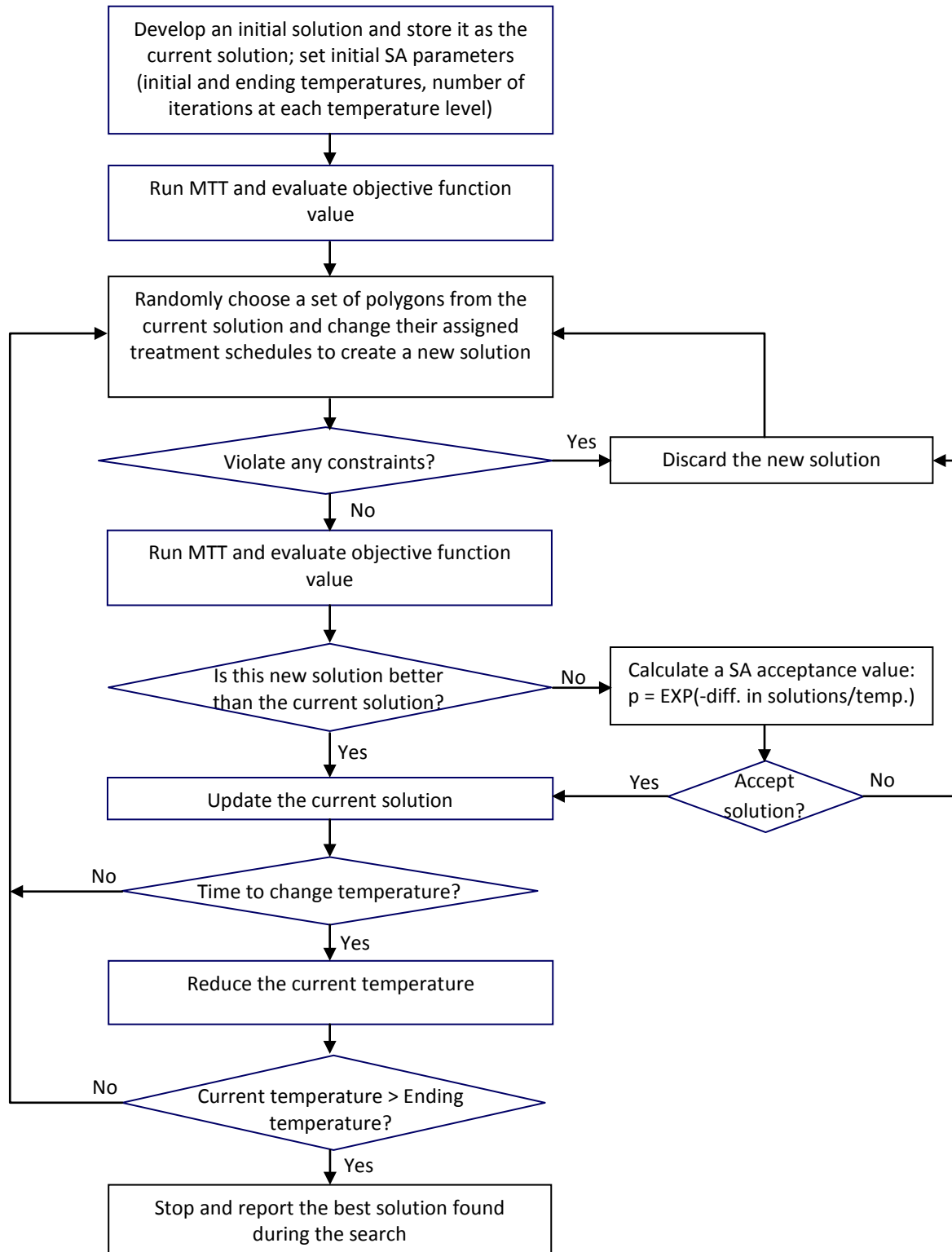


Figure 3. Simulated Annealing algorithm employed in the Heuristic Solver to optimize fuel treatment schedules.

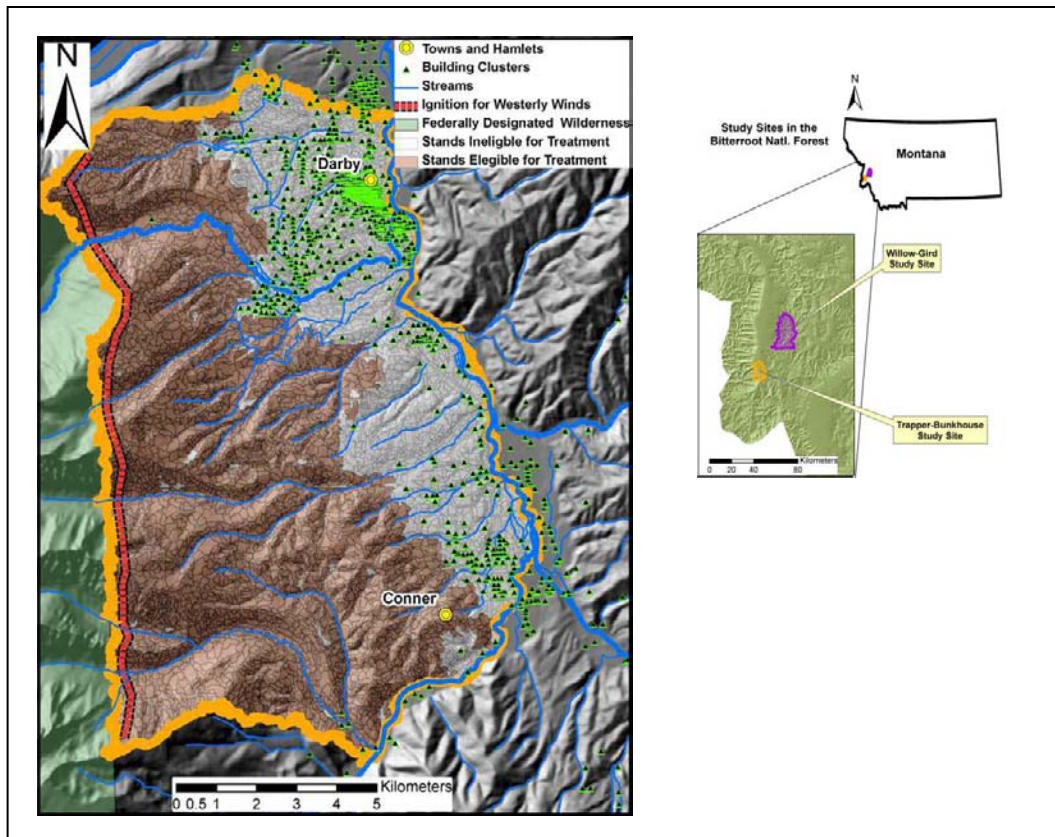


Figure 4. Trapper-Bunkhouse study area.

Service/private boundary and onto private property. This scenario has been demonstrated by the Ward Mountain Fire (1994) and the Blodgett Fire (2000) in which there were homeowner evacuations. The Little Blue Fire (2000) started more than four miles from private property on a remote portion of the West Fork Ranger District, but within 10 hours resulted in home evacuations in the wildland urban interface.

The vegetation structure in the majority of the project area has grown into overstocked, dense stands that are at increased risk of stand-replacing crown fires or intensities that cannot be directly attacked by fire fighters. These dense stands are also susceptible to insect infestations. Eighty-two percent of the project area is highly departed (fire regime condition class 'FRCC' 3) and eighteen percent is moderately departed (FRCC 2) from historical fire frequency and severity, and from historic vegetation structure and fuel loads.

