Applying Knowledge-Based Methods to Design and Implement an Air Quality Workshop

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ABSTRACT / In response to protection needs in class I wilderness areas, forest land managers of the USDA Forest Service must provide input to regulatory agencies regarding air pollutant impacts on air quality-related values. Regional workshops have been convened for land managers and scientists to discuss the aspects and extent of wilderness protection needs. Previous experience with a national workshop indicated that a document summarizing workshop discussions will have little operational utility. An alternative is to create a knowledge-based analytical system, in addition to the document, to aid land managers in assessing effects of air pollutants on wilderness. Knowledge-based methods were used to design and conduct regional workshops in the western United States. Extracting knowledge from a large number of workshop participants required careful planning of workshop discussions. Knowledge elicitation methods helped with this task. This knowledge-based approach appears to be effective for focusing group discussions and collecting knowledge from large groups of specialists.

The 1964 Wilderness Act gives the USDA Forest Service responsibility and authority to manage designated wilderness areas to preserve, protect, and enhance their wilderness character. Many wilderness areas within the nation's national forests contain ecosystems and resources that have the potential to become degraded by existing or future air pollution emissions. Air quality and air pollution protection for these areas have not been addressed directly by Wilderness Act legislation. However, protecting the earth and its community of life, and promoting, perpetuating, and, where necessary, restoring the wilderness character of the land have been promulgated. [1]

Congress, through the federal Clean Air Act of 1977[2] (CAA), as amended, gave federal land managers (FLMs) an affirmative responsibility to protect all those values possessed by a wilderness area that may be affected by changes in air quality. These air quality-related values (AQRVs) include visibility, odor, flora, fauna, geological resources, archaeological resources,

historical resources, cultural resources, soils, and water quality (Christian and Scruggs 1985). Protection of AQRVs is provided through the prevention of significant deterioration (PSD) provision of the legislation. PSD sections of the Clean Air Act provide a permitting program for certain new sources of air pollution. The purposes of PSD include preservation, protection, and enhancement of air quality in national wilderness areas and other areas with special national values or regional natural, recreational, scenic, or historic values.

Before construction approval, a proposed major emitting facility must apply for and receive a PSD permit from the appropriate air regulatory agency (usually a state agency or the US Environmental Protection Agency). In addition to certain other restrictions noted in the CAA,[3] any new or increased pollution source must not cause or contribute to adverse impacts of AQRVs in any class I wilderness.[4] The regulatory agency can deny a construction permit if the FLM can demonstrate that there will be an adverse impact to an AQRV in a class I area. The definition of "adverse impact" for an individual wilderness depends on the answers to three questions: (1) What are the specific

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wilderness components that should be protected? (2) To what degree should those specific wilderness components be protected? and (3) Will the proposed Facility result in concentrations or atmospheric deposition within wilderness areas that could cause established protection levels to be exceeded? The first two questions must be answered largely by FLMs in consultation with the public sector. The last question requires understanding and extrapolating scientific results to estimate potential effects of pollutant exposure on AQRVs.

Although legislation is in place to protect air quality in class I wilderness, there has been no mechanism for FLMs to evaluate the potential effects of air pollutant concentration and deposition in these areas. There are approximately 150 PSD applications each year for new or increased pollution sources that potentially affect class I areas (R. Fisher, personal communication). The Forest Service and other resource management agencies must review these applications and accompanying environmental impact statements and make recommendations to the permit-granting authority. This process has been extremely difficult because there has been no analytical procedure to provide scientific guidance for reviewers.

An initial step to provide this guidance was summarized in a Forest Service report, "A Screening Procedure to Evaluate Air Pollution Effects on Class I Wilderness Areas" (Fox and others 1989). This document describes a screening procedure for helping wilderness managers conduct adverse impact determinations as part of PSD permit applications. It includes the results of the Workshop on Air Pollution Effects on Wilderness, held 2–5 May 1988, at the Institute of Ecosystem Studies, Millbrook, New York. This workshop convened 40 participants, divided evenly among research scientists and Forest Service resource managers. The resulting publication reflects the divergent viewpoints of these groups. The document contains values of nitrogen deposition, sulfur deposition, and ozone concentration for which adverse impacts on terrestrial systems would be expected. It also includes values of nitrogen and sulfur deposition for which adverse impacts would be expected on aquatic systems with different hydrologic regimes and buffer capacity. These threshold, or screening, values were intended as guidelines for identifying pollutant deposition scenarios that were acceptable, unacceptable, or required more information before a decision on the permit application.

These screening values represent extensive scientific information but do not provide an operational tool for managers. The national screening procedure (Fox and others 1989) provides assistance for review of PSD permit applications only at a broad level of resolution for terrestrial and aquatic wilderness resources. It supplies little information relevant to a specific wilderness, unique resources within a wilderness, or individual plant and animal species. Although visibility is specifically mentioned as an AQRV in the CAA, there was no attempt to address that topic at the national workshop. Furthermore, the information collected on terrestrial and aquatic resources cannot be updated readily while in a published format. A similar approach is needed at a finer level of resolution to furnish guidance for review of PSD permits applications for specific wilderness and regions of the United States. In addition, it is desirable to furnish this guidance in a format that can be readily modified as prevailing pollutant levels change or as new scientific results emerge.

