Available online at www.sciencedirect.com
ScienceDirect
ELSEVIER
Landscape and Urban Planning 80 (2007) 312–319
LANDSCAPE AND URBAN PLANNING
This article is also available online at: www.elsevier.com/locate/landurbplan

Using stand-level optimization to reduce crown fire hazard

David H. Graetz[a,*], John Sessions[b], Steven L. Garman[c]

[a] Department of Forest Resources, Oregon State University, Corvallis, OR 97331, USA
[b] Department of Forest Engineering, Oregon State University, Corvallis, OR 97331, USA
[c] National Park Service, Moab, UT 84532, USA

Available online 21 November 2006

Abstract

This study evaluated the ability to generate prescriptions for a wide variety of stands when the goal is to reduce crown fire potential. Forest managers charged with reducing crown fire potential while providing for commodity and ecological production have been hampered by the complexity of possible management options. A program called Stand-Level Optimization with Multiple Objectives (SLOMO) was developed that uses a dynamic programming based algorithm to find near-optimal solutions for a number of problem formulations. Sixty-four stand types from eastern Oregon were evaluated with SLOMO with the goal of reducing crown fire potential. Two attributes of stand canopies were manipulated, canopy base height (CBH) and canopy bulk density (CBD). Additionally, a baseline case of "grow only" was evaluated for each stand to help understand the potential effects of active management. Results illustrate the potential for optimization methods to provide useful management strategies to reduce crown fires. Relative to the grow only goal, treatments are derived that achieve and maintain target levels for CBH and CBD over a 100-year projection. Simulations show a substantive decrease in crown fires, especially active crown fires, with treatments derived from optimization procedures.

Keywords: Stand-level optimization; Dynamic programming; Crown fire; Northeast Oregon

1. Introduction

Forestland managers are under increasing pressure to reduce the threat of wildland fire in managed stands in dry forests while achieving ecological and traditional wood-production objectives (O'Hara et al., 1994). Forest-management strategies traditionally have been based on expert knowledge and field experience with a number of different treatment regimes (Palahi and Pukkala, 2003). Reducing a stand's susceptibility to fires largely has been accomplished with traditional silvicultural strategies that are designed more for wood-production than for the reduction of fire risk (Keyes and O'Hara, 2002). Management approaches need to be developed to especially reduce crown fire potential. Crown fires are of special concern because they are more difficult to control than a surface fire (Scott and Reinhardt, 2001) owing to faster spread rates and intensities (Rothermel, 1991), and they have more lethal stand effects. Also, spotting and increased radiation make crown fires much more dangerous when trying to defend structures within the increasing wildland-urban interface (Cohen and Butler, 1998).

Understanding the underlying processes of crown fire behavior is a key step in evaluating management strategies to reduce fire risk. This understanding exists in quantitative form as mathematical models. These crown fire models largely are based on the works of Van Wagner (1977) and Rothermel (1991). Equations for the spread and behavior of surface fire are based on the seminal work of Rothermel (1972, 1983), and have been incorporated into wildfire models such as FARSITE (Finney, 1998) and BEHAVE (Andrews and Bevins, 1999). The Van Wagner (1977) model describes the conditions needed to introduce and sustain a fire into the canopy from a surface fire or adjacent crown fire. Scott and Reinhardt (2001) established linkages between surface and crown fire behaviors by integrating Rothermel's (1972) surface fire model, Van Wagner's (1977) crown fire transition model, and Rothermel's (1991) crown fire spread model. These linkages are used extensively in the Fire and Fuels Extension to the Forest Vegetation Simulator (FVS-FFE) (Dixon et al., 2003; Reinhardt and Crookston, 2003).

Ultimately, for land managers to be effective they must create silvicultural treatments that can be understood and applied by the people doing the work. Vague goals to "reduce a stands'

* Corresponding author.
E-mail address: davidg@peak.org (D.H. Graetz).

0169-2046/$ – see front matter © 2006 Elsevier B.V. All rights reserved.
doi:10.1016/j.landurbplan.2006.10.011

crown fire potential", while important, are difficult to achieve on the ground if the crews doing the work cannot realistically determine if they have achieved the desired effect. Keyes and O'Hara (2002) quantified silvicultural guidelines for reducing crown fire potential in terms useful for both silviculturists and ground crews. These guidelines and procedures were based on relationships by Rothermel (1972) and Van Wagner (1977) but were described in a way to be understandable by a wider audience-especially those who may not have the background to understand the complex surface and crown fire models. The Keyes and O'Hara (2002) procedure, however, still requires a significant effort on behalf of the user in prescribing silvicultural treatments. This paper applies stand-level optimization methods to the issue of determining stand-level treatments for the purpose of reducing the hazard of crown fire.

2. Stand-level optimization

The objective of stand-level management planning is to determine the optimum combination of entries, the timing of entries, and the type of treatments applied to a stand to best meet management goals. It is difficult to determine this combination of activities through non-computerized processes as generally only a small portion of the potential combinations of treatments can be evaluated. Operation research techniques applied to stand-level management started appearing in the literature in the 1960s (Amidon and Akin, 1968; Chappelle and Nelson, 1964; Hool, 1966). Since that time substantial research has been devoted to solve problems for even-aged, uneven-aged, and any-aged stand management using a variety of optimization methods (Brodie et al., 1978; Brukas and Brodie, 1999; Gong, 1992; Haight et al., 1985; Valsta, 1990; Wikstrom, 2001).

