Considerations in the Use of Models Available for Fuel Treatment Analysis

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***Abstract**—Fire managers are required to evaluate and justify the effectiveness of planned fuel treatments in modifying fire growth, behavior and effects on resources and assets. With the number of models currently available, today's fire manager can become overwhelmed when deciding which model to use. Each model has a required level of expertise in order to develop the necessary data, run the model(s), and analyze and interpret their associated outputs. In addition, each model has an appropriate temporal and spatial scale for its use, e.g., stand level versus landscape level. Traditional fuel treatment analyses have focused on stand level changes in fire behavior and effects. This approach does not to account for the topological effects of treatments in modifying fire growth, fire behavior and fire effects. To fully investigate fuel treatment effectiveness requires the examination of the spatial interaction of fuel treatments. This requires the use of spatial models to analyze and display these effects.*

Introduction

The fire behavior triangle consists of fuels, weather, and topography. The only element managers have direct control over is fuels. Management strategies of the 20th century, and the unintended consequences of fire suppression have contributed to the increase in large fires across the western U.S. (Agee and Skinner 2005). During the time period 1970-2002, 97-99% of all fires reported on U.S. Forest Service lands were still less than 121 ha (300 acres) (Calkin and others 2005) suggesting that suppression is still effective on small fires. However, 1.1% of all fires (greater-than 121 ha) during this time period accounted for 97.5% of the burned area and current data trends suggest that the number of large fires and their average size is increasing (Calkin and others 2005). It is the 1% of fires that are of greatest concern because of their effect across large portions of forested landscapes. This is the great irony of successful fire suppression; past success has contributed to failure today (Brown and Arno 1991; Agee and Skinner 2005).

The success of fire suppression, especially in dry forest types of the western United States has lead to drastic changes in the horizontal and vertical continuity of fuels as well as a buildup of surface fuels (Agee and Skinner 2005). This success has changed the fire regime from frequent low-intensity surface fires to more intense fires capable of becoming crown fires in these forest types (Arno and Brown 1991; Agee and Skinner 2005). The accumulation of fuels contributing to larger fires in the future has long been identified (Weaver 1943; Dodge 1972; Brackebusch 1973). Individual large fires as well as large scale fire events since 1988 have garnered much political attention and resulted

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in numerous reports by federal land management agencies (for example, 10-Year Cohesive Strategy; National Fire Plan). The focus of these reports on fuels treatments and fuels management aimed at reducing "catastrophic" and large wildfires resulted in increased funding for these activities.

In the last decade the annual area burned by wildfire has continued to rise despite an increase in funding for fire suppression resources and fuel hazard reduction projects (Stephens and Ruth 2005). This should not be a surprise for several reasons. There is an inherent delay from the initial identification and funding to implementation of projects. It takes time to work through the NEPA process and then implement the plans. Additional delay or failure to implement a planned project can occur due to funding availability, personnel availability, weather conditions and administrative appeals or litigation (GAO 2003a). Also, the amount of area treated nationally has been focused around high-risk high priority areas, primarily Wildland Urban Interface (WUI) where from 2001-2004 greater than 65% of available fuel treatment monies have been spent and more than 50% of the treated acres have occurred (USDI-USDA 2006). As such, the opportunity for wildfires to test fuel reduction treatment areas at a landscape scale and their potential effect on reducing fire size and changing fire movement has likely been low. Lastly, most projects fail to adequately analyze treatments from a spatial perspective. While treatments are often recognized as having a positive localized effect on fire behavior and fire effects (Graham and others 1999; Graham and others 2004) the topological effect of strategically placed treatments designed to interact with one another at changing fire movement and size across a landscape are not (Finney 2001, 2003; Agee and Skinner 2005; Finney and others 2005). Thus, large fires still generally have free reign to move across the landscape essentially unimpeded.

This has lead to a number of reports and reviews of Federal agencies' fuels management practices, primarily by the General Accounting Office (GAO). Most, if not all are critical of federal agencies in this area. Criticisms include a need for improved planning to identify and prioritize those areas needing treatment (GAO 2003b) and that a systematic and defendable approach was not being used to assess risks and environmental consequences of fuels treatments as well as taking no-action, e.g., no fuel treatment (GAO 2004). No treatment is still an action and not always with the desired outcome (Agee 2002).

The General Accounting Office (GAO 2004) identified that neither the Forest Service nor Bureau of Land Management (BLM) have an institutionalized systematic way to analyze fuel treatment effectiveness at the landscape level. Furthermore, it concludes that fire management planning guidance is not specifically provided by the National Environmental Policy Act (NEPA) on how fuel management projects are to be accomplished (GAO 2004). Franklin and Agee (2003) also identified a need for a comprehensive national fire policy dealing with all aspects of wildfire management including, fire suppression, fuels management and issues surrounding when, how, and why fuels projects are conducted, as well as salvage and restoration treatments following wildfire events.

However, localized grassroots efforts have been undertaken to look at fuels treatments at the landscape level and the topological interaction of fuel treatments. The Fireshed Assessment Process as developed in the Pacific Southwest Region (R-5) of the USDA, Forest Service is one such program. Fireshed assessments offer a methodology to assess the strategic placement of treatments across large landscapes that are meant to interact with each other in reducing adverse fire behavior and ecological effects (Bahro and others, in press).

In the past fire managers were left to their own devices when it came to analyzing fuel treatments and navigating through the often confusing and contradictory list of models to choose from. Currently an abundance of tools exists with a dearth of data, especially for spatial fire models, and the local manager is often uncertain as to which model to select and how to go about the process. Recent publications (Graham and others 1999, 2004; Agee and Skinner 2005; Peterson and others 2005) have provided the principles, concepts, effects, and scientific basis for changing stand structure through the use of thinning, prescribed fire or a combination of these on altering fire behavior and fire effects. However, rarely is there an in-depth discussion of various fire decision support systems for analyzing pre- and post-treatment effects. The goals of this paper are to leave the manager with information on models and modeling concepts, a general discussion of fuel treatment analysis, and the models currently available for conducting these types of analyses.

Models in General

Models are used for a variety of reasons such as making inferences concerning processes and parameters of interest, determining potential effects of management actions or changes in environmental conditions on the subject of interest, evaluation of management alternatives by displaying the modeled effects, to display or communicate the effects of changes to concerned parties or in public meetings, and to test theories and assumptions one may have about conditions that can not easily be accomplished with formal experiments, for example, crown fire experiments.

Modeling itself is both an art and a science (Burnham and Anderson 1998). Modeling is an art because one must understand the inner workings of the model and the data and how adjustments must be made to achieve realistic, defendable, and quantifiable results. It is a science, because the user must have a fundamental understanding of the biological, mathematical and statistical relationships contained and used within the model as well as the assumptions and limitations inherent to the model. The user must be cognizant of the limitations and assumptions of the respective model, realize that all models need to be validated and calibrated to some past or current documented and observed condition, and that all results need to be tempered based on the user's experience, knowledge and observations.

