An Analytical Framework for Quantifying Wildland Fire Risk and Fuel Treatment Benefit

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***Abstract**—Federal wildland fire management programs have readily embraced the practice of fuel treatment. Wildland fire risk is quantified as expected annual loss ($ yr^{-1} or $ yr^{-1} ac^{-1}). Fire risk at a point on the landscape is a function of the probability of burning at that point, the relative frequency of fire behaviors expected if the point does burn, and the response of various resources to those expected fire behaviors (net value change). The probability of fire burning at any point on the landscape is a function of the spatial arrangement of fuel, weather, topography, and ignition locations surrounding the point of interest, but not characteristics of the point itself. Relative frequency of fire behavior is a function of the local fire environment and the likelihood of burning at various portions of an assumed elliptical fire. Fire loss is assumed to be a function of fire behavior characteristics. Fire behavior can be measured by the Fire Intensity Index (FII), the common logarithm of fireline intensity. A risk reduction treatment is an investment of capital today for a benefit to be reaped in the future. The benefit of a risk reduction treatment is the present value of the difference in risk with and without treatment. Cost is the present value of current year and future treatment expenditures. Fuel treatment benefit-cost ratio is a measure of efficiency; it is one of many factors that inform a fire management decision.*

Background

The 1995 Federal Wildland Fire Management Policy and Program Review established that (1) life safety as the highest fire management priority, (2) wildland fire is a natural ecosystem process, and (3) fire management decisions must be consistent with approved land management plans. The 2001 review and update of the 1995 Federal Wildland Fire Management Policy included as guiding principles that (1) "sound risk management is a foundation for all fire management activities," and (2) "fire management programs and activities are economically viable, based upon values to be protected, costs, and land and resource management objectives." The document establishes the objectives and priorities of fire management on federal land in the United States, but does not require that the objectives be achieved in any particular way.

In the late 1990s the United States Forest Service refocused its fire management program and budget toward hazardous fuel reduction. Congress established the Joint Fire Sciences Program in 1998 to better assess fuel management problems and solutions. In 1999, the General Accounting Office (GAO) noted that significant barriers existed to achieving the agency's stated goal of mitigating wildland fire threat by 2015, and recommended development of a cohesive wildland fire mitigation strategy (GAO 1999). In 2000, the Secretaries of Interior and Agriculture prepared a report to

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President Clinton outlining how to (1) respond to the still-burning fires of that year, (2) reduce the impacts of wildland fires on rural communities, and (3) ensure sufficient firefighting resources in the future. That report recommended a budget increase of $1.2 billion for the next fiscal year, including $390 million for fuel treatment and burned area rehabilitation. Under the heading of investing in projects to reduce fire risk, the report recommended the "establishment of a collaborative effort to expedite and expand landscape-level fuel treatments."

The National Interagency Fuels Coordination Group (NIFCG) was chartered in 2004 with the purpose of developing and implementing "an effective, interagency fuels management program to address risks from severe fires…" One of the group's enumerated objectives is to "[d]evelop strategies that safely and effectively mitigate [wildland fire] threats to communities and resource values…" The NIFCG's 2005 Strategic Action Plan ranks encouragement of landscape-level fuel treatments among its highest priorities.

In 2004, the GAO noted that "Without a risk-based approach at the project level, the [United States Forest Service and Bureau of Land Management] cannot make fully informed decisions about which effects and projects alternatives are more desirable" (GAO 2004). The report recommended the agencies develop a better understanding of the negative effects of wildland fire, and create a systematic framework for landscape-level risk assessment in order to efficiently locate risk reduction activities.

Clearly, federal fire policy as first set in 1995 and updated in 2001 not only allows but encourages a holistic, risk-based approach to wildland fire management. Federal fire policy recognizes that wildland fire is neither good nor bad; it simply exists, and causes both losses and benefits at different places and times. Federal fire policy suggests that the cost of our response to the existence of wildland fire (prevention, suppression, fuel treatment, *etc.*) should be in balance with the benefits and losses that it confers. Despite the lack of a systematic framework for assessing wildland fire risk, fuel treatment has emerged as a significant risk management tool of the new millennium. Even so, no scientifically defensible metric has yet emerged to guide managers in deciding *where*, *when*, and *how* such treatments should be implemented, much less to confirm *whether* they are even cost-effective to implement.

This paper presents a framework for quantifying wildland fire risk and the benefit of risk reduction activities, including fuel treatment. The analysis framework suggests alternative strategies for mitigating wildland fire loss, as well as a means of comparing the relative efficiency of the alternatives.

Introduction

A fuel treatment is an intentional modification of fuelbed characteristics (load, bulk density, horizontal and vertical continuity, fuel particle size class distribution, *etc.*) for the purpose of mitigating negative fire effects (fire loss), either *directly* by making fire characteristics more benign, or *indirectly* by reducing the probability of fire burning a particular area. Negative fire effects include (1) socio-cultural losses, and (2) uncharacteristically severe wildfire. Socio-cultural losses—damage to or destruction of buildings, utility lines, recreation facilities, watersheds, commercial timber, *etc.*—can occur wherever those values are exposed to wildland fire. In fact, protection of socio-cultural values from fire is the primary reason for suppressing fire in the first place. Thus, to the extent that fuel treatment is undertaken to reduce the ultimate size of a future fire, fire suppression and fuel treatment are two sides of the same coin; the main difference between them is where and when the activities are undertaken.