Dynamic Programming (DP) is a stand-level optimization approach, which has characteristics and capabilities that provide a useful solution framework for the timing and intensity of typical silvicultural actions such as thinning, fertilization, pest control, and rotation age decisions (Hann and Brodie, 1980; Paredes and Brodie, 1987). DP approaches have the ability to avoid including multiple local optima in the final solution to a stand-level problem (Yoshimoto et al., 1990). The Projection Alternative TecHnique (PATH) algorithm (Paredes and Brodie, 1987) was developed to solve for the optimal solution at every stage in a DP program, reducing the computation and storage space requirements because the problem is reduced to a one-state, one-stage DP problem. Yoshimoto et al. (1988) introduced the look-ahead process to establish that the optimum solution has been located at each stage. Then Yoshimoto et al. (1990) introduced a region-limited strategy combined with the PATH algorithm (RLS-PATH) that has two parts. In part one, a restricted domain of the state space is established. In part two, DP (via the PATH algorithm) is applied to the restricted domain. Once the optimal solution has been located, a new, tighter restricted domain of the state space is established. The process continues until convergence on a local optimum has been established (Yoshimoto et al., 1990).

This paper demonstrates the use of the RLS-PATH algorithm to generate prescriptions for reducing crown fire hazard in representative stands in the Blue Mountains of eastern Oregon. The RLS-PATH algorithm is used within an automated prescription generator that uses the Forest Vegetation Simulator (FVS) (Dixon et al., 2003), a single-tree, distant-independent growth model to project stand growth. The term "prescription" is used in this paper to refer to the overall schedule of activities that occur in a stand over a planning horizon. Inherent in the term prescription is the fact that individual tree data are explicitly tracked over time. Thus, a prescription also implies knowledge about what a stands' attributes are over the planning horizon.

3. Crown fire hazard

This paper focuses on reducing crown fire hazard, but other types of wildland fires also exist (Pyne et al., 1996). There are three main types of wildland fires: ground, surface, and crown fires. Ground fires are characterized by burning ground fuels such as roots, buried logs, duff, organic soils, etc. A surface fire is one that burns in the fuel layer that lies just above the ground fuels. Surface fires burn fuels that consist of leaves, needles, grasses, down woody debris, logs, and shrubs. Crown fires burn in elevated canopy fuels that consist of the live and dead foliage, lichen, and the fine live and dead branchwood. These fuels tend to have the lowest bulk density of all the fuels.

Van Wagner (1977) differentiated three types of crown fire. A passive crown fire is often referred to as torching or candling. In passive crown fires the flames spread from a surface fire to the canopy, but the flame is not maintained in the canopy. This torching effect may occur in single trees or in small groups of trees. Short-range spotting is often associated with passive crown fire increasing the potential for ignition of new fires downwind. A second crown fire type is active crown fire; also commonly called running or continuous crown fires. In active crown fires there is a linkage between an advancing surface fire and a dependent fire in the crowns that is advancing with the surface fire. There is generally a solid wall of flame extending from the surface fuel bed through the upper canopy. Spotting of all ranges (short to long) is possible with active crown fires making them very difficult to control through containment. The last crown fire type is independent crown fire. An independent crown fire is one that sustains itself without requiring heat contributions from an underlying fire. Van Wagner (1993) found that independent crown fires rarely occur and only under extreme weather and topography conditions.

There are three main characteristics of canopy fuels that must be quantified in order to use the integrated model of crown fire potential: canopy bulk density (CBD), canopy base height (CBH), and foliar moisture content. Of these three, CBD and CBH can be directly influenced by silvicultural activities. Both CBD and CBH refer to the overall canopy property of a stand and not an individual tree (which are often referred to as crown bulk density and crown base height, respectively). The effect of foliar moisture content is uncertain. Van Wagner (1993) found that foliar moisture content has a less important influence on crown fire initiation (compared to CBH), but it may have a stronger effect on the crown fire spread rate (Scott, 1998).

CBD can be described as the mass of available canopy fuel per unit canopy volume (Scott and Reinhardt, 2001). However, in practice this can be difficult to measure. The FVS-FFE model (Reinhardt and Crookston, 2003) uses a methodology derived from Sando and Wick (1972) whereby an "effective" CBD can be estimated from stand inventory data. This method does not assume uniform distribution of canopy fuels and thus lends itself well to a wider application of stand structures. See Reinhardt and Crookston (2003) for a more detailed explanation of the necessary calculations and Scott and Reinhardt (2001) for alternative methods that can be considered in calculating CBD.

CBH is the lowest height above the ground at which there is sufficient canopy fuels to propagate fire vertically through the canopy (Scott and Reinhardt, 2001). Neither the lowest crown base height in a stand (from individual trees) nor the average stand crown base height does a good job of representing the stand CBH as a whole. Ladder fuels such as small trees, dead branches, and lichen are often unaccounted for in inventory data and thus not represented in the inventory data. Based on the work of Sando and Wick (1972) and Brown (1978), the FFE-FVS model uses a calculation whereby the CBH is determined as the lowest height at which the CBD from a 0.91-m running mean is greater than 0.11 kg/m^3.

Keyes and O'Hara (2002) proposed two broad objectives that forest managers could specify when trying to minimize the crown fire hazard for a stand: (1) prevent crown ignition by manipulating CBH, or (2) prevent crown fire spread by manipulating CBD. A third objective is the combination of the two above whereby the forest manager's goal is to reduce both crown ignition and crown fire spread. For these goals to be useful, a method is required to quantify a target CBD and CBH for any given stand. It should be noted that this paper is not a review of the nuances and particulars in calculating fire behavior indices (fireline intensity, spread rates, reaction intensity, heat of pre-ignition). However, the calculations presented in this paper assume some background level of understanding between the linkages and variables used in modeling fire behavior. See Albini (1976), Van Wagner (1977), Rothermel (1983, 1991), Scott and Reinhardt (2001), or Reinhardtand Crookston (2003) for a more thorough treatment on modeling fire behavior.

