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ANALYSIS

Assessing ecosystem sustainability and management using fuzzy logic

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ABSTRACT

Concern about the negative impacts of growth and development on protected area ecosystems has drawn attention to methods for assessing ecosystem sustainability and management. Existing non-stochastic and stochastic methods for assessing weak and strong sustainability of ecosystems have several limitations. The non-stochastic method does not account for errors in measuring attributes, stochastic variability in attributes, and uncertainty about the relationship between ecosystem attributes and states (degrees) of ecosystem sustainability. Although the stochastic method better accounts for errors in measuring attributes, and stochastic variability in attributes than the non-stochastic method, it requires information about the probability distributions of attributes for different states of sustainability. Such information is not readily available. The fuzzy logic method overcomes the limitations of the non-stochastic and stochastic methods, but requires fuzzifying an index of sustainability in the case of weak sustainability, fuzzifying individual attributes in the case of strong sustainability, specifying and estimating membership functions for low, medium and high ecosystem sustainability, selecting a rule to determine whether an ecosystem is strongly sustainable based on the conclusions for fuzzy propositions, and specifying fuzzy sets for truth qualifiers when evaluating conditional and qualified propositions. Whether the benefits outweigh the costs of using the fuzzy logic method depends on the knowledge, data, and information available about the ecosystem, the expertise of the persons doing the assessment, and other factors. The non-stochastic, stochastic and fuzzy logic methods can be used to rank management alternatives and select a preferred alternative in cases where the current state of the ecosystem is unsustainable. Ranking management alternatives using a fuzzy logic method requires ordering the fuzzy scores for alternatives. All three methods for ranking management alternatives call for a group preference ordering for management alternatives in cases where individuals in the group have different preferences for alternatives.

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1. Introduction

Rapid growth and development in gateway communities for protected areas, such as national parks and wilderness areas, threaten the sustainability of protected area ecosystems (Howe et al., 1997; Baron et al., 2000; Parks and Harcourt, 2002). To illustrate this predicament, consider the situation that currently exists in protected area ecosystems, such as the

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Greater Yellowstone Ecosystem (Keiter and Boyce, 1991; Hansen et al., 2002; Parmenter et al., 2003) and the Crown of the Continent Ecosystem (Konrad et al., 1999; Long, 2002; Pedynowski, 2003). Both ecosystems contain a national park, wilderness areas, national forests, state-owned public land, urban and commercial developments, farms, ranches, mines and timber harvesting operations. Population and economic growth in these ecosystems are driving increases in personal income, employment and other socioeconomic indicators. Conversion of land from undeveloped to developed uses, which accompanies development, is reducing and degrading fish and wildlife habitat, and decreasing water quality. Habitat loss and degradation make it more difficult to recover threatened and endangered species, and lower water quality degrades tourist/recreational experiences, decreases fish and wildlife values, and increases the cost of water treatment. Growth in personal income and population is occurring at the expense of losses in biodiversity and water quality, which implies tradeoffs between economic (personal income) objectives and environmental (biodiversity and water quality) objectives. Tradeoffs raise the possibility that the ecosystem is not sustainable.

One way to determine the extent to which growth and development adversely affect protected area ecosystems is to assess their sustainability. Suppose ecosystem sustainability is assessed by an ecosystem assessment group (EAG) composed of public land managers, community planners, developers, environmental interests, scientists, and others. If the assessment indicates the ecosystem is sustainable, then there is no need to change management practices and policies. On the other hand, if the assessment indicates the ecosystem is not sustainable, then the EAG can rank management alternatives and select a preferred management plan for achieving sustainability.

This paper compares two crisp (non-stochastic and stochastic) methods and a fuzzy logic method for assessing weak and strong sustainability of a protected area ecosystem. The two crisp methods, proposed by Prato (1999, 2000a,b), are based on the concepts of weak and strong sustainability. The fuzzy logic method is based on the principles of fuzzy sets and fuzzy inference (Bellman and Zadeh, 1970; Bass and Kwakernaak, 1977; Barrett and Pattanaik, 1989; Klir and Yuan, 1995; Carlsson and Fuller, 1996).

2. Selecting and measuring attributes

Suppose the EAG wants to determine whether a protected area ecosystem is weakly or strongly sustainable in terms of three attributes: personal income, biodiversity, and water quality. Selection of these attributes is consistent with two of the three goals proposed by Daly (1992) and Costanza and Folke (1997) for valuing ecosystem services. The three goals are economic efficiency, ecological sustainability, and distributional equity. Personal income is an economic efficiency goal and biodiversity and water quality are ecological sustainability goals. The methods discussed here are operative with more attributes of ecosystem sustainability than personal income, biodiversity, and water quality.

Personal income is the sum of total personal income in the counties located within the ecosystem, and can be measured using data published by state bureaus of business and economic research, and the U.S. Department of Commerce. Biodiversity can be measured by a multispecies conservation value index, like the one developed by Root et al. (2003). This index weights habitat-suitability maps for individual species by species-specific extinction risks. Water quality can be measured by an index of concentrations of pollutants in surface water and groundwater using data on stream and aquifer contaminants collected in the U.S. Geological Survey's National Water-Quality Assessment Program (USGS, 2004).

3. Non-stochastic assessment methods

The non-stochastic assessment methods employ a crisp, non-stochastic criterion to assess weak and strong sustainability of the ecosystem. Weak sustainability and strong sustainability concepts were defined by Pearce et al. (1990). Prato (1999, 2000a) proposed that weak sustainability be assessed by the condition $\bar{E} = \sum_{i=M,D,W} w_i a_i \geq T$, where $\bar{E}$ is a weighted average of the three attributes, w_i is the relative importance (weight) of the ith attribute ($\sum_{i=M,D,W} w_i = 1$, $w_i \geq 0$, M stands for personal income, D stands for biodiversity, W stands for water quality), a_i is the average value of the ith attribute ($a_i \in [0, 100]$), and T is the threshold value of $\bar{E}$. For this specification, $\bar{E} \in [0, 100]$ and $T \in [0, 100]$. The EAG would have to measure current attributes for the ecosystem, and determine weights and establish threshold