Neural, Parallel, and Scientific Computations 21 (2013) 51- 66

DECISION MAKING STRATEGIES FOR ENVIRONMENTAL MANAGEMENT

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Abstract. The concept of adaptive management has become a foundation of effective environmental management for initiatives characterized by high levels of ecological uncertainty. In this paper we propose explicit criteria for helping managers and decision makers to determine the appropriateness of either passive or active adaptive-management strategies as a response to ecological uncertainty in environmental management. Four categories of criteria are defined and applied using hypothetical yet realistic case-study scenarios that illustrate a range of environmental management problems.

We also deal with the interaction between optimisation technologies and the environmental management. In recent years, the environmental impact of planning decisions has received increasing attention, as negative effects on the ecosystem may affect production and consumption. Hence, there is a need to assess and quantify environmental services as well as environmental impacts, so that these can be included in the decision making process. At the same time, recent trends in optimisation software and Internet technology have spawned a new research area in the field of distributed optimisation applications for several domains, including environmental management.

Keywords - environmental management, environmental optimisation, decision support systems

1. INTRODUCTION

Most of the environmental problems are characterized by two main features. On one side, environmental processes and resources are often characterized by irreversibility, i.e. their consumption, conversion, exploitation and degradation can be a one-way decision, and therefore appropriate modelling is required (Tassopoulos & Papaioanou, 2005).On the other side, the uncertainty deriving from incomplete knowledge concerning natural processes and the effects of our actions on those processes, call for a particular attention in choosing the modelling techniques to be deployed. The theoretical framework for decision making in environmental applications in the presence of uncertainty is the quasi-option value approach, first discussed by (Arrow et al.,1974; Henry, 1974) and subsequently investigated, in its different features, in papers by (Conrad, 1980; Hanemann, 1989; Coggins & Ramezani, 1998; Gillote & De Lara, 2005), among others. In the same dynamic decision framework, (Pindyck, 2000), has

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Received August 10, 2012

discussed the problem of global environmental damage mitigation. However, it is in (Clarke et al., 1990) that greater emphasis is for the first time given to problems of gradual conversion optimal strategies rather than optimal timing of ‘jump’ decisions, involving a stochastic dynamic programming approach. Finally, other operational research approaches have been largely applied to forestry management, see for example (Gassmann, 1987), and other environmental planning problems.

The environmental management can be classified into three main categories. The first category concerns multicriteria optimisation methods (Cassidy, 1996; Dente, 1995). These take into account various environmental goods and are used to determine the basis for sustained land use and to examine the efficiency of economic instruments for the maintenance of biodiversity. Multicriteria optimisation methods are typically applied to public management problems that are concerned both with economic efficiency and some environmental impact targets, an example being the development of integrated systems for waste management. Such decision support systems enable the decision maker to evaluate integrated policies in all their aspects (e.g. waste collection, treatment and disposal), both from an economic and an environmental perspective. On one side, alternative policies are analysed in a cost/benefit framework. On the other side, an environmental index is calculated to synthesize impacts associated to each policy, in order to account for environmental externalities which cannot be captured in the economic analysis. Each policy is the result of an optimisation process aiming to minimize financial costs and environmental impact (both aspects can be weighted according to the decision maker attitude). Policies that have shown to be efficient under both criteria are the output of the decision support tool. Although much of the input data can be highly case dependent, a decision support framework may have a general structure that can be personalized by each user through a set of questions and requirements input.

The second category is represented by complete conversion problems modelled as optimal stopping problems. The investment in pollution control or the transformation of an island in a tourist village could be examples of environmental problems where the control variable can only take the value 0 and 1. Dynamic programming models, originally developed in order to time and evaluate financial and real projects investments in the presence of market uncertainty, can be fruitfully applied to decisions and investments concerning environmental resources.

Stochastic Programming (SP) is the third approach considered. SP can be applied to model those problems where the main objective is to find the evolution of a portfolio of mixed allocation of environmental resources over time. We refer to these problems as gradual conversion problems, where the control variables can take continuous values. The reader can refer to (Cassidy, 1996; Dente, 1995) for an in-depth treatment of multicriteria optimisation methods.

Furthermore environmental decision problems are usually characterized by a high level of complexity. In such a context, Multi Criteria Decision Analysis (MCDA) represents an important and crucial step (Goodwin et al., 2001). MCDA consists of one or more procedure to assist the decision maker(s) (DM) during the phases of the decision process, and takes into account possible sources of uncertainty and/or different utility functions. Sometimes the problem is expressed in the form of a decision table connecting benefit or cost criteria and alternatives. Despite the Multiple Objective Decision Making (MODM) in the MCDA problems, only a finite number of criteria and alternatives are considered. After having eliminated all the dominated alternatives (if any), the problem consists of selecting the *best* alternatives (optimal choice problem), or ranking all the alternatives (ranking problem). Moreover, we could consider both stochastic and deterministic approaches, but in what follows only the deterministic approach will be considered.

