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The challenge of quantitative risk analysis for wildland fire

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Abstract

Quantitative fire risk analysis depends on characterizing and combining fire behavior probabilities and effects. Fire behavior probabilities are different from fire occurrence statistics (historic numbers or probabilities of discovered ignitions) because they depend on spatial and temporal factors controlling fire growth. That is, the likelihood of fire burning a specific area is dependent on ignitions occurring off-site and the fuels, topography, weather, and relative fire direction allowing each fire to reach that location. Research is required to compare computational short-cuts that have been proposed for approximating these fire behavior distributions. Fire effects in a risk analysis must also be evaluated on a common scale for the variety of values susceptible to wildland fire. This means that appraisals of fire impacts to human infrastructure and ecological values must be measured by the same currency so that the risk assessment yields a single expectation of fire effects. Ultimately, this will help guide planning and investment into management activities that can alter either the probabilities of damaging fire or the susceptibility to those fire behaviors.

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Keywords: Wildland fires; Quantitative risk analysis; Net value change

1. Introduction

Fire planning and risk assessment are concerned with how often fires burn, what effects they have on wildland and urban values, and what opportunities exist to improve the situation through management actions. In the United States, most wildland fires are suppressed. Fires are detected, reported, and initial attack resources dispatched. Fire statistics for federally managed public lands reveal that 99% of all reported fires are suppressed by initial attack forces (NIFC, 2002). Other measures from around the United States similarly suggest about 98% of fires in 2002 are less than 100 ha (250 acres; Neuenschwander et al., 2000; Cardille and Ventura, 2001). The remaining percentage escapes initial attack for many reasons, mostly involving extreme weather, overwhelming of suppression resources by multiple ignitions, and fuel types producing fire behavior that exceeds fire-fighting capabilities. Where management policies explicitly disallow free-burning fires, the rare escaped fires burn under weather scenarios among the most extreme and in fuel conditions that have often been exacerbated by the overall success of fire exclusion under more moderate conditions. Even if fuels remain unchanged during the long fire-free intervals, these policies shift the distribution of fire behaviors toward

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the extreme end. Escaped fires are of most practical concern to risk assessment, although the same procedures are applicable to the broader range of weather conditions where the management policies permit the growth of free-burning fires (Parsons and van Wagtendonk, 1996; Rollins et al., 2001).

A quantitative definition of fire risk includes two main factors: fire behavior probabilities and fire effects. This definition applies to a particular geographic area and time period and can be formulated as an expected net value change (E[nvc]) which is the summed losses and benefits from for all N fire behaviors (e.g. under all weather conditions from all ignitions locations) and n values:

$$E[\mathrm{nvc}] = \sum_{i=1}^{N}\sum_{j=1}^{n} p(F_i)[B_{ij} - L_{ij}] \qquad (1)$$

where $p(F_i)$ is the probability of the ith fire behavior, and B_{ij} and L_{ij} are the respective benefits and losses afforded the jth value received from the ith fire behavior. Since benefits and losses from a given fire change through time, estimates of E_{nvc} will be the sum of Eq. (1) for a fixed period post-fire. For example, benefits of an underburn that removed surface fuels would be accrued for many years in the form of reduced fire hazard (i.e. reduced potential fire behavior) although losses may be incurred in the initial year (Hesseln and Rideout, 1999). The purpose of this paper will be to discuss the components of this equation and the methods used for approximating them. This nomenclature corresponds to the terminology common to fire risk assessment (e.g. Bachmann and Allgower, 2000) where the fire behaviors (F_i) constitute ''hazards'' and ''risk'' applies only to the final summary of net value change.

