Chapter 1

Basic Principles of Decision Making in Natural Resources and the Environment

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Abstract: As public land management merges biophysical, social, and economic objectives, management decision criteria become more extensive. Many of these criteria are value-laden, and yet are not easily expressed in monetary terms. Utility theory has traditionally been the decision model proffered by the management science and operations research communities. More recently, however, the analytic hierarchy process (AHP) has also received considerable attention, primarily because it places greater emphasis on the decision makers' preferences structures. A simple example of the AHP, for college enrolment, illustrates many of the method's salient features, and some of the underlying mathematics. A brief review of some applications of the AHP in natural resources management is also included. Land management agencies need to establish decision models that provide some structure for how decision-support information is organized and applied, so that decisions are made openly within a well-defined framework. In doing so, decision accountability and justification are achieved concomitantly with the process itself.

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1. INTRODUCTION

Early in the beginning of the twentieth century, Gifford Pinchot defined effective natural resource management as "…providing the greatest good for the greatest number, in the long run" (q.v., Pinchot 1947). Interpretation of this principle has varied over time, depending on how the pivotal terms "greatest" and "good" were defined. Nevertheless, the statement's essence still retains validity as active land management enters the next century. Once satisfactory agreement is reached on those value judgments ("good" and "greatest"), it remains to determine *how*, *where*, *when*, *how much*, etc. Someone must decide among alternative courses of action, so that future events can achieve desired values.

The most recent embodiment of the Pinchot principle is *ecosystem management*. In this paradigm, an attempt has been made to remove the chasm that has treated people as separate from their biophysical environment (Unger and Salwasser 1991, FEMAT 1993, Lackey 1998). Now, biophysical, social/political/cultural, and economic processes together encompass the important interactions between people and the land resources upon which they depend. Economics has always been an important component of land management, but now social institutions (e.g., rural communities, indigenous cultures) and biophysical integrity (e.g., ecosystem processes, biodiversity) must also be considered. Nevertheless, one invariant that is still part of effective land management, regardless of how "effective" is defined, is the need to make rational and justifiable choices when faced with alternatives.

Multiplicity in land management objectives and in land management beneficiaries (which ultimately includes everyone) precludes the simultaneous satisfaction of everyone's wishes fully. In some cases, land management objectives are mutually inconsistent, and in other cases, our objectives cannot be fully met given practical limitations of space and time. Despite the fact that not everyone can have everything, land management must address the needs and desires of all stakeholders within the biophysical limitations of the land and the social and political institutions within which people live. To do so requires decision processes that are flexible and that are able to accommodate both subjective/qualitative and quantitative information.

Land management decision making is further handicapped by the uncertainty surrounding future events and by limitations of our knowledge about how the world works (Schmoldt and Rauscher 1996). Unforeseen changes in any of the biophysical, social/political, or economic components of management can render even the most "optimal" choice today ineffective tomorrow. Furthermore, the best science available can often only generalize about future scenarios because scientists do not thoroughly understand most ecosystem components individually, much less how they interact with each other and with human social and economic systems. As with multiple objectives and stakeholders, our decision methods must likewise address uncertainty and allow for periodic re-evaluation over time.

To aid human ability to understand and evaluate management situations and scenarios, a wide variety of analytical tools have been developed. These include, for example, simulation models, geographic information systems, expert systems, econometric models, and optimisation techniques under the umbrella of decision support (Reynolds *et al.* 1999). These aids are important adjuncts to good decision making, but each typically addresses only one aspect of land management. The decision maker must still integrate each tool's analytical results into a rational choice about *what* to do *where* and *when*. Decision analysis techniques take this natural next step to assist with selecting among competing alternatives. The following section provides a brief review of multiple criteria decision making and introduces the analytic hierarchy process (the subject of this book) as an important decision-making tool. After this decision analysis review, some of the existing literature and applications of the analytic hierarchy process (AHP) in natural resources are summarized.

2. MULTIPLE-OBJECTIVE DECISION MAKING

Given that people, monetary resources, facilities, equipment, time, and space are limited, most multi-objective decision problems cannot fully satisfy all objectives. Therefore, decision analysis attempts to compromise on some middle ground, covering all objectives, that maximizes "value" or "utility" or that minimizes "cost" or "loss"—where those terms are defined appropriately within the context of the problem at hand. Because, in most cases, the intent is to prescribe the best decision alternative (as opposed to describing how decisions are typically made, i.e. *behavioural analysis*), decision analysis is often referred to as *normative*. That is, a rational standard is prescribed as the best alternative, given the way that the current problem has been structured.