The OptFuels model for this area contained fuel treatment options for 23,957 acres of the 34,000-acre study area. The Restore option was available on 17,014 acres on which prescribed burning could not be accomplished without first reducing ladder fuels. Restore is a mechanical thinning from below designed to remove ladder fuels and reduce stand density to approximately 50-60 ft² of basal area per acre, followed by a broadcast burn to remove activity fuels and small trees. The RxFire option, which applies prescribed fire without mechanical thinning, was available on 6,933 acres.

Five value-at-risk categories (Figure 5) were used in the expected loss calculation: 1) residential parcels that were stand polygons that contain structures, 2) wildland urban interface (WUI) that was defined as polygons within one-half mile of private structures, and 3) national forest system (NFS) acres not having any other risk category. Loss response functions from Calkin and others (2010) provided the basis for assigning percent loss by flame length categories. Percent loss for residential parcels received an importance weight of 10, wildland urban interface a weight of 8, national forest systems acres not in any other category received a weight of 1.

The fire scenario was a line of ignition on the west boundary of the study area with winds out of the west at 20 mph (Figure 4). Foliar moisture content used the FlamMap default of 100%. Fuel moisture conditioning was used.

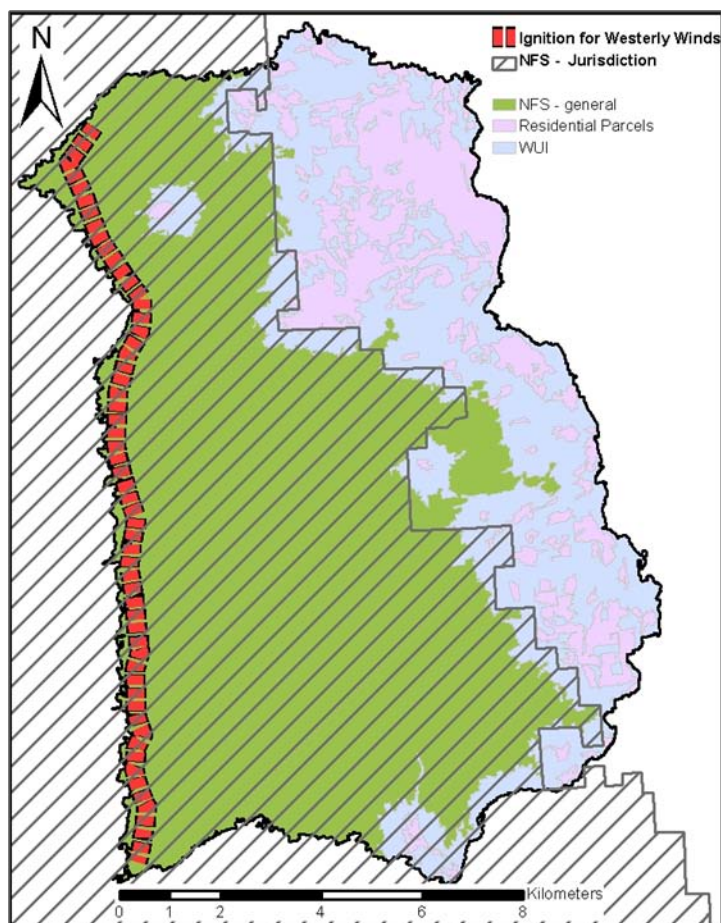


Figure 5. Value-at-risk categories for the Trapper-Bunkhouse study area.

The fire duration probabilities used were derived from weather station data:

<u>Duration category</u> (minutes of active spread)	<u>Probability of a fire of that duration</u>
< 840	0.9
840 – 1680	0.7
1680 – 2520	0.6
2520 – 3360	0.6
3360 – 4200	0.6
4200 – 5040	0.5
5040 – 5880	0.2
5880 – 6700	0.1
6700<	0

Figure 6 compares the expected loss index for no action with three treatment scenarios with increasing percentages of the 23,957 candidate acres treated per period: 10, 20, and 25 percent. The graphs show the percent of pixels in the entire planning area having each category of loss. In period 1 there is a higher percentage of the area in the 2-6 loss category with increasing percentages of candidate acres treated per period. This result indicates that the acres in the higher loss value categories with no action have moved to the low loss category (2-6) as a result of treatment.

In period 2 the differences with increasing amounts of treatment are much greater, reflecting the residual effects of treatments in period 1 plus the effects of treatments in period 2. Figure 7 compares the loss value index summed across periods for the treatments scenarios with no action and 100% of the area treated in period 1, the lowest possible loss with the treatment options modeled. Treating 20% of the candidate acres per period achieved 28% of the reduction relative to treating the entire landscape in period 1, while treating 25% per period achieved 55% of the reduction.

The flame lengths and arrival times modeled by MTT for the treatment scenario and no action are presented in Figures 8 and 9, respectively. Differences in flame length in period 1 are not pronounced, with somewhat larger differences shown for period 2. Again, the result shows that the acres in the higher flamelength categories with no action have moved to the lower flame length categories (e.g., 0 or 1) as a result of treatment. By comparison, the differences in arrival time across the scenarios were larger, particularly in period 2. The arrival time differences appear to account for the majority of the reductions in expected loss with the higher treatment rates.

Figure 10 shows arrival times across the landscape for the 10% and 25% treatment scenarios compared with no action. Arrival times are most increased in period 2 which includes the effects from both period 1 and 2 treatments. Arrival times are most increased in the wildland urban interface in this fire scenario, resulting in less expected loss in that portion of the study area (Figure 11).

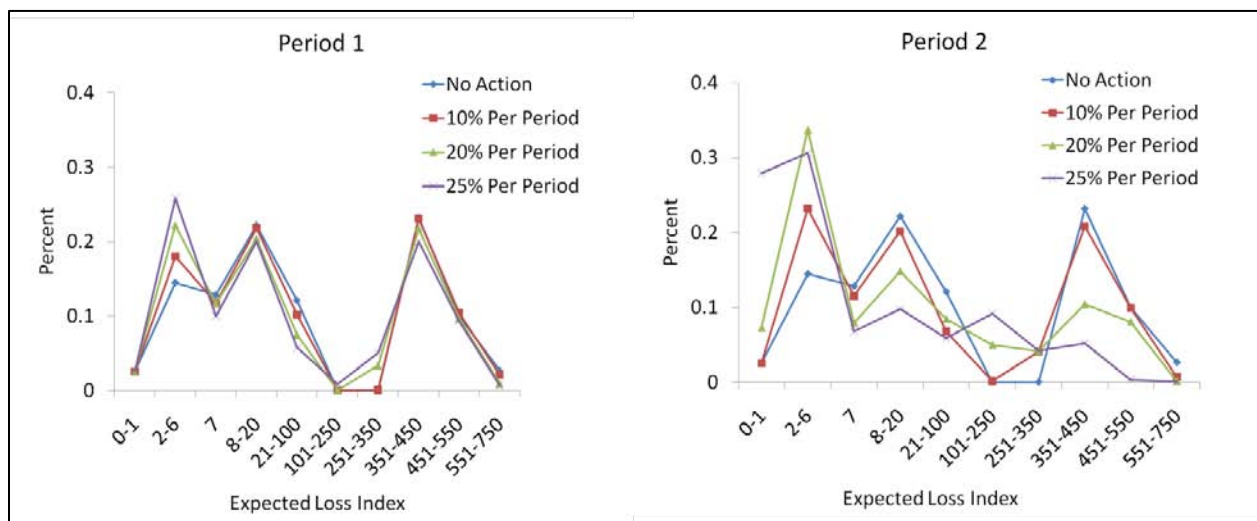


Figure 6. Expected Loss Index by percent of planning area compared across three treatment schedules and no action for periods 1 and 2.