A target CBD can be calculated by rearranging Van Wagner's (1977) model of a critical crown fire spread rate that is required for a crown fire to be sustained with a given crown bulk density. The rearranged equation is given as follows:

$$\mathrm{CBD_{tar}} = \frac{3.0}{\mathrm{ROS_c}} \quad (1)$$

where $\mathrm{CBD_{tar}}$ is the target CBD in (kg/m^3) below which crown fire spread will not occur for the given crown fire spread rate ($\mathrm{ROS_c}$) (m/min) estimated under specified conditions (Keyes and O'Hara, 2002). Calculating an anticipated $\mathrm{ROS_c}$ first requires calculating a correlated surface rate of spread ($\mathrm{ROS_r}$). Rothermel (1991) observed a ratio of 3.34 between the crown rate of spread and surface rate of spread by using parameters for the National Forest Fire Laboratory Fuel Model 10 (Anderson, 1982) and with a wind reduction factor of 0.4. Other environmental variables such as slope, open winds peed, and fuel moisture values remain constant. Given Rothermel's correlation rate, Eq. (1) can be reformulated as:

$$\mathrm{CBD_{tar}} = \frac{3.0}{(3.34)(\mathrm{ROS_r})} \quad (2)$$

Quantifying a target crown base height relies on equations derived from convection theory and the estimates of heat release rate (fireline intensity) for transferring heat from a surface fire upward into the canopy (Scott and Reinhardt, 2001; Van Wagner, 1977). Van Wagner (1977) proposed that when heat is supplied from a surface fire, the upward heat flux would reduce the canopy fuel moistures and eventually raise the canopy fuels to ignition temperature. By rearranging Van Wagner's equation for calculating a critical fireline intensity for a given CBH, Keyes and O'Hara (2002) calculated the critical CBH for a given fireline intensity (FU) as:

$$\mathrm{CBH_{tar}} = \frac{\mathrm{FLI}^{(1/1.5)}}{(0.01)(460 + 26(\mathrm{FMC}))} \quad (3)$$

where $\mathrm{CBH_{tar}}$ (m) is the target CBH above which crown fire ignition is resisted for the predicted surface fireline intensity (kW/m) and percentage foliar moisture content (FMC) (oven-dry weight) under specified conditions. We assumed a FMC of 100% for this study (FMC value is 100 for 100%,90 for 90%, etc.) as suggested by Scott and Reinhardt (2001). It should be noted that both $\mathrm{CBD_{tar}}$ and $\mathrm{CBH_{tar}}$ will change over time for any given stand. Whether the target value increases or decreases is ultimately dependent upon the fuel model assigned to a stand at any point in time. The same logic used by the FVS-FFE model (Reinhardt and Crookston, 2003) for fuel model selection was employed.

4. Methods

4.1. *Problem formulation*

The example presented in this paper is best described as an any-age stand management problem. Haight (1987) and Haight and Monserud (1990) described the any-age stand management problem as determining the best temporal sequence of harvest and planting levels without constraints on the stand age or size structure. Without constraints on the stand age or size structure, the optimal management solution may yield stands that have irregular structures or the solution may yield stands with conventional even- or uneven-aged structure, thus the term any-aged is used.

In this paper, harvesting decisions and growth predictions occur at discrete time intervals, every 10 years. The problem is to determine, for each stand, the number of trees to be removed in each period over the planning horizon, in order to maximize the weighted value associated with the stand's ability to avoid crown fire over a period.

The state and control vectors and variables are as follows:

$\mathbf{s}(t)$	stand state in period t (vector)
$s_i(t)$	the attributes of tree record i at the beginning of period t (element)

$\mathbf{x}(t)$ cutting levels in period t (vector)
$x_i(t)$ percentage of record i cut in period t (element)
$\mathbf{h}(t)$ the harvest controls in period t (vector)
$h_j(t)$ percentage of trees cut in diameter group j and $h_j(t)$ = [0-1] (element)
C_j a unique diameter class group
J total number of diameter class groups = 4 (scalar)
P number of look-ahead periods = 5 (scalar)
T total number of simulation periods = 10 (scalar)

A mapping occurs within the solution process such that h -> x by:

$$x_i(t) = h_j(t), \quad \forall i \in C_j,\ \forall J$$

The weighted value associated with the stands ability to avoid crown fire is the summation of the two factors: (1) a user-defined weight times a scalar bonus for each period that a stand has a calculated CBH that is greater than the calculated target CBH; (2) a user-defined weight times a scalar bonus for each period that a stand has a calculated CBD that is less than the calculated target CBD. The variables used in the objective function evaluation are:

S 100 (scalar bonus value)
$\mathrm{WT_{cbh}}$ weight for meeting CBH target = (0–1) (user-defined)
$\mathrm{WT_{cbd}}$ weight for meeting CBD target = (0–1) (user-defined)
$\mathrm{CBH}[s(t)]$ stand canopy base height with state s at period t
$\mathrm{CBD}[s(t)]$ stand canopy bulk density with state s at period t
$\mathrm{CBH_{tar}}(t)$ calculated target CBH at period t
$\mathrm{CBD_{tar}}(t)$ calculated target CBD at period t
$\mathrm{CBH}_v(t)$ 1 if $\mathrm{CBH}[s(t)] > \mathrm{CBH_{tar}}(t)$, 0 otherwise
$\mathrm{CBD}_v(t)$ 1 if $\mathrm{CBD}[s(t)] < \mathrm{CBD_{tar}}(t)$, 0 otherwise

Therefore, in employing the RLS-PATH algorithm, the per-stage objective function is to maximize the scalar function ($Z[\mathbf{s}(t), \mathbf{h}(t)]$) at each period t, for all $\mathbf{h}(t)$, and can be formu-

$$\mathrm{Max}\ Z = \sum_{t=0}^{t+P} [(\mathrm{WT_{cbh}})(S)(\mathrm{CBH}_v(t))] + [(\mathrm{WT_{cbd}})(S)(\mathrm{CBD}_v(t))] \tag{4}$$

where $t = 0$ is the moment just after any harvest activity (including the decision not to harvest) and $t = 1$ represent the end of one period of growth (10 years). When Eq. (4) is solved the thinning levels $h_j(t)$ will be known for *each* j and t.