It is incumbent on the end user to understand and comprehend these issues. After all, good models used poorly are no better than guessing. One must remember that all models are simplifications of reality (Burnham and Anderson 1998). If the model developer adheres to the concept of parsimony then the model itself cannot hope to account for all the complexities and interactions encountered in the modeling of natural or biological phenomena. A statement that rings very true is "All models are wrong but some are useful" (Box 1976; Burnham and Anderson 1998). Therefore the end user must accept and realize that some level of error and uncertainty exists, even if the "best" available model is used.

The advantage of using models is they have often undergone some type of peer review process, either through academia, evaluation through the formal publication process or by use and acceptance by experts in the field. Models generally incorporate previously published relationships, interactions or equations often bundling them as sub-models into a decision support system (Finney 1998; Andrews and Queen 2001). By using widely accepted, formally published and peer reviewed models one can state they are using the best available science for the time in their analysis. Models also provide an instrument to quickly evaluate multiple sets of conditions, alternatives, and theories or assumptions the end user may have.

However, models have a downside. Models that operate at the landscape scale are data intensive and require a certain level of expertise by the end user. Because computers are capable of making very fast and very accurate mistakes, the modeled solution may become generally accepted as fact. That is, it does not matter about the quality of the data, the expertise of the user, the applicability of the model to appropriately assess the situation or the interactions of all these in contributing to the solution. A common mantra is "Garbage In Garbage Out (GIGO)" perhaps a more appropriate revision would be the warning "Garbage In Gospel Out."

Models do not replace your knowledge and experience; beware of falling into the "Black Box Syndrome." The nirvana of modeling expertise and understanding tempered with an adequate knowledge and expertise in fire behavior is difficult to achieve and not often found. Harry T. Gisborne (1948), one of the founding fathers of fire research coined the term, experienced judgment, and defined it as: Opinion based on knowledge acquired by experience. However, Harry also points out the following (Gisborne 1948, page 23):

> "If you have fought forest fires in every different fuel type, under all possible different kinds of weather, and if you have remembered exactly what happened in each of these combinations your experienced judgment is probably pretty good. But if you have *not* fought all sizes of fires in all kinds of fuel types under all kinds of weather then your experience does not include knowledge of all the conditions."

Sage advice and something to consider, especially when model outputs are contrary to *your* experienced judgment. When this occurs it is easy to disregard the model output as spurious and thus unworthy of consideration. However, are the results flawed due to the data, the model or the user, or are there other plausible explanations? Are the results within your acquired knowledge base? Are the model parameters outside those you have experienced first-hand? Perhaps the model has shown you some possible outcome that you have not considered or previously experienced. While all model output should be evaluated with an appropriate level of skepticism, do not disregard it off-hand without due consideration.

Error Sources

General sources of error in the modeling process can be attributed to the data, the user, the model or the complex intersection and unions of these respective areas (Personal Communication, Dave Sapsis) (Figure 1). From personal experience, data and associated issues can account for up to 75% of encountered modeling difficulties. For example, Jones and others (2004) found that errors in the fuels map resulted in greater changes to model outputs than errors in terrain while erroneous weather information resulted in highly unstable outputs for a wildfire threat model for Australia. The remaining general sources of modeling error can be attributed to the user, model and interactions of error components (data, user, model).

Spatial modeling requires a seamless landscape of data attributes regardless of ownership or jurisdictional boundaries. Rarely, do the necessary data exist wall-to-wall thus necessitating some larger modeling exercise be undertaken

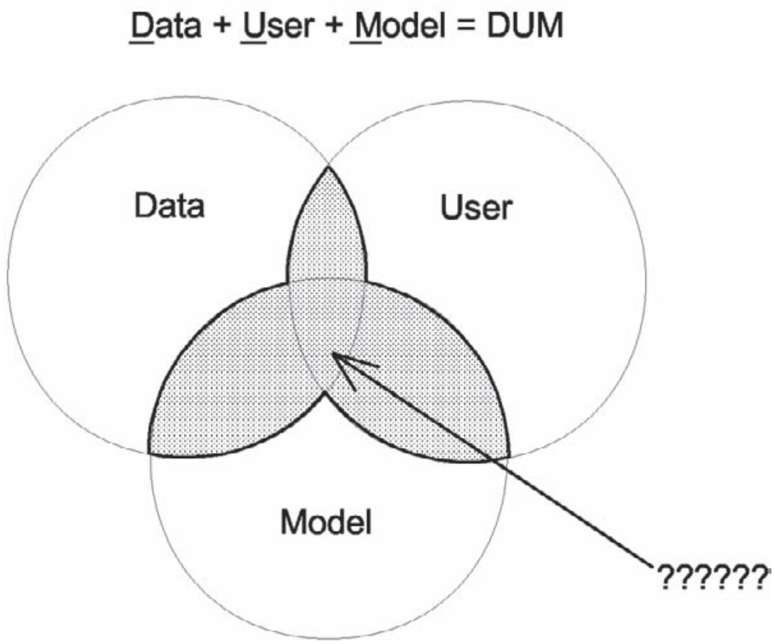

Figure 1—Components of modeling errors and their respective interactions.

to populate the landscape. This is typically accomplished using biophysical attributes, remote sensing, and statistical techniques such as Most Similar Neighbor (MSN; Crookston and others 2002) or Gradient Nearest Neighbor (GNN; Ohmann and Gregory 2002). Issues related to data such as inappropriately collected field data, limitations of the data in modeling natural or biological phenomena, inappropriate construction of data sets, assignment of the wrong units associated with the data, extrapolation of existing data to areas without data based on some other modeling exercise, and inappropriate rule sets used to develop data sets given the respective ecology and biological processes for the area. Additionally, data are often developed over large areas and assumed to represent some homogeneous condition within an artificially assigned boundary, such as a timber-stand. Because of this assumption critical data attributes may often represent the "average condition" for data values. This can have adverse consequences for some fire behaviors such as crown fire. In these instances the "average" crown base height likely does not reflect the minimum values that permit crown fire to initiate. Rarely, does the average condition account for problem fire behavior (Fulé and others 2001; Scott and Reinhardt 2001).

The end user can introduce error into the process by using an inappropriate model or user-defined model settings, simulating scenarios outside the limitations and assumptions of the model, from errors introduced during input of data, and in output interpretation. All models have assumptions and limitations associated with them. Error associated with the limitations of the data used to develop the model, using the model for phenomena outside that which the model was intended for and the models themselves have an associated error factor.

Finally, the area where all three components interact through the process of compensating errors can introduce uncertainty into the modeling process as well. Results may be correct or incorrect and the complexity of these interactions can make it difficult to discern which component is contributing to the modeled outcome.