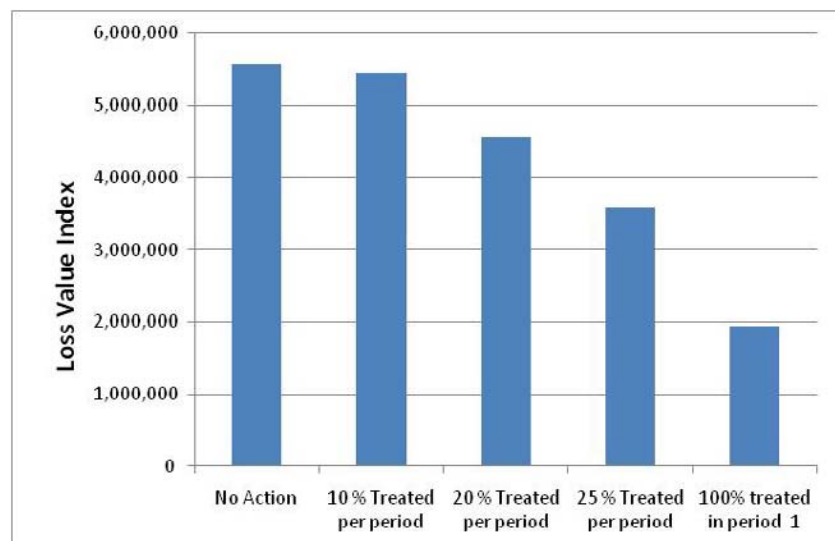


Figure 7. Loss value index summed across periods.

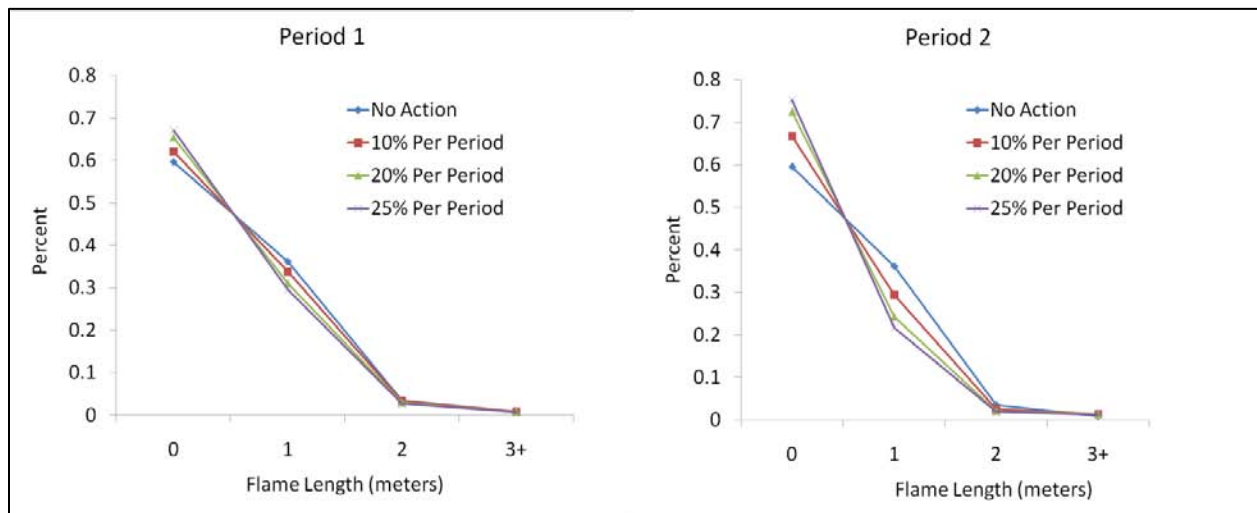


Figure 8. Flame length by percent of planning area compared across three treatment schedules and no action for periods 1 and 2.

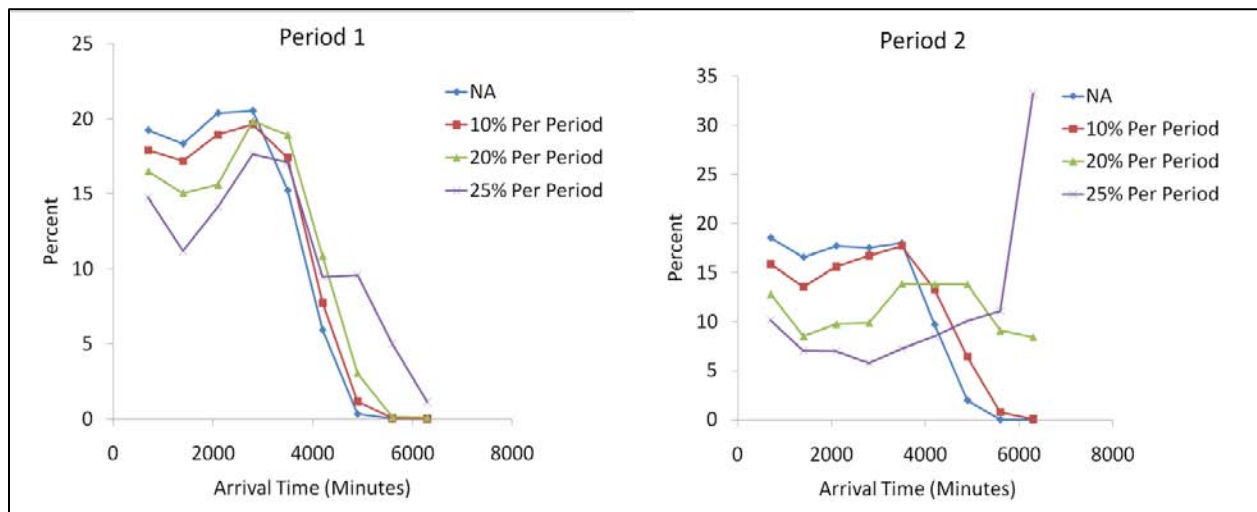


Figure 9. Arrival time by percent of planning area compared across three treatment schedules and no action for periods 1 and 2.

