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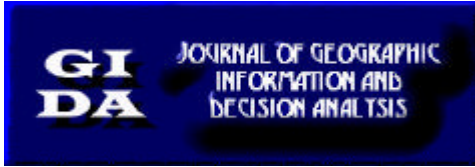Follow this and additional works at: https://scholarworks.umb.edu/msis_faculty_pubs

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Combining Multi-Attribute Utility and Geographic Information for Boundary Decisions: An Application to Park Planning

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ABSTRACT **The quality and value of an area depend primarily on what is found within its designated boundaries. To determine the value of such areas in terms of boundaries, we have developed a methodology for integrating multi-attribute utility functions with spatial analysis so that desirable, or appropriate, boundaries can be determined on the basis of the goals and objectives for the park. The key to successful evaluation is the development of measures for what decision makers value, rather than merely using what is easily measured. In a detailed example for planning of national parks, the fundamental objectives are conservation and societal use of the park resources. These are divided into sub-objectives, and then functional objectives, which are measured with a family of spatial analysis functions. Modeling is iterative, so that available spatial-analysis techniques may be used to produce acceptable measures from available information. The resulting value model is a key component in an integrated decision-support system that allows the decision maker to evaluate alternative plans before selecting one of them. Mathematical and other definitions used in structuring this problem are generalizable to other geographic decision support applications.**

KEYWORDS: Decision analysis, multi-attribute utility, geographic information system, spatial analysis, park, boundary.

Contents

1. Introduction

The quality and value of a park or protected area depend on what is found within its designated boundaries. We have integrated multi-attribute utility theory (MAUT) with spatial analysis so that the value of a park can be measured in terms of its boundaries; this method can be used to determine desirable boundaries. To explain the approach, some background information on MAUT has been provided. This is followed by a discussion of how to combine MAUT with geographic information systems (GISs) in the form of a geographic multi-attribute utility system (GMAUS). Finally, this concept is applied to make decisions about park boundaries.

1.1 Park Boundary Decisions

What is meant by a park boundary decision? In general, there must be a decision-making body with preferences over outcomes; otherwise, it does not matter what is done. Also, there must be different actions that the decision maker can take that may affect the status of the region, or else there is no decision to be made. Finally, there must be some model to show how actions affect outcomes, otherwise there is no information on which to base the decision.

In considering a single, canonical park-boundary decision, assume that (1) there is a region, (2) lines can be drawn that define what parts of that region are inside park boundaries, and (3) the value of the park is determined. In order to develop rational and by efficient plans, decision makers must make trade-offs among multiple objectives and balance objectives among different border configurations. Many objectives are not easily compared as they are not naturally expressed in comparable terms. At the same time, there may be idiosyncratic objectives, the importance of which depends on the context (e.g., the value of the whole may be more or less than the sum of its parts). Some objectives are of decreasing marginal importance after reaching a certain level, while others may have no value until a certain level is attained. Different people will consider different objectives to be important, and some objectives deemed to be important may not be easily met by park management policies and directives.

Given all these complexities, it might be possible to identify small changes in park boundaries that are clearly beneficial. However, it is almost impossible to look at a large area and simply decide what it should look like, nor is it possible to look at a sheet of statistics about an area and decide what should be done to further the goals of society or of the park service. In fact, it is difficult even to hold a discussion about whether planned changes are good or bad without degenerating into argument and confusion. The framework in this paper can be used to clarify discussions and planning considerations.

1.2 A Mathematical Statement of the Problem

We assume that the value of an area is determined by its boundaries (e.g., what regions are in national parks, what regions are in national forest, etc.). We define the boundaries of an area as a partition $p \in P$, and

$$P = \{(a_1, \ldots, a_n) \mid a_i \in \mathbf{R}^2, \cup_i(a_i) = A, \cap_i(a_i) = \varnothing \},$$

where A is the area under consideration.

First, we consider a special case of the general problem, where $n = 2$, which corresponds to areas inside and outside the park. The value or "utility" of the area with a given set of boundaries (which we will discuss in more detail shortly) is denoted as

$$U(p): P \rightarrow \mathbf{R}.$$

Some potential boundaries may not be feasible (e.g., too expensive, too complex, etc.) Denoting the set of allowable partitions by P*, the decision problem can now be stated as finding

$$MAX_P \{U(p) \mid p \in P^*\}.$$

Defining the function $U(*)$ in a usable and useful manner is difficult, because there is no obvious connection between the lines on a map and societal value. This task can be simplified by breaking it into two subtasks: (1) develop a set of n measures, x, derived from the map with the proposed partition, $x : P \rightarrow \mathbf{R}^n$, and (2) define a function, $U(x): \mathbf{R}^n \rightarrow \mathbf{R}$, that operates on the measures.

2. A Multi-Attribute Utility Theory Approach

Prior state-of-the-art decision-making tools consisted of two major approaches: suitability indices and site evaluation. Because the approach used in this paper attempts to combine the best features of both, these two approaches are reviewed before the proposed approach is presented and discussed.

2.1 Additive Suitability Indices

Decision makers use the approach of additive suitability indices (Sundell 1991) to develop measures and to rate cells (small square regions on a map) with respect to those measures (e.g., suitability for natural habitat for particular species, recreation, historical value, or other uses). A score is generated for each cell on the basis of its suitability indices; cells above a certain threshold score may be defined as critical resource areas. A typical (though simple) suitability index, for example, is the quality of a particular cell (the smallest area differentiated within GIS data) as a habitat for a given species, such as the prairie chicken:

· Poor if there is no cover and no food.
· Medium if there is cover, but no food.
· Excellent if there are both cover and food.

In this example, cover is defined as an area of more than 65 ha of contiguous fair or good (native/late successional) grassland, and food is defined as areas within 600 m of a (man-

made) food plot. This definition is fairly straightforward to implement in a GIS. Of course, land planning usually encompasses many parameters, not just a single habitat. Sundell shows how to determine an overall critical resource index by assigning to each cell a weighted sum of scores on a range of suitability indices. Suitability indices are used with a GIS to measure the important considerations in land management. Specific critical resource indices, (e.g., critical biodive rsity resource, critical archaeological resource, critical economic resource) are also used.

