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Developing an objectives hierarchy for multicriteria decisions on land use options, with a case study of biodiversity conservation and forestry production from Papua, Indonesia

Sahotra Sarkar and James S Dyer
University of Texas at Austin, USA

Chris Margules
Conservation International Asia Pacific Division, Australia; James Cook University, Australia; University of Indonesia, Indonesia

Michael Ciarleglio
University of Texas at Austin, USA; Navis LLC, USA

Neville Kemp
Conservation International Indonesia Program, Indonesia; PT Ekologika Consultants, Indonesia

Grace Wong
Conservation International, USA; Center for International Forestry Research, Indonesia

Daniel Juhn
Conservation International, USA

Jatna Supriatna
Conservation International, Indonesia; University of Indonesia, Indonesia

Abstract
A framework was developed for the construction of an objectives hierarchy for multicriteria decisions in land use planning. The process began through identification of fundamental objectives; these were iteratively decomposed into a hierarchy of subobjectives until a level was reached at which subobjectives had measurable attributes. Values were derived for attributes through a variety of methods and weights assigned to objectives through preference elicitation.

Corresponding author:
Sahotra Sarkar, Departments of Integrative Biology and Philosophy, University of Texas at Austin, Austin, TX 7871, USA.
Email: sarkar@mail.utexas.edu

The framework assumed that the objectives could be incorporated into a linear value function; this required attributes to satisfy preference and difference independence conditions. Strategies were developed to address typical features that distinguish land use decisions from many other multicriteria decisions. The methodology was illustrated with a case study of land use planning in a forestry concession in the Merauke region of Papua Province, Indonesia. The problem involved severe hard constraints; the analysis showed how these can be accommodated within the framework. Results integrated interests and preferences of a diverse set of stakeholders (resident peoples, developers, and conservation professionals) and were intended for implementation. This methodology is extendible to other land use problems.

Keywords

Conservation area networks, decision analysis, fundamental objectives, Indonesia, land use planning, multicriteria analysis, objectives hierarchy, Papua, tabu search, trade-offs

Introduction

Land use decisions, from the identification of optimal locations for production to the prioritization of areas for biodiversity conservation, routinely require simultaneous consideration of multiple conflicting goals inducing the need for trade-offs between them (Hopkins, 1977; Lai and Hopkins, 1989; Malczewski, 2006; Moffett and Sarkar, 2006; Sarkar and Illoldi-Rangel, 2010). Selecting areas for agricultural development requires attention to climatic suitability, soil suitability, market access, etc. (Machado et al., 2006; Sarkar et al., 2006). Selecting areas for biodiversity conservation often involves incorporating sociopolitical opportunities or constraints such as economic and social costs or benefits, recreation, or esthetic value, besides biodiversity representation (Moffett and Sarkar, 2006). Incorporating multiple criteria into such decisions presents a conceptually and computationally difficult problem (Chang et al., 1982).

The methodology that we propose is a form of structured decision making that presumes the ability to involve representatives of stakeholder groups in a constructive dialog. This requires cooperation from those stakeholder groups, and it typically requires the leadership of some influential entity that is recognized as legitimate and trustworthy in carrying out this role. In some cases, this leadership role will be played by a government agency, as illustrated by the experiences documented by Gregory and Keeney (1998), Keeney (2006), and McDaniels et al. (2006). Or it may be carried out on behalf of a company that is planning to operate in an environmentally sensitive area, as was the case in this study and in a study at British Columbia Hydro (Keeney et al., 1995). In other cases, a similar analysis will be carried out by companies or governmental agencies where the goals and trade-offs are provided by professionals making judgments that are intended to represent the values of the stakeholder groups. For a broader survey of applications of structured decision making in areas other than biodiversity, see Keefer et al. (2007).

The goal of this paper is methodological. Its purpose is to develop a framework for the use of multicriteria analysis (MCA) in land use planning, particularly when it includes biodiversity conservation. This framework is designed to be consistent with formal decision theory. The focus of the paper is on the construction of an objectives hierarchy (OH), including a biodiversity conservation objective. The approach consists of a structured framework (“MCA” section) that requires explicit formulation of: (i) the problem to be solved; (ii) available options; (iii) socioeconomic, biological, and other factors that have to be taken into account, including how they should be operationalized and measured; and (iv) a step-by-step protocol for the solution of the problem.

Such an explicit approach has the following four advantages:

(1) The analysis will be transparent with all objectives and methodological choices available for scrutiny.
(2) The analysis, when repeated by others using the same data, should give the same results.
(3) The method of analysis will be transportable from one decision scenario to another because of the explicitness of the steps.
(4) A structured protocol enables the development of computer-based decision support tools which make feasible the rapid exploration of the consequences of a large number of possible decision choices.

Central to this framework is the development of an OH which organizes the goals of the analysis so as to identify fundamental objectives and subobjectives along with measurable attributes that specify the extent to which these objectives are met (Keeney, 1992). Consistency with the precepts of economic analysis and decision theory requires some subtle considerations during the development of the OH. Since explicit OH construction does not appear so far to have been broached during the implementation of MCA in biodiversity-related land use decisions, this paper focuses on that process (“The OH” section). The inclusion of biodiversity conservation as a goal requires some modifications of the standard use of MCA and construction of the OH (see “Complications for biodiversity conservation planning” section).

The methodology developed will be illustrated using a new and complex case study: a land use plan developed for a forestry concession in Indonesia (“Case study: Merauke” section). With one partial exception (discussed in “Discussion and conclusions” section), this analysis appears to be the first attempt at an explicit construction of an OH based on elicitation of preferences in the context of land use planning that includes biodiversity conservation.

MCA

Formal MCA can be used for a variety of purposes including the evaluation of alternative solutions to problems, making decisions under uncertainty, and probabilistic inference. Attention will be restricted here to evaluating problems in the absence of uncertainty which is the simplest case. The stages of MCA are listed in Table 1.

The stages are not intended to be sequential: they may interact with each other, with later stages providing feedback loops into earlier ones. The analytical methodology used in the case study (“Case study: Merauke” section) is also indicated in the table.

Table 1. Stages of multi-criteria analysis (MCA).

Stage	Methodology
Problem formulation	Stakeholder discussions
Alternatives	Possibilities predefined by planning context
Objectives	Preference elicitation
Analytic Strategy	Multiattribute value theory
Analysis	Tabu search as implemented in ConsNet

Problem formulation

Decision analysts have observed that problem formulation is a nontrivial issue because it may be inappropriate to assume that the problem as initially presented will turn out to be the real problem that needs to be addressed (Keeney, 1992). Problem formulation requires discussions among stakeholders, and between them and an external decision analyst if one is involved, during which the problem may be revised and restated a number of times before all parties can agree that it is settled enough to proceed. In some cases, it may be impractical to involve stakeholders directly, and subject matter experts from public agencies or from other organizations may be asked to ensure that the problem formulation includes consideration of values and concerns of the various interest groups.

