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# Conceptual model for comparative ecological risk assessment of wildfire effects on fish, with and without hazardous fuel treatment☆

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**Abstract**

Wildfire poses risks to fish and wildlife habitat, among other things. Management projects to reduce the severity of wildfire effects by implementing hazardous fuel reduction treatments also pose risks. How can land managers determine which risk is greater? Comparison of risks and benefits from fuel treatment projects to risks from severe wildfire effects is consistent with policies requiring public land managers to analyze short- and long-term environmental effects. However, formulating the problem as a comparison of temporal considerations often results in decisions to reject fuels treatment projects near imperiled species habitat, even though the adverse effects of short-term project actions may result in substantial long-term net benefits from reducing the severity of wildfire effects. Consistent with widely accepted ecological risk assessment methods, the problem is formulated in a conceptual model. Salmonid fish populations are the risk assessment endpoint, and one stressor adversely affecting them is sediment from wildfire or logging. The model compares short-term effects of implementing fuels reduction treatments to longer-term wildfire effects with and without fuel treatments, including risk reduction benefits. Used quantitatively or qualitatively, the model may contribute to sustainable resource management decisions by improving communication among stakeholders, risk managers in land and resource management agencies, and risk assessors in agencies responsible for enforcing the Endangered Species Act.


*Keywords:* Endangered Species Act; Fire regime condition class; Habitat quality; Hazardous fuels reduction; Healthy forests; Integrated management; Multiple-objective decision analysis; National Environmental Policy Act; Population viability; Risk analysis; Risk management; Salmonid fishes; Sediment; Silviculture; Sustainable resource management

## 1. Introduction

Forestry decision-making is increasingly difficult (Hollenstein, 2001). Land and resource management decisions always involve risk, including the decision not to take action (Thomas and Dombeck, 1996).

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Resource assessments of western USA federal lands reveal two related management challenges: (1) restoring salmonid fish populations, some of them imperiled and protected by the Endangered Species Act (ESA, 1973); and (2) reducing the potential for lethal fires that can damage fish habitat, water quality, and other resources (Quigley et al., 1996; Quigley and Bigler Cole, 1997). Any approach to integrating fire, fuels, and aquatic ecosystem management has inherent risks and uncertainties (Bisson et al., 2003). Federal managers also are challenged by the decision ''process predicament'' that tends to inhibit management action (USDA, 2002).

Managers need an integrated problem-oriented approach to reduce wildfire risks by treating fuels without causing irreparable harm to fish populations. I call this the ''fire/fish risk problem'' and use the US Environmental Protection Agency's *Guidelines for Ecological Risk Assessment* (US-EPA, 1998) to develop a simple conceptual model to support risk-based decisions. The main idea is that sustainable resource decisions are more likely to result from long-term comparisons of the magnitude of adverse and beneficial effects of management action than from the current approach of trying to determine an acceptable level for short-term adverse environmental effects without considering long-term effects. In fire-adapted forests typical of the western USA, adverse environmental effects from the inevitable wildfire burning under uncharacteristic conditions cannot be ignored, nor should the benefits of management designed to reduce the magnitude of wildfire's adverse effects.

Decision analysis and other structured problem-solving methods emphasize the need for clearly articulated objectives, along with criteria to evaluate how well various alternatives might meet those objectives (NRC, 1995). Sustainable resource management depends on clear objectives describing desired future conditions. Objectives provide managers with targets and others with benchmarks for holding managers accountable for their actions. For risk analysis objectives, called assessment endpoints, the EPA *Guidelines* recommend specific ecological entities and their attributes. The *Guidelines* caution against the use of vague concepts, such as ''sustainability'' and ''integrity'' (US-EPA, 1998).

The ultimate utility of decision analysis, including risk analysis, is not necessarily articulating the best policy option, but avoiding extreme events (Haimes, 1998). Decision analysis can improve endangered species conservation by making the connection between values, objectives, and decisions more transparent, helping to disarm criticisms that the government is capricious or partisan in implementing the ESA (NRC, 1995). Risk analysis traditionally has been used for other purposes, but it can address forest management issues in a transparent way and disclose risk trade-offs that are often not accounted for in other analysis techniques (Hollenstein, 2001). The problem formulation phase of the EPA *Guidelines* relies on a conceptual model consisting of a risk hypothesis with supporting rationale, and a diagram of predicted relationships. I begin by defining terms, formulating the problem, and identifying model parameters. Three diagrams related to the problem demonstrate the utility of conceptual models. This introductory material rationalizes the choice of selected parameters for the comparative risk assessment model and underpins concluding discussion of several issues associated with potential application of risk models.

## 2. Definitions

Risk terms are defined (Table 1) because they can pose a barrier to effective communications. At least nine federal agencies, including the US Department of Agriculture, Forest Service, have used the EPA *Guidelines* and agreed that they provide a common basis for analyzing risks (CENR, 1999). The *Guidelines* provide some definitions but are flawed. For example risk analysis is defined too narrowly as determining stressor–response relationships. Elsewhere, risk analysis is the all-encompassing process of risk assessment, characterization, and management (e.g. NRC, 1996; Haimes, 1998; Schierow, 2002; SRA, 2002; von Gadow, 2001). The *Guidelines* also rely on jargon developed in the 1980s for human health and toxicological risk assessment, such as ''stressor''—a term that seems synonymous with hazard (Table 1). Furthermore, the *Guidelines* do not define risk or hazard, which are two closely related fundamental concepts.