Modeling Process

Fire modeling should not be thought of as a linear process, but rather as an open system of feedback loops whereby each idea can interact with the other causing a completely open system (Figure 2). While the following is offered in a linear fashion it is only to facilitate discussion and not intended to imply a linear, step-by-step operation.

- Define the modeling objective or question
- Model selection based on modeling objective or question
- Spatial and temporal data development required by selected model
- Gather supporting spatial and temporal data
- Data critique and analysis of developed data
- Calibration of the model to a past event(s)
- Simulations, evaluation and critique of results, and documentation
- Gaming-out, and what-if scenarios of fuel treatment location and prescription
- Evaluation, write-ups, and presentation of results

The framing of any project and defining the question or objective in a very specific nature is critical to selection of an appropriate model. For example, fuel treatments should be designed for a specific prescription of wind, weather and fuel moistures, should identify and target those fuel properties able to impact the targeted fire behaviors, e.g., surface fire versus crown fire, and take into account the short lived nature of treatments (Finney 2001; Finney and Cohen 2003; Agee and Skinner 2005; Finney and others 2005). Objectives and treatment prescriptions must be specific if the analysis is to adequately address the identified problem. Finally, after the questions and objectives have been defined this will assist in guiding one to a likely list of models to select from.

However, choosing the appropriate model is also data dependent. If a model relies on spatial data, these data must be available. If not, what data do you have and how long will it take to collect and develop the missing data sets? Can you develop the required data and still meet project deadlines? Are the data you have appropriate for the question you want to answer? For example, to examine the occurrence of crown fire do you have the additional required information (crown base height, crown bulk density, and stand height)? Do monitoring data exist from past fuel treatment or timber sale projects that could provide information on fuel models, fuel loadings and stand structure pre- and post-treatment? Additionally, does monitoring data from previous prescribed burn projects within treated areas exist that could provide insight into fire behavior and intensity following treatment? Monitoring data from previous projects, informal feedback, and an adaptive management approach is useful in developing and refining data and modeling scenarios as well as in the evaluation and validation of simulation results.

Temporal information on weather, wind, and fuel moisture parameters for the model will also be needed. This requires the user acquires, critiques,

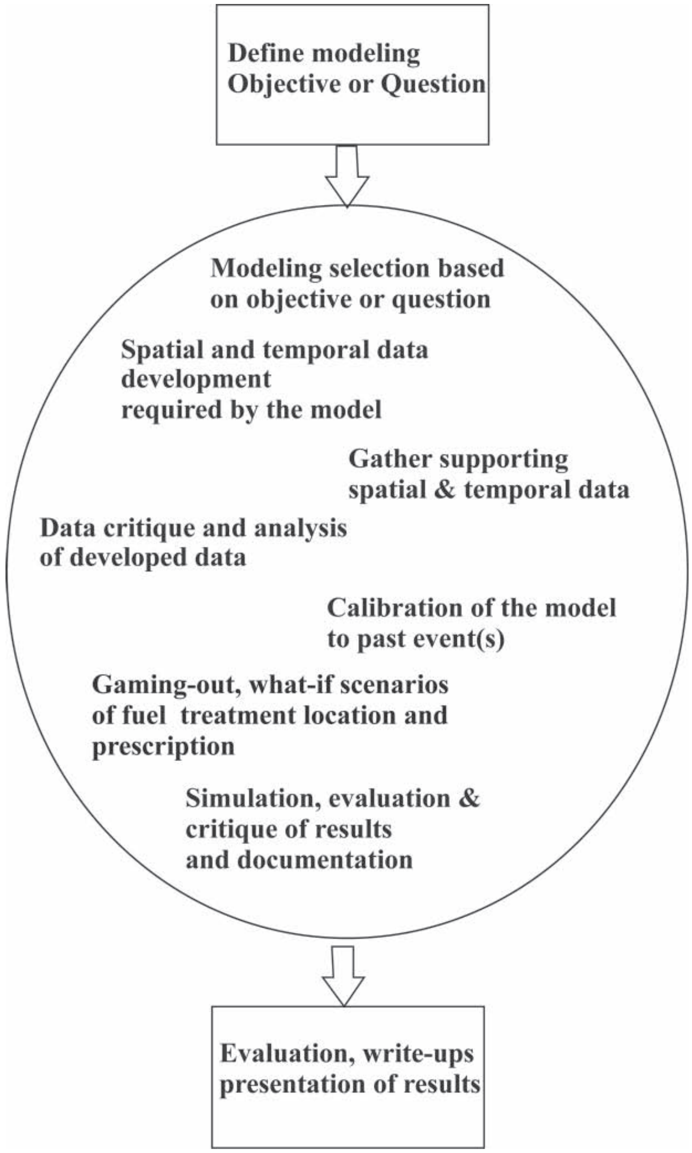

Figure 2—Conceptual representation of the modeling process. The process should not be considered linear in nature but rather as an open series of feedback loops within the circle.

analyzes historical climatological data or base all modeling scenarios on well known critical fire weather and fuel moistures for the respective area. Other potential sources of this information include fire behavior summaries from past fire events or monitoring reports from previous prescribed burn projects. Either can be very useful in the calibration of simulations and in developing critical fire weather and fuel moisture information for modeling scenarios.

Critique and analysis of weather data can be performed using FireFamily Plus (Bradshaw and Brittain 1999; Bradshaw and McCormick 2000). FireFamily Plus allows the user to interrogate historical climatological information for erroneous data as well as summarize fuel moistures and analyze critical weather and wind variables. Prior to any analysis the user should evaluate the values recorded for windspeed and direction, temperature, relative humidity, and precipitation amount and duration for erroneous values.

The modeler should also be cognizant that windspeed values based on the reported observation time from the selected Remote Automated Weather Station (RAWS) will likely be too low for most extreme fire weather modeling scenarios. Crosby and Chandler (1966, 2004) provide some guidance on interpolating average wind speeds to maximum wind speeds and the probable momentary gust speed. Another option is to access the Western Regional Climate Center's RAWS climate archive (http://www.raws.dri.edu/index.html). From this location one can access the hourly wind information for 10-minute average as well as the peak gust speed and direction, conduct a wind probability analysis and develop a Wind Rose for an individual RAWS station.

The gathering of ancillary spatial data can be very useful in providing spatial context to simulations and greatly assist in the critique and analysis of data and model outputs. At a minimum the following data should be considered; fire history (point, polygon, and progression), roads, hydrology, ownership, and vegetation.

Data critique and review should be considered an ongoing and never ending practice throughout the modeling exercise. During this process it is important to document your modeling assumptions, weather/wind and fuel moisture development used in simulations, limitations in the data, and data/model interactions. Data critique and review should take place during the initial spatial and temporal data development, immediately following the completion of data development, during the calibration of datasets to past fire events, during actual simulations, and again while analyzing model outputs. Critique of data during simulations and post-simulation is critical. Often, erroneous results due to model and data interactions will not manifest themselves until model simulations are run. Error examples may include but are not limited to the fire moving in the wrong direction, due to bad wind direction information, or too little crown fire activity due to the interaction of crown base height and fire behavior model.