The Forest Service has taken this next step by scheduling workshops in each of its administrative regions to develop screening procedures appropriate for local application. A challenge for these workshops is to elicit the best available scientific information for air pollution effects on natural resources, integrate managerial concerns, and develop an analytically sound and efficient procedure that can be used for screening PSD permit applications. This must be accomplished with relatively little specific information on air pollution effects and wilderness characteristics in some cases.

Regional workshops are relatively expensive and time consuming, entail a great deal of planning, as well as post-workshop compilation of results, and, therefore, must be efficient and achieve the desired objectives. These objectives include: (1) identifying resource values, (2) evaluating pollutant impacts on those resources, and (3) determining protection levels for those values.

In this article we propose an approach to conducting these regional workshops using knowledge-based methods to elicit information and synthesize results. We also propose a subsequent knowledge-based analytical tool that can be used to screen future PSD permit applications. This article presents concepts and rationale used to structure elicitation of air pollutant issues at the workshop. An example of workshop results illustrates some of these conceptual ideas. Based on our experiences, we note some advantages and disadvantages of this approach and discuss future plans for our analytical tool.

Workshop Design

PSD Decision Making

Decision making, in general, can be viewed as consisting of three general components (von Winterfeldt and Edwards 1986): (1) identification of important fac-

tors that describe a problem, (2) analysis of the interactions of these factors in relation to alternatives or outcomes, and (3) selection of some criteria to follow in choosing among possible alternatives. Traditional decision analysis (von Winterfeldt and Edwards 1986), consists of a set of techniques for selecting among alternative decisions; these focus on the value, or utility, of alternatives and on the probabilities of events leading to those alternatives. Maximization of expected value or expected utility is the criterion most often used in decision analysis. FLMs, however, must make an exclusionary decision about a PSD permit application based on a possibly singular effect, that is, an adverse impact on a single AQRV might possibly lead the FLM to recommend permit denial. Maximized utility or maximized value are not easily applied criteria when f-aced with this type of decision because one single effect can completely overshadow other factors and, therefore, dominate the final decision.

It seems reasonable to divide the PSI) screening process into two parts based on prior experience with the national workshop and the three components of decision making listed above. One part contains the important factors necessary in PSD screening, how they are defined, measured, and monitored, and the criteria used to decide on a final permit application. This part includes components 1 and 3 above. The second part provides analytical techniques to assess potential effects on all AQRVs, given AQRV descriptions and current understanding about pollutant impacts. This part corresponds to component 2 above. These two parts are complementary; the first is represented by published documents (e.g., Peterson and others 1991a, Peterson and others 199 lb) and the second by a computerized analysis procedure. These items reside in the public domain and are available to anyone interested in scrutinizing the general process applied to permit application review and how the process was applied to any particular permit. As in any analysis, pencil and paper can be used to perform necessary steps of the process. However, such an approach is tedious, error prone, and time-consuming, and a computer-based analytical tool is more efficient.

We propose a more information oriented scheme that addresses how a particular permit might fail to satisfy class I area protection and the steps necessary for an applicant to satisfy PSD regulations. In this way the Forest Service, the permit applicant, and any interested third parties can easily understand where a permit stands in relation to desired protection. Future results of scientific research in the area of air quality and its environmental effects would normally cause frequent changes in a document that tried to capture this type of evolving information. In this methodology the processes of analysis and decision making have been separated and distinguished. Future changes in scientific understanding therefore can be reflected in the analysis system with no modification to the published document.

Rationale for a Knowledge-Based Approach

The objective of workshops for screening regional air quality was to provide a forum for managers and scientists to determine AQRVs and to describe air pollution impacts on them. Time constraints demanded, however, that this forum also circumscribe boundaries to direct conversation toward relevant topics and away from peripheral issues. For this reason, we developed a conceptual framework to govern group discussion. The structure is designed to be sufficiently flexible to allow participants to describe wilderness components and to establish realistic estimates of pollutant impacts, monitoring procedures, and decision criteria. The nature of the information collected from workshop participants (some of it, experienced-based judgment) and its incorporation in an analytic software tool suggested that we apply methods used for knowledge-based system development.

By identifying the type of subjective judgment needed for construction of an analysis system, we designed workshops to do the following: produce exactly the knowledge needed by that system, scrutinize the current state of knowledge about targeted discussion topics in air quality management, and obtain valuable workshop output for a published report. The first point, of course, is the inherent goal of knowledge elicitation. The second idea has been mentioned in the literature (e. g., Starfield and Bleloch 1986) as an ancillary benefit of knowledge-based system development but has not been exploited previously in the manner proposed here. Production of a workshop document is closely tied to the second idea and represents one of our primary objectives for the overall project.