A hazard is something that can cause an adverse effect. Judgments of adversity are value-based (Lackey, 1997). Risk gives meaning to things, forces,

Table 1
Ecological risk assessment definitions

| | |
|---|---|
| Adverse (ecological) effect | Changes that are considered undesirable because they alter valued structural or functional characteristics of ecosystems or their components. An evaluation of adversity may consider the type, intensity, and scale of the effect as well as the potential for recovery (US-EPA, 1998). |
| Assessment endpoint | An explicit expression of the environmental value that is to be protected, operationally defined by an ecological entity and its attributes. For example salmon are valued ecological entities; reproduction and age class structure are some of their important attributes. Together ''salmon reproduction and age class structure'' form an assessment endpoint (US-EPA, 1998). |
| Conceptual model | A written description and visual representation of predicted relationships between ecological entities and the stressors to which they may be exposed (US-EPA, 1998). |
| Danger | (1) Exposure to possible evil, injury, or harm; (2) a source or instance of peril or risk (Webster's, 2001). |
| Ecological entity | A general term that may refer to a species, a group of species, an ecosystem function or characteristic, or a specific habitat. An ecological entity is one component of an assessment endpoint (US-EPA, 1998). |
| Ecological risk assessment | The process that evaluates the likelihood that adverse ecological events may occur or are occurring as a result of exposure to one or more stressors (US-EPA, 1998). |
| Hazard | (1) A chance happening; (2) a chance of being harmed or injured; or (3) a possible source of danger (Webster's, 2001); (4) an act or phenomenon that has the potential to produce harm or other undesirable consequences to humans, or what they value (NRC, 1996); (5) a condition or physical situation with a potential for undesirable consequence (SRA, 2002). |
| Risk | (1) the possibility of suffering harm or loss (cross-reference: danger); (2) a factor, course, or element involving uncertain danger (cross-reference: hazard); (3) the danger or probability of loss to an insurer (Webster's, 2001); (4) a concept used to give meaning to things, forces, or circumstances that pose danger to people or to what they value (NRC, 1996); (5) the probability of an occurrence of a particular adverse effect on human health or the environment as a result of exposure to a hazard (Schierow, 2002). |
| Stressor | Any physical, chemical, or biological entity that can induce an adverse response (US-EPA, 1998). |

or circumstances that pose danger to people or what they value (NRC, 1996). Risk is usually defined as the probability and severity of adverse effects (e.g. Haimes, 1998; Schierow, 2002). Risk has two components: one is real (the potential damage, or unfavorable adverse effects and consequences); the other is an imagined, mathematical human construct called probability (Haimes, 1998). Many people have difficulty comprehending risk, and its quantification has challenged and confused lay persons and professionals (Haimes, 1998).

## 3. Problem formulation: model parameters

The first phase of ecological risk assessment is problem formulation, and a conceptual model is an essential part of the process (US-EPA, 1998). The way the problem is defined determines what the risk assessor models and analyzes. The inability of management and regulatory agencies and the public to articulate common goals and conceptual approaches to land management is part of the problem; and until there is improved coordination and recognition of a common conceptual framework for management actions, conflicts are likely to continue (Bisson et al., 2003). Risk analysis experts suggest two ideas. Haimes (1998) cautions that sub-optimal decisions are likely unless the beneficial as well as adverse effects of current decisions on future options are assessed and evaluated to the extent possible. Instead of trying to determine the acceptable level of risk from adverse effects, Slovic (2003) recommends focusing on the benefits of managing wildfire.

Table 2 identifies the essential parameters of the fire/fish risk problem situation in a formulation consistent with the EPA *Guidelines*. Framing resource management problems as questions is a clarifying exercise. Lackey (1997): if ecological risk assessment is the answer, what is the question? Rieman et al. (2003a): which is worse, new fires that may result from past management, or new management intended

Table 2
Problem formulation parameters for the fire/fish risk situation in the western USA

| | |
|---|---|
| Situation | Multiple-objective decision about wildfire and fishery management alternatives: attain desired forest conditions with hazardous fuel reduction treatments while maintaining or restoring fish populations |
| Management objective | Avoid extreme effects of fire on fish and other resources by reducing fuel load |
| Management alternatives | Compare effects on fish of forest management: • *With* fuel treatment (logging and/or prescribed burning) • *Without* fuel treatment (''no action'' alternative) |
| Risk analysis: | • Identify assessment endpoint (risk assessment objective): salmonid fish reproduction and age class structure • Identify stressor–response profile (hazard and effect mechanism on endpoint): sediment–fish response • Describe relationship quantitatively as data allow or qualitatively with expert opinion |
| Probability: | • Wildfire is certain to occur in fire-adapted forests and produce a sediment pulse • Fuel treatment is certain to produce a sediment pulse |
| Appropriate time frame: | • At least 100 years if imperiled species are in the project area • Time horizon based on fire frequency return interval assures wildfire is a certainty |

to mitigate those fires? To consider this question in a decision model, the relevant parameters are the adverse environmental effects of fire with and without fuel treatments, and beneficial effects of treatments.

## 4. Conceptual models: problem parameter relationships

Risk cannot be managed unless it has been properly assessed, and some form of model provides the best assessment process (Haimes, 1998). A conceptual model is a written description and visual representation of predicted relationships between ecological entities and the stressors they may be exposed to. Conceptual models can represent many relationships, including exposure scenarios qualitatively linking land-use activities to stressors (US-EPA, 1998).

