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Evaluating Soil Risks Associated With Severe Wildfire and Ground-Based Logging

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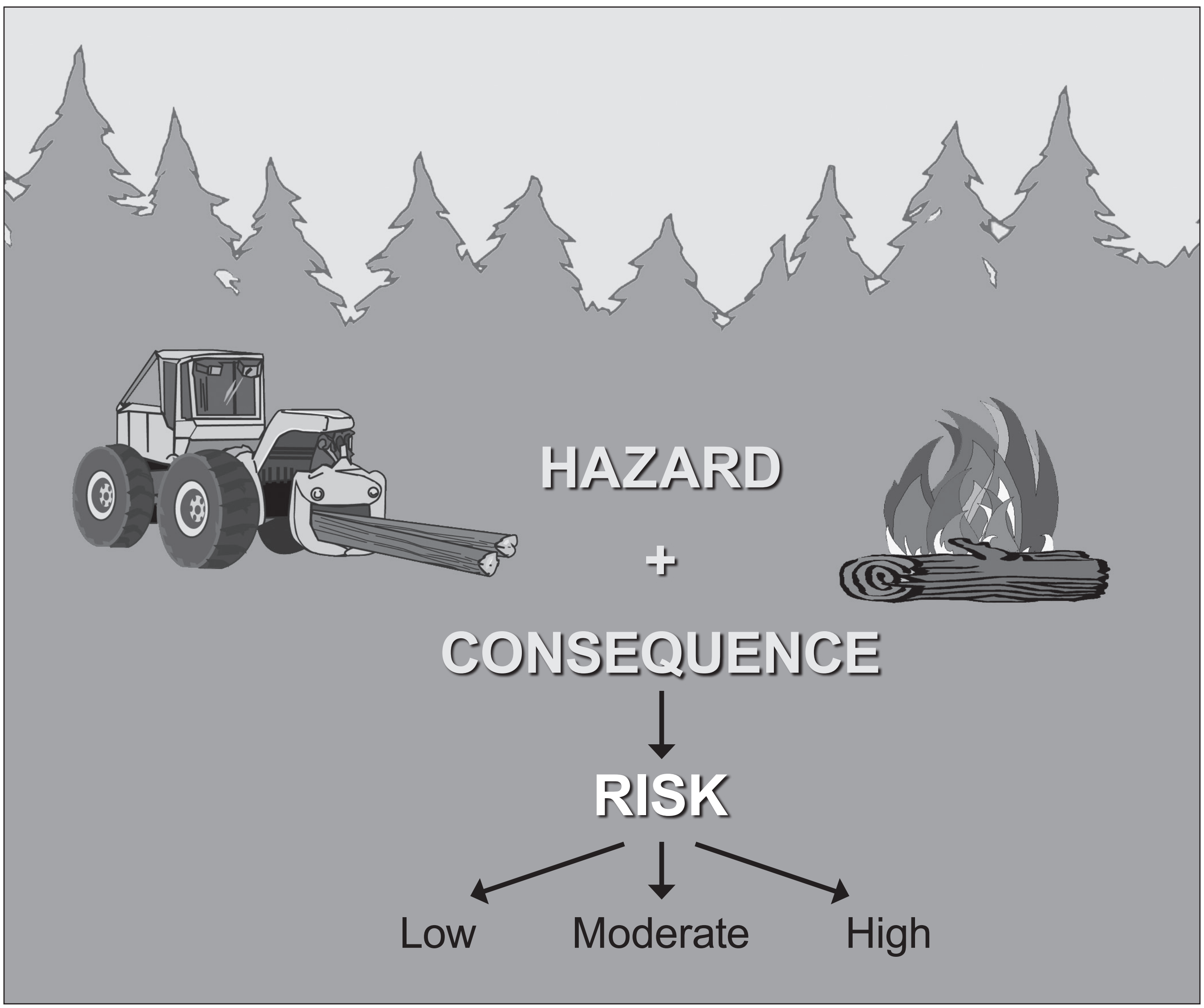

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Abstract

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Rehabilitation and timber-salvage activities after wildfire require rapid planning and rational decisions. Identifying areas with high risk for erosion and soil productivity losses is important. Moreover, allocation of corrective and mitigative efforts must be rational and prioritized. Our logic-based analysis of forested soil polygons on the Okanogan-Wenatchee National Forest was designed and implemented with the Ecosystem Management Decision Support (EMDS) system to evaluate risks to soil properties and productivity associated with moderate to severe wildfire and unmitigated use of ground-based logging equipment. Soil and related data are from standard National Cooperative Soil Surveys. We present results from one national forest management unit, encompassing 6,889 soil polygons and 69 438 ha. In the example area, 36.1 percent and 46.0 percent of the area were classified as sensitive to impacts from severe wildfire and unmitigated use of logging equipment, respectively, and there was a high degree of correspondence between the map of units sensitive to wildfire and the map of units sensitive to heavy equipment. We discuss options for extending the current model and considerations for validating key model components.

Keywords: Decision support, wildfire, logging equipment, risk, logic models, forest management, soil surveys.

Introduction

Wildfire and ground-based logging equipment (hereafter, logging equipment) both can change soil properties in ways that may adversely affect subsequent plant growth. Here, we describe results of a decision-support application that evaluates risk of both agents to forest soils and their functions. This tool is especially useful for guiding decisions about rehabilitation and timber salvage after wildfires.

An application that evaluates risk to forest soils of both wildfire and logging equipment is useful for guiding decisions about rehabilitation and timber salvage.

Use of decision-support systems in management of natural resources has steadily increased over the past 20+ years. Conceptual models that verbally describe ecological risk can be translated to quantitative, site-specific models (O'Laughlin 2005). An increasing benefit to natural management agencies of such systems is capturing the local knowledge of resource specialists and field practitioners. This paper presents a knowledge-based approach for interpreting risks to soil from fire and logging equipment. In the next two sections, we summarize the scientific rationale for this application.

Effects of Wildfire on Forest Soils

Fuels have accumulated in many dry forests of the inland Northwest owing to human settlement and forest management activities (Agee 1998, Hessburg and Agee, 2003, Huff et al. 1995). Consequently, many recent fires in dry forests have been extensive, high-intensity, stand-replacing events (Agee 1998, Hessburg et al. 2005). Such events represent a significant change in fire regime, particularly in the ponderosa pine (*Pinus ponderosa* Dougl. ex Laws.), Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco), and grand fir (*Abies grandis* (Dougl. ex D. Don) Lindl.) zones (Franklin and Dyrness 1988), where relatively frequent, variably sized, low- and mixed-severity fires naturally occurred (Agee 1994, Hessburg et al. 2007a).

In recent wildfires, fuel consumption is often more complete than under historical fire regimes, and large fuel loads release considerable energy (Huff et al. 1995). This fire intensity and energy release can result in significant alterations to soil properties and processes, and hence to soil quality (Harvey et al. 1999). Increasingly, forest managers are treating landscapes to reduce fuel loads and potential impacts of wildfires on soils, forest resources, human life, and property. Constrained by funding limitations, managers of public lands must prioritize vegetation and fuel treatments. Thus, assessing risk to soils from severe fires may be an important consideration for setting treatment priorities.

Effects of fires on soils are variable, depending on fire intensity, fire duration, and amount of heat transferred (Harvey et al. 1994). Large accumulations of fine to coarse fuels on the soil surface increase risk that fires may consume nutrients and organic matter in aboveground and surface soil layers. This increases risk

Resiliency is the relative ability of a soil to recover from a stress.

