Putting Data, Experience and Professional Judgment to Work in Making Land Management Decisions

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ABSTRACT

Biological evaluations and resource decision-making entail use of administrative procedures, quantitative scientific data, and expert knowledge. Four kinds of information are needed to make good management decisions: scientific data, ecological theory, professional judgment, and personal experience. Each kind of information is unique in its utility for legal, scientific, and administrative settings. Scientific uncertainty can be evaluated with risk analysis techniques and used in guiding resource management decisions with decision theory techniques. Monitoring the application, results, and underlying assumptions of management guidelines are ways to decrease uncertainty, particularly if the monitoring is conducted in an adaptive management framework. A useful adaptive management approach requires measurable parameters, a scientifically sound study design, management trigger points, availability of management options, and willingness to change.

Several examples of analyzing risk and using decision theory are illustrated in this paper, including methods of expected value of perfect information and expected value of sample information, decision tree analysis, and use of expert systems. A hypothetical case study of managing down wood for a mycophagous small mammal guild is presented to illustrate the use of various kinds of information and the application of monitoring and adaptive management.
ACKNOWLEDGMENTS

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1 INTRODUCTION

The art of wildlife management is a unique marriage of scientific method and intuition. The science portion of the marriage provides a theoretical basis and quantitative data for managing populations and habitats. The intuition portion fills in the blanks when scientific knowledge is unavailable, and consists of mostly unarticulated expertise. When developing management guidelines, most wildlife managers and applied researchers use intuitive knowledge above and beyond their explicit scientific knowledge. This paper addresses how data, experience, and professional judgment are combined in environmental assessments and resource planning decisions.

The objectives of this paper are to explore: 1) concepts related to using information from a variety of sources and levels of precision; 2) appropriate uses of incomplete information; 3) ways of dealing with uncertainties in assessments and decisions; and 4) ways of constructing advisory models from various sources of information. Much of this paper refers to management of wildlife habitats on public, multiple-use lands (such as in U.S. National Forests), but the concepts are applicable to any land base where management decisions entail uncertainties.

2 USE OF INFORMATION IN WILDLIFE EVALUATIONS

Many kinds of information are typically brought to bear when environmental assessments are being conducted and management guidelines developed. Statistically accurate data gathered on-site or in similar environmental contexts are of high value, but such site-specific data are not always available. Thus, personal expertise is commonly part of the tool kit as well.

An example is the USDA Forest Service biological evaluation for project assessment (a similar methodology can be used by the B.C. Ministry of Forests). A biological evaluation as conducted by wildlife biologists on National Forests in the U.S. is a procedure for assessing what degree of impact proposed forest management activities will have on specific wildlife habitats or populations, and for identifying ameliorative or mitigative actions. For instance, a biological evaluation can be used to assess how a proposed timber harvest might affect desired habitat conditions of mature and old-growth forests for pileated woodpeckers (Dendrocopos pileatus) in a specific set of forest stands.

2.1 Kinds of Information Used in Biological Evaluations

The information used in biological evaluations can be classified as administrative, quantitative, and expert. Administrative information consists of explicit wildlife objectives in terms of kinds, amounts, and distributions of habitats necessary for managing the species of interest. This defines desired habitat conditions. Administrative objectives may or may not be based solely on scientific data. Amounts of habitat allocated for a species objective, for example, may be compromised by competing uses for the same forest land.

Quantitative information in a biological evaluation consists of scientific data on wildlife–habitat relationships. Quantitative information might consist of scientifically collected facts, as well as more general ecological theory. An example is the amount of mature and old-growth forest occurring within an annual home range of a breeding pair of pileated woodpeckers. Other quantitative information might include inventory data on forest habitats and models of tree growth and timber yield.

Finally, expert knowledge is used to synthesize inventories, projection models, and other quantitative information to compare conditions in the project against conditions currently existing or desired. Expert knowledge often extends what we know quantitatively about how projects affect environments by applying tacit rules that identify when particular effects of a project are important. For instance, a particular timber sale may not significantly affect quality of pileated woodpecker habitat if the project entails small group selection, occurs in less wind-prone areas, is timed outside the breeding season, and is not placed close to
key nesting or feeding stands. Expert rules of this type are not inherently contained in inventory information, in scientific data on the species, nor in quantitative models of forest stand development and wildlife–habitat relationships. Rather, they are derived from professional judgment, personal experience, and an understanding of the species' ecology and site-specific properties of the location of the project. Expert rules can be assembled, shared, stated explicitly in documenting decisions and management guidelines, and even tested.

2.2 Characteristics of Information

What are the characteristics of various kinds of information used in making land management evaluations and decisions? Scientific data are derived from direct field observations and are thus applicable to specific circumstances (Table 1). As well, scientific data are collected in a repeatable manner, although such studies are often not duplicated over large areas. They are statistically reliable, and those presented in publications are reviewed by peers. Scientific knowledge in the field of wildlife management is best gathered by hypothesis-testing (Romesburg 1981) through the use of the “hypothetico-deductive process.”

<table>
<thead>
<tr>
<th>Category</th>
<th>Characteristics</th>
</tr>
</thead>
<tbody>
<tr>
<td>Scientific data</td>
<td>Direct field observations (specifically applicable)</td>
</tr>
<tr>
<td></td>
<td>Scientifically collected (repeatable)</td>
</tr>
<tr>
<td></td>
<td>Statistically accurate (reliable)</td>
</tr>
<tr>
<td></td>
<td>Peer reviewed (credible)</td>
</tr>
<tr>
<td>Ecological theory</td>
<td>Conceptual (generally applicable)</td>
</tr>
<tr>
<td></td>
<td>Global (based on principles)</td>
</tr>
<tr>
<td></td>
<td>Peer reviewed (credible)</td>
</tr>
<tr>
<td>Professional judgment</td>
<td>Expert knowledge (credible)</td>
</tr>
<tr>
<td></td>
<td>Deep understanding of relationships</td>
</tr>
<tr>
<td></td>
<td>Heuristic (deals with uncertainties)</td>
</tr>
<tr>
<td></td>
<td>Legally admissible</td>
</tr>
<tr>
<td>Personal experience</td>
<td>Anecdotal (contextual, not repeatable)</td>
</tr>
<tr>
<td></td>
<td>Diverse (useful, eclectic, synthetic)</td>
</tr>
</tbody>
</table>

Ecological theory, on the other hand, is mostly conceptual. Its application to particular contexts is general rather than specific. Theories are global principles induced from site-specific information or extrapolated from mathematical treatment of concepts. In publications, ecological theory is reviewed by peers and accepted, to varying degrees, by the scientific community. Ecological theory is robust, not site-specific, and applies on a broader scale than empirical scientific data.