Modern fire suppression is highly successful at containing incipient fires. As noted in a 2004 panel report to the Wildland Fire Leadership Council, from 1980 through 2002, almost 99 percent of wildland fires were contained to 300 acres or less; cost to suppress the remaining 1.4 percent of fires accounted for 94 percent of the total suppression expenditures. The fires that escape initial attack and burn more than 300 acres are not determined randomly; they are "selected" because their behavior (spread rate, intensity, fuel consumption) exceeds our ability to contain them. In other words, they burn in extreme fire environments that often result in uncharacteristic severity. By eliminating the most benign 99 percent of fire starts from the landscape, fire suppression has resulted in much longer fire return intervals—and higher fire severity when a fire does occur—compared to the historic fire regime. This unintended change in fire-regime is most pronounced in high-frequency, low-severity historic fire regimes (Heinselman 1981), but is also present in longer-interval fire regimes. To paraphrase Shakespeare, we have suppressed fire not wisely but too well. Thus, fire suppression was a solution to one problem (socio-cultural fire loss) that created another (too much uncharacteristically severe fire, too little low-severity fire).

Landscape-scale application of fuel treatments may reduce the incidence of uncharacteristic fires. However, in areas where fire was frequent but not severe, restoring the historic fire regime will also require dramatically *increasing* the incidence of low-severity fires. Increasing the prevalence of low-severity fires—through fire use, prescribed fire and fire surrogates—over time should result in a reduction of uncharacteristic fires. Treating fuel to reduce uncharacteristically severe fire, however, does nothing to increase the desirable fires.

The change in value associated with suppression-caused fire regime change is difficult to quantify (Finney 2005). Socio-cultural fire losses, on the other hand, are amenable to quantitative analysis. Therefore, this framework is focused on socio-cultural resources at risk; a different framework must be used to support fuel treatment decisions regarding restoration of historic fire regimes.

Minimizing cost plus net-value-change ($C+NVC$) is an accepted objective for optimizing fire program level (Althaus and Mills 1982, Mills and Bratten 1982, Mills and Bratten 1988). In this paper, the $C+NVC$ optimization concept is adapted to project-level analysis of fuel treatment options. A fuel treatment is an investment of capital *today* for benefits—reduction in expected annual NVC—to be received *in the future*. Therefore, investment analysis tools such as benefit-cost (BC) ratio should be useful for comparing fuel treatment options.

Quantitative Wildland Fire Risk Assessment

Quantitative wildland fire risk is defined as expected annual NVC (Bachman and Algöwer 2000, Finney 2005, Finney and Cohen 2003) for any spatially explicit land area (plot, pixel, stand, parcel, watershed, *etc.*). Expected annual NVC is the sum-product of NVC_i (cost plus net-value-change should fire occur at the i^{th} fire behavior) and $p(F_i)$ (the annual probability of observing the i^{th} fire behavior). If NVC_i is expressed on a per-acre basis (*e.g.*, \$ ac^{-1}), then annual *risk density* (\$ ac^{-1} yr^{-1}) is

$$E(NVC) = \sum_{i=1}^{N} p(F_i) * NVC_i \qquad [1]$$

The annual probability of observing fire of *any* behavior at a particular location is the sum of probabilities over all fire behaviors. Geographic extent for equation [1] is not explicitly specified; it refers to any homogeneous land unit (pixel, plot, or stand). Risk density is the appropriate quantitative metric for mapping wildland fire risk, especially where mapping units may be of varying sizes. Risk accumulates to larger geographic or political reporting units (*e.g.*, stands, watersheds, or political units like counties or states) composed of many land units. Landscape-level wildland fire risk ($ yr^{-1}) is the sum of risks of the M land units that comprise the landscape.

$$E(NVC)_{landscape} = \sum_{k=1}^{M} E(NVC)_k * A_k \qquad [2]$$

where

A_k = the area of land unit k

$E(NVC)_k$ = $E(NVC)$ for land unit k (eqn. [1])

Assessing the effects of a spatial fuel treatment array (Finney 2001) requires calculating risk at this larger landscape scale to fully account for their potential landscape-level effects.

A wildland fire risk assessment consists of two separate parts: $p(F_i)$ and NVC_i. Conceptually, $p(F_i)$ is a function of $p(F)$, the overall probability of fire burning under *any* behavior, and $p(F_i)/p(F)$, the relative frequency of different fire behaviors given that a fire does occur

$$p(F_i) = p(F) * \left(\frac{p(F_i)}{p(F)} \right) \qquad [3]$$

Mitigating risk entails modifying $p(F)$, $p(F_i)/p(F)$ or NVC_i.

Probability of Burning — p(F)

The probability of fire burning any particular point on the landscape is a function of ignition locations and fire travel from the ignitions to the point of interest. The factors affecting whether fire can reach a given point on the landscape from a given ignition point include: spatial and temporal arrangement of fuel, weather and topography across the landscape, and the level of perimeter containment (suppression) attempted. The probability of burning is inversely proportional to the general level of suppression effort. The fire environment at any point of interest has no bearing on *whether* a fire might reach that point—that is determined by the up-fire environment—but does affect *how* the fire would behave if it does reach it.

Two approaches are possible for estimating $p(F)$—simulation modeling and fire data. Simulation modeling, like that implemented in FlamMap (Finney and others 2006) uses a fire spread model in conjunction with spatial and temporal fire environment information and an assumed or measured pattern of ignition locations to estimate the probability of fire burning each landscape element, assuming no suppression action is taken. This approach provides spatially resolved estimates of $p(F)$, as a function of spatial arrangement of the surrounding fire environment and distribution of ignition locations. However, without some kind of verification, the accuracy of the method is unknown.