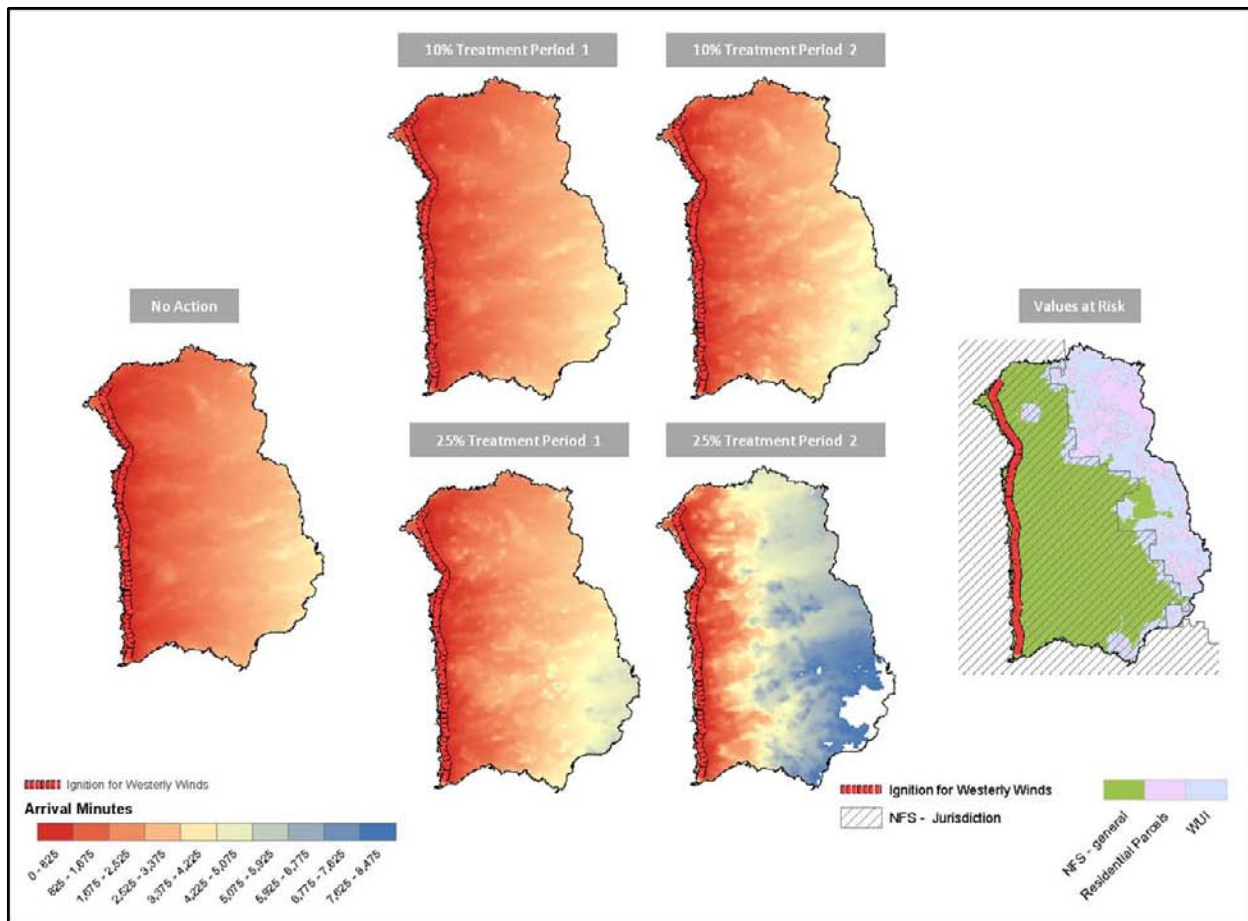


Figure 10. Period 1 and 2 arrival times for the 10% and 25% treatment scenarios compared with no action.

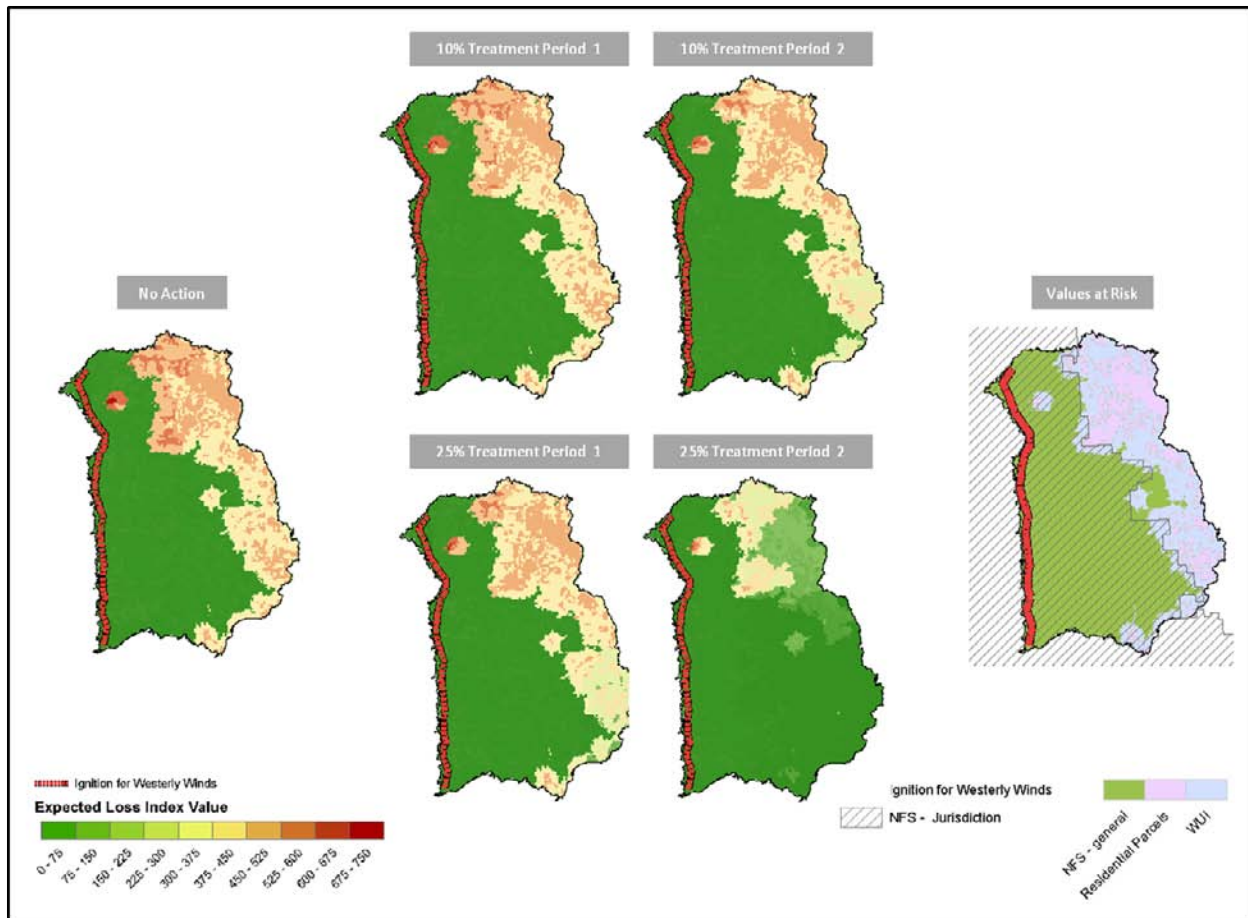


Figure 11. Period 1 and 2 loss values for the 10% and 25% treatment scenarios compared with no action.

Willow-Gird study area

The Willow-Gird study area of 103,689 acres is on the north-east side of the Bitterroot National Forest, straddling the Stevensville and Darby Ranger districts (Figure 12). It is bounded on the west by the Bitterroot Valley and Corvallis, MT, where there is rapid development of residential areas up into the area between Corvallis and the National Forest. To the east are the Sapphire Mountains forming a divide into another developed residential area, Rock Creek, a premier fishing area. The vegetation structure in the majority of the project area has grown into overstocked, dense stands that are at increased risk of insect and disease attack. The area is being considered for restoration treatments to thin dense stands of Ponderosa pine and Douglas-fir at lower elevations, and regenerate native lodgepole pine at higher elevations where it has become decadent and is undergoing active mistletoe infestation, and is therefore at increasing risk for stand-replacing fire.

