Research Journal of **Forestry**

ISSN 1819-3439

Academic
Journals Inc.

www.academicjournals.com

Research Journal of Forestry 3 (1): 8-22, 2009
ISSN 1819-3439

A Prototype Method for Integrating Spatially-Referenced Wildfires into a Tactical Forest Planning Model

Pete Bettinger
Warnell School of Forest Resources, University of Georgia, Athens, GA 30602, USA

Abstract: The prototype model described here demonstrates the use of a heuristic technique in conjunction with a spatial wildfire simulation model to examine the impact of wildfires on timber harvest strategies. Within the modeling process, optimal stand-level management prescriptions are assigned to timber stands to generate an initial plan of action that leads to the highest and most even scheduled timber volume. The spatial location of wildfires and their intensity, are then simulated period-by-period. Timber stands that are affected by wildfire are re-assigned management prescriptions based on their resulting vegetative condition. The scheduled wood volume is then re-evaluated from the period in question forward through the time horizon. A case study shows the development of a plan for a large forested area (178,000 ha). Multiple simulations would be necessary to determine a range of impact for each type of wildfire scenario, since the wildfire ignition points are randomly located each time a wildfire is started. However, the main drawback of the modeling approach is the time required to generate a single simulation, as both the heuristic selected and the wildfire modeling process are time-intensive. This research represents more than a modest refinement of previously published study in this area and thus this research represents a fundamentally new application of operations research techniques to realistic forest planning problems.

Key words: Tabu search, combinatorial optimization, wildfire simulations, forest landscape planning

---

INTRODUCTION

The introduction or modification of land use regulations in the last thirty years has resulted in increasingly complex goals and objectives for the management of forests in the United States. As a result, both spatial and temporal characteristics of desired future conditions have increasingly become important measures of forest plan success, as plans seek to emulate realistic responses to management. Compliance with regulatory restrictions, voluntary forest certification programs and organizational goals and policies related to landscape conditions now outweigh economic objectives for forests in many areas of the world, particularly areas with a high proportion of public land ownership. Economic objectives are still important, however, as the feasibility of forest management plays a significant role in the dynamics of local communities. Forest landscape planning efforts that incorporate complex, yet realistic economic, ecological and social goals therefore play a significant role in decision-making (Jørgensen, 2000). However, one of the most difficult challenges is to incorporate disturbance processes into planning or simulation models (Keane *et al*., 2004).

Wildfire can either be human-caused or viewed as a natural disturbance and the behavior of wildfires is a function of topographic and vegetative conditions across a landscape. Fire plays an important ecological role in forest ecosystems, especially where forest biomass accumulation is faster than natural decomposition rates (Kalabokidis *et al*., 2002). Over the past decade and particularly on publicly managed land in the United States, there has been an increase in the interest in developing forest management approaches that emulate natural disturbance regimes, thus favoring the maintenance of biodiversity values and other essential ecological functions (Bergeron *et al*., 2002). Incorporating disturbances into a forest planning framework may allow managers to think about the potential effects of natural disturbances in association with their management planning goals. This coordination of effort should be considered when the potential for wildfire loss is high, when losses from wildfire could significantly affect timber supplies and when losses from wildfire might destabilize local economies.

Modeling forest fire management and behavior has captured the imagination of many researchers in the past two decades. Dimopoulou and Giannikos (2001), for example, developed an optimization approach for the location of fire-fighting resources. Models have been developed to simulate the fundamental mechanisms that control forest fires, such as the fireline spread model developed by Morvan and Dupuy (2001), or the 2-dimensional wildfire spread model that incorporates slope conditions, developed by Santoni and Balbi (1998). Other models have been designed to incorporate various aspects of wildfires into land management planning. For example, by Kurz *et al*. (2000) the total area to be simulated as disturbed (burned) is defined a priori, along with the distribution of sizes of disturbances. Disturbances are then simulated by randomly selecting a management unit and aggregating enough suitable neighboring units until a suitably-sized disturbance event has been achieved. These types of approaches, however, lack the wildfire behavior characteristics of other wildfire simulation models such as FARSITE (Finney, 1998).

A number of landscape-level wildfire succession models have been developed for evaluating the fire-vegetation linkages (Keane *et al*., 2004). The methods for incorporating wildfire effects into long-term forest planning vary considerable. Two decades ago Montgomery *et al*. (1986) used binary search to examine the allowable cut effect associated with wildfire losses. More recently Beukema and Kurz (2000) used a state-transition model to examine successional pathways associated with wildfires. Kalabokidis *et al*. (2002) recently developed a conceptual model to incorporate a classification of wildfire danger and wildfire resistance into forest management planning. Thus wildfire was accounted for in terms of modifications to the forest inventories and in the evaluation methodology. Armstrong *et al*. (1999) modeled the effects of wildfires on boreal landscapes non-spatially by assuming a distribution of forest types would be regenerated each year. Reed and Errico (1986) modeled the effects of wildfires in a linear programming model (again, non-spatial), but found that while wildfire losses may be stochastic, 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. One approach in forest planning has been to design clearcuts that are intended to emulate wildfires, since both types of disturbances result in the complete removal of overstory vegetation and conventional forest management is often considered as a disturbance that has effects similar to natural disturbances (Bergeron *et al*., 2002). However, the knowledge needed to do so is incomplete, since wildfires have greater variability in their frequency, severity and intensity than clearcuts (Schroeder and Perera, 2002) and the resulting regenerated forests are composed of different structural characteristics. In addition, the ability to plan large clearcuts may be contrary to current management policy. Most attempts to incorporate wildfire into a landscape planning system have taken a very generalized approach, thus we perceive a need for new models and methods for landscape planning that includes the explicit representation of wildfires as fire disturbances.

Johnson *et al*. (1998) used a heuristic forest planning process to schedule management activities with the hope of reducing the potential for severe wildfires using a fuel modeling approach. The SafeD (Graetz, 2000) model is one example of a simulation / optimization model that explicitly incorporates wildfire into a planning process. The model evolved from the landscape planning efforts of the Sierra Nevada Ecosystem Project (Sessions *et al*., 1999) and the Applegate Project (Graetz, 2000) and uses a spatially explicit, hybrid simulation model that allows the achievement of multiple resource goals at the landscape level. One of the main limitations, however, is that it schedules management activities at a pixel (30 m^2) scale, thus providing an unrealistic emulation of management behavior. Keane *et al*. (1996) also presented a landscape simulation model to simulate annual losses from wildfire using a mechanistic, biogeochemical, individual tree succession model, where tree growth is modeled using assumptions of daily carbon fixed through photosynthesis.