Several studies of fire effects on soils were conducted in our study area, the Wenatchee-Okanogan National Forest.

of nutrient loss and decreased productivity. Fire effects on productivity may also depend on resiliency—the relative ability of a soil to recover from a stress. Shallow and moderately deep soils, in which moisture is limited for significant periods of time, and in which amounts of organic carbon and total nitrogen are relatively low, tend to display low resilience; on such soils, fire effects are likely to be more severe and long lasting (Meurisse 1999). Conversely, deep soils, in which moisture is less limited and organic carbon (C) and total nitrogen (N) are more plentiful, are less affected and more resilient.

Fire affects soil properties by altering organic matter on or near the surface (Neary et al. 2005). Soil physical properties dependent on organic matter, such as soil structure, porosity, and aggregation, are affected by heating during fire. Another important physical effect of fires is to reduce water infiltration because of repellency (DeBano 1991), which can contribute to soil erosion. The extent of fire-induced erosion also depends on fire severity, slope, storm size, and rainfall (Miller et al. 2003). For example, sediment yield from areas in a ponderosa pine forest after low-severity fire recovered to normal levels within 3 years, after a moderate-severity fire within 7 years, and after high-severity fire within 14 years (DeBano et al. 1996). First-year erosion rates after a wildfire in a mixed ponderosa pine/Douglas-fir forest in eastern Oregon were more than twice as great on 60-percent slopes as on 20-percent slopes (Robichaud and Brown 1999).

Soil chemical properties may also change with surface heating because organic C is volatilized at relatively low temperatures (280 °C, DeBano 1991). Nitrogen and sulfur are also sensitive because they volatilize between 200 and 375 °C, whereas potassium and phosphorus are moderately sensitive, volatilizing near 774 °C.

Soil micro-organisms may be killed directly by heating or be indirectly affected by organic matter alteration. Among the more sensitive micro-organisms are mycorrhizae (DeBano 1991, Neary et al. 2005); in fact, intense wildfire affects mycorrhizal community composition and structure more adversely than does clear-cutting (Visser and Parkinson 1999). Soil micro-organism activity and related nutrients are more concentrated and vulnerable near the soil surface where fire exclusion has created higher accumulation of organic debris than in the past when there were frequent fires (Harvey et al. 1999).

Several studies of fire effects on soils were conducted in our study area, the Wenatchee-Okanogan National Forest. For example, Helvey et al. (1985) reported large increases in stream sediments 2 years after high-severity fires in the Entiat drainage in 1970. They concluded that most sediment was from debris torrents after an intense rainfall on heavy snowpack in 1972, and from dry ravel on steep slopes near streams. After those same fires in the Entiat Watershed, Grier (1975) measured nutrient distribution in and leaching from soils that averaged 2 m depth and contained strata of ash and pumice ejecta from Glacier Peak. Large nutrient losses occurred from volatilization during the fire; other mineralized cations leached rapidly into the soil, where most were retained. Grier reported that only 3 percent of the N in the original forest floor remained after the fire, that N of the A1-horizon was reduced by one-third, and that a heavy residue of fuel ash on the soil surface initially contained high concentrations of base cations, much of which leached into the soil after rain and snowmelt. With more intense rains or less porous soils, these nutrients would be more susceptible to loss in runoff.

Baird et al. (1999) examined nutrient pools in soil and aboveground debris in ponderosa pine/Douglas-fir forest and lodgepole pine (*Pinus contorta* Dougl. ex Loud.)/Engelmann spruce (*Picea engelmannii* Parry ex. Engelm.) forests severely burned in 1994. In both forest types, fire initially reduced total C in the forest floor by 90 percent and total N by 95 percent. One year after the fire, soil C and N in the mineral soil remained reduced by 30 and 46 percent, respectively.

Effects of Logging Equipment on Forest Soils

The National Forest Management Act of 1976 instructs managers to avoid actions that significantly and permanently reduce the productive capacity of forest soils (USDA Forest Service 1983). Two key questions emerge from this instruction: What types, severities, and extents of soil disturbance significantly reduce soil productivity? How long must the reduction in capacity persist before it is considered permanent? Although tree growth is a common measure of soil productivity (Powers et al. 1999), reduced tree growth after disturbance may or may not persist.

The National Forest Management Act of 1976 instructs managers to avoid actions that significantly and permanently reduce the productive capacity of forest soils.

Soil disturbances caused by logging equipment include compaction, churning (incorporating organic debris), topsoil removal and displacement, and topsoil mixing with subsoil. For example, compaction and churning reduce amount and continuity of macropore space, and thereby reduce exchange of gas and moisture. Reductions in volume and continuity of large pores also reduce infiltration rates (Greacen and Sands 1980), slow saturated water flux, reduce gaseous flux (Grable 1971), increase thermal conductivity and diffusivity (Willis and Raney 1971), and increase soil resistance to penetration (Sands et al. 1979).

Because soils differ in various properties, they differ both in their initial resistance to these impacts and subsequent rate of recovery. Differences in soil properties are used by soil scientists to predict or to make interpretations about the hazard or likelihood of these types of soil disturbance occurring when heavy equipment is used. Such interpretations imply consequences for soil functions, and by logical extension, consequences for plant growth. In fact, consequences for plant growth also depend on interactions with climate and other factors.

Compared to visual and measured effects on soil properties, consequences of soil disturbance to subsequent tree growth are not as well predicted, researched, and experimentally controlled (Greacen and Sands 1980, Miller and Anderson 2002, Wronski and Murphy 1994). For example, trees planted on skid trails and landings are subjected to the most severely disturbed soils, yet these altered soil properties do not always result in poorer tree growth or survival (Firth and Murphy 1989, Greacen and Sands 1980, Miller et al. 1996, Senyk and Craigdallie 1997). In some coarse-textured soils, seedling performance can be better on compacted than on undisturbed soil because more moisture is retained in the smaller pores created by compaction (Gomez et al. 2002). Site-to-site differences in climatic stress also weaken generalizations about tree performance on disturbed soil.

Among inland Northwest forests, we found data for 20 locations for which tree growth was measured on logging-disturbed and nondisturbed soils: three locations in northern Idaho (Clayton et al. 1987); one location near Bend, Oregon (Cochran and Brock 1985); and one location each near Priest River, Idaho, and Diamond Lake Ranger District, Oregon (Page-Dumroese, personal communication[1]); one location near Headquarters, Idaho (Roche 1997); 12 locations in the Blue Mountains, Oregon (Geist et al. 2008); and one location on the Ochoco National Forest, Oregon (Froehlich et al. 1979). Based on site characteristics and tree response at these locations, Miller and Anderson (2005) calibrated a model to assign risk to tree growth after heavy equipment usage.

Evaluating Consequences of Wildfire and Logging Equipment Impacts on Soils

The Ecosystem Management Decision Support system integrates logic-based modeling into the geographic information system environment.

In this study, we used the Ecosystem Management Decision Support (EMDS) system (Reynolds et al. 2003) to evaluate anticipated risks to soils associated with moderate to severe wildfire and with heavy equipment used for harvesting and site preparation. The EMDS is an extension to ArcMap™ (Environmental Systems Research Institute, Redlands, CA) that integrates logic-based modeling into the geographic information system (GIS) environment. Since 1997, this modeling system has been used around the world for a variety of applications in natural resource management. For example, applications of EMDS in the Western United States include decision support for severe wildfire danger evaluation and treatment planning in central Utah (Hessburg et al. 2007b), landscape evaluation and restoration planning in eastern Washington (Reynolds and Hessburg 2005), biodiversity conservation in the Sierra Nevada (White et al. 2005), watershed assessment in

[1] D. Page-Dumroese. 2004. Personal communication. Research soil scientist. Rocky Mountain Research Station, 1221 South Main, Moscow, ID 83843.

northern California (Bleier et al. 2003), landscape-change analysis in eastern Washington (Hessburg et al. 2004), and watershed monitoring of the Northwest Plan Aquatic Conservation Strategy (Reeves et al. 2003).