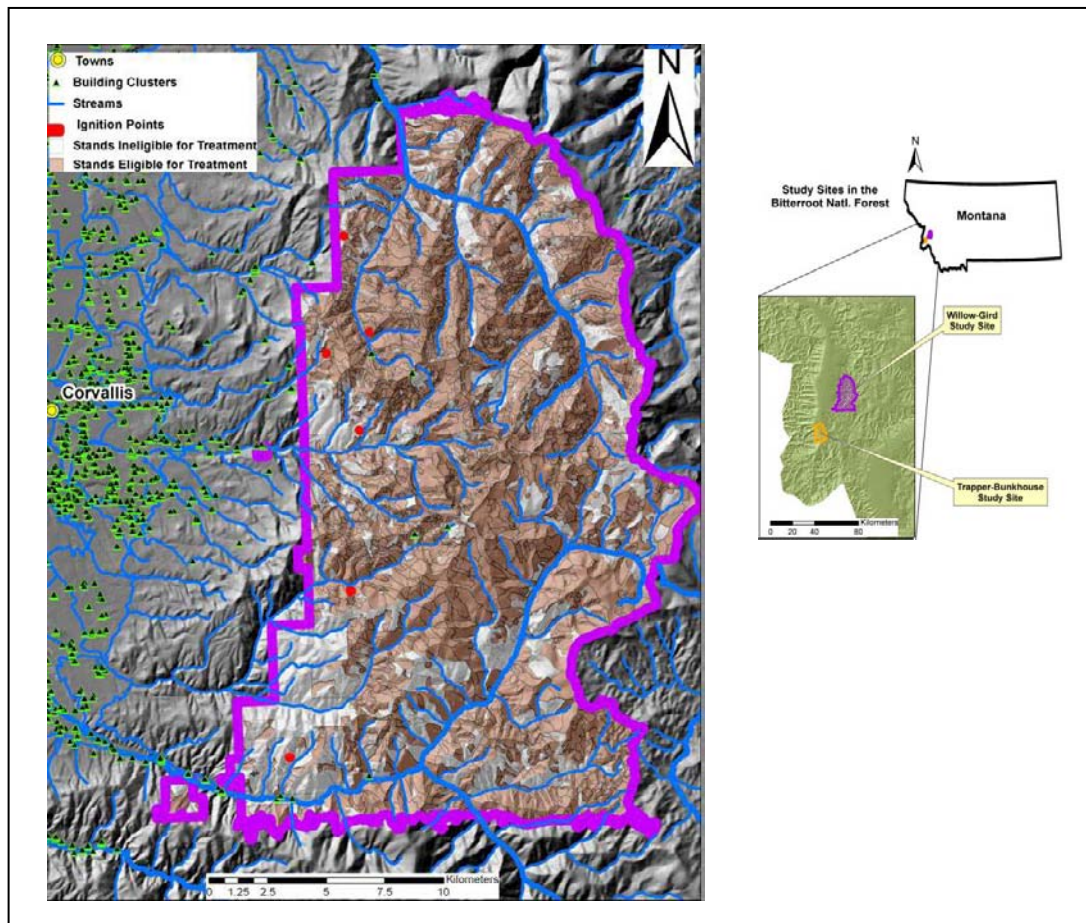


Figure 12. Willow-Gird study area.

The OptFuels model for this area contained fuel treatment options for 78,027 acres. The Restore option (same as described for the Trapper-Bunkhouse Area) was available on 23,354 acres on which prescribed burning could not be accomplished without first reducing ladder fuels. The RxFire option was available on 46,354 acres. The Lodgepole Pine Clear Cut option was available on 8,319 acres.

Five value-at-risk categories (Figure 13) were used in the expected loss calculation: 1) WUII (wildland urban interface) – extends 0.5 mile into the national forest from the forest boundary, 2) State or Private lands, 3) Timber represents national forest acres not having any other risk category, 4) Roadless Timber is designated roadless area in the national forest, and 5) Right of Way is a power-line corridor. Loss response functions from Calkin and others (2010) provided the basis for assigning percent loss by flame length categories. Percent loss in the right-of-way power-line corridor category received an importance weight of 10, wildland urban interface a weight of 5, and all other categories received a weight of 1. The fire duration probabilities were the same as used in the Trapper-Bunkhouse Study Area.

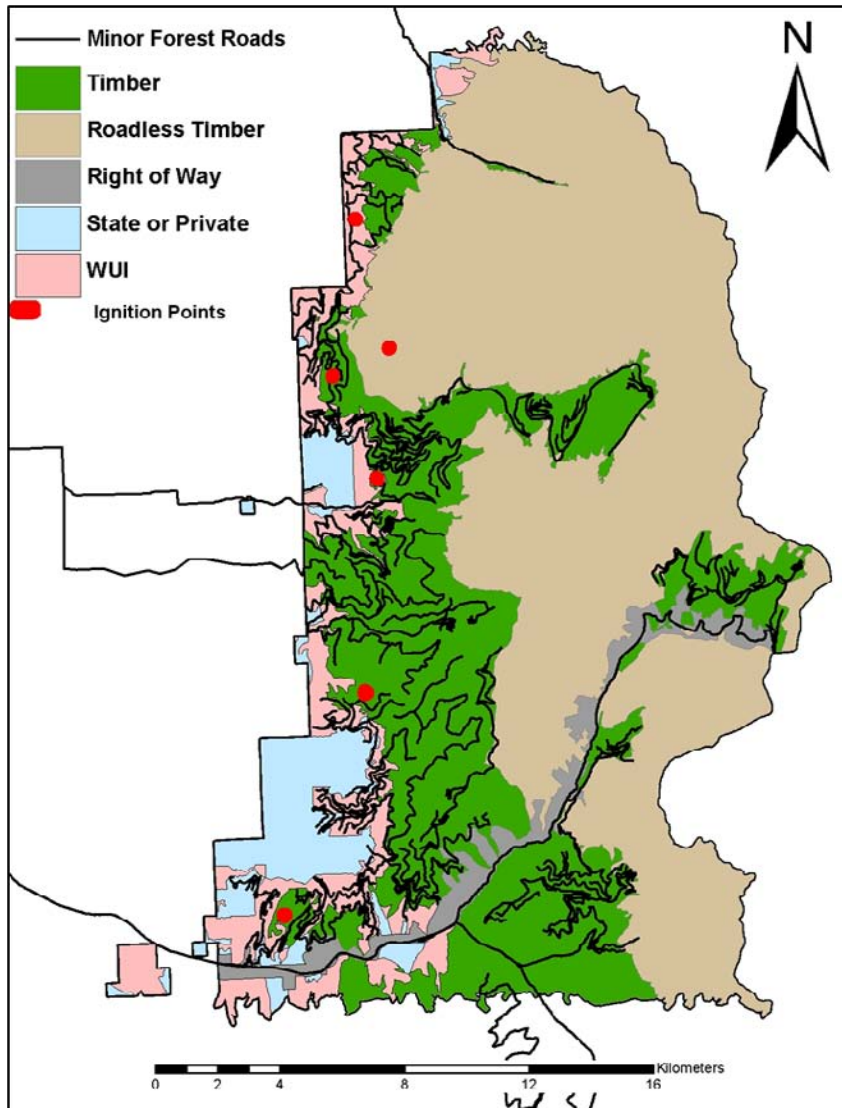


Figure 13. Value-at-risk categories for the Willow-Gird study area.