2. MULTI-CRITERIA DECISION ANALYSIS

A form of MCA that has found many applications in both public and private sector organisations is multi-criteria decision analysis or MCDA for short (also known as multi-attribute decision analysis, or MADA). This chapter explains what MCDA is and then outlines what is required to carry out such an analysis.

MCDA is both an approach and a set of techniques, with the goal of providing an overall ordering of options, from the most preferred to the least preferred option. The options may differ in the extent to which they achieve several objectives, and no one option will be obviously best in achieving all objectives. In addition, some conflict or trade-off is usually evident amongst the objectives; options that are more beneficial are also usually more costly, for example. Costs and benefits typically conflict, but so can short-term benefits compared to long-term ones, and risks may be greater for the otherwise more beneficial options.

MCDA is a way of looking at complex problems that are characterised by any mixture of monetary and non-monetary objectives, of breaking the problem into more manageable pieces to allow data and judgements to be brought to bear on the pieces, and then of reassembling the pieces to present a coherent overall picture to decision makers. The purpose is to serve as an aid to thinking and decision making, but not to take the decision. As a set of techniques, MCDA provides different ways of disaggregating a complex problem, of measuring the extent to which options achieve objectives, of weighting the objectives, and of reassembling the pieces. Fortunately, various computer programs that are easy to use have been developed to assist the technical aspects of MCDA, and these are set out in the Software review.

The first complete exposition of MCDA was given in (Keeney & Raiffa, 1976) whose book is still useful today. They built on decision theory, which for most people is associated with decision trees, modelling of uncertainty and the expected utility rule. By extending decision theory to accommodate multi-attributed consequences, (Keeney & Raiffa, 1976) provided a theoretically sound integration of the uncertainty associated with future consequences and the multiple objectives those consequences realise. The main assumption embodied in decision theory is that decision makers wish to be coherent in taking decisions. That is, decision makers would not deliberately set out to take decisions that contradict each other. No-one would place several bets on the outcome of a single race such that no matter which horse won they were certain to lose money. The theory expands on this notion of coherence, or consistency of preference, and proposes some simple principles of coherent preference, such as the principle of transitivity: if A is preferred to B, and B to C, then A should be preferred to C, which is a requirement if preference is to be expressed numerically. By treating these rather obvious principles as axioms it is possible to prove non-obvious theorems that are useful guides to decision making. A parallel can be found in the study of geometry. Simple principles like ‘The shortest distance between two points is a straight line’ are combined using the rules of logic to prove theorems that are not obvious, like the Pythagorean principle, that the square of the hypotenuse equals the sum of the squares of the other two sides. (Communities and Local Government, 2009).

Over the past several decades, environmental decision-making strategies have evolved into increasingly more sophisticated, information-intensive, and complex approaches including expert judgment, cost-benefit analysis, toxicological risk assessment, comparative risk assessment, and a number of methods for incorporating public and stakeholder values. This evolution has led to an improved array of decision-making aids, including the development of Multi-Criteria Decision Analysis (MCDA) tools that offer a scientifically sound decision analytical framework. The existence of different MCDA methods and the availability of corresponding software contribute to the possibility of practical implementation of these methods. However, even though a great deal of work has been done in justifying the theoretical foundation of these methods, real-life applications is rare. The critical attitudes of different MCDA schools toward alternative approaches may have been an obstacle in the application of MCDA. Additionally, no MCDA method is theoretically appropriate for group decision processes, and all MCDA methods and tools necessarily use significant simplifications and assumptions to rank environmental policy alternatives.

2.1 Multi criteria decision analysis methods and tools

Environmental managers must decide what they wish to achieve through environmental management and how much they are willing to pay to achieve it. Controversy arises when managers:

(1) have different objectives with different priorities or
(2) expect different outcomes from management decisions.

Those affected and involved in the decision-making must also decide what they care about, how they prioritize those concerns, and how much they are willing to pay to achieve stated objectives. There are many alternatives for the management of contaminated sediments, and there are important tradeoffs among ecological, economic, technical, and societal objectives. As an example of a trade off, achieving significant benefits and minimizing cost are two conflicting objectives. As a consequence, a given alternative may not take clear precedence over other alternatives with respect to every objective. This may present a dilemma to a decision-maker trying to choose a single alternative. The common purpose of MCDA methods is to evaluate and choose among alternatives based on multiple criteria using systematic analysis that overcomes the limitations of unstructured individual or group decision-making (Belton & Steward, 2002; Von Winterfeldt & Edwards, 1986).