In addition, PBS Engineering and Environmental (2003) developed an EMDS application to evaluate wildfire risk to soils that encapsulated many of the considerations discussed above. Here, we revise that PBS application to allow easier updating of key data elements such as fire regime and fuel condition class, and add an evaluation of risk associated with using logging equipment, based on an equipment-use model developed by Miller and Anderson (2005). Similar to the PBS application, the equipment-use model encapsulates many considerations presented above.

In the remaining text, we (1) describe logic models used to evaluate risks associated with wildfire and logging equipment, (2) present results for an example soil survey area, and (3) discuss considerations for model validation and for extending the current model to incorporate other threats.

Materials and Methods

Study Area

The study area is located within the Okanogan-Wenatchee National Forest. Soils within the forest are dominantly Andisols, Inceptisols, and Alfisols with cryic, frigid, and mesic temperature regimes and a xeric moisture regime. Spodosols occur at higher elevations. We evaluated soil risks in all soil polygons classified as forest land within an area of about 888 000 ha (fig. 1). All forested soils in this area are influenced by or are dominantly from volcanic ash, cinders, and pumice. Volcanic ash and tephra deposits are common on or near the mineral surface of most forested soils throughout the interior Columbia River basin (ICRB). These materials, originating from Mount Mazama and Glacier Peak eruptions, impart unique properties that influence vegetation communities of the ICRB (Harvey et al. 1994, Meurisse 1987).

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Great variety and complexity of soil properties and external features exist throughout the study area. For purposes of illustration, we present an example that is limited to the Okanogan East soil survey area (fig. 1). Within this example area of about 69 438 ha, soils are forming in volcanic ash over glacial till or granitic bedrock and are moderately deep to very deep (50 cm or more). Most soils are on slopes less than 45 percent, and are distributed across xeric moisture regimes and frigid to mesic temperature regimes. Soil textures are mostly fine sandy loams, loams, and silt loams with coarse fragment (>2 mm) content ranging from few to more than 35 percent. Organic matter content in the top 30 to 40 cm usually ranges from 1.5 to 3 percent by weight.

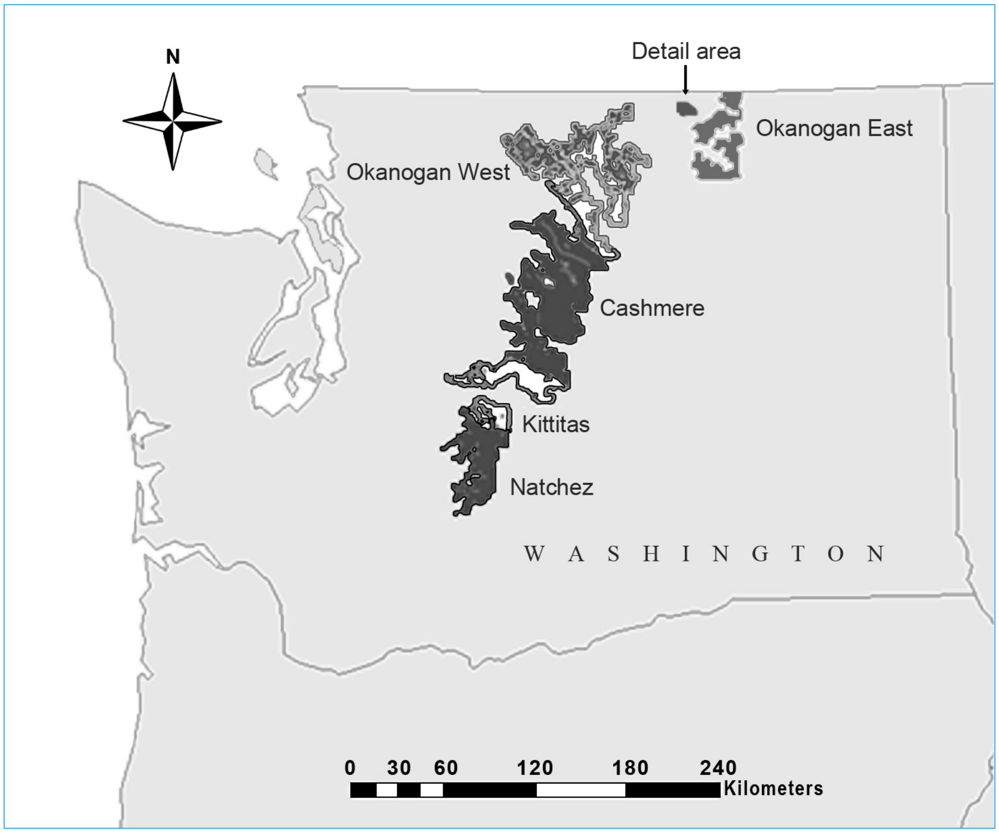

Figure 1—General location of project area in eastern Washington. Labeled features are soil survey areas on the Okanogan-Wenatchee National Forest. Results are presented for the Okanogan East unit. The feature labeled "Detail area" indicates the portion of Okanogan East displayed in figure 6.

Logic Models

Logic models for evaluating risk to soils from severe wildfire (fig. 2) and logging equipment (fig. 3) were implemented with the NetWeaver Developer system (Miller and Saunders 2002). A NetWeaver model represents an evaluation as a network of topics, each of which evaluates the strength-of-evidence for a proposition associated with the topic. The two logic models (figs. 2 and 3) are presented here in reduced form, in which three logic operators (and, or, union) have been omitted for simplicity.

Elementary topics (those occurring at the lowest level of the network, tables 1 and 2), evaluate observed data (tables 3 and 4) against functions (hereafter, membership functions) that map the observed value into a measure of strength-of-evidence for the elementary topic. Evidence from elementary topics is combined by using logic operators to evaluate higher order topics that depend on those elementary topics. If one thinks of a higher order topic as testing a conclusion, then the propositions of its elementary topics represent its premises. For example, the two elementary topics, fire hazard and soil resilience, represent premises of the higher-order topic, nutrients volatilized (fig. 2).