2. Fire occurrence versus burn probability

Fire occurrence is defined as the frequency of fires that have been reported and recorded within a finite area and historical period of time (e.g. number of fires/ha/year). Data for calculating fire occurrence must be obtained from fire records, which often document the geographic coordinates of the fire. These differ from fire dates procured from fire scarred trees that really record the passage of a fire of unknown size, not necessarily a discrete occurrence (i.e. multiple records for the same fire may exist elsewhere on the landscape). Fire occurrence data are often summarized for different time periods, often by daily, weekly, or monthly intervals to help depict variation in fire activity through out the season (Andrews et al., 2003; Garcia Diez et al., 2000; Neuenschwander et al., 2000). Records may be summarized for the entire fire season, which is a period determined by fire climate and especially precipitation patterns (Schroeder and Buck, 1970). Nearly all analyses of fire occurrence relate fire occurrence to effects of fuel moisture and thus ratings of ''fire danger'' (Andrews et al., 2003). Fire occurrence can be expressed as a single value for the land area or as a spatial data theme through use of spatial moving averages (Harkins, 2000) if the ignition location is known (Fig. 1(a)). The fire occurrence probability for the entire Deschutes National Forest in Oregon is about 0.0001 fires/acre/year. These summaries are descriptive of the average, but imply that fire probabilities were stationary through time and distributed evenly across the landscape, which may not be the case if climatic and human influences have changed during the period of summary data (Schuster, 1999; Keeley et al., 1999). Spatial fire occurrence data often reveal correlations with land ownership and developed areas because of human-caused ignitions (Bradshaw et al., 1984; Cardille and Ventura, 2001) and land cover types. The definition of fire occurrence implies nothing about fire size, the size distribution of the fires, or the probability of an area burning. Fire occurrence is often summarized by cause (human, arson, lightning, etc.) and may be further refined by the area ''protected'' or under the fire management responsibility of a particular agency (fires by acre protected) rather than the total area encompassed or owned.

Although straightforward to analyze, fire occurrence data by themselves are of limited value to risk assessment because they do not reflect probability of burning at a given geographic location. A fire start does not imply spread, yet risk produced by Eq. (1) uses the probability of how fires of a given characteristic burn a piece of land and what changes are produced, not how often they ignite. Characterizing fire probability for risk assessment requires an estimate of the probability of burning with a given fire behavior for all areas within the area of interest.

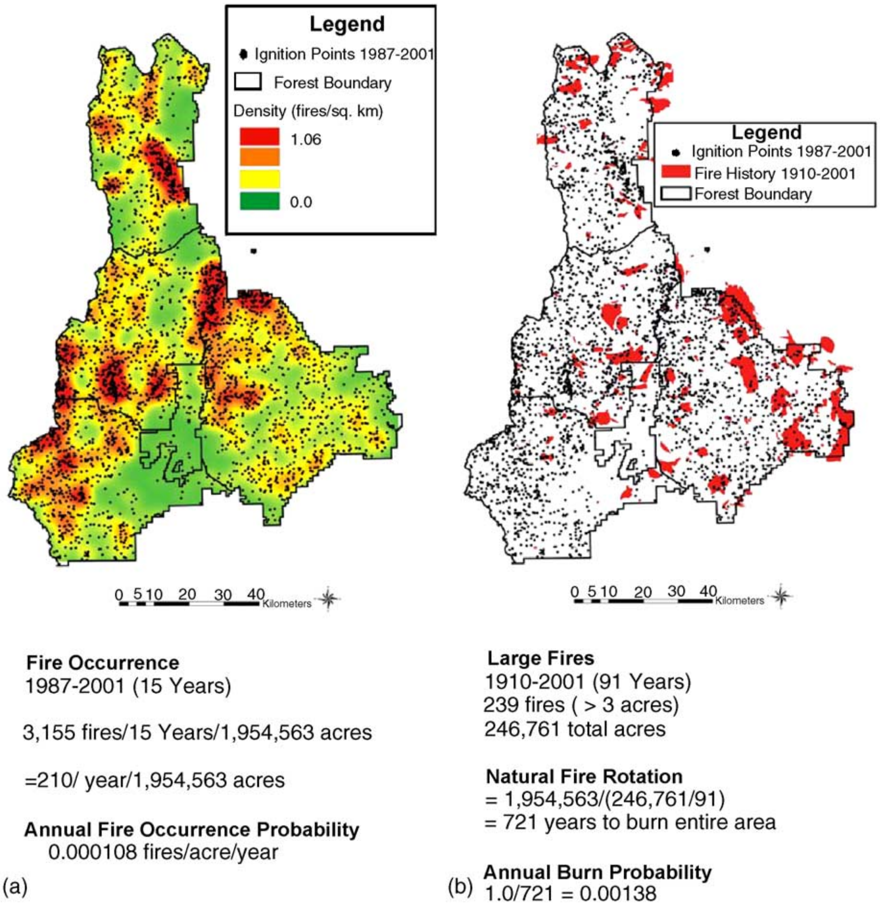

Fig. 1. Fire occurrence data from the Deschutes National Forest in Eastern Oregon. (a) Fire occurrence locations from 1987 to 2002 are shown and summarized by a spatial moving window to estimate a probability surface. The average fire occurrence probability is 0.000108 fires/acre/year. (b) Large fire occurrence from 1910 to 2002 can be summarized using the Natural Fire Rotation to suggest a burn probability of 0.00138, or about 10 times higher than the ignition probability because large fires that grow from their point of origin account for most of the burned area.