One of the seminal ideas in the knowledge-based approach is a focus on knowledge—its acquisition, representation, and utilization, Knowledge is treated as an entity, separate from any algorithms used to apply it to specific problems. This concept provides a powerful mechanism for structuring workshops, in which the objective is to elicit knowledge about a relatively restricted subject area. Because the number of participants involved in discussions at such a meeting is large, satisfying workshop objectives within a limited timeframe requires a well-defined outline of discussion topics and desired results. The following section presents a conceptual basis for the structure of these workshops.

Conceptual Basis for Air Quality Workshops

Analyzing knowledge about a particular subject area helps one elucidate which knowledge is important, how the different pieces of knowledge are related to one another, and how that knowledge is applied to decision making or problem solving. These three elements constitute the stages of knowledge analysis and correspond to the components of decision making mentioned above. We refer to these as factor analysis, structure analysis, and strategy analysis, and describe them in more detail below.

Factor analysis. Factor analysis consists of several steps that describe the concepts, or factors, that are relevant to problems in a subject area. First, all factors must have a name to label them. This is not always as trivial as it may sound; some abstract concepts are difficult to enclose within a meaningful label (Benfer and Furbee 1989). Most people encounter some degree of difficulty with the task of creating lists of factors ab initio. We were fortunate to have a fairly well-established list of terms that were understood by most participants (e.g., AQRVs, sensitive receptors, pollutant loadings). These terms are really classes, and participants are left to define specific instances of these classes (e.g., subalpine forest as an example of an AQRV) for particular wilderness areas. Second, each term must have a description to clearly distinguish it from other terms and to minimize any ambiguity. Third, possible values that a factor may assume also need to be identified. If the values are qualitative rather than quantitative, then there also should be definitions for those qualitative values (e.g., significant deterioration of native fish might be defined as: a measurable reduction in density of fish populations). These three factor analysis steps create a sort of vocabulary with which statements about air quality can be generated.

Structure analysis. A list of factors without any cohesive structure conveys little knowledge about a subject area, just as a vocabulary without any grammar results in poorly formed sentences. Structure analysis produces a framework that arranges the three factor analysis steps into highly organized relationships. As a result, the one-dimensionality of lists from factor analysis is transformed into a deeper, higher dimensional structure. Organizing factors by defining interrelationships permits the construction of powerful ideas. These ideas are represented by associations between factors, associations that allow one to hypothesize a statement about a particular factor given some knowledge about other factor(s). The result of this organization is an operational description of how to use the factors formulated in the factor analysis stage.

Strategy analysis. To continue with the linguistic analogy, strategy analysis deals with rules of composition. That is, under what conditions does one use particular factors (vocabulary elements) and their interrelationships (grammar) to solve particular problems (compose meaningful prose) ? Strategy analysis deals with the utilization of factor and structure knowledge and is essentially knowledge about knowledge, or "metaknowledge." Strategies are most often used to focus a search for solutions (therefore reducing effort) or to select between particular alternative solutions during the final decision steps.

Strawman

These three knowledge analysis ideas were incorporated into the design of a workshop "strawman," which provided guidance for technical discussions. A strawman is an object (in our case a discussion outline) erected to provide a target for criticism. As such, it becomes, in reality, an artificial construct that is unimportant in itself. Rather it is designed to stimulate thoughts and/or actions by a critical audience. By creating such a foil we hoped to provide a relatively unrestricted structure for workshop conduct, Any meaningful outcomes from its use do not reside in the strawman, but in the discussions and ideas it generates.

The general topics to be addressed by workshop participants were threefold; these are reiterated in the left-hand portion of Figure 1. There is a one-to-one correspondence between these three topics and the aforementioned knowledge analysis components. Factor analysis pertinent to PSD screening include: AQRVs and their components (sensitive receptors) and air pollutants specified in the CAA. Structure analysis addresses the relationship of sensitive receptor health to associated pollutant exposure levels. Finally, strategy analysis produces decision criteria for applying the knowledge about factors and exposure-effect relationships. We now examine more closely the details of factor, structure, and strategy knowledge depicted on the right-hand side of Figure 1 and how they were integrated into the strawman.