Most of the earlier research on the effects of forest management on wildfire behavior has been focused on the development of forest planning models to facilitate an analysis of the impact of uncertainties associated with the loss of resources (timber stocks, vegetation, etc.), as well as the impact of these losses of resources on timber supply or landscape condition. Either wildfire risk was modeled in a non-spatial manner using hazard ratings or disturbance probabilities, or wildfire spread models were incorporated into a landscape which lacks the scheduling processes typical for forest planning. To enable one to examine landscape-level processes and the implications on economic, ecological and social goals, new planning models (or new approaches within mature planning models) need to be developed that incorporate both current scientific advances with management behavior projection models. This research presents a landscape modeling effort that attempts to do just that. Here, we describe a prototype computer model that integrates more closely the processes for modeling wildfire and for planning timber management activities. This process utilizes fine-scale spatial detail for both modeling wildfire and representing vegetation, yet schedules management activities at a scale that is reasonable (from a management perspective) and includes feedback processes to adjust the schedule of management activities in relation to the wildfires that are modeled.

MATERIALS AND METHODS

The prototype model was initially developed in 2005 in conjunction with the Interior Northwest Landscape Analysis System (INLAS) project, which was funded mainly by the United States Forest Service to develop a suite of tools for informing forest and range managers of potential policy alternatives. Research continued on the prototype model through 2008. The main study area was the Upper Grande Ronde watershed in Northeastern Oregon (USA).

The distinctions between strategic planning and tactical planning processes have become less clear in the past few years as planning models have been demonstrated that can accommodate both large areas and long time frames and include spatial restrictions and fine-scale detail (Sessions and Bettinger, 2001). As advances in computer technology and search algorithms continue to be available to the general public, the thought that spatial relationships can only be accommodated in tactical planning may no longer hold true, particularly when one considers large, complex landscape management problems. In the US interior northwest (USA) region, land managers are faced with the problem of managing a landscape to both promote the development of forest structural conditions representative of healthy forests, as well as to continue to meet higher-level goals such as those economic and commodity production measures that influence community stability. Planning at the stand-level, however, could inadvertently ignore higher-level landscape objectives. One example of this type of management situation is where a management plan for a forest supplies a widely fluctuating level of harvest each decade based on the stand-level optimal management regimes. Obviously, one could argue that to better benefit local communities, the harvest levels should be less variable from decade to decade. One measure of concern is the effect these forest plans might have on associated employment levels. To provide further insight into the relationship between timber management activities and wildfire responses, we show a prototype process by which a higher-level goal is sought given a set of optimal stand-level decisions.

Problem Formulation

The prototype model described here covers a 100 year time horizon that is divided equally into ten planning periods (decades). The objective function of the planning problem is designed to seek a maximize the even-flow of timber harvest volume by minimizing the squared deviation of the difference between a target harvest volume and the scheduled timber harvest volume.

$$\text{Minimize } \sum_{t=1}^{T}\left(\text{target volume} - H_t\right)^2 \tag{1}$$

Where:
t = A time period (decade)
T = The total number of time periods in the planning horizon
Target volume = A target periodic harvest volume defined a priori
H_t = The actual scheduled harvest volume in each time period t

A linear programming problem formulation, consisting of about 7,000 continuous decision variables (700 strata × 10 management prescriptions) was developed to provide a relaxed solution to a hypothetical forest planning problem. In this case, strata are developed to represent the forested areas (timber stands) and potential prescriptions could be applied to each. Due to the continuous nature of the values assigned to the strata within the linear programming problem, the exact spatial location of each prescription is difficult to locate. Thus one should assume that the solution is a relaxed version of a more complex problem. The resulting even-flow timber harvest volume of this relaxed problem was 200,716 thousand board feet (MBF) per decade. This value was then used as the target harvest level (H_t) in the problem formulation described above.

Ten potential stand-level management prescriptions were designed for each stand (Table 1). The spatial location of activities is important in the modeling of wildfire behavior, therefore only one of the ten stand prescriptions is assigned in an effort to achieve the landscape-level objective in Eq. 1. Thus the decisions are modeled with binary integer variables.

$$\sum_{p=1}^{P} X_{ip} \leq 1 \quad \forall i \tag{2}$$

Where:
p = A single management prescription
P = The entire set of potential management prescriptions
i = A forested stand
X_{ip} = A binary integer decision variable for management prescription p assigned to stand i

Table 1: Stand-level management prescriptions developed for the forest planning process, each of which desired to maintain stand density index between 35 and 55%

Management prescription	Maximum harvested tree diameter (cm)	Minimum harvested tree diameter (cm)	Minimum residual basal area (m^2 ha^{-1})	Minimum harvest volume (board feet ha^{-1})
0 (grow only)	---	---	---	---
1	---	17.8	18.4	0
2	53.3	17.8	13.8	0
3	---	17.8	18.4	3,707
4	---	17.8	18.4	7,413
5	---	17.8	18.4	11,120
6	53.3	17.8	13.8	3,707
7	53.3	17.8	13.8	7,413
8	53.3	17.8	13.8	11,120
9	76.2	12.7	16.1	11,120

Equations similar to accounting rows used in linear programming problems are employed to aggregate the scheduled harvest volume during each time period.

$$\sum_{i=1}^{N}\sum_{p=1}^{P}\left(X_{ip}\ V_{ipt}\right)=H_t \qquad \forall t \tag{3}$$

Where:

N = The total number of forested stands

V_{ipt} = The available timber harvest volume during time period t, from stand i, when assigned prescription p

Once scheduled harvest volumes have been aggregated for each time period, they are inserted into the objective function to evaluate the quality of the resulting plan.