A decision support system (DSS) based on this approach assigns cells to different uses, depending on their critical resource scores and their relation to certain threshold values. For example, a DSS might recommend that any cell with a biodiversity score above 75 (on a scale from 0 to 100) be set aside as a preserve. This approach has several strengths. It allows the computer to process large amounts of data, yet provides for human input where expertise about natural processes and value judgments are needed. In a complex environment, this flexibility is not just a matter of convenience; it might be impossible for decision makers to recognize intuitively whether an area meets certain scientific requirements, especially when every square meter must be considered. A DSS also allows any number of considerations to be included, through separate input from experts on separate issues.

A DSS can be extremely informative to a planner, and for continuous decision variables (e.g., how far to expand a park in different directions), it serves as an appropriate starting point for a more thorough defined process for making decisions. However, the approach is not very useful for making explicit trade-offs. In some cases, there is diminishing marginal value to assigning land to a particular use; for example, the recreational value of observing 100 waterfalls might not be much more than the recreational value of viewing only 10 waterfalls to some park users. In other cases, a certain threshold must be reached before there is any value to assigning land to a use. For example, since 50 ha of good wolf habitat is not enough to sustain a pair of wolves, it has no value in terms of protecting the species, while 1000 ha might be of significant value (i.e., 20 times as much land has more than 20 times the value). Threshold values may apply to fragmented areas or to a whole site. Another problem is that the same land area cannot be assigned simultaneously to all of the uses for which it has potential, and so its overall value is not simply the sum of its suitability value for different purposes.

In summary, the suitability index approach essentially defines a function x(p), where the components of the vector x are the numbers of cells containing each critical resource within the different areas defined by p. However, the major deficiency in this approach is that it does not assign an explicit value to a set of boundaries (i.e., it does not utilize a function like U(p)).

2.2 Site Evaluation

This approach is used to develop measures for evaluating sites ranging in size from a specific point, to a linear feature, and to a large area. A good example is the value model described by Jankowski and Richard (1994) for siting a water transmission line, on the basis of cost, right-of-way acres, daily traffic on roads, erosion hazard acres, seismic hazard areas, area of wetlands, and the length of stream segments falling within the right-of-way. A linear weighting of these scores is used to generate a total score for each of several proposed areas (sites).

Site evaluation uses a mix of objective measures (which may or may not be computer generated) and subjective measures. The site evaluation approach has been used largely for deciding where to build things and, has not been used explicitly in park boundary delineation. In this approach, a multi-attribute utility function is used to describe the attractiveness of a site. For example, a planned nuclear waste facility could be sited (Keeney and von Winterfieldt 1994) in Nevada, South Carolina, or Washington, among other places. The attractiveness of a site is a function of its distance from population centers, proximity to existing sources of waste, capacity, political fairness, and susceptibility to earthquakes. The scales are defined in detail, often in terms of geographic features. Because the scales are defined in a hierarchical manner, starting with decision makers? fundamental needs, they reflect decision-maker preferences well, including non-linearity, the interactions between objectives, and considerations that are more social rather than spatial in nature.

This approach, however, has limitations with respect to making decisions about park boundaries. The main limitation is that it is labor-intensive. Separate subjective input for each evaluation can be costly and time-consuming when innumerable alternatives must be evaluated. Also, many subjective values may be difficult to measure precisely (e.g., minimize damage, maximize water quality, minimize fragmentation, minimize feral species, etc.). Although an expert might be able to look around and give a subjective score for each attribute, better definitions would make this process more time-consuming. This approach defines the function $U(x)$, however $x(p)$ is not explicitly defined. Instead, a planner must supply subjective measures.

2.3 Proposed Approach

Researchers have applied the MAUT approach to numerous environmental and planning problems. Our approach is similar to the above approaches, but integrates them in a two important ways. First, it starts with the definition of the decision makers' fundamental objectives and works backwards to define useful measures that can be derived from available data. It must be possible to obtain these measures, or the utility function is not practical. Second, measures are related back to an overall score for the site through a structure that includes nonlinear relationships and interactions among terms, rather than with linear weights, thereby accounting for such factors as risk and diminishing marginal benefits. The result is a score that, if correctly constructed, should correspond perfectly to decision-maker preferences (i.e., $U[x(p_1)] > U[x(p_2)]$ if, and only if, the decision maker prefers p_1 to p_2 for all p in P). This last condition is the acid test for a rule to score alternatives. Although simpler approaches can be useful for decision support, they are unlikely to pass this test.

A good multi-attribute utility function (MAUF) will improve decision making by speeding the identification of the most attractive alternatives. When making intuitive comparisons is difficult because there are many factors in play at once, a multi-attribute utility function provides the summary information necessary to sort out the best alternatives. By separating the process of thinking about values from thinking about the specific attributes of a proposed set of boundaries, there is a better chance of having logical consistency in a comparison of alternatives. People are the source of the value judgments, but calculations about those judgments are fallible, especially when they rely on huge amounts of data and multiple dimensions. In these areas, a MAUT-based decision-support system helps a planner (or a society), who cares about certain objectives to achieve those objectives to a greater extent.

The proposed approach is to take the front-end provided by site evaluation and attach it to the back-end provided by suitability indices. With this approach, a hierarchical MAUF can be constructed with measures that are based on the same type of map layers as used for suitability indices. This approach requires an iterative process, in which important decision attributes are repeatedly compared to proxy measures derived from available information. Attributes and measures are refined (it is possible to have different representations of the value function) until a sufficient and complete set of measures and a corresponding value function are defined.

From raw data (input map layers), thematic map layers can be derived that consist of suitability indices for individual cells. Descriptive statistics from these thematic maps can then be generated. A number of techniques adapted from decision analysis and spatial analysis make it possible to have quite rich measures, as described below. The objectives hierarchy is then modified so that it is completely supported by these statistics as measures. In our experience, this requires both a high level of effort in developing definitions and several meetings between actual decision makers and the developers of the DSS. At this point, an MAUF can be assessed in the usual way. First, a single attribute utility function (SAUF) is defined over varied attribute levels (where the attributes are chosen for ease of assessment, so long as their relationship to the measures is unambiguous). Then an MAUF is defined in terms of the SAUFs. The term GMAUS (Geographic Multi-Attribute Utility System) describes a system that would implement U[x(p)], which would consist of geographic and spatial analysis for identifying x(p) and a compatible utility function.