4.2. Solution method

A program called Stand-Level Optimization with Multiple Objectives (SLOMO) was written in the C and C++ languages to solve stand optimization problems of the type given in this study. SLOMO is designed with a graphical user interface that allows a user to enter multiple stands and solve for multiple objectives. The user completes a nine-step process to set up and specify all the necessary parameters, inputs, and outputs. SLOMO uses the growth and yield functions from the Blue Mountain variant of the FVS (Dixon et al., 2003). This permits reduced computational times as it removes the overhead associated with running FVS in its stand-alone format. Additionally, the equations and procedures from the FVS-FFE extension (Reinhardt and Crookston, 2003), Blue Mountain variant, were also recoded into SLOMO.

The harvest control vector, $h(t)$, represents the fraction of trees harvested by diameter classes for a specified period. Four diameter class breaks were defined for this study (0-10.1 cm, 10.2-30.5 cm, 30.6-53.3 cm, >53.4 cm), These four classes were chosen to strike a balance between having a useful management utility (for either wildlife, ecological, or economic uses) and the desire to have breaks that allow enough silvicultural flexibility to manage the stand. By flexibility, we are loosely referring to the concept that thinnings are typically described as low, crown, selection, and mechanical thinnings-describing which trees are to be thinned first (Smith et al., 1997). These class breaks allow the DP algorithm to break the solution process into logical subparts that reflect how silviculturists and ground crews actually implement activities in a stand. Within each diameter class, five or six levels of thinning are specified. The potential percentage of trees to be harvested in each class, $h_j(t)$, is a function of which diameter class is being evaluated. For the bottom three diameter classes (0-53.3 cm) the thinning levels are 0, 20, 40, 60, 80, and 98. These values can be interpreted as follows: if $h_j(t) = 20$ for a particular iteration during the optimization process, then 20% of the trees per unit area from each record in class j will be harvested. This could be considered a proportional method of harvesting because the value of the element is applied proportionally to each record in the class. The top diameter class (>53.4 cm) has a slightly different setup. The thinning levels for this class are 0, 25, 50, 75, and 98. These values can be interpreted as follows: if $h_j(t) = 25$, then 25% of the total trees per unit area in that diameter class are harvested, either starting from the top or bottom record within that class (i.e., the record with the largest or smallest diameter). This could be considered a non-proportional method of harvesting because the element is applied non-proportionally to each record in the class.

We have already outlined the basic formulation for a problem that attempts to maximize the weighted function associated with a goal of reducing a stands' potential for crown fire over time. The earlier formulation was for an unconstrained problem. SLOMO has some built-in constraints that can be turned on or off for particular stand goals. Two constraints applied to this study are: (1) an upper size limit when evaluating whether to harvest a particular tree (maximum of 60.9 cm dbh); (2) a minimum volume that must be taken if any harvest activity is to occur (21 m^3/ha). These constraints now need to be included and linked in our model formulation (Eq. (4) with the following scalar function $L[s(t), x(t)]$:

$$\mathrm{Max}\ Z = \sum_{t=0}^{t+P} [(\mathrm{WT_{cbh}})(S)(\mathrm{CBH}_v(t))] + [(\mathrm{WT_{cbd}})(S)(\mathrm{CBD}_v(t))]$$

subject to:

$$L = \begin{cases} x_i(t) = 0, & \text{if dbh of } s_i(t) > 60.9\,\text{cm} \\ x_i(t) = 0, & \text{if total stand volume cut by} \\ & \text{evaluating } x_i(t) \text{ is } < 21\,\text{m}^3/\text{ha} \end{cases} \tag{5}$$

5. Study design

This study was designed to demonstrate the utility of SLOMO to generate good (i.e., near "optimal") prescriptions for a variety of stands with the objective of reducing the long-term potential of crown fire in the stands. This study was originally designed as part of the Interior Northwest Landscape Analysis System (INLAS) study in northeast Oregon, USA (Barbour et al., 2004); however, at the time of this analysis, the stand exam data were under development and subject to further refinement. Time constraints dictated that we proceed with our analysis and we choose to use a sample of the stands with the caveat that the underlying stand data may not be accurate. The utility of SLOMO can still be demonstrated regardless of the quality of the stand data. We do acknowledge, however, that the practicality of using such results would be specious at best.

For this study we chose 64 stands located in the La Grande Ranger District of the Wallowa-Whitman National Forest. Stands were chosen based on two criteria: (1) current basal area was between 22.9 m^2/ha and 34.4 m^2/ha, and (2) dominant overstory species was either Douglas-fir *(Pseudotsuga menziesii),* grand fir *(Abies grandis),* lodgepole pine *(Pinus contorta),* or ponderosa pine *(Pinus ponderosa).* These criteria were chosen because they represented enough stands in which the underlying stand exam data appeared to be the most complete and had the greatest potential to be accurate.