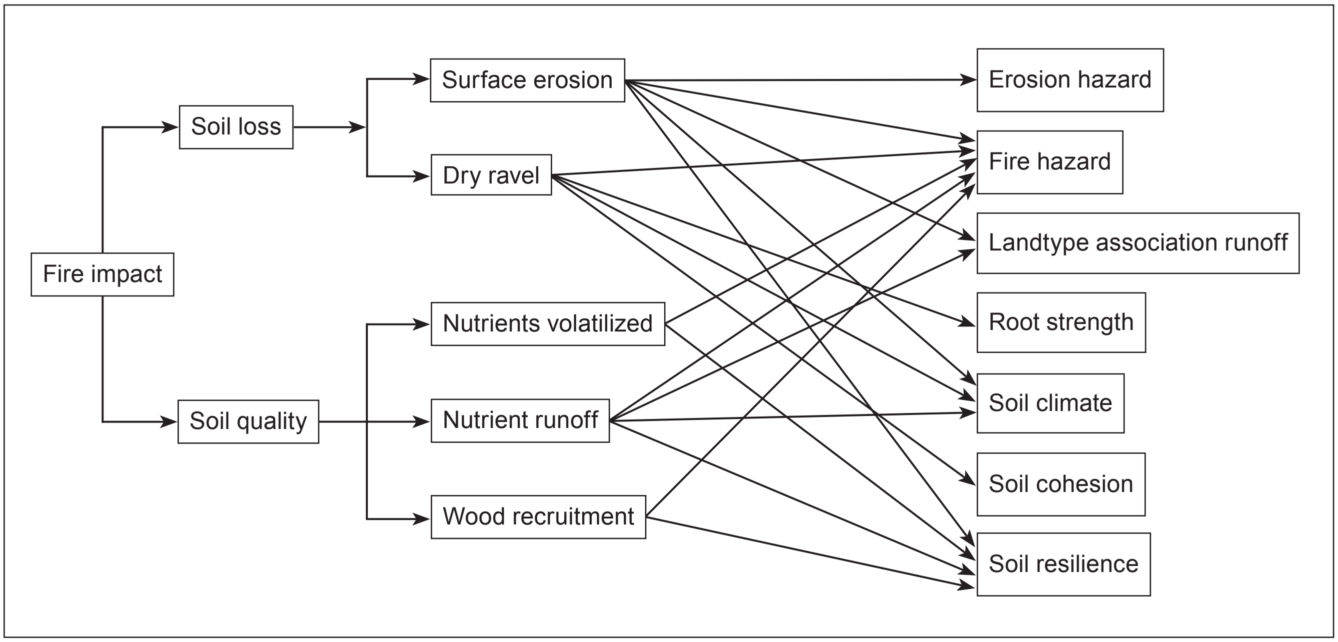

Figure 2—Logic tree for risk to soils from moderate to severe wildfire. Each topic evaluates a proposition (table 1). Topics on the far right are elementary topics and evaluate data. Elementary topics are indicated in bold in table 1. Data requirements for each elementary topic are listed in table 1 and defined in table 3.

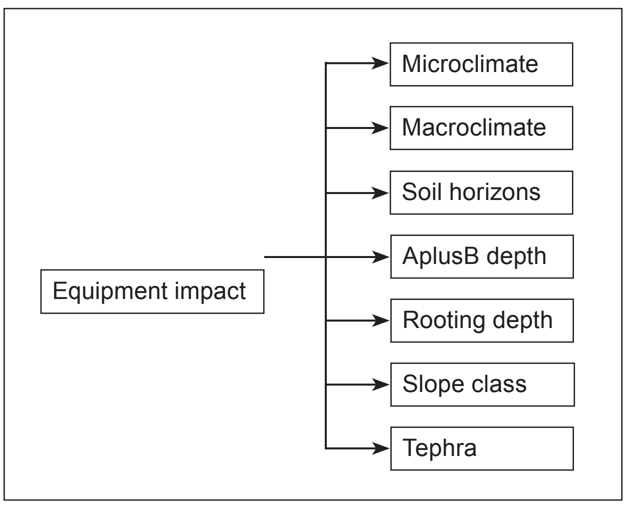

Figure 3—Logic tree for risk to soils from ground-based equipment. Topics on the far right are elementary topics that evaluate data. Elementary topics are indicated in bold in table 2. Data requirements for each elementary topic are listed in table 2 and defined in table 4.

Higher order topics may themselves serve as premises of still higher order topics. So, for example, the topics surface erosion and dry ravel are premises of the soil loss topic. The complete logic structures for wildfire risk (fig. 2) and logging equipment risk (fig. 3) can thus each be construed as a formal logical argument leading to a conclusion about risk from wilfire or logging equipment. Although detailed specifications of elementary topics have been omitted for brevity, the complete model specification may be downloaded from ftp://ftp2.fs.fed.us/incoming/pnw/CFSL/Reynolds/soil%20risk/soilImpact.nw.

Higher order topics may themselves serve as premises of still higher order topics.

Table 1—Logic topics for risk of soil impacts from moderate to severe wildfire[a]

Topic[b]	Proposition	Data inputs[c]
Dry ravel	Soil lost to dry ravel is low.	
Erosion hazard	Sheet and rill erosion are low.	ehrSoil
Fire hazard	Vegetation cover on slopes remains good.	fireReg fcc
Fire impact	Risk of soil degradation is low.	
Landtype association (LTA) runoff	Runoff associated with landtype association is low.	**slopeClass** hydro
Nutrient runoff	Ash loss (from burned organic matter) with runoff is low.	
Nutrient volatilization	Loss of soil nutrients and organic matter is low.	
Root strength	Root strength is not impaired.	**slopeClass** aspect rtst
Soil climate	Soil climate is mild.	**slopeClass** aspect climt
Soil cohesion	Soil cohesiveness is not impaired.	**slopClass** cohe
Soil loss	Soil loss owing to physical removal from the site is low.	
Soil quality	Risk to soil quality from biochemical effects is low.	
Soil resilience	Soil resilience is high.	slopeClass aspect resil
Surface erosion	Loss of soil to sheet and rill erosion is low.	
Wood recruitment	Recruitment of coarse woody material is high.	

[a] The structure of the logic model is displayed in figure 2.
[b] Topics displayed in bold text are elementary topics in figure 2.
[c] Only elementary topics evaluate data. Data elements listed in this column are defined in table 2. Data elements displayed in bold indicate data used to switch the logic path according to context.

Table 2—Logic topics for risk of reduced tree growth after worst-case equipment operations[a]

Topic[b]	Proposition	Data inputs[c]
AplusB depth	Thickness of A and B horizons indicates low risk.	depthSoil
Equipment impact	Thickness and tephra size indicate low risk.	**tephraPres**
Macroclimate	Macroclimate is mild, indicating low risk.	pvt
Microclimate	Microclimate is mild, indicating low risk.	aspect slopeClass
Rooting depth	Deep depth of fine roots indicates low risk.	depthRoot
Soil horizons	Characteristics of soil horizons indicate low risk.	**depthA** depthSoil fragClassA fragClassB **textureA** **textureB**
Slope class	Slope of soil unit does not contribute to risk.	slopeClass
Tephra	Condition of soil tephra indicates low risk.	**tephraPres**

[a] The structure of the logic model is displayed in figure 3.
[b] Topics displayed in bold text are elementary topics in figure 3.
[c] Only elementary topics evaluate data. Data elements listed in this column are defined in table 4.

Table 3—Definition of data elements used by the logic model to assess wildfire impact[a]

Data input	Definition	Source
aspect	Indicator for north versus south slopes.	LCIT[b]
climt	An indicator for rate of vegetation recovery following wildfire, interpreted from seven broad vegetation groups associated with the soils.	NCSS[c]
cohe	Soil cohesion classified as low, moderate, or high, based on clay content of soil (< 18 percent, 18–35 percent, and >35 percent, respectively).	NASIS[d]
ehrSoil	Erosion hazard classified as low, moderate, high, or very high, based on inherent erodibility of the soil (Kw) and slope classes.	NASIS
fireReg	Modal fire regime of a soil map unit (polygon).	LCIT
frcc	Proportion of map unit with fire regime condition class rating > 1.	LCIT
hydro	Surface runoff potential classified as slow, moderate, or flashy, based on an interpretation of landtype association geomorphology, stream density and pattern, soil material, and slope.	LTAs[e]
resil	Soil resilience classified as low, moderate, or high, based on thickness of surface layer, soil depth, and organic matter content.	NASIS
rtst	Root strength classification, interpreted from seven broad vegetation groups associated with the soils.	NCSS
slopeClass	Classes 1–4 represent slope intervals of 15 percent from 0 to 60 percent slopes. Class 5 was assigned to slopes > 60 percent.	LCIT

[a] Definitions of data elements in table 1.
[b] Landscape and Climate Interactions Team (Forestry Sciences Laboratory, Pacific Northwest Research Station, USDA Forest Service, Wenatchee, WA).
[c] National Cooperative Soil Surveys.
[d] National Soil Information System.
[e] Landtype Associations of North Central Washington, preliminary report (1/12/2000).