The following main categories of problems are considered on the basis of MCDA (Belton & Steward, 2002):

- *Sorting* alternatives into classes/categories (e.g., “unacceptable,” “possibly acceptable,” “definitely acceptable,” etc.).
- S*creening* alternatives, eliminating those alternatives that do not appear to warrant further attention; i.e., selecting a smaller set of alternatives that (very likely) contains the ‘best’ alternative.
- *Ranking* alternatives (from “best” to “worst” according to a chosen algorithm).
- *Selecting* the “best alternative” from a given set of alternatives.
- *Designing* (searching, identifying, creating) a new action/alternative to meet goals. (Kicker et al., 2005).

3. ADAPTIVE MANAGEMENT: AN INTRODUCTION

AM (Adaptive Management) is designed primarily to help managers learn about complex ecological systems by monitoring the results of a suite of management initiatives. In this sense, it is a systematic approach to improving the management process and accommodating change by learning from the outcomes of a set of environmental management policies and practices (Holling, 1978; Walters, 1986). The generally stated goal of AM is to improve managers' knowledge about a set of well-defined ecological objectives through the implementation of carefully designed quasi-experimental management interventions and monitoring programs. At least in theory, the increased knowledge should also assist resource managers in responding to the inevitable ecological surprises that arise over the course of a management intervention (Clark, 1980). However, economic and social and political surprises also can arise over the course of a management intervention, thus creating problems for an ecologically focused adaptive management plan.

Two primary types of adaptive management have been defined, "passive" and "active", which vary in their degree of scientific rigor and experimental design (Walters & Holling, 1990; Halbert, 1993). Both approaches are valuable and (as discussed in more detail in the next sections) either may be considered more or less appropriate depending on the circumstances of a given management problem. In passive adaptive management, managers typically use historical data, from the specific area under consideration or from areas considered to be ecologically comparable, to develop a "best guess" hypothesis and to implement a preferred course of action. Outcomes are monitored and new information is used to update the historical data set and, if necessary, the hypotheses and management action. Under active adaptive management, in comparison, managers typically seek to define competing hypotheses about the impact of management activities on ecosystem functions and, in turn, design management experiments to test them. In this way, systems are deliberately tested through management interventions, often with several alternative types of management activities attempted in sequence or in parallel so as to observe and compare results. Thus, the scope of an active AM initiative, as conventionally interpreted, can vary from that of a broad, organizing framework for management of a natural environment to a more limited scope that addresses a specific management problem or even one aspect of a problem (Gregory et al., 2006).

3.1 Assessing the viability of environmental management

When considering an environmental management problem, we believe there are four topic areas that should be used to establish sensible criteria regarding its appropriateness for the application of AM techniques. These include:

(1) the spatial and temporal scale of the problem,
(2) the relevant dimensions of uncertainty,
(3) the associated suite of costs, benefits, and risks, and
(4) the degree to which there is stakeholder and institutional support.

Each of these criteria can be cast as questions to be posed by resource managers contemplating the use of an AM approach. These questions, and the responses they naturally imply, are intended to form a more defensible basis on which resource managers can systematically probe the pros and cons of various options for the selection and implementation of AM approaches. In order to illustrate use of these criteria, the ensuing discussion employs four hypothetical but realistic case-study scenarios that exhibit a range in complexity. They are realistic in the sense that they are grounded in actual examples for which resource managers and land-use planners have either considered or implemented an AM approach. As summarized in Table 1, these four cases include (at lower levels of complexity) a tree-fertilization application and a fisheries-restoration example and (as complexity increases) an assessment of wildfire fuels management and a regional land-use planning example.

Spatial and temporal scale: Most environmental management problems cover multiple geographic and temporal scales. Understanding the spatial and temporal dimensions of the decision context is an important starting point for probing opportunities to successfully apply AM. The basic question is whether it is reasonable to design experimental management regimes that might cover large geographic areas or extend many years - in some cases, decades - into the future.