The 64 stands were run through the SLOMO program with the following harvesting parameters set for a goal of reducing crown fire hazard:

(1) A weight of 0.5 for meeting the CBH target.
(2) A weight of 0.5 for meeting the CBD target.
(3) An upper diameter limit of 60.9 cm.
(4) No lower diameter limit.
(5) A minimum volume of 3.4m^3/ha for any solution that requires harvesting.
(6) A minimum of 18.4 m^2/ha basal area must exist in stand before harvesting.
(7) Harvesting in consecutive 10-year periods is not allowed.

Additionally, the stand prescriptions in this paper were developed for a slope of 15%, a 6-m windspeed of 32km/h, and temperature of 28 °C (air temperature during period of burning).

As a benchmark comparison, the 64 stands were also run through SLOMO with a "grow only" goal. That is, SLOMO bypassed all the optimization routines and simply grew each stand forward in time by using the imbedded growth and mortality equations. For all the runs made with SLOMO regeneration was turned off.

At each period, the fire behavior and crown fire algorithms were exercised to determine if a crown fire is capable of occurring, and if so whether crown conditions supported a passive or active crown fire. If a crown fire was not possible, the fire type was identified as a surface fire only. The percentages of stands by crown fire type (or surface fire) were recorded by time period for each of the two goals.

6. Results

It took 2 min and 10 s to generate the prescriptions on a Windows'" -based computer with a 3.2 GHz processor. There were a total of 128 prescriptions generated (64 grow only goal + 64 reduce crown fire goal). Stand CBD and CBH of the 64 stands were averaged for each of the two goals and plotted (Figs. 1 and 2).

For the grow only goal, there is a dip at period 2 where the average CBH dips to 3.9 m after initially starting at 4.5 m (Fig. 1). This is an artifact of the growth and modeling procedure that omits small trees in the CBH calculations in the initial stand. These small stems grow to a height such that they are included in the CBH calculations by period two. After period 2, the average CBH for the grow only goal steadily increases to reach a high of over 7 m in period 10. **In** contrast, there is a dramatic increase in the average CBH immediately with the reduce crown fire goal prescriptions. Period 2 shows an average CBH of over 6.9 m, which is over 3.1 m higher compared to the period 2 height of the grow only goal. A dip in the aver-

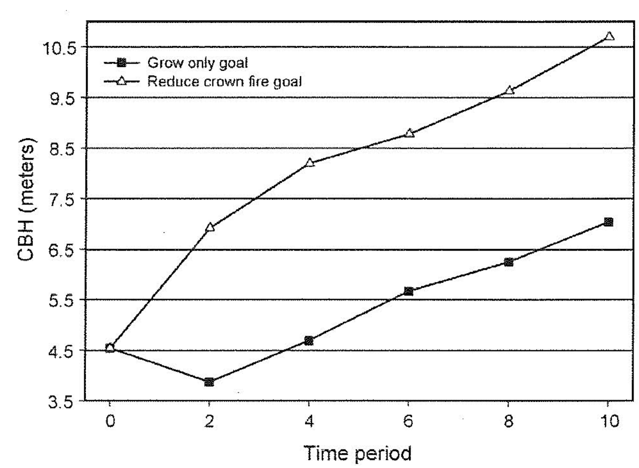

Fig. 1. Average canopy base height (CBH) over time for the grow only and the reduce crown fire goals. Year 0 corresponds to initial conditions.

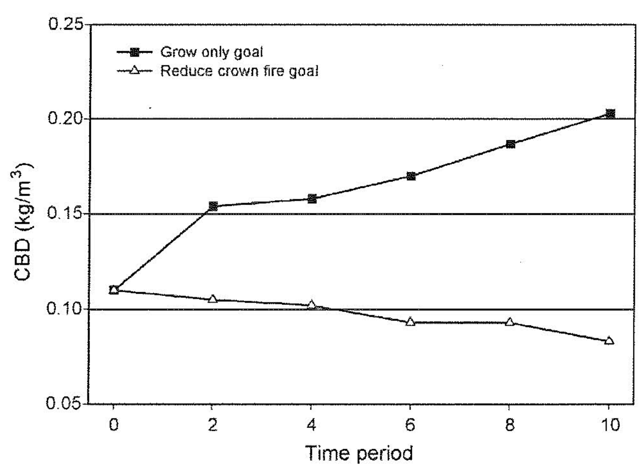

Fig. 2. Average canopy bulk density (CBD) over time for the grow only and the reduce crown fire goals. Year 0 corresponds to initial conditions.

age CBH at period 2 for the reduce crown fire goal does not occur because the optimization process has selected most of the smaller trees for harvesting during the first or second periods. The 3.1-m difference between the two goals remains almost constant over the planning horizon. By period 10 the reduce crown fire goal has resulted in an average CBH of over 10.6 m. This ability to achieve higher CBH is important in that it makes it harder for surface fires to reach the crown and initiate crown fires.

For the grow only goal there is a rising average CBD over the planning horizon (Fig. 2). In the absence of harvesting, establishment of shade-tolerant understory stems, and the tendency for individual crowns to fully occupy the available space promote a dense, continuous, canopy cover. In contrast, the reduce crown fire goal produces a decreasing average CBD pattern. Another important difference is the disparate trends in CBD of the two goals. In period 2 average CBD differs between the two goals by 0.049 kg/m^3, but by period 10 CBD differs by more than 0.12kg/m^3. This implies that there may be an increasing value in maintaining older trees in fire-prone landscape as long as the sequence of harvest activities is followed.