Calibration can be defined as a procedure by which the factors controlling fire growth are verified and adjusted to make the predicted fire behavior match the observed or past event as closely as possible (Personal Communication, Robert C. Seli). Calibration of modeling scenarios to past events is critical. Calibration provides a mechanism for testing interactions of the data and model, allows one to evaluate model and data performance in predicting or matching to past documented fire events, provides insight into the respective fire models and how the interactions of data and user-defined model settings can affect modeled outputs. Additionally, and most importantly, it provides a means to evaluate the relevancy and accuracy of the data and instill confidence in future modeling projections.

Simulations allow the user to test silvicultural and fuel treatment prescriptions, treatment location and size and their effectiveness in altering fire behavior and growth under specified wind/weather and fuel moisture conditions for a specific project. However, simulations can also be used to game-out different scenarios which is critical in evaluating treatment locations, treatment prescriptions, and their effectiveness. The modeler can efficiently evaluate changes in treatment location, prescription intensity, treatment effectiveness, and treatment longevity based on temporal changes to fuels, stand structure, and user defined model settings. With the gaming-out of each new scenario an alternative pattern of treatment locations and prescription can be evaluated providing insight into fire spread and behavior across a landscape under various ignition locations, model duration, and wind/weather, and fuel moisture scenarios (Bahro and others, in press).

Evaluation and critique of results not only occurs during calibration but during modeling scenarios. This provides another opportunity to evaluate predicted fire behavior and fire growth, the review of spatial and temporal data quality and model-data interactions. It is important the user consider the predicted fire behavior and growth for the fuels and weather conditions, the effects of user-defined model settings and whether the selected model is appropriate for the simulated fire type. At this stage, documentation of results, user-defined model settings, wind/weather and fuel moisture values and assumptions concerning changes to landscape data pre- and post-treatment, fuel model assignment logic, treatment time span and time since treatment, and an organized filing structure is encouraged. Having a succinct and organized record of what was done can prove to be very beneficial in the future.

Evaluation and presentation of results following fuels treatments is the last 5% of the process and perhaps the most critical. Analyzing the results appropriately and presenting them in a concise and meaningful manner can be difficult. The modeling results should demonstrate reduced fire damage from an ecological standpoint, and show improved controllability, e.g., increased line production rates, reduced rates of spread, reduced spotting, changes in the proportion of crown fire type, thus allowing for flexibility in employed tactical and strategic options. This section should also address short and long-term risks, fire effects, fire behavior, and compare and contrast the consequences of no fuel treatment to conducting fuel treatments.

Fuel Treatment Analysis

In the dry forest types of the western United States the effect of fuel treatments on fire behavior at the localized or stand level is well documented (Graham and others 1999, 2004; Graham 2003; Finney and others 2005; Peterson and others 2005; Raymond and Peterson 2005; Cram and others 2006). Documentation has consisted of anecdotal and observational, literature reviews, theoretical analyses, and more recently empirical evidence. Published papers on this topic have done an adequate job of identifying and reviewing past work in these areas (Graham and others 1999, 2004; Raymond and Peterson 2005; Stephens and Moghaddas 2005b; Cram and others 2006). Due to the opportunistic nature of wildfire impact studies, empirical evidence of fuel treatment efficacy has been severely lacking. However, empirical evidence on the efficacy of fuel treatments is becoming more evident and for a larger portion of the western United States (Pollet and Omi 2002; Agee and Skinner 2005; Finney and others 2005; Raymond and Peterson 2005; Cram and others 2006). In some instances, the effects of fuel treatments have been captured by Landsat-7 satellite imagery (Figure 3), the most demonstrative to date has been the Rodeo-Chediski fire in northern Arizona (Finney and others 2005).

Fuel Treatment Principles

Fuels treatments can be effective when they are targeted at specific components of the fuel complex; specifically surface, ladder and canopy fuels (Agee 1996; Scott and Reinhardt 2001; Finney 2004; Graham and others 2004; Agee and Skinner 2005; Peterson and others 2005). Treatment of these fuels components should occur in a hierarchal manner from the bottom up (Figure 4) with the following order of precedence: 1) Surface fuels, 2) ladder