Table 4—Definition of data elements used by the logic model to assess equipment risk[a]

Data input	Definition	Source
aspect	Indicator for north versus south slopes.	LCIT[b]
depthA	Depth of A (or AB) horizon (inches).	NASIS[c]
depthRoot	Depth of fine and very fine roots (inches) at which intensity is ≥ 6 roots in^{-2}.	NCSS[d]
depthSoil	Depth of A and B horizons (inches).	NASIS
fragClassA	Coarse fragments in A horizon classified as low (0–35 percent), moderate (36–60 percent), high (> 60 percent).	NASIS
fragClassB	Coarse fragments in B horizon classified as low (0–35 percent), moderate (36–60 percent), high (> 60 percent).	NASIS
pvt	Potential vegetation type.	LCIT
slopeClass	Slope of soil map unit classified into one of five classes (0–15, 16–30, 31–45, 46–60, > 60 percent).	LCIT
tephraPres	Thickness and type of tephra present (ash mantle, mixed ash-soil, mixed pumice-soil, pumice mantle, or none).	NASIS and NCSS
textureA	Texture of A (or AB) horizon classified as sandy, loamy, or clayey.	NASIS
textureB	Texture of B (or BC) horizon classified as sandy, loamy, or clayey.	NASIS

[a] Definitions of data elements in table 3.
[b] Landscape and Climate Interactions Team (Forestry Sciences Laboratory, Pacific Northwest Research Station, USDA Forest Service, Wenatchee, WA).
[c] National Soil Information System.
[d] National Cooperative Soil Surveys.

The original model considered the two components of risk: (1) hazard, and (2) consequences for subsequent tree growth.

Submodel for wildfire risk—
This model (fig. 2, tables 1 and 3) was adapted from a version designed by PBS Engineering and Environmental (2003) that provided the logic operators and membership functions. Changes to that original version include (1) allowing for aspect adjustment in the soil-climate topic, (2) revising the wildfire risk topic by replacing the forest cover type look-up table with one based on fire regime and fuel class (table 3), and (3) splitting the original 30–60 percent slope class interval into intervals of 30–45 and 45–60 percent.

Submodel for equipment risk—
The original model for logging equipment risk was implemented as a spreadsheet application by the third author. The model considered the two components of risk: (1) hazard, if rubber-tired skidders were used in unrestrained scheduling and access, and (2) consequences for subsequent tree growth over a range of climatic stress created by macro- and microclimate. Recognizing the wide variation among soils and their inherent characteristics, we assumed that potentially high-hazard equipment usage is mitigated by soil characteristics that resist initial compressive and shearing forces of heavy equipment; these include properties promoting rapid infiltration and percolation of water, and large content of coarse fragments in the top foot (0.305 m) or more of soil that enhance load-bearing capacity.

Soils having many characteristics that supported vigorous plant growth were assumed to be less affected by soil compaction or displacement than soils with few supportive characteristics.

In assessing consequences for tree growth, we used two major assumptions. First, each soil was considered like a bank account; small withdrawals from a deep, fertile soil account had small effects, and conversely, large withdrawals from a shallow, infertile soil account had large consequences. In short, soils having many characteristics that supported vigorous plant growth were assumed to be less affected by soil compaction or displacement than soils with few supportive characteristics. For example, the productivity of soils with thick volcanic ash or pumice mantles, or thick A- or AC-horizons were assumed to be less likely to lose productive capacity than those with shallow tephra mantles or topsoils. Further, soils with few rock fragments were assumed to be less affected by soil degradation than shallow, rocky (skeletal) soils. The second assumption about consequences was that impacts on soil properties and processes were more likely to reduce subsequent tree growth in stressful climatic conditions than in favorable moisture and temperature environments. A priori, we assumed more risk of reduced vegetative growth in climatically harsher areas because: (1) vegetative growth is more dependent on soil conditions, which could be degraded by fire or heavy equipment and (2) more time may be needed for soil and vegetation to recover. Specific to the ICRB, equipment impacts to soils on north aspects (favorable microclimate) or in macroclimates with more favorable temperature and precipitation have least consequence for subsequent tree growth. Such assumptions based on general knowledge will remain necessary until long-term tree response to soil disturbance is reliably measured and reported for a wide range of soil types and climatic conditions.

The original spreadsheet application (Miller and Anderson 2005) was translated into a logic model to enable complementary evaluation with the fire-risk model. Although the two risk models were designed independently, they shared several data inputs and similar assumptions about soil and plant response to fire and equipment. Thus, the two original models were revised and integrated as submodels into a single model.

Impacts on soil properties and processes were more likely to reduce subsequent tree growth in stressful climatic conditions than in favorable moisture and temperature environments.

Examples of Logic Processing

Figures 2 and 3 and tables 1 through 4 provide a broad overview of model logic in terms of topics treated and data inputs required. A comprehensive description of the logic is beyond the scope of this paper, but full documentation can be found at ftp://ftp2.fs.fed.us/incoming/pnw/CFSL/Reynolds/soil%20risk/html.zip. However, here we illustrate some basic methods of logic processing using examples from the wildfire impact submodel. In the following, keep in mind that the logic is always testing for a condition (strength-of-evidence) of low risk.

Fire hazard is evaluated in terms of **fireReg** and **frcc** (tables 1 and 3). The contribution of **fireReg** (table 3) to fire hazard is evaluated in a lookup table, in which values of **fireReg** (1, 2, and 3, corresponding to low, moderate, and strong departure from historical fire regime, respectively) are assigned values for strength-of-evidence of 1, 0, and -1, respectively. The lookup table is a part of the model specification (ftp://ftp2.fs.fed.us/incoming/pnw/CFSL/Reynolds/soil%20risk/soilImpact.nw), and can be edited by users in NetWeaver. The contribution of **frcc** (table 3) to fire hazard is evaluated by a membership function, in which **frcc** = 0 evaluates to 1, **frcc** = 1 evaluates to -1, and intermediate values are interpolated by a linear function. The membership function for **frcc** also represents a model specification that can be edited by users if desired. The aggregate contribution of **fireReg** and **frcc** to fire hazard is represented by a union operator, which in NetWeaver semantics means that **fireReg** and **frcc** incrementally contribute to the overall prediction of fire hazard. An alternative way to think about the union operation is that its arguments (in this case **fireReg** and **frcc**) are additive and compensatory, meaning that a negative result on one argument can be offset by a positive result on the other.

Predictions of landtype association (LTA) runoff, root strength, and soil climate (table 1) are slightly more complex than the first two examples. In each of these three evaluations, one of four or five possible logic pathways is selected, depending on **slopeClass**. Each logic pathway corresponding to a **slopeClass** is then evaluated with a look-up table. For example, similar to **fireReg**, values for **hydro**, **rtst**, and **climt** (tables 1 and 3) are translated into strength-of-evidence, but now there are separate look-up tables depending on **slopeClass**. Predictions for root strength and soil climate are both slightly more complex than that for LTA runoff, because both include an additive adjustment for **slope aspect** (table 1), with south aspects evaluating as less favorable than north aspects.