Given the nearly infinite number of possible interactions of weather sequences (Martell, 1999) and spatial landscape features, this has proven difficult, and may require the use of spatial fire simulations or related methods (Farris et al., 2000; Miller et al., 2000). An example process for fire spread probability in one-dimension along a straight line was described by Wiitala and Carlton (1994). The probability of fire movement between two points was calculated using the distribution of the length of fire season (from a nearby weather station), segments of fuel types encountered, and frequency distributions of weather days associated with slow common spread and days of rare very long spread distance. This method was devised to estimate fire movement probabilities and assumes independence of the order of weather events and terrain or fuel segments along the line. Similar methods were applied to produce maps of spatial burn probabilities (Anderson et al., 1998).

A simple and perhaps simplistic description of the burn probability from historic data can be obtained from fire records that list the sizes or the mapped perimeters of fires that spread significantly beyond their ignition location (i.e. large fires). Assuming that the landscape is uniform and the burning conditions are stationary over time (i.e. ignition frequency, climatology), the Natural Fire Rotation (Heinselman, 1973) reflects the time required to burn an area equal in size to the study area. The NFR is calculated as:

$$\mathrm{NFR} = A_\mathrm{t}/(A_\mathrm{f}/N_\mathrm{y}) \tag{2}$$

where A_t is the total area of the land, A_f the total area burned by all fires (re-burned areas included) and N_y the years in the record. For the Deschutes National Forest (Fig. 1(b)), the NFR was 721 years, which implies an average probability of burning as 1/721 = 0.00138. This means that the burn probability from large fires would have been about 10 times greater than the fire occurrence probability and signifies the difference between fire occurrence and burn probabilities. This burn probability does not discern any fire behavior characteristics or any parameter involving the distribution of behaviors. It would be similar to the sum of all N behaviors in Eq. (1). Although the NFR methods can be easily calculated, its application to fire risk assessment is of limited value because the fire behaviors with respect to spatial landscape properties are not differentiated and literally assume that the landscape has a uniform probability of burning. NFR calculations also assume that the sample size or length of record is sufficient and stationary over that time period to include rare large fire events. This is often false, however. Van Wagner (1988) found wide variation over six decades. The Deschutes National Forest data record used here in Fig. 1 ended before the largest fire occurred in 2003 (B&B Complex – 35,900 ha or 88,700 acres).

To move beyond the NFR's assumptions of spatial uniformity and temporal stationarity requires accounting for effects of spatially varying fuels, topography, and weather on the growth and behavior of fires. This will produce local differences in the probability of fire behaviors (i.e. at a given point) because of the local properties and the interaction of landscape topology and contagion due to fire growth (Farris et al., 2000). A simple example was developed to illustrate the topological implications of spatially non-uniform burning conditions. Fire simulations were performed using a minimum travel time algorithm that can efficiently simulate fire growth over complex landscapes using temporally static weather conditions (Finney, 2002). Between 10,000 and 40,000 fires driven by southwest winds were simulated for uniform weather and ignition probability across a flat landscape containing a few patches of slower-burning fuel types (Fig. 2). The simulations produced burn probability maps for three scenarios involving fires of different durations (i.e. fire sizes) and show a probability shadow formed on the lee-side of the slower-burning patches as well as the edge effect extending into the landscape from the windward direction. The lee-side probability reductions extend farther from the widest obstruction with the largest fires, but are nearly eliminated behind the narrow obstructions. Note that the absolute probabilities increase with fire size, meaning that a given point was more likely to burn as fire size increased. Similarly, 98th percentile weather conditions were applied to a 900 km^2 area near Missoula, MT, where topography and fuel types varied (Fig. 3). Fuel moisture varied by adiabatic adjustment of temperature and humidity, and topographically altered solar radiation. Wind speeds were 25 mph from the southwest. The results show that burn probabilities for 20,000 random ignitions are not uniform and were higher downwind of the fastest-burning fuel types because a larger "fetch" for ignitions can influence those areas. In summary, this simulation illustrates that burn probabilities are topological, depending on the upstream properties of the landscape. These simulations were not intended to calculate absolute burn probabilities, which would require more complex sequences of weather.