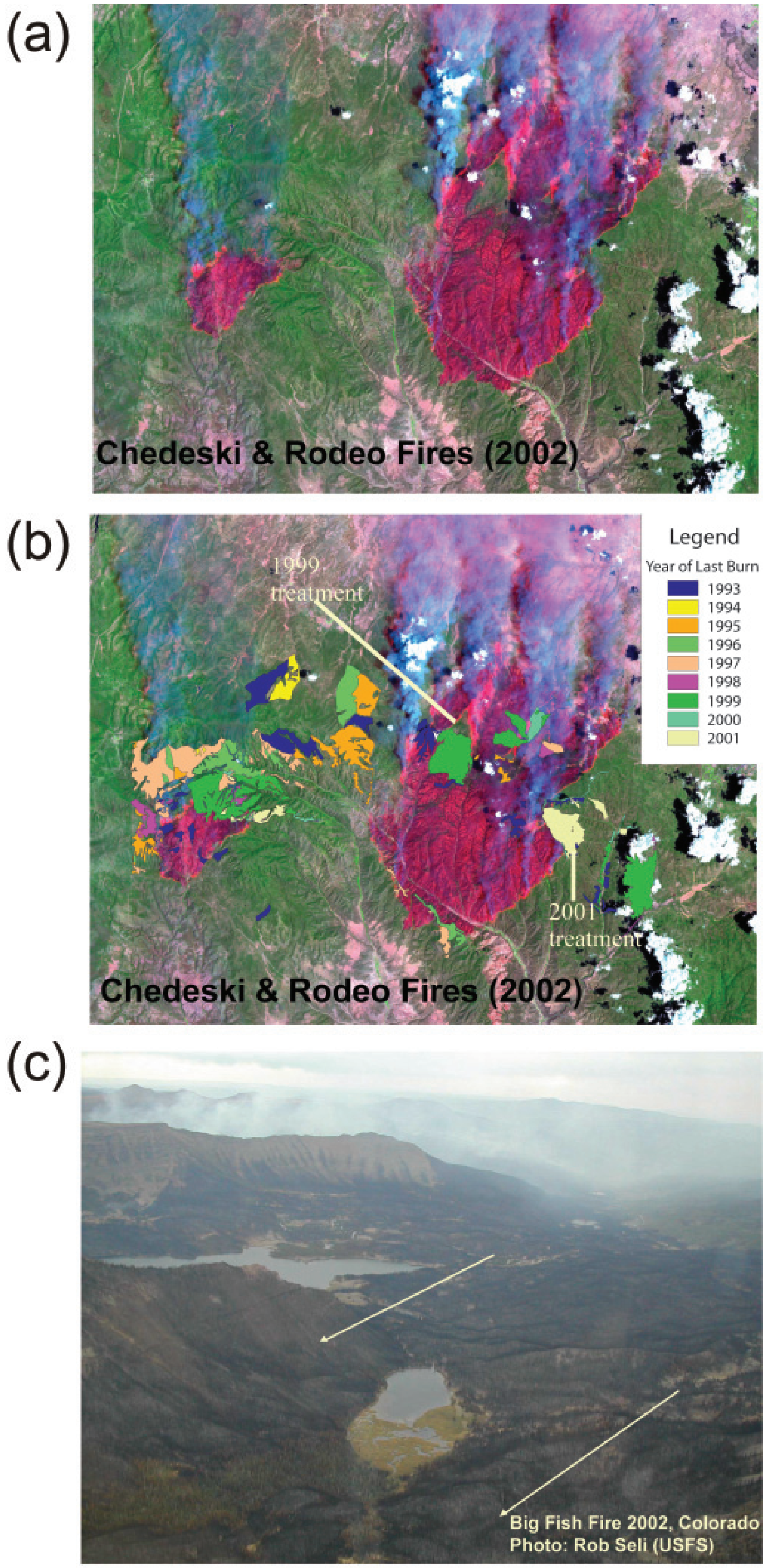

Figure 3—Landsat-7 ETM Plus satellite image of the Rodeo-Chediski fire on June 21, 2002 (a); Chevron shaped areas within the fire front (a) correspond to recent fuel treatment activities 1999 and 1993 (b); (c) Natural barriers such as lakes can cause fires to exhibit the same behaviors as fuel treatments. Note area on the leeside of the lake in the foreground. Example from the Big Fish Fire 2002, arrows show path of fire movement.

fuels, and lastly 3) canopy fuels (Agee 2002; Hessburg and Agee 2003; Finney 2004; Graham and others 2004; Agee and Skinner 2005). Fuels treatments must be of appropriate intensity to significantly change those fuel components at the stand or local scale critical to identified fire behaviors of concern in the context of their spatial location and size, anticipated treatment effectiveness, temporal changes to fuel and stand structure (treatment longevity) under the targeted wind/weather and fuel moisture conditions.

Surface fuel treatments consist mainly of broadcast prescribed burning which has proven effective at changing fire behavior, fire severity, and even in limiting the extent of future fires (Weaver 1943, 1957; Wagle and Eakle 1979; van Wagtendonk 1996; Pollet and Omi 2002; Fernandes and Bothello 2003). Removal of surface fuels limits the spread rate and intensity of surface wildfire, which reduces the ability for fire to heat and ignite tree canopies (Van Wagner 1973, 1977).

Ladder fuels consist of small trees and limbs that facilitate the vertical movement of a surface fire into the tree canopy (Van Wagner 1973; Scott and Reinhardt 2001). Mechanical methods can be used to remove small trees or even prune lower limbs, which increases the vertical gap between the surface and canopy fuel stratum (Graham and others 1999, 2004; Scott and Reinhardt 2001). When followed by prescribed burning, such low thinning hinders the initiation of crown fire (Graham and others 2004). Cram and others (2006) and Raymond and Peterson (2005) reported that a combination of mechanical treatments followed by prescribed burning had the greatest effect on reducing fire severity in the Rodeo-Chedeski and Biscuit fires respectively.

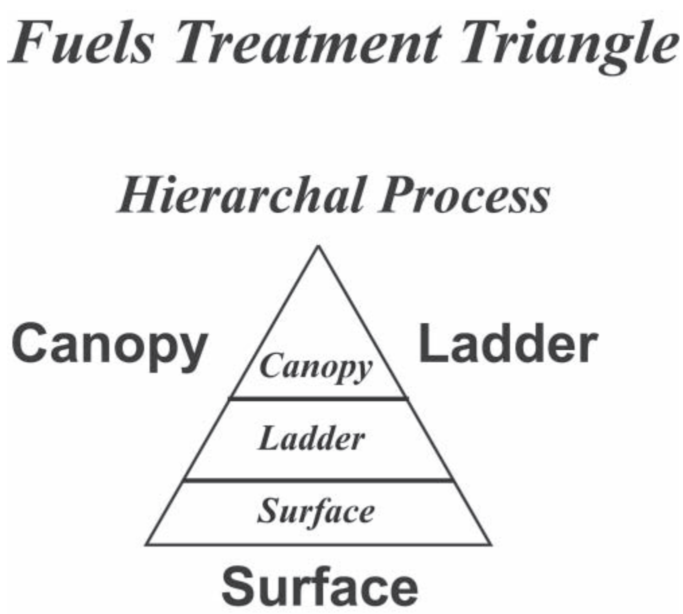

Figure 4—Fuel treatment triangle. Treatment of fuel components should be considered a hierarchal process starting with the surface fuels moving upward into the canopy fuels.

Finally, canopy fuels might be thinned to limit the potential for active crown fire spread presuming fire has been initiated into the crowns (Finney 2004; Graham and others 2004; Agee and Skinner 2005). Large trees with foliage held high above the ground surface and their thicker bark are more resistant to fire damage (Peterson and Ryan 1986). Dominant canopy trees offer the least available fuel source and are generally more fire resistant and thus should be the last stratum considered purely for fuel treatment prescriptions. However, balancing the financial feasibility of fuel treatment prescriptions may require removal of some large trees to offset costs of the treatments themselves (Larson and Mirth 2001; Lynch 2001; Franklin and Agee 2003). Over time, the costs of treatments will be much less-than the costs associated with fire suppression, post-fire rehabilitation, and long-term ecological damage to watersheds (Lynch 2004).

Fuel Management Scale

Fuel treatments affect fire behavior at two spatial scales: the stand or local scale, and at the landscape scale (Finney 2001, 2003). A *stand* is considered a reasonably homogeneous unit that can be clearly differentiated from surrounding stands by its age, composition, structure, site quality, or geography (Daniel and others 1979). While there is no precise size attached to a stand, their smallest unit of size is defined by the land management agency based on a minimum mapping unit, typically around 2-4 ha (5-10 acres). *Landscapes* represent larger areas and typically are aggregations of individual stands that can be burned by a wildland fire. This is a functional definition related specifically to fire and fuel treatment analysis. While there is no set number of stands or area limitation to define a landscape it should be large enough to allow treatments the ability to disrupt large fire growth that has occurred in the past. While watershed boundaries are the most common, ecological management units, range allotments, fireshed assessment area or some other arbitrarily defined extent may be used to define an individual landscape.