Step 1: Define AQRVs. An extremely critical aspect of the effort at these workshops was for managers and scientists to identify exactly which AQRVs are present in each wilderness. Before each workshop AQRV descriptions were written by FLMs on the basis of general national guidelines. While these guidelines proved useful, they omitted some important attributes of AQRVs that might confuse an AQRV's response to pollutants. Consequently, we extended the national guidelines by defining AQRVs in the following way:
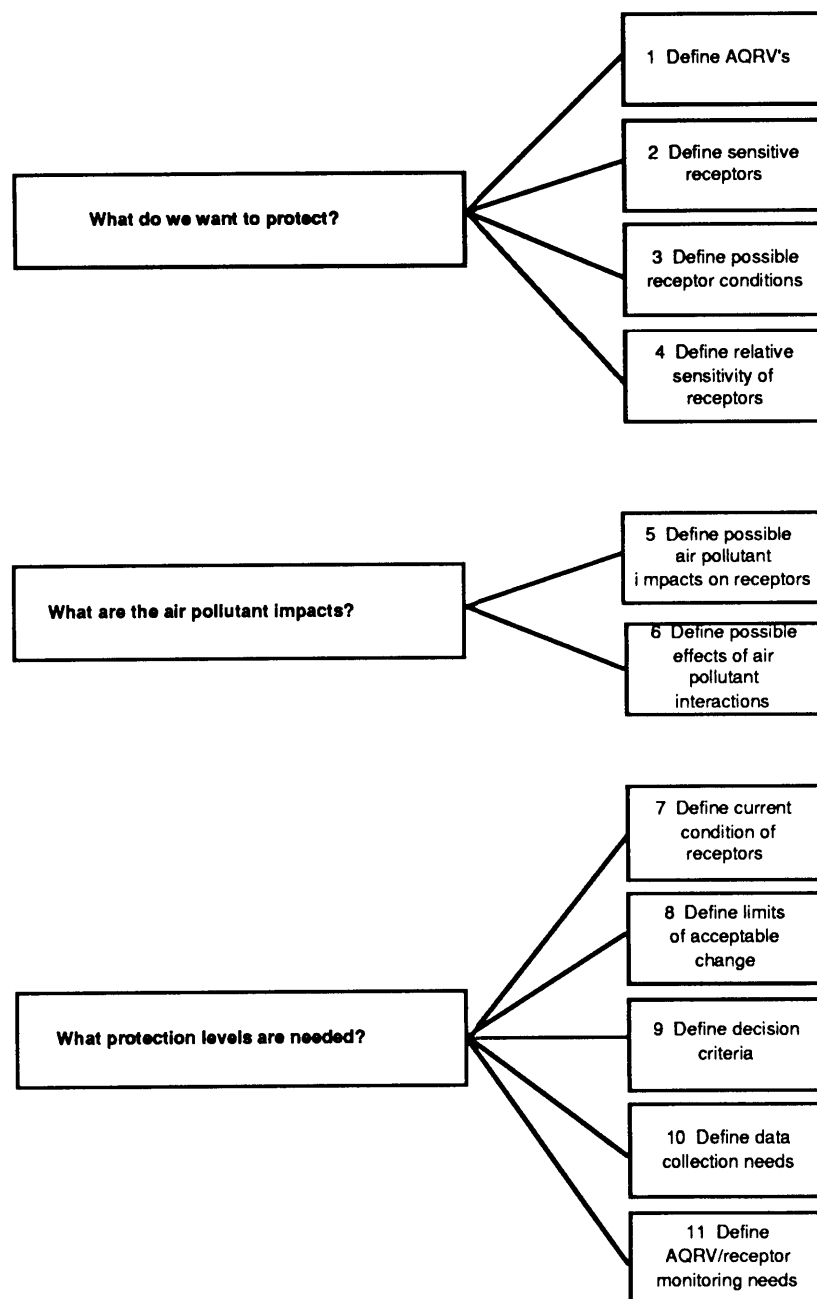
Figure 1. Each workshop focused on the three major questions of air resource management listed on the left. These were translated into the three separate aspects of knowledge (factor, structure, and strategy analysis) and then used to prepare a strawman discussion guide.

1. An AQRV is a major aspect of a wilderness that can be substantially affected, directly or indirectly, by air pollution.
2. An AQRV contains "significant parts" that are readily impacted by air pollution.
3. An AQRV should be, at least, (a) an ecosystem level component of the wilderness, (b) a unique feature of the wilderness (often this uniqueness provided the impetus for wilderness designation), or both of these.

4. An AQRV should be delineated so that air pollutant impacts are homogeneous throughout.

The first two points are part of the original guidelines; the terminology adopted for significant parts is "sensitive receptors." The relationship between AQRVs and sensitive receptors is illustrated in Figure 2. By appending points 3 and 4, we attempt to circumscribe the notion of an AQRV. In this way an AQRV possesses some minimum value worth protecting and yet does not ex-
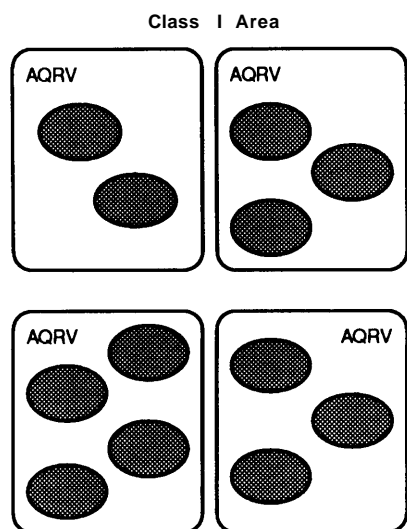
Class I Area

Figure 2. Class I wilderness areas are composed of air quality-related values (AQRVs) that also may be divided into significant parts or sensitive receptors (shaded ovals).

hibit a heterogeneous response to pollutants throughout its defined range. Using these guidelines, an AQRV should be described in terms of landscapes, ecosystems, or watersheds, i.e., large cohesive collections of related biogeographic features, or as a unique feature of the wilderness.