Data on area burned and fire size distributions are often useful for summarizing aspects of general fire occurrence and its variability. Wiitala (1999) used empirical data on fire size distributions to calculate probabilities of exceeding a given fire size. Data on only the largest fires in a given area have also been examined (Erman and Jones, 1996; Moritz, 1997). Theoretical work on fire size distributions have also been examined (Gill et al., 2003; McKelvey and Busse, 1996) and consistently suggest a log-log reduction in the frequency of larger fires. An idea proposed to explain this relationship concerns the influence of many small fires in reducing the frequency of large fires. However, fire data used to

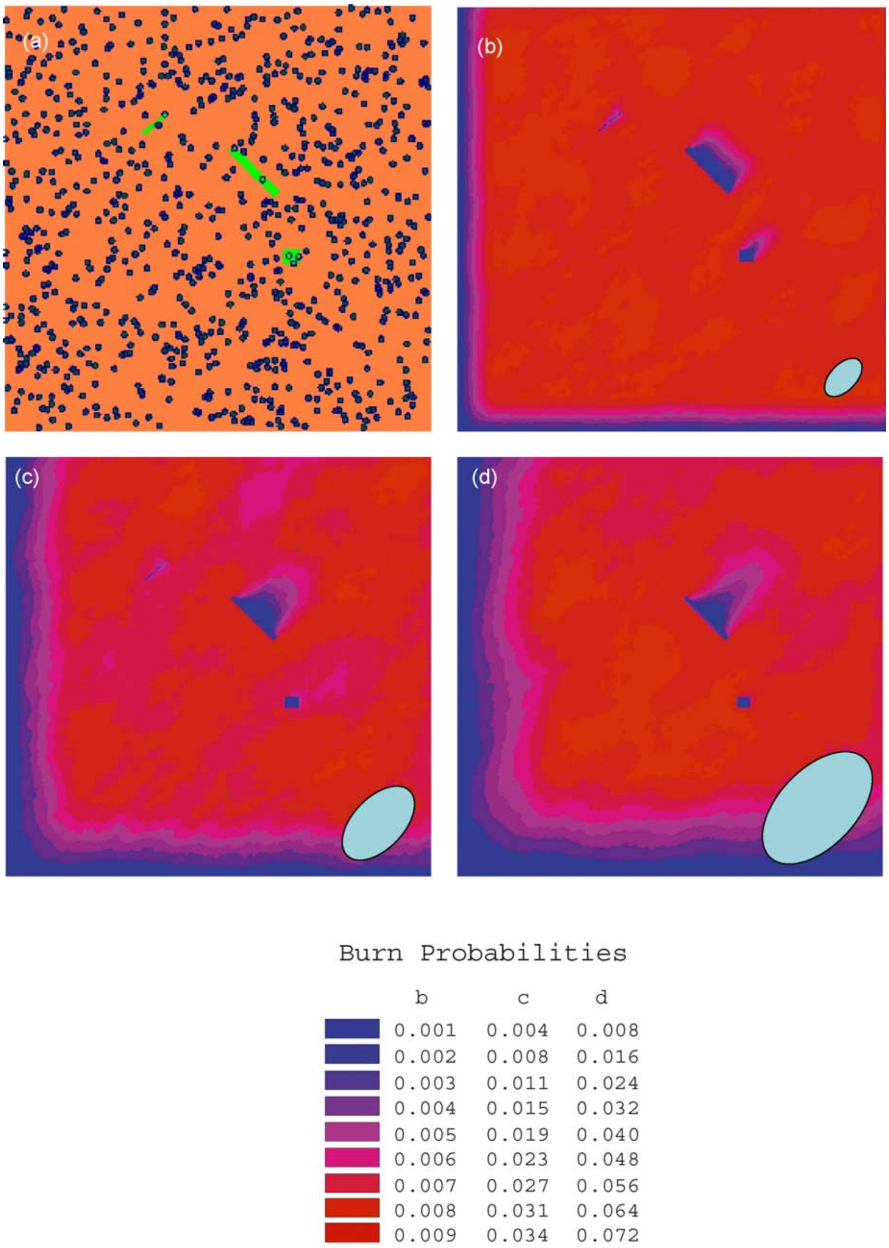

Fig. 2. Simulations of burn probabilities for (a) random ignitions and artificial landscapes composed of uniform conditions except in three patches of slower-burning fuels of different shapes. With constant wind conditions from the southwest (225°) the fire sizes or duration of burning determines the size of probability shadows resulting from these slower fuel patches. Simulations for 40,000 short duration fires (b) (see fire size in lower right) produce a relative burn probability surface that contains a ‘‘shadow’’ on the lee-side because some fires are blocked from burning through the slower fuels. Larger fires (c) and (d) increase the absolute burn probability and the length of the lee-side probability shadow. All simulations show downwind landscape effects and edge effects on south and west edges of the landscape.