2.1 Normative Decision Making

The aim of any decision analysis is to lend support to decision making in problems that are too complex to be solved by the intuitive use of common sense alone. Strategic natural resource management decisions are typical examples of such problems. In a decision-theoretic approach, a decision is considered as a choice between two or more alternative measures. In a normative approach to decision-making, the starting point is that a rational decision-maker aims to choose the alternative which most probably maximizes the decision-maker's utility (or value system), based on information available to him or her on the decision alternatives (Kangas 1992). This is the viewpoint in the situation of a single decision maker. In group decision making, the total utility to be maximized can be taken as the combined utilities of the persons belonging to the group. In participatory decision-making processes, some or even all the decision-making power might be allocated to the participants.

In decision support, the aim is to ensure that the decision maker is as informed as possible. Information is produced regarding the decision situation, on alternative courses of action, and on consequences of alternative choices. A complete decision model constitutes the basis for decision support. Three things are included in the decision basis: the alternatives available, information about the consequences associated with these alternatives, and the preferences among these consequences (Bradshaw and Boose 1990). Keeney (1982) has divided decision analysis into *four* phases (the previous three plus one additional aspect): (1) structure the decision problem, (2) assess possible impacts of each alternative, (3) determine preferences of decision-makers, and (4) evaluate and compare decision alternatives. Each aspect of decision-support information has to be sound, so that the best, a good, or at least a satisfactory alternative can be selected. Errors or misinformation in any part of decision analysis can lead to questionable or invalid results.

In decision analysis, the decision situation is viewed holistically. Generally, numerical encoding of information concerning the decision situation can be taken as a precondition for an effective and thorough treatment of a complex decision problem (von Winterfeldt 1988, Guariso and Werthner 1989). Numerical decision analysis is based on logical axioms and a methodology founded on these axioms. This methodology must incorporate decision makers' and other stakeholders' preferences somehow.

A utility model is a mathematical tool that describes problem features, such as goals, objectives, opinions, etc. Decision makers then evaluate alternatives with respect to those problem features. This model is a key to combining the three parts of a decision basis. Utility—explicitly modelled or not—can be seen as an underlying basis of any rational choice. Often, the criteria for decision making are variables of the utility function, and the parameters indicate the importance of the criteria. A very simple utility model represents a decision consequence as the utility value U, which is the weighted (a_i's) sum of the decision criteria X_i evaluated on a particular alternative:

$$U = \sum_i a_i X_i . \tag{2.1}$$

The alternative that produces the highest utility value is accepted as having the most desirable outcome and, hence, should be the one selected. Typically, the approach is *normative* when the aim is neither to explain observed behaviour nor to predict how decisions will be made, but rather to facilitate better decisions than would be possible otherwise. Although human behaviour might not be explained using models of rational choice, preferences of decision makers can be analysed and decision alternatives can be evaluated based on those preferences by an analytical decision model (Kangas 1993). This process adds rigor to decision making and also makes it more explicit.

Utility is influenced by all attributes of the decision problem that have value to the decision maker. It is a measure of subjective desirability. Utility of a single decision maker can also include altruistic elements related to other people's preferences. In which case, maximizing one's expressed utility does not necessarily mean purely self-seeking behaviour. In most cases, utility cannot be expressed in physical quantities, e.g., monetary cost or benefit. The real utility of physical units is determined by their value to the decision maker, and it is, by no means, always linearly related to the units of physical quantities. In decision analyses, it is often better to use relative values instead of physical measures (Forman 1987). In the AHP, relative utility values are referred to as "priority," and the utility model as formulated in the AHP can be called a priority model.

If, by means of a priority model, decision alternatives can be arranged only from the best to the worst, one speaks of *ordinal* priority. If the priority model can be interpreted on an interval or a ratio scale, one speaks of *cardinal* utility. In principle, it is sufficient to determine the ordinal priorities only when the best decision alternative is sought. Estimating the cardinal utility, however, also enables a versatile analysis of a complex decision situation. Cardinality in a ratio scale, as applied in the AHP for instance, also enables sensitivity analysis and risk analyses, among other things, of the decision process (e.g., von Winterfeldt and Edwards 1988). This allows decision makers to conduct "what-if" scenarios and to evaluate the impact of uncertain preferences.