The alternatives set

A decision involves a choice among alternatives. It is important that these alternatives be clearly formulated and understood by decision makers. An important question is whether the set of alternatives is fixed or whether it changes, for instance, with the emergence of new alternatives during the decision analysis. For the sake of simplicity, this discussion will assume that the set of alternatives is fixed. However, this may often not be the case. For instance, for land use planning, a decision analysis may begin with an assumption that 10% of an area would be conserved for biodiversity. But, as the analysis proceeds, agreement may emerge that this target area is not enough. In addition, the discussion of alternatives may provide insights that lead to the identification of new and better alternatives during the decision-making process (Owen, 2015). The discussion here assumes that a revised decision analysis will be performed (including all stages) whenever the alternative set changes. This is what happened during the case study (‘‘Case study: Merauke’’ section).

Relevant criteria and the OH

The purpose of a decision analysis should be explicitly formulated. For any MCA, the most important task is to identify all relevant criteria and the relations between them. This stage of decision analysis occupies most of this paper (‘‘The OH’’ section). It will be assumed that the set of relevant criteria remains fixed.

Analytic strategy

The purpose of a decision analysis is to produce a ranking of policy alternatives. It will be assumed that this ranking must be cardinal; that is, the performance or value of each alternative must be specified on a numerical scale that can only be modified by a linear transformation. As a result, this cardinal scale will not only reflect the rankings of the alternatives, but it will also measure the strength of preference between any two pairs of alternatives. That is, this scale will quantify the intuitive notion there may be a larger difference in the decision maker’s preferences between alternatives *a* and *b* than between alternatives *c* and *d* (Keeney and Von Winterfeldt, 2007). The intended contrast here is with an ordinal ranking which merely orders the alternatives without trying to specify how much better or worse one alternative is compared to another.

In many circumstances all that is needed is an ordinal ranking because the ultimate objective is only to make the ‘‘best’’ choice (Margules and Sarkar, 2007; Sarkar, 2005; Sarkar and Garson, 2004). Such rankings could either be produced using purely ordinal information about the performance of alternatives (i.e. whether a decision maker prefers one or the other of two alternatives or is indifferent between them) and the importance of the criteria, or using cardinal (quantitative) information. The ordinal strategy has the advantage of making fewer assumptions than the latter about the performance of alternatives according to the criteria (Sarkar, 2005; Sarkar and Garson, 2004). For instance, it may be much easier to say whether one area is better for silviculture than another, but it may be difficult to produce credible quantitative estimates of benefits and costs. It may be easy to say whether the shape of one biodiversity reserve is preferable to that of another but very difficult to quantify the difference in performance such a ranking implies.

Unfortunately, purely ordinal methods almost always produce rankings which exhibit intractable degeneracy; that is, many alternatives have the same rank with this problem being exacerbated as the number of criteria increases (Sarkar and Garson, 2004). Consequently, these methods often do not have sufficient resolving power to address complex decision scenarios. In contrast, cardinal rankings of the alternatives do not suffer from excessive degeneracy. In addition, when MCA value functions are used to rank alternatives, rather than using direct comparisons of the alternatives, the assessment methods for developing these functions are simpler for the case of cardinal scales (Keeney and Von Winterfeldt, 2007). Any uncertainties associated with the estimation of their cardinal rankings should be explicitly addressed, for instance through robustness and sensitivity analysis (Moffett et al., 2006).

Method of analysis

Once an analytic strategy has been chosen, the last step before proceeding with the analysis is to choose a specific scoring method to determine the cardinal measure of value. A large variety of methods have been proposed for MCA (reviewed by Figuera et al. (2005) and Moffett and Sarkar (2006)). This discussion will assume the use of a special case of multiattribute utility theory (MAUT), which is an extension of ordinary (single-criterion) utility theory (Moffett and Sarkar, 2006). MAUT was developed to evaluate alternatives with outcome measures that are uncertain and are assessed using probability distributions. The utility score of an alternative is defined as an expected value under some probability distribution. However, if there is no explicit consideration of uncertainty associated with outcome measures, MAUT becomes multiattribute value theory (MAVT), the methodology of this analysis.

The OH

Objectives

The objectives that guide a decision are usefully represented in an OH. The development of such a structure involves the identification of fundamental objectives followed by a construction of a hierarchy that decomposes these objectives until quantifiable attributes are reached that allow the performance of the alternatives to be measured on cardinal scales.

Fundamental objectives are those that are ends in themselves; that is, there is no further answer to the question, "Why is this objective important?" (Keeney, 1992). Objectives lower in the hierarchy (subobjectives) are important for what they contribute to the fundamental objectives.

Appropriate fundamental objectives must satisfy two criteria (Keeney, 1992):

(1) They must be *controllable*: The set of feasible alternatives determines the extent to which the objective is achieved without requiring recourse to additional decisions.

(2) They must be *essential*: All the feasible alternatives influence the extent to which the objective may be satisfied.

An additional five criteria are desirable for fundamental objectives and subobjectives without being strictly necessary: completeness, nonredundancy, conciseness, specificity, and comprehensibility (Keeney, 1992).

Construction of the OH is driven by elicitation from stakeholders. In principle, the process involves the iterated use of variants of two questions: ''What are the objectives of the decision?,'' and the one mentioned earlier, ''Why is this objective important?'' The first of these provides the set of objectives for the OH; the second establishes the structure of the hierarchy. The elicitation process stops at the top (of the hierarchy) when fundamental objectives are reached. It stops at the bottom when the lowest level objectives are identified such that they can be associated with measurable attributes. In practice, informal discussion may allow a first pass at a putative OH, which can then be subject to iterative revision and discussion. This was the strategy followed in the case study (''Case study: Merauke'' section).

Thus, constructing the OH for a decision scenario consists of the elicitation, decomposition, and structuring of the values or preferences of the stakeholders. It may vary from stakeholder to stakeholder (reflecting individual preferences). It is also not unique, as there may be alternative ways to define and to structure the alternatives.

Attributes

Once the OH has been constructed, the next step is to identify a measure or attribute for each objective at the bottom of the hierarchy. There are three types of attributes: *natural attributes*, *constructed attributes*, and *proxy attributes* (Keeney, 1992). *Natural attributes* are those that are often used and have a common interpretation. Typically they can be directly measured (e.g. cost measured in monetary units). *Proxy attributes* are similarly measurable, but they do not directly measure the performance of objectives. Rather, they are supposed to covary with them. For example, the distance from a conservation area to major human population centers may be a proxy measure for an objective of reducing the level of human impact on the conservation area. *Constructed attributes* are developed to measure an objective when no natural attribute exists. If a constructed attribute is commonly used for an extended period of time, it may come to be regarded as a natural attribute. For instance, it is fairly commonplace in ecology today to use the circumference-to-area ratio of a habitat patch as a natural attribute for compactness of shape (even though it originated as a constructed attribute, given that geometry provides no generally accepted definition or natural measure of compactness).

There may be more than one appropriate attribute for an objective. For instance, a common (sub)objective in many spatial problems is connectivity. At least four attributes can plausibly be used for connectivity: (i) the total number of contiguous clusters of areas in the network, (ii) the inverse of the average distance between each pair of disjoint contiguous clusters, (iii) the inverse of the maximum such distance between pairs, and (iv) compactness as measured by shape. Whether any—or all—of these attributes is deemed appropriate will reflect how a given context affects a decision maker's preferences.