The results for both goals indicate that for period 0, 73% of the stands do not have the potential for a crown fire, 19% have the potential for passive crown fires, and 8% have the potential for active crown fires (Fig. 3). Ideally, a forest manager would prefer to have a forest with increasing amount in the no crown fire type and decreasing amount in the active fire type. This is exactly the pattern seen with the reduce crown fire goal. For every period shown, the percentage of stands with no crown fire in the reduce crown fire goal is greater than the grow only goal with differences ranging from 5% to 24%. The relatively high percentage of stands that have no crown fire for both goals may indicate that the initial stands were fairly crown fire resistant to begin with (for the assumed topographic and weather conditions).

A notable feature is the percentage of stands in the active crown fire type. The reduce crown fire goal significantly reduces the percentage of stands that fall in the active crown fire type. A reduction of about 15% is seen in four of the demonstrated periods.

We also looked at surface fire flame lengths because this parameter is more often easier to understand and is emblematic of surface fire behavior. In this study, the predicted surface fire flame lengths did increase in the >2.4 m category for the reduce crown fire goal in periods 2 and 4 (Fig. 4). The majority of harvest occurs in the first two periods and results in an increase of surface fuels, which is reflected in the selection of a standardized fuel model that represents the increased litter on the ground. Even with potential compaction of the surface fuels from the harvest activity it is possible that the increase in these fuels creates higher flame lengths as seen here. We did not examine opportunities to directly manipulate flame length. The flame length variables that have the greatest potential for alteration owing to harvesting activity (or not) are the availability of additional ground fuels from the activity and the impact of machinery on the fuel bed depth. Conversely, the ground fuels could be reduced after harvesting by various slash disposal

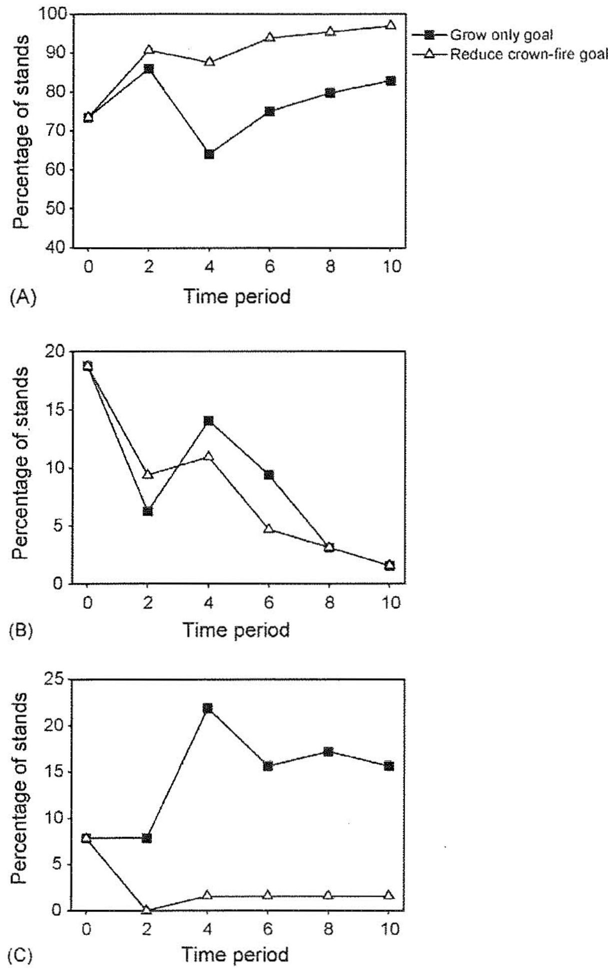

Fig. 3. The potential for different types of crown fires over time for the grow only and the reduce crown fire goals. See text for description of the different types of crown fires. Year 0 corresponds to initial conditions. (A) No crown fire; (B) passive crown fire; (C) active crown fire.

methods. SLOMO has the capability to incorporate these effects, and further research by the authors will examine management options.

7. Discussion

Results of this initial study illustrate the potential use of optimization methods in designing forest-management strategies to reduce crown fire hazard. Concentrating on only two stand attributes, CBH and CBD, prescriptions are derived that achieve and maintain these attributes at relatively low fire-risk levels, at least over the projected 100-year timeframe. Modeled crown fire hazard further illustrates the derived treatments to quickly reduce the likelihood of active crown fires over a planning horizon. The ability to achieve specified trends and the effectiveness of these trends in reducing crown fire hazard combine to illustrate the utility of optimization procedures to derive management prescriptions.

There are numerous fire-related factors not considered in this analysis, such as topographic effects, wind patterns, and