The fire scenario was the same as used in the Trapper-Bunkhouse Area except in the Willow-Gird area six ignition points were used along the west boundary to represent human-ignited fires in the wildland urban interface.

Figure 14 compares the expected loss index for no action with three treatment scenarios with increasing percentages of the 78,027 candidate acres treated per period: 6.25, 12.5, and 25 percent. While treatments increased the percent of acres in the lowest category of expected loss (drawing acres from higher expected loss categories without treatment) the amount of change was small compared to the Trapper-Bunkhouse area. This is especially true for period 2.

Figure 15 compares arrival times for the treatment scenarios and no action. Much larger differences occurred for arrival time with treatment than were shown for expected loss. Although increases in arrival time were created by the treatments, treatments were unable to

increase the arrival times sufficiently in the areas on the landscape having the highest expected loss. This occurs because of the relatively close proximity of the ignition points and the WUI which represents the greatest concentration of values at risk (Figure 13). Thus, relatively little reduction in expected loss was achieved by the fuel treatments modeled.

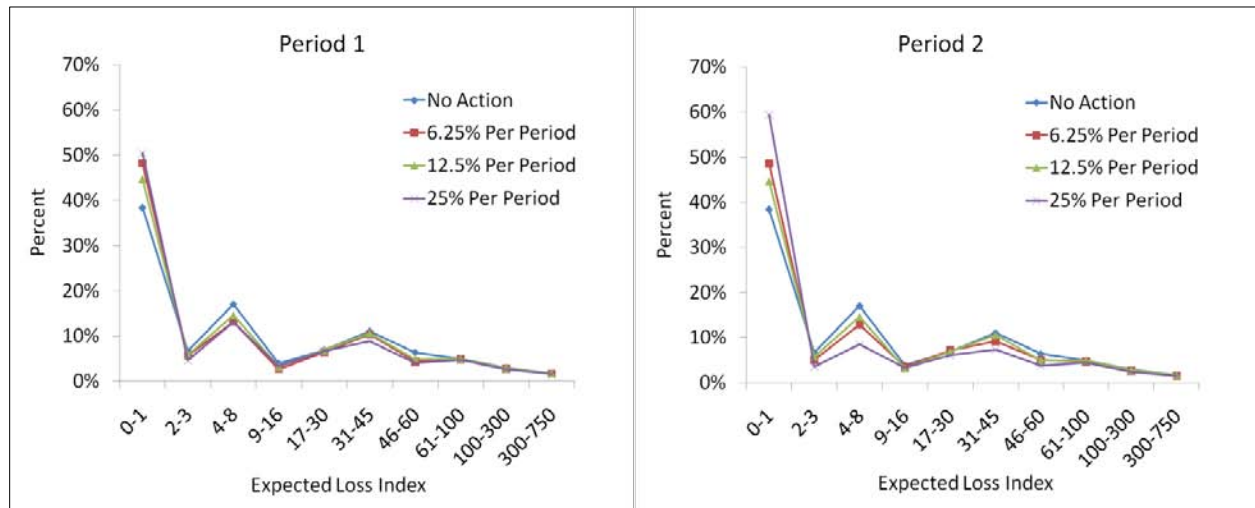


Figure 14. Expected Loss Index by percent of planning area compared across three treatment schedules and no action for periods 1 and 2.

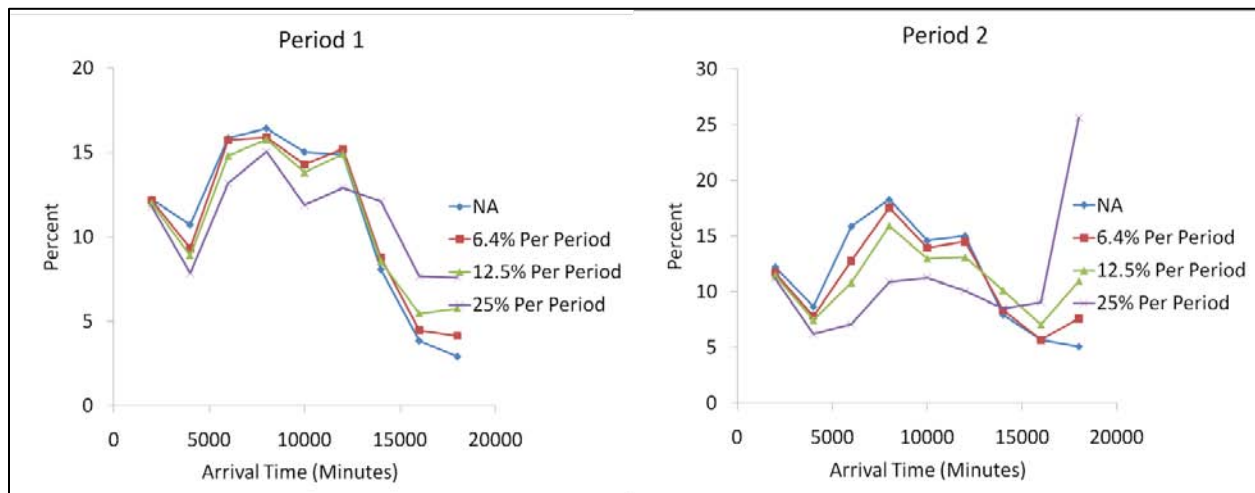


Figure 15. Expected arrival by percent of planning area time compared across three treatment schedules and no action for periods 1 and 2.

IV. Key Findings

A. Simultaneous multi-period fuel treatment analysis is feasible

This study shows that it is possible to simultaneously schedule fuel treatments across multiple planning periods, which is a computationally challenging problem. This is accomplished by computing and storing all information required by the solving process prior to entering that process. The solver makes spatial fuel treatment selections by period, and updates the landscape fuel grid files for these treatments for each planning period prior to running the minimum travel time fire behavior algorithm for each planning period. The solver also runs on a multi-processor computer to increase the efficiency of the solution process. Earlier approaches to multi-period fuel treatment planning scheduled fuel treatments for one planning period at a time without considering the continuing treatment effects in future periods and whether they can complement the effectiveness of treatments in future periods.

B. Effectiveness of system for scheduling fuel treatments across multiple planning periods

The OptFuels heuristic solver has been able to schedule fuel treatments across multiple planning periods that result in substantial reductions in the expected loss from values at risk across the landscape compared to the untreated landscape given the same fire scenario conditions. These reductions in expected loss with fuel treatment were the result of slower rates of spread (which reduces the probability that the fire duration would be sufficiently long to reach specific locations on the landscape) and lower flame lengths. Continuing effects in period 2 of fuel treatments undertaken in period 1 have been observed by comparing the arrival times and flame lengths predicted for period 2 with another scenario in which only the period 2 treatments were undertaken.

C. Limited availability of inventory data for stand polygons

OptFuels, as well as any planning process that utilizes FVS-FFE to project stand growth and predict fuel parameters for fire behavior modeling, requires FVS-ready inventory data that accurately represent each stand polygon in a planning area. Unfortunately, inventory data needed to produce FVS-ready tree list and stand data are essentially unavailable for stand polygons in forested landscapes. This means that anyone interested in conducting this type of analysis must develop FVS-ready inventory data for each polygon (or grid cell if the analysis is strictly raster-based) if the data does not exist. The best option for accomplishing this appears to be imputation, which in essence matches available inventory plots (such as FIA plots) with stand polygons.