Heuristic Search Algorithm

The prototype model utilizes integer decision variables for scheduling timber harvests and a spatial wildfire model for simulating wildfires. Management planning issues that rely on the use of integer variables are combinatorial problems by nature, thus as the problem size increases, the solution space increase, but at a disproportionately greater rate (Lockwood and Moore, 1993). Mixed integer and integer programming techniques are useful for producing natural resource management plans that include integer decision variables, but these techniques are of limited value when spatial and non-linear functions are necessary, as in this case. A heuristic search technique, tabu search, is employed to schedule the harvests (Bettinger *et al*., 2007). Some examples of the usefulness of tabu search in forest planning include Bettinger *et al*. (1997, 1998, 2002), Boston and Bettinger (1999) and Murray and Church (1995). Tabu search was introduced by Glover (1989, 1990) for application to industrial problems and was chosen for this prototype model because we have previously shown it is as good (or better) than other heuristics for these types of forest-level planning problems (Bettinger *et al*., 2002). A randomly generated schedule of timber harvests is first assigned to the landscape. The prototype model then uses diversification and intensification processes to improve the development of forest plans. The first process involves 1-opt moves, where the management prescription applied to a timber stand is changed. An iteration of 1-opt moves involves adjusting the current solution, x_j, using a move, σ_{pi} (the choice of assigning management prescription p for stand i). Two tabu search neighborhood sizes are used: the full neighborhood (total number of stands × total number of prescriptions) and a region-limited, smaller neighborhood. The full neighborhood is used once every 10 iterations of the scheduling process, since it requires a significant amount of computational time to develop. The region-limited neighborhood is developed for each set of 2,000 sequentially numbered timber stands (1 to 2,000, 2,001 to 4,000, etc.). Aspiration criteria (accept the move if tabu, yet the resulting solution is the best observed) and short-term memory (tabu state = 1000 iterations, based on several trials using tabu states ranging from 500 to 5000 moves) are also included in the model.

A second tabu search process to diversify the search uses moves made from a 2-opt neighborhood. This strategy is initiated at the conclusion of the 1-opt move process described above. A 2-opt moves consist of swapping the prescription assigned to one stand with that assigned to another stand. This is similar to methods employed in traveling salesman problems. The 2-opt move process for this prototype was developed using a region-limited neighborhood of moves, where only 1,000 sequentially numbered stands are examined at one time. After selecting a choice from the neighborhood, the region-limited neighborhood shifts by 20 stands. For example, the first 2-opt move selection comes from the set of potential management prescription swaps among stands numbered 1-1,000, the second 2-opt move selection comes from the set of stands numbered 21-1,020 and so on.

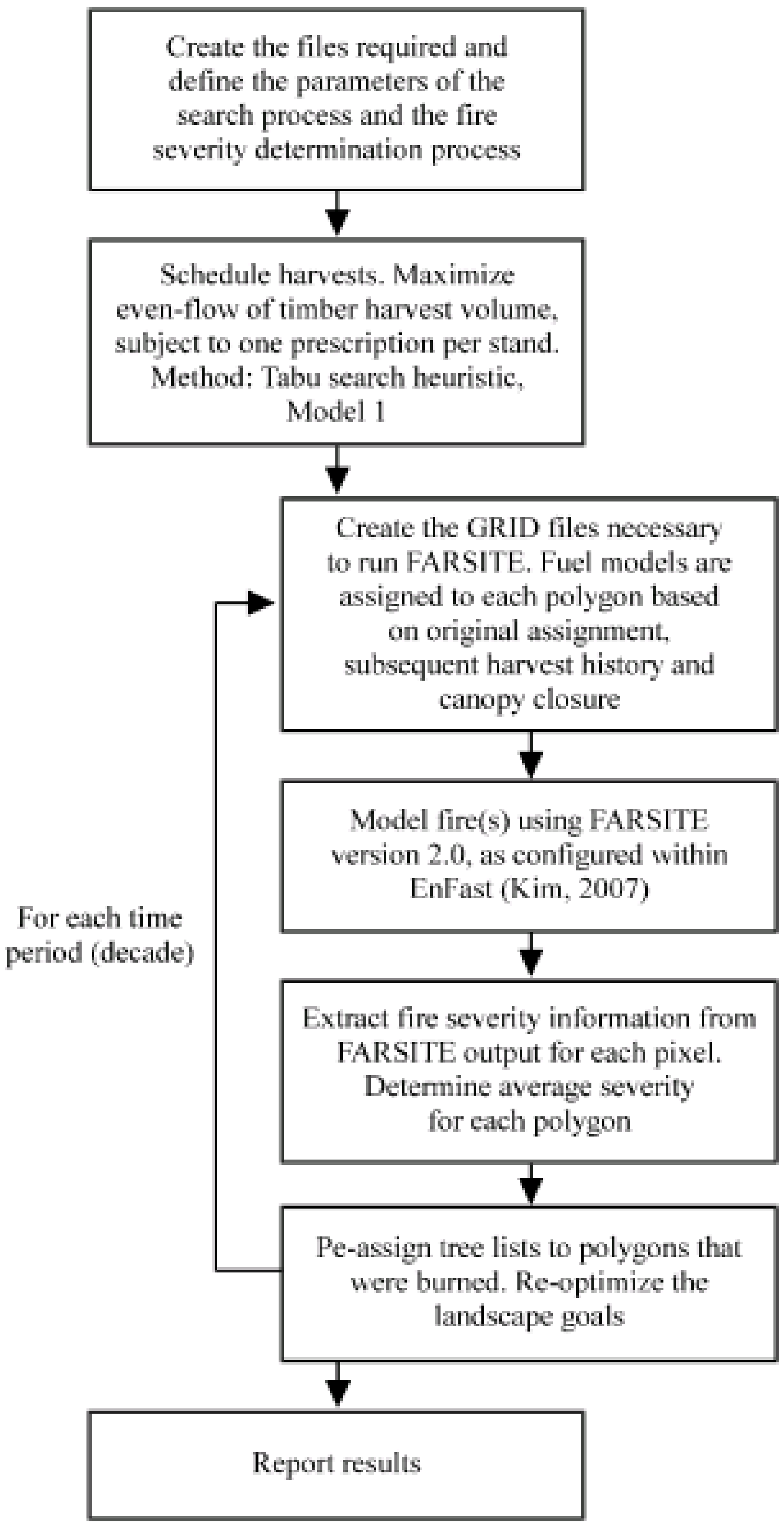

Fig. 1: A basic flow chart of the prototype scheduling process

This diversification process is used only once during the development of a forest plan. Earlier research (Bettinger *et al*., 1999, 2002; Caro *et al*., 2003; Heinonen and Pukkala, 2004) has shown the potential for using 2-opt tabu search neighborhoods on forest planning problems. However, the computational cost of using a 2-opt tabu search neighborhood for large forest planning problems is daunting, thus the need for smaller neighborhoods of choices.