Professional judgment consists of an expert understanding of resource consequences. It is a deep comprehension of concepts, ecological theory, and environmental effects, as well as knowledge of local conditions. As heuristic knowledge, professional judgment enables the expert to make educated guesses when necessary, to recognize promising approaches to solving problems, and to deal effectively with errors and uncertain or incomplete data. Professional judgment also is legally admissible in U.S. courts as a source of knowledge and understanding, as any expert witness can testify. Professional judgment can be subjective and biased according to one's experience and training.

Finally, personal experience differs from scientific data in being based on anecdotal observations. Thus, personal experience may not be repeatable and is often unarticulated (Polanyi 1962). Personal experience, along with scientific data and theory, forms the foundation for professional judgment, although it varies greatly among individuals. Personal experience is not subject to a repeatable, statistical framework or to peer review. It is a diverse and eclectic bank of knowledge, subject to individual biases and predilections, but it still may yield reliable and useful information. In legal settings, however, it is often subject to debate.
How useful are each of these sources of knowledge in various arenas of forest resource management? Collectively, scientific data and ecological theory are most useful in legal and scientific settings, but generally must be interpreted through development and technology transfer programs for use in administration and on-the-ground resource management. On the other hand, professional judgment and personal experience best fit the kinds of information needed for management, although they are of limited utility in scientific circles (e.g., for including in publications or helping advance scientific knowledge) and legal settings, unless they constitute the sole pertinent information available and are well documented with field notes, affidavits, and depositions.

All four kinds of information — scientific data, ecological theory, professional judgment, and personal experience — are needed for making decisions for resource planning. However, any of these sources of information can be fraught with uncertainties. One must be aware of the limitations and risks of using each kind of information in environmental evaluations and resource management decision-making. For example, “soft data” — such as those afforded by personal experience and professional judgment — allow for quick decisions but can be heavily biased. Such information should be independently evaluated or monitored, or applied first on a case study or pilot project. When soft data are used, peer review and public participation in decision-making are paramount. The next section explores ways to make uncertainties more explicit by using various evaluation techniques.

3 HANDLING UNCERTAINTY IN RESOURCE ASSESSMENTS AND DECISION-MAKING

Much of resource evaluation and decision-making deals with uncertainty. It is the hallmark of scientists, but the lament of decision-makers, to qualify conclusions with uncertainties.

3.1 Risk Analysis and Risk Management

Scientists can estimate scientific uncertainty by using risk analysis. Forms of scientific uncertainty include variability in the biological system, errors of estimation, invalid prediction models, and ambiguous or inappropriate questions (Marcot 1986a).

These sources of uncertainty are but part of what needs to be considered when one is making resource management decisions. Scientific uncertainty might increase risk in decision-making. Evaluating and weighing the costs and potential outcomes of acting in the face of uncertainties is the business of risk management. Risk management is conducted by decision-makers, managers, line officers, politicians, and courts, and ultimately the public in the form of electing governmental representatives, voting on resource management issues, and participating in the natural resource planning process. Evaluating risk in natural resource management is the domain of decision theory.

In the U.S., the National Environmental Policy Act (1976) mandates the prediction, evaluation, and documentation of environmental impacts caused by any activity potentially affecting natural conditions. Recently, regulations from the U.S. Council on Environmental Quality have called for resource persons to acknowledge unavailable information, disclose areas of significant uncertainty, state if and at what cost such information can be gathered, and evaluate the relevance of the unavailable information. The regulations also call for impacts from projects to be evaluated using theoretical approaches or research methods generally accepted in the scientific community. The purpose of the regulations is to encourage scientific risk analysis, results of which can then be used in risk management. It is expected that this process better informs decision-makers and the public of the risks and costs associated with a project.

3.2 Monitoring

One method of dealing with uncertainty is through monitoring, as mandated by the regulations pursuant to U.S. National Forest Management Act of 1976 (36 CFR 219). Monitoring entails tracking key biological
parameters and validating crucial assumptions. Monitoring is one vital part of the adaptive management process (Walters and Hilborne 1976; Marcot et al. 1986; Walters 1986).

Three basic kinds of monitoring can help track implementation, effectiveness, and validity of management guidelines. **Implementation monitoring**, or compliance monitoring, refers to verifying that the management guidelines are indeed carried out on the ground in the time and procedure stipulated. For example, are the requisite numbers of hard snags and replacement green trees actually left on site after a timber harvest? **Effectiveness monitoring** refers to testing whether the biological system responds as anticipated. For example, do primary and secondary cavity-nesting birds and mammals actually use the snags provided? **Validation monitoring** refers to assessing the veracity of underlying assumptions used to generate the guidelines in the first place. For example, is the assumed relationship between snag density and woodpecker population density really linear and sloped according to expectations? Much of the following discussion refers to effectiveness and validation monitoring.

A monitoring program can help the manager deal with uncertainty by providing basic, empirical information. Inventory and monitoring information, along with research results, can be used to model effects of project implementation. Modeling helps us to articulate what we think we understand about the system and guides us in identifying key unknowns and assumptions (Bunnell 1989). In the modeling process, sensitivity analysis is useful for identifying potential effects of uncertain parameters, and for prioritizing parameters for further study or monitoring.