2.4 Methodology

Applying an MAUF to GIS-based problems presents some new methodological issues, which will be described in Section 3, along with the standard steps of a decision analysis. The steps involved are as follows:
(i) Develop an objectives hierarchy, including
- Fundamental objectives (what is really important)
- Operational (means) objectives
- Indicators that would be used in a multi-attribute utility function if there were no GIS
(ii) Define maps that will generate measures (critical resource variables) and relate them to indicators.
(iii) Quantify the utility function for the attributes in terms derived from measures; this effort entails defining minimum and maximum values for each attribute, the shape of SAUFs, the constructive and destructive interactions between them (Smith 1994), and weights.

3. How Can This Work for Park Boundary Decisions?

In this section, the use of a multi-attribute utility study is described for considering modifications to a single park's boundaries. This prototypical analysis has not been executed but is based on experiences with natural resource land managers at Glacier National Park and at several military installations (although the goals and objectives may be substantially different for these two types of managers, the basic decision analysis process is similar).

3.1 Defining Objectives and Measures

First, a decision maker must be identified (or other affected parties) whose values need to be incorporated in the utility function. For present purposes, assume that (1) the decision maker

is a park manager and (2) the park system operates with a single set of values. Although this is not exactly the case, values are much more likely to be consistent within a single organization than across groups. Other groups are likely to have objectives that overlap with park service objectives, but with different relative weights attached to the objectives.

Once the appropriate people are identified, they are consulted. First a brainstorming session is undertaken to identify all the objectives that these decision makers may want to achieve. These objectives must be defined explicitly, with a direction attached (e.g., maximize the preservation of archaeological sites). Next, the objectives are arranged in a loosely hierarchical structure. At one end are fundamental objectives for the context, which are the things desirable for their intrinsic value (e.g., preserving beauty); a stylized example is shown in Figure 1.
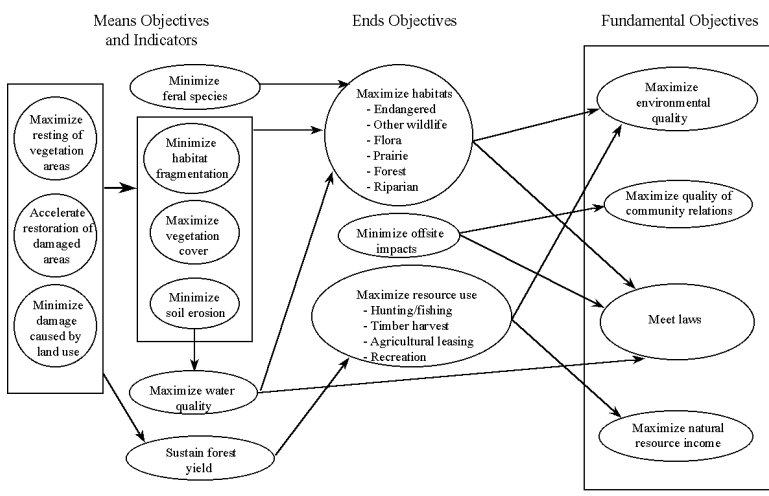

Figure 1. A stylized objectives network from a previous study

Figure 1 A stylized objectives network from a previous study

There may also be objectives that are partially outside the context of a given situation, (e.g., maxim-izeing global biodiversity might be important), that are not completely under the control of any single agency or nation. For a park service, contribut-ions to world biodiversity needs and establishing significant biodiversity within national borders may be separate objectives. However, the value of local actions still must be considered in light of global needs (e.g., park land that serves as habitat for a globally threatened species might be more important to protect than if the species were threatened only locally).

Returning to Figure 1, to the left of *fundamental objectives* are *ends objectives* - desirable because they are integral to fundamental objectives. For example, preserving forests is a part of preserving beauty. To the left of these are *means objectives* and *indicators* - characteristics which are desirable because they lead to the end objectives, but which would not be important if something else accomplished the same ends. An example of a means objective is minimizing the acidity of rain, which is desirable because it affects the quality of flora and fauna. At the left end of the structure are measures, indicators, or proxies - elements whose presence is a sign that other desirable elements have occurred. For example, the presence of an indicator species would indicate that the whole ecosystem is still functioning in the desired manner.

For land-management problems, there are usually two fundamental objectives to consider: use value and conservation value. For Glacier National Park, conservation value has two components: natural conservation and cultural conservation. Use value has a number of components, some of which are positive (education, recreation, etc.), and some of which are the extent to which negative consequences are averted (safety, carrying capacity).

These objectives sound as if they would be difficult to measure, and even more difficult to assign trade-offs, but by adding one more level to the hierarchy of objectives, it can be done. Cultural resources include archaeological, architectural, historical, recreational, and religious sites.

Once objectives have been defined to the point at which they are explicit, unambiguous, and complete (i.e., nothing important is left out), measures are defined. Defining the objectives hierarchy and the measures are interrelated tasks. Not every objective needs to measured explicitly; but at some point, every fundamental objective must either be assigned a measure or defined explicitly in terms of something else that is assigned a measure (i.e., no loose ends).

Identifying suitable measures for use with a GIS requires some thought about what quantifiable proxies for these measures might be captured in electronic form. The process of identifying measures is described well in Keeney (1992). The examples in this article illustrate how the set of useful measures and the set of measures that are obtainable electronically measures can be expanded to the point where their intersection contains complete electronically obtainable measures for each fundamental objective. The sites of each type included within proposed boundaries are already marked on existing maps so the numbers of these sites are convenient measures. Assuming the map layers are in electronic form, the measures can be an output automatically generated from input data consisting of the proposed boundary decisions and the existing maps. It is important to use definitions that are as precise as possible, although definitions can always be refined as the utility function is developed.

3.2 Quantifying Values and Trade-Offs

Once the objectives and measures have been defined, values and trade-offs can be quantified. Quantifying values and trade-offs can be emotionally difficult for participants because it requires soul searching on issues about which people may care deeply but have not given considerable thought to their value (e.g., the simple fact that for some creatures to live, others must die). However, because this part of the process brings new data (about decision maker values), it often makes the biggest difference in the quality of the decision.