The prototype model (Fig. 1) begins with the development of data necessary for scheduling timber harvests and for modeling wildfires. Harvests are scheduled for the entire planning horizon (100 years) using the tabu search process described above. At the end of the initial tabu search process, wildfires are simulated across the landscape, representing a typical decade's worth of wildfire events. Fire severity is determined for each timber stand impacted by a wildfire and these timber stands are placed into one of five classes (20, 40, 60, 80, or 95% burned). Trees that were represented in the original tree lists of the affected timber stands are removed, starting with the smallest trees, up to the percent basal area assumed affected (killed) by a wildfire. These adjusted tree lists are then assigned to each affected timber stand and the landscape-level harvest goals are once again re-optimized using tabu search. Once this has been accomplished, wildfires are simulated for the second decade, tree lists are adjusted and the landscape-level goals are re-optimized. This process continues for each of the remaining decades and at the conclusion, results are generated reflecting the potential timber harvest levels given the wildfires that were simulated.

Wildfire Simulation Model

In performing spatial wildfire simulations, we used the source code of FARSITE (Finney, 1998) to develop a module named EnFast (Kim, 2007). EnFast is essentially FARSITE, yet was embedded within the harvest scheduling model so that wildfires could be simulated once per decade after scheduled harvests had been planned. FARSITE has been used in a number of research projects (Van Wagtendonk, 1996; Stephens, 1998; Finney, 2001, 2003; Stratton, 2004). For each wildfire simulation, spatial information on topography and fuel condition (fuel type, canopy cover, stand height and crown base height) is required. These databases are a function of the current state of the vegetation resources in the period of wildfire simulation. Thus earlier wildfires (and subsequent re-analysis of management prescriptions) affected the behavior of future wildfires. Along with spatial information regarding topography and fuels, the wildfire simulations require a set of assumptions regarding the weather conditions. For the purposes of this report, these were developed for a hypothetical extreme wildfire season in eastern Oregon, the area in which the case study forest resides.

Output files from FARSITE are contained in raster databases composed of 30 m grid cells. Each grid cell contains a value related to the simulated wildfires (e.g., fireline intensity). From grid cells burned by simulated wildfires, the weighted average severity of each timber stand burned was determined. Although the break points at which burn severity define different vegetative conditions can be modified easily in the prototype model, we assumed for this paper that a stand with a 20% burn severity had an average fireline intensity of 100 BTU ft^{-1} sec^{-1} or less using the scale provided by Rothermel and Rinehart (1983). The 40, 60 and 80% fireline intensity cut-offs were 500, 1,000 and 1,500 BTU ft^{-1} sec^{-1}. In order to model wildfires and to determine wildfire severity within a timber stand, one needs the following data: (1) the size of each timber stand and the original data describing the vegetative resources (2) a fuel model that is assigned to each timber stand based on the vegetation currently residing in each and (3) canopy closure estimates for stands in both the burned and unburned condition over time.

Case Study Landscape

The landscape used to demonstrate the prototype method consists of 178,000 ha of forest and range just west of La Grande, Oregon (USA), most of which is in public ownership. The landscape has been classified into its current silvicultural condition by public land managers and is described by 17,246 polygons, or stands, averaging in size about 10 ha each. About 700 tree lists (strata), data used to model responses of forests to various silvicultural prescriptions, are used to characterize the structural conditions of the forested stands.

The optimal stand-level prescriptions were developed using a RLS-PATH program (Bettinger *et al*., 2005), which is based on similar study of Yoshimoto *et al*. (1990). Each optimal stand-level prescription (Table 1) seeks to maintain stand density between 35 and 55% of the maximum level appropriate for the dominant tree species of each tree list. This range of stand density was suggested by forest managers familiar with the landscape as the most desirable for maintaining healthy forest conditions. Each of the ten optimal prescriptions also contains constraints that either (1) limit the harvest of large trees, or (2) limit harvest opportunities to those that can provide a minimum volume per unit area to be harvested. The second of these constraints represents a range of minimum harvest volumes, as consensus on a minimum volume is lacking due to the variety of harvest systems available and variations in the cost structure of logging businesses. Each of the prescriptions allows partial cutting to occur and subsequent entries into stands are allowed after a one-period delay (i.e., the minimum time prior to re-entry into a stand is 20 years). These management prescriptions were applied to the original (un-burned) timber stands, as well as the timber stands that might be placed into one of the five wildfire severity classes (20, 40, 60, 80, or 95% burned) after the tree lists have been adjusted. Therefore, options (management prescriptions) are available for un-burned stands as well as stands that have been burned. Further, once a timber stand has been burned, the management prescription applied comes from a set related to burned stands. Therefore, a typical timber stand may be managed in an un-burned state for a number of time periods, then after a wildfire, it may be managed in a burned state.

Within the guise of a larger research and technical assistance program, it was assumed that only partial cutting activities are allowed in this landscape, as the goals of forest management focus on the development of healthy forests and the maintenance of structural conditions that can reduce the risk of damage from wildfire, insects, disease and other destructive agents. Other prescriptions can be argued to also meet these goals, but the activities we model closely resemble the current philosophy of public land management in the interior northwest. Thus each of the ten prescriptions, with the exception of a grow-only prescription, allow various timing of partial cutting activities as well as volumes harvested per unit area. Theoretically, each prescription will contain a different harvest volume and timing of entry. Although only 700 tree lists are used to characterize the forest conditions of the 17,246 polygons, each polygon has a different size, ensuring a wide range of potential harvest volumes with each choice.

We arrived at the assumptions regarding the management prescriptions based on discussions with the dominant landowner (US federal government) in the region studied (eastern Oregon, USA). The range of minimum harvest volumes and minimum basal areas that remain after partial cutting were determined from these discussions as well as a survey of landowners in the region. Obviously, one assumption will not fit all landowners or management situations, therefore we generated a set (10) of prescriptions that seemed to cover the range of activity currently being employed in the region. Some of these assumptions, such as those that regard the minimum levels of harvestable volume per unit area, are modeled based on manager's opinions of the volume that may be required before a harvest is considered economically feasible. Obviously, the forest-level solution will only be as good as the quality of the stand-level management prescriptions. We made a concerted attempt, therefore, to develop what we felt were reasonable prescriptions for the landowners and region studied. While the results are optimal at the stand-level, given the assumptions we made for each prescription, the flexibility provided from the set of ten should provide a forest-level solution with a higher even-flow volume than would be found if a smaller set (or even simply one prescription) were used.

RESULTS

The computer interface for the prototype planning model was developed within the Microsoft Visual Basic 6.0 (professional edition) environment and implemented on a personal computer equipped with a 2.4 GHz processor. The scheduling process and the wildfire simulation process were both coded in the C programming language and are called from the interface after all of the input files, output files and scheduling parameters are assigned. The amount of time required to develop a solution without simulated wildfires (tabu search only) was about 30 min. The amount of time required to re-optimize after simulating the wildfires was about 200 min.

