

AN OVERVIEW OF METHODS FOR INCORPORATING WILDFIRES INTO FOREST PLANNING MODELS

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ABSTRACT. The introduction or modification of land use regulations and sustainability initiatives over the last few decades has arguably increased the complexity of forest planning processes. Given the planning goals of a land management organization, both spatial and temporal characteristics of desired future landscapes may now be important to recognize. In some cases of planning, wildfire plays an important economic and ecological role. Efforts to model the potential effects of forest wildfires have ranged from manipulation of vegetation strata using hazard ratings or disturbance probabilities, to recognizing the spread of wildfires across a landscape in a more spatially-explicit manner. This paper describes a range of options for incorporating wildfires into forest planning models. Linear programming, binary search, simulation models, and heuristics have all been used to assess the impacts of wildfire on forest planning goals. Wildfire has been incorporated into forest planning processes in both deterministic and stochastic manners, with some suggesting that the deterministic route provides a close approximation to historical stochastic events. When stochastic measures are employed, the position of the wildfire, the frequency, and the intensity can all be drawn from probability distributions, although only a few of the recognized works model these to the full extent. In general, the greater the stochastic measures employed, the stronger the implication is that multiple simulations are necessary to assess potential impacts. Further, the more complex the wildfire integration process becomes, the implication seems to be that simulation models and heuristics are necessary.

Keywords: Operations research, linear programming, binary search, dynamic programming, simulation, heuristics

1 INTRODUCTION

Forest planning processes have become increasingly complex over the last few decades, due to advances in computer technology, advances in basic scientific knowledge of the functional relationships among natural resources, and the introduction or modification of land use regulations. Both spatial and temporal characteristics of desired future landscapes may now also be important to recognize. In some cases, the potential impact of wildfires on timber supplies and other natural resources is desired by decision-makers. One might logically ask why the incorporation of wildfire effects into forest planning is important. First, the potential for wildfire loss is high in some regions, given the climate, ownership pattern, and extent of forest resources found in certain areas. Second, and perhaps most challenging for planners, is that the potential for wildfire loss is highly variable and unpredictable. Obviously, wildfire is a significant concern, because losses from wildfire can significantly affect timber supplies for organizations

with economic or commodity production goals. Further, losses from wildfire might destabilize local economies that are dependent on a stable supply of un-burned timber, redistributing wealth among producers and consumers through changes in short-term and long-run timber prices (Butry et al., 2001). In addition to these concerns, recent literature in forest planning has attempted to address a number of concerns of land managers, as they relate to wildfire. For example, Kim et al. (2009) attempted to understand whether the threat (or impact) of wildfire could be reduced through alternative landscape management policies, whether forest management activities planned at the stand-level could affect the behavior of large wildfires, and whether the arrangement (spatial and temporal) of management activities affects wildfire behavior. Others have also attempted to understand whether stand-level goals (e.g., economic or ecological optimum regimes) prevent the attainment of landscape-level goals (e.g., mitigation of wildfire impact), or whether landscape-level goals (e.g., mitigation

of wildfire impact) prevent the attainment of stand-level goals or preclude the use of stand-level optimum regimes.

The range of modeling and planning work that describes wildfires placed on a landscape, and the resulting ecological and economic effects, is very broad. Efforts to model the potential effects of wildfires have varied from the manipulation of non-spatial vegetation strata, to the spatial recognition of the spread of wildfires across a landscape. The objective of this paper is to describe a suite of methods people have used for incorporating wildfires into forest planning models. To make this discussion tractable, it is limited to published work that attempts to account for wildfire in a forest planning processes using operations research techniques. The techniques include linear programming, binary search, benefit / cost analysis, simulation, heuristics, and other methods. As a result, this discussion does not cover specific wildfire modeling processes (e.g., FARSITE, BEHAVE and others), wildfire simulation exercises that are not integrated with forest planning processes, and other ecosystem models that do not involve or describe the scheduling of management activities. A few ecosystem models are presented here, where the integration of management activities and wildfire effects analyses (or simulations) is clearly described in their content. The omission of other similar work is not meant to down-play their significance, but rather can be attributed to the limited time and space available to provide this review.