To quantify value (Keeney and Raiffa 1976; Keeney 1992), SAUFs must first be defined. For each measure, a range with a minimum and a maximum for the values the measure may take over the set of potential decisions must be identified. Then the way these measures relate to the fundamental objectives must be defined explicitly (e.g., the measure of cultural conservation value can be defined as a function of the numbers of several types of sites). For example, a raw score for cultural conservation value could be 20 times the number of archaeological sites plus 0.5 times the number of architectural sites. This score will then be transformed to a score between 0 and 1. In this range, the relationship can be assigned so that a change from a score of 0 to 0.5 is valued as much as a change from 0.5 to 1. This is accomplished by determining its minimum value and assigning 0 to this value; 1 is assigned to the maximum value. The decision maker decides what the score is at the midpoint between 0 and 1. Thus, a SAUF has been defined in terms of its measures.

Once SAUFs have been constructed for all our fundamental objectives (ideally objectives between which there are no interactions), they can be combined to form a multi-attribute utility function by assigning weights (which sum to 1) to all SAUFs. The result looks like the following:

$$U(x) = \Sigma \ w_i \ w_{ij} \ u_{ij}[f(x)], \tag{1}$$

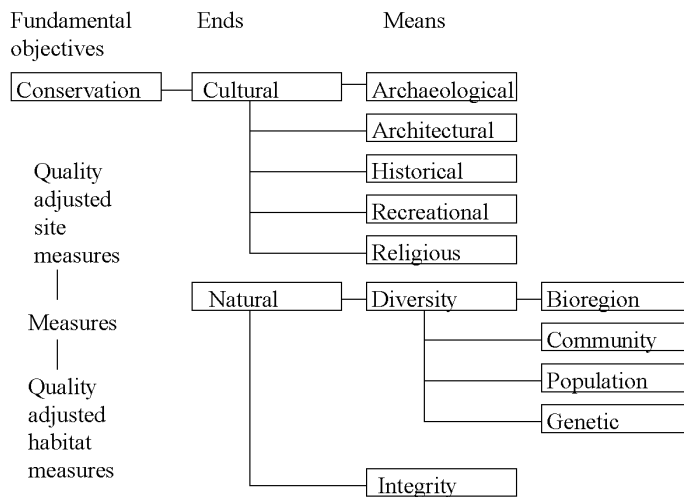where the subscript, ij, refers to the i-th attribute and the j-th sub-attribute.

Figure 2 A value hierarchy for conservation

To illustrate, a hypothetical utility function can be constructed and compared to two hypothetical alternatives. This utility function is an outgrowth of the function developed by the Argonne National Laboratory for the purpose of natural resource management at Fort Riley, Kansas (Sundell et all, in preparation). Starting with the conservation objectives hierarchy shown in Figure 2 (which is only one of the three pillars of the complete objectives hierarchy), the archaeological measures could be defined as the number of quality-adjusted sites within protected boundaries (not necessarily the park itself), where the quality of the site is subjectively estimated and recorded on a map (this must be done for each site) and the adjustment factors are:

· Low importance = 0.2
· Medium importance = 0.4
· High importance = 1.0

The definition of the quality adjustment for a site uses a constructed scale, for which the meaning of low importance would have to be verbally described, unless unambiguous or quantitative data are already available. The classification of an individual site would necessarily be subjective. This scale is used to translate qualitative measures into quantitative measures, over which we define a SAUF. The SAUF is defined in terms of the number of quality-adjusted sites. First, the range of possible values is identified as follows:
· Minimum = 0.6, because there is one low-importance site and one medium-importance site that will be within protected boundaries no matter what.
· Maximum = 4.0, because there are no other sites in the region under consideration.

3.3 Single Attribute Utility Functions for Social/Cultural, Conservation, and Consumptive Values

Numbers can now be attached to the hierarchical value structure in Figure 2 to generate SAUFs for park boundary decisions. The purpose of this exercise is twofold. First, much of the basic structure identified and many of the attributes defined are applicable over a wide range of park boundary decisions, so this structure can serve as a template to be modified as needed for many types of decisions. Second, the interaction between the attributes of concern and the measures defined for them is very interesting; a variety of qualitatively different measures to illustrate some of the numerous techniques used in quantifying values are included. The precise structure and the numbers used here are merely illustrative, although several are inspired by our experience interacting with natural resource planners and

decision makers. For brevity, and because the results are not for an actual decision, not all attributes and SAUFs are defined here.

First, all SAUFs will be normalized so they are 0 when the attribute is at its minimum value and 1 when the attribute is at its maximum. Next, the shape of the SAUF between 0 and 1 will be defined. A fairly easy way to do this is by finding the "value midpoint," where the incremental value of moving from the minimum value to the midpoint is the same as the incremental value of moving from the midpoint to the maximum value. An exponential curve can be fit to the three available points, i.e.,

$$U(W) = (1 - e^{kw})/(1 - e^{k}) \qquad (2)$$

where k is such that $U(W) = 0.5$. W is the normalized midpoint found from the equation for the attribute. W = (midpoint value - minimum value/maximum value - minimum value).

The attributes from the basic structure shown in Figure 2 serve as examples. Three major types of uses are described here and are grouped by: (1) social/cultural, (2) conservation, and (3) consumptive values.

Social/Cultural Values The first major objective to be considered is how well the park serves as an asset for human society. The attributes considered here tend to be discrete, the measures fairly obvious (i.e., number of sites), and the tradeoffs between them based on necessarily subjective judgments.

(i) Attribute: Historical Sites
Measure: Quality adjusted number of sites located within protected boundaries.
Suitability Index Scale:
- Low = 0.1 (location where significant event occurred; e.g., a deserted battlefield)
- Medium = 0.4 (location of an event, including generic artifacts; e.g., houses standing from the time of the event)
- High = 1.0 (location of event with intact artifacts from the event, e.g., a fortress)
SAUF Parameters: Minimum value = 0, maximum value = 3.5, midpoint value = 2.5
Note: In this case, the value midpoint is above the numeric midpoint because a critical mass is needed to attract visitors.

(ii) Attribute: Recreation Areas
Measure: Recreational use areas located within the park boundaries.
Suitability Index Scale:
- Low = 0.33 (functional, but not an especially attractive camping area)
- Medium = 0.5 (interesting feature enjoyed by users; e.g., campground near waterfall)
- High = 1.0 (anything that would be on a postcard)
SAUF Parameters: Minimum value = 2, maximum value = 10, midpoint value = 6
Note: Here, the value midpoint is the numeric midpoint, because what is there will be used, and a linear value in terms of dollar receipts is appropriate.