Duration: AM must account for the response time of parameters chosen as suitable end points for the resource-management problem. Support for AM initiatives is likely to be lower in cases where results of the proposed manipulation will take a longer time to become known. Holding other things constant, waiting a longer time for results means higher costs and a greater opportunity for contamination of the study design due to the influence of external factors. With respect to costs, evaluation schemes comparing alternative AM design options generally involve calculating the discounted sum of the expected annual net benefits (i.e., benefits minus costs), with annual values defined in terms of expected results based on probability-weighted hypotheses (Walters & Green, 1997). Given the typical practice of using a positive discount rate (most often in the range 3%-6%) to estimate present-day equivalents, the value assigned to benefits or costs occurring in the near future (i.e., in 1-5 years) is substantially greater that those occurring in the medium-term of far future (i.e., more than two or three decades hence). To some extent the duration of a management strategy is a function of the problem context. In our simplest case, monitoring the growth response of seedlings to fertilization (Problem 1 in Table 1), the response time would be short (two or three years) and unproblematic from an experimental design point of view. On the other hand, monitoring the accumulation of forest fuels across alternative treatment regimes, as required in the wildfire fuels management case (Problem 3), might require decades. And taking into account the lag-time response of key landscape-level indicators of biodiversity to climate change (Problem 4), such as might be required to validate the selection of a protected area boundary within a land-use plan, suggests that very long timelines (several decades or more) would be required. The duration of an AM plan is also a function of the selected design, and here AM proponents often have failed to do a careful job stating and/or analyzing their case (Gregory et al., 2006). Consider Problem 2, which could involve changes in water flows to encourage higher salmonid populations. An active AM approach (assuming baseline data of reasonable quality) might see three or four different flow levels, each held for up to four years, for a total duration of 12-16 years. Replication of these results would double this timeline. These are long time periods for any results-oriented management agency. One option is to consider setting the experiments up using a titration or step-down strategy, where rules are developed to help decide whether the results of the first or second trials are sufficiently strong that no further experimentation is necessary. Decision-analysis techniques are helpful in setting up this type of a priori analysis (i.e., by formally estimating the value of additional information (VOI) to be gained through additional trials) but they rarely have been used as supporting justification when proposing an AM plan.

Spatial complexity: AM plans that involve large areas, such as Problem 2 (due to restrictions on other land uses) and the climate-change land-use problem (Problem 4), face numerous management hurdles due to the spatial extent of the associated impacts. From the standpoint of the ecological sciences, the types of broad-scale questions often being addressed at this scale (e.g., the best location for a protected area as part of Problem 4) often preclude the use of replication and other important experimental-design elements; there is simply no comparable geographic area because of the extent of the AM related consequences. This is significant, be-cause learning requires a comparison to something, be it a control plot or a differently managed river or forest or landscape. While observational designs (Schwarz, 1998) and retrospective studies (Smith, 1998) offer a good deal of analytical support in such situations, these methods represent a compromise away from a "pure" experimental design. A direct correlation also often exists between the geographic scale of the problem and the number of jurisdictions, policies, and stakeholders that must formally be taken into consideration. Not surprisingly, there are few examples of successful "true" experimental designs at the scale of watersheds or large ecosystems. What often happens, instead, is that AM initiatives are initiated on subsets of the problem (e.g., individual reaches or tributaries of a river) with few opportunities for the transfer of this learning to other areas or back to the overall management plan. Yet this lack of connection between subsets of a given AM plan need not be the case. If thoughtful choices are made about where to conduct assessments so that they focus on key uncertainties and can be "scaled up" so as to be applicable to larger areas, and then AM initiatives can work well - for an example, see (Bunnell & Dunsworth, 2004).

External effects: A further consideration is control-ling for background trends, including both other developments in the area that themselves create environmental changes and cumulative effects that result from other management initiatives taking place over the duration of a trial. Designing experiments, based on explicit hypotheses that are sufficiently powerful to unravel the causal webs of interaction between management actions and ecosystem responses in the midst of large-scale environmental changes - what statisticians would call "nonstationarity" and others simply a "shock" - is no trivial matter. The sheer analytical complexity of designing AM experiments to cope with the confounding of results with trends external to the experimental treatment can be overwhelming. As a result, AM applications (especially in more dynamic management environments) are more likely to be successful when the management problem is tightly specified in terms of its temporal and spatial bounds. From an AM-design perspective, anticipating the impact of external effects can add significantly to the complexity of an experimental design. Yet if this complexity is viewed as a blanket reason to forego learning opportunities through AM, then a host of potentially significant applications - involving questions such as those at the forefront of Problems 3 and 4 - may be neglected and the scientific uncertainty associated with proposed strategies will largely be hidden from the view of decision makers. When the management environment is very active, and particularly if multiple resource- management agencies are involved in the study area, a better approach is to set up an AM design that recognizes complexity and has sufficient predictive capability to allow for a choice among management actions depending on the status and significance of anticipated external events. If this design capability is not possible - because of financial or temporal constraints or due to a lack of predictive capability regarding the nature or timing of significant external events - then serious consideration should be given to restricting the scope of the trial so as to increase confidence in the anticipated ecosystem response.