Independence assumptions

The attributes used for the evaluation of alternatives should also be chosen in a manner that will simplify the task of aggregating their measures into a single composite score for each alternative. Intuitively, the simplest and most obvious way to aggregate the scores on the individual attributes would be to add them together, perhaps adjusting for their relative importance by assigning "weights" to the individual measures. This approach is appealing due to its transparency and simplicity (and will be used in "Case study: Merauke" section), but requires that these attributes are "independent" from one another in two important ways: *preference independence* and *difference independence* (Dyer, 2005; Keeney and Von Winterfeld, 2007).

Preference independence incorporates the following consideration: Suppose that two alternatives that are evaluated based on n attributes differ only on m of these n attributes and have exactly the same values on the other $n - m$ attributes. Preference independence is satisfied if preferences between these two alternatives are determined only by the m attributes that have different values, and they are not affected by the common values on the other $n - m$ attributes. Intuitively, this corresponds to situations where there would be an agreement that the choice between alternatives with common values on some attributes would be determined by focusing only on the attributes that have different values; this condition is commonly met in practice.

If preference independence among the subsets of the n attributes is satisfied, then an additive model can be used to aggregate some value functions defined on them. However, the assessment of these value functions may require the simultaneous consideration of changes in the levels of two attributes, which is impractical in most applications. For example, suppose that the decision maker's true preference can be represented by the product of the n attributes. The preference between two alternatives would not change if m of the attributes differs while the other n-m attributes have common values. An additive model of these preferences could be obtained by taking the logs of the attributes and adding them, which is an order-preserving transformation of the true value function, but this model would be difficult to assess by focusing on one attribute at a time.

The *difference independence* condition is based on this intuition: Suppose that two pairs of alternatives have common values on all but one attribute, and the decision maker is asked to specify the preference differences between these two pairs of alternatives. That is, the decision maker is asked to think about how much more value one alternative has than another in terms of his or her preferences for each of these two pairs. Presumably, this valuation of the preference differences is affected by the different values on the one attribute, but it could also be affected by the common values on the other n-1 attributes. Now, suppose these common values on the other n-1 attributes of the two alternatives in each pair are changed to a different set of common values, but the values on the one attribute where they differ are not changed. If the decision maker still has the same valuation of the preference differences between the two pairs of alternatives, then that valuation is determined only by the different values on the one attribute, and not by the common values on the other n-1 attributes. In this case, the decision maker's preferences are difference independent of the common values on the other attributes which implies that the shape of the value function on the attribute with changing values is independent of the values of the other attributes.

As a result, the only allowable order-preserving transformation of that value function is a linear transformation, which means that the value function is a cardinal measure which captures strength of preference. Since this is true for one of these attributes and they can be combined linearly, then it must also be true for all of the other attribute value functions as well, which rules out the case of an additive representation that is the result of a logarithmic transformation, for example. This greatly simplifies the assessment task since the value function for each attribute can be assessed by simply holding all of the other attribute values constant at an arbitrary level.

To illustrate using an example, suppose what is at stake is the shape of a land unit such as a nature reserve and that there are two candidate units (the alternatives), x and y, both with the size, s. Assume that the attribute for size is area and for shape is the circumference-to-area ratio. If s is small, the shapes of x and y may be regarded as being very important. In contrast, if s is very large, small differences in the shapes of x and y may be regarded as being of little importance: difference independence is violated.

What is relevant are the preference and difference independence of attributes, and not the (subobjectives) that they are supposed to measure. Given that there may be more than one potential attribute associated with a given objective, independence may be achieved with one set of attributes but not with another. This makes possible a strategy of a judicious choice of attributes to ensure independence. For instance, in the example of the last paragraph, if shape performance is measured by the congruence of a unit with an ecological type (such as a watershed), then difference independence may well not be violated.

If preferences among alternatives are preference independent for all of the attributes, and difference independent regarding any one of the attributes, then the multiattribute value function will be additive and the value functions for each attribute may be assessed without concern about the values of the other attributes (Dyer, 2005; Keeney and Von Winterfeld, 2007). These independence assumptions will be defended for the case study ("Case study: Merauke" section).

Assessing the additive multiattribute value function

In an analysis of alternatives based on their performance on n attributes, measures for each alternative on each attribute, and a vector of scores for any two alternatives $x = (x_1, x_2, \ldots, x_n)$ and $y = (y_1, y_2, \ldots, y_n)$ are first obtained. If the preference and difference independence conditions are assumed to be satisfied, then an additive multiattribute value function can be assessed such that the alternative x is preferred to the alternative y if and only if

$$\sum_{i=1}^{n} \lambda_i v_i(x_i) > \sum_{i=1}^{n} \lambda_i v_i(y_i)$$

where v_i is a single-attribute value function over x_i scaled from 0 to 1 and $\sum_{i=1}^{n} \lambda_i = 1$.

Some subtleties should be recognized for the assessments of the scaling constants λ_i or "weights." These weights reflect the value trade-offs among objectives (or subobjectives and measures within objectives) and are dependent on the ranges of outcomes possible for the alternative set. The weights on objectives are not simple measures of the "relative importance" of each objective. Loosely speaking, they are measures of the importance of the increase from the worst to the best level of performance on one objective compared to the increase from the worst to the best level of performance on another objective. Therefore, weights must be assessed carefully to ensure that the results of the evaluation are consistent with the preferences of the stakeholder(s).

Complications for biodiversity conservation planning

The description of MCA thus far is supposed to be fully general and applicable to all contexts. However, many scenarios present a special set of problems. The discussion of this section will be directed to complications that especially arise when considering the biodiversity conservation component of land use planning (though not unique to that context).

Hard constraints

Many biodiversity conservation decisions are made under hard constraints; for instance, that a certain fraction of the habitat of a species must be put under protection or that a certain area cannot be included in a conservation area network—trade-offs are not permitted with respect to them. These constraints then reduce the feasible alternative set. For this reduced set, an OH can be constructed and a MCA carried out as described earlier. Thus, formally, there is no difficulty, since the problem to be solved can still utilize the framework being developed.

However, in practice, not only are these hard constraints ubiquitous but they often involve the most important factors in the decision scenario; for instance, they may fully incorporate the conservation value being attributed to a species. Once these factors are removed from the OH it may become difficult to interpret the fundamental objectives of the OH; that is, to specify what they are supposed to accomplish. The OH no longer represents the full hierarchy of values of the decision maker. Particular care must be taken, therefore, when assigning preferences about features which form part of the OH but are also partly incorporated into the decision through such hard constraints. In the case study ("Case study: Merauke" section), hard constraints emerged as a critical determinant of the performance of feasible alternatives.