2 METHODS

A literature review was conducted regarding the integration of wildfire considerations (models and other assumptions) and forest planning processes (operations research methods, simulation models, or economic analyses). The literature review was initially based on the work of Bettinger and Chung (2004), which identified much of the early North American work in this area. A widespread Internet search was then employed to determine more current work, using the key words "forest," "planning," and "wildfire." Literature identified was then read closely to determine whether it met the criteria for this discussion, which included the following: (a) an acknowledgement of wildfire impacts through direct modeling processes, transition probabilities, or reductions in areas affected, and (b) an integration with a forest planning model that scheduled management activities for a property over some distinct time frame. The literature that was located for this review was then categorized by forest planning method, and a discussion of the process ensued (below). In addition to understanding how the planning process worked, an attempt was made to determine the details of how wildfire was incorporated into the process, although in some cases this

was not entirely clear.

3 RESULTS

There are a number of complex methods for incorporating wildfire into forest planning processes, such as the seminal work of Van Wagner (1979), who was one of the first to develop a simple model examining wildfire loss appraisals. This discussion follows a methodological rather than temporal framework, beginning with non-spatial classification and sorting of inventories, then leading to non-spatial operations research methods, and finally to methods that specifically account for spatial complexities of the landscape. Table 1 summarizes the approaches discussed along with references demonstrating their ability to support forest management and planning.

One of the more straightforward methods (Kalabokidis et al. 2002) uses a land classification process to assess wildfire vulnerability. This model quantifies potential wildfire conditions through inventory methods and landscape analyses (GIS). With this model, planners would first estimate external environmental factors to determine the risk of a forest to wildfire. Then, internal factors to determine the productivity and resilience of the forest would be estimated. The two estimates would then be combined to rank the vulnerability of the land and to evaluate wildfire loss potential across a forest. As Kalabokidis et al. (2002) note, there are a number of problems with approaches such as these, which include: (a) some of the factors are qualitative, (b) some of the factors are measured using non-standard measurement units, and (c) incorporating these factors into a decision process may be difficult. In any event, Kalabokidis et al. (2002) suggest that one might estimate the relative weight of the factors influencing wildfire, rank these into "danger classes," and use a benefit / cost analysis to inform decisions related to forest planning.

Linear programming has long been used to develop forest plans and to assess alternatives for land managers and decision-makers (Bettinger and Chung, 2004). Reed and Errico (1986) were one of the first to develop methods for assessing the impacts of wildfire within a linear programming framework. They developed a generalized form of a Model II planning problem, and accounted for wildfire by assuming a deterministic (fixed) proportion of area in each age class would be lost to wildfire during each planning period. Their process began by determining the harvest level in the first time period in the absence of wildfire. Then, after harvesting activities were scheduled, they applied the wildfire "effects" (reductions in areas of strata) to the forest. The harvest level in the first time period was adjusted, and the problem proceeded to the subsequent time peri-

Table 1: Fire modeling reference according to method employed.

Method	Reference(s)
Binary Search	Montgomery et al. (1986)
Deterministic scheduling models	Peter and Nelson (2005)
Dynamic programming	Stevens (1986)
Heuristics	Bettinger (2009) Campbell and Dewhurst (2007) González et al. (2005a) Johnson et al. (1998) Kim et al. (2009) Thompson et al. (2000) Zuuring et al. (2005)
Land classification methods	Kalabokidis et al. (2002)
Linear programming	Boychuk and Martell (1996) Gassmann (1989) Martell (1994) Moll and Chinneck (1992) Reed and Errico (1986) Zuuring et al. (2005)
Linear programming / simulation	Armstrong (2004)
Non-linear programming	González et al. (2005b)
Simulation models	Armstrong et al. (1999) Konoshima et al. (2008) Kurz et al. (2000) Shifley et al. (2000) Van Wagner (1979) Van Wagner (1983) Yang et al. (2004)
State-transition models	ESSA Technologies, Ltd. (2009) Keane et al. (2006)
Stochastic optimization	Hyytiänen and Haight (in press) Konoshima et al. (2008)