(iii) Attribute: Religious Sites
Measure: Status of religious sites within protected park boundaries.
Suitability Index Scale:
- Low = 0.1 (remnant of sacred site no longer used; within boundaries of park)
- Medium = 0.3 (complete sacred site no longer used; within boundaries of park)
- Medium = 0.6 (sacred site accessible to users and protected from desecration)
- High = 0.1 (intact sacred site protected from desecration and still used)
SAUF Parameters: Minimum value = 0, maximum value = 1.5, 25% value point = 0.2, 75% value point = 1.25

Note: In this case, the SAUF is shaped like an inverted S; a midpoint is not used, instead two percentile points are used to estimate the function. The definitions used must be precise, because the goal is to use the park as a means of protecting sites; to some, the fact that a religious site is in a national park might be viewed as a form of desecration. The process used to determine these numbers is difficult and quite possibly political, but it should be included in the utility function if decision makers are forced to make trade-offs on these issues.

Discussion

The weight of each of the above attributes is now identified as a component of social/cultural utility (e.g., how far in single-attribute-utility space would you go in one dimension to protect another). A set of numbers is generated that sums to 1: architectural sites = 20%, archaeological sites = 10%, religious sites = 20%, historical sites = 25%, and recreational use areas = 25%.

In practice, one would not just sit down and try to assign weights to each attribute. First the attributes would be ranked in importance, for example, by asking such questions as if only one of the above could be brought from its minimum to its maximum value, which one should it be? Second, taking the value midpoint from the most important attribute, determine whether it would be more valuable to change that measure from its midpoint to its maximum, or to change another attribute from its minimum to its maximum. By repeatedly applying this approach, specific numbers can be determined to eventually yield weights that decision makers find reasonable.

It should be noted that these are not necessarily independent weights. Recreation is worth less when religious value is high than when it is low. This is called destructive interaction and is dealt with by adding a term (e.g., with weight -0.1) multiplied by the product of the single-attribute-utility value for recreation and the single-attribute-utility value for religion.

Conservation Values So far, the attributes have been defined mostly in terms of precise counts of physical objects (e.g., sites). Other attributes of this utility function require different types of measures. Natural conservation value is a function of the integrity of the system and the diversity of the biota found within that system. The definition of these measures requires more creativity than do those of the previous measures.

(i) Attribute: Ecosystem Integrity

Measure: Integrity is fundamentally subjective and measuring it would require solicitation of expert and citizen reactions about how well a wide variety of scenarios would compare with an ideal environment. Since it would be prohibitively costly to acquire such information for each alternative, GIS-based measures can still be constructed. For illustrative purposes, a simple proxy would be the percentage of cells in which there is predominantly indigenous vegetation.

Suitability Index Scale: exotic = 0, indigenous = 1.

SAUF Parameters: Minimum value = 0%, maximum value = 75%, and midpoint value = 30%.

Note: the value midpoint is below the numerical midpoint, because it is important to leave a small but sustainable area.

(ii) Attribute: Biological Diversity

Biodiversity consists of the bioregion, community, population, and genetic levels. Resource managers generally attempt to measure biodiversity at the bioregional and community levels,

and if provided adequate data and given enough time, the population level. Although sufficient information concerning genetic diversity is rarely available, it is shown here so that the complete value hierarchy may be used as a reference point by future decision makers. Therefore, the diversity at each of these levels can be measured as follows.

- Bioregion diversity:

Measure: Habitat of species critical to the region is defined as the number of hectares of quality-adjusted suitable habitat for species. Because modeling this parameter is difficult, a utility between 0 and 1 is directly assigned by the decision maker. This inelegant shortcut plugs holes in a model under construction.

SAUF Parameters: The minimum, maximum, and midpoint do not have to be defined.

- Community diversity:

Measure: The number of different natural communities that are present and of sufficient quantity and quality within the park. These would be taken from a list of the representative communities for the region (e.g., woodland, aquatic, grassland).

SAUF Parameters: The minimum value = 0, maximum value = 8, and midpoint value = 6.

- Population diversity:

Measure: Ability of local contiguous habitat to support sufficient numbers of key species. Defined in terms of habitat size and species requirements.

SAUF Parameters: This value is directly assessed by the decision maker between 0 and 1, in a manner similar to assessing bioregion diversity.

- Genetic diversity:

Measure: The number in the gene pool overall, worldwide. This attribute is not easily measured in spatial terms.

SAUF Parameters: Where appropriate, a constructed scale could be used where the decision maker subjectively assigns a score.

Discussion

Concerning ecological integrity and biological diversity, each level could be considered equally important for diversity; also, it might be determined that for these ranges, diversity is twice as important as integrity. Translating these to algebraic identities (A = B = C = D, A + B + C + D = 2 * E, and A + B + C + D + E = 1), the following weights for natural conservation value are obtained: 0.33, 0.167, 0.167, 0.167, 0.167.

Consumptive Values The third pillar of the value hierarchy (after social and natural conservation), consumptive value, has many attributes. The authors believe that these are important attributes to be considered in the park boundary value hierarchy. The actual measures, suitability index scales, and SAUF parameters will be very specific. For this reason, full descriptions will not be defined at this time, although hypothetical numbers will be included later to illustrate the complete utility calculations. Instead, the attributes are listed, accompanied by a proposed measure which planners should modify as needed.

(i) Attribute: Visual Resources

Measure: defined in terms of the integrity of the terrain with interesting features within 100 meters of roads and within 200 meters of camping or other stopping points. SAUF Parameters: not applicable.

(ii) Attribute: Human Carrying Capacity

Measure: proxies for how many users a park can accommodate without sustaining damage would include robustness to erosion (which is a function of cover and erodability, defined

using the Universal Soil Loss Equation [USLE] or the revised USLE) as well as the presence of natural firebreaks in areas close to roads and access points.

SAUF Parameters: not applicable.

(iii) Attribute: Education

Measure: defined in terms of easy access to roads of the previously defined archaeological and historical points, high-quality habitats, etc.

SAUF Parameters: not applicable.