Monitoring is useful for testing the anticipated effects on biological systems of implementing management standards and guidelines. In this framework, the timing of implementing the standards and guidelines, as well as the time frame over which the biological system should respond, must be clearly identified. Although effects of short-term elimination or changes in habitats and environments are often readily apparent, some biological responses to less drastic measures are not always immediate.

To monitor effects of guidelines, it is of course essential to have a clear understanding of what those guidelines are. They should be complete, biologically sound, credible, practical, and clearly written and understandable by managers and the public alike. Where possible, they should be derived from an appropriate mix of scientific research, ecological theory, professional judgment, and, in some cases, personal experience. To aid decision makers in assessing guideline effects on resource conditions, trade-offs as a result of implementing the guidelines should be clear. Furthermore, the guidelines themselves should be no more complex than necessary to be effective, and — perhaps most importantly — should be clearly linked to quantifiable management objectives.

To monitor guidelines properly, a monitoring implementation plan should be written, reviewed, and officially sanctioned. The plan should describe standards for data collection and analysis. It should also specify goals, objectives, funding, and indicators of implementation success. Such indicators should entail identifying an acceptable range of reliability and standards for including subjective (but not arbitrary!) evaluation of results.

What, specifically, should be monitored? A simple risk analysis might help prioritize budgets and guide levels of confidence needed in monitoring programs. The risk analysis might set up a two-by-two matrix listing risk of error across the top and risk of loss down the side (Figure 1). Risk of error refers to the likelihood that implementing a particular management guideline will fail to result in anticipated biological responses. Risk of loss refers to environmental results should such a failure occur.

An example is the implementation of management guidelines intended to provide down wood habitat for wildlife (see below for further explanation of this scenario). The risk of error is the likelihood that providing down wood at particular densities, amounts, and distributions would **not** meet the population objectives stated for the associated wildlife species. Ideally, to assess this risk of error, one would use local scientific data, for example, from a regression model that predicts wildlife population abundance given down wood attributes and abundance. Where such data are lacking, the next resort is to use ecological theory, including results of empirical studies on other, related species or habitats, or theory on down wood amounts and distributions needed to provide for the foraging and cover needs for each species. Where theory or other studies are lacking, professional judgment and personal experience can help provide guidelines, although these constitute much “softer data” and likely carry a much higher risk of error.
FIGURE 1. A simple risk analysis model to help prioritize monitoring activities. Risk of error refers to likelihood that implementing a particular management guideline will fail to result in anticipated biological responses. Risk of loss refers to environmental results should such a failure occur. See text for explanation and an example.

In this example, risk of loss refers to implications of declines or losses of wildlife associated with down wood. It could also include increases in risk of fire incidence, intensity, and spread in unburned down wood (fuels) as a basis for trade-off analyses.

When both risk of error and risk of loss are high, effectiveness monitoring and validation monitoring studies become imperative. Other combinations of risk of error and risk of loss carry lesser priorities, depending on the situation, and monitoring programs can be guided accordingly. Obviously, if the wildlife species involved is threatened or endangered, risk of loss is always high. More subtly, however, if the species plays a key function in the ecosystem, such as being an important pollinating or dispersal vector for maintaining forest health, risk of loss can also be high even if the species is not threatened or endangered. Again, evaluating such outcomes demands clearly stated objectives and assumptions for the management guidelines.

Over time, such a risk assessment can be updated from experience and new data. Because risk attitudes tend to change with time and circumstances, it may be useful to monitor shifts in public and managerial opinions. When monitoring information is used in the broadest sense to realign guidelines, this process becomes adaptive management.

3.3 Adaptive Management

The adaptive management process views a management decision as a hypothesis. The hypothesis consists of the key assumptions underlying a management guideline. To test the key assumptions, relevant biological variables are monitored in the field and management guidelines adjusted if the biological system responds less favorably than expected. The foundation of management guidelines is often a combination of scientific information and professional and personal knowledge. Thus, testing key assumptions of management guidelines amounts to evaluating the validity of expert rules derived from professional judgment.

Four factors are necessary for the adaptive management mechanism to work correctly. First, **clear and measurable parameters must be identified** that represent the assumptions being tested. A feasible method for estimating the values of those parameters must also exist. For example, when monitoring the efficacy of established pileated woodpecker habitats, one must have a reliable protocol for inventorying the presence of breeding pairs of birds. Second, **clear evaluation criteria must be written** that would trigger reevaluation of management direction. For example, locations of habitats allocated for pairs of woodpeckers might be changed if monitoring revealed a lack of occupancy for three consecutive breeding seasons. Third, **options must be available** for altering management direction. For example, monitoring home range characteristics of pileated woodpeckers with the intent of setting habitat sizes according to amounts of mature and old-growth forest used per pair is fruitless if such habitat is unavailable for
reallocation. A combination of scientific data, such as field methods and habitat inventories, and professional experience can provide the basis for appropriate application of the adaptive management process. And fourth, management must be willing to change if monitoring experience suggests that change is needed.

No monitoring and adaptive management program should be started without each of these four conditions first being evaluated. Nothing replaces measurable parameters, a scientifically sound study design, management trigger points, availability of management options, and willingness to change. Monitoring programs lacking any of these components simply waste time, money, and talent.

Ways of modeling environmental effects in light of uncertain or incomplete information include risk analysis and related approaches. Two examples are estimating the expected value of information and developing decision trees. Also, computer programs known as expert systems are a means of articulating professional judgment. These tools are useful in an adaptive management framework. The next sections discuss these approaches.

3.4 Analyzing Risk and Using Decision Theory: Examples

Risk assessment and decision theory refer to a suite of tools for depicting, estimating, and evaluating implications of uncertain information in decision-making (Hillier and Lieberman 1980). Such approaches make uncertainties and assumptions explicit for monitoring and testing. They are also useful for identifying risk attitudes of managers, as with the use of utility theory. Finally, they aid decision-making by accounting for uncertain outcomes, as with the use of decision tree analysis.

Incomplete information can be dealt with in a variety of ways. The examples that follow illustrate how risk assessments and decision theory approaches can be used for project assessment in the presence of incomplete information.