McKenzie and others (1996) found in previous fire ecology studies, generally the area represented by a stand to vary from 10 to 1,000 ha (24.7 to 2,417 acres) while landscapes ranged from 1,000 to 1,000,000 ha (2,471 to 2,471,044 acres). Recently, Finney and others (In Review (a)) analyzed landscapes ranging in size 40,500 to 54,600 ha (100,077 to 134,919 acres) with stand sizes ranging from 4 to 515 ha (10 to 1,273 acres) to simulate the spatial-temporal effects of landscape level fuel treatments and their affect on large wildfires. Both studies report sizes similar to those proposed by Simard (1991) for analogous classifications.

Fuel Treatments and Topology

Fire whether at the stand or landscape scale is a *contagion* process, meaning the fire behavior at one site or point in space is directly influenced by the characteristics of the adjacent site or point in space (McKenzie 1991). *Topology* is the spatial relationship of one feature to another (ESRI 2004). Because of fire's contagion process the topological relationship of treatments and their interaction become important when locating fuel treatments at the landscape scale (Finney 2001). However, rarely is placement of treatment units based on topological considerations and this effect on altering fire growth and behavior across a landscape (Finney 2001, 2003). Treatment placement is typically based on other management considerations and thus unlikely to have little impact on changing the overall growth and size of fires until significant portions of any one landscape are treated (Finney 2001). Topologically placed treatments collectively interact at changing fire growth and fire behavior across the landscape and can require fewer acres treated than when treatments are located without this consideration (Finney 2001, 2003; Finney and others, in review (a)). It is important to remember the importance of treatment topology, treatment intensity, and the proportion of the landscape treated when designing landscape level fuel treatments (Figure 5). Based on these findings and the impracticality of treating every acre, the strategic placement of treatments, treatment intensity, and the proportion of treated landscape and their resultant effect in changing fire behavior and growth should be considered when designing and implementing fuel treatments (Finney 2001, Finney and others, in review (a)).

Analyses of fuel treatment effectiveness typically display, describe and summarize fire behavior at the stand or local level. While this is important in displaying stand level treatment effects in changing fire behavior, it does not model the topological effects of treated stands in altering fire movement between treated stands at the landscape scale. This is the problem of stand or local-scale fire behavior analyses. This methodology can indicate a change in fire behavior at the stand scale as well as an overall change in fire behavior and fire effects summarized across the defined landscape. However, stand-level analyses offer no means to analyze, display, or show the topological effect of these treatments in changing fire growth and movement nor the off-site leeward protection (leverage) afforded by fuel treatments (Finney 2001; Loehle 2004; Agee and Skinner 2005; Finney and others 2005). Thus, aggregation of localized effects is not an appropriate method to analyze at the landscape scale, the effects of treatments in changing fire behavior, fire growth and movement.

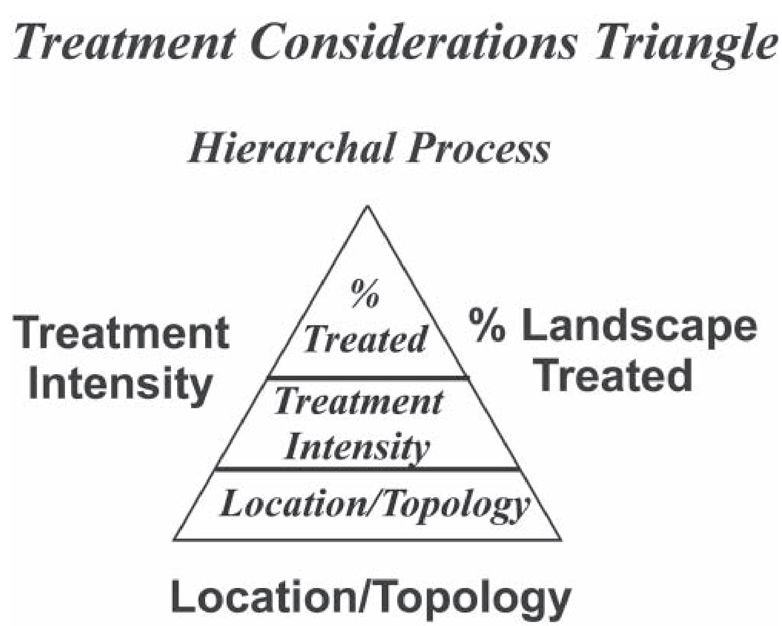

Figure 5—Theoretical illustration of the relative importance (starting from the base up) of treatment topology, fuel treatment prescription intensity, and proportion of landscape treated.

Fire Modeling Tools

With increased emphasis on fuel management, fire managers are continually asked to offer analytical support related to fuel management decisions. There are numerous tools available to the fire manager to model fire behavior which can provide critical insight in assessing current situations, forecasting future fire scenarios, and evaluating fuel treatment alternatives (Andrews and Queen 2001). However, the availability of these tools and supporting data (or lack of data) from the internet can often lead to confusion on which tool is appropriate and at what spatial scale (stand or landscape). Additionally, users are commonly guilty of the misapplication of the respective model, the data and interpretation of outputs (Andrews and Queen 2001).

Terminology

The terminology proposed by Andrews and Queen (2001) is used when referring to the tools discussed here. They define a *fire model* as a mathematical relationship that describes an aspect of fire while a *decision support system* incorporates multiple individual fire models under a unifying architecture to provide various outputs related to fire behavior and fire growth (Andrews and Queen 2001). *Fuel models* are lists of numbers that describe the fuels as required by the respective fire model (Andrews and Queen 2001). All of the decision support systems here use fuel models as described by Anderson (1982) and initially formulated by Rothermel (1972) and Albini (1976) and those recently developed by Scott and Burgan (2005). For the purposes of this discussion I presume all the tools discussed here are decision support systems (DSS) (table 1).

Table 1 outlines each of the individual DSS applicable scale (stand, point or landscape), their required inputs and associated outputs. Tools designated as a point or stand can only be used to analyze or display fire behavior for an individual stand or location. Decision support systems with a landscape designation are also capable of analyzing the topological effects of treatments as

Table 1—Decision support systems available for fuel treatment analysis.

Model	Applicable Scale	Inputs		Outputs		
		Spatial	Temporal	Spatial	Tabular	Graphical
Behave/BehavePlus Andrews (1986) Andrews and others (2005)	Point/Stand	NO	NO	NO	YES	YES
FARSITE Finney (1998)	Stand/Landscape	YES	YES	Vector & Raster	YES	YES
FlamMap Finney (this proceedings)	Stand/Landscape	YES	NO	Vector & Raster	NO	NO
FMA Plus Carlton (2005)	Point/Stand	NO	NO	NO	YES	YES
Fire Fuels Extension (FFE) Reinhardt and Crookston (2003)	Point/Stand	NO	YES	NO	YES	NO
NEXUS Scott (1999)	Point/Stand	NO	NO	NO	YES	YES

fire moves across a landscape. Those DSS with *Spatial inputs* require data for fuel model, topography, stand structure and canopy fuels generated within a GIS and provided to the model in the form of Grid-ASCII raster data. Decision support systems with *temporal inputs* allow for modeling fire behavior and growth over time thus requiring information on duration and intervals of the modeling scenario as well as time dependant wind and weather streams. *Spatial outputs* indicate the DSS is capable of generating simulation results as shapefiles or GRID-ASCII raster data that can be directly ingested into a GIS system for display and further analysis.