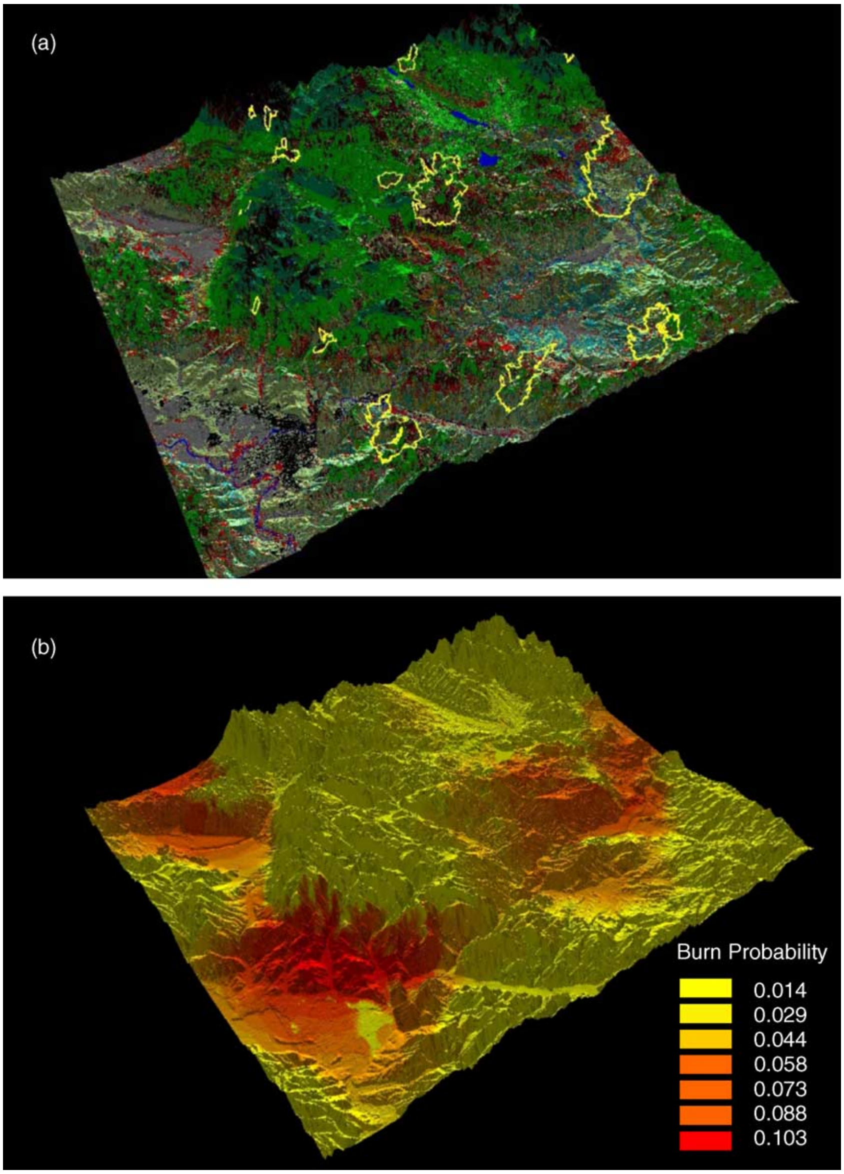

Fig. 3. Example burn probability simulations using 20,000 fires on a real landscape around Missoula, MT under extreme (98th percentile) conditions with winds from the southwest. No suppression effects are simulated. Thus, the different fire sizes that result, for example shown as yellow outlined perimeters (a) are a function of the fuel type, topography, over a fixed time period. The burn probability surface that results from all fires (b) shows the down-stream effects of faster-burning fuel types as increased probabilities on the northeast sides of the valleys. Fires starting along the southwest side of the valley create a greater "fetch" for areas to burn down wind.

test these relationships (Malamud et al., 1998; McKelvey and Busse, 1996) come from such large geographic areas (e.g. continental scale) that interactions among fires is practically impossible. Furthermore, Reed and McKelvey (2002) point out that these relationships may not be as universal as once thought. Theoretical processes that generate fire size distributions can produce many trends on log–log scales.