(iv) Attribute: Economic Resource Use

Measure: First, it can be defined as the ability of indigenous peoples to use the land, defined in terms of the number of hectares of land available for sustainable food and goods production. Second, it can be defined as the number of hectares of marked areas to be used for commercial mining, assuming it is done in an ecologically responsible fashion. Finally, it can be defined in terms of the number of hectares of marked areas with sufficient tree cover for sustainable timber harvesting (consistent with current policy for harvesting); or instead the timber foregone may be quantified when land is incorporated into a park, depending on the rules to be imposed within the park. Both the second and third part of the definition can be translated to economic value measures. The resource use measure may be quantified as the linear sum of these numbers, with weights reflecting economic value. For reasons of equity, a higher weight is put on the economic value for indigenous peoples. The weights could be 1.0, 0.5, or 0.3.

SAUF Parameters: not applicable.

(v) Attribute: Safety

Measure: defined in terms of unsafe conditions (e.g., unmaintained roads, geological hazard areas). This attribute translates to the number of injuries prevented. Because it is desirable for this attribute to be as small as possible, it is measured in negative numbers.

SAUF Parameters: minimum value = -5, maximum value = -0.5, midpoint value = -1.5.

(vi) Attribute: Recreation

Measure: sites weighted by their quality and defined in terms of the number of recreational sites (e.g., water use potential), further adjusted to reflect accessibility. This attribute would interact with human carrying capacity, because with a low carrying capacity, additional attractions cannot be used without risking damage.

SAUF Parameters: minimum value = 3, maximum value = 20, midpoint value = 10.

(vii) Attribute: Scientific Value

Measure: defined in terms of the number of existing habitats of interest (with specialized maps) and the number of sites of interest (e.g., archaeological, natural), both of which are quality adjusted to reflect accessibility (secondary roads or primary roads).

SAUF Parameters: should be linear and would be: minimum value = 2, maximum value = 12, midpoint value = 7.

Discussion

The relative weights of these attributes must be determined. In practice, the relative weights of the consumptive values would be done in the same manner as for the other two sets of attributes.

3.4 Forming a Multi-Attribute Utility Function

From the above measures, a conservation utility and a consumptive utility are obtained. These utilities are combined into the overall utility, which can be described in the following

way. Total conservation value is linear. Total consumptive value is s-shaped, because if there is too little overall attraction, the region will not have critical mass; above a certain level, the region is saturated and additional use would detract from the quality of the experience. For this location, conservation is slightly more important than use (let us assume the relative weights are 60 and 40) within the ranges defined. Finally, there is a negative interaction between conservation value and consumptive value: if the land is to be conserved, its use will be more restricted. (Do not include this last consideration more than once.) All these considerations are combined into the following equation:

$$U(x) = 0.6\ u_1\ (x_1) + 0.4\ u_2\ (x_2) - 0.2\ u_1\ (x_1)\ u_2\ (x_2). \qquad (3)$$

To implement this model, the following map layers need to be generated (some of them are constructed only after the need for them becomes apparent while building a utility function):

· Habitats
· Roads and proximity to primary and secondary roads
· Mineral areas
· Existing sites
· Recreational sites / camp sites
· Safety index
· Erosion index

A fire hazard index and contiguous regions of indigenous plants are among other themes that could be used for additional map layers.

These layers would be combined into the map layers needed for each objective. Generating map layers could take over one hour of computer time for the first alternative and perhaps 15 minutes for later alternatives (or a full hour if map layers are not used efficiently; e.g., if reusable or static layers are thrown out after statistics are calculated). Then, the number of cells in each category (or the number of sub-regions qualifying as a category) is recorded as the summary statistics (r-stats) from the maps. These data are transformed into the measure by multiplying the quality and importance coefficients for each category.

Taking the measure for each objective as the xij, we insert them into the utility function to find the total utility for a proposed boundary. Table 1 illustrates how the parameters of this utility function might be entered in a spreadsheet. Let us consider a decision in which there are three hypothetical alternatives, each a different set of proposed boundaries that would require the same budget:

p_1 - Draw the minimum map that holds all high-quality sites.

p_2 - Use natural boundaries (mountains, rivers, etc.) such as those used in previous example.

p_3 - Draw a 10-km by 10-km square around the most salient features of the region.

Table 1 Parameters for a Multi-Attribute Utility Function

Measure	Var-iab	Utility Function				Normalize Midpoint	Calculate Statistic form GIS	Norma-li Measur (0-1 scal	SAU (0-1 scal	Contribution to Total U
		Min	Mic	Max	Weig %					
Conservation	x1									
Archaeological	x111	0.6	1.8	4	2.0	0.353	2.000	0.412	0.564	0.011
Architectural	x112	1	4	25	4.0	0.125	4.000	0.125	0.125	0.005
Historical	x113	0	2.5	3.5	5.0	0.714	3.000	0.857	0.715	0.036
Recreational	x114	2	6	10	5.0	0.500	8.000	0.750	0.750	0.038
Religious	x115	0	0.4	1.5	4.0	0.233	1.200	0.800	0.948	0.038

Measure	Variable									
Integrity	x121	0	0.3	0.7	8.0	0.400	0.500	0.667	0.753	0.060
Commun. div.	x131	0	6	8	2.0	0.750	5.000	0.625	0.344	0.007
Pop. diversity	x132	0	0.5	1	2.0	0.500	0.800	0.800	0.800	0.016
Genetic div	x133	0	0.5	1	2.0	0.500	0.200	0.200	0.200	0.004
Bioregion div.	x134	0	0.5	1	2.0	0.500	0.530	0.530	0.530	0.011
Use	x2									
Aesthetic	x21	0	0.1	1	10	0.700	0.900	0.900	0.803	0.080
Carrying cap.	x22	0	0.5	1	10	0.500	0.500	0.500	0.496	0.050
Educational	x23	0	0.4	1	5	0.400	0.750	0.750	0.821	0.041
Resource use	x24	0	0.5	1	3	0.500	0.350	0.350	0.347	0.010
Safety	x25	-5	-1.	-0.	10	0.256	-2.000	0.333	0.601	0.060
Recreational	x26	3	10	20	15	0.412	7.000	0.235	0.304	0.046
Scientific	x27	2	8	12	10	0.600	10.000	0.800	0.729	0.073
Total Utility										0.585

After entering these parameters into our GIS, measures $x(p_1)$, $x(p_2)$, and $x(p_3)$ are found and the utility computed for each (Table 2). Alternatives p_2 and p_3 are close to each other in utility, but both are worse than p_1. The contributions of the different factors shown in the table affect the computed utilities. If p_1, p_2, and p_3 were our only options, p_1 would be recommended. On the other hand, the DSS output may be used to improve the plan. A graph could be used to illustrate how the different alternatives compare in terms of the sources of their value. Once all the relevant data are in this form, a sensitivity analysis can be performed quickly, without recalculating maps (e.g., What if recreation was twice as important as assumed? What if the available land for timber use was reduced to 0?) quickly, without recalculating maps. This can also be done systematically to find how much increased utility per unit can be obtained from each measure for a given baseline plan.