Step 2: Define sensitive receptors. Because an AQRV often consists of several distinct "features" (even in broad terms), using an AQRV as the smallest unit of interest may be too broad and diverse. There is little scientific understanding about air pollutant impacts on extensive, ecosystem-level values. Varying amounts of knowledge do exist, however, for individual components (i.e., sensitive receptors) of an ecosystem or AQRV. Sensitive receptors represent distinct components of an AQRV that are (or may be) affected by air pollution and have some management priority for protection. Generally, sensitive receptors indicate degradation prior to detectable changes to an extensive AQRV. As such, sensitive receptors are useful both as indicators of pollutant impact and as conceptual descriptors of an AQRV.

Step 3: Define possible receptor conditions. In the next step of the strawman, participants specify greater detail about each AQRV sensitive receptor. In addition to a description of each sensitive receptor completed in the previous step, possible conditions exhibited by each sensitive receptor are identified. An obvious descriptor of receptor condition is a numerical scale by which the receptor is usually measured, e.g., pH for lake water acidity. While it is possible to use pH values and talk

about them, at some point it becomes necessary to interpret what particular pH values really mean in terms of the observed condition of lake acidity. To incorporate this interpretive step into PSD screening analysis, we asked participants to define condition classes for each sensitive receptor. Condition classes are defined in terms of ranges of values from the underlying measurement scale. For example, a condition class of "no deterioration" for lake pH might be defined as "long-term reduction in pH of 0.0-0.5." Similarly, other qualitative condition classes can be defined, e.g., "slight deterioration," "moderate deterioration," and "severe deterioration."

We emphasized guidelines to aid participants in writing condition class descriptions of sensitive receptors.

- The number of condition classes and their labels need not necessarily be identical for all sensitive receptors. For example, a sensitive receptor whose response to air pollution ranges over a broader set of distinguishable characteristics might be described using more condition classes because additional classes can be easily discriminated.
- Sensitive receptors that are more important for protection may also warrant greater discriminatory capability through more condition classes.
- Because these classes describe general categories, utilize uncertain numerical values, and represent possibly vague interpretations, value ranges used to define these classes may reasonably be expected to overlap somewhat. This notion attempts to incorporate the concept of fuzzy sets as described by Zadeh (1965). Sensitive receptor conditions are difficult to divide into distinct classes with absolute boundaries. Crisp boundaries are not observed when viewing these receptors in the real world; we often impose boundaries and thresholds for convenience. Rather, our representation and interpretation of measurable quantities, such as lake pH, should reflect the intuitive nature in which we reason about them.

Step 4: Define relative sensitivity of receptors. For a manager to monitor and assess pollutant impacts on an AQRV, it is useful to understand which receptors are most sensitive to pollutants. Subjective comparisons are made between receptors by ranking them in order of sensitivity, 1 ton (1 being most sensitive), indicating how sensitive that receptor may be to various pollutants. Receptor sensitivity varies by pollutant, so a separate ranking may be necessary for each pollutant. Two different receptors may have an identical ranking if they have similar sensitivity to a particular pollutant. Elasticity, re-

silence, and inertia to change of each receptor are important criteria when determining relative sensitivity.

Step 5: Define possible air pollutant impacts on receptors. In this step, specific pollutant loadings are associated with the different sensitive receptor condition classes. The idea is to estimate the resource impacts that can be expected from various levels of different pollutants. These exposure-effects relationship are extremely critical to the FLM for making decisions about "adverse impacts." In general, each sensitive receptor–pollutant pair will have its own list of exposure-effect relationships. Furthermore, a reliability value maybe appended to each exposure-effect relationship to reflect the confidence that a particular pollutant exposure may produce a particular effect in a sensitive receptor. These reliability values are subjective assessments, phrased in qualitative terms (e.g., low, moderate, high). Loading values listed in these exposure-effect relationships indicate likely shifts in sensitive receptor condition. Again, overlapping ranges of loading values are used to indicate uncertainties associated with loading value effects and to incorporate condition class vagueness. The FLM's definition of "adverse impact" will ultimately be based on these relationships, on the biophysical limitations of the resource, and on FLM perceptions of the public's preferences.

Step 6: Define possible effects of air pollutunt interactions. Some scientific evidence exists for interaction effects between pollutants. That is, the presence of a particular pollutant can modify the effect of another. Interactions between pollutants may result in impacts that are either synergistic or antagonistic. When the resultant effect of two or more pollutants is different than each of them acting independently, an interaction has occurred. An interaction effect is recorded as a belief, i.e., reliability, that a particular interaction will occur between pollutants. Because of the current state of scientific knowledge about individual pollutants, specifying interactions can reasonably only be expected to include the following: the pollutants involved, the type of interaction (antagonistic or synergistic), and the reliability that such an interaction does occur.