In most decision-making situations, the preferences of decision makers have been more or less neglected when alternatives are evaluated (e.g., Keeney 1988, Bradshaw and Boose 1990). This is also the case in natural resource management (Kangas 1992). For decision support based on operations research methods, problem structuring is too often technique oriented. When applying artificial intelligence methods, the decision-theoretic methodology is typically forgotten (O'Keefe 1988). This being the case, decision analyses in natural resource management can be improved significantly by developing and applying methods that place greater emphasis on the decision makers' and stakeholders' preferences when prioritising decision alternatives. The following section illustrates how the analytic hierarchy process offers an alternative approach to traditional operations research and normative decision methods.

2.2 The Analytic Hierarchy Process

Many decision-making situations involve preferential selection among alternative items, events, or courses of action. When the selection criterion is "least cost," the measurement scale is obvious and choosing becomes easy. In most real-world situations, however, there is not a single scale for measuring all competing alternatives. More often, there are several scales that must be used and often those scales are related to one another in fairly complex ways.

The AHP (Saaty 1980) is designed to help with multiple-criteria decisions. Three important components of the AHP are: (1) the structuring of a problem into a hierarchy consisting of a goal and subordinate features (decomposition), (2) pair-wise comparisons between elements at each level (evaluation), and (3) propagation of level-specific, local priorities to global priorities (synthesis). Subordinate levels of a hierarchy, may include: objectives, scenarios, events, actions, outcomes, and alternatives. Alternative courses of action to be compared appear at the lowest level of the hierarchy. Pair-wise comparisons are made between all elements at a particular level with respect to elements in the level above it. Comparisons can be made according to preference, importance, or likelihood—whichever is most appropriate for the elements considered. Saaty (1980) developed the mathematics to combine pairwise comparisons made at different levels in order to produce a final priority value for each of the alternatives at the bottom of the hierarchy.

As a simple and easily understood example, consider the hierarchy in Figure 1, which is designed to enable one to select a "best" college to attend. The goal, *satisfying college*, appears at the top of the hierarchy. The criteria appear on the next level: *academic reputation*, *cost*, *campus beauty*, *local living climate*, and *social life*. The colleges to be considered are labelled A, B, and C at the lowest level. First, the criteria are compared pair-wise with respect to their importance for producing a satisfying college experience. The scale of integers in the range 1-9 is used for comparison (Saaty 1990). One possible matrix resulting from these pairwise comparisons appears in Table 1. In this matrix, each value a_{ij} indicates how much more important, preferred, or likely row heading i is than column heading j. Corresponding matrix entries a_{ji} equal $1/a_{ij}$. Elements on the matrix diagonal are always unity. The normalized principal right eigenvector **c**' = [0.465, 0.326, 0.085, 0.097, 0.038] of this matrix represents the priority values of those criteria (Saaty 1980).

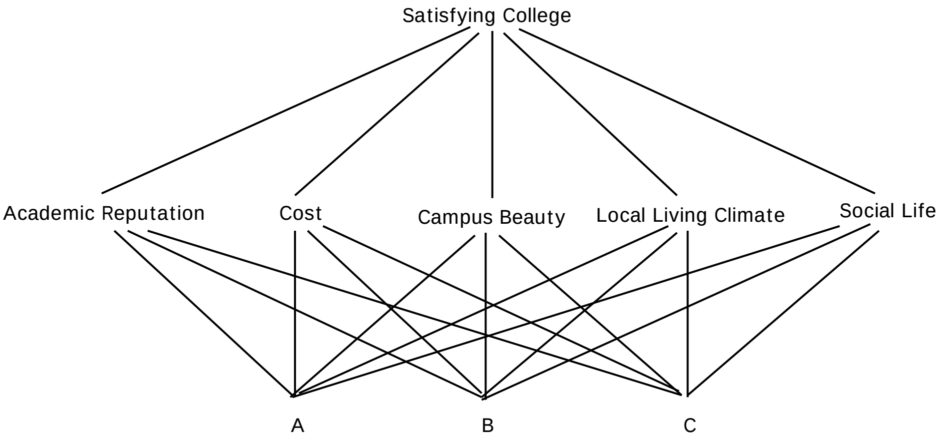

Figure 1. A simple analytic hierarchy for selecting a satisfying college from among three alternatives, A, B, and C, makes use of five criteria. Each of the alternative colleges is scored on each criteria. In general, however, a hierarchy need not be fully connected in this way.