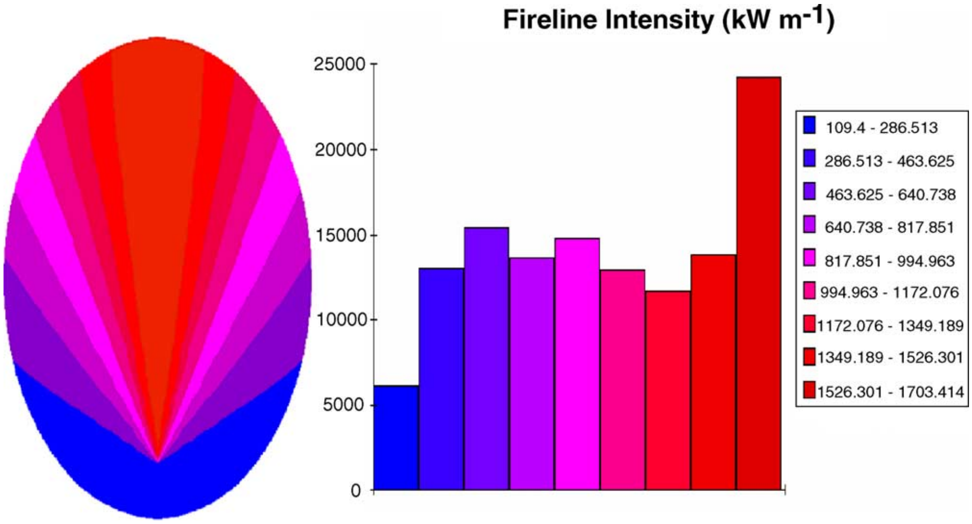

Fig. 4. Elliptical fires burning under uniform conditions produce radial patterns of fireline intensity and spread rate (A). The variability within simple fires forms a distribution (B) that shows more area burned by the faster-moving higher-intensity portion of a fire. This illustrates the potential for different fire effects to occur within burned areas.

3. Fire behavior

Burn probabilities as approximated by the reciprocal of NFR or by simulation represent a summation or integration of the distribution of all fire behaviors. A burn probability is a useful summary of the likelihood component of a risk analysis but it does not distinguish the probabilities of different behaviors that are needed to determine fire effects or value changes. Fireline intensity (Byram, 1959) is one behavior that determines crown scorch and ignition of trees (Van Wagner, 1973, 1977). It varies with the spread rate which, in turn, depends on the fuels, weather, and topography, and direction of movement (heading, flanking, backing). Relative fire spread direction alters fire behavior as fires burn in two-dimensions (Catchpole et al., 1982, 1992). An elliptical fire shape that ideally evolves under uniform and constant conditions displays a pattern of fire intensity and spread rate that varies radially from the ignition point (Fig. 4). Fires cannot be purely elliptical on complex landscapes, but this pattern reveals that the relative location of an ignition point and spread direction of the fire front determine the spread rate and intensity at each point on a landscape. Thus, a given point would often experience fireline intensities from flanking or backing fires with lower intensities than the maximum intensity of the heading fire.

In an ideal calculation, combinations of all factors for all ignition points would be combined to produce a distribution of fire behaviors each summing to the total burn probability at each point on the landscape. The brute-force calculation of this distribution is probably computationally and practically impossible because of the nearly infinite sequences of weather and ignition timing and location. Approximations have, therefore, been attempted by several different methods. Each method involves assumptions that affect the distribution of fire behavior and might be classified as follows:

1. Ignore fire growth and any spatial/temporal interactions – calculate probabilities of heading fire behavior only.
2. Simulate fire growth only for extreme events which burn the most area.
3. Simulate fire growth for all fire events using averages of space–time interactions (before calculations).

The simplest short-cut involves ignoring any spatio-temporal interactions that produce fire growth across landscapes and simply calculate heading fire behavior (i.e. fire behavior potential) for all raster cells that comprise that landscape. Kafka et al. (2000) examine two methods for determining fire behavior potential maps for the range of weather conditions. One uses actual weather recorded for all days over many years and the other uses percentile conditions from a distribution of those observations. Both methods produce a series of maps of fire behavior for the range of weather conditions. At each point on the landscape, a distribution of fire behaviors could be then constructed by taking values from all percentile maps. These distributions would contain higher proportions of high intensity fires compared to the ideal distribution because only the heading fire behavior would be represented.

Another possible short-cut is to use fire simulation to characterize fire growth and behavior under relatively short-term extreme events (similar to Fig. 3). Simulations attempt to represent fire behaviors by mechanistically incorporating spatial and temporal factors that produce fire growth and behavior (e.g. Finney, 1998, 2002), but are not easily validated for long-duration fires under all possible conditions. Assuming that simulations are reliable, the exclusion of all but extreme weather conditions could be justified in jurisdictions where fire suppression policies are enforced. This reasoning is implicit in the methods of simulating burn probabilities by Farris et al. (2000) and Miller et al. (2000) and shown in Fig. 3. In this management context, fires escape mainly under extreme weather and achieve the majority of growth under those dry and windy conditions even after becoming large (Graham, 2003). Since weather is the ultimate arbiter of suppression success on large fires, some method of determining the distribution of burning times would also be necessary to regulate fire sizes, perhaps derived from analysis of extreme intervals in local weather records (Martell, 1999) or theoretical considerations (Reed and McKelvey, 2002). Fire simulations under these conditions would produce distributions of fire intensities at each point on the landscape. These would likely be skewed toward the higher intensities because of the restricted set of weather conditions, but fire growth simulations would generate a range of fire behaviors at each point because all spread directions are potentially simulated.