Expected value of perfect information. From decision theory, one approach is to evaluate the expected value of perfect information (EVPI) by estimating the expected loss with available estimates of conditions. That loss becomes the maximum amount we would pay to eliminate risk completely.

For example, with available habitat inventories and habitat relationships models, we might estimate that one-third of habitat capability for reproductive pairs of pileated woodpeckers might be incurred with a particular timber sale in a specific basin. Such an estimate, let us say, would be made from our professional judgment based on incomplete information on the species’ local distribution and our general knowledge of its response to changes in habitat conditions. The value of the amount of habitat lost then becomes the amount we would pay (EVPI) to get perfect information on the species’ local distribution and the response of the population to the project in question. For instance, the value of pileated woodpecker habitat affected by, and possibly lost to, a timber sale may be $4 million (undiscounted stumpage value). Thus, using EVPI, we would find it valuable to spend up to, but no more than, $4 million to gain perfect information on the response by pileated woodpeckers to that project.

Typically in this approach, uncertainty of our understanding can be thought of as variability in response of the species. Uncertainty is modeled as variance (standard deviation) of the response. For example, initial inventories of pileated woodpeckers might result in an estimate of the average crude density of breeding pairs and some sample standard deviation around that average. The greater our uncertainty of habitat capability, the greater the range of possible responses, expressed as the expected response plus or minus the standard deviation of population response. Thus, with great uncertainty, the cost of additional information on impacts to the pileated woodpecker population could be very small — or very great.

Expected value of sample information. A related approach entails estimating the expected value of sample information (EVSI). In this approach, the value of incremental additions to knowledge is evaluated with respect to how well it narrows the standard deviation of predicting outcomes. Following the above example, using existing, imperfect information, we might project a 30% local decline in habitat capability for pileated woodpeckers with a standard deviation of 40% of the expected value. Let us say that before the project, the habitat is estimated to be capable of supporting 10 reproductive pairs of pileated woodpeckers, with a standard deviation of 40% of the expected value. Let us say that
before the project, the habitat is estimated to be capable of supporting 10 reproductive pairs of pileated woodpeckers, with a standard deviation of ±40% of 10 (thus, 10 ± 4 pairs, or from 6 to 14 pairs). The timber sale project would reduce that capability by 30%, to 7 ± 2.8 pairs (2.8 = 40% of 7), or from 4.2 to 11.8 pairs.

Let us also say that our original planning objectives dictate that habitat capability for no fewer than six pileated woodpecker pairs be maintained in the area. Six pairs becomes our “breakeven” point, below which we incur a cost of creating new habitat. This cost of new habitat is called the “unit loss,” and in this case represents the value of standing timber needed as habitat for one pair of pileated woodpeckers. The (undiscounted) unit cost can be estimated as the area needed per pair times the value per acre. Let us say that, by administrative objective, 300 acres are required per pair of woodpeckers and that the current undiscounted stumpage value of mature and old-growth timber averages $50,000 per acre. Thus, the unit cost of maintaining a pair of pileated woodpeckers is $15 million (300 acres needed per pair × $50,000 per acre). This is the mitigation cost per pair of woodpeckers of reducing habitat capability below the objective six pairs.

At this stage, we can calculate the expected loss of providing pileated woodpecker habitat (procedure follows Levin and Kirkpatrick 1975). First, calculate the number of standard deviations between the current mean habitat capability and the break even point:

\[
\frac{10 \text{ pairs} - 6 \text{ pairs}}{4 \text{ pairs S.D.}} = 1.0 \text{ standard deviation}
\]

Next, look up the value that corresponds to 1.0 standard deviation in a statistical table of unit normal loss integral (e.g., Levin and Kirkpatrick 1975:577). This value is 0.08332. Third, calculate the expected loss by multiplying the unit loss, the standard deviation, and the table value:

\[
$15,000,000 \times 4 \times 0.08332 = $4,999,200
\]

or about $5 million. This value is an estimate of what is at risk in providing pileated woodpecker habitat, given the uncertainty (standard deviation) in estimating habitat capability, for this particular project. The manager can compare this value with the expected revenue derived from the timber harvest project, and decide on a course of action.

If we had perfect information, we could conduct projects that reduce habitat capability down to, but not below, the break even objective of six pairs. However, with imperfect information, the range of one standard deviation might fall below the break even point even if the expected value of habitat capability is above it. This calls for caution in conducting projects that irretrievably reduce habitat capability, unless the response of the population is known more precisely. (Remember that one fundamental tenet of the adaptive management process is that options are available for reallocating the land base.)

Now, what if a research contract could be issued to inventory pileated woodpeckers within the proposed project area and to evaluate their local habitat conditions? Let us say such a research contract would cost $100,000 and would double our precision of estimating population response, thus cutting the standard deviation of our habitat capability estimate roughly in half, from 40 to 20% of expected values. If the expected value is currently 10 pairs, then the standard deviation would decrease from 4 to 2 pairs. Is the new information worth $100,000?

Evaluating the expected value of the new information is a three-step process. First, determine how many standard deviations there are between the present expected habitat capability for pileated woodpeckers (10 pairs) and the break even point management objective (6 pairs), using the standard deviation expected to result from the new study:

\[
\frac{10 \text{ pairs} - 6 \text{ pairs}}{2 \text{ pairs}} = 2.0 \text{ standard deviations}
\]

Second, look up the unit normal loss integral corresponding to 2.0 standard deviations. This value is 0.008491. Third, calculate the expected loss by multiplying the unit loss, the expected new standard deviation, and the table value:
$15,000,000 \times 2 \times 0.008491 = $254,730

Thus, the expected loss of the research contract, should it fail to provide us with twice the precision of estimating habitat capability, is about $250,000. This is a reduction in loss from the previous amount — a saving of about:

$5,000,000 - $250,000 = $4,750,000

Since we can capture this potential saving by expending only $100,000 for the research contract, we should conduct the research; the potential value of the new information is worth the cost. Eventually, however, the value of new information will be worth less and less as our initial estimates of habitat capability become more and more precise.