Weights on attributes

Elicited preferences measure mental attitudes about some feature, not facts about the world. Consequently, OHs should consist only of elements that are appropriately evaluated on the basis of these attitudes. Yet, in MCA for biodiversity conservation (and many other ecological) decisions, some of the criteria—for instance, shape or connectivity—are supposed to reflect facts about the world. A patch of habitat that has a regular shape has less edge habitat and more core habitat than one with an irregular shape and patches that are connected, say by corridors of habitat, are more likely to exchange individuals and their genes. Thus, the contribution that shape or connectivity would make to the persistence of biota is presumably determined by ecology, not mental attitudes.

Thus, assigning weights to attributes for such objectives must reflect a judgment about an implicit correlation between the attribute and the true objective or subobjective. The best way to conceptualize this situation is to view the preferences on facts as arising from a mental model about the factors in question, and that the numerical values express degrees of belief about the relative importance of these factors (Butler et al., 2006). Interpreted in this way, the quantitative values for preferences on facts express mental attitudes just as in the case of the other preferences.

One implication of this insight is that different stakeholders and/or different experts might be asked to make the judgments necessary to assign weights to different sets of attributes. That is, stakeholders representing the population that may be affected by decisions that impact biodiversity may be asked to make trade-offs among those attributes that measure those impacts, while experts (biologists and other scientists) may be asked to make judgments about attributes that measure impacts on different animal and plant species.

Unknown preferences

Many preferences that have to be taken into account often cannot be reliably elicited in the timeframe available for decisions. There exist a wide variety of methodologies to address this problem. A standard one, which is also used to address uncertainty about preference values, is to use sensitivity analysis (Moffett et al., 2006). The MCA is repeated for a large number of different compatible sets of weights. If the results remain within an acceptable range of variation, the conclusions are deemed to be robust. If they do not, then the appropriate response would be to indicate the range of conclusions that are compatible with known ranges of the preferences. This is the strategy used in the case study below (''Case study: Merauke'' section).

Case study: Merauke

In 2008, Conservation International (CI) contracted with the Medco Foundation, established by the Medco group (an Indonesian conglomerate), to devise a land use plan for an industrial forestry plantation concession obtained by the latter in the Merauke region of Papua Province in Indonesian New Guinea. Medco's intention was to grow trees for pulp on this concession. The goal was to achieve sustainability of forestry production, the conservation of biodiversity, the maintenance of ecosystem function, and satisfaction of community interests through an integration of values (Conservation International, 2010). Medco made an initial commitment to conserve 40% of the area by exempting it from plantation farming.

The planning process began with a meeting between Medco and CI representatives and other stakeholders in the presence of decision analysts (from the University of Texas) in Jakarta in December 2008. All stakeholders identified by CI were present except, critically, representatives of the communities affected by Medco's proposed development who (in CI's judgment) could not be included at this early stage for logistical reasons but whose values were integrated into the spatial planning decision process once they had been fully investigated in the field, as explained below.

The decision context was reviewed and a consensus achieved on the criteria to be incorporated, though some criteria changed over time (''Decision context'' section). The alternative set was selected (''The alternatives set'' section). After much discussion—which continued beyond the original meeting—the hard constraints on the decision were identified (''Hard constraints'' section). A tentative OH was constructed at the original meeting (''OH'' section). Weights on criteria were assessed through extensive elicitation discussion over the next 12 months (''Deriving the weights'' section). Finally, the MCA was performed through a search for optimal alternatives using the ConsNet software package (Ciarleglio et al., 2009a, 2010). Generating the relevant data layers took about eight months. This included creating the production suitability layer, the biodiversity layer of habitat types, and community landscape use maps. Obtaining the solutions took about eight weeks. Final results were communicated to MEDCO for potential implementation. The discussion here focuses on the OH with enough attention to other aspects to make the study intelligible. (For more details, see Ciarleglio et al. (2009b) and Conservation International (2010).)

Decision context

The concession area consisted of 166 028 ha, mostly flood plain (Figure 1). The study area in which the concession was embedded is 140° 00′–140° 38′ E and 7° 25′–8° 05′ S. MEDCO's

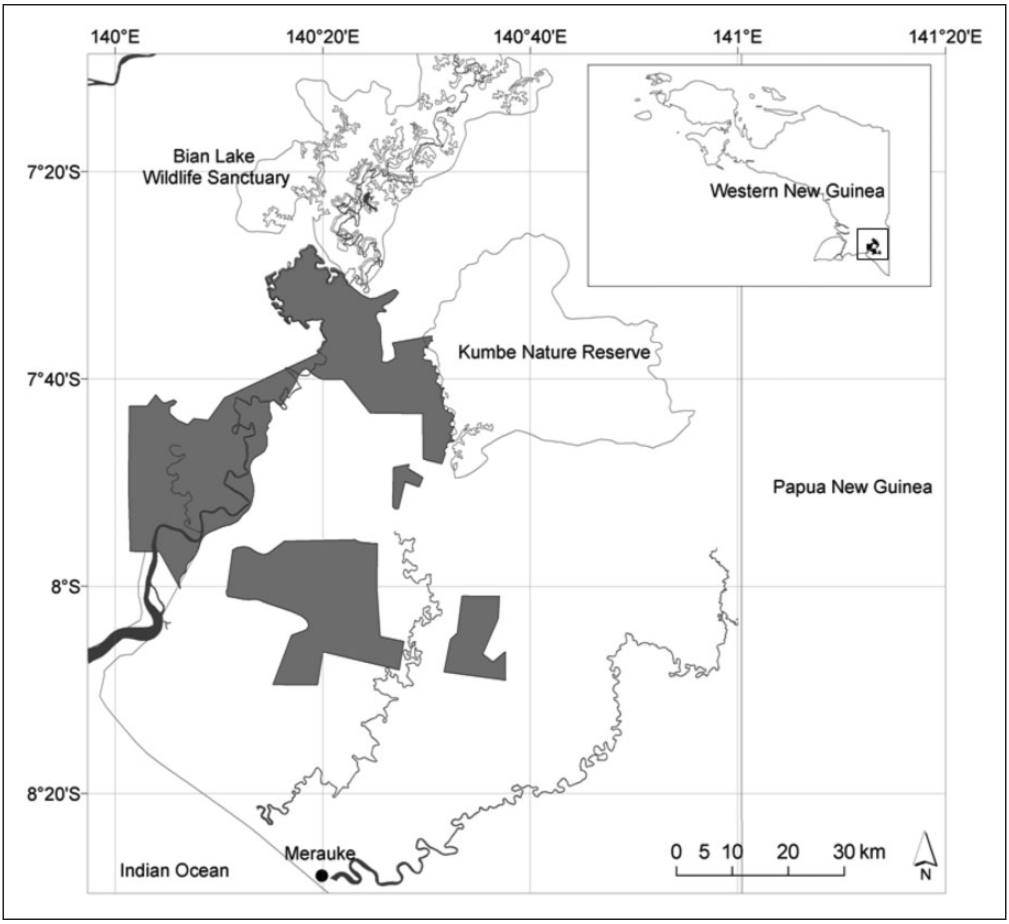

Figure 1. Study area. The area shown is part of the Papua province of Indonesia. The concession consisted of the areas shaded in gray. Two adjoining protected areas are shown.

initial commitment to conserve 40% of the area included sites that would be set aside for sociocultural reasons and to avoid potential land use conflicts with local communities but not areas set aside for potential village expansion. However, the initial results of the decision analysis convinced MEDCO to set aside up to 80,620 ha or 49% of the concession area. This figure became a hard constraint ("Hard constraints" section).