We went through this imputation process numerous times for our two study areas using different combinations of x and y imputation variables with somewhat less than satisfactory results, using a combination of FIA plots and additional plots taken in the project area. In particular, the percent crown closures calculated for the imputed data were consistently much lower across the study area than the crown closure percentages predicted by both R-1 V-Map (Brewer and others 2004) and Landfire, which the study team believed to be a better representation of the study area. These lower density representations of the stand polygons affected the FVS-FFE simulations and the resulting fuel parameters, both with and without treatment. This in turn affected the fire behavior modeling, which even with severe fire conditions consistently predicted less severe fire for the untreated landscape than observed from recent past fires in the same general area.

D. Importance of selecting effective fuel treatment options

It is important for obvious reasons to select fuel treatment options that are effective at reducing undesired fire behavior, namely reducing the rate of spread and/or flame length. If the OptFuels solver does not have effective treatments options to select from, it cannot be expected to develop spatial fuel treatment schedules that effectively reduce expected loss from the values-at-risk on the planning landscape. Our experience has been that developing effective fuel treatment options is not as straightforward as one might think. There have been many cases in which thinning to remove ladder fuels followed by a broadcast burn to treat the activity fuels and remove small trees resulted in the same fire behavior as the untreated stand. This highlights the importance of thoroughly testing both the untreated and treated stand fire behavior while selecting treatment options for use in OptFuels.

V. Management Implications

A. Benefits to analyzing spatial fuel treatment schedules over multiple planning periods

This project has developed and tested OptFuels, an approach for spatially scheduling fuel treatments over time based on minimizing the expected loss of values-at-risk from future wildland fires. OptFuels utilizes FVS-FFE, a well known model for simulating vegetation change, and the Minimum Travel Time option in FlamMap, a well known model for simulating fire spread spatially across landscapes. The OptFuels solver accounts for treatment effects across planning periods in selecting the locations for treatments in each period. Thus the treatments selected for period 1 are not only selected for their effectiveness in modifying fire behavior in period 1, but also for their continuing effect subsequent periods, which is combined with treatments taking place in those subsequent periods.

In addition, OptFuels provides for various types of constraints that can be used to assess trade-offs to better inform decision makers. For example, multiple OptFuels runs with increasing budget constraints can be used to assess the additional fuel treatment benefits that can be achieved over time with increasing fuel treatment costs for a planning area. The effect of increasing budget levels can be measured in terms of change in fire arrival times in specific locations within the planning area, change in flame lengths in specific locations, and change in expected loss from the values-at-risk across the planning area.

Constraints on acres treated can be used to assess trade-offs associated with the amounts of specific types of treatments applied in specific management zones in a planning area. Assume for example, that mechanical fuel treatments are detrimental in a wildlife habitat management zone. Multiple OptFuels runs (in which increasingly limiting constraints are placed on acres of mechanical fuel treatments in that zone) can quantify how much fuel treatment effects are compromised across the landscape by reducing or eliminating mechanical treatments in that zone.

In addition, the connection with FVS provides OptFuels with the ability to estimate wood products and woody biomass that is produced by mechanical fuel treatments. Both the volume and value of wood products can be estimated, as can the net value (revenue minus cost) of mechanical fuel treatments.

The capability of OptFuels to spatially schedule fuel treatments over multiple planning periods and to constrain those treatment schedules in a variety of ways provides the ability to quantify trade-offs between fuel treatment objectives and other resource management issues and constraints.

B. Important to support development of landscape GIS vegetation coverage with FVS ready data

OptFuels as well as any planning process that utilizes FVS-FFE to simulate stand growth and predict fuel parameters for fire behavior modeling requires FVS-ready data that accurately represent each stand polygon in a planning area. This problem has been addressed in the research community by statistically imputing FIA and other available plot data to either stand polygons or directly to grid cells. This process is quite technical and as of this report has provided less than satisfactory representations of the landscape vegetation on the two study areas in this project (see Key Findings section). We believe it will be difficult for field users to go through the imputation process for each fuel treatment planning area they want to analyze spatially over time. This data issue threatens to hamper the use of this suite of analysis tools. Thus, we believe it is important for management to support development of landscape GIS vegetation coverage with FVS ready data.

C. Important to support development of workforce skills with the models employed by OptFuels

The models employed by OptFuels as well as OptFuels itself require GIS and other computer skills. It is important to support the development of these skills in the workforce for these models to be used effectively. In addition, these models can be run most efficiently by people who work with them on a regular basis. It is difficult for anyone to be proficient at running these models when it is done only once or twice a year. This suggests that the most cost-effective way of organizing work assignments is having a substantial portion of a position devoted to performing analyses with these models, perhaps serving multiple ID team zones or even multiple forests.

VI. Relationship to Other Recent Findings and Ongoing Work

Finney and others (2006) developed a system for spatially placing fuel treatments on a landscape over multiple planning periods to minimize undesired fire behavior. That system stepped through the analysis sequentially, one planning period at a time. After treatments for a period were selected using the TOM (Finney 2006), the post treatment landscape was projected to the next planning period using a custom version of the Parallel Processing extension of FVS (Crookston and Stage 1991). Although their conceptual design for modeling across multiple periods differed from the design we wanted to implement in OptFuels, discussions with the authors of that study were very helpful.

The expected loss computation used by the OptFuels heuristic solver is adapted from the expected net value change calculations in Finney (2005), Ager and others (2007), and Calkin and others (2010). The method of expressing loss as a result of fire as a percentage reduction in value by flame length categories was adapted from Calkin and others (2010).

This JFSP study provides the basis for a new study centered in the Lake Tahoe Basin. The objective of this new study is to develop an integrated decision support system that optimizes fuel treatment locations in time and space that can also achieve multiple management objectives. Management objectives will be implemented in a flexible manner and can include the reduction of the probability of catastrophic fire, the reduction of sediment inputs into Basin streams, the promotion of species of special concern, among others. The system will identify where, when, and how to treat fuels to maintain desired fuel reduction, forest restoration, and water quality goals at a landscape scale.

The Joint Fire Science Program, the National Wildfire Coordinating Group Fuels Management Committee, and Sonoma Technology, Inc have developed a conceptual design for the Interagency Fuels Treatment - Decision Support System (IFT-DSS). The IFT-DSS organizes fuels-planning software and data into a seamless user environment. OptFuels could provide the process in IFT-DSS for scheduling fuel treatments spatially. OptFuels utilizes FVS-FFE and fire behavior modeling for fuel treatment analyses in the same ways as does IFT-DSS. As a result, the vegetation and fuels data used in OptFuels are the same as well. We will continue to investigate the option of integrating OptFuels into IFT-DSS.

VII. Future Work Needed

A. Modify the heuristic solver to analyze the effectiveness of fuel treatment patterns on two or more fire conditions simultaneously

The current version of the heuristic solver schedules fuel treatments spatially to minimize the expected loss in values-at-risk for one fire scenario (ignition points, wind direction and speed) at a time. Solving for different fire scenarios separately is likely to schedule fuel treatments in different locations, leaving unanswered the question “What is the best pattern of treatments to minimize expected loss from these two fire scenarios over multiple periods?” In future work we plan to add the capability of developing fuel treatment schedules that minimize expected loss for a small number of fire scenarios of concern. This will involve modeling fire behavior for each of these scenarios (rather than just one scenario) at each iteration in the solution process. Users would weight these alternative fire scenarios based on their relative importance in fuel treatment planning.