**Decision tree analysis.** Another approach to risk assessment is decision tree analysis. A decision tree is a diagram that represents all possible combinations of environmental responses and decisions that can be made over time. Decision tree analysis can be used, for example, in evaluating habitat conditions for managing habitats and maintaining viable wildlife populations (Bentley and Kaiser 1967; Nnaaj et al. 1983; Maguire 1986; Maguire et al. 1987; Marcot 1).

A decision tree consists of outcomes and decision points. Outcomes are depictions of possible responses by the biological system and estimates of probabilities associated with each outcome. An example is the likelihood of wildfire in particular kinds of forest stands. Decision points are alternative actions that could be taken, such as ways to deal with wildfire. Different decisions entail different costs, such as a zero direct cost associated with letting the fire burn, or a high direct cost associated with maximum fire control efforts. Decisions, in turn, can affect probabilities of outcomes. For example, doing nothing might greatly increase the likelihood of a severe fire.

A decision tree is evaluated for the best sequence of management decisions by weighting the costs of each decision with the expected outcomes. The best decision at any one point in the tree is that with the lowest cost and greatest probability of favorable outcome. Variations in probabilities and cost parameters can also be analyzed in decision trees in more complex sensitivity assessments. See Levin and Kirkpatrick (1975) and Marcot2 for decision tree analysis procedures.

**Other decision-theoretic models of uncertainty.** A number of other models that account for uncertainty can be used to aid environmental assessments and decision-making. One such approach is simulation modeling with random variables representing uncertain factors (Gordon 1978; Law and Kelton 1982). Simulation models have been used to evaluate habitat reserves (Rapoport et al. 1986); Buechner (1987), stand growth (Curtis et al. 1981), demographic characteristics of populations (Maguire et al. 1988; North et al. 1988), and management of populations (Rabinovich et al. 1985).

Other decision-theoretic approaches to dealing with uncertainty include loss-minimization analysis, marginal analysis, and conditional probability assessments (Levin and Kirkpatrick 1975; Hillier and Lieberman 1980). Bayesian statistics are also useful for synthesizing and representing incomplete knowledge (Mangel and Clark 1982; Morawski 1989b). Bayesian statistics form the basis of pattern recognition (PATREC) models used to evaluate wildlife—habitat relationships (Williams et al. 1977; Kirkman et al. 1984). For more on Bayesian statistics, see Hillier and Lieberman (1980), Jaynes 1986, Denning 1989 and Morawski 1989a.

### 3.5 Modeling Resource Effects with Expert Systems

One major tool for assessing the effects of projects on resources is the development and use of expert systems (Marcot 1986b; Marcot et al. 1988). An expert system is a computer program that reasons like a human expert to solve a narrowly defined problem. Expert systems are being developed in a wide variety of areas in natural resource management, including geobased information systems, remote sensing, wildlife habitat management, forestry and silviculture, road construction, and fire management (Stock 1987).

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1 Marcot, B.G. Use of decision tree analysis for assessing wildlife-silviculture relationships. Manuscript submitted for publication.
2 Ibid.
Expert systems can help solve a variety of problems relevant to making land management evaluations and decisions (Table 2). They can be useful for helping to classify habitats, diagnose environmental conditions, interpret environmental data, predict habitat and population responses, and monitor conditions.

### TABLE 2. Kinds of tasks suitable for expert systems in land management evaluations and decisions

<table>
<thead>
<tr>
<th>Kind of task</th>
<th>Example</th>
</tr>
</thead>
<tbody>
<tr>
<td>Classification</td>
<td>Classifying habitat types</td>
</tr>
<tr>
<td>Diagnosis</td>
<td>Evaluating environmental conditions and identifying circumstances requiring amelioration</td>
</tr>
<tr>
<td>Interpretation</td>
<td>Assessing habitat conditions in the context of specific management objectives</td>
</tr>
<tr>
<td>Prediction</td>
<td>Projecting wildlife population response to habitat conditions; also, projecting habitat conditions resulting from management alternatives</td>
</tr>
<tr>
<td>Monitoring</td>
<td>Checking if habitat (or wildlife population) conditions assumed to result from specific vegetation manipulations actually occur; also, identifying when vegetation manipulations occur that violate standards and guidelines</td>
</tr>
<tr>
<td>Design</td>
<td>Recommending amounts and configurations of habitats that would meet stated objectives</td>
</tr>
<tr>
<td>Planning</td>
<td>Recommending project activities and their scheduling that would produce desired habitat conditions</td>
</tr>
<tr>
<td>Debugging</td>
<td>Evaluating ongoing activities to determine those most likely causing adverse effects</td>
</tr>
<tr>
<td>Repair</td>
<td>Recommending ameliorative actions to reduce adverse environmental impacts or to restore conditions</td>
</tr>
<tr>
<td>Instruction</td>
<td>Tutoring of apprentice resource managers on project evaluation and environmental impact assessments</td>
</tr>
<tr>
<td>Control</td>
<td>Recommending a reevaluation of management direction based on comparing monitoring results with desired or expected conditions</td>
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</tbody>
</table>

To build expert systems, professional judgment is written down in a series of statements called production rules. Production rules constitute the so-called knowledge base of the expert system and are structured in an “if-then-else” format. Following is an example of a simple two-rule expert system knowledge base that evaluates pileated woodpecker habitat according to regional management requirements of the Pacific Northwest Region, USDA Forest Service:

#### Rule No. 1

<table>
<thead>
<tr>
<th>IF</th>
<th>THEN</th>
<th>ELSE</th>
</tr>
</thead>
<tbody>
<tr>
<td>habitat is good for pileated woodpeckers</td>
<td>management requirements are being met</td>
<td>requirements are not met</td>
</tr>
</tbody>
</table>

#### Rule No. 2

<table>
<thead>
<tr>
<th>IF</th>
<th>THEN</th>
</tr>
</thead>
<tbody>
<tr>
<td>≥45 snags at least 20 inch DBH occur within 300+ acres AND ≥2 snags/acre at least 10 inch DBH occur within the same 300-acre area, AND 1 core area of mature or old growth forest occurs per 12000–13000 acres of land, AND there is a 300-acre core area of mature or old-growth forest in 1 block OR in stands ≥50 acre each AND each separated by &lt;0.25 mile,</td>
<td>habitat is good for pileated woodpeckers (0.8).</td>
</tr>
</tbody>
</table>