One wildfire per year (10 per time period) was simulated in this example to show the usefulness of the prototype modeling process (Fig. 2). The location of the initiation point of each wildfire was randomly determined and the wildfires were simulated using severe wildfire season parameters. The results from the initial, pre-wildfire simulation harvest schedule show a relatively even

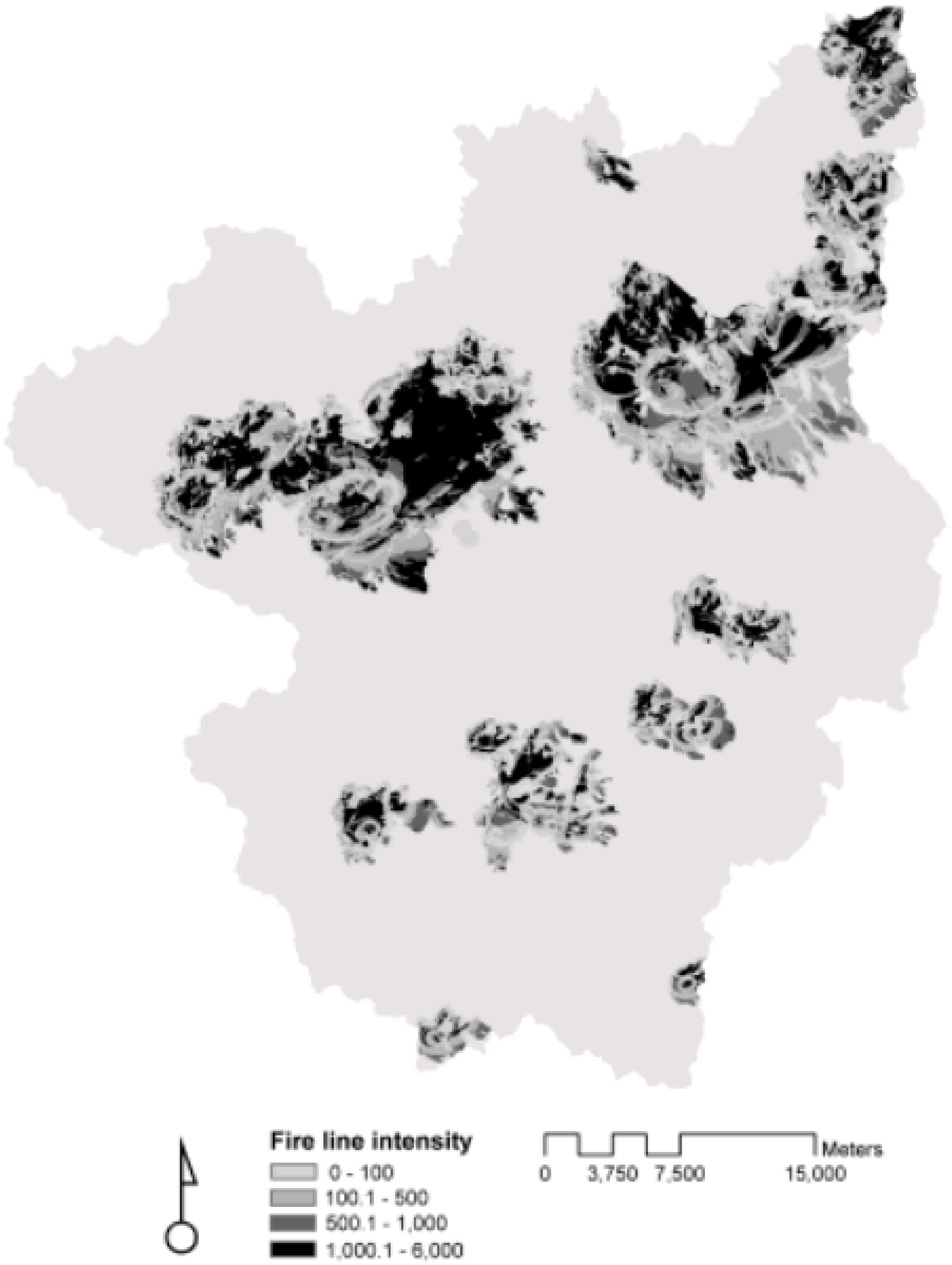

Fig. 2: Randomly located wildfires in the first decade of the planning process

harvest has been scheduled after the fourth decade (Table 2). These results are reflective of the fact that only ten different management prescriptions could be applied to the timber stands and show that fact that given the initial forest conditions, fewer opportunities for partial harvests are available during the second and third time periods than the other seven time periods. In fact, most of the management prescriptions, given the initial condition of the forest, require a partial harvest in the first decade. With a larger set of available management prescriptions, the level of timber volume scheduled would likely be smoother than these results. After wildfires had been applied to the first three decades, the re-optimized harvest schedule is much more even (Table 3), reflective of the fact that a new suite of management prescriptions were available to timber stands that were burned. These new management prescriptions provided a different entry timing and level of volume harvested for selected (burned) stands and allowed a reconfiguration of the assigned management prescriptions to the un-burned stands, facilitating a better and more realistic schedule of the available timber harvest levels.

Table 2: Results of a forest plan developed prior to the simulation of wildfires

Decade	Scheduled harvest volume (MBF)
1	197,845
2	139,677
3	177,954
4	199,396
5	197,914
6	207,047
7	201,385
8	200,981
9	204,790
10	199,011