ods. This was termed an "iterative state updating procedure," and as we will see, processes such as these are used in other methods as well. Reed and Errico (1986) determined that a close approximation to an optimal solution for a forest plan can be developed using deterministic wildfire distributions that closely resemble the stochastic disturbance levels, since over broad areas the variance in the proportion of land burned should be small. Other similar work in this area includes Moll and Chinneck (1992), who developed a linear programming model to examine the effects of both wildfire and insect outbreaks using average disturbance values for each. In this work, it was also determined that a deterministic method was a good enough approximation to solutions obtained using randomly generated wildfire and insect outbreak probabilities. Moll and Chinneck (1992) also used an iterative state updating process (linear program-

ming and simulation method) to test the robustness of the straightforward, deterministic linear programming process. Martell (1994) developed a similar problem structure for an assessment of the impact of wildfires on timber supplies in Ontario. Here, wildfire was assumed to consume a fixed proportion of the unharvested area in each age class (strata), and the proportion of disturbed areas did not vary from one time period to the next. Boychuk and Martell (1996) developed a linear programming model using multistage stochastic programming to deal with the uncertainty of wildfire. Rates of wildfire were selected from a probability distribution, and the same loss proportion was applied to each cover type in each time period, before harvests were scheduled. They noted a number of limitations of linear programming models, including the assumptions that were made about the transition of forests from a burned state

to other states, and the use of a limited number of management regimes for burned areas (i.e., no salvage harvests), both in order to keep the problem formulation to a reasonable size.

Gassmann (1989) developed a method to maximize timber harvest levels over a finite time horizon, while tracking areas and management actions using a Model II linear programming problem formulation. In general, some area in each age classes would be scheduled for harvest, then a random portion of the remaining area would be destroyed by a disturbance (assumed here to be a wildfire). The loss rates from wildfires could be deterministically or randomly chosen, and in the latter case were assumed to not be fixed proportion of each age class during each time period. As mentioned above, problems involving a deterministic proportion of disturbance in each age class were first addressed using linear programming. When probabilities of wildfire loss were considered, in order to model stochastic proportions of disturbance, a special computer program based on the Dantzig-Wolfe decomposition principle was employed.

As planning methods evolved, Armstrong (2004) developed an iterative procedure using linear programming and Monte Carlo simulation to integrate harvest scheduling and wildfire effects. In this procedure, areas burned by wildfire were randomly generated from a log-normal continuous distribution after linear programming was used to schedule activities and determine the allowable cut. The areas assumed to be burned were therefore not a fixed proportion of the age classes during each time period, but allowed to vary within the confines of the lognormal distribution. These randomly burned areas were deducted from their previously forested strata and placed in a regeneration stratum. However, the wildfires were only assumed to occur after management activities were scheduled in a time period. Therefore, the forest inventory at the end of a time period was updated by passing the burned areas to the youngest forest age class. The model then moved to the next time period, and using the updated inventory, areas burned from wildfire were again randomly generated from a lognormal continuous distribution. This sequential updating procedure continued through the end of the time horizon. The entire process was repeated 1,000 times to generate probability distributions for allowable cut levels.