In this simple knowledge base, the IF portion of the first rule would be tested initially. The logical portion of the expert system — the “inference engine” — would then skip down the rules to see whether the IF portion of the first rule can be solved by some other rule. In this case, the second rule can be used in this way. That is, the THEN portion of the second rule solves for the IF portion of the first rule. In this way, the first rule acts as a “control rule,” guiding the sequence of what the system asks of the user. Thus, the expert system would begin by querying the user for values for the IF portion of the second rule. Eventually, if all conditions are met, the second rule would conclude that habitat is good for pileated woodpeckers. This conclusion would then be passed back to the IF portion of the first rule, which in turn would conclude that
management requirements are being met. The ELSE portion of the first rule — that management require-
ments are not met — would be displayed if any of the conditions in the second rule fail. A well-structured
knowledge base consisting of such production rules can harbor a great deal of knowledge on a specific
topic (Pedersen 1989).

Furthermore, such an expert system can incorporate an explanation facility. With this feature, at any
time in the query process, the user can ask “why?” and the system responds by showing the rules it is
currently trying to verify and by further explaining the logic and source references used to build the rules in
the first place. Of course, the references and logic structure had to have been first explicitly created by the
expert. Note the inclusion of a likelihood factor (0.8) in the THEN portion of the second rule. Likelihood factors
can have a variety of meanings in expert systems. In this hypothetical example, the 0.8 might refer to results
of a monitoring study that showed that 80% of all sites conforming to the criteria in rule 2 were occupied by
pILEated woodpeckers. If such empirical data are lacking, likelihood factors can also represent human
experts’ best professional judgment as to how often conditions provide correct outcomes.

This example demonstrates that management standards for establishing and assessing habitat condi-
tions can be formalized into an expert system format. The main point is that most biological evaluations,
planning guidelines, and management assessments can be written down similarly as a set of expert
system-type rules. Ultimately, the rules are just statements of how we think biological systems — habitats
and populations — will respond to our management manipulations. The rules derive from a combination of
scientific data, ecological theory, professional judgment, and, in some cases, personal experience. The
challenge is to articulate rules explicitly so they can be shared, tested, and refined.

An example is the expert system by McNay et al. (1987) that evaluates habitat conditions for black-
tailed deer (Odocoileus hemionus) in coastal British Columbia. The expert system helps identify important
black-tailed deer habitat. This helps the manager tailor activities commensurate with providing deer habitat
and avoiding conflicts with competing uses. The rules in the system are derived from a combination of field
research on deer use of habitats, ecological theory on value of various forest structures to ungulates, and
professional judgment and personal experience on ranking the importance of various habitat conditions.

An area related to expert systems is that of intelligent databases. These are data banks with rules
implanted in them to help the user recognize patterns in the data and to flag specific conditions. For
example, an intelligent database might consist of a habitat inventory data file in a geographic information
system depicting stand conditions for a variety of species. The intelligent portion of the database might be
rules that tally the area extent of particular scarce or declining habitats. The system would send a message
to the user when such habitats drop to or below threshold levels within particular watersheds.

The advantages of expert systems and intelligent databases lie in their capability to synthesize
heuristic knowledge (professional and personal) with precise data. These systems are most useful for
narrowly defined problems with answers that are specific and recognizable, but not necessarily mutually
exclusive. An example of a problem well suited to an expert system approach is: what logging systems can
be used to help maintain standing and down wood, given site-specific conditions of topography, soils, and
management objectives for a particular watershed?

Expert systems are typically programmed by a “knowledge engineer” who takes information from the
experts and writes the computer program to mimic their reasoning. Sometimes experts adept in computers
can themselves write an advisory system. A key question in developing expert systems is: Who should
provide the expert knowledge? Typically, only one expert at a time contributes to development of an
advisory system. Using multiple experts may result in conflicting logic or advice. However, approaches such
as the Delphi technique (Zuboy 1981; Richey et al. 1985a,1985b; Schuster et al. 1985) exist for combining
knowledge from multiple experts.

Validation of an expert system, as with most models, is a difficult and often costly process. It is
especially difficult to validate the combination of statistical facts and heuristic judgment that constitutes a
typical knowledge base. The best approach is to validate parts of the system — each rule or small sets of
rules that can be treated more or less independently. Validation entails defining specific criteria such as
robustness, generality, accuracy, and precision, by which performance of the system will be evaluated. Rauscher (1987) recommended that useful knowledge meet four criteria: relevance, validity, timeliness, and reliability. For more on model and expert system validation, see Lancia et al. (1982), Marcot (1987) and Bunnell (1989).

Rauscher (1987) reviewed the use of knowledge-based tools. He recommended that a new type of “knowledge processor” be developed that manages chunks of information and their relationships. Links between information chunks provide useful ways to synthesize and condense knowledge. Such a system would force information to be written down explicitly, serving to highlight the presence of, and gaps in, known facts.

In the future, knowledge bases will be developed to complement current, simpler databases. Rauscher’s “knowledge processors,” including expert systems and intelligent databases, will be maintained by domain-specific experts who compile, update, and abstract specific areas of expertise (Menzies 1989). Eventually, knowledge systems may surpass humans in capacity and capability for evaluating conditions, raising interesting ethical and political questions (deGaris 1989). At present, progress is being made in developing logical computer programs that can reason under ambiguous evidence and that combine useful approaches from decision theory and expert systems alike (Langlotz and Shortliffe 1989).

3.6 Where Can Information Go Wrong?

Thus far, emphasis has been on positive aspects of combining kinds of information for making biological evaluations, accounting for uncertainty, developing advisory tools, and making land management decisions. There are pitfalls too. Incomplete or uncertain information can misguide as well as inform. Also, use of professional judgment and, especially, personal experience can be fraught with bias. One good solution is to seek peer review of evaluations, guidelines, and decisions that are based heavily on incomplete or uncertain information or on personal knowledge.