For the purpose of the analysis, the concession area was divided into 166,028 square cells, each of size 1 ha. The total area consisted of four discontinuous "zones" (contiguous sets of cells). Mapping habitat types at this resolution, mainly from remote sensing data, was carried out by CI (Conservation International, 2010). Fifty-eight habitat types were used as biodiversity surrogates (Margules and Sarkar, 2007) for the analysis. Additionally, a set of cells corresponding to rare biotic community types were designated for inclusion in the conservation areas (as another hard constraint).

Traditional lands of nine Marind communities (Baad, Buepe, Kaiza, Kaliki, Kaptel, Koa, Senegi, Wapeko, and Wayau) intersect with the concession area. The presently occupied village areas of five communities (Baad, Buepe, Kaiza, Kaptel, and Senegi) were outside the concession area but intersected with the concession area if a 2 km buffer was put around the village center. Deliberations involving the villagers used a form of Focus Group Discussions with these groups being constituted by the individual communities. These deliberations determined that the 2 km buffer was sufficient for current use and future increases in community size in the mid-term (20 years). However, all nine communities used forest resources from a much larger area within their traditional lands which, for every community, intersected with the study area. Thus, their interests had to be incorporated into the MCA. There was a set of important cultural sites and essential natural resources including sago groves (which consist of palms from which starch-rich sago is extracted). These sites merited protection as another hard constraint. Sago groves produce an important component of people's diets and have typically been maintained for generations. CI personnel were also responsible for eliciting preferences about the use of natural resources from different parts of the landscape from local residents (see "Deriving the weights" section).

CI used an adapted multidisciplinary landscape assessment (MLA) tool (Sheil et al., 2002) to document which communities used which biodiversity features in different parts of the landscape, how important it was to them, and why this was so. CI staff visited each village the traditional lands of which intersected with the concession for at least two weeks during two survey phases. The MLA methodology used detailed participative mapping and, where possible, ground-truthed maps, to plot traditional land boundaries and locations of sacred and important sites essential for maintaining the identity and socioeconomy of the communities.

The alternatives set

The alternatives set was naturally defined. It consisted of any set of cells in the concession area that satisfied the hard constraints described in "Hard constraints" section. The goal of the analysis was to find the set that ranked highest according to the OH. The number of feasible alternatives was astronomical. The starting set of 166,078 cells was reduced to 166,028–73,163 = 96,865 cells due to the hard constraint. From these, in the smallest solutions, 7507 had to be selected. Thus, the number of feasible solutions was $\binom{92865}{7407} = \frac{92865}{7407!85458!}$ which is large (and beyond the computational capability of the R statistical package). This made it important to use tractable search algorithms that can handle such large search spaces.

Hard constraints

This case study illustrates the problems discussed in "Complications for biodiversity conservation planning" section: in particular, hard constraints determined most features of the nominal conservation area networks that were produced by the analysis. There were five hard constraints:

(1) The total area designated for conservation was restricted to 80,620 ha. All stakeholders were in agreement that it was unreasonable to expect MEDCO to set aside more land.
(2) The village expansion areas (a radius of 2 km) were not included in either the plantation areas or the conservation areas. The communities considered this a generous allocation.
(3) Cells with rare communities of species were permanently included. Rarity was measured as the inverse of the spatial extent of a community type in the Merauke region.

(4) Areas of cultural importance were permanently included. These included: (i) sago sites; and (ii) sites of religious importance. The former were given a 200 m buffer; the latter a 500 m buffer based on assessments of how communities ordinarily treated these sites.
(5) Water bodies were permanently included. These consisted of (a) swamps including rivers in swampy areas, (b) large rivers, and (c) small rivers. Indonesian law required buffers of 200, 100, and 50 m, for these, respectively.

These hard constraints were so severe that 73,163 ha were set aside based on them, leaving only an additional 7457 cells to be selected based on the MCA.

We view these restrictions as excessive, and acknowledge that they may have reduced the value of proceeding with the MCA. See Keeney (2002) for a discussion of the pitfalls of using hard constraints in MCA studies. However, we feel that the results of the study did add value to the solution with 7457 ha subjected to trade-offs between production and protection. The lessons learned from the process provide a useful example for future studies in which it will become increasingly important to make such trade-offs explicitly as stakeholders more often call for decisions based on evidence.

OH

When the preliminary OH was constructed at the December 2008 meeting it was expected to be subsequently modified through further discussion and consultation with the local communities not represented at this meeting. However, the OH underwent little revision in the ensuing 12 months. The only part of the OH that was modified was that for the spatial configuration fundamental objective—see "Subobjectives" section.

The process of constructing the OH was carried out in a manner that was intended to identify objectives and attributes that would satisfy the independence assumptions discussed in "Independence assumptions" section. The decision analysts on the project team would subjectively consider different values for the attributes under consideration, and judge whether or not they would be mutually preference independent. As described in "Independence assumptions" section and the relevant references, these judgments are based on an understanding of the problem and whether or not it would be necessary to know the values of other attributes in order to make value judgments about the ones in question.

Fundamental objectives. There were four of these:

(1) *Biodiversity representation*: CI had biodiversity conservation as one of its priorities. MEDCO viewed incorporating this goal into the plan as an important contribution they expected from collaboration with CI. This goal was explicitly interpreted broadly to include the maintenance of ecosystem services. During the analysis, the incorporation of ecosystem services was achieved through a hard constraint: inclusion of wetlands and buffers as required under Indonesian law. As a result, ecosystem services maintenance did not form part of the MCA (which was relevant only for goals between which trade-offs were allowed). Consequently, ecosystem services maintenance was not in the OH.
(2) *Spatial configuration*: For conservation, representation of biodiversity surrogates in designated areas is not enough; their persistence must be ensured (Margules and Sarkar, 2007). The spatial configuration of conservation area networks is expected to influence persistence. In the concession, spatial configuration was also relevant to: (a) efficiency in management of conservation areas; and (b) design of production areas for

plantation crops. Spatial configuration thus emerged as a fundamental objective for the analysis. Finally, spatial configuration was also important for the communities. (For example, forest resources close to villages were preferred to those that were far away.)

(3) *Production suitability*: The goal of this project included sustainable development, which must take the economic viability of the proposed plantation into account. Thus, land units were to be assayed for their suitability for production. This was accepted as a fundamental objective by all stakeholders.

(4) *Community interests*: Sustainable development, as envisioned for this project, was intended to benefit not only MEDCO but resident communities in the concession area and those having traditional use lands within it. Consequently, community interests, as perceived by communities, were adopted as a fundamental objective. It was important for planners that communities did not view the development plan as an external (''top-down'') imposition without meaningful participation from residents.

Subobjectives. The only part of the OH that underwent significant revision after the original 2008 Jakarta meeting was that for optimization of the spatial configuration of conservation area networks. It will be discussed in some detail below.