Armstrong et al. (1999) illustrate the use of area-volume check along with simulation methods to arrive at estimates of the amount of volume "disturbed" across the landscape, and compare this natural disturbance regime against the sustainable harvest level. The method for incorporating wildfire into the planning process involved understanding the natural disturbance rates (e.g., areas burned annually) for the region in question (Alberta), and then re-directing an amount of land

equal to this area to a regeneration stratum each time period. The growth and condition of the forest is then re-assessed and future time periods are modeled. Armstrong et al. (1999) suggested through this work that land managers should schedule timber harvests at a rate implied by the local natural disturbance model, although they acknowledge that the spatial elements of the landscape are ignored completely.

Dynamic programming has frequently been used to address the stand-level optimization problems (e.g., Brodie et al., 1978; Brodie and Kao, 1979), and to a much lesser extent, the forest-level optimization problem (Borges et al., 1999). However, in a Master's thesis, Stevens (1986) described the development of a multi-objective problem that incorporated the value of timber harvest and a value to describe the smoothness of wood flows from the planned management activities under the risk of wildfire. The state variable used to describe the forest was the even-flow level that was determined by area-volume check (a proxy for the age-class distribution of the forest at any point in time). State-transition matrices were then generated from a Monte Carlo simulation model that recognized different harvest levels and wildfire regimes, the latter of which were based on lognormal distributions. Non-linear stand-level optimization using the Hooke and Jeeves method has also been used to account for the risk of wildfire (González et al. 2005b). Here, wildfire probabilities, along with repeated simulations, were necessary to understand the effect of wildfire frequency on optimal economic management regimes for *Pinus sylvestris* in Spain. Hyytiäinen and Haight (in press) examined the effect of wildfire risk on stand-level decisions using stochastic optimization in conjunction with a growth and yield model. Wildfire probabilities are employed and diameter distributions are adjusted (when wildfires are assumed to occur) in the development of optimal management regimes for coniferous forests in Idaho.

Binary search is a form of simulation model that is generally used to determine the maximum timber harvest levels over time using schedules developed through trial and error (Bettinger et al., 2009). Montgomery et al. (1986) used the SHRUB model (an enhanced version of the HARVEST model) to examine how even-flow harvest levels may change when wildfire is acknowledged. Forest age classes (strata) and growth assumptions were used in conjunction with harvest rules to assess the impacts of wildfire on a long-term harvest schedule. The process began, after defining objectives and constraints, with the development of a forest plan using the binary search model. At this point, the wildfire risk was ignored, however, they assumed that a single wildfire would occur in time period 1. Areas assumed to be burned were removed from their strata, and placed

in the youngest age class stratum. Another forest plan, using this burned forest age class structure was then developed using binary search, and a comparisons of the two (burned and unburned) ensued. A comparison of the with, and without, assumptions of wildfire revealed trade-offs in the growth and harvest of individual age classes (strata) over time. Montgomery et al. (1986) suggested that applying this approach to different types of forests helps one understand how the impact of wildfire on timber supplies can perhaps be significant.

State-transition models are generally non-spatial in nature, yet involve stochastic processes to evaluate alternative states of the landscape given uncertain relationships between management activities, natural disturbances, and forest transition. VDDT (Vegetation Disturbance Dynamics Tool, ESSA Technologies, Ltd., 2009) has been widely used of late to assist in the development of U.S. National Forest plans. VDDT was initially developed for the Interior Columbia River Basin Project (Haynes and Quigley, 2001), and represents a non-spatial state-transition model that incorporates disturbance probabilities and successional pathways to project landscapes into the future. A spatial version of this model has also been developed (TELSA, to be described later). Within VDDT, pathway diagrams for forest and rangeland vegetation complexes are developed using the following: expert opinion, disturbance probabilities, and impacts of disturbances and management actions on stand structure and composition. Given the stochastic transition probabilities, multiple simulations of VDDT help one understand the potential trajectory (and inherent variability) of a forest managed under a given set of operational assumptions, and subject to a certain suite of natural disturbance regimes.