Dimensions of ecological uncertainty: Dealing effectively with what ecological uncertainty implies for the design of environmental management plans is the core purpose of AM. Yet the term "uncertainty" covers a wide range of phenomena relating to the outcomes of a plan, the assumptions that underlie management interventions, the values associated with the anticipated consequences, and a variety of institutional responses. Resource managers who want to apply AM must carefully assess these various dimensions of uncertainty and the confidence which they and other participants (community residents, resource users, First Nations, academic scientists) have in the resulting assessments.

Structural uncertainty: Structural uncertainty results when important relationships between ecological variables have not been identified correctly or when their functional form is not known with precision. Enthusiastic AM supporters optimistically claim the surprises that may arise in such circumstances can provide some of the best opportunities for learning. Unfortunately, the very notion of clearly documenting what we do not know as the basis for experimenting with valued and, in many cases, fragile ecosystems can pose a dilemma for any manager. It is hard to envision participants engaged in a land-use planning exercise that is addressing fundamental climate-change uncertainties who would willingly accept any experimental approach that could have 'surprising' adverse outcomes on an at-risk species, other conservation objectives, or even timber supply. Implementation of AM is difficult whenever significant surprise outcomes related to pre-identified structural uncertainties (and subject to multi-stakeholder examination) are possible. Before proceeding with an AM plan, therefore, managers must have some confidence in the level of resilience (i.e., the adaptability to change) that exists within both the ecological and social systems to be managed. Low levels of resilience must be considered carefully, regardless of AM's potential to reduce ecological uncertainty over time.

Parameter uncertainty: A common point of contention in the design of AM plans is examination of the statistical uncertainty inherent in a proposed AM application. This dimension refers to the uncertainty associated with parameter values that are not known precisely but can be assessed and reported in terms of the likelihood or chance of experiencing a range of defined outcomes. A variety of methods exist for representing probabilistic variables and model inputs, typically involving probability distributions (Morgan & Henrion, 1990; Cullen & Frey, 1999). When the underlying (ecological or causal) mechanisms are known, there can be a theoretical basis for selecting a particular distributional form; variables derived from multiplicative processes often approach a lognormal distribution, purely random processes often are represented by a Poisson distribution, and so forth. Yet even when such theoretical models are applicable, real world conditions often lead to significant deviations. In some cases (particularly if data quality is high), parameter estimation techniques can be used to identify an appropriate distribution. In other cases (particularly if data quality is low or if there is substantial controversy or disagreement among experts), there is often no substitute for expert-judgment elicitation techniques. In such cases, technical experts might (for example) be asked to estimate the 90 percent confidence intervals for a calculated expected value, such as the maximum seedling growth in five years (e.g., Problem 1) or the expected juvenile salmon biomass (e.g., Problem 2). AM seeks to apply the techniques of formal scientific investigation so as to reduce parameter uncertainty through the design of experimental trials or effective monitoring regimes that will be capable of refining or redirecting implementation methods. In the case of assessing alternative forest-fertilization regimes, the opportunity to develop statistically powerful experimental trials is readily evident. Unfortunately, the ability to successfully meet the strict requirements for randomization, replication, and representation lessens with both the number and scope of the uncertainties that must be probed. Consider the case of the land-use plan (Problem 4): developing an experimental or monitoring design capable of dissecting the interacting effects of changes induced by climate change on forest growth rates, natural disturbances, and species composition using end points that include timber supply and biodiversity conservation would be a monumental task. This suggests that scientists must be realistic about the ability of AM experiments to reduce uncertainty, rather than simply develop a better understanding of it, and that careful screening of uncertainties is required to distil which sources of uncertainty are thought to matter the most from the standpoint of stated management objectives and feasible alternatives.