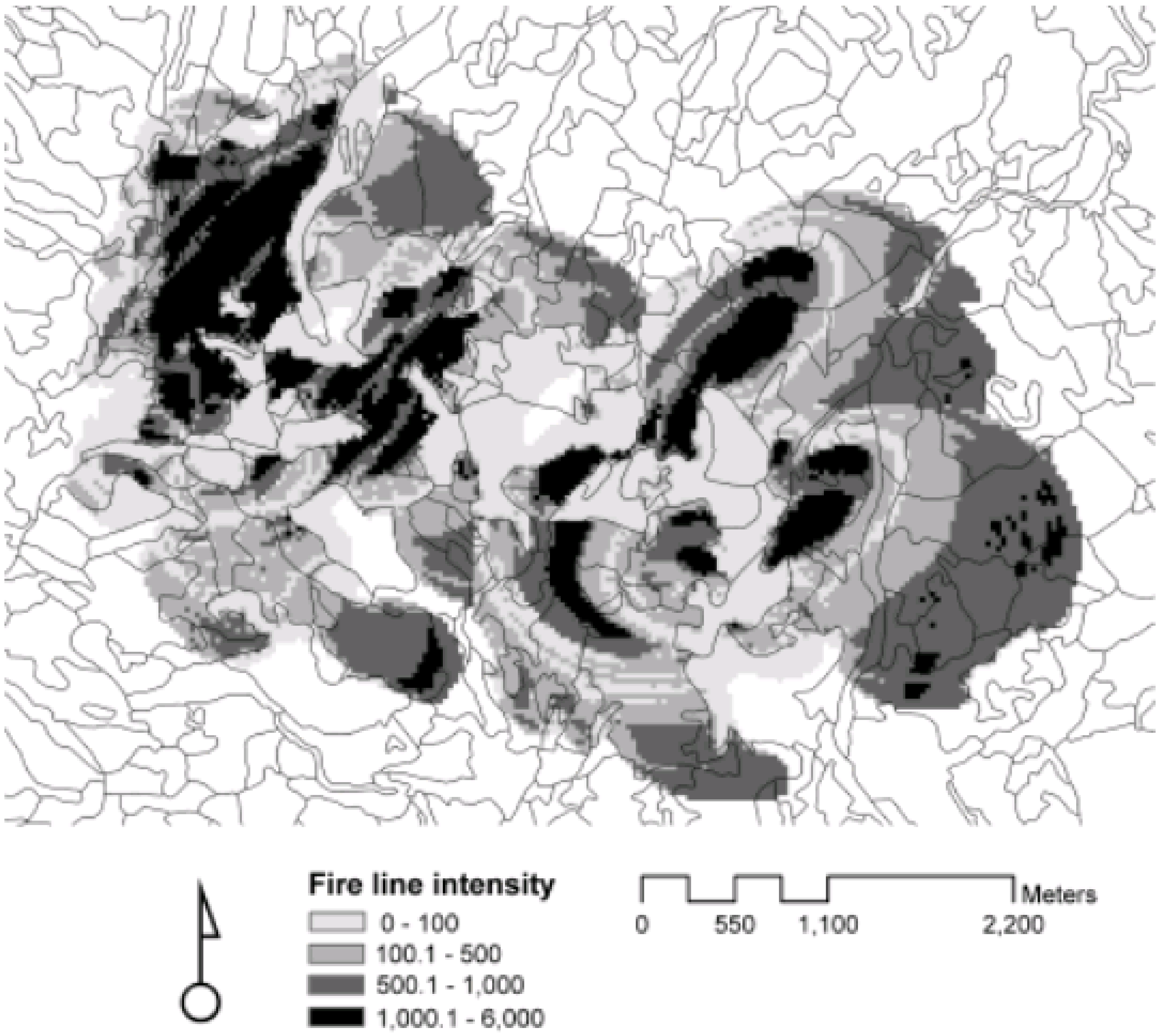

Fig. 3: Fireline intensity of a single simulated wildfire in relation to timber stands located on the landscape

An example of the fireline intensity of a simulated wildfire, in relation to the timber stands situated on the landscape, is provided in Fig. 3. As one can see, some portions of the simulated wildfires are more severe within individual timber stands than other portions of the wildfire. In addition, the wildfire terminated in a number of cases prior to burning through an entire timber stand. It is for these reasons that a weighted average fireline intensity was calculated, with knowledge of the pixels that reside within each timber stand. The prototype model uses both vector and raster data and currently is designed to arrive at a weighted average vegetative condition for each timber stand. Therefore, while some portions of a timber stand may have been more heavily affected by a wildfire,

Table 3: Results of a forest plan developed after the simulation of wildfires

Decade	Scheduled harvest volume (MBF)
1	200,362
2	171,584
3	194,381
4	200,444
5	201,279
6	202,392
7	204,290
8	211,154
9	203,537
10	203,174

the average intensity is used to determine the percent of the basal area to remove (kill) and subsequently to determine the appropriate yield table to assign after the wildfire simulation. While this may be considered a drawback to the process, in many cases management actions are typically assigned to pre-determined areas representing timber stand boundaries. These boundaries may consist of roads, streams, or other topographical features.

DISCUSSION

The prototype model for integrating spatially-referenced wildfires into a forest planning environment was developed with the intention of better representing the effects of natural disturbances on the sustainability of a resource (timber harvest volumes). While the location of the initiation point of the simulated wildfires was randomly assigned, the model show the incorporation of processes that would normally be treated independently in an ad hoc manner. In fact, predicting the location of future wildfires is nearly impossible, given that they are created by both natural processes (lightning) and human processes (accidental or intentional ignition). Given these facts, it may be of value to planners using a model such as this to develop a number of forest plans and average the effect on scheduled timber harvest volumes.

In using an approach such as this to determine the potential effects of wildfires on the sustainability of timber harvest volume, the parameters of the modeling approach need also to be fully explored. There are parameters associated with the heuristic search technique that could affect the quality of results. For example, with tabu search, the tabu state and the length of time the search is allowed to progress could significantly affect the resulting forest plan. In addition, without the use of a 2-opt process within tabu search, the results would likely be sub-optimal to a higher degree (Bettinger *et al*., 2007). Further, the assumptions used regarding the number of wildfires to simulate and the severity of the average wildfire season could dramatically affect the resulting analysis. An investigation into the natural disturbance processes of a modeled region, along with a sensitivity analysis (involving multiple runs of a model such as the one described here) of variations to these assumptions would help one understand the limits within which reasonable effects may be found.

The prototype model described here focused on representing the spatial location of wildfires simultaneous to the development of a forest plan. The objective of the forest plan was to determine the schedule of activities that would result in the highest and most even timber harvests over a long period of time. If other measures of sustainability are important, or if the objective of the forest plan contained different metrics, these too could be incorporated into a model such as this. Earlier research has shown that spatial wildlife goals could be recognized and used to control forest management activities (Bettinger *et al*., 1997, 2002). In addition, various measures of biodiversity could be acknowledged, given the appropriate input data to measure the attainment of these, as either constraints or portions of a multi-objective forest planning system (Kangas and Pukkala, 1996). As a result, the stress placed on the sustainability of timber production is not necessarily an issue that constrains the use of a model such as the one proposed here. The broader issues involve the determination of the appropriate objectives and constraints, the location of the functional relationships that link the landscape metrics to the objectives and constraints and the time required to develop the necessary databases and modeling structure.