Spatial simulation models expand on the set of tools available to assess the impacts of wildfire on forest plans. Van Wagner (1979) was one of the first to develop a simple model examining wildfire loss appraisals. Using a net present value approach, the focus of this work was on a regulated forest assigned to a grid of "units" that were all of equal size. The process begins with a deterministic selection of the units within which wildfires damage the timber resources, which occurs at the beginning of the simulation. These affected forested stands are assigned the youngest age class, and regeneration is assumed to have occurred. Harvests are then scheduled for the entire time horizon using a rule of scheduling oldest age classes first. With this work, Van Wagner (1979) showed how the impact of wildfire can influence the net present value of the entire forest, particularly when discount rates and growth rates vary. Basically, substitutions for what would have been the next scheduled harvest units are made, after assuming some of these areas were destroyed from wildfire and subsequently re-

generated. Van Wagner (1983) later expanded on this approach, and again focused on a regulated forest assigned to a grid of "units" that are all of equal size. In this second approach, a random selection is made of the units within which wildfires damage the timber resources. The affected stands are assigned the youngest age class, and regeneration is assumed to have occurred. Although stands are randomly selected, the rate of wildfire disturbance is fixed. After wildfires have assumed to occurred, harvests are scheduled for other units at a pre-defined percentage cut per year, using a "highest volume" first approach. Through this simulation approach, given the percent of harvest allowed and the percentage of area burned, annual harvest levels could be simulated.

In terms of more sophisticated landscape simulation models, the LANDIS model (Yang et al., 2004) takes a grid-based modeling approach to management actions and natural disturbances across broad landscapes. The size, frequency, and intensity of wildfires can be simulated in LANDIS using probability distributions, and these simulated disturbances remove land from older forest age classes and place it in a recently regenerated age class. To accomplish this task, the sites to be disturbed are selected randomly, a disturbance intensity is drawn from a probability distribution, and tree cohorts are removed from age classes within the areas disturbed. These initially are considered "ignitions" rather than wildfires that spread across the landscape. However, if an ignition becomes an initiated wildfire, it is grown (spread) up to a pre-determined size drawn from a size distribution. Shifley et al. (2000) also describe an application of LANDIS to simulate the effects of wildfire and windthrow disturbances in a forest plan; in this case the setting was the Missouri Ozarks in the central region of the United States. Ignition frequencies and wildfire return intervals were also involved to simulate disturbance events that affect age classes of forests.

In contrast to raster-based simulation models, the FPS-ATLAS harvest scheduling simulator (Peter and Nelson, 2005) uses vector polygons to represent forested stands, and allows the scheduling of management activities along with natural disturbances. The size and frequency of wildfires are simulated using probability distributions, and when a disturbance is initiated, a polygon is randomly selected, then a patch size target is selected. Adjacent polygons are added to the burned patch until a size target is met or there are no more eligible polygons. Wildfire spread models are not used to direct the wildfire across a landscape, thus burned patches are allowed to spread in any direction, up to the stochastically generated patch size. To accomplish the task of integrating wildfire into a planning process, harvests are scheduled for the first time period, using a modified "oldest-first" rule, and accounting for adjacency and green-up restric-

tions. A routine is then called that determines the areas that are burned. Decision rules are then used to determine whether to salvage or naturally regenerate the burned areas. The process is then repeated for the remaining time periods in the time horizon, and an assessment is performed to determine whether a sustainable harvest level has been achieved. Peter and Nelson (2005) suggest that multiple runs of the model may be necessary to understand the range of sustainable harvest levels with a given disturbance regime, and to understand the probability of harvest shortages within a range of harvest levels and wildfire suppression scenarios.

Another vector-based simulation model is the LANDSUM (LANDscape SUccession Model, version 4.0) model which is described as a spatial, state-transition model that operates at the stand level (Keane et al., 2006). In contrast to the FPS-ATLAS model, LANDSUM includes a spatially-explicit wildfire spread model, which operates at the pixel level within stands. Wildfires are then spread using directional vectors of wind and slope. Disturbance initiations are modeled stochastically, and effects are based on current vegetation conditions. Three wildfire approaches can be used: maximum wildfire sizes, ellipses, and cellular automata approaches. If stands are partially burned, the burned and unburned portions are assigned different successional classes and stand ages. The LANDSUM model can work in conjunction with VDDT to determine successional pathways, and human-induced disturbances (harvests) can also be modeled stochastically.