The fire data approach relies on records of past fires to indicate the probability of burning of future fires. The annual probability of burning for a landscape is estimated as the average annual landscape fraction burned

$$p(F) = \frac{\sum_{t}^{x} \left(B_t / A \right)}{x} \qquad [4]$$

where

B_t is the area burned in year t

A is the analysis area, and

x is the length of the time period

There are many limitations when using this method to predict future burn probability: fire climate, suppression effort, ignition density, and fire regime are all assumed to be constant. The fire-data estimate is not spatially resolved; it applies to the whole landscape regardless of spatial pattern of fuel, weather, topography and ignitions. Increased precision may be obtained with this method by replacing the geography-based landscape with a fire environment classification within which the fire environment and ignition pattern are more homogeneous. For example, applying equation [4] for individual vegetation types will produce an estimate of $p(F)$ for that vegetation type, regardless of geographic location. Although this method may be more accurate because it is based on observation, its poor spatial resolution limits its use for assessing the effects of landscape-level fuel treatments.

The advantages and disadvantages of the simulation and fire data approaches suggest that a hybrid method combining the spatial resolution of the simulation method with the accuracy of the fire data method would be worth pursuing. For example, one could apply the simulation method heuristically, adjusting simulation parameters as necessary until the weighted average landscape level $p(F)$ from the simulation method equals that of the fire data method. More research and development of methods of estimating $p(F)$ is obviously necessary.

Relative Frequency of Fire Behaviors — $p(F_i)/p(F)$

The relative frequency distribution of fire behaviors at a particular point, given that the point does burn, is the final piece of information needed to estimate $p(F_i)$ using equation [3]. Relative frequency distribution of fire behavior at a point is a function of the fuel and topography at the point, the weather at the time it burns, and the direction of spread (with respect to the heading direction) as fire passes the point. Fuel and topographic characteristics can be known and mapped without consideration for any particular fire. The weather history for a location can be analyzed to identify live and dead fuel moisture contents when burning is most likely (that is, during the extreme conditions during which two percent of all fires escape initial attack and go on to burn most acres). Because most acres are burned under very dry conditions (98th percentile ERC), it is reasonable to simplify the analysis by focusing on very dry conditions.

Head fire behavior predicted for very dry conditions is then predicted over a range of open wind speeds (fig. 1a). Fireline intensity, the product of fuel consumption and flame front spread rate (Byram 1959), seems a logical choice for measuring fire behavior as it "… contains about as much information about a fire's behavior as can be crammed into one number" (Van Wagner 1977). Alexander (1982) provides an excellent discussion of the calculation and interpretation of Byram's fire intensity. The Fire Intensity Index (FII; Scott in

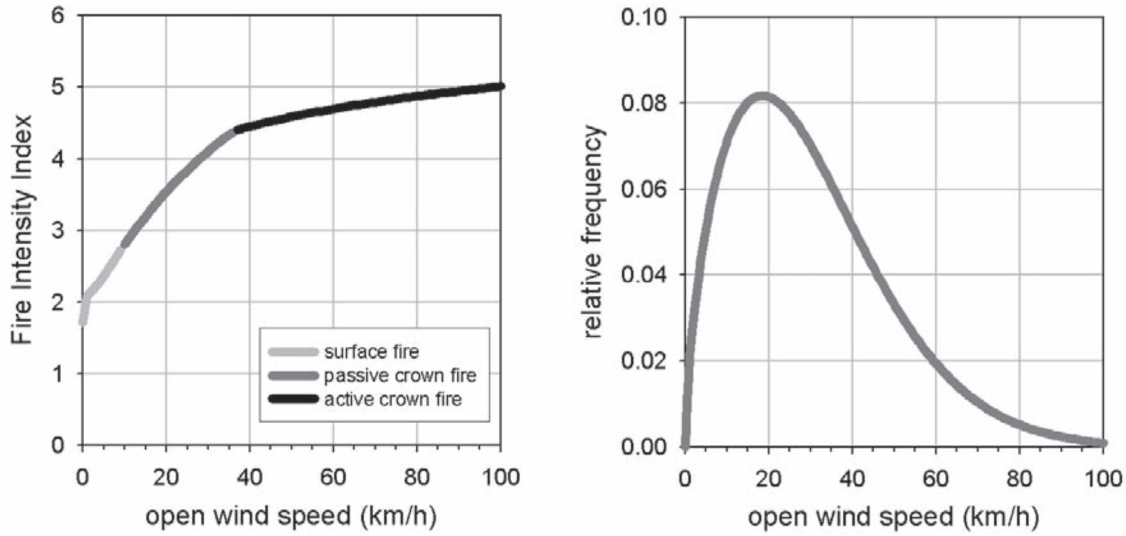

Figure 1—Two components for estimating *p(Fi)*: (a), Fire Intensity Index (FII) over a range of open wind speeds for the very dry moisture conditions during which most acres are burned, and (b) the relative frequency of observing those wind speeds. FII is the common logarithm of fireline intensity expressed in kW/m.

preparation) is the common logarithm of fireline intensity (kW/m). Like the Richter Scale for earthquakes, a unit change on the FII scale corresponds to an order of magnitude change in fire intensity (table 1). Slow-spreading fires burning in very light fuels may exhibit FII < 1; fast-spreading active crown fires through heavy forest fuels may exhibit FII > 5. The effect of wind speed on FII is analyzed separately from fuel moisture because it is not necessarily correlated with fuel moisture. For determining how often the FII predicted in fig. 1a would be observed, a distribution of open wind speeds must be obtained from the weather record (fig. 1b).