Table 1. The five criteria for selecting a college are compared in a pairwise fashion and assigned a relative importance score.

	Academic Reputation	Cost	Campus Beauty	Local Living Climate	Social Life
Academic Reputation	1	3	5	3	7
Cost	1/3	1	5	5	9
Campus Beauty	1/5	1/5	1	1	3
Local Living Climate	1/3	1/5	1	1	3
Social Life	1/7	1/9	1/3	1/3	1

When all pair-wise comparisons in the judgment matrix **A** are absolutely consistent, i.e. $a_{ij}a_{jk}=a_{ik}$ for all $i \neq k$, then (2.2) holds, where **w** is the vector of priority values. This mathematical statement (2.2) also says that **w** is an eigenvector of **A** with associated eigenvalue n. Because the matrix multiplication occurs on the right, **w** is called a right eigenvector. In the consistent case, n is the only non-zero eigenvalue of **A**. As judgments become inconsistent, however, small changes occur in the a_{ij}, and **A** becomes inconsistent. Then, multiple eigenvectors and eigenvalue solutions exist for (2.2). The largest (or principal) eigenvalue remains close to n as long as changes to the a_{ij} are small and **A** does not become too inconsistent (Saaty 1980). Therefore, the principal right eigenvector is still a good approximation to the consistent-case eigenvector **w**.

$$\mathbf{Aw} = n\mathbf{w} \tag{2.2}$$

Then alternative colleges are compared regarding the extent to which each has these criteria. One matrix, such as Table 2, would be produced for each criterion. Similar to the first matrix (Table 1), a priority vector $\mathbf{w}_1' = [0.637, 0.258, 0.105]$ can be calculated from Table 2. Priority vectors $\mathbf{w}_2, ..., \mathbf{w}_5$ can also be generated for each of the remaining criteria. The degree to which the colleges possess each criterion (stored in the $\mathbf{w}_i$) is weighted by the importance of that criterion c_i and summed across all criteria to obtain a final priority value for that college. In matrix arithmetic, the final priority vector for the colleges is calculated as

$$\mathbf{w} = \left[\mathbf{w}_1 \mathbf{w}_2 \mathbf{w}_3 \mathbf{w}_4 \mathbf{w}_5\right] \mathbf{c} \tag{2.3}$$

A more detailed example of the AHP process appears in Schmoldt *et al.* (1994) with some of the mathematical derivations. Because the final result of the AHP is a numerical priority value for each alternative, the decision maker may then select the highest scoring alternative as the "best." The decision process that has been made explicit in the hierarchy and in the comparisons determines this "best" alternative.

Table 2. The three colleges are compared with respect to the criterion, academic reputation.

Academic Reputation	College A	College B	College C
College A	1	3	5
College B	1/3	1	3
College C	1/5	1/3	1

The analytic hierarchy process has been applied to a wide variety of decision-making problems, both in a practical, as well as academic, context (Zahedi 1986). For example, it has been used for planning, resource allocation, and priority setting in business, energy, health, marketing, forest management, and transportation. The AHP is relevant to nearly any natural resource/environmental management application that requires multiple opinions, multiple participants, or a complex, decision-making process. The next section highlights a few of the many such AHP applications.

3. THE AHP AND NATURAL RESOURCE MANAGEMENT

Because natural resource management often entails making choices among alternative management regimes, decision support tools are proposed as instruments for making rational, carefully reasoned, and justifiable decisions. This section briefly reviews some of the applications of these decision support tools, particularly the AHP, for forestry and natural resources. The review does not focus on technical issues; the chapters contained in this book offer excellent expositions on both the technical aspects of the method and novel approaches used to apply the method to different problem situations.

While the AHP was developed only in the late 1970's, it has become one of the most widely used techniques as shown by the extensive literature published in journals and books, most of which are in areas outside natural resources. AHP applications in forestry, agriculture, and natural resources are still surprisingly limited. Chapter contributions contained in this book constitute perhaps the most updated compendium of recent applications of the AHP in natural resource and environmental management. These chapters also contain extensive reviews of literature that may not be covered in this section.