The final class of short-cut methods relies on statistical averaging to reduce the combinations of fuels, topography, and weather prior to simulating fire growth. These have been attempted for one-dimension (Wiitala and Carlton, 1994) and two-dimensions (Anderson et al., 1998) for individual fires. In both cases, it is unknown what the implications are to non-linear fire behaviors caused by averaging the environmental inputs over space and time before fire growth is calculated. In the one-dimensional case, comparison with observed fire behavior is probably not possible because the probability of fire movement cannot be observed. However, the two-dimensional case can perhaps be compared against the observed fire growth to give a relative indication of agreement among all spread directions.

At present, these methods have yet to be rigorously researched. The author is aware of no published efforts where short-cut approximations of burn probabilities or fire behavior distributions have been compared to either real data (which are probably non-existent) or to an artificial data set. Thus, a recommendation as to the most appropriate method must be considered premature.

4. Fire effects and value changes

A quantitative risk assessment as described by Eq. (1) for a particular land area requires fire effects for all values of interest to be evaluated. Ideally, they must be evaluated using a common currency so that the relative importance of fire effects on, for example, ecological and cultural values can be factored into the expectation across all fire behaviors. Values of human-created property, for example houses, roads, and power lines, are easily appraised in terms of replacement or rehabilitation costs (i.e. money). However, environmental and ecological effects of fires are not easily assigned monetary value, even though the relative changes in appearance or functioning of ecosystems caused by fire are readily apparent. Some methods have been applied to estimating non-market values such as ecological impacts in terms of cost-benefit analysis and contingent valuation (Rideout et al., 1999). Yet for the wide variety of ecological effects, there is a considerable difference between appraisal of value changes and identification of ecological impacts. The former is required for risk assessment and requires values to be assigned, whereas the latter assumes no requirement that ecological impacts are in fact important. In other words, dramatic effects may physically occur and be detectable yet not be valuable. Alternatively, a risk assessment may be performed solely for ecological or intangible considerations, assuming that these have intrinsic values that can be scaled in some way but which may not be compatible with economic values and measures. Difficulties will still arise when separate analyses for the various kinds of values are combined or interpreted for decision making and priority setting.

Ecological impacts of some fires are sometimes labeled as ‘‘uncharacteristic’’ when changes to vegetation or soils or other ecological attributes are said to be beyond ranges of historic variability. This is a difficult determination to make because the spatial variability within a particular fire must be assessed against the multivariate nature of the *distribution* of fire attributes associated with a reference fire regime. Satellite maps of fire severity have recently become useful to provide a comprehensive picture of some kinds of effects across an entire burned area. One measure of fire severity is the difference-normalized burn ration (DNBR: Key and Benson, 1999; Kotliar et al., 2003), which indicates the changes caused by the fire to the near infrared reflectance. This measure of severity is difficult to compare against historic fire regime data directly. A fire regime, defined as the spatial and temporal patterns of variation in fire behaviors and effects (Heinselman, 1981; Agee, 1993), often comes from incomplete and historic conditions over some reference period. In theory, with detailed distributions of fire regime components (fire intervals, sizes, severities, seasons, etc.), severity and other attributes of a particular fire could be assigned a probability based on these distributions. The category of ‘‘uncharacteristic’’ would then be defined below a low-probability threshold of historical occurrence. Yet in practice, even a well documented fire regime typically contains limited estimates mainly of fire frequency variation, although sometimes fire sizes are indicated (Swetnam, 1993; Brown et al., 1999; Niklasson and Granstrom, 2000) and rough categories of severity. This fire frequency information also relates to a short time frame compared to the thousands of years over which fire frequency can vary in response to climatic and human influences. The presence of fire-scarred trees from previous centuries does prove, however, that the fires recorded by them did not kill them, and thus gives a gross indication of severity at certain points in space. Large fires can include contiguous patches of hundreds of square kilometers of complete mortality which would be unprecedented within long fire history records (Graham, 2003) and difficult and expensive to manage in terms of watershed recovery and forest growth. The characteristics of these fires, aside from the sheer measure of size, may warrant the term ‘‘uncharacteristic’’.