(1) *Biodiversity representation*: This fundamental objective had the more specific subobjective of the achievement of percentage targets for the inclusion of each of the 58 biodiversity surrogates. A constructed attribute was used which incorporated the extent to which each surrogate met a target of 10, 20, 30, and 40%.

(2) *Spatial configuration*: In the final analysis, there were three subobjectives at the next level, biological spatial preferences, Medco's spatial preferences, and community spatial preferences (Figure 2). The first and third were included from the beginning of the discussions; the second arose after Medco reviewed some initial solutions. Subsequently, the entire exercise was reiterated from the beginning as a new MCA. The biological spatial preferences subobjective was decomposed to two others at the next level: shape and connectivity. Shape had the usual proxy attribute: circumference-to-area ratio. Connectivity was interpreted as the selection of a contiguous body of cells connecting to the Bian Lake Wildlife Sanctuary and the Kumbe Nature Reserve to the north and northeast of the study area, respectively. It had a proxy attribute: the number of cells in the north zone of the concession area. The Medco spatial preferences had two subobjectives at the next level, both referring to spatial location or ''alignment.'' The first was ''zone alignment'' which referred to which zones had cells included in the conservation area network. Zone alignment was decomposed into preferences for cells in the north zone, southeast zone, and the south zone, with the first two encouraged and the last discouraged. Each of these had a natural attribute: the number of such cells. These subobjectives reflected MEDCO's preference for having large contiguous accessible areas for plantation farming. The second was ''distance alignment'' which had two subobjectives with natural attributes: closeness of conservation areas to the concession boundary and distance to the Senegi community area (which MEDCO desired). Finally, community spatial preferences had a single subobjective, closeness to each community, with the natural attribute of distance.

(3) *Production suitability*: This fundamental objective had the more specific subobjective of increasing economic performance. The assessment used a constructed attribute developed by CI based on (a) the estimated biomass (correlated with the expected volume of plantation products), (b) the extent of flooding (which has the same

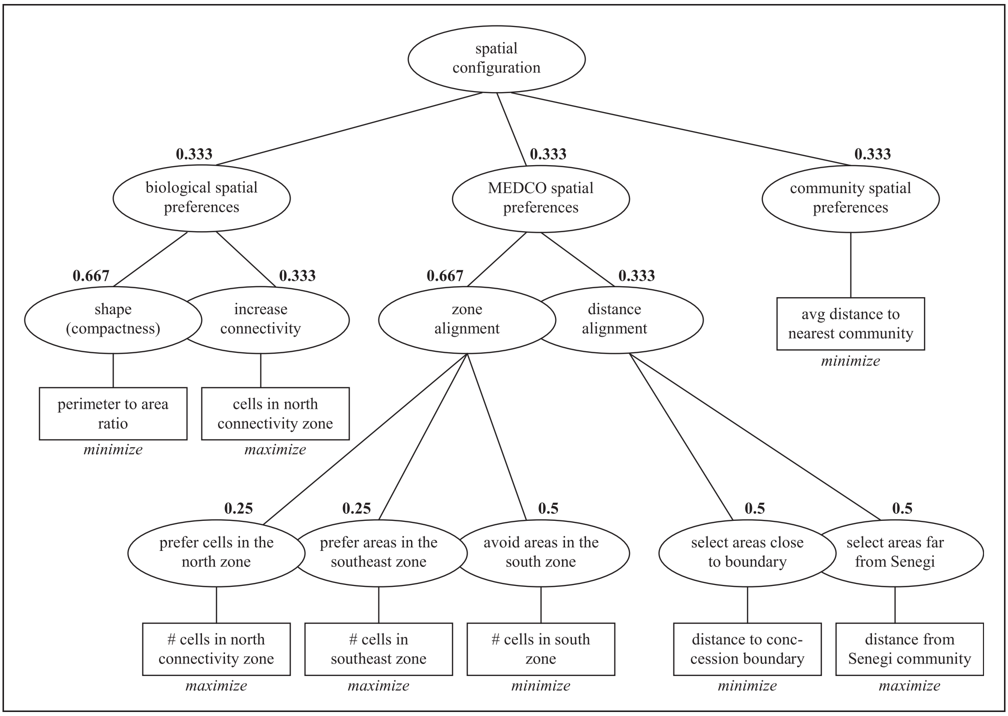

Figure 2. Objectives hierarchy for spatial configuration fundamental objective. For further discussion, see the text.

correlation), and (c) distance to a road or waterway (which measures accessibility) (Conservation International, 2010).

(4) *Community interests*: The first level subobjectives consisted of the interests of each of the nine communities in the concession area (see Figure 3). There are, thus, nine such subobjectives. The second-level subobjective, for each community, consists of the maintenance of different habitat types deemed to be important for that community by that community. These have a natural attribute in the number of cells occupied by each habitat type that are designated for protection.

Deriving the weights

Weight derivation for this OH exhibited fully the complexity of MCA in the context of planning under severe time constraints; that is, when there was insufficient time for all stakeholders to meet repeatedly to settle on a set of preference values. Different stakeholder groups would be likely to have different weights on the fundamental objectives, with the equal weights on the objectives shown in Figure 2 providing one of many possibilities. Consequently, a decision was made to use a variety of weights and to analyze the results for robustness. This is a type of sensitivity analysis designed to handle uncertainty about the weights ("Complications for biodiversity conservation planning" section) and has been used in other applications of MCA for public policy decisions

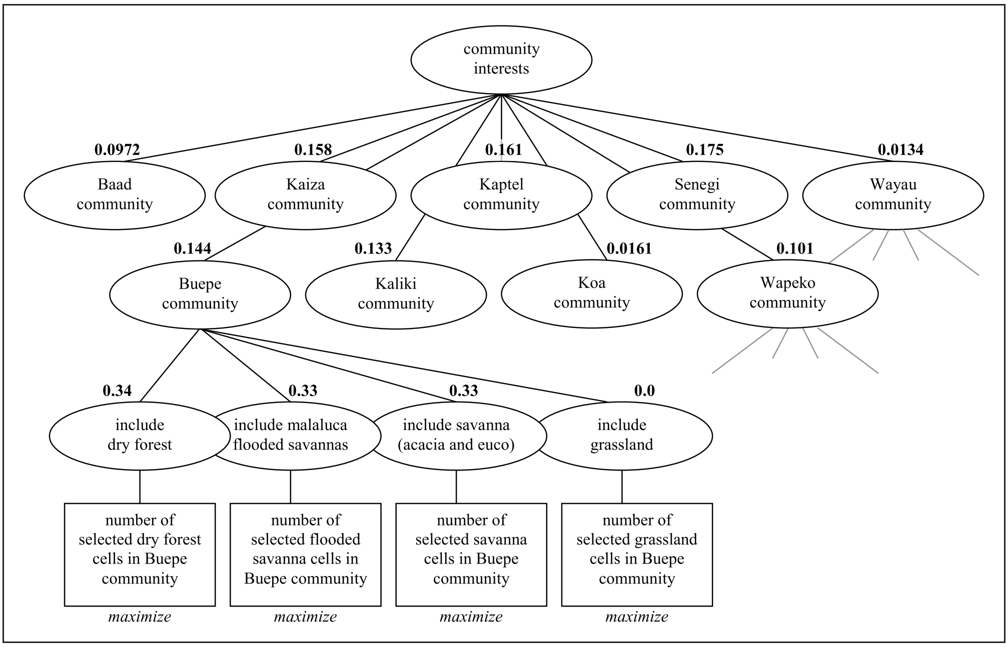

Figure 3. Objectives hierarchy for community interests fundamental objective. For further discussion, see the text. Because of space limitations, the subobjectives corresponding to different habitats are shown only of the Buepe community.