Using evaluation tools outside the scope in which they were built carries risks of error. This applies to prediction models of wildlife–habitat relationships, as well as to standards and guidelines for habitat management. Also, applying ecological theory and professional judgment outside contexts in which they evolved might be a formula for error, although the expert should know where and where not to extrapolate such information.

Johnson et al. (1985) argue that the degree of accuracy of information used in modeling depends on the objectives, but that generally trustworthy data are essential for use in management. They illustrated how assumptions drawn from a model on canvasback ducks (Aythya valisineria) were not supported by biological evidence. Use of such a model could greatly misguide management of the species. Models used for management should be based on as reasonable and realistic hypotheses as possible. Thorough biological examinations of underlying assumptions should be conducted of any model used for guiding resource management.
4 COMBINING DATA, EXPERIENCE, AND PROFESSIONAL JUDGMENT: A CASE STUDY

This section provides an example of building a set of management guidelines from various sources of information. The example used is the development of guidelines for a problem in integrated forest-wildlife management. Specifically, the guidelines are intended to provide forest and down wood habitat for a guild of small mammals that disperse spores of underground fungi important for maintaining the trophic health of the forest ecosystem. The example illustrates: 1) how to approach solving a problem combining data, experience, and professional judgment; 2) where each kind of information enters the process; and 3) how to identify key assumptions for further testing and monitoring. The section ends with a series of questions to be addressed when data and experience are combined in this manner.

4.1 The Case Study: Providing Habitat for Mycophagous Mammals

In this scenario, we are interested in providing habitat for a guild of small mammals sharing a common trait of mycophagy, that is, eating underground-fruying (hypogeous) fungi. In British Columbia, Washington, and Oregon, some nine species regularly engage in mycophagy (Table 3), including four squirrels or chipmunks, three voles, and two jumping mice. For summaries of life histories, see Ingles (1965), Maser et al. (1981), Chapman and Feldhamer (1982), and Mathews (1988). Brown (1985) provides information on general habitat relationships.

<table>
<thead>
<tr>
<th>Sciuridae</th>
</tr>
</thead>
<tbody>
<tr>
<td>Townsend chipmunk (Eutamias townsendi)</td>
</tr>
<tr>
<td>yellow pine chipmunk (Eutamias amoenus)</td>
</tr>
<tr>
<td>western gray squirrel (Sciurus griseus)</td>
</tr>
<tr>
<td>northern flying squirrel (Glaucomys sabrinus)</td>
</tr>
<tr>
<td>Cricetidae</td>
</tr>
<tr>
<td>California red-backed vole (Clethrionomys californicus)</td>
</tr>
<tr>
<td>Gapper vole (Clethrionomys gapper)</td>
</tr>
<tr>
<td>Oregon or creeping vole (Microtus oregoni)</td>
</tr>
<tr>
<td>Zapodidae</td>
</tr>
<tr>
<td>jumping mouse (Zapus princeps)</td>
</tr>
<tr>
<td>Pacific jumping mouse (Zapus trinotatus)</td>
</tr>
</tbody>
</table>

The management guidelines should provide sufficient habitat conditions for maintaining viable populations of each species of this mycophagous guild. More specifically, the guidelines should prescribe the type, amount, and distribution of habitat conditions, particularly down wood, needed to maintain well-distributed populations of each species. While this example will not provide such guidelines per se, it will demonstrate the process of considering available information and identifying key assumptions.

4.2 What is at Risk?

The interest in this example arose from recent studies on how hypogeous fungi, especially mycorrhizae, help maintain health of coniferous trees of commercial and ecological value, including pines (Pinus spp.), hemlocks (Tsuga spp.), spruces (Picea spp.), true firs (Abies spp.), Douglas-fir (Pseudotsuga menziesii), oaks (Quercus spp.), and alders (Alnus spp.) (Bartels et al. 1985). Mycophagous rodents are important dispersers of spores of these fungi, and down wood plays a major role in providing habitat for this small mammal guild (Maser et al. 1978; Maser and Trappe 1984).

Down wood also provides sites for nutrient accumulation, nitrogen fixation by nonsymbiotic bacteria (Maser et al. 1984; Cromack 1988), habitats for a variety of other wildlife species, and regeneration sites for
tree seedlings such as western hemlock (*Tsuga heterophylla*), and helps stabilize soils on slopes. These additional roles of down wood contribute to maintaining long-term productivity of forests in the Pacific Northwest.

What are the costs and benefits of implementing guidelines for a mycophagous mammal guild? Such a set of guidelines would not be without trade-offs. Without guidelines, project activities such as site-specific treatments for timber production (clearcutting, slash piling and burning, scarification, etc.) might inadvertently reduce or eliminate suitable microhabitats and resources for the species. Once the guild is locally eliminated, long-term site productivity might be much reduced.

On the other hand, with guidelines, some resources (e.g., standing or down wood) might need to be retained on most project sites. Alternatively, some portion of the landscape might need to be left in suitable habitat (unharvested mature or old-growth stands). This might entail reduction in productivity of some forest resources such as timber.

### 4.3 Guidelines for Maintaining the Mycophagous Guild

What information would be needed for developing management guidelines? At the least, the following assessments would be essential:

1. forest types, ages, and structures in which each small mammal species finds suitable habitat;
2. distribution of habitats to ensure that the guild would transport beneficial fungal spores among forest stands throughout the landscape;
3. specific microhabitat components, especially type, amount, and distribution of down wood, that contribute to suitable habitat for each small mammal species;
4. degree to which species of this guild contribute to maintaining health of forest stands, such as effects on stand volume growth or increased survival of trees; and
5. population numbers, densities, and distributions of each species of this guild necessary for ensuring their long-term continued existence, well distributed across the landscape.

What information is available to conduct these assessments? First, available scientific data on species life histories and studies of habitat relationships can begin to address items (1) and (3) on habitat attributes. However, no published studies to date have quantified specific stand structures for each species. Rather, the literature (e.g., Brown 1985) addresses general forest types in which each species is expected to be found.