Rather than trying alternatives and learning from them by hand, one could attempt to find the truly optimal boundary. This problem is difficult, and possible algorithms that could be applied have been explored. Each of these has strengths (i.e., genetic algorithms) and weaknesses with respect to speed and accuracy. Regardless of the algorithm chosen, it must maximize the value of an automated utility function over many alternatives so that the very best alternative is chosen. This outcome would not be possible, given the large number of necessary evaluations, if a multi-attribute utility function was not defined in terms of digitally available measures.

Table 2 Utility Calculations for Three Different Alternatives

Measure	Variable	Calculated Statistic from GIS	Normalized Measure (0-1 scale)	SAU (0-1 scale)	Contribution to Total U
p1; 10-km x 10-km square					
Archaeological	x111	2.000	0.412	0.564	0.011
Architectural	x112	4.000	0.125	0.125	0.005
Historical	x113	3.000	0.857	0.715	0.036
Recreational	x114	8.000	0.750	0.750	0.038
Religious	x115	1.200	0.800	0.948	0.038
Integrity	x121	0.500	0.667	0.753	0.060
Commun. div.	x131	5.000	0.625	0.344	0.007

Measure	Variable	Calculated Statistic from GIS	Normalized Measure (0-1 scale)	SAU (0-1 scale)	Contribution to Total U
Pop. diversity	x132	0.800	0.800	0.800	0.016
Genetic div.	x133	0.200	0.200	0.200	0.004
Bioregion div.	x134	0.530	0.530	0.530	0.011
Use	x2				
Aesthetic	x21	0.900	0.900	0.803	0.080
Carrying cap.	x22	0.500	0.500	0.496	0.050
Educational	x23	0.750	0.750	0.821	0.041
Resource use	x24	0.350	0.350	0.347	0.010
Safety	x25	-2.000	0.333	0.601	0.060
Recreational	x26	7.000	0.235	0.304	0.046
Scientific	x27	10.000	0.800	0.729	0.073
TOTAL UTILITY					0.585
p2: minimum are including high-quality sites					
Archaeological	x111	3.500	0.853	0.919	0.018
Architectural	x112	15.000	0.583	0.583	0.023
Histrorical	x113	3.500	1.000	1.000	0.050
Recreational	x114	9.000	0.875	0.875	0.044
Religious	x115	1.350	0.900	0.978	0.039
Integrity	x121	0.200	0.267	0.351	0.028
Commun. div.	x131	3.000	0.375	0.143	0.003
Pop. diversity	x132	0.600	0.600	0.600	0.012
Genetic div.	x133	0.200	0.200	0.200	0.004
Bioregion div.	x134	0.500	0.500	0.500	0.010
Use	x2				
Aesthetic	x21	0.700	0.700	0.500	0.050
Educational	x23	0.850	0.850	0.897	0.045
Resource use	x24	0.300	0.300	0.297	0.009
Safety	x25	-1.000	0.111	0.255	0.025
Recreational	x26	5.000	0.118	0.158	0.024
Scientific	x27	7.000	0.500	0.399	0.040
TOTAL UTILITY					0.459

Table 2 Utility Calculations for Three Different Alternatives (Continued)

Measure	Variable	Calculated Statistic from GIS	Normalized Measure (0-1 scale)	SAU (0-1 scale)	Contribution to Total U
p3: natural boundaries					
Archaeological	x111	1.500	0.265	0.395	0.008
Architectural	x112	6.000	0.208	0.208	0.008
Histrorical	x113	2.000	0.571	0.338	0.017
Recreational	x114	6.000	0.500	0.500	0.025
Religious	x115	0.250	0.167	0.388	0.016
Integrity	x121	0.350	0.467	0.568	0.045
Community div.	x131	3.000	0.375	0.143	0.003
Population div.	x132	0.700	0.700	0.700	0.014
Genetic div.	x133	0.200	0.200	0.200	0.004
Bioregion div.	x134	0.500	0.500	0.500	0.010
Use	x2				
Aesthetic	x21	0.800	0.800	0.638	0.064
Carrying cap.	x22	0.450	0.450	0.446	0.045
Educational	x23	0.700	0.700	0.781	0.039

Resource use	x24	0.350	0.350	0.347	0.010
Safety	x25	-3.000	0.556	0.807	0.081
Recreational	x26	5.000	0.118	0.158	0.024
Scientific	x27	5.000	0.300	0.219	0.022
TOTAL UTILITY					0.434

4. Using a GMAUS to Make Park-Boundary Decisions

Previous sections discussed the use of a MAUT approach to decide between several alternatives for the boundaries of a single park. Applying the same approach to a variety of related decisions may also be productive, both to improve the individual decisions and to improve the consistency across decisions. In this section, we take the decision analyst? s viewpoint and present several different scenarios to which the MAUT approach may be applied.

Greenfield One scenario is in greenfield planning. In this scenario, there is no park or reserve, but there is a sum of money to buy land. Where should the park boundaries be drawn? Assume that a park consists of contiguous regions. By using a GIS, planners can define the boundaries leading to maximum value (for both conservation and other purposes) of the land within the boundaries, subject to the available budget (or some lower amount of money, if there is nothing worthwhile to buy). This scenario is more appropriate for decisions related to consumptive value than those related to conservation.

Noah's Ark Within a region, a certain amount of money is available to purchase land in order to protect it. In this scenario, a map must be developed that estimates the value of the land as it will be used if it remains outside of the park system; some regions will be reasonably well-conserved, even if they are not within protective boundaries (e.g., non-arable land), while others might be more vulnerable. When a boundary is proposed, the conservation value of the land within the boundaries and of the conservation land value outside the boundaries is calculated. The decision maker attempts to draw boundaries that can be acquired with the available budget in a way that maximizes the incremental conservation value achieved by setting aside land within the park system.