(e.g. Butler et al., 2007). As the typical results reported below (''Typical results'' section) show, because of the severity of the hard constraints, this choice did not have a significant impact.

No further weights were necessary for the subobjectives under the biodiversity representation and production suitability objectives since these were each assessed through a single constructed attribute. The weights assigned to the various subobjectives under the spatial configuration fundamental objective (Figure 2) were based on extensive discussion between members of the planning team.

For the subobjectives under the community interests fundamental objective, weights were assigned to the communities in proportion to the area of each community's traditional use land that intersected with the concession. The justification for this choice was that this provides a reasonable relative measure of the impact on each community. Explicit preference elicitation was carried out for the lowest part of this sub-OH, to determine the extent to which each community valued each surrogate or habitat type (generally a forest type) in its own traditional use area using the pebble distribution methodology developed by the Centre for International Forest Research for the MLA (Sheil et al., 2002). During Focus Group Discussions in the villages, communities jointly distributed a pile of a hundred beads (pebbles) to indicate relative preferences for these and the results were interpreted as percentage weights. This approach is analogous to the direct assignment of weights to attributes by a decision maker where care must be taken to ensure that the decision maker recognizes that these relative weights are being used to express the importance of changing each attribute from its lowest to its highest value. These ranges were an important part of the Focus Group Discussions.

In general, preference and difference independence assessments were made through extensive discussions of pairwise and more complex comparisons of attributes by the analysts. Given the severity of the hard constraints, the ranges of attribute values for the feasible alternatives were quite limited. Consequently, it proved easy to explore the preferences for differences in any given attribute's value against a large combination of values of the other attributes. Independence assumptions were uniformly satisfied.

Typical results

Five scenarios were explored (Ciarleglio et al., 2009b); results from only one of them are shown here: Figure 4 shows the results when the weights on biodiversity conservation and spatial configuration were twice as large as the weights on production suitability and community interests.

However, all scenarios produced very similar results because many of the areas designated for biodiversity conservation were selected by the hard constraints leaving very little opportunity for the MCA using the OH to differentiate them. In Figure 4, the addition of the new selected sites enabled continuity to be achieved between the Bian Lake Wildlife Sanctuary and the Kumbe Natural Reserve (compare to Figure 1). (Here continuity was measured by the number of protected and selected cells in the region between the two reserves.) However, the trade-off was to reduce the satisfaction of community interests.

If the solution shown in Figure 4 is compared to one that gave all fundamental objectives equal weight (results not shown), biodiversity representation and production suitability achieved almost identical performance (value under the elicited multiattribute value function in both cases 0.96 and 0.95 for biodiversity, and 0.84 and 0.85 for production, respectively, all on a linear scale of 0–1); moreover, in accordance with MEDCO's spatial preference, in both cases, the selected conservation areas avoided the southern zone leaving a large contiguous area for plantation forestry (scores of 0.54 and 0.49, respectively). The only difference was that the solution in Figure 4 satisfied community interests to a lesser degree (0.42 versus 0.51).

Discussion and conclusions

Areas have been prioritized for biodiversity conservation under multiple constraints and objectives before but as far as we can determine, this case study is the first time that an explicit OH has been constructed for that purpose. Most previous multicriteria analyses were relatively simple, analyzing objectives involving a small set of criteria which were presumed to have no further structure (Faith, 1995; Moffett et al., 2006; Sarkar and Garson, 2004). In these contexts, constructing an OH was not necessary.

Some recent work in biodiversity conservation planning has begun to incorporate a large number of criteria and one study presented a hierarchy of objectives (Regan et al., 2007). However, that attempt used the analytic hierarchy process which is problematic (Moffett et al., 2006) and, partly because of that, has two additional problems: (1) The objectives themselves were given (relative) weights with no explicit attention to the range of values associated with their attributes for the relevant set of alternatives (compare to "Assessing the additive multiattribute value function" section). (2) There was no discussion of attribute independence even though the methodology assumed an additive model (compare to "Independence assumptions" section). Consequently, the hierarchy constructed by Regan et al. (2007) does not satisfy the requirements of a valid OH. This is the kind of error that the discussion of this paper is supposed to prevent. As Moffett et al (2006) note, these issues with the AHP and its use with an OH can be overcome by incorporating the two concerns

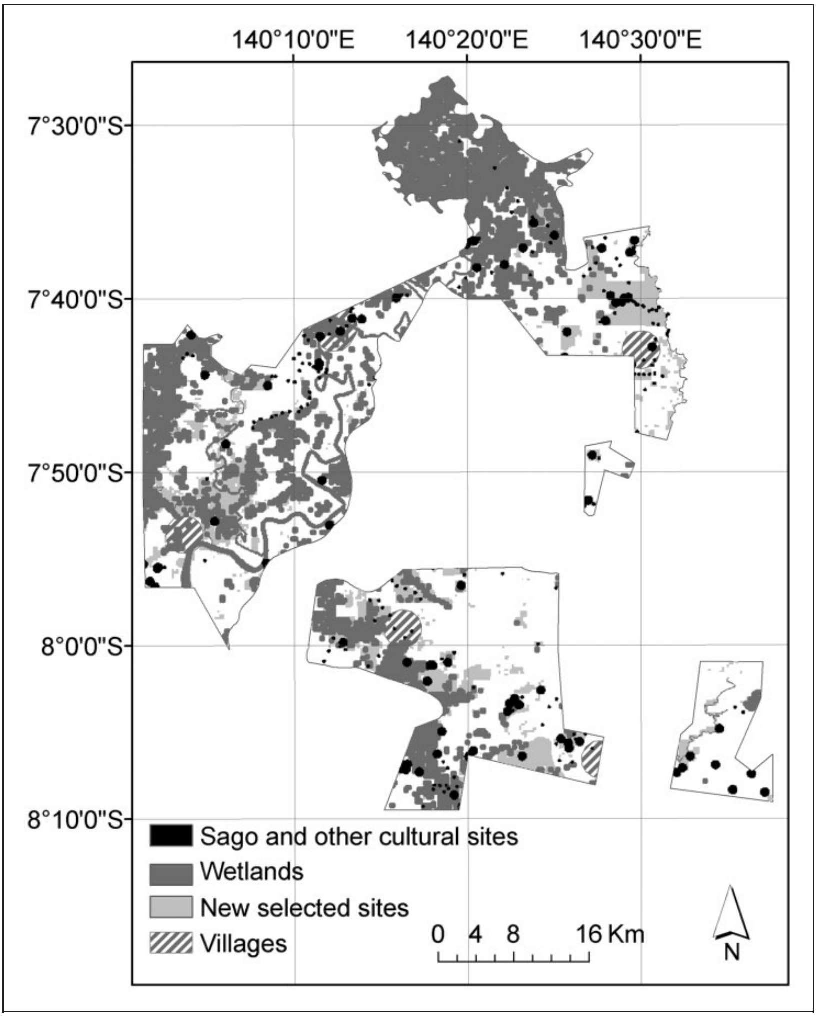

Figure 4. Selected cells in final proposed network of conservation areas. In this solution the weights on the four fundamental objectives were as follows: biodiversity representation: 33%, spatial configuration: 33%, production suitability: 17%, and community interests: 17%.

identified above into the construction of the OH and into the assessment procedure, and by the appropriate scaling of the weights.