Published applications in forestry include: forest management (Mendoza and Sprouse 1989); forest planning and decision making (Kangas *et al.* 1996, Pukkala and Kangas 1993); risk assessment in assessing reforestation alternatives (Kangas 1993a); risk and attitude toward risks in forest planning (Pukkala and Kangas 1996); eco-labelling and certification of forest products (Pesonen *et al.* 1997); forest protection through selection of risk factors for spruce beetle outbreaks (Reynolds and Holsten 1994); setting priorities for restoration projects (Reynolds 1997); identification and prioritisation of fire research needs (Schmoldt and Peterson 2000); and assessment of criteria and indicators for evaluating forest sustainability (Mendoza and Prabhu 2000). Other forest-related applications of the AHP include: assessment of forests' scenic values (Kangas *et al.* 1992); assessment of factors affecting timber bridge materials (Smith *et al.* 1995); development of resource management plans for National Parks (Peterson *et al.* 1994); and resource inventory and monitoring in National Parks (Schmoldt *et al.* 1994).

Wildlife management is another area that has received considerable attention for AHP-related studies. Pereira and Duckstein (1993) combined the AHP with geographic information system (GIS) to study habitat suitability for Mount Graham red squirrel. Mendoza (1997) also described an integrated model combining the AHP with GIS to generate habitat suitability indices for desert tortoise. Kangas *et al.* (1993b) used the AHP to estimate wildlife habitat suitability functions using experts' judgments.

Other applications include: measurement of consumer preferences for environmental policy (Uusitalo 1990); evaluation of irrigation systems (Mingyao 1994); managing fisheries (DiNardo *et al.* 1989, Imber 1989, Levy 1989); energy planning and resource allocation (Hamalainen and Seppalainen 1986, Gholamnezhad and Saaty 1982); and sustainable agriculture (Mawampanga 1993).

One of the areas where the AHP has received wide application is land use suitability analysis. Banai-Kashani (1989) and Xiang and Whitley (1994) offer excellent reviews describing the potential of the AHP for general site suitability and land capability analyses. Huchinson and Toledano (1993) describe the use of the AHP in conjunction with GIS for designing land use plans considering multiple objectives and participatory approaches to planning and decision making. As land use become more constrained and the land allocated to various activities continues to shrink, suitability analyses take on added importance.

4. CONCLUSIONS

The days are long gone when natural resource decisions could be based on a single metric, e.g. net present monetary value, while addressing a single resource, e.g., timber. Even the decision-making protocol has changed, now including multiple participants with vastly different value systems. Normative decision methods (offering a rational choice) must now include both decision makers and stakeholders, and must quantify their preferences in a realistic way.

The analytic hierarchy process not only offers some advantages over traditional decision methods, but it can integrate with those other approaches to take advantage of the strengths inherent in each. Several AHP applications are mentioned above, while the remainder of this text provides many detailed examples. Even though the number of AHP applications described in forestry and related disciplines is growing steadily, real-world examples of the AHP in actual resource management use are extremely limited. Given the method's relative ease of use, and yet broad applicability, its disuse is somewhat surprising. In our experience, though, it seems that many land management organizations expend a great deal of time and effort collecting information about managed resources, decision alternatives, and decision consequences, but pay relatively little attention to how all that information must be integrated into a rational choice. The assumption seems to be that the correct decision alternative will materialize automatically from enormous data gathering efforts. Rather, a decision framework, like multi-attribute utility theory or the AHP, is the glue that binds all of the decision support information together, and helps the decision maker create some sense out of it. Even with volumes of information, there is no guarantee that good decisions will result. Significant effort must also be placed on how preferential choices are made.

Considering the complexity of most management issues and compliance regulations, the AHP can extend to a wide array of managerial and planning tasks. For example, management and planning for a large watershed may include issues related to water quality and quantity, forest management, wildlife management, and recreation. Input is required from subject matter experts in each of these disciplines in order to establish priorities and make informed decisions regarding spatial and temporal distributions of resources. Because watersheds generally involve the flow of materials between public and private lands, additional input is often needed on social, legal, and political aspects of resource condition and value. In addition to its breadth of application, the AHP is relatively easy to apply, to understand, and to interpret. These attributes of the AHP validate its focus in this book as a valuable tool for decision making.

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