Conceptual models have two principal components: (1) risk hypotheses describing predicted relationships among stressor, exposure, and assessment endpoint response, along with rationales for their selection; and (2) diagrams illustrating these relationships. By highlighting what we know and do not know about a system, a conceptual model provides an opportunity for others to evaluate explicit expressions of the assumptions underlying decisions. Models also are a framework for prediction and a template for generating more risk hypotheses (US-EPA, 1998). Presented below are three conceptual model diagrams developed elsewhere. Each provides a rationale for the fire/fish risk problem parameters (Table 2) and the risk hypothesis and comparative risk decision model diagram presented in Section 5.

### 4.1. Assessment endpoint: population viability model

Many factors affect fish populations, including habitat quality (Fig. 1). This general model or ''influence diagram'' helped biologists consider the potential efficacy of different forest management options for conserving imperiled northern spotted owl (*Strix caurina occidentalis*) populations in the Pacific northwest region of the USA (Cleaves and Haynes, 1999).

Fuel treatments can substantially alter habitat quality by changing stand structure, but fires generally have a more extreme impact on wildlife (Mason et al., 2003). Wildfire can cause fish mortality directly and indirectly by modifying habitat quality (Rieman and Clayton, 1997). By affecting vegetation, wildfire can accelerate soil erosion rates and sediment delivery to streams (Wondzwell and King, 2003).

Population viability assessment need not involve a mathematical model and quantitative estimates of persistence probabilities. Risk assessments can be made by comparing qualitative models of species–habitat relationships to maps of habitat envisioned under various management scenarios. If data are available, more sophisticated spatially explicit assess-

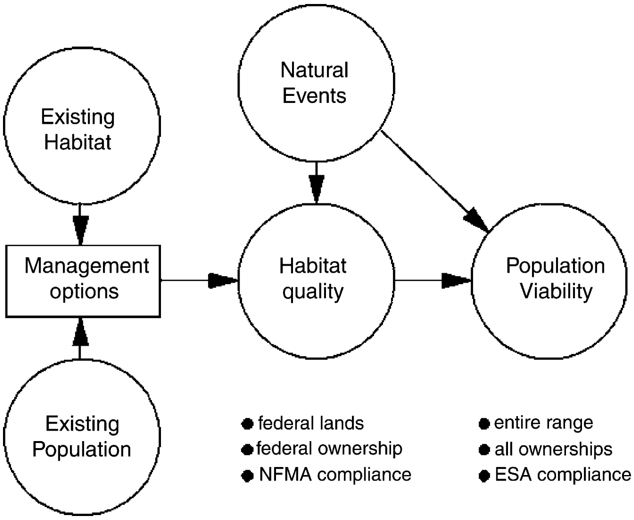


Fig. 1. Conceptual model for population viability influences (modified from Cleaves and Haynes, 1999).

ments of risk can be made by linking demographic rates to spatial variation in habitat quality (Scientists' letter, 2003).

### 4.2. Stressor: logging sediment model

Implementing management options can adversely affect fish populations through a variety of "stressor" mechanisms. A conceptual model from the EPA *Guidelines* identifies logging sediment as a stressor affecting salmonids via several pathways (Fig. 2). Logging also affects salmonids by altering streamside shade, instream wood recruitment, and allochthonous insect and litter inputs. Logging, defined as any activity in which woody material is removed from a site by mechanical means (Helms, 1998), and prescribed burning are the primary means of reducing hazardous fuels. Logging activities range from thinning and removal of pre-commercial sized trees to clear-cut harvesting. Improving forest conditions by logging is a complex issue that eludes simple generalizations (NRC, 2000).

The condition of federal forests in the western USA has deteriorated. These forests are denser and have higher mortality rates than forests in other ownerships and regions, which puts many resources at risk from severe wildfires effects (O'Laughlin and Cook, 2003). Judicious logging may be a good tool to improve health conditions in some forests, but each situation should be evaluated on its own merit and operations planned carefully to ensure that the cure is not worse than the disease (NRC, 2000). In risk management, avoiding actions in which the cure is worse than the disease means avoiding extreme events, which are the worst and the most disastrous situations (Haimes, 1998).

Successful projects for reducing fire hazard depend on taking many factors into account and developing protocols for deciding which stands should be thinned and how much (NRC, 2000). Different types of erosional and masswasting events will influence stream ecosystem processes and the stream habitats required by aquatic species, but we know little about these relationships (Wondzwell and King, 2003).

From what is known, biologists conclude that compared to other options, pre-emptive management before a fire has clear advantages and is likely to be the most effective approach for sustaining fisheries (Dunham et al., 2003). Mitigating severe effects from wildfires after the fact will always be harder than preventing them from being so severe in the first place (Arno and Allison-Bunnell, 2002). Management activities in areas where fuels have accumulated after decades of fire suppression can reduce the probability of uncharacteristically severe fires, and thus, reduce the need for post-fire rehabilitation; some regional