Data Sources

For wildfire-risk evaluation (table 3)—

Four data inputs were provided by the Landscape and Climate Interactions Team (Pacific Northwest Research Station, Forestry Sciences Laboratory, Wenatchee, Washington); another six were developed from interpretations of National Soil Information System (NASIS) data by PBS Engineering and Environmental (2003). Seven vegetation groups were obtained from the woodland interpretations table and map unit descriptions associated with each soil survey. Erosion hazard was derived from the K-factor (from NASIS) and soil properties including percentage silt and very fine sand, percentage organic matter, soil structure, and permeability. The amount of rock in the soil modified the K-factor; for example, high rock content reduced the value of K. Runoff rates were derived from a map of Landtype Associations (USDA FS 2004) that were interpreted from stream density, geomorphology, soil materials, type of bedrock, and precipitation characteristics.

Soil resiliency was assigned to reflect the ability of the soil to recover its functions after disturbance. Low resilience values were assigned to shallow soils with thin surface layers and organic matter contents ≤ 1.5 percent, and high values were assigned to deep and very deep soils with thick surface layers and organic matter contents > 4 percent. Moderate values were assigned to intermediate cases. Root strength was derived from the seven broad vegetation groups. Ponderosa pine was considered low risk because of normally abundant, well-distributed roots, and a strong taproot. Grand fir and lodgepole pine were assigned high risk because of many fine roots near the surface that could be injured or killed by fire.

For the equipment risk evaluation—

Data sources included soil and site factors that were available as modal profile characteristics or descriptions from National Cooperative Soil Surveys (table 4).

We used potential vegetation types as surrogates for macroclimate.

We used potential vegetation types (PVT) as surrogates for macroclimate. A PVT indicates the most shade-tolerant conifer that would occur in the absence of disturbance (Arno et al. 1985, Steele and Geier-Hayes 1989). In a broad-scale assessment of the ICRB, 88 PVTs were mapped across the basin (Hann et al. 1997). Hessburg et al. (2000) combined this map of PVTs along with other GIS layers to develop their ecoregions. The additional layers represented mean annual temperature (°C), total annual precipitation (mm), and averaged annual daylight solar radiative flux (W/m^2) from modeled raster maps for the 1989 weather year, which was considered an average weather year (Thornton et al. 1997).

We used the PVT and climate data from the Hessburg et al. (2000) ecoregionalization to calculate the percentage area of 30 forested PVTs in each of the precipitation, temperature, and solar radiation classes. For most PVTs, ≥ 60 percent of their area was associated with a single, combined precipitation-temperature-solar flux class; a few PVTs tolerated a wider range of solar flux values. Based on these classes, a climate value was assigned to each PVT in the equipment risk submodel.

Data Processing and Analysis

Most data for evaluating risk to soil from wildfire were assembled from the NASIS database and associated to soil polygons of the Okanogan-Wenatchee National Forest (PBS Engineering and Environmental 2003). Polygons not classified as commercial forest by Miller and Anderson (2005) were deleted from the analysis to simplify and focus interpretations for subsequent analysis. Data for evaluating risks from logging equipment were tabulated by soil type either as a single mapping unit or as a component within soil complexes that contained two or more soil types. At least 50 percent of the original polygons consisted of complexes with two or more soil types that were not mapped individually. For each complex, we assigned the risk rating of the most extensive component (soil type). In most complexes, this was also the highest risk component, so our ratings for equipment may have a conservative bias. To produce more environmentally homogeneous polygons, soil polygon delineations were refined by intersecting that soil map with a map of slope and aspect (north versus south) polygons derived from a digital elevation model. With this refinement, we assessed those portions of the original soil polygon that had least- vs. most-favorable microclimate for soil development, and soil recovery and tree growth after equipment usage.

At least 50 percent of the original polygons consisted of complexes with two or more soil types.

Results

Of the 69 438 ha evaluated in the Okanogan East soil survey area, almost all measures of strength-of-evidence for low wildfire impact fell within the range of -0.6 to 0.2 (fig. 4). Note that the potential range lies between -1 (weak strength-of-evidence) and +1 (strong evidence). Consequently, the five intervals on the abscissa (fig. 4) can be interpreted as classes corresponding to very high, high, moderate, low, and very low risk associated with wildfire, progressing from left to right. Assuming the very high and high risk classes to be generally indicative of wildfire sensitivity, 21 196 ha

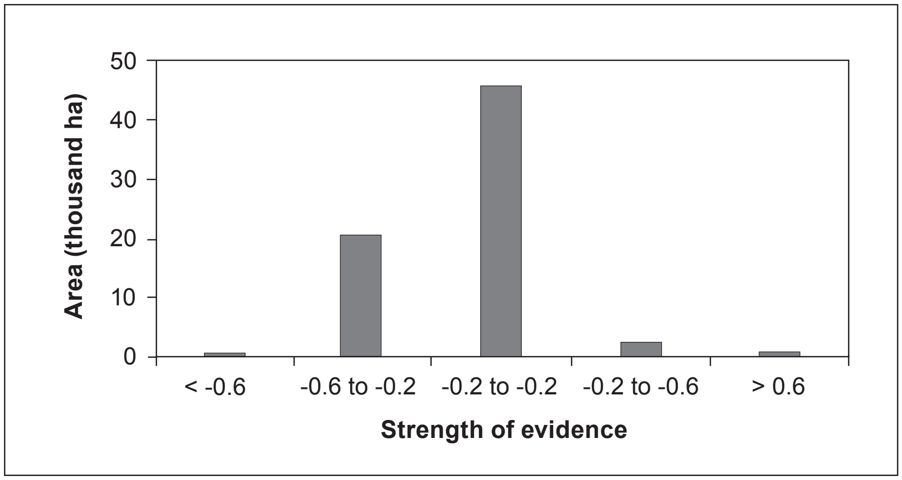

Figure 4—Area (ha) of expected risk to soil quality from wildfire owing to nutrient volatilization, nutrient runoff, and reduced organic matter inputs from recruitment of woody debris. The five intervals on the x axis can be interpreted as risk classes corresponding to very high, high, moderate, low and very low risk, progressing from left to right.

(30.5 percent) can be considered sensitive to wildfire in the Okanogan East soil survey area.

The range of response in strength-of-evidence for low risk of logging equipment was similar (fig. 5). Following the same classification scheme for strength-of-evidence as above, 31 913 ha (46.0 percent) were predicted to be sensitive to reduced tree growth after worst-case (unmitigated) use of logging equipment. A modest proportion of soil polygons evaluated as relatively insensitive (risk classes low and very low) to logging equipment.

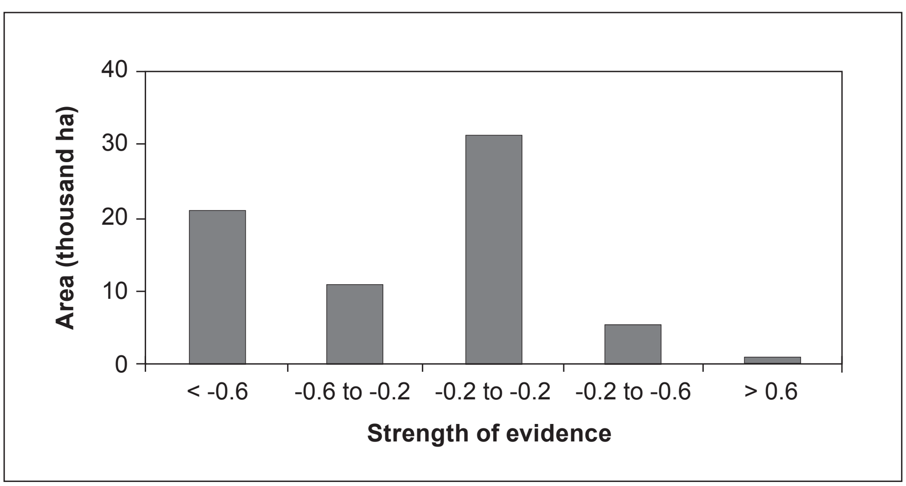

Figure 5—Area (ha) of expected impacts to tree growth from unmitigated equipment operations. The five intervals on the *x* axis can be interpreted as risk classes corresponding to very high, high, moderate, low and very low risk, progressing from left to right.