TELSA (Tool for Exploratory Landscape Scenario Analyses) is a spatially-explicit simulation model (Kurz et al., 2000) that requires stand polygons, streams, wetlands, lakes, and transition probabilities (from VDDT). TELSA is integrated with geographic information systems, and the disturbances are modeled by polygon. Adjacency and activity limits can be controlled, just as they can be in FPS-ATLAS. During the planning process, natural succession is simulated, using the state-transition model VDDT (described earlier) in the first time period. Then natural disturbances are simulated in the stand polygons, up to a user-defined limit per year and size, thus disturbances can be spread to eligible neighboring polygons. Salvage logging is then simulated, and management activities are assigned to stands deterministically from a sorted list of stands. Management activities are scheduled until the activity limit for the time period in question has been reached, or until there are no more eligible management units in which to schedule activities. The process is repeated for all other time periods in the time horizon. Multiple runs of scenarios are encouraged to assess the range of variability that may be suggested in future representations of the landscape. However, if natural disturbances are not

assumed in the model, it reduces to a deterministic harvest scheduling process. Strand et al. (2009) describe an application of TELSA to aspen (*Populus tremuloides*) forests of the intermountain region of the United States, and Provencher et al. (2007) describe an application of TELSA to public lands in Nevada, where livestock grazing, forest management, and natural disturbances are all taken into account.

Heuristic models have also been used to incorporate wildfire processes into forest planning process. Campbell and Dewhurst (2007) modeled the temporal pattern and process of wildfire disturbance through traditional harvest scheduling methods. In this work a simulated annealing heuristic was used to schedule harvests, and the objective function was designed as a goal programming problem. The goals were developed to minimize deviations from desired landscape conditions. This planning process also requires vector data (stand polygons, etc.). As with harvests, disturbances are modeled by polygon, and are randomly located regardless of stand age. The chance of a natural disturbance is based on wildfire probabilities, and the intent was to make inferences of the impact of the frequency of disturbance on timber supply. Thus the temporal pattern of disturbance is modeled as a harvest from historical evidence of the frequency of wildfires in the area studied (British Columbia). This planning process does not directly model the disturbances (i.e., harvests are used as a proxy for wildfires), and targets regarding the size and configuration of wildfires were noted as future directions for the work.

González et al. (2005a) used both tabu search and the Hero model (Pukkala and Kangas 1993) to locate near-optimal landscape-level plans that incorporated landscape metrics and wildfire risk. In this work, wildfire was spread spatially across the landscape using wildfire strike probabilities and probabilities related to the spread of wildfire to adjacent forested stands. Each stand was assigned a resistance index that was related to the stand conditions, and through repeated landscape-level simulations, the mean burned area of the landscape was used to describe the overall resistance to wildfire. Thompson et al. (2000) also used tabu search to maximize economic objectives subject to wood flow and harvest adjacency constraints. This work also involved minimizing wildfire hazard ratings, since it was assumed that the average area burned was proportional to areas which were rated as having high or extreme wildfire hazard. In contrast to other work, wildfire spread was not explicitly modeled in this approach.