Table 1—The behavior characteristics of a wildland fire can be measured using the Fire Intensity Index (FII; Scott in preparation). FII is the common logarithm of fireline intensity (FLI; kW/m). Slow-spreading surface fires in very light fuels exhibit FII < 1; fast-spreading crown fires in heavy forest fuels may exhibit FII approaching 5. FII is classified into six classes (I – VI); each class represents a 10-fold increase in fireline intensity. The range of flame length (FL) as predicted by Byram's (1959) and Thomas' (1963) models is shown for each FII class.

Category	FII	FLI range, kW/m	FL range, m (Byram's FL model)	FL range, m (Thomas' FL model)
I	FII < 1	FLI < 10	< 0.22	FL < 0.12
II	1 ≤ FII < 2	10 ≤ FLI < 100	0.23 – 0.64	0.13 – 0.58
III	2 ≤ FII < 3	100 ≤ FLI < 1000	0.65 – 1.86	0.59 – 2.72
IV	3 ≤ FII < 4	1 000 ≤ FLI < 10 000	1.87 – 5.36	2.73 – 12.7
V	4 ≤ FII < 5	100 000 ≤ FLI < 100 000	5.37 – 15.46	12.8 – 59.42
IV	FII ≥ 5	FLI ≥ 100 000	≥ 15.47	≥ 59.43

The final factor affecting the distribution of FII at a point is the effect of spread direction (relative to the head fire) as fire passes the point. By assuming fire spreads as a simple ellipse (Van Wagner 1969), we can predict the area burned in different FII classes through different areas of a fire (fig. 2). Probability of burning in each FII class is proportional to the relative area burned in those classes.

Using the above factors, a relative frequency distribution of FII for any given fire environment can be constructed (fig. 3). The product of that frequency distribution and probability of burning is $p(F_i)$ (fig. 4a).

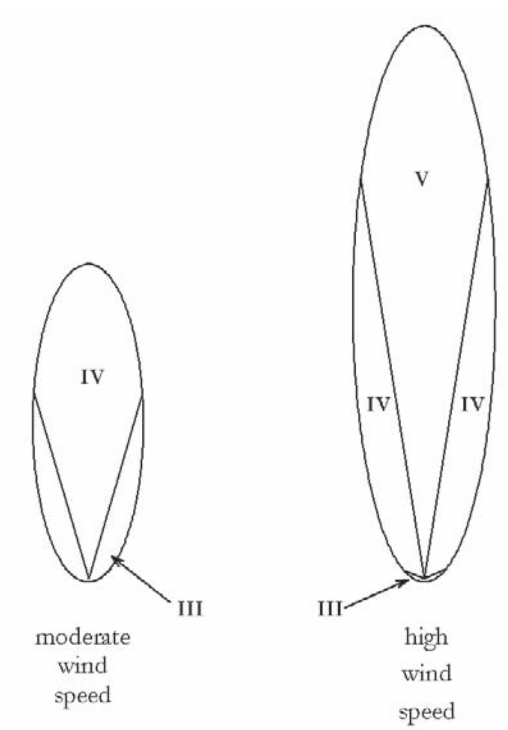

Figure 2—Distribution of FII class as a function of location within an elliptical fire. At moderate wind speed, the head of the fire falls in FII class IV, which extends around to the flank. Backing and flanking intensity fall in class III. At high wind speeds, the head of the fire falls in FII class V, the flanks are in class IV, and the extreme rear of the fire is in FII class III. The probability of burning in an FII class is assumed proportional to the ratio of area in that class to total fire area.

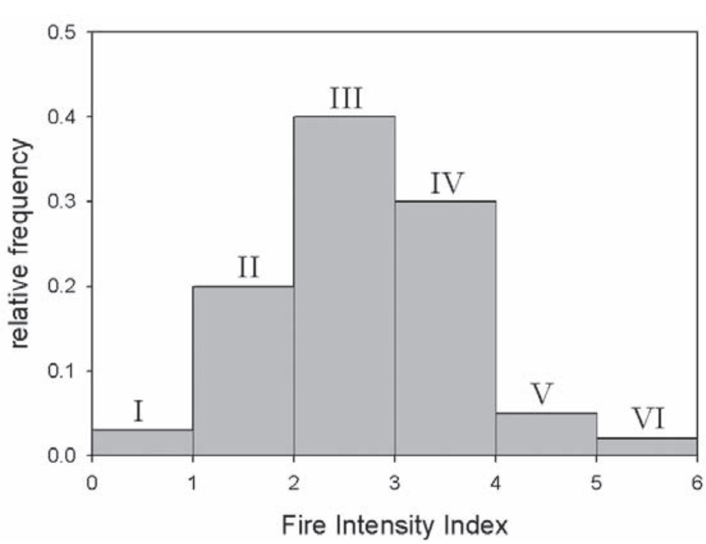

Figure 3—Relative frequency of Fire Intensity Index (the common logarithm of fireline intensity) given that a fire does occur at a given point. The sum of probabilities of observing individual FII classes is one. Relative frequency of FII is a function of the local fire environment at the time of the fire and the distribution of fire intensity at different parts of an assumed elliptical fire. FII class is indicated in Roman numerals.