There are no published scientific studies quantifying items 2, 4, and 5 for these species. Instead, one would have to rely on the use of ecological theory for these assessments. For example, assessing the arrangement of forest habitats needed to maintain well-distributed populations could be based on an understanding of each species’ specific habitat requirements and its dispersal capabilities through a variety of habitat types. Spatial models simulating dispersal through patchy habitats would be helpful for assessing effects of forest stand configurations (e.g., Chesson 1981; Bovet and Benhamou 1988; Fahrig and Paloheimo 1988; Murray 1988; Hastings and Wolin 1989). The guidelines could place suitable habitats, of sufficient amounts to maintain local breeding populations, no further than each species’ effective dispersal distance (e.g., see Gliwicz 1988). Effects of fragmentation of forest stands could also be assessed (Quinn and Hastings 1987; Wilcove 1987). This is an example of using ecological concepts rather than direct scientific data.

Similarly, item 5, assessing population sizes and distributions contributing to long-term viability, could entail use of current concepts and theory on population dynamics and extinction probabilities (e.g., see Reed *et al.* 1986; Soule 1987; Burgman *et al.* 1988; Iwasa and Mochizuki 1988; Maguire *et al.* 1988; Harris and Allendorf 1989; and see Shaffer 1981 for basic concepts of factors affecting population viability). Demographic models (e.g., Slade and Levenson 1982) can be used to estimate population trends and extinction probabilities. Similar demographic assessments have been conducted for grizzly bears (*Ursus arctos horriblis*) in the Yellowstone ecosystem (Knight and Eberhardt 1984).
From a theoretical perspective, other factors might be taken into account, including effects of environmental fluctuations on population stability (Lande and Orzack 1988; Pease et al. 1989), behavior (Tamarin 1988), and effects of disease (May 1988).

Neither scientific data nor ecological theory would offer sufficient information to implement the general guidelines. Thus, professional judgment and personal experience will be necessary. For example, the guidelines might specify the proportion of a general forest landscape that should contain suitable forest stages, and type, amount, and distribution of down wood to be provided. However, how these guidelines are carried out operationally is dependent on professional experience with, and personal understanding of, forest management activities.

4.4 Key Assumptions

Key assumptions for monitoring and testing would be those based on extrapolations from ecological theory and those based on professional judgment and personal experience. Such tests might include assessing expected presence and densities of small mammal populations assumed to be provided by forest stands, and specific amounts and distributions of down wood. They might also include comparing empirical yield tables in landscapes with and without the guidelines applied. Information based on scientific data, such as life histories of each species, would not require testing.

4.5 Questions to Address

When data and experience are being combined, a general set of questions can be asked to help guide development, monitoring, and evaluation of guidelines:

Questions about effects of uncertain or incomplete information.
1. What available information is the “softest” or most uncertain? Why?
2. How does this specifically affect devising, evaluating, and implementing these standards and guidelines? How would you use such information in an advisory system?
3. What additional information, aside from that on the biology or ecology of the species, is needed to make an “informed decision”? Why?

Questions about developing guidelines despite incomplete information.
1. What additional information on the biology or ecology of the species is needed? Why?
2. In question (1), how do you assess “need”? How would you know or evaluate which additional information is worth spending money on?
3. Can you, and should you, proceed with developing standards and guidelines with currently available information? Why or why not? What assumptions and evaluations would this entail?
4. What are the ramifications if you do not develop standards and guidelines at this time? If you do? How would you go about evaluating such ramifications?

Questions about filling in the blanks of knowledge.
1. Whether or not standards and guidelines are currently implemented, how would you decide what additional information needs to be gathered? How would you set priorities?
2. If standards and guidelines are to be currently implemented, how would you identify additional information needed for testing or revising them?
3. How would you gather additional, needed information? Would scientifically designed field studies provide all necessary information? If not, what else would be needed?

Questions about development and use of evaluation tools.
1. What tools would you develop for evaluating alternative forms of standards and guidelines?
2. What specific parameters would be assessed by the tools devised in question (1)? How would the tools be structured?
3. Given available information, which parameters (from question 2) could you currently derive from hard facts, and which from softer expert judgment and personal experience?

4. Is information derived from personal experience, statistical data, ecological theory, and professional judgment substantially different in usefulness? How so? (Define "usefulness": legally, scientifically, administratively, etc.) How would this affect your evaluations of the tool?

Questions about implementing and evaluating plans.

1. How would you evaluate the standards and guidelines? (Hint: use evaluation criteria such as practicality, acceptability, implementation, effects on site productivity, etc.)

2. What would you monitor and why?

3. What specific aspects of the standards and guidelines would you likely reevaluate after the monitoring information was gathered, and why?

4. What roles do personal knowledge, scientific facts, ecological theory, and professional judgment play in such reevaluations?

5 SUMMARY AND CONCLUSIONS

Four main kinds of information are generally used to solve a problem in integrated resource management: scientific data, ecological theory, professional judgment, and personal experience. These kinds of information are often combined in biological evaluations and resource decision-making. Professional judgment and personal experience are relied on more heavily when scientific information is more uncertain.

Methods of evaluating uncertainty include assessments of expected value of perfect or sample information; decision-tree analysis; and a host of other methods from decision theory and risk analysis. Articulating biological assessments and resource management guidelines in an expert system format of knowledge rules can also help clarify what is known and what is derived from theory or judgment. Such an approach helps one articulate key assumptions in evaluations, guidelines, and decisions.

Uncertainty of knowledge should not preclude decision-making. However, critical assumptions and extrapolations should be made explicit. They can be tested under an adaptive management paradigm if measurable parameters and feasible field methods are identified, re-evaluation criteria are specified, and management options are available.

When management guidelines are being devised and resource decisions made, it is helpful to consider key questions about the sources of information used, their reliability, and the ramifications (costs, benefits, and risks to the resources) of proceeding in light of uncertain information.
**LITERATURE CITED**