Stochastic uncertainty: Stochasticity, or variation due to pure chance and unrelated to systemic factors, is a particular form of uncertainty that requires special attention in the design of AM initiatives. The problem from a design perspective is that inherent randomness, associated with many aspects of nature, is irreducible in principle. Stochastic uncertainty thus affects the design of AM experiments to the extent that outcomes are dependent on the frequency of, and control over, an unpredictable yet important triggering event or condition. Consider the assessment of fuel-management treatments in Problem 3. While it is possible in theory to apply most of the tools for a powerful statistically designed experiment, the ultimate outcome - under-standing the efficacy of treatments in reducing wildfire impacts - is dependent on experiencing a wildfire itself. However, a wildfire may occur partway through a multi-year treatment program or 50 years afterwards or not at all; it may be very intense or slow; and it may have a wide range of different effects on the forest (e.g., it may affect only tree crowns or burn surface debris and soils). Such an uncooperative (from an AM standpoint) natural event may "test" certain treatment areas and not others. Under these circumstances, then, the question becomes: To what extent will managers be able to attribute identified outcomes (e.g., a low-intensity fire within a certain treatment area or the absence of a destructive fire altogether) to a specific AM plan? If managers have little or no confidence in their ability to provide a positive response, then the added value of conducting experimental trials (in contrast to passive AM or even simple "best-guess" management) may be minimal. Thus, experimental AM may be an unreasonable concept when the resolution of key sources of uncertainty relies on low probability, randomly triggered, and highly variable events. One response to stochastic uncertainty could be to expand the duration of the AM treatment, since randomness will tend to "settle out" over time and thus make it easier to separate signal from noise. However, such a strategy may conflict with other objectives such as cost or external effects and would also need to be balanced with a temporal scale tolerated by managers and key stakeholders.

Confidence in assessments: A final important dimension of ecological uncertainty is the degree of confidence in assessments held by scientists and other participants. If the level of uncertainty is high (for any of the reasons discussed above), then the use of AM may be inappropriate because the results of planned experiments will not be interpretable. Moreover, if very little is known, then it may be impossible to develop testable hypotheses or to separate the effects of experimental manipulations from external influences without the benefit of additional data (e.g., from baseline field studies, modelling, etc.). However, it is unclear in many cases if the lack of confidence in assessments is brought on by real uncertainty surrounding the system or if it is the product of limited precision across the sciences. One response to this dilemma is to import information from another ecologically comparable area (at least with respect to key dimensions of the problem under consideration) about which substantially more is known. Another response is to make use of expert-judgment techniques, based on the methods of decision analysis, which can help to clarify assessments of confidence in two ways: they can help to make assessments of confidence explicit, for example by moving from verbal to quantitative statements of uncertainty and thus overcoming linguistic imprecision, and they can help by making explicit any differences between experts. Formal techniques for ascertaining the level of confidence in assessments are well defined (Morgan & Henrion, 1990; Keeney & Von Winterfeldt, 1991) and analytical approaches to explicitly express the degree of confidence in judgments continue to improve. For example, methods for documenting a "traceable account" - i.e., a formal record of the lines of evidence used and the means of reconciling any differences among them - have become more common (Moss & Schneider, 2000). More recently, Van der Sluijs in (Van der Sluijs et al., 2005) and others have developed formal approaches to documenting the pedigree of information sources as a semi-quantitative rating of reliability. These advances are encouraging and should be promoted further when considering the implementation of AM, as should the general use of formal expert-judgment elicitations (Gregory & Failing, 2002). Nonetheless, numerous writers on the topic of AM have pointed out the inherent difficulties associated with bridging the gap between scientists, managers, and stakeholders on the topics of confidence and credibility. Walters in (Walters, 1997), for example, has chastised scientists who promote research self-interests, political decision makers who blame inaction on the need to first resolve uncertainties, and stakeholders who focus on a single uncertain ecological value. A skilled participant can nearly always spin issues of uncertainty management in creative and self-serving ways. In our fuels management case study, for example, individuals opposed to pre-scribed burns due to misperceptions about their ecological risks can emphasize a lack of confidence in estimates of smoke impacts on the elderly or aesthetic effects on tourism to the extent that they feel these arguments will help to win over a larger - and similarly opposed - audience. While this type of strategizing can occur at almost any scale of AM application, its likelihood mounts as the uncertainties become more profound, the consequences more severe, and self-interests increasingly threatened.

Evaluating costs, benefits, and risks: Many AM approaches fail or are abandoned because proponents do not fully understand, or have not taken the time to identify, the targets that they seek to achieve. Accurate predictions of future costs, benefits, and risks that will result from an AM plan hinge upon the careful specification of its often wide-ranging consequences. To this end, the basic framework for evaluating the costs, benefits, and risks of adaptive-management options should be no different from that required for any other resource-management initiative: first clearly define management objectives (which can broadly be characterized as controlling costs, maximizing benefits, and reducing risks) and then use these multiple objectives to evaluate a plausible range of alternatives, while taking into account key uncertainties regarding both consequences and likely institutional responses. Added to this basic framework is the requirement to state a range of possible hypotheses about the response of the natural system, and to evaluate design options based on the probability of each hypothesis being correct.