Beyond this simple aspatial summarization of results, there is the obvious question: "Where are the most sensitive soil polygons within the landscape of the East Okanogan soil survey area?" Because the analysis area contained 6,889 relatively fine-scale polygons, it was not feasible to present a readable map of the spatial dispersion of sensitive soils. To illustrate the power of spatial information, however, we focused on a small example area, indicated as "Detail area" in figure 1, which includes 656 soil polygons with forest cover. The two maps of soil polygons sensitive to wildfire (fig. 6A) and logging equipment (fig. 6B) appear remarkably similar; indeed the reader may need to carefully compare the two maps to be convinced that they are different. The degree of similarity in the two maps was not anticipated, especially considering that each is derived from a submodel that was developed mostly independent of the other. Although the two submodels share a few variables in common, most of their data inputs are distinctly different (see tables 1 and 2).

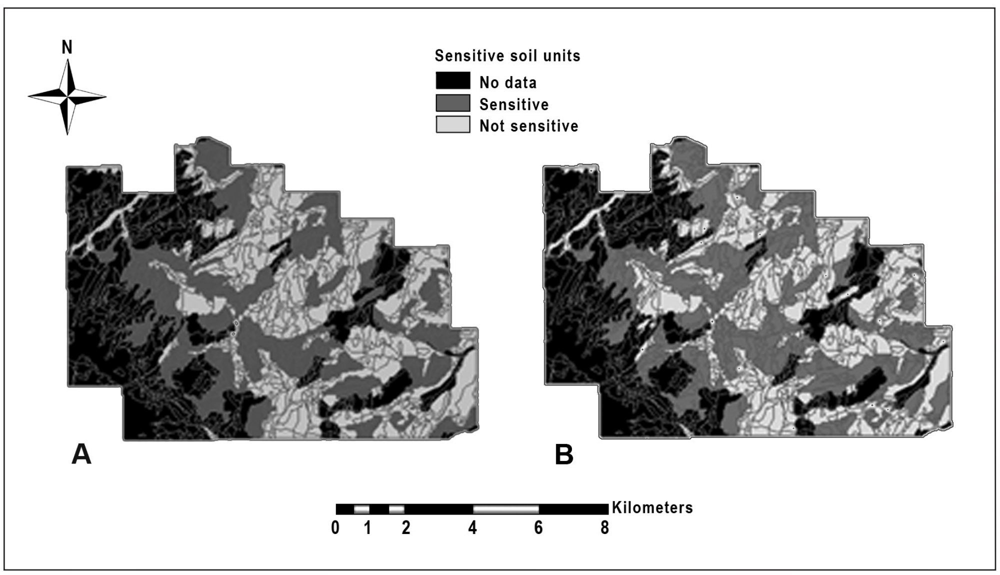

Figure 6—(A) Detail area from figure 1, indicating soil units sensitive to wildfire. (B) Detail area from figure 1, indicating soil units sensitive to ground-based equipment. A map unit was classified as sensitive if the strength-of-evidence for low impact was ≤ -0.2.

Discussion

Our decision-support application could help assess the environmental consequences of postwildfire rehabilitation and timber salvage as well as guide management of forest fuels (McCaffrey and Graham 2007). Several recently developed methods help managers evaluate prescribed burning and thinning options for reducing current and future fire hazard (for example, Johnson et al. 2007). However, risk of these prescriptions to soil productive capacity and subsequent tree growth was not considered, despite these productivity considerations being required by environmental impact assessments.

The majority of the Okanogan East analysis area is rated moderate risk for moderate and severe fires.

Risk Associated With Wildfire

The majority of the Okanogan East analysis area is rated moderate risk for moderate and severe fires (fig. 4). About 30 percent of the analysis area is high or very high risk. Only a minor amount is rated low or very low risk. Although some soils have total depths >50 cm to >150 cm, 84 percent of the example area has soils with <50 cm of developed soil (A- and B- horizons) (table 5). Generally, soils in this area have a surface layer of volcanic ash that is about 20- to >35-cm thick. Such soils often have organic matter contents >1.5 percent in the surface layer. Also, more than 70 percent of the area is on slopes of ≤30 percent (table 5). These properties contribute to moderately resilient soils, and to moderate or lower erosion hazards. When these favorable soil conditions are combined with current fire regime and fuel condition classes that are within historical ranges or are only moderately altered from historical conditions, there is a strong likelihood that fire risk would be moderate or low, as our results demonstrate.

More than 60 percent of the area has a southerly aspect (90 to 270 degrees, table 5). Where soils are shallow (<50 cm depth), have high coarse-fragment contents, and are on slopes exceeding 30 percent, this combination of factors contributes to high and very high risk for moderate and severe fires. This is especially true if they also happen to have fire regime and fuel condition classes that are moderately or significantly altered from historical ranges.

Table 5—Distribution of soil polygons and area, by aspect, slope, and soil depth

Aspect	Slope	Thickness of A+B horizons	Polygons[a]	Area[b]
	Percent	*Centimeters*	*Percent*	*Percent*
North	≤ 30	≤ 50	20.32	18.79
		> 50	4.72	5.04
	30–60	≤ 50	8.52	8.52
		> 50	1.74	2.31
	> 60	≤ 50	0.44	0.59
		> 50	0.19	0.17
South	≤ 30	≤ 50	39.63	42.29
		> 50	6.47	6.96
	30–60	≤ 50	14.33	12.72
		> 50	2.64	1.94
	> 60	≤ 50	0.45	0.30
		> 50	0.55	0.39
Total			100.00	100.00

[a] Total count of soil polygons in the study area was 6,889.
[b] Total study area was 69 438 ha.

Risk Associated With Logging Equipment

About 70 percent of the analysis area is on slopes ≤30 percent and therefore accessible for ground-based logging equipment. Yet nearly half of the example area is rated high or very high risk for reduced growth after unmitigated use of logging equipment (fig. 5). Risk ratings for unmitigated or "worst-case" use of logging equipment can alert users about the relative need for mitigative measures, such as avoiding use of rubber-tired skidders, scheduling logging when soils are dry or covered with deep snow, stopping equipment operations where soil is wet or very moist, placing a protective layer of logging slash before trafficking, designating skid trails or optimizing the yarding pattern. Risk-rating models should also help to implement project plans and assist in addressing soil issues during the NEPA (National Environmental Policy Act) process.

About 70 percent of the analysis area is on slopes ≤30 percent and therefore accessible for ground-based logging equipment.

As previously stated, there is considerable overlap of risk to soil functions from fire and logging equipment in this area. Several factors could cause this overlap. Nearly two-thirds of the example area has south aspect (table 5), which indicates less favorable microclimate for soil development and plant growth and greater fire hazard and consequences than on north aspects. Depth of soil development, which we defined as the combined depths of the A- or AC- plus the B-horizon, is 50 cm or less on about 84 percent of the area. Based on propositions and premises of our modeling, these characteristics support an inference of high risk for both severe fire and unmitigated use of heavy equipment. Although we gauged consequences simply in terms of potential impacts on growth of commercial tree species, we assume that most other plants or soil organisms would respond in a similar direction and magnitude.