In conjunction with the Sierra Nevada Ecosystem Project (Centers for Water and Wildland Resources, 1996), "Safe Forests" (Johnson et al., 1998), a gradient search heuristic, was developed to schedule timber

harvests and fuel treatments. The goal of this planning process was to find ways to reduce the potential for high severity wildfires with management actions. Elevation, slope, aspect, custom fuel models, and the BEHAVE model (Burgan and Rothermel, 1984) were used to estimate the potential damage for each vegetation class based on flame length. Given the objectives and constraints of the problem, wildfires were generated for all time periods from a probability distribution (amount, size, location), up to an average amount of wildfire over a given period of time. Selected polygons were burned based on their wildfire risk factor and the likely wind direction, and the wildfires were spread up to the desired size. After wildfires were simulated, the system used rules to decide whether to salvage stands immediately or to postpone harvests. Sessions et al. (1999) expanded on this and developed a process where effects of fuel breaks could be modeled within the context of wildfire and forest transition. Here, a spatially explicit simulation / optimization model that included a forest stand dynamics model, a stand management optimizer for dynamically selecting prescriptions at run time (i.e., not-prescheduled prescriptions), and a spatially explicit wildfire spread model (FARSITE, Finney, 1998) were incorporated into a heuristic technique. This planning process facilitated the scheduling of management activities, the simulation of wildfire, and the associated growth and mortality of vegetation, all of which were guided by stand-level and landscape-level objectives.

Konoshima et al. (2008) incorporate a spatial wildfire spread model into a stochastic optimization process to evaluate optimal patterns of fuel management activities across the landscape. Another process for scheduling forest management activities in a spatial pattern (dispersed, clumped, random, and regular) across the landscape, in an attempt to mitigate the impacts of wildfire, is presented in Kim et al. (2009). Here, a heuristic (the great deluge algorithm) was developed to schedule management activities, both operational and those aimed at fuel reduction, and wildfires are simulated using FARSITE methods. In this work, fifteen randomly located ignitions were placed on the landscape after management activities were scheduled, and the impact on wildfire behavior and scheduled timber harvest volume was assessed. One limitation of the Kim et al. (2009) work was that wildfires were only simulated after the first time period in the time horizon, given the computer processing requirements. Bettinger (2009) extended this work using a feed-back mechanism for stochastic processes that was incorporated into the development of a forest plan. The heuristic in this effort was a combination of 1-opt and 2-opt tabu search, and again wildfire was simulated using FARSITE code. Non-complete mortality was assumed, based on fire line intensity. These two processes be-

gin with the development of a set of optimal stand-level management prescriptions, which are assigned to timber stands to generate an initial plan of action that leads to the highest, and most even scheduled timber volume. In the second effort, the spatial location of wildfires are then simulated period-by-period using FARSITE code. The number of wildfires per period was fixed, yet the location of ignition was random. Further, timber stands that are affected by wildfire are re-assigned management prescriptions based on their resulting vegetative condition, using a burn severity rating (i.e., stands were not necessarily redirected to a regenerated forest structure). The scheduled wood volume is then re-evaluated from the period in question forward through the time horizon.

Finally, the MAGIS (Multi-resource Analysis and GIS) model (Zuuring et al., 2005) was developed by the U.S. Forest Service and the University of Montana. This spatial harvest scheduling model develops a treatment schedule based on the hazard ratings from SIMPPLLE (Simulating Patterns and Processes at Landscape Levels), the treatment locations from TOM (Treatment Optimization Model), and the potential wildfire behavior from MTT (Minimum Travel Time), along with other socio-economic goals. MAGIS is integrated with geographic information systems, and linear programming, mixed integer programming, or heuristic methods are available for optimizing management actions. Tactical, long-range planning is facilitated, and treatments account for disturbance processes such as wildfire. Using SIMPPLLE and MAGIS in an iterative manner can allow one to plan the optimal size and location of forest treatments that are most effective in reducing the size of wildfires. MAGIS is one of the few decision-support models that is currently publicly available and supported by the developers.