Another area of consideration for future improvements in the modeling structure rests on the management prescriptions that were assumed. We chose to utilize direction from managers in the case study area to limit the management prescriptions to a small set of possible choices (ten potential optimal management prescriptions given certain stand-level goals). These were developed a priori to the forest planning process. It goes without saying that a larger set of management prescriptions could be utilized, although justification for a larger set may be necessary if the results are being used to influence forest plan development. A more sophisticated version of the prototype model could involve the integration of a forest growth simulator directly into the modeling structure, so that alternative management prescriptions are developed as needed. This would involve the development of a forest planning model that integrated three main processes: (1) the scheduling of management activities based on landscape-level goals, (2) the simulation of wildfires and (3) the simulation of alternative management regimes. Since most growth and yield models were developed specifically for a region of the world, the integration of a universal growth and yield model is problematic. Few growth and yield models, such as the Forest Vegetation Simulator (Dixon, 2002), have the capability to provide a consistent modeling framework for large areas (in the case most of the United States and portions of Canada).

While the model described here has been alluded to as a landscape-level optimization process, it is different than much of the earlier study describing the juxtaposition of management activities across the landscape. Recent research has mainly focused on the location and timing of clearcut harvests and the need to control opening sizes (McDill *et al*., 2002). In fact, spatial restrictions on the location and timing of management activities are currently included in the prototype model in a minor manner. The current model disallows scheduling management activities (logging entries) to stands that share an edge (or are considered adjacent). This assumption was meant to spread the activities across the landscape, yet it is an process that can easily be removed. However, integer variables are used in the prototype model to represent the assignment of management prescriptions to timber stands. This was necessary to recognize the notion that a single management prescription could be assigned to a timber stand and the exact location of activities needed to be known to develop the vegetation data necessary for the wildfire simulations. Partial assignment of a management prescription to a timber stand would impede the ability to spatially simulate wildfires across the landscape. Therefore, while previous efforts to incorporate the potential effects of wildfires into forest plans have been performed in an aspatial manner (using vegetation strata, rather than actual timber stands and non-integer decision variables), moving to a spatially-explicit modeling and planning system would seem to require a more direct approach.

Tabu search represents a reasonable heuristic process for developing feasible and efficient forest plans, although the addition of diversification or intensification processes may be necessary to produce high-quality results. The deterministic approach we employed may intuitively seem advantageous over the stochastic nature of other heuristic search processes, such as genetic algorithms or simulated annealing. However, almost any heuristic could be used to assign management activities to timber stands. The alternatives are a function of the creativity and skills of the model developer. One area of future work would be to determine whether a heuristic that is characteristically fast (such as simulated annealing) would allow the search process to quickly reach a local optima without the need to re-define parameters (such as the initial temperature and the cooling rate associated with simulated annealing) as harvest levels are adjusted after simulating wildfires.

CONCLUSIONS

The prototype model described here demonstrates that a heuristic technique can be used in conjunction with a wildfire simulation model to examine the impact of timber harvest strategies when wildfires are spatially simulated. Optimal stand-level management prescriptions were assigned to timber stands to generate an initial plan of action that led to the highest and most even scheduled timber volume. Wildfires were then simulated period-by-period and stands that were affected were re-assigned management prescriptions based on their resulting condition. The scheduled wood volume was also then re-evaluated from the period in question forward through the time horizon. Wildfires were simulated for all time periods in the planning horizon and the resulting forest plan then takes into account the potential impact of wildfire on scheduled management activities and timber volumes. Multiple simulations would be necessary to determine a range of impact for each type of wildfire scenario, since the wildfire ignition points are randomly located each time a wildfire is started. However, the prototype model described in this paper represents the first attempt to use spatial representations of wildfires over large areas to develop adequate forest plans complex objectives.

The main drawback of the modeling approach is the time required to generate a single simulation. The tabu search heuristic search process includes 2-opt moves to improve the quality of forest plans and fine-tune the scheduling of harvests. The development of a 2-opt neighborhood can significantly increase the computational time required to develop a solution, depending on the neighborhood size. The wildfire modeling process also is time-intensive, as the current state of the vegetation on the landscape is required each time period and as the wildfires are allowed to progress across the landscape. Reverting to a re-scheduling of the management actions after wildfires have been simulated also adds to the time required to generate a solution, yet this adds realism to the model, since the burned areas are recognized and a management reaction is assumed.

This research represents more than a modest refinement of previously published work in this area. Other studies have simply assumed that the amount of land affected by a wildfire would be non-spatially adjusted each time period. While the vegetation in these affected strata would be modified to reflect the impact of a wildfire, there is generally no relation to fire spread nor to the topography of the landscape. However, as computing power increases and our ability to spatially represent environmental impacts moves forward, the prototype described here can be used as a reference for future study in this field.

ACKNOWLEDGMENTS

This research was supported by a Joint Venture Agreement (02-JV-11222046-230) between Oregon State University (recipient of the grant) and the US Forest Service, Rocky Mountain Research Station (funding agency).

REFERENCES

Armstrong, G.W., S.G. Cumming and W.L. Adamowicz, 1999. Timber supply implications of natural disturbance management. For. Chron., 75: 497-504.

Bergeron, Y., A. Leduc, B.D. Harvey and S. Gauthier, 2002. Natural fire regime: A guide for sustainable management of the Canadian boreal forest. Silva Fenn., 36: 81-95.

Bettinger, P., J. Sessions and K. Boston, 1997. Using tabu search to schedule timber harvests subject to spatial wildlife goals for big game. Ecol. Model., 94: 111-123.

Bettinger, P., J. Sessions and K.N. Johnson, 1998. Ensuring the compatibility of aquatic habitat and commodity production goals in eastern Oregon with a Tabu search procedure. For. Sci., 44: 96-112.

Bettinger, P., K. Boston and J. Sessions, 1999. Intensifying a heuristic forest harvest scheduling search procedure with 2-opt decision choices. Can. J. For. Res., 29: 1784-1792.

Bettinger, P., D. Graetz, K. Boston, J. Sessions and W. Chung, 2002. Eight heuristic planning techniques applied to three increasingly difficult wildlife planning problems. Silva Fennica, 36: 561-584.

Bettinger, P., D. Graetz and J. Sessions, 2005. A density-dependent stand-level optimization approach for deriving management prescriptions for interior Northwest (USA) landscapes. For. Ecol. Manage., 217: 171-186.

Bettinger, P., K. Boston, Y.H. Kim and J. Zhu, 2007. Landscape-level optimization using tabu search and stand density-related forest management prescriptions. Eur. J. Operat. Res., 176: 1265-1282.

Beukema, S.J. and W.A. Kurz, 2000. Vegetation Dynamics Development Tool Users' Guide, Version 4.0. ESSA Technologies Ltd., Vancouver, BC.