Specifying benefits and costs: Identifying the benefits of AM plans begins with all the standard problems (How will changes in habitat quality affect future numbers of a key species? How will changes in land prices over the next 30 years affect population densities near to a protected area?) but adds to these the problems of addressing multiple trials that will achieve their results with varying probabilities of success. Simply collecting the information required to complete each of these evaluations can be particularly difficult, and time consuming, when considering alternative AM proposals. With active AM plans, for example, the plausible range of values for the outcomes of interest need to be estimated for each of several hypotheses about the prevailing states of nature (Gregory et al., 2006). Small wonder that decision makers often need (and do not always receive) help in deciding between a single non-experimental plan (i.e., passive AM, with monitoring for the key sources of uncertainty and flexibility in future management options) and an experimental program of comparative trials (i.e., active AM, involving several explicit experimental treatments). Technical specialists who work over many months or years on an experimental regime often feel that their design is close to ideal in the sense that all possible influencing factors have been taken into account. In our experience (as outside analysts, called in to evaluate such plans), we have yet to see the perfect strategy. This point is not intended to confuse good decision making, which is within the control of managers, with the success of outcomes, which - because of factors such as variability and stochastic uncertainty - will remain, to some degree, outside their control. Instead, the conclusion is that the predictive capacity of study hypotheses is generally less than anticipated - often substantially so. Within the context of these general difficulties in anticipating the benefits and costs of AM plans, there are two issues of particular concern. The first is the need to weigh the impact of potential opportunity costs. As discussed above, long time lines can make it difficult for managers to take other actions in the same geographic area or affecting the same resources. To the extent that other beneficial actions (e.g., one-time-only habitat enhancements with a short turn-around time) are postponed in order to preserve the clarity of experimental results, this represents an opportunity cost (associated with foregone options) that might not be possible to define at the inception of the AM initiative. The second issue arises when definitive actions may need to be taken sooner than expected due to institutional or political reasons, which could (in the extreme) result in the midcourse termination of an AM plan. Either way, unanticipated changes in the experimental design will have the unfortunate effect of decreasing the relevance of a priori evaluations and will make it more difficult, if not impossible, to interpret with sufficient accuracy the results of trials or ongoing monitoring.

4. CONCLUSIONS

When dealing with environmental planning problems, one of the main goals is to compare development versus conservation opportunities, trying to capture all sources of value from a private as well as a social perspective. Environmental models are often common to several classes of end users, at a national and, sometimes, global level. Pollution levels, constraints on minimum natural area size or on development of natural reserves, are generally imposed at a national level. However, data are frequently extremely case specific and should be collected and managed at a local level. Therefore, the local manager should be able to remotely communicate information concerning data specific to the problem and ask for the most suited model and a rapid and clearly comprehensible summary of the results. Inversely, in some cases, data may be very difficult and costly to be collected, but can then be exported to several domains or applications (as for example data on public good valuation).

Taking into account these considerations, it becomes immediately clear that the availability of decision making tools via an ASP model is a very valuable resource in investigating this kind of problem. In this work, we have introduced the OSP platform and a DSS for land allocation problems based on a SP model. The Appiano Gentile Park was chosen as a case study because it is emblematic of a class of problems arising in the European context of environmental management, where wilderness areas are scarce and investments in land remediation are often required. We believe that the outsourcing of such decision tools through ASP is a viable and promising approach, considering the growing acceptance and interest in OR-based methods for environmental planning problems.

Decision making in environmental applications can be profitably enhanced by the use of quantitative models, capable of capturing the inherent uncertainty and accounting for both economic and social/environmental aspects of the problems. However, the quantification of some of the parameters and variables at stake can be non-trivial. This is particularly true when dealing with public goods (e.g. water, air, landscapes, etc., as in Figure 1, see in Appendix 1) that are not exchanged in the market because their value may be only partially or not at all reflected in a price. In this paper, we are also concerned with the practical implementation and deployment of these models. Several software tools (algebraic modelling languages and solvers amongst others) are available to modelling experts for the development and testing of optimisation models. The maintenance of local installations of these tools can often be time consuming, mainly because the software components required in the modelling and solution process are provided and supported by several different companies. In order to be deployed for decision-making, optimisation models need to be ‘wrapped’ by easy-to-use interfaces. Having taken this into account, we have identified the Application Service Provision (ASP) architecture as a viable approach to

(1) provide modellers with remote integrated modelling and solution systems for the development and testing of optimisation models;

(2) enable decision-makers to remotely access customisable decision support systems based on optimisation models.