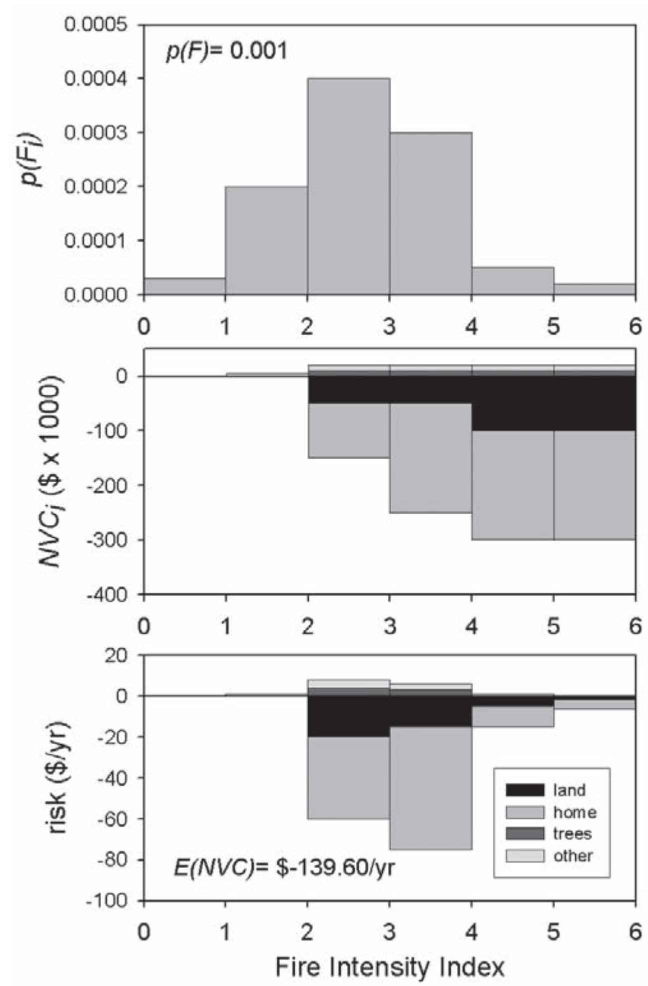

Figure 4—A "Risktogram"—a graphical display of the elements of a quantitative fire risk analysis. Chart (a) displays the frequency distribution of the Fire Intensity Index (FII) at a point. The sum of probabilities in individual FII classes is the annual probability of burning. Chart (b) displays the predicted net change of different values to fire of the various FII classes. Chart (c) displays the resulting wildland fire risk. The sum of *E(NVC)* over all FII classes is wildland fire risk.

Net Value Change — NVC_i

Conceptually, net value change due to fire is a function of initial value and susceptibility. For example, consider two buildings of equal initial value surrounded by flammable wildland fuel, one with a flammable roof covering and the other with a non-flammable covering. The building with a non-flammable roof covering is less susceptible to fire damage—it is more resistant to loss should it experience a fire—and therefore has a lower NVC_i. Conversely, for two buildings of equal susceptibility, NVC_i is proportional to their total value.

Net value change is the post-fire minus pre-fire value of a given place on the landscape (expressed as present value). Net change in land value due to fire is assumed to be a function of fire behavior, and includes both positive and negative effects of fire. NVC_i is quantified by summing over the many different market and non-market values or resources present at a given place.

$$NVC_i = \sum_{j=1}^{n} NVC_{ij} \qquad [5]$$

The mix of values and resources that can be affected by fire at any given point depends on ownership and management emphasis. The values can include market values (timber, water, forage, commercial mushroom production, *etc.*), human developments (buildings and infrastructure), and non-market values (recreation, fisheries, clean air, wildlife habitat, ecosystem function, *etc.*). Net value change must include the potential benefits of fire. One often overlooked benefit of an otherwise destructive wildfire is the reduction of future loss it confers [by reducing $p(F)$ or $p(F_i)/p(F)$].

Positive NVC_i indicates that expected benefits of fire exceed losses, such as might occur in uninhabited areas; negative NVC_i indicates a net loss should fire occur (fig. 4b). Estimating NVC_i across a landscape is a difficult yet critical task that would support fire management decisions regarding both fuel treatment and fire suppression. Detailed spatial information on NVC_i could prove to be even more useful to managers of wildfires or fire-use incidents than predictions of fire growth or potential fire behavior. Due to the large areas to be mapped and the wide array of market and non-market values that are affected by fire, it may be necessary to create a stylized set of "value models" for estimating fire loss as a function of FII. Further research into how different values are affected by fire and development operation tools for implementing that research is clearly needed.

Suppression cost is not included in a quantitative risk analysis; it is part of a larger analysis of fire program level. However, suppression efforts influence the burn probabilities as described above.

Wildland Fire Risk — E(NVC)

Equations [1], [3], and [5] form the foundation of quantitative wildland fire risk analysis. Wildland fire risk is the product of three elements: fire probability, fire behavior, and fire effect (fig. 5). Fire probability is the *whether* component and is estimated through fire simulation or using fire data records. Fire behavior is the *how* component, and is estimated by relative frequency distribution of FII. Fire effect is the *so what* component, and is estimated by predicting the positive and negative effects of fire on various values as a function of FII (NVC_i).

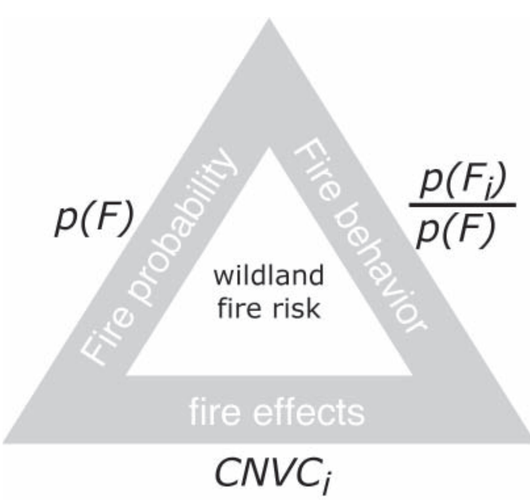

Figure 5—Quantitative wildland fire risk is a function of fire probability, fire behavior characteristics (given that a fire does occur), and fire effects (for given levels of fire behavior). Fire probability at any discrete point on the landscape is a function of the upfire environment (spatial pattern of fuels, weather, topography and ignitions in the area from which fire can be expected to arrive at the point) and suppression actions. Fire behavior is a function of the local fire environment at the time of the fire and the distribution of fire intensity around the perimeter of an assumed elliptical fire. Fire effects are the costs and value changes as a function of fire behavior.