Risk ratings for unmitigated or "worst-case" use of logging equipment can alert users about the relative need for mitigative measures.

A Recent Application of Our Model

We applied our model after the 2006 Tripod Fire that burned more than 70 800 ha (175,000 acres) near Winthrop, Washington. The model displayed several classes of risk, by contrasting colors, on two separate maps. One map provided an assessment of risk for erosion and loss of soil productivity within the burned area; the other map identified estimated risk of reduced tree growth after salvage logging with rubber-tired skidders and without mitigative practices to reduce impacts.

Soil-Climate Interaction Affects Vegetative Response to Disturbance

We assume that risk of growth reductions should differ by climatic areas or ecoregions. A priori, we assume more risk to vegetative growth in climatically harsher areas because (1) longer periods may be needed for soil and vegetation to recover

We assume that risk of growth reductions should differ by climatic areas or ecoregions, with more risk to vegetative growth in climatically harsher areas.

and (2) vegetative growth is more dependent on soil conditions, which could be degraded by heavy equipment. Important differences in climate exist within and among soil survey areas, as indicated by differences in soil temperature and moisture classes that are used to classify soils taxonomically. Although soil taxonomic information (e.g., xeric vs. udic moisture or cryic vs. frigid temperatures) could be added to our database, we did not do so because of resource limitations. Perhaps climatic differences are sufficiently captured by differences in modal soil characteristics, e.g., shallow, low-fertility soils in which harsh climate slows natural soil development and resilience after disturbance, and by the potential vegetation types that we used as a surrogate for gross climate.

Our ratings are based on modal characteristics within soil polygons. Most polygons include two or more taxonomically different soil series or types. In some polygons, taxonomic differences may have little significance for predicting the consequence of interest (erosion, dry ravel, resilience, tree response). Before using risk ratings or other interpretations derived from soil surveys, one should verify by field inspection the location and actual characteristics of these taxonomically different soils. Note also that our stratifying the original soil polygons by slope-aspect classes was intended to identify strata of differing microclimate that can affect soil development and tree growth response.

Practical Issues

The EMDS application for evaluation of soil risks from wildfire and use of heavy equipment requires Microsoft Windows 2000® or later, ArcGIS 9.0®, and the EMDS 3.1[2] extension to ArcMap (http://www.institute.redlands.edu/emds/). The ease with which this decision-support technology can be transferred to potential users is context dependent. Forest managers on the Okanogan-Wenatchee National Forest can easily learn to use this application with a few training hours. Additionally, most data fields rarely need changing, but a few will need to be updated sometime in the next few years (for example, fire-regime condition class, table 2). Updating data fields will require a few days of geoprocessing by a GIS technical specialist.

Managers on the forest also may want to modify components of the logic model as knowledge or data quality increase. Training in the design of logic models requires about 2 days, thus representing a slightly more substantial effort to transfer technology and improve predictions based on new information. Although this application of EMDS can be extended to new geographic areas within the ICRB, the effort to do this is substantial, because of the need to build databases and perform

[2] The use of trade or firm names in this publication is for reader information and does not imply endorsement by the U.S. Department of Agriculture of any product or service.

the required geoprocessing. Fortunately, the existing application provides a detailed, documented template for new applications because the logic model already exists, and data requirements are defined and can be readily adapted.

Integrating Knowledge and Communicating Results

Applications that translate the reasoning, knowledge, and field experiences of subject-matter experts into formally specified logic models serve several important purposes in resource management. First, they make large, abstract, and relatively complex problems solvable by nonexperts. We note that technical staff with high levels of expertise in specific subject-matter areas are often in short supply. Second, logic models provide a means of capturing relatively rare knowledge, and making it available as institutional knowledge that can be readily shared. Third, in contrast to many modeling applications that operate as "black boxes," logic-based systems provide a documented interface to a solution that transparently shows the derivation of model outputs. This is true of the logic component in EMDS, although space does permit us to illustrate this point. Access to intuitive explanation of results is important to model users who need to understand the basis for model results, and to detect when models are misbehaving. Particularly for land managers, this capacity for intuitive explanation also provides a basis for effective communication with partners. Continuing assessments of watershed conditions in areas covered by the Northwest Forest Plan illustrate the methods and benefits of an interactive approach (Gallo et al. 2005).

Logic-based systems provide a documented interface to a solution that transparently shows the derivation of model outputs.

A Related Tool

Detailed soil surveys are unavailable for parts of the interior Columbia Basin. This potentially limits the utility of our application. Recognizing this limitation, we developed a companion application that interactively prompts the user for data rather than batch-processing database tables. In contrast to our GIS application that was designed to handle tens of thousands of soil map records, the interactive version was designed to evaluate individual sites in the field when used by field personnel equipped with a laptop PC. The interactive version is available upon request to the first author.

The interactive version of our application was designed to evaluate individual sites in the field when used by field personnel equipped with a laptop PC.

Extending the Model

Another virtue of model implementation in EMDS is that the current soil-risk application can be extended to include additional topics such as of the likelihood of a severe wildfire (as opposed to risk of impacts from a wildfire) or likelihood of introductions of exotic species. Hessburg et al. (2007b) have previously presented an EMDS application for evaluation of severe wildfire danger based on national data layers delivered by the LANDFIRE program (http://www.landfire.gov), and this latter model could be integrated with the present application with relative ease. Similarly, a new submodel relating to invasive species could be developed based on current research supported by the Western Wildland Environmental Threat Assessment Center (Prineville, Oregon). There is a clear need for models that simultaneously can evaluate multiple, interacting threats. Moreover, significant economies in application development can be gained from common data requirements across model components.

The current model could also be extended to provide priorities for various management activities across soil polygons. For example, the decision-model component of EMDS can be used to rate soil polygons for remedial treatments after wildfire—based on expected impacts from wildfire as well as practical considerations related to feasibility and effectiveness of restoration measures (Reynolds et al. 2003)—or for timber salvage using ground-based equipment without mitigative practices.

Model validation is a more demanding task that requires model predictions to be confirmed with new, independent data.

Verification and Validation

An important part of model development is verifying that the model accurately represents observations of a subject-matter expert. This is similar to goodness-of-fit testing in regression analysis. Two authors are the subject-matter experts for the risk submodels (figs. 2 and 3); both have carefully reviewed a representative set of polygons to verify model performance.

In contrast, model validation is a more demanding task that requires model predictions to be confirmed with new, independent data. The submodel for risk of impacts from wildfire was partially validated during initial development by PBS Engineering and Environmental (2003), but more extensive validation testing is warranted. The submodel for risk from equipment usage was not validated. Validation would entail measurement of tree growth after controlled or operationally created soil disturbances across a representative sample of soil types and climates.

Conclusions

Our risk-rating scheme can aid in prescribing, planning, and scheduling harvest and restoration activities. Ratings identify and locate sensitive areas where mitigative or restorative efforts could be focused to maximize benefits and minimize costs and ecological consequences.

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English Equivalents

When you know:	Multiply by:	To find:
Millimeters (mm)	0.0394	Inches
Centimeters (cm)	.394	Inches
Meters (m)	3.28	Feet
Hectares (ha)	2.47	Acres
Degrees Celsius (°C)	1.8 °C + 32	Degrees Fahrenheit

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