Values considered in a risk analysis are usually susceptible, or respond differently, to the range of possible fire behaviors. For example, fire effects on homes are probably uniformly negative, with ignition and burning possible from firebrands and even low intensity fires (Cohen, 2000).

For some ecological objectives, some fire behaviors and effects may be desirable for achieving management objectives (immediately and for some period into the future) and some are considered ‘‘characteristic’’ of fire regimes from historical periods. Low-intensity fires that thin stands of ponderosa pine and reduce fuels are similar to the majority of fires before the 20th century (Swetnam and Baisan, 1996; Brown and Shepperd, 2001). Positive effects such as these are realized in future years in terms of mitigating effects of subsequent fires and alleviating the need for expensive additional fuel treatments. Very often however, ecological effects of fires may be perfectly acceptable within an ecological frame of reference yet be completely incompatible with human values. For example, crown fires in chaparral shrub lands (Keeley et al., 1999) and in coastal and subalpine forests (Agee, 1993) are typical of those fire regimes and plant communities which may benefit from periodic renewal or at least not incur lasting negative impacts. But crown fires near cities or in municipal watersheds are rarely perceived as acceptable and may destroy or damage human-managed systems. Regardless of whether ecological and human values have conflicting or mutual responses to a given fire, the important theme for risk assessment is that wildland fires are inevitable. The ecological consequences of fires and the susceptibility of human values, however, are not inevitable because management activities can be undertaken to change these outcomes. This suggests that the most important benefit of a risk assessment process may be to explicitly recognize the variable nature of fire behaviors and that social choices can be made for how to deal with their impacts, whether the impacts are on houses or on ecosystems.

5. Management options and opportunities

Management actions have the potential to alter the expected losses as expressed in Eq. (1) by reducing the susceptibility of the values to negative fire impacts, increasing the positive results from fire, changing the probabilities of the fire events, or changing the values themselves. Managers cannot change weather or topography, but fuels and values can be modified to change the burning and loss characteristics at specific locations as well as across large landscapes.

The hazard or fire behavior distribution for a given area is partly a function of the combustible materials located on site. Fuel management activities, thinning and prescribed burning, have been repeatedly shown to reduce fire intensities and increase survival of some forest types (Kallander et al., 1955; Helms, 1979; Pollet and Omi, 2002). This not only reduces the negative impacts on those forests but the wildfire itself may very well provide benefits in the form of additional fuel management and ecological process. Structure survival has been shown to be exclusively be a function of the building materials, maintenance, and vegetation in the immediate vicinity (Cohen, 2000). Thus, fuel management at a specific location can be used to alter the susceptibility of those values to wildland fire, reducing the expected net value change.

The probability of fire occurrence is affected by traditional programs in fire prevention (e.g. 10AM policy), detection, and initial attack responses. Collectively, these have likely reduced the probability of a fire burning in any particular year, but paradoxically increased the severity of fires that ultimately do occur (Arno et al., 1991). Evidence exists, however, that fire occurrence may be reduced by prescribed burning (Kallander et al., 1955; Davis and Cooper, 1965; Wood, 1982), yet Pye et al. (2003) found no statistical evidence in Florida that prescribed fire changed the overall burn probability during drought conditions. Spatial patterns of fuel treatments can theoretically alter the movement rate of large fires (Finney, 2001, 2003). The example in Fig. 2 illustrates how the movement of fires skews the distribution of fire behaviors experienced at a given location. By reducing the overall growth rate of a fire, the probability is reduced that a fire will impact a given site in a given time period as a heading fire. Slower moving fires have reduced intensity and create less negative net value change for some ecosystem resources as characterized in Eq. (1). If the active growth of escaped fires is largely determined by the duration of weather conditions (Reed and McKelvey, 2002), then slower moving fires are smaller. This increases the chance that periods of moderate weather or suppression action can intervene in fire growth before reaching certain portions of the landscape.

6. Conclusions

Development of a quantitative risk assessment procedure is dependent on spatially characterizing fire probabilities, fire behavior distributions, and value changes from those fires. Although pieces of this procedure are possible at present, much work is yet to be done on simulating or characterizing fire behavior distributions and probabilities across large landscapes. Given the difficulty with these calculations, most risk assessments will likely be driven mainly by the susceptible values rather than on the probability of fire behaviors or fire-related loss. Although this procedure may illustrate the locations of valuable property relative to hazards and opportunities for land management, it does not factor in the likelihood of loss. Thus, without an expected net value change (Eq. (1)) it is not possible to estimate the cost-effectiveness of management activities that may be proposed for mitigating potential fire impacts.

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