Approaches to Risk Reduction

The framework suggests several theoretical approaches to risk reduction. Wildland fire risk is a function of three main factors: $p(F)$, $p(F_i)/p(F)$ and NVC_i. Reducing any of those components reduces risk. Risk reduction activities fall under two broad categories—fuel treatment and value treatment. A fuel treatment modifies fuel characteristics with the intention of affecting $p(F_i)$. A value treatment modifies characteristics of a value or resource with the intention of reducing NVC_i.

Fuel treatment—Fuel treatments are implemented in discrete geographic units that are generally small in comparison to the large fires whose effects they are intended to mitigate. There are two primary fuel treatment effects on risk reduction —*within-unit*, and *among-units*. Because a treatment unit is small, changing its fuel characteristics does not change its probability of burning; that is determined by the "upfire" fire environment (Finney 2005). Within-unit effects are limited to changing the relative frequency of FII. Within a unit, surface and canopy fuel characteristics are directly modified by a treatment. Dead fuel moisture content and midflame wind speed are indirectly affected by many fuel treatments, usually adversely. The topography and weather elements of the fire environment are not affected by treatment.

Because the probability of burning in discrete treatment unit is determined by the spatial and temporal arrangement of the up-fire environment, only a coordinated array of fuel treatments can potentially reduce the overall probability of burning. The reduction in $p(F)$ is not expected to be constant throughout the fuel treatment array. At the extreme up-fire edge of an array, probability of burning is dominated by the unmodified up-fire environment, and $p(F)$ is not reduced. At the down-fire edge of the array, reduction in $p(F)$ reaches a maximum because the greatest disruption of fire growth can occur. The maximum theoretical reduction in $p(F)$ (as indexed by the pre- and post-treatment fire growth rates), occurs only if the treatment array is as large as the largest fires expected to occur. Otherwise, a fire could grow unmitigated in the untreated area up-fire of the array before encountering the array; the fire's growth could have been further disrupted if treatments were located in that area as well.

Not only does a fuel treatment array potentially reduce $p(F)$, both within and between treatment units, but it can possibly shift the relative frequency of fire behaviors toward lower classes by increasing the amount of flanking fire compared to the predominantly heading fire that would have occurred without the treatment array (Finney 2005). The magnitude of this effect depends on the size of the treatment units relative to fire and the relative spread rates between the treatment unit and the surrounding untreated area. Simulation modeling may confirm and quantify this effect.

Because spatial fuel treatment arrays create effects that occur both within and between treatment units, they must be analyzed at the landscape level (eqn. [2]) rather than at the treatment unit level (eqn. [1]) to be sure that off-treatment benefits are fully accounted for.

Value treatment—A value treatment is a risk reduction treatment that modifies a *value* to reduce NVC_i. Recall that NVC_i is a function of initial value and susceptibility. A value treatment must therefore reduce either initial value or susceptibility. Reducing initial value is not within the scope of risk reduction activities, so value treatments are limited to activities that reduce susceptibility. (However, NVC_i can be mitigated proactively by choosing not to place a susceptible value in a hazardous environment in the first place.) Modifying the physical characteristics of a building—changing to a more fire-resistant roof covering, adding exterior sprinklers, screening attic vents—is one example of a value treatment. Value treatments reduce risk by reducing damage (NVC) for any given level of fire behavior without changing exposure to that fire behavior. Instead of making modifications to a building, the owner may instead (or in addition) choose to implement a fuel treatment in the immediate vicinity of the building. Such a treatment, often referred to as defensible space, affects the relative frequency of fire behaviors at the building, but not NVC_i or the overall probability of fire reaching the building in the first place.

Analysis of Risk Reduction Treatment Alternatives

Quantitative wildland fire risk is useful for comparing with other risks faced by a land manager. For example, homeowners and natural resource managers may be interested in knowing how wildland fire risk compares with risk associated with other natural hazards like flood, earthquake, hail, tornado, and hurricane. A homeowner may be interested in comparing his wildland fire risk with technological risks he also faces like structure fire, automobile crashes, and terrorism.

By itself, a quantitative risk analysis is insufficient to prioritize areas for risk reduction treatment because it does not consider the cost or benefit of the possible risk reduction activities. High-risk areas may not respond well to treatment (the relatively high risk may not be easily reduced). Low-risk areas may be so inexpensive to treat that they are a cost-effective option (many more acres can be treated). To make efficient fuel treatment decisions, we must compare treatment benefits with their costs. The benefit-cost ratio of a risk reduction treatment is the present value of its benefits divided by the present value of its costs.