In general, ASP deliver and manage applications and computer services from remote servers to multiple users via the Internet or a private network. Taking into account these considerations, it becomes immediately clear that the availability of decision making tools via an ASP model is a very valuable resource in investigating this kind of problem. We believe that the outsourcing of such decision tools through ASP is a viable and promising approach, considering the growing acceptance and interest in OR-based methods for environmental planning problems.

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APPENDIX 1

Example case-study scenarios, presented in order of increasing level of complexity.

Problem 1. *Tree fertilization* A field test to assess seedling growth response to alternative fertilization regimes on a set of cutblock regeneration sites. The problem refers to a classical experimental design including replication and randomization, allowing strong inferences to be made about causal relationships. The test sites are located within a large forest tenure area that has an approved long-term management plan in place and no significant jurisdictional/regulatory considerations nor stakeholder controversies.

Problem 2. *Fisheries restoration* Assessing the choice of alternative restoration plans to meet federally mandated minimums for resident populations of salmonids downstream of a mid-sized hydroelectric dam near to a major metropolitan area. Two species of salmon, have been declared as endangered under the terms of the Endangered Species Act. Developing a recovery plan will require a mix of both standard and innovative restoration actions designed to improve habitat quality and quantity. These actions are expected to require flow restrictions on water passing through the dam, reduced access to some upstream forest activities (to reduce siltation of spawning grounds), and limitations on further development of roads and housing projects in the area.

Problem 3. *Wildfire fuels management* Assessing the efficacy of forest fuels management treatments to reduce wildfire risk in a wildland urban interface community. Fuels management alternatives include using mechanical fuels treatments, thinning, and prescribed burns. Developing the plan will require the direct involvement of provincial (or state) officials, local government, two forest companies holding tenure in the area, and community residents. Key issues to be considered are wildfire risks to community residents and to properties, smoke management and air quality, and the financial and socio-economic feasibility of alternative treatments.

Problem 4. *Climate change and land-use planning* Assessing the effect of climate change on land use designations as part of a major regional land-use plan. The plan must indicate the location and extent of future protected areas (e.g., parks and biodiversity reserves) which, in turn, has implications for competing and complementary land uses (e.g., agriculture, forestry, urban development) as well as recovery and restoration activities in area rivers, lakes, and wetlands. Major climate change uncertainties include the effects of temperature changes on the health of fish populations, the effects of extended growing seasons on agricultural crops and tree growth and yield, increased threats from pests that might affect forest health, biodiversity, the possible influx of invasive plant species, and the influence of changing soil conditions on species compositions and distributions.

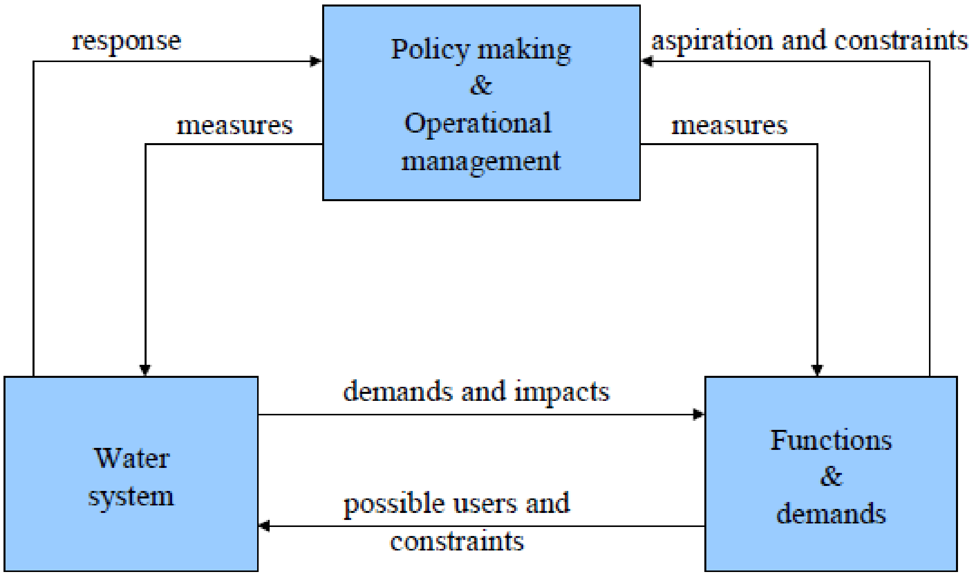

Figure 1