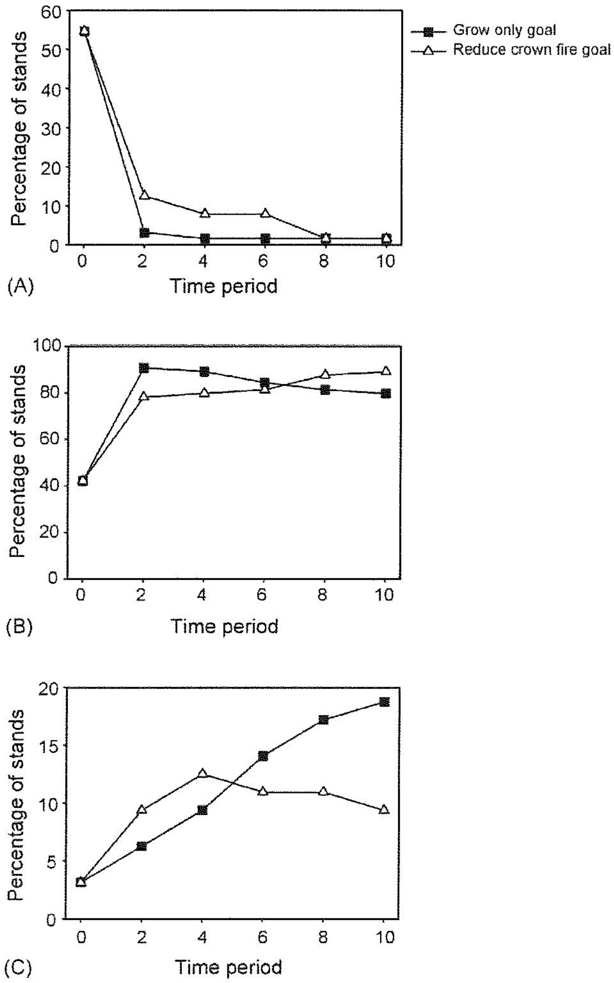

Fig. 4. The potential for different classes of flame lengths over time for the grow only and the reduce crown fire goals. Year 0 corresponds to initial conditions. Flame lengths: (A) 0–1.2 m; (B) 1.2–2.4 m; (C) >2.4 m.

the proximity of burning stands. The stand prescriptions in this paper were developed for specific topographic and weather conditions as well as specific surface fuel conditions. An identical stand facing a greater wind, and/or a stand located on a steeper slope, and/or under different weather conditions would have a different optimal prescription. By using SLOMO it is possible to quickly develop a management prescription for each combination of slope, wind condition, and temperature class that would be expected on the landscape. Furthermore, each decision maker needs to identify their level of risk. A stand that may be resistant to crown fire at one windspeed may not be safe at a higher windspeed.

Also, we have only indirectly considered operational constraints through thinning frequency and amount. We could directly consider constraints such as a treatment must pay for itself. This would allow us to consider operational conditions such as slope, season of operation, and distance from roads. An economically feasible operation on a flat area may be infeasible on a steeper area. Similarly, treatments in stands near roads may be more economically feasible than areas away from roads.

We have only considered one form of the objective function following work by Keyes and O'Hara (2002). Critical torching and crowning windspeeds are the principal indices used by Reinhardt and Crookston (2003) in the FVS-FFE model. Other forms could be considered such as directly incorporating goals for the torching and crown wind indices (e.g. the introduction of one-way goals that keep the torching and crowning windspeeds above user-defined thresholds). In this way managers may be better able to express their risk levels.

With the incorporation of the FVS-FFE model (Blue Mountain variant), SLOMO has the ability to derive near-optimal prescriptions for managing stand structures with fire-safe characteristics. Previous models and efforts in the area of optimization have been hampered by the disjointed nature ofthe programs used-one program would feature optimization; another program would model stand growth and yield; another program would model fire effects, etc. SLOMO bundles those elements into a single program with a graphical user interface. This bundling allows a wider range of goals to be considered at one time. Forest managers charged with reducing crown fire hazard while providing for commodity and ecological production have been hampered by the complexity of possible management options. SLOMO allows managers to consider a range of complex and often conflicting goals in a rapid manner. As with all model predictions, the effectiveness of model-derived management treatments will be known only after field implementation and monitoring.

Acknowledgements

The study presented here would not have been possible without the support of many people. In particular, Pete Bettinger, University of Georgia, was instrumental in orchestrating the collaboration between Oregon State University and the U.S. Forest Service, as well as guiding the lead authors' Ph.D. program of study. We would also like to thank the reviewers who provided many valuable suggestions. This manuscript is a product of the U.S. Forest Service INLAS project led by Jamie Barbour.

References

Albini. F.A., 1976. Estimating wildfire behavior and effects. Gen. Tech. Rep. INT-30. USDA Forest Service, Intermountain Forest and Range Experiment Station, Ogden, UT, 92 p.

Amidon, E.L, Akin, G.S., 1968. Dynamic programming to determine optimum levels of growing stock. For. Sci. 14 (3), 287-291.

Anderson, H.E, 1982. Aids to determining fuel models for estimating fire behavior. Gen. Tech. Rep. INT-122. USDA Forest Service, Intermountain Forest and Range Experiment Station, Ogden, UT, 22 p.

Andrews, P.L., Bevins, CD., 1999. BEHAVE fire modeling system: redesign and expansion. Fire Manage. Notes 59 (2), 16-19.

Barbour, R.J., Ager, A.A., Hayes, J.L, 2004. A framework for the development and application of INLAS: the interior northwest landscape analysis system. In: Hayes, J.L., Ager, A.A., Barbour, R.J. (Eds.), Methods for Integrated Modeling of Landscape Change: Interior Northwest Landscape Analysis System. Gen. Tech. Rep. PNW-GTR-610. USDA Forest Service, Pacific Northwest Research Station, Portland, OR, pp. 1-16.

Brodie, J.D., Adams, D.M., Kao, C, 1978. Analysis of economic impacts on thinning and rotation for Douglas-fir using dynamic programming. For. Sci. 24 (4), 513-522.

Brown, J.K., 1978. Weight and density of crowns of Rocky Mountain conifers. Res. Pap. INT-RP-197. USDA Forest Service, Intermountain Forest and Range Experiment Station, Ogden, UT, 32 p.

Brukas, V, Brodie, J.D., 1999. Economic optimisation of silvicultural regimes for Scots pine using dynamic programming. Bait. For. 5 (1), 28-34.

Chappelle, D.E., Nelson, Te., 1964. Estimation of optimal stocking levels and rotation ages of loblolly pine. For. Sci. 10 (4), 471-502.

Cohen, J.D., Butler, B.W., 1998. Modeling potential structure ignitions from flame radiation exposure with implications for wildland/urban interface fire management. In: 13th Conference on Fire, Forest Meteorology, Lone, Victoria, Australia, October 27-31, 1996. International Association of Wildland Fire, Fairfield, WA, pp. 81-87.