B. Develop processes to assist users with preparing input data

OptFuels, as well as any planning process that utilizes FVS-FFE to project stand growth and predict fuel parameters for fire behavior modeling, requires FVS-ready data that accurately represent each stand polygon in a planning area. Unfortunately, FVS-ready data are not generally available for an entire landscape. Associating inventory data (such as FIA plots) to either stand polygons or directly to grid cells is most often accomplished by statistical imputation. This process is quite technical and as described in the Findings section, use of this technique on our study areas provided less than satisfactory representations of the landscape vegetation. Processes are needed to help fuel treatment analysts through the imputation procedures. Alternatively, agencies could supply FVS-ready data to potential users.

C. Investigate evolutionary optimization algorithms and implement the best choice in OptFuels to run the system in a multi-threading environment to more efficiently solve the large combinatorial optimization problem of fuel treatment scheduling

OptFuels currently employs a simulated annealing (SA) algorithm for its optimization engine. While SA is known as an efficient neighborhood search algorithm for solving large combinatorial problems, it is not ideal for a multi-threading/multi-processing environment due to its sequential approach to generate and evaluate neighbor solutions. In the future work, we plan to investigate evolutionary optimization algorithms, such as the genetic algorithm (GA) and genetic programming (GP), and implementing the best choice in OptFuels so that the system can be more efficiently run in a multi-threading/multi-processing environment. This modification is expected to largely reduce the system's computation time for developing quality fuel treatment schedules.

D. Integrate FARSITE into OptFuels through dynamic link libraries (DLL) to simulate fire behavior under varying weather and fuel conditions

In the future work, we plan to build a linkage between OptFuels and FARSITE using the FARSITE DLL. OptFuels currently employs FlamMap to estimate changes in fire behavior as the effects of fuels treatments across a landscape. However, FlamMap assumes constant weather and fuel moisture during its run. FARSITE overcomes this limitation and can provide more realistic fire behavior simulation with varying weather and fuel moisture conditions. The FARSITE dynamic link library (DLL) is currently under development by the RMRS Fire Sciences Lab, and will be available soon. We plan to use the DLL to dynamically link FARSITE with OptFuels for automatic data transfer during the program execution.

E. Analyze the effects of treatment polygon size (project area) on solution quality and efficiency

Dealing with individual stand polygons entails a large number of decision variables in the solution process, which increases the size and complexity of scheduling problem. In addition, decisions made on individual polygons that are independent from neighboring polygons makes it difficult for the solver to efficiently converge to the optimal or near-optimal solutions because there is a relatively small chance to simultaneously select adjacent polygons for treatment and thus the synergic effect of treating a larger and contiguous area is not easily evaluated by the solver. To further improve the efficiency of solution process in the solver, we plan to pre-define groups of treatment polygons where treating a larger and contiguous area can generate bigger treatment effects than small, distant polygons of equal total area. Decisions within the heuristic solver will be then be evaluated and made on groups of polygons in the solver as opposed to individual polygons. This will result in much fewer decision variables and narrower solution space to explore.

VIII. Deliverables Cross-Walk

Proposed	Delivered	Status
Data transfer interfaces between MAGIS, FlamMap and FVS-FFE that automate and integrate model information.	OptFuels application interfaces that include windows data entry forms, program procedures, and a recommended method for using FVS-ready data for landscape-level vegetation and fuels simulation.	Prototypes ready 2008. See Integrated DSS entry below.
Heuristic optimizer that integrates resource issues/economics with fire behavior projections for various treatment options.	C++ executable. Requires multiprocessor machine for reasonably timely results. Prototype FIREMAGIS.exe	1. First version integrated with OptFuels October, 2009. 2. Solver is functional Feb. 2010. 3. In Progress: testing with different data sets.
Integrated decision support system (DSS) with enhanced solution display to optimize fuel management schedules with enhanced GIS-based solution displays for MTT results.	Decision support system that integrates GIS, FVS-FFE, and FlamMap as a single user-driven application (OptFuels). Generates optimal feasible schedule of fuel treatments. Outputs GIS maps and files of solutions. Outputs FlamMap FMP file to allow user to run MTT on solution landscape files.	Complete (beta) version with working interfaces and procedures. Solutions can be analyzed with MTT and ArcGIS. In progress: solution reports and procedures for GIS statistics.
Test models using data from National Forest(s) with input from local management for resource objectives and constraints.	Test models from Bitterroot National Forest analyses: Willow-Gird and Trapper-Bunkhouse.	1. Trapper-Bunkhouse, September 2008. 2. Willow-Gird, May 2009. 3. Maps posted on JFSP website.
Workshops with field managers: 1. Gather feedback on proposed system 2. Present system to potential users	1. 'FIREMAGIS' workshop held September 2008. 2. Workshop scheduled April 2010.	1. Powerpoint presentation on JFSP website.
JFSP reports	Annual and final reports.	Completed, posted on JFSP website.
Publications and Presentations 1. Development. 2. Effects of budget constraints.	1. OptFuels: Optimizing Placement of Fire and Non-fire Fuel Treatments over Time at Landscape Scales.	1. Paper presented at AFE 4 th International Congress on Fire Ecology & Management. Savannah, GA Nov 30- Dec 4, 2009.

	2. Developing a Decision Support System to Optimize Spatial and Temporal Fuel Treatments at a Landscape Scale. 3. OptFuels: A decision support system to optimize spatial and temporal fuel treatments. 4. Effects of budget constraints on optimal hazardous fuel reduction treatment scheduling using fire behavior modeling.	2. Paper presented at Council on Forest Engineering, Kings Beach, CA June 15-18 2009. 3. Presented at the 13th Symposium on Systems Analysis in Forest Resources, Charleston, SC May 26-29, 2009. 4. In progress.
DSS Technology transfer: Website and User Documentation with active tutorials. DSS Distribution System for Software Delivery: Installation package and software delivery system (ftp and website for downloads and updates).	1. Project website: www.fs.fed.us/rm/human-dimensions/optfuels 2. Draft user guide and tutorial: www.fs.fed.us/rm/human-dimensions/optfuels/OptFuelsUsersGuide.pdf	1. Project Website live. 2. In progress: Userguide (draft manual posted), context-sensitive help, tutorials, installer.
Other Presentations / Posters.	1. Spatial and Temporal Optimization of Fuel Treatments. 2. OptFuels: Optimizing Placement of Fire and Non-fire Fuel Treatments over Time at Landscape Scales. 3. Fire-MAGIS: A Decision Support System to Optimize Spatial and Temporal Fuel Treatments at Landscape Scales. 4. Optimizing Spatial and Temporal Treatments to Maintain Effective Fire and Non-fire Fuels Treatments at Landscape Scales.	1. Poster presented at the 5th Biennial Lake Tahoe Basin Science Conference, Incline Village, NV, March 16-17, 2010. 2. Poster presented at AFE 4th International Congress on Fire Ecology & Management. Savannah, GA Nov 30- Dec 4, 2009. 3. Poster presented at IUFRO All-D3 Conference, Sapporo Japan, June 15-20, 2008. 4. Poster presented at International Mountain Logging and 13th Pacific Northwest Skyline Symposium, Corvallis OR April 1-6 2007.

	5. Optimizing Spatial and Temporal Treatments to Maintain Effective Fire and Non-fire Fuels Treatments at Landscape Scales	5. Poster presented at 2 nd Fire Behavior and Fuels Conference, Destin, FL March 26-30, 2007
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