Multiple Use In a more general scenario, land outside a park's boundaries has an explicit, economic consumptive value (although it could be argued that the price of land allows the market mechanism to tell the park service about consumptive value). This scenario could apply, for example, if boundaries are being drawn between park service and the forest service land. In this case, the incremental consumptive and conservation value of the land when it is inside park boundaries rather than outside park boundaries must be examined. The goal is to draw the boundaries that maximize the value for both parcels of land.

Different Boundaries for Different Uses The previous approaches are all special cases of the situation in which land can be subjected to various restrictions, and there is a price negotiated with current landowners for changing restrictions on their land. The price for going from totally unrestricted to totally restricted use would be higher than going from partially unrestricted to partially restricted. For example, an extreme case is where the landowner gives up all rights to develop the land in any way and agrees to allow camping, hiking and fishing, for example, in exchange for a payment. This case is the same as purchasing land in the greenfield case. A more interesting case would be where on one parcel of land there is an agreement not to cut down trees, on a second parcel an agreement not to divide a corridor, a third is transferred outright to the park service, a fourth is unrestricted, and a fifth is left as

preserve land on which some hunting is allowed. Boundaries are not considered absolute. Rather, different boundaries apply to different sets of restrictions.

In this case, the measures for consumptive and conservation value for each parcel or on the total region are computed for each set of restrictions and then summed. The measures and the land are partitioned so as to maximize the weighted value function on those measures, so long as the cost of creating that partition is within budget constraints. The constraining factor may not be budget, but rather the political process, whereby different parties give up different rights in exchange for concessions that they perceive as more valuable. Obtaining the scores from different parties for the various alternatives can help in negotiating a solution. This solution may still not please everybody, but at least it will not be because potential win-win solutions have been overlooked. If the problem is simply that one party has more power than the others (particularly problematic if their values are different from those of the others, which could be the case with the logging industry), this is an issue for the political process to resolve.

Portfolio Problem A number of nearly independent regions may be of concern. The park service can acquire land in several counties of several states. Should it acquire a large amount of land in one location, or smaller amounts in many locations? In this case, the same values should be applied at one level (e.g., conservation vs. consumptive value), but the specific sources of value will be different at each site. Even if there are physical interactions among sites, there may or may not be interactions among the value contributions from different sites.

For some dimensions, the single-attribute utility scores can simply be summed across individual sites in the portfolio (e.g., local happiness). For other dimensions, the measures from the sites may be summed and a SAUF applied (e.g., number of national treasures). For still others, a combination of these two approaches might be necessary (e.g., biodiversity at the national level is a function of the number of high-quality, medium-quality, and low-quality protected areas across the country, where the quality level is derived from SAUFs at the site level). By using a measure for value that allows comparison among different sites and yet considers a site in the context of the rest of the portfolio, a set of acquisitions that maximizes the total system value can be selected. A similar approach would be applicable if the goal is to add, through actions at the national level, to the world?s portfolio of protected areas, even though it is not possible to affect actions of other nations.

Acquiring Land that Becomes Available for Sale Sometimes land that was previously unavailable becomes available for sale. Should land be bought on the basis of availability, urgency, or price? This problem is one of looking into the future. A dollar spent today is not available tomorrow. Ideally, we would want to consider the long-term value of the land, (e.g., the value 100 years from now). What happens if the land is acquired, restricted in some way, or ignored by the park service? This problem is essentially the same as the Noah?s Ark scenario. However, in this case, decisions are made sequentially. In general, this approach is not as good as making a coordinated set of decisions at one time to make sure that where there are potential synergies, the land being acquired has them. If decisions must be made sequentially, however, the decision should be made on the basis of how much value is added to the final portfolio for the price. This cannot be done precisely, because the whole of the future portfolio is not known However, if a good baseline estimate of the future portfolio is used as a starting point, the incremental value of a parcel of land added to that portfolio can be calculated.

If the ratio of incremental value to cost is above a specified cutoff (e.g., what society is willing to pay per unit of utility), the land should be acquired. This cutoff value would be high when either many acquisition opportunities are expected or many parcels are expected to be "needed" in the near future because the current acquisition is "competing" with other attractive possibilities. In economic terms, there is a high shadow price to acquisition funds. The cutoff value would be lower when few such possibilities are looming or when more funds are expected to be available in the future. If the incremental value for a parcel of land is high enough (e.g., high current value and low future value if not protected), it might make sense to acquire the parcel whether or not it is on the market, even if a 25 percent premium must be paid. The use of a single, consistent set of criteria for purchase decisions will increase the value of land protected in the long term, because important future opportunities will not be passed up because a less important opportunity with a short time window uses up funds today.

5. Conclusion

Multi-attribute utility theory can be combined with spatial analysis tools to support land management planning by providing a logical, scientific foundation into which stakeholder values can be consistently incorporated. Some lessons have been learned about how to create map layers rich enough to support an multi-attribute utility (i.e., what must be in a GMAUS). These techniques include the following (as illustrated in the examples):
· Iteration - the objectives in the utility function can be changed if they do not lend themselves to easy measurement. New map layers may also be developed in response to the need identified by the presence of quantities in the utility function that are hard to estimate intuitively.
· Nested indices - quality on selected sites can be adjusted before applying a utility function defined over the number of sites.
· Recursive definition of map layers-a habitat is defined by map layers, and a threatened habitat would result from combining a threat map layer and a habitat map layer.
· Proxy variables - if injuries prevented cannot be measured directly, the amount of high risk areas accessible to the public can be measured.
· Manual entries - manual entries may be used to account for genetic diversity, which is difficult to compute from the available data.
· Predefined and static maps-the materials provide information on the proximity of cells to fixed roads and historic sites, which need not be recalculated when different alternatives are considered.
· Hierarchical utility functions-these functions address cultural value as a function of historical, religious, archaeological, and other values.

This is not an exhaustive list, as possible techniques are limited only by the user's creativity. The main lesson is that with some effort, the measures available from spatially encoded data (e.g., site maps and remote sensing data) can be quantitatively linked with the achievement of fundamental objectives of decision makers and stakeholders. Systems such as those described will result in a more supportable decision process, where heartfelt disagreements about values will not be mixed up with more objective disagreements about scientific issues. By clarifying values, a GMAUS provides a new level of decision support to land-management decision makers.

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