Dixon, Gary E. et al., 2003. Essential FVS: A user's guide to the Forest Vegetation Simulator. Internal Rep. Fort Collins, CO: U. S. Department of Agriculture, Forest Service, Forest Management Service Center. 193 p.

Finney, M.A., 1998. FARSITE: fire area simulator-model development and evaluation. Res. Pap. RMRS-RP-4. USDA Forest Service, Rocky Mountain Research Station, Ogden, UT, 47 p.

Gong, P., 1992. Multiobjective dynamic programming for forest resource management. For. Ecol. Manage. 48, 43-54.

Haight, R.G., 1987. Evaluating the efficiency of even-aged and uneven-aged stand management. For. Sci. 33 (1), 116-134.

Haight, R.G., Brodie, J.D., Adams, D.M., 1985. Optimizing the sequence of diameter distributions and selection harvest for uneven-aged stand management. For. Sci. 31 (2),451-462.

Haight, R.G., Monserud, R.A., 1990. Optimizing any-aged management of mixed-species stands. I. Performance of a coordinate-search process. Can. J. For. Res. 20, 15-25.

Hann, D.W., Brodie, J.D., 1980. Even-aged management: basic managerial questions and available or potential techniques for answering them. Gen. Tech. Rep. INT-83. USDA Forest Service, Intermountain Forest and Range Experiment Station, Ogden, UT, 29 p.

Hool, J.N., 1966. A dynamic programming-Markov chain approach to forest production control. Ed. For. Sci., Monogr. 12,26 p.

Keyes, e.R., O'Hara, K.L., 2002. Quantifying stand targets for silvicultural prevention of crown fires. West. J. Appl. For. 17 (2), 101-109.

O'Hara, K.L., Seymour, R.S., Tesch, S.D., Guldin, J.M., 1994. Silviculture and our changing profession. J. For. 92 (1), 8-13.

Palahi, M., Pukkala, T, 2003. Optimising the management of Scots pine (*Pinus sylvestris* L.) stands in Spain based on individual-tree models. Ann. For. Sci. 60, 105-114.

Paredes, VG.L., Brodie, J.D., 1987. Efficient specification and solution of the even-aged rotation and thinning problem. For. Sci. 33 (1), 14-29.

Pyne, SJ., Andrews, P.L., Laven, R.D., 1996. Introduction to Wildland Fire: John Wiley & Sons Inc., New York.

Reinhardt, E.D., Crookston, N.L., 2003. The fire and fuels extension to the Forest Vegetation Simulator. RMRS-GTR-116. USDA Forest Service, Rocky Mountain Research Station, Ogden, UT, 209 p.

Rothermel, R.C., 1972. A mathematical model for predicting fire spread in wildland fuels. Res. Pap. INT-115. USDA Forest Service, Intermountain Forest and Range Experiment Station, Ogden, UT 40 p.

Rothermel, R.e., 1983. How to predict the spread and intensity of forest and range fires. Gen Tech. Rep. INT-143. USDA Forest Service, Intermountain Forest and Range Experiment Station, Ogden, UT, 161 p.

Rothermel, R.C., 1991. Predicting the behavior and size of crown fires in the northern Rocky Mountains. Res. Pap. INT-RP-438. Intermountain Forest and Range Experiment Station, Ogden, UT, 46 p.

Sando, R.W., Wick, C.H., 1972. A method of evaluating crown fuels in forest stands. Res. Pap. RP-NC-84. USDA Forest Service, North Central Forest Exp. Station, St. Paul, MN, 10 p.

Scott, J., 1998. Sensitivity analysis of a method for assessing crown fire hazard in the northern Rocky Mountains USA. In: Viegas, D.X. (Ed.), Third International Conference on Forest and Fire Research-14th Conference on Forest Fire Meteorology. Luso-Cimbra, Portugal, November 16-20. ADAI University of Coimba, pp. 2517-2532.

Scott, J., Reinhardt, E., 200l.Assessing crown fire potential by linking models of surface and crown fire behavior. Res. Pap. RMRS-RP-29. USDA Forest Service, Rocky Mountain Research Station, Fort Collins, CO, 59 p.

Smith, D.M., Larson, B.C., Kelty, M.J., Ashton, P.M.S., 1997. The Practice of Silviculture: Applied Forest Ecology. John Wiley & Sons Inc., New York.

Valsta, L.T., 1990. A comparison of numerical methods for optimizing even-aged stand management. Can. J. For. Res. 20, 961-969.

Van Wagner, C.E., 1977. Conditions for the start and spread of crown fire. Can. J. For. Res. 7, 23-34.

Van Wagner, C.E., 1993. Prediction of crown fire behavior in two stands of Jack pine. Can. J. For. Res. 23, 442-449.

Wikstrom, P., 2001. Effect of decision variable definition and data aggregation on a search process applied to a single-tree simulator. Can. J. For. Res. 31, 1057-1066.

Yoshimoto, A., Haight, R.G., Brodie, J.D., 1990. A comparison of the pattern search algorithm and the modified PATH algorithm for optimizing an individual tree model. For. Sci. 36 (2), 394-412.

Yoshimoto, A., Paredes, VG.L., Brodie, J.D., 1988. Efficient optimization of an individual tree growth model. In: Kent, B.M., Davis, L.S. (Eds.), The 1988 Symposium on Systems Analysis in Forest Resources. Gen. Tech. Rep. RM-161. USDA Forest Service, Rocky Mountain Research Station, Ogden, UT, pp. 154-162.