The nominal benefit of a risk reduction treatment is a reduction in risk—that goes without saying—and is quantified as the difference between risk *without* treatment and risk *with* treatment. For example, if risk without treatment is $-\$50$ ac^{-1} yr^{-1} and a treatment reduces that risk to $-\$40$ ac^{-1} yr^{-1}, then the benefit of the treatment in that year is $[-\$40 - (-\$50)]$, or $\$10$ ac^{-1} yr^{-1}. Unless periodic maintenance is incorporated, the amount of risk reduction due to fuel treatment will diminish with time since treatment due to fuel accumulation and vegetation growth. Even without treatment, risk is not necessarily constant over time. NVC_i may change as new values are added to the landscape, increase in value, or become more (or less) susceptible to fire; and $p(F_i)$ may change due to fuel accumulation, vegetation growth, human activity, climate change, or natural disturbance. The present value of fuel treatment benefits (PVB) over some period of time is therefore

$$PVB = \sum_{t=1}^{x} \frac{E(NVC_t)_{Treatment} - E(NVC_t)_{noTreatment}}{(1+r)^t} \qquad [6]$$

where

r is the discount rate

x is the planning horizon (yr),

$E(NVC_t)_{Treatment}$ is the risk in year t if the treatment is implemented, and

$E(NVC_t)_{noTreatment}$ is the risk in year t if no treatment is undertaken.

Choice of planning horizon and discount rate can affect present value of benefits. Different landowners have different planning horizons—a forest homeowner might not care about benefits further than a decade or two in the future, while government-managed land is generally planned up to 100 years into the future. Because treatment effectiveness diminishes over time, and because of the time value of money, marginal fuel treatment benefit (present value) diminishes to near zero after just a couple of decades, so little is to be gained with longer planning horizons. Also, natural and anthropomorphic changes in the fire environment during that time are likely to require reassessment of risk.

Risk reduction expenses are comparatively straight-forward to calculate. Expenditures for improving fire resistance or implementing a fuel treatment can occur in any year, especially if the fuel treatment plan calls for a spatial array of treatments installed over time. Also, maintenance of the fuel treatment may be prescribed for future years or even annually. Therefore, present value of risk reduction treatment cost is

$$PVC = \sum_{t=1}^{x} \frac{C_t}{\left(1+r\right)^t} \qquad [7]$$

Expenditures associated with fuel treatment activities are routinely documented and modeled. For treatments that generate revenue (for example, commercial thinning), cost is net cost after accounting for revenue. If a treatment generates more revenue than the treatment costs to implement, then BC ratio analysis is no longer an appropriate analysis tool—there's no economic downside. Such treatments can be ranked by present net value rather than BC ratio. Treatment costs depend on many factors, including the type and intensity of treatment, location on the landscape, size and shape of the treatment unit, access to treatment area, distance to forest products markets, and regulatory analysis requirements.

As an investment of capital *today* for benefit *tomorrow*, potential fuel treatments should be analyzed in a manner similar to any other forestry investment. When choosing among possible projects for which capital is the only limiting resource, the economically optimal solution is to implement the projects with the highest BC ratios until the available capital is expended (Gilles and BuonGiornio????). In reality, many resources may be limiting, and operational or political constraints may not allow the optimal economic solution. The BC ratio is just one of many factors that inform a fire management decision. Investments with BC ratios less than one cannot be justified based on quantitative analysis of benefits and costs alone; other benefits not included in the analysis must presumably be present to offset the otherwise negative return. BC ratio less than one implies that available capital is better invested at the specified discount rate and proceeds used to fund any losses when a fire does occur.

Prioritizing Risk Reduction Treatments

In the absence of an analytical framework for estimating the efficiency of alternative fuel treatments, such as that presented here, fuel treatment planners must resort to experience and instinct in selecting the type and location of individual fuel treatments. Their selection criteria include potential fire behavior reduction, the general location and value of resources-at-risk and variables related to treatment cost (access, ability to meet NEPA analysis requirements, etc.). Treatment locations selected through such a process have been termed "easy acres" because they were often the easiest areas to treat.

Such treatments are placed individually without regard for an overall spatial pattern that may reduce $p(F)$. Their locations have been considered random for comparison against a theoretically optimal spatial pattern designed to reduce large fire growth (Finney 2001). While their locations on the landscape may be random in terms of spatial pattern (and therefore sub-optimal in terms of reducing $p(F)$), they are anything but random in terms of treatment cost. In fact, the factors used to select the “easy acres” also result in relatively low treatment cost. Treatment units that are truly random would be quite costly to implement, because factors that affect treatment cost are not considered; randomly located treatments could require costly road construction, fireline building, and NEPA analysis. Fuel treatments located based on a theoretically optimal spatial pattern can be considered random with respect to treatment cost. The BC analysis framework outlined here can shed light on the relative cost efficiency of each strategy.

This analysis framework suggests a new risk reduction treatment strategy—optimizing landscape-level risk by selecting a spatial and temporal risk reduction treatment regime that maximizes the BC ratio.

Discussion

Following significant wildland-urban interface fires in 1923 and 1991, it is well established that the fuels, fire weather and fire-susceptible values in the Oakland-Berkeley Hills of Northern California present a significant wildland fire risk to area homeowners. That same area is also exposed to potentially devastating earthquakes on several faults in the area. According to a recent USGS study, there is a 27% chance of a Richter magnitude 6.7 or larger earthquake occurring in the immediate vicinity of the Oakland-Berkeley Hills between 2003 and 2032 (Hyndman and Hyndman 2005), an annual probability of 0.009 (nearly one in one-hundred). Given the proximity of the probable fault rupture and magnitude of the potential earthquake, significant damage to or total destruction of homes and utilities is likely. Assuming an earthquake loss of just $250,000 per home, the resulting annual earthquake risk is $2250 per home.