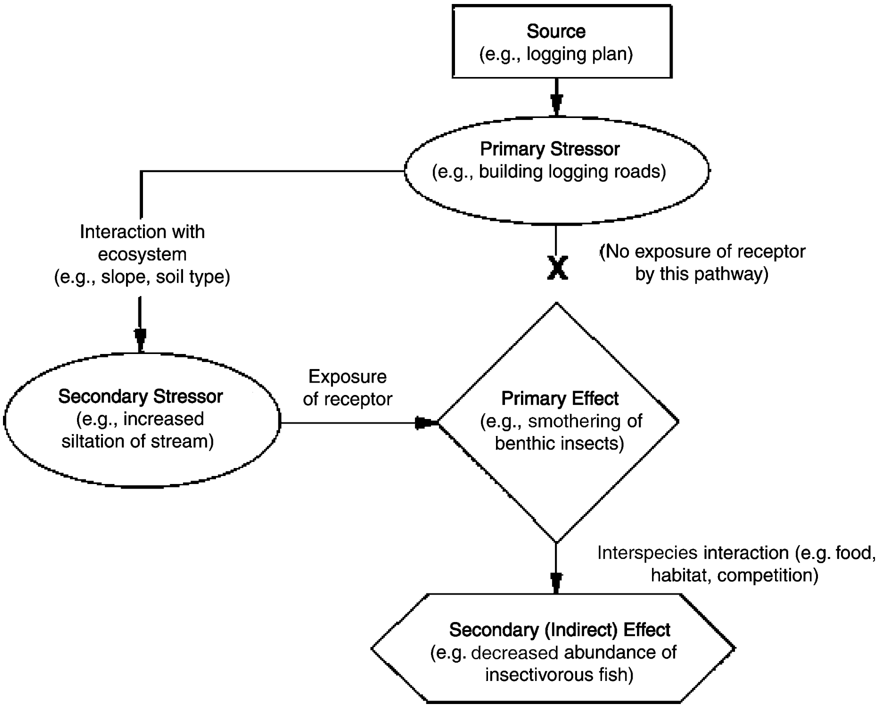


Fig. 2. Conceptual model for logging (from US-EPA, 1998).

examples are the lower and mid-elevation forests in California and southwest Oregon and the pine forests of Arizona and New Mexico (Bisson et al., 2003). A comprehensive thinning program can have lasting benefits in dry mixed-conifer ponderosa pine and Douglas-fir forests that were historically adapted to low-intensity fire. These forest types are generally near human settlement and are high priorities for treatment (Fiedler et al., 2003). Across the western USA are 29 million acres of such high-priority "hotspots" (Vissage and Miles, 2003).

Benefits from pre-fire management are most likely to come from prioritizing treatment areas (Dunham et al., 2003). Priorities can be based on ecological value, evolutionary significance and the risk of loss (Bisson et al., 2003). Some watersheds and populations are vulnerable to risks from disturbance events, such as wildfire, the invasion of exotic species, or environmental changes such as climate shifts. Active management can mitigate those risks in some situations, but in others forest management may not be effective (Bisson et al., 2003). Improving situations in which fires pose significant risks and/or benefits to fishes depends on meeting the challenge of developing effective management guidelines based on models that can assess the relevance of emerging concepts and theories plus solid empirical data to test them (Dunham et al., 2003).

### 4.3. *Stressor–response: sediment–fish model*

Under the EPA *Guidelines*, the objective of risk analysis is called the assessment endpoint. The ecological effects on the endpoint are described in stressor–response profiles. The *Guidelines* illustrate these concepts using salmonid fish as an assessment endpoint (see Table 1) and sediment as a stressor (Fig. 2). A key assumption in the fire/fish risk model presented in Section 5 is that hazardous fuel reduction treatments will reduce wildfire intensity and subsequent severity of environmental effects by reducing the post-fire sediment pulse. This is illustrated in a conceptual model diagram (Fig. 3) describing the relationship of quantities of sediment delivered to the

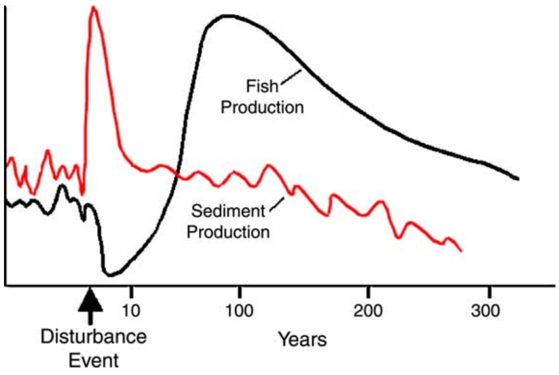


Fig. 3. Conceptual model for sediment and fish production relationship (from Rieman, 2003).

stream and fish production (Rieman, 2003). It serves as the stressor–response profile called for in the EPA *Guidelines*. Fish populations respond almost immediately to sediment from a disturbance event, either wildfire or logging, by reduced production. Although sediment production rapidly returns to the pre-event level, according to the diagram it may take decades for fish production to return to the pre-event level, but in the long-term future fish production becomes higher than before the event, and remains there for centuries (Fig. 3). In other words, sediment produced by a disturbance will have short-term adverse effects on fish, offset by long-term benefits.

## 5. Conceptual model: comparing fire/fish risks

When considering extinction in the fire/fish risk problem context, it is important to balance the short-term risk to individuals, the potential loss of habitat, and measures to mitigate these factors against the long-term benefits to the species as a whole (USDA/USDI, 2000). Although the short- and long-term effects of fire on fish are poorly understood, we know that the vulnerability of fish to fire depends on quality, amount, and distribution of affected habitats; for example in highly degraded and fragmented systems, fishes with narrow habitat requirements are likely to be most vulnerable to fire and fire-related disturbance (Dunham et al., 2003). For sensitive fishes in more remote forests with a potential for uncharacteristically severe fires, there is a great need to coordinate aquatic conservation objectives with fire and fuels management (Bisson et al., 2003). Although closer integration of terrestrial and aquatic management is necessary, the lack of a common understanding or conceptual foundation is a fundamental challenge to progress (Rieman et al., 2003b).