Decision Support Systems

The DSS listed in table 1 comprise the more common tools used to analyze fuel treatments from either a stand or landscape level. While some are more appropriate for certain scales of analysis than others, all essentially incorporate the same mathematical fire models for surface fire spread rate, crown fire initiation and crown fire spread rate models (Scott 2006). Furthermore, all the DSS discussed here use the previously discussed fire behavior fuel models.

The most common approach to analyzing fuel treatment effects have been on a stand or point basis. BEHAVE (Andrews 1986), BehavePlus (Andrews and others 2005), Fuels Management Analyst Plus (FMAPlus; Carlton 2005), Fire Fuels Extension (FFE; Reinhardt and Crookston 2003), and NEXUS (Scott 1991; Scott and Reinhardt 2001) have all been used to conduct these types of analysis (table 2). All these systems can generate information on fire behavior, crown fire, and fire type. However, they are only valid for the point or stand information provided. None of the DSS are capable of simulating

Table 2—Publications using fire decision support systems in fuel treatment analysis. NO: Study tested treatments based on Non-site specific locations.

Author	Modeling System(s)	Location
Kalabokidas and Omi (1998)	BEHAVE	Colorado
Brose and Wade (2002)	BEHAVE	Florida
Keyes and O'Hara (2002)	BEHAVE	NO
Hummel and Agee (2003)	BEHAVE	Washington
Van Wagtendonk (1996)	*FARSITE*	NO
Rice and Miller (1998)	*FARSITE*	California
Stephens (1998)	*FARSITE*	California
Finney and others (2002)	*FARSITE*	California
Stratton (2004)	*FARSITE*/FlamMap	Utah
Stephens and Moghaddas (2005a,b)	FMAPlus	California
Scott (1998a)	NEXUS	Montana
Fulé and others (2001a)	NEXUS	Arizona
Fulé and others (2001b)	NEXUS	Arizona
Fulé and others (2002)	NEXUS	Arizona
Scott (2003)	NEXUS	NO
Fulé and others (2004)	FVS-NEXUS	Arizona
Raymond and Peterson (2005)	NEXUS	Oregon
Scott (1998b)	FFE-FVS	Montana
Fiedler and Keegan (2003)	FFE-FVS	New Mexico
Fiedler and others (2004)	FFE-FVS	Montana

fire spread between points or stands. However, using GIS, simulation outputs from these models such as, flame length or crown fire can be linked back to a stand boundary data layer and displayed spatially across a landscape. However, this still provides no information on the topological effects of the treatments in altering fire behavior and growth at the landscape scale.

Analyzing topological effects of fuels treatment must also be done to examine their effectiveness in altering fire movement and behavior at the landscape scale (Finney 2001, 2003). To accomplish this a DSS capable of modeling fire behavior at the stand level and incorporating the topological effect of treatments in altering fire movement across the landscape is needed. Only *FARSITE* (Finney 1998) and the Minimum Travel Time (MTT; Finney 2002) or Treatment Optimization Model (TOM) component within FlamMap (Finney, this proceedings) are widely available for this analysis. Simulation outputs of fire growth and behavior from these models are spatial and easily brought into a GIS for display and further analysis.

Available Tools

BEHAVE/BehavePlus—BEHAVE (Andrews 1986) and BehavePlus (Andrews and others 2005) are decision support systems that are only capable of determining fire behavior at the point or stand level, do not require spatial information or model fire behavior temporally and can only provide limited outputs in the form of tables, graphs or diagrams (table 1). Previous efforts using this system were completed using BEHAVE (Andrews 1986) and examined the effectiveness of fuel treatments in changing fire behavior as well as changes in fire behavior associated with changes in stand structure following a spruce budworm outbreak (table 2). While BEHAVE and BehavePlus can be used for evaluating fuel treatment effectiveness, its primary uses have been in projecting the behavior of ongoing fires and in planning prescribed fires. BehavePlus (Andrews and others 2005) is the successor to BEHAVE and should be used for future modeling exercises. BehavePlus can model surface fire spread and intensity, crown fire spread and intensity, safety zone size, size of point source fire, fire containment, spotting distance, crown scorch height, tree mortality, wind adjustment factors, and probability of ignition (Andrews and others 2005).

NEXUS—NEXUS links existing models of surface and crown fire behavior that can be used to assess crown fire potential at the point or plot scale (Scott and Reinhardt 2001). NEXUS does not require spatial or temporal data inputs and the outputs from NEXUS include tables, graphs, and text files (table 1). While NEXUS can provide an index of crown fire hazard, fire type, and potential fire behavior it cannot determine or simulate fire spread or the spread of fire between stands or points. NEXUS has been used to analyze changes in crown fire hazard following fuel treatments with crowning index and torching index used to reflect these changes (table 2). NEXUS version 2.0 has the ability to run in batch mode, which can process up to 32,000 records at one time.

FVS-FFE—The Fire and Fuels Extension (FFE; Reinhardt and Crookston 2003) contained within the Forest Vegetation Simulator (FVS; Wykoff and others 1982) allows one to model stand dynamics and changes to fuels over successional time and the associated behavior and impacts of fire as stands grown and change (Reinhardt and Crookston 2003) or associated with specific treatments (table 2). Because of this ability FFE can add a temporal effect to the analysis and display the changes in stand structure and potential fire hazard as a time-series over periods of a year to decades. While FFE can determine potential fire behavior it cannot determine fire probability or simulate fire spread or the spread of fire between stands (Reinhardt and Crookston 2003). The data used to determine potential fire behavior and effects is based on the stand averages which leads to some homogenization of the data and can influence the simulated outputs. Results can be displayed visually using the Stand Visualization System (SVS) (McGaughey 1997) or in tabular format. Exporting the data out in a spreadsheet format allows the user to construct graphs of the simulation. Since data sets used in the modeling are typically tied to a spatial representation of stand boundaries, simulation results can be displayed spatially in GIS. With the spatial relationship of the stand data, and the ability of FVS-FFE to model stand dynamics and fuel accumulations over time one could use the model to develop spatial-temporal data (fuel models, stand structure, canopy fuels) that can be imported into spatial models such as *FARSITE* or FlamMap. A recent study used FVS-FFE in just this way (Finney and others, In Review (a)).