Clearly, *eliminating* risk of any natural hazard is well beyond the capability of both individuals and governments. In the face of limited mitigation resources, a strategy for optimally managing risk is required. It is tempting to simply compare the quantitative levels of risk from all natural and technological hazards and allocate mitigation resources to the hazard posing the highest risk, or to each hazard in proportion to its relative contribution to total risk over all hazards. Neither strategy is efficient, however, because they do not consider the cost of mitigation efforts in relation to the benefit. The economically optimal solution would be to allocate resources to efforts with the highest return on investment (that is, the highest BC ratios) until all resources have been used up, regardless of the absolute or relative level of risk. The economically optimal solution may not be feasible for technological or political reasons, so calculation of risk reduction treatment BC ratio must simply be part of a larger decision support framework that accounts for constraints other than available capital.

This analysis framework estimates treatment costs and benefits without considering to whom those benefits and costs accrue. Costs may be borne by one party while benefits are reaped by another. For example, federal or state governments may implement a fuel treatment on public land that benefits nearby private ownerships, or a government agency may subsidize fuel treatment on private land. Potential fire losses may also be transferred among parties. Insurance is a risk management tool used to deal with risks that include potential for catastrophic loss. In exchange for a periodic premium, an insurance company agrees to repair or replace insured values if a loss should occur. The insurance premium is composed of the insurance *rate* and the insured value. Insurance rate is a function of the hazardousness of the environment in which the value resides (the physical situation). Insured value represents *NVC*. In other words, an insurance premium is a function of quantitative risk; the higher the hazard or *NVC*, the higher the premium. This is a potentially helpful concept because insurance rates and premiums can be used as surrogates for hazard and risk. The majority of wildland homes are covered by an insurance policy that includes coverage for fire loss (no distinction is made between wildland fire loss and fire loss due to other causes). In other words, some of the fire risk a homeowner faces has been transferred to an insurance company. In such cases, benefits of risk reduction treatment are received by the insurance company rather than the homeowner. The analysis here makes no consideration for disconnected costs and benefits.

The exclusion of fire suppression costs from this analysis of fuel treatment may seem unjustified. Fire suppression and fuel treatment are similar endeavors—fire suppression is just-in-time fuel treatment; fuel treatment is fire suppression without prior knowledge of where or when a fire will escape initial attack. Both activities are intended to mitigate fire loss. In a risk analysis we wish to account for the *NVC* incurred if an area burns, whereas suppression is an attempt to prevent areas from burning. Therefore, suppression costs should be assigned to the acres that did *not* burn rather than to the areas that did. In this analysis framework, suppression is assumed constant at some level. The effects of fuel treatment are simulated as (1) a shift toward more benign fire behavior (lower FII) within treated areas, and (2) a reduction in fire size and therefore $p(F)$ in fuel treatment arrays. A holistic fire management approach would seek the optimal mix of fuel treatment and fire suppression that minimizes their combined cost plus *NVC*.

When a fire near homes escapes initial attack, it is common to witness last-minute fuel treatments around the homes (defensible space) or preparation of the home itself to resist fire damage (a value treatment). Fire suppression organizations discourage homeowners from relying on these just-in-time mitigation efforts. Instead, homeowners are urged to create defensible space and make their homes resistant to ignition well in advance of a fire start. However, the just-in-time mitigation behavior may actually be quite rational from a purely economic standpoint. Without a nearby ignition, $p(F)$ at a home is quite small, perhaps as low as 1 in 1000 per year, resulting in relatively low risk and corresponding low benefit of defensible space and value treatments; their costs may far exceed potential benefit. Once a fire has ignited nearby, however, $p(F)$ increases drastically, thereby increasing risk, and therefore treatment benefit, by as much as two orders of magnitude. Suddenly, the treatment benefits may exceed treatment costs by a wide margin. Of course, there may not be time or resources available to treat fuels and homes immediately before a fire, and homes will be destroyed. Unfortunately, that does not make treating the home when no fire is present a better investment.

Just-in-time fuel treatment behavior is not restricted to private landowners. Government property is frequently managed in the same manner. The headquarters area of Glacier National Park, in West Glacier, Montana, which includes office, industrial and residential buildings, is located in a fire-prone landscape with a recent history of large fires in the region. Despite the obvious need, defensible space was not maintained throughout the headquarters area. Only when the 2003 Robert fire threatened to burn through West Glacier did activities to create defensible space commence. One reason often cited for this type of behavior is the availability of suppression resources assigned to the fire. Because those suppression resources are not funded by the local unit. Since treatment cost to the local unit decreases to zero, they have even more incentive than a homeowner to engage in just-in-time mitigation. Aggressive suppression actions prevented the Robert fire from reaching West Glacier. Interestingly, after experiencing a rapid rise in $p(F)$ when the Robert fire started nearby, $p(F)$ in future years should be expected to fall below pre-Robert levels because the fire acts as a large fuel modification directly upfire from West Glacier. The corresponding reduction of risk is an example of an unexpected benefit of an unplanned, unwanted wildland fire.

The analytical framework presented here considers only values for which benefits and losses can be quantified. Non-market values are not easily quantified and therefore difficult to bring into such an analysis. Two possible solutions to this problem are (1) attempt to quantify non-market values through techniques such as contingent valuation, or (2) implement the framework with the full understanding that it does not account for all values, and should be used as one piece of information among many to support a fuel treatment decision.

Conclusion

Managing wildland fire risk is an important function of any fire management program. Fire risk exists wherever human values are located in areas where wildland fire can occur. Wildland fire risk is a function of probability burning, potential fire behavior, and fire effects on human values. Fire risk is mitigated by affecting one or more of those factors. The benefit of a risk reduction treatment is the present value of risk reduction. The cost-efficiency of a risk reduction activity can be measured by its benefit-cost ratio.

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