Step 7: Define current condition of receptors. Before assessing the impact of air pollutants on a wilderness, an FLM must have some knowledge of the current state of its AQRVs. Current pollutant exposure levels in wilderness are not well established because of difficulties associated with monitoring air quality in remote areas. Before these workshops, there was some attempt to collect and organize the data that exist on pollutant loadings. Based on these loading data and on the exposure–effect relationships discussed above, it is possible for the FLM to estimate what the current condition of sensitive receptors might be. He or she may then use this knowledge about the resource to help formulate the limits of acceptable change.

Step 8: Define limits of acceptable change. From the information that has been gathered in the previous steps, it should be possible to produce an informative analysis for any particular permit application. For that analysis, a permit applicant must provide estimates for projected pollutant loadings, and current pollutant loadings (if otherwise unknown), in any wilderness that might be affected by the proposed construction. All of the preceding steps deal with aspects of analysis designed to summarize and simplify current scientific knowledge. Nonetheless, before this knowledge can be applied to any particular PSD permit, a FLM must determine what constitutes "adverse impact" for wilderness resources, i.e., what are the limits of acceptable change. Particular AQRVs, or even individual sensitive receptors, may have different limits of acceptable change. These limits provide constraints on the amounts and dispersal of pollutants in terms of the impacts they produce.

Step 9: Define decision criteria. An informed decision then becomes possible, but the manager must apply this information based upon some decision criteria. Given that air pollutant effects have been estimated and limits of resource change have been set, FLMs must also decide how much deterioration, if any, can be allowed. This is where economic, social, and political issues, as well as physical and biological science considerations, come into play. Previously, air pollutant impacts were only described for sensitive receptors. So, before a FLM can extrapolate this knowledge to prevent significant deterioration of AQRVs, air pollutant effects on individual sensitive receptors must be aggregated to describe their collective contribution to deterioration of each AQRV. This aggregation process is, essentially, a decision procedure because it specifies those conditions that signal significant deterioration of AQRVs. Some considerations that are important for this aggregation process are the following: numbers of receptors in an AQRV; sensitivity of those receptors; diagnostic importance of those receptors, i.e. how strongly they indicate AQRV health; and human consequence of deterioration.

Step 10: Define needs for data collection. As noted above, there are few data on pollutant depositions in wilderness in the western United States. In some cases there may be insufficient information or inadequate quality of information to make a reliable permit recommendation. Consequently, there may be a need for additional data collection before making an informed de-

termination of possible adverse impacts. Such a data collection effort is designed to improve decision reliability. A data collection effort often may be requested of the permit applicant.

Step 11: Define need to monitor AQRVs and receptors. In addition to a lack of reliable loading data, there may be little information available on sensitive receptors in a particular wilderness and their current health status. Workshop participants may also outline needs for inventory and monitoring of particular receptors. Inventory and monitoring programs identify both the occurence and ongoing condition of sensitive receptors. These programs increase the knowledge base of wilderness resources that the FLM has available to manage the wilderness and to make permit recommendations.

These 11 strawman steps constitute an outline for discussions of technical issues at the workshops. The methods used to implement this format in a group setting, however, must still be specified. A brief review of some pertinent techniques are presented in the following section.

Knowledge Elicitation from Workshop Participants

The process of extracting knowledge from people is often referred to as knowledge elicitation. once extracted, this knowledge must be organized and formalized so that it can be represented and processed by a computer. Elicitation can be difficult due to the unexplicit nature of human knowledge-the manner in which it is stored and used. This bottleneck is exacerbated when multiple experts are used, for example, in a workshop setting. Complications associated with pursuing multiple experts include these: consuming additional time; obtaining agreement between experts; and providing a forum, document, or medium that records and facilitates dialog between experts (Schmoldt and Rauscher 1991). Benefits of knowledge elicitation from multiple experts can be substantial, however, despite these disadvantages (Mittal and Dym 1985). In fact, these benefits are essential for the success of the workshops.

A number of structured group interaction and elicitation techniques exist (e.g., Boose 1986, Crawford and Demidovich 1981, Dalkey and Helmer 1963, Schmoldt and Bradshaw 1988, Van de Ven and Delbecq 1971). A more loosely structured method was desirable, given the size of the workshops and the flexibility we felt was essential. However, the method had to direct workshop participants to discuss and resolve the issues outlined in the strawman.

Questionnaires have been used in situations in which it is difficult to physically meet with an expert or where it maybe necessary to extract very detailed and specific knowledge about some topic (Olson and Rueter 1987, Schmoldt and Rauscher 1991). Questionnaires may provide for short answers, extended prose, or multiple-choice answers. Composing lists and categories of lists represents a variation on this idea and has been used to elicit knowledge about insects and pathogens (Schmoldt 1987). We designed our workshop discussion guide (strawman) around the concept of a questionnaire format. Questions that required short answers or completion of predesigned tables were used to implement most aspects of the strawman. Longer prose responses were expected and were recorded by a member of each group for some of the latter discussion points.