4 DISCUSSION

Much of the work involving methods for incorporating wildfires into forest planning models is aimed at emulating the effects of wildfires so that the impacts on timber resources can be estimated. Among the efforts that were reviewed that specifically incorporated some form of wildfire effect into a forest planning model that scheduled management activities, it is interesting that most of the developmental work was accomplished in the western U.S. and Canada, with a few exceptions. This is not surprising given the importance of wildfire to the health of the ecosystem in the dry, interior portion of northwestern North America, nor is it surprising that land managers have viewed the risks of wildfire to be more important here than in areas such as the southeastern United States, where road systems are more dense and

the climate generally more humid. One of the main conclusions of several of the works presented in this paper is that a buffer stock of forests should be maintained in each age class to counteract the probability of losing some of these areas to wildfire each year. How wildfires have been incorporated into and accounted for in forest planning models is interesting as well, and tends to follow the evolution and development of computers, operations research techniques, and mapping systems. The earlier models simply reduced strata (bins of acres) by either a deterministic or random amount, then seek to re-define allowable harvest levels. In later models, vector polygons, which are commonly used in tactical forest planning models, have been used to represent the spatial location of wildfires, although grid-based approaches are perhaps the most realistic (yet most complex as well).

The variety of operations research approaches that have been used generally reflect the state of the art in this area at the time that the work was developed. Some researchers opted for relatively simple representations of wildfire effects to match the requirements of the operations research technique used, although it seems that advances in operations research have been prompted by the desire to accommodate wildfire effects. It is also possible that some of the relatively simple approaches have been opted for given the stochastic nature of wildfires and the resulting uncertainties regarding ignition location, wildfire intensity, and wildfire behavior. Boychuk and Martell (1996) noted a number of limitations of linear programming models, each made with the intent of maintaining a small model size. With advances in computer technology and optimization software, these issues may not be as important today. Simulation models and heuristics can be designed to accommodate a wide variety of functional relationships among disturbances, landscape conditions, and forest goals. However, these models can become too complex for land managers to use in practice.

There are a number of differences in the models described here that reflect the evolution of computer modeling and our knowledge of wildfire behavioral processes. First, the impact of wildfires are accounted for in the various planning processes in a variety of ways, from strata reductions, to pixel-based growth and assessment of wildfires, to vector-based polygon impacts and the spread of wildfire from one polygon to other adjacent polygons. Second, the frequency, intensity, and spread of wildfires have been both deterministically and randomly assumed. When randomly estimated, either statistical distributions are used to estimate intensity and frequency, or a wildfire spread model is employed to let wildfires burn across the landscape. Finally, when wildfires are assumed to occur, they are either incorporated into a planning process before harvests and other activi-

ties are scheduled, or after harvests and other activities are scheduled. Given the length of some of the time periods (perhaps a decade or longer), one area of research seems to be to find ways to simultaneously schedule harvests and other activities along with wildfires.

5 CONCLUSIONS

Drawing conclusions about the impact of wildfires on outputs desired from forest plans has prompted planners to find ways to creatively account for these natural disturbances along with proposed management activities in planning models. The depth and scope of this integration is partly a function of the educated ability of the planner to address these concerns, partly a function of the technology and data available, and partly a function of the time and effort that is allocated to the effort. The difficulty in incorporating wildfires into forest plans is that no one knows when and where they will occur, and to what extent wildfires will affect natural resources. Probability distributions or rates of disturbances are adequate proxies for modeling these events, yet given the uncertainties involved, numerous simulations may be necessary, as some has proposed, to gain an understanding of what might happen to timber supplies and other services over time. For this reason, others have suggested that deterministic rates of damage may be just as appropriate as more refined and complex models for estimating the impacts. Perhaps due to the evolution of science and technology (functional relationships among resources, computers, operations research techniques, other software) or perhaps due to the fact that researchers can only publish novel work, there has been an obvious evolution in the methods that can be employed to integrate wildfire into forest planning processes. These advances, however, may exceed the current ability of planners to implement the processes, and thus recent advances may only be of value to research organizations that support landscape planning efforts. In any event, there are a few avenues of research still open, and time will tell how valuable recent (and future) developments will be to society in general.

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