Using a long-term time horizon, I developed a conceptual model for the fire/fish risk problem that compares the short-term effects of fuel treatment project implementation to long-term effects with and without fuel treatment, including project benefits from reducing post-wildfire environmental damage. Consistent with the parameters of the fire/fish problem (Table 2), sediment production is the environmental effect analyzed. The idea that active management can improve conditions is a testable risk hypothesis and can be visualized in a conceptual model diagram. The model provides decision rules and is illustrated with a quantitative example.

### 5.1. Risk hypothesis

A risk hypothesis is a fundamental component of an ecological risk assessment model (US-EPA, 1998). Hypothesis: the benefits of restoring natural (historical) fire regimes and native vegetation on a particular site, plus the benefits of reducing the severity of effects from stand-replacing wildfires balance favorably against any adverse effect, either short- or long-term, from hazardous fuel reduction treatments.

The hypothesis is derived from language in a memorandum from the directors of the ESA Service agencies (Williams and Hogarth, 2002). The memo provides guidance for ESA regulatory personnel engaging in interagency consultation with resource management agencies. It is consistent with National Environmental Policy Act (NEPA, 1969) requirements that federal agencies analyze and document short- and long-term environmental effects of proposed major actions, including the ''no action'' alternative.

### 5.2. Model diagram

A diagram of the conceptual model visualizes the risk hypothesis. The US Department of Energy has developed several conceptual models for long-term analysis of environmental risks and benefits. One example deals with net environmental benefits for remediation or restoration of petroleum-contaminated sites (Efroymson et al., 2003). More pertinent is a model from a NEPA (1969) environmental impact statement of management options for radioactive hazardous waste accidents (US-DOE, 2002). Italicized terms in this section are from that document. The project concept involves changing *initial environmental risk* to a lower *residual environmental risk* level with management activities involving some *implementation risk* and subsequent *environmental risk reduction*. I modified this conceptual model only slightly to fit the fire/fish risk problem (Fig. 4).

The model (Fig. 4) presumes that in fire-adapted forests typical of western USA, fire is inevitable. If the analytical time horizon is far enough in the future, fire is a certainty and its environmental effects are realized, i.e., there is a 1.0 probability of the environmental hazard exemplified by the sediment–fish relationship becoming an *environmental risk*. From a forest management perspective, preferable to today's uncharacteristically high fuel loads is the level of historical fuel loads before the 20th century fire suppression policy, i.e., prior to 1910 (Pyne, 2001). In terms of the supporting conceptual models, the effect of fuel treatment management options on fish population viability (Fig. 1) is a short-term reduction in habitat quality resulting from additional sediment from logging (Fig. 2) that may adversely affect fish production via a short-term sediment pulse triggered by the logging disturbance event (Fig. 3). From a fish conservation perspective, the risk to fish from short-term logging sediment may be acceptable if it is offset by future net benefits from sediment reduction.

*Environmental risk* on the vertical axis (Fig. 4) is sediment that adversely affects fish habitat. Effects other than sediment, such as increased stream temperature from reduced shade, could be analyzed similarly. Line (a) is the *initial environmental risk* of sediment produced by a wildfire burning under uncharacteristic fuel conditions. Point $R_2$ is the current risk of post-fire sediment; line (a) is the post-fire sediment load at any given time without fuel treatment, which over time increases as fuels accumulate. In NEPA (1969) terminology, line (a) is the effect of the ''no action'' alternative. Line (b), a constant at $R_1$, is *residual environmental risk*, which is post-fire sediment associated with the management target fuel reduction objective. When a wildfire occurs at any point in time, the *environmental risk* from the

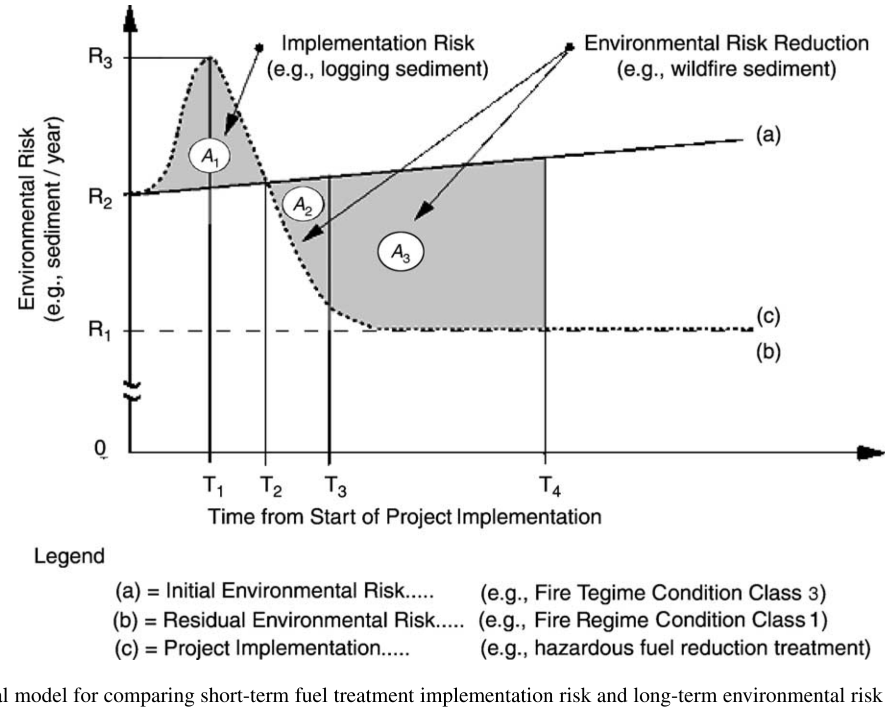


Fig. 4. Conceptual model for comparing short-term fuel treatment implementation risk and long-term environmental risk reduction (modified from US-DOE, 2002).