Workshop Output: An Example

The knowledge-based methods described here were implemented at two of the Forest Service regional workshops in May 1990. This approach was successfully applied for the Pacific Northwest Region (16 class I areas in Washington and Oregon) and the Pacific Southwest Region (20 class I areas in California). Approximately 25 scientists (from universities, federal agencies and private industry) and 25 resource managers from the National Forests in each region participated in each workshop. Considerable introductory material was provided prior to the workshop, and additional information on air pollution effects and regulatory requirements was covered at the workshop.

Explaining the use of the strawman required approximately two hours before actually using it to elicit information. Workshop participants were divided into subgroups that specialized in developing screening procedures for terrestrial resources, aquatic resources, or visibility. They remained in these subgroups throughout the workshop, although there was considerable interaction among groups, to share expertise. For example, a soil scientist could provide valuable information to both terrestrial and aquatic subgroups and a resource manager assigned to a terrestrial group could provide information pertinent to a specific wilderness that was needed by an aquatic subgroup. This exchange of information among subgroups was a key to the success of the strawman process. The total time required to develop the screening guidelines and supporting information for each wilderness was approximately two days (800 person-hours).

Each subgroup had a group leader, a facilitator, and a recorder. The group leader guided discussion of technical issues. The facilitator was charged with managing group dynamics. This arrangement ensured that discussions remained focused, that input was provided by everyone in the group, and that dominance by one or

Table 1. Potential effects of ozone on ponderosa pine are described via condition classes[a]

Condition class	Age (yr) of needles with chlorotic injury	Needle retention (percent of normal)
No injury	None	>80
Slight injury	5	70-80
Moderate injury	3-4	40-70
Severe injury	1–2	0-40

[a]Two separate criteria are used to define condition classes, age of injured needles, and percent needle retention.

Table 2. Associating pollutant exposure levels with condition classes of each sensitive receptor is an important result of the workshop[a]

Condition class	Ozone concentration (ppb)
No injury	≤ 45
Slight injury	46-55
Moderate injury	50-80
Severe injury	>80

[a]Ponderosa pine response to ozone exposure is listed here.

two individuals was avoided. The recorder took notes throughout the discussions and summarized information at the end of the workshop. When possible, the task of recording was rotated among subgroup members to avoid removing any single individual from involvement in the discussion. Each subgroup had a microcomputer into which all written information was entered during and after discussion periods. Each subgroup submitted their summaries in hardcopy and on diskette at the end of the workshop.

The results of these workshops are summarized in Forest Service publications and the knowledge-based system software associated with them (Peterson and others 1991a, Peterson and others 1991b). A brief example is presented here to illustrate how the strawman process works. The information in the example is from the Pacific Northwest Region workshop and summarizes the screening guidelines for one aspect of terrestrial resources for a particular AQRV. It follows closely the conceptual model in Figure 1 for detailing factor, relationship, and strategy knowledge.

This example will focus on the Eagle Cap Wilderness located in eastern Oregon. Five different AQRVs were defined for this wilderness: alpine meadows, subalpine forest, low-elevation forest, high-elevation lakes and streams, and visibility. With the exception of visibility, each of these AQRVs is a discrete ecosystem-level component of the wilderness. We will focus only on low-elevation forest in this example. Three sensitive receptors were identified within this terrestrial AQRV: ponderosa pine, Douglas-fir, and lichens.

Various condition classes were defined to encompass the range of possible conditions of ponderosa pine with respect to the effects of ozone. Four condition classes were defined for ponderosa pine (Table 1) based on level of chlorotic injury (yellowing associated with symptomatic ozone damage) and needle retention in the crown. These condition classes are based on several published studies on the effects of ozone on ponderosa pine and other conifers (e.g., Pronos and others 1978,

Miller and others 1983, 1989, Duriscoe and Stolte 1989). It should be noted that two condition class descriptions are provided here-one using age of injured needles and a second using percent needle retention. Because the FLM has "affirmative responsibility," he or she may err on the side of AQRV protection (D. Haddow, personal communication). Hence, the criterion actually used in any particular case can represent a worst-case scenario.

Ozone is potentially the worst phytotoxic air pollutant to these receptors. The relative sensitivity of these receptors to ozone is: lichens $\geq$ ponderosa pine > Douglas-fir. This relationship is based on previous studies of the effects of ozone on trees (e.g., Hogsett and others 1989) and lichens (e.g., Nash and Wirth 1988). Lichens and ponderosa pine are about equally sensitive to ozone, hence the use of " $\geq$ " symbol. The dose-response relationship for the effects of ozone is better quantified for conifers than lichens, so we will focus on ponderosa pine as a sensitive receptor in the rest of this example.

The next step in the process was to identify how exposure to various levels of ozone is related to these condition classes. Ranges of ozone concentration exposure, based on 7-h growing season means, are associated with each condition class (Table 2). These values represent expert judgment on the relationship between exposure and injury, based on published literature and personal knowledge and experience of workshop participants. Despite our recommendation to use overlapping ranges of values, it was often difficult to convince workshop participants of their utility. Reluctance to adopt this approach is evidenced in the two tables. The current condition of the sensitive receptor ponderosa pine in low-elevation forests of the Eagle Cap Wilderness was judged to be "no injury," based on the criteria stated above, knowledge about the current health of ponderosa pine at that location, and sketchy data on current ozone concentrations.