FMAPlus—FMAPlus incorporates previously established methodologies and fire models to produce fuel inputs, outputs of fire behavior, crown fire potential, crown scorch and mortality based on field collected data (Carlton 2005). It is appropriate for point or stand level analyses. FMAPlus requires no temporal or spatial inputs, and only produces tabular or graphical outputs (table 1). Because it can incorporate field-collected data and import tree list data from FVS (Wykoff and others 1982), temporal analysis over time (year or decades) could be accomplished. Within FMAPlus fuel treatment analysis is accomplished by altering the tree list data to reflect post-treatment stand conditions. Only recently has the use of this model to display fuel treatment effects been published (table 2).

FARSITE—With the development of the Fire Area Simulator *FARSITE* (Finney 1998) the ability to analyze fire growth at the landscape scale in a spatially dependent environment became available. *FARSITE* uses spatial information on elevation, slope, aspect, canopy cover, fire behavior fuel model, stand height, crown base height, and crown bulk density as well as temporal information concerning weather, wind, and fuel moisture to run fire growth simulations and generate fire behavior outputs (table 1). Outputs consist of spatial (shapefiles and GRID ASCII) for fire growth and behavior as well as tabular and graphical information on area burned, fire perimeters, and fire numbers. Examples of the use of *FARSITE* in evaluating the efficacy of fuel treatments in changing fire behavior and the effectiveness of fire suppression following fuel treatments in changing fire size and economic damage have been published (table 2). Its reliance on spatial data and the common lack of availability of these data have been a major impediment to its use. However, the LANDFIRE (http://landfire.gov/) project is tasked with the development of spatial data for use in *FARSITE* for the lower 48 States, which should alleviate this data barrier over time.

FlamMap—FlamMap (Finney, this proceedings) is a simplified version of *FARSITE* requiring the same data inputs while generating similar fire behavior outputs. One of the benefits of FlamMap over *FARSITE* is many scenarios can be run very quickly and many of the assumptions required by *FARSITE* are simplified or eliminated. However, there is no temporal component in FlamMap, as such it uses spatial information on topography and fuels to calculate potential fire behavior characteristics at a specific instant for the landscape under a specified set of conditions for every raster cell on the landscape with without contagion between data cells. FlamMap does not simulate temporal variations in fire behavior caused by weather and diurnal fluctuations, nor will it display spatial variations caused by backing or flanking fire behavior. Because of this, FlamMap is an ideal tool to compare relative fire behavior changes resulting from fuel modifications. Using just the fire behavior option, FlamMap is much like a point/stand fire model, however, the ability to analyze many stands in their georeferenced position does offer some degree of landscape perspective, albeit without topological influences. To get around this issue Stratton (2004) incorporated both FlamMap and *FARSITE* to analyze fuel treatment effectiveness in southern Utah. However, Version 3 of FlamMap can also evaluate the topological effects of fuel treatments by using the Treatment Optimization Model (TOM; Finney, In Review (b)) and evaluate the spatial movement of fire across a landscape based on Minimum Travel Time (MTT; Finney 2002; Finney, this proceedings; Finny In Review (b)).

Model Selection

Given this list of potential models, which model is the best or appropriate model? As mentioned previously the objective and questions that need to be answered are of paramount importance, however, one should select the model based on the intricacy of the question(s) or objectives. Associated with this decision process one should also consider the following.

First, what are the intended uses of the model? Is the objective to assess changes to crown fire hazard following fuel treatments? Then perhaps NEXUS is the appropriate model. If one wishes to examine the effects of fuel treatments on changes to fire behavior then, BehavePlus or FlamMap may be more appropriate.

Secondly, what are the required inputs of the model? If one decides to use a spatial model such as *FARSITE* or FlamMap do you have the required spatial data? If not, do you have the time to acquire any needed ancillary data, develop the data, critically analyze and assess the accuracy of the data, and develop the required data layers needed for the questions of interest?

Thirdly, what are the outputs generated by the model and will they allow the user to fully answer and analyze the questions or objectives of the modeling exercise? Do you need only tabular or graphical outputs of fire behavior characteristics or do you need these outputs to be spatially represented across the landscape. All of the previously mentioned fire behavior tools generate tabular and graphical outputs of data, but only *FARSITE*, FlamMap, FVS-FFE generates outputs that can easily be applied spatially within GIS.

Lastly, what is the complexity and time frames associated with the current project? Complexity is directly related to the type of analysis being performed, e.g., Categorical Exclusion (CATEX), Environmental Analysis (EA), or Environmental Impact Statement (EIS). All of these processes require a certain level of analysis and time commitments to meet their respective legislative intents. As such, it can have a direct impact on the required decision support system. For a CATEX the use of BehavePlus may be the appropriate tool to use to assess changes in fire behavior associated with fuel treatments, especially if one needs to develop many of the required spatial layers to use *FARSITE* or FlamMap. The project timelines associated with each of these also controls whether the fire manager has the time to develop the required data layers taking into account those items mentioned in previously.

Summary

Large wildfires have impacts well outside the localized effect of individually treated stands. Treatment placement that does not consider treatment topology is unlikely to have any impact on changing the overall growth and size of fires until significant portions of any one landscape is treated (Finney 2001, 2003). Based on this and the fact it is impractical to treat every acre the strategic placement of treatments and their collective effect in changing fire behavior and growth needs to be considered (Finney 2003). An effective landscape fuel management scheme should do the following:

- Treatments burn at a reduced severity
- Treatments are located to collectively reduce fire sizes and severity
- Change probability of fire movement
- Facilitate a change in suppression tactics and strategy
- Reduced fire sizes and fire severity under target environmental conditions
- Reduced large-fire suppression costs

When using any decision support system to analyze fuel treatment effectiveness or ongoing fire events, there are three potential sources of error: data, user, and model (DUM). The end user needs to be cognizant of these errors at all times during data development and the modeling process.

Fuel treatment prescriptions should focus on defined elements of wildland fuel structure following a hierarchal order of treatment (surface, ladder and canopy fuels). Treatment design should also consider treatment topology, treatment prescription intensity, treatment size and planned longevity, and the amount of landscape treated.

While treatments are focused on altering fire behavior at the stand level, it is the topological placement of treatments that is important in changing fire growth and behavior at a larger landscape scale. Treatment locations that are strategically placed and based topologically may actually require fewer acres be treated to achieve an equivalent reduction in affected acres when this is not considered (Finney 2001, 2003; Finney, in review (a)). Because topology of treatments is important we can no longer rely on the number of acres treated as a metric for treatment success. Developing a more appropriate metric to measure fuel treatment effectiveness and success is an area requiring further investigation and should be included in any future national fire policy (Franklin and Agee 2003; Stephens and Ruth 2005).

Modeling fuel treatment effectiveness is one of the more difficult applications of fire decision support systems. It requires the modeler to make assumptions about the future conditions of fuels and vegetation structure, which is difficult at best. This analysis however is critical to assist in management decisions. When modeling fuel treatment effectiveness, it is best to remember the advice of Yogi Berra: "Prediction is very hard, especially when it's about the future."

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