condition represented by line (a) is considerably greater than that of line (b). This reflects the difference in pre-fire forest conditions and post-fire effects severity as measured by sediment production.

Line (c) traces over time the effect of implementing fuel treatments. Shortly after project initiation, the *implementation risk* of additional post-fire sediment due to logging rises above and exceeds that of the *initial environmental risk* on line (a). At time $T_1$, *implementation risk* is maximized at $R_3$ and then begins to decline. At $T_2$, *environmental risk reduction* commences as the benefit of reduced post-fire sediment from the fuel treatment project on line (c) drops below the amount of post-fire sediment on line (a) that would occur without fuel treatment. At $T_3$, project benefits continue to increase, but *implementation risk* still exceeds *environmental risk reduction* ($A_1 > A_2$). Over time *environmental risk reduction* continues, and at $T_4$ project benefits exceed *implementation risk* ($A_1 < A_2 + A_3$).

The objective of the project described by line (c) is post-fire *environmental risk reduction*. To reiterate, this results from management actions to change an ecosystem from the condition represented by line (a), or *initial environmental risk* to that of line (b), or *residual environmental risk*. In today's forestry terminology, the project objective is to change the fire regime condition class (FRCC) moving from a higher FRCC to a lower one.

FRCC is a classification of the amount of departure from the natural fire regime (Hann et al., 2003). The three condition classes are low (FRCC 1), moderate (FRCC 2), and high (FRCC 3) departures from the central tendency of the natural (historical) fire regime. Each level of departure puts ecological values at higher risk. Although FRCCs have been defined and mapped at a coarse scale of 1 $km^2$ (Schmidt et al., 2002), they are appropriate for use at a project-level scale (Hann et al., 2003). In 2000, approximately 151 million acres of federal forest land was in FRCC 2 or 3 (USDA, 2001). Ideally these lands, 85% of them in the western USA, would either be in FRCC 1 or within the historical fire regime range.

### 5.3. Decision rule

This model (Fig. 4) asks, what is the relationship of *implementation risk* in the short-term (time $T_1$) to long-term *environmental risk reduction*? At time $T_2$, project effects on line (c) no longer pose additional risk as they drop below *initial environmental risk* on line (a). At some time between $T_3$ and $T_4$, project effects on line (c) approach the target *residual environmental risk* on line (b), a constant at level $R_1$.

Two decision rules are possible. The first rule, consistent with the US-DOE (2002) model, is to accept the project if at time $T_1$ the maximum *implementation risk* ($R_3 - R_2$) is less than *environmental risk reduction* (value of line (a) − value of line (c)). The second rule is based on comparing cumulative risk over time, i.e., comparing areas under curves. Assuming the decision time horizon is $T_4$, the project is acceptable if *implementation risk* ($A_1$) is less than *environmental risk reduction* ($A_2 + A_3$) resulting from the project. Because *implementation risk* is relatively short in duration, this places more emphasis on long-term effects than the first decision rule and may be more appropriate because although fire is certain, its exact timing and post-fire effects are uncertain. The magnitude of effects on line (c) varies over time, but the probability of a fire at time $T_1$ is the same as at $T_4$ or any other time.

Under either decision rule, the chosen time horizon is crucial. If a decision is based upon time $T_3$ or earlier, the fuel treatment project decision is likely to be "no go." However, it would be a biased decision because the full benefits from treatment have not yet occurred. At time $T_4$ or later, the decision is likely to favor implementing the fuel treatment project.

### 5.4. Quantitative example

The decision whether to undertake the management project in Fig. 4 depends on the decision-maker's time horizon, the decision rule, and the relationship of lines (a), (b), and (c). For this discussion, the contours of the lines are similar to those in the US-DOE (2002) model. The lines may take on different configurations for specific forest types, fire regime conditions, and sediment production relationships. For example there is no particular reason to expect that line (a) would be linear.

The relationships in Fig. 4 seem realistic. For western USA ecoregions, researchers compared thinning effects to wildfire effects with a quantitative sediment production model. The predicted results, on a per unit area affected basis, were that wildfire would yield 70 times as much sediment as thinnings used to reduce hazardous fuels (USDA, 2003). In lieu of empirical data on sediment production from different FRCCs on a particular forest site, consider a hypothetical example based on this 70:1 relationship. In Fig. 4, $R_2 = 70$ units of post-fire sediment under current conditions in a project area. A thinning project would add one unit of sediment, i.e., $R_3 = 71$. Assume that a target fuel reduction goal would result in a 2% post-fire sediment reduction, i.e., $R_1 = 68.6$. These quantitative relationships closely fit those in Fig. 4.