The rest of the strawman exercise was primarily descriptive and expository. The terrestrial subgroup

noted that some interactive effect was likely to result from exposure to combinations of elevated levels of ozone and sulfur, ozone and nitrogen, and sulfur and nitrogen. However, there are insufficient experimental data to predict the nature of this interaction. There are also probable interactions with other environmental stresses such as low soil moisture, unfavorable temperature, insect pests, and pathogens. Workshop participants were encouraged to take extensive notes during the strawman process to document their conclusions and rationale, as well as to provide appropriate references.

The final steps of the strawman process were primarily recommendations and criteria for decision making with respect to a permit application relevant to each AQRV. For example, the terrestrial subgroup recommended that much more data be collected on exposure of ponderosa pine and other plant species, especially lichens, to pollutants in the Pacific Northwest. They suggested that effects be dealt with at the population level, because detecting effects would be easier than at the ecosystem level. The subgroup also recommended that additional research be conducted on sensitive receptors in the AQRV to determine their tolerances for air pollutants under controlled experimental conditions. Finally, they recommended that decisions about effects on AQRVs in the Eagle Cap Wilderness required some inventory and monitoring of resources by the permittee or the Forest Service or both. It was suggested that this information be collected over a period of at least three years to describe adequately biological and chemical features of natural processes in the wilderness.

The strawman example summarized above for an AQRV and sensitive receptor represents expert judgment by scientists and resource managers at the workshop. The quantitative and qualitative information are to be used as guidelines only in the decision-making process. The recommendation by the Forest Service to grant or not grant a permit can rely on these guidelines in addition to any other information that might affect the decision, including information that was not available at the workshop. The decision can, of course, be based on political or economic criteria. The screening guidelines provide guidance from a scientific perspective.

Workshop Evaluation and System Implementation

The knowledge-based approach described here has now been used to develop screening guidelines to pro-

tect air quality in wilderness in the Pacific Northwest and Pacific Southwest regions of the USDA Forest Service. These regions include 36 of the 88 class I areas under Forest Service management.

The workshop format as guided by the strawman process proved to be an efficient approach to eliciting high-quality information from a group of experts in a short time, It may be possible to obtain the same type of screening guidelines through a distributed questionnaire (de Stieguer and others 1990, Pye and others 1989), Delphi process (Schmoldt and Bradshaw 1988), or expert opinion from a few scientists and resource managers. However, the workshop forum provides a much broader range of expertise and opinions than would be possible by these other methods. In the case of the workshops for the Pacific Northwest and Pacific Southwest regions, many of the scientists were regarded as leaders in the field of air pollution effects. The resource managers who attended provided input to a system that they will ultimately use. The merging of scientific and managerial perspectives was a unique feature of the workshops.

Although knowledgeable experts use their judgment and experience almost daily, they often are reluctant to have these intuitions scrutinized and recorded. Their approximate, and heuristic, mental models may be lacking in experimental scientific support and their rationale is often difficult to explain to others; however, these internal models often perform well with limited information and represent the best knowledge available on poorly understood scientific questions. This hesitance frequently is experienced in one-to-one interactions with experts; our experiences in this workshop setting did not differ substantially from this norm. The strawman structure, however, provided a strong sense of purpose and a stepwise progression that encouraged participants to overcome difficulties with expressiveness. Facilitators were also instrumental in encouraging the extraction and recording of judgments.

Subgroups at the workshops usually ranged from 6 to 16 individuals. Even with smaller subgroups, however, group dynamics became very important. Facilitators and group leaders are crucial ingredients to workshop success and should be selected carefully. A positive, "can do" attitude toward workshop objectives, an unbiased manner on technical issues, and people-management skills are important qualities for people in these positions. We observed large differences in group effectiveness and efficiency depending on the skills and attitudes of the individuals in these key roles.

One of the interesting features of this workshop approach to knowledge elicitation is the finite time horizon it imposes. In traditional knowledge elicitation sce-

narios, there often exists no definite termination point to the interview process. Hence, it becomes possible for one of several involved parties to protract the elicitation procedure. In the workshop setting, however, a definite end point exists and everyone is aware of it. Participants recognize what must be accomplished because of the strawman format. Even in instances when a group did not budget its time carefully to conform to these constraints, group members found a way to complete their work as the remaining time diminished. In our methodology, subject matter experts must assume more responsibility for the pace of their progress and the quality of the results.

Workshop results are currently being implemented in a knowledge-based analytical system. FLMs in two regions of the western United States will have access to the best available science regarding air pollution impacts in particular wilderness areas. At the present time permit applications are reviewed at the regional level. However, given the distributed nature of Forest Service land management, it may be reasonable to expect future application of this system to filter down to more local management levels, i.e., individual forests. In such a capacity, this system can serve as another tool available to FLMs as they strive to meet land management objectives.

Acknowledgments

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