Boston, K. and P. Bettinger, 1999. An analysis of Monte Carlo integer programming, simulated annealing and tabu search heuristics for solving spatial harvest scheduling problems. For. Sci., 45: 292-301.

Caro, F., M. Constantino, I. Martins and A. Weintraub, 2003. A 2-opt tabu search procedure for the multiperiod forest harvest scheduling problem with adjacency, greenup, old growth and even flow constraints. For. Sci., 49: 738-751.

Dimopoulou, M. and I. Giannikos, 2001. Spatial optimization of resources deployment for forest-fire management. Int. Tran. Oper. Res., 8: 523-534.

Dixon, G.E., 2002. Essential FVS: A User's Guide to the Forest Vegetation Simulator. US Department of Agriculture, Forest Service, Forest Management Service Center, Fort Collins.

Finney, M.A., 1998. FARSITE: Fire Area Simulator-Model Development and Evaluation. US Department of Agriculture, Forest Service, Rocky Mountain Research Station, Ft. Collins, Co., USA.

Finney, M.A., 2001. Design of regular landscape fuel treatment patterns for modifying fire growth and behavior. For. Sci., 47: 219-228.

Finney, M.A., 2003. Calculation of fire spread rates across random landscapes. Int. J. Wildland Fire, 12: 167-174.

Glover, F., 1989. Tabu search-Part I. ORSA J. Comp., 1: 190-206.

Glover, F., 1990. Tabu search-Part II. ORSA J. Comp., 2: 4-32.

Graetz, D.H., 2000. The SafeD model: Incorporating episodic disturbances and heuristic programming into forest management planning for the Applegate River watershed, southwestern Oregon. M.Sc. Thesis, Department of Forest Resources, Oregon State University.

Heinonen, T. and T. Pukkala, 2004. A comparison of one and two compartment neighbourhood heuristic search with spatial management goals. Silva Fennica, 38: 319-332.

Johnson, K.N., J. Sessions, J., Franklin and J. Gabriel, 1998. Integrating wildfire into strategic planning for Sierra Nevada forests. J. Forestry, 96: 42-49.

Jørgensen, S.E., 2000. Editorial: 25 years of ecological modelling by Ecological Modelling. Ecol. Model., 126: 95-99.

Kalabokidis, K.D., S. Gatzojannis and S. Galatsidas, 2002. Introducing wildfire into forest management planning: towards a conceptual approach. For. Ecol. Manage., 158: 41-50.

Kangas, J. and T. Pukkala, 1996. Operationalization of biological diversity as a decision objective in tactical forest planning. Can. J. For. Res., 26: 103-111.

Keane, R.E., K.C. Ryan and S.W. Running, 1996. Simulating effects of fire on northern Rocky Mountain landscapes with the ecological process model FIRE-BGC. Tree Phys., 167: 319-331.

Keane, R.E., G.J. Cary, I.D. Davies, M.D. Flannigan, R.H. Gardner, S. Lavorel, J.M. Lenihan, C. Li and T.S. Rupp, 2004. A classification of landscape fire succession models: Spatial simulations of fire and vegetation dynamics. Ecol. Model., 179: 3-27.

Kim, Y.H., 2007. Spatial patterns of fuel management activities and their effects on wildfire behavior. Ph.D Thesis, Department of Forest Resources, Oregon State University, Corvallis.

Kurz, W.A., S.J. Beukema, W. Klenner, J.A. Greenough, D.C.E. Robinson, A.D. Sharpe and T.M. Webb, 2000. TELSA: The tool for exploratory landscape scenario analyses. Comp. Elect. Ag., 27: 227-242.

Lockwood, C. and T. Moore, 1993. Harvest scheduling with spatial constraints: A simulated annealing approach. Can. J. For. Res., 23: 468-478.

McDill, M.E., S.A. Rebain and J. Braze, 2002. Harvest scheduling with area-based adjacency constraints. For. Sci., 48: 631-642.

Montgomery, C.A., J.D. Brodie and D.A. Cleaves, 1986. Allowable cut effect and fire-damage appraisal. West. J. Applied For., 1: 100-103.

Morvan, D. and J.L. Dupuy, 2001. Modeling of fire spread through a forest fuel bed using a multiphase formulation. Combust. Flame, 127: 1981-1994.

Murray, A.T. and R.L. Church, 1995. Heuristic solution approaches to operational forest planning problems. OR Spektrum, 17: 193-203.

Reed, W.J. and D. Errico, 1986. Optimal harvest scheduling at the forest level in the presence of fire. Can. J. For. Res., 16: 266-278.

Rothermel, R.C. and G.C. Rinehart, 1983. Field procedures for verification and adjustment of fire behavior predictions. USDA Forest Service, Intermountain Research Station, Ogden, UT. General Technical Report INT-142. http://www.fs.fed.us/rm/pubs_int/int_gtr142.pdf.

Santoni, P.A. and J.H. Balbi, 1998. Modelling of two-dimensional flame spread across a sloping fuel bed. Fire Safety J., 31: 201-225.

Schroeder, D. and A.H. Perera, 2002. A comparison of large-scale spatial vegetation patterns following clearcuts and fires in Ontario's boreal forests. For. Ecol. Manage., 159: 217-230.

Sessions, J., K.N. Johnson, J.F. Franklin and J.T. Gabriel, 1999. Achieving Sustainable Forest Structures on Fir-Prone Landscapes While Pursuing Multiple Goals. In: Spatial Modeling of Forest Landscape Change, Mladenoff, D. and W.L. Baker (Eds.). Cambridge University Press, Cambridge, England.

Sessions, J. and P. Bettinger, 2001. Hierarchical planning: pathway to the future. Proceedings of the First International Precision Forestry Symposium, June 17-20, University of Washington, Seattle, WA., pp: 185-190.

Stephens, S.L., 1998. Evaluation of the effects of silvicultural and fuels treatments on potential fire behaviour in Sierra Nevada mixed-conifer forests. For. Ecol. Manag., 105: 21-35.

Stratton, R.D., 2004. Assessing the effectiveness of landscape fuel treatments on fire growth and behavior. J. For., 102: 32-40.

Van Wagtendonk, J.W., 1996. Use of Deterministic Fire Growth Model to Test Fuel Treatments: Sierra Nevada Ecosystem Project. Centers for Water and Wildland Resources, University of California, Davis, pp: 1155-1167.

Yoshimoto, A., R.G. Haight and J.D. Brodie, 1990. A comparison of the pattern search algorithm and the modified PATH algorithm for optimizing an individual tree model. For. Sci., 36: 394-412.