## 6. Discussion

Scale issues of time and space are addressed. Risk terminology can be an issue. Discussion concludes with a list of ideas for applying the EPA *Guidelines for Ecological Risk Assessment* (US-EPA, 1998) and some observations on the utility of ecological risk assessment and decision analysis models.

### 6.1. Temporal scale

Compliance with NEPA (1969) short- and long-term effects analysis raises the issue of appropriate time horizon selection and whether future effects should be discounted at some rate to the present. Davies (1996) instructs that comparison of risks should be done within the same time period, and risks prevented by management programs should be included in the comparison. It would not be meaningful to compare the risks controlled or prevented by program A over 5 years with the risks controlled by program B over 25 years (Davies, 1996). Obviously, both programs must be considered over a 25-year horizon. That is too short for imperiled species conservation.

The effects of decisions made today about many environmental policies, including climate change and loss of biodiversity, will be felt across hundreds and perhaps thousands of years (Portney and Weyant, 1999). Some "crises" involving imperiled species may call for short time horizons on the order of tens of years, but ordinarily it will be necessary to view extinction over longer periods, on the order of hundreds of years so that short-term considerations do not create long-term problems (NRC, 1995). For risks to fish, 100 years is a minimum (Rieman et al., 2003b).

Discount rates are often used by analysts to compare present and future costs and benefits when issues have such long-term ramifications (Portney and Weyant, 1999). Davies (1996) asked whether the analyst comparing future risks should discount them to the present. Because discounting favors current over future generations, Solow (1994), a Nobel laureate economist, questioned whether discounting should be done at all to support sustainable and meaningful conservation decisions. If so, he said, the discount rate should be very small. For most comparative risk analysis purposes, the difficulties of discounting can be avoided by not discounting (Davies, 1996). No discounting seems appropriate for ecological dimensions of the fire/fish risk problem, but most economists would favor discounting if social and economic values are included in the analysis. Portney and Weyant (1999) provide authoritative but inconclusive discussions on choosing an appropriate discount rate, well summarized in Solow's Foreword.

A time horizon for sustainable resource management would be longer than that shown at time $T_4$ (Fig. 4). From this analysis, it would be difficult to argue that a decision using only information at time $T_3$ or earlier would be more sustainable than a decision using information at time $T_4$ or later. Sustainability is about many things, but first among them is the consideration of intergenerational equity. Fairness of current decisions for future generations of either fish or people cannot be determined with a short-term outlook.

### 6.2. Spatial scale

To improve forest health conditions on federal lands, managers must comply with NEPA (1969) analysis requirements to support decisions. Project-level analyses allow managers to consider protecting or enhancing specific resources (Barbour et al., 2003). For example Lee and Irwin (2003) concluded that fire risk and northern spotted owl habitat suitability are complex issues requiring site-specific assessment and management.

Projects need to be prioritized so that scarce resources can be used effectively (Bisson et al., 2003).

Tying small area project-level analyses to larger scales helps managers think about the importance of different resources through space and time. Refining analyses at the mid-scale helps to understand how different resources interact. Considering resource conditions and management objectives at very broad scales can help managers understand where they might concentrate efforts (Barbour et al., 2003).

A guidance document for federal fuel treatment projects recognizes the importance of scale and assumes assessments at scales larger than individual projects have been done (USDA/USDI, 2004). The document states that:

Fuel treatment projects on federal lands must operate within the established guidelines of resource management plans and other legally applicable guidance. Interdisciplinary processes are used to identify goals at the landscape scale and to establish stand-treatment priorities and objectives within the context of those goals. Concepts such as the emulation of natural disturbances and the range of natural (historical) variability may be useful when setting landscape and stand goals and objectives (USDA/USDI, 2004).

A tactical schedule of priority vegetation-treatment projects should result from strategic assessments of the need for fuel treatments conducted at appropriate landscape scales. Broad-scale assessments should set priorities for reducing the risk to social and ecological values caused by uncharacteristically dense vegetation. To reduce risk, the assessments should evaluate the potential for vegetation treatments, such as mechanical treatments and prescribed fire (USDA/USDI, 2004).

### 6.3. Post-fire environmental effects: hazard or risk?

To enhance communications in endangered species conservation, technical terms should be used precisely (O'Laughlin, 1997). Some may be concerned that *environmental risk* (the vertical axis in Fig. 4) is more like hazard than risk. Risk is a likelihood; hazard is a potential (see Table 1). In the US-DOE (2002) model, the vertical axis was labeled "Health and Safety Risk (fatalities per year)." I relabeled it "Environmental Risk (e.g., sediment per year)" for Fig. 4. Rationale: over the long term, fire in a fire-adapted forest is a certainty (probability of 1.0) and the hazard to a fish population from a change in sediment production is certain to be realized. Thus, sediment is an environmental risk to fish, whether the source is logging or wildfire.

Nuances of definitions are less important than the risk management question—which effect on fish is greater: (a) management designed to reduce wildfire intensity, or (b) wildfires burning uncharacteristically under high fuel load conditions? As discussed earlier, the question can be converted during the problem formulation phase of ecological risk assessment to a risk management hypothesis and visualized in a diagram like Fig. 4.

### 6.4. Applying the EPA Guidelines for Ecological Risk Assessment

Forest resource managers may believe that fuel treatments will improve environmental conditions over time, but they should expect skepticism from fishery managers and ESA regulatory agency personnel. Compared to not taking any action, fuel treatments may or may not reduce adverse environmental effects accompanying uncharacteristic wildfires. Managers lack the tools and information to demonstrate the beneficial effect project activities may have on sensitive species and the quality of their habitat. The fire/fish risk conceptual model (Fig. 4) can be applied to many situations in the fire-adapted forests typical of the western USA. The model can compare the effects of a fire's aftermath on valued ecosystem components, such as fish or wildlife populations, with and without such intervention at any point in time.