The framework developed in this paper should enable such OH construction in other contexts, with the case study providing further guidance (though more case studies would also be useful). In the process of this analysis, the following subtleties emerged (as noted earlier) and several became relevant to the case study. They deserve further emphasis because they have often been ignored in multicriteria conservation decisions:

(1) The OH is a structured decomposition of the values or preferences of those making decisions. It may vary between individuals. Thus, because the OH influences every aspect of the subsequent analysis, care should be taken to ensure that *all* decision makers are satisfied with the structure of the OH.

(2) As the case study illustrated, constructing an appropriate OH can be a time-consuming process and require several iterations.
(3) Even for MCA techniques that are consistent with standard economic analysis, there is a choice between linear or more complex value functions. While linear value functions have the advantage of simplicity and transparency, they require preference and difference independence of attributes.
(4) Preference and difference independence are questions about attributes used to measure objectives, not about the objectives themselves. If a set of attributes violate either of these conditions, it may be possible to use other attributes for the same set of objectives which do not violate them.
(5) Weights on the criteria must be interpreted properly. They do not represent relative importance of the criteria in general. Rather, they reflect relative preferences between them when the values of alternatives according to each criterion vary within the range obtained for the set of alternatives being assessed.
(6) As with OH construction, deriving appropriate weights is a time-consuming process and, in the case study, took more time (12 months) than developing the final plans based on the weights (eight weeks). The same situation is likely in many contexts in which results of a decision analysis are intended for implementation.

The message that emerges from these observations is that a proper MCA takes time and effort. First, choosing an appropriate methodology takes care. Second, it is not sufficient to reduce the process to formulating an intuitively plausible OH, assigning weights, and running software without full consultation with stakeholders and careful elicitation of their preferences, as is far too often done by conservation professionals, consultants, and other such groups. There is an ethical dimension to this process that should also always be kept in mind: conservation decisions often affect the livelihoods of people who are, therefore, stakeholders who cannot legitimately be excluded from the process (Sarkar, 2005).

The methodology developed here is intended to be generally applicable to all multicriteria decision contexts relevant to land use planning though what was perhaps unique about the case study was the presence of highly restrictive hard constraints. In general, such hard constraints will make OH construction more difficult since the criteria incorporated into the OH may not include the ones that are most salient to the fundamental goals of a decision. This problem merits more attention.

Finally, the complexity of multicriteria decisions translates into significant computational complexity when the alternative set is large as it typically is when a land- or seascape is divided into a large number of potential management units. There is thus the possibility that problems may become intractable preventing a representative sampling of the full space of alternatives. In the case study reported here, the tabu search algorithm incorporated in the ConsNet software package (Ciarleglio et al., 2009a, 2010) proved computationally efficient for satisfactory solutions to be obtained within hours, times typically characteristic of the planning sessions for this project. This computational tractability was critical to the success of this analysis. While other search algorithms can potentially be used for this problem, at present, ConsNet (which incorporates tabu search) is the only publicly available software that implements MAVT-based decisions for systematic conservation planning.

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Sahotra Sarkar is Professor in the Departments of Integrative Biology and Philosophy at the University of Texas at Austin. He was educated at Columbia University and the University of Chicago. He has previously taught at McGill University and been a Fellow at the Wissenschaftskolleg zu Berlin and the Max-Planck-Institut fur Wissenschaftsgeschichte. Besides the philosophy and history of science, his principal research interests include systematic conservation planning for biodiversity protection and disease ecology and epidemiology.

James S Dyer holds the Fondren Centennial Chair in Business in the McCombs School of Business at The University of Texas at Austin. He is the former Chair of the Decision Analysis Society of the Operations Research Society of America (now INFORMS). He received the Frank P. Ramsey Award for outstanding career achievements from the Decision Analysis Society of INFORMS in 2002. Dr. Dyer's research interests include the valuation of risky investment decisions and risk management.

Chris Margules is Adjunct Professor at James Cook University in Australia and Research Associate at the Research Center for Climate Change, University of Indonesia. His research focuses on integrating conservation and development. He was a research scientist and research manager at the Commonwealth Scientific and Industrial Research Organisation for 32 years and then Senior Vice-President and leader of the Asia Pacific Division at Conservation International from until 2011. He received Order of Australia honours in the General Division in 2005.

Michael Ciarleglio received an interdisciplinary PhD from the University of Texas at Austin, from the Institute for Computational Engineering and Sciences. His areas of research include metaheuristic algorithms, combinatorial optimization, and decision support systems. He is the principal developer of the ConsNet decision support system for conservation area network selection. Since 2012, he has been working at Navis to write software and optimization solutions to support automated marine terminals.

Neville Kemp is a forest ecologist and environmental consultant with 20 years of experience working in Southeast Asia. His work has cent red on conservation and sustainable natural resource use. He has worked within the protected area system of Indonesia and for Conservation International where the project reported here for trading off conservation against production was conceive and implemented. He now assist s some of Indonesia's largest plantation companies to develop and implement approaches to reconciling conservation, product ion and social issues.

Grace Wong leads research projects on REDD+ benefit sharing and on forestry and livelihoods in swidden landscapes at CIFOR. Prior to CIFOR, Grace worked for the United Nations Development Programme (UNDP) in Vientiane, Lao PDR on the effects of l and use commercialization policies on poverty and the environment, and for Conservation International (CI) in Washington, DC on landscape scale planning and economics. Grace has a PhD in forest economics from the University of Florida.

Daniel Juhn is a Senior Director at the Science Division of Conservation International (CI). During his 25 years in conservation and development he has conducted work on landscape planning , monitoring, and modelling, and more recently, ecosystem accounting. He has previously worked with Doctors Without Borders and the United Nations managing project s on food security, aquaculture and agriculture development, and malaria programs for indigenous groups in the Amazon. Juhn earned a Masters in Geography, Environment and Development from Clark University.

Jatna Supriatna is director of the Research Center for Climate Change, University of Indonesia. He was Indonesia Country Director and Vice- President at Conservation International from 1994-2010. He is an Officer of the most Excellence Order of the Golden Ark, the Netherlands, awarded 1999. He was appointed to the Indonesian Academy of Science in 2012 for contributions to primate biology and evolution, and conservation biology. He has a PhD in Biological Anthropology from the University of New Mexico.