Table 3 lists some ideas risk assessors and risk managers should consider when adapting the ecological risk assessment framework (US-EPA, 1998) in a decision analysis model for fuel treatments. These steps could be adapted to fit risk management situations other than the fire/fish risk problem. The conceptual model diagram (Fig. 4) offers a method for enhancing communications between risk managers, risk assessors, and stakeholders. It can visually demonstrate whether the reduction in environmental risk following a wildfire, represented by a change in sediment production, would exceed the implementation risk of pre-emptive fuel treatment.

Ecological risk assessment parameters can be represented quantitatively with existing data or

Table 3
Considerations for applying *Guidelines for Ecological Risk Assessment* (US-EPA, 1998) to managing wildfire effects on ecosystems

| | |
|---|---|
| 1 | Keep it simple. Resource managers need project-level decision support models. Start with the essentials (Table 2) and add complexity only as necessary to fit the management situation. |
| 2 | Determine desired future forest conditions. The management objective is attaining a specific forest condition that will reduce wildfire risks, expressed clearly in terms the manager can be held accountable for. Many areas in the western USA have accumulated levels of fuels that represent uncharacteristically hazardous conditions that can be categorized by fire regime condition classes (Hann et al., 2003). An appropriate objective would be historical species composition and stand structure prior to the time fire suppression policy was implemented. |
| 3 | Select risk assessment endpoints consistent with management objectives. An appropriate endpoint for assessing logging effects is viable salmonid fish populations and appropriate quality of spawning and rearing habitat conditions (US-EPA, 1998). The EPA *Guidelines* caution against using vague concepts like ''sustainability'' and ''integrity.'' |
| 4 | Develop a stressor–response profile. One effect of either wildfire or management on population viability (Fig. 1) is additional sediment, a ''stressor'' from either logging management options (Fig. 2) or wildfire disturbance events. The response is an effect on fish production (Fig. 3). A similar approach could be taken with reduced riparian vegetation and shade effects on stream temperature, or vegetation change and wildlife habitat effects. |
| 5 | Use an appropriately long time horizon to compare post-wildfire sediment production *with* and *without* fuel treatment. If the fire/fish risk management situation involves imperiled species, anything less than 100 years is inappropriate (NRC, 1995; Rieman et al., 2003b). |
| 6 | Wildfire is certain to occur in fire-adapted forest ecosystems. This can be assured in risk analysis by selecting an appropriate long-term time horizon, such as the fire return interval of natural (historical) or characteristic fire regimes. This deterministic approach avoids the difficulty of assessing and communicating a probability distribution of fire risk potential, but probabilistic refinements, such as the relationship of precipitation and sediment production could be used to add stochastic elements if appropriate data are available. |
| 7 | Compare the magnitude of adverse environmental effects (e.g. sediment production) on aquatic habitat quality from wildfire *with* and *without* fuel treatment. |
| 8 | Include the benefits of fuel treatment in the analysis. Fire regime condition class (FRCC) categorizations are useful for this. The effects of wildfire *with* fuel treatment (e.g. restoring to FRCC 1 or historic fuel load levels) should reflect the reduction of adverse post-fire environmental effects, such as sediment that can be attributed to fuel treatment. The effect of wildfire *without* fuel treatment is the ''no action'' alternative represented by current FRCCs 2 or 3. The benefit is obtained by management actions that change forests from a higher to a lower FRCC. |
| 9 | Focus on the benefits of pre-emptive or pre-fire management of forests instead of trying to determine safe or acceptable levels of risk (Slovic, 2003). The problem of determining the level of risk society is willing to accept is avoided altogether, and analysis focuses on comparing two options, one against the other, rather than against a nonexistent or elusive, value-laden socially determined standard of acceptable risk. |
| 10 | Avoid the difficulties involved in discounting future ecological effects to the present time by not discounting (Davies, 1996). If economic or social considerations are added, discounting may be appropriate. To reduce bias against future generations, use a very low discount rate (Solow, 1994). |
| 11 | Use quantitative data when they exist. Qualitative assessments and comparisons of ecological risks can provide useful insights for environmental decision-making, even if the scientific understanding of them is poor (NRC, 1996). |
| 12 | Display relationships in a conceptual model decision model diagram (Fig. 4) that compares effects over time. |

qualitatively with expert opinion. Scientific quantification exists to aid judgment, not to supplant decisions (Clark, 2002). Qualitative assessments of relative ecological risks can provide useful insights for environmental decision-making (NRC, 1996). None of the scientific difficulties of estimation negate the importance for policy decisions of considering ecological outcomes. Interested and affected parties may want to take account of ecological effects even if the scientific understanding of them is poor (NRC, 1996), as in the fire/fish risk problem.

Simple conceptual models used in decision analysis frameworks can be powerful communication tools (US-EPA, 1998). The model in Fig. 4 is capable of demonstrating to the public, regulatory agencies, and the courts the long-term net benefits of active forest management. The transparency and clarity of such models can help people think through the questions of if, where, and when hazardous fuels reduction projects should be undertaken. Further development and use of this model may guide us along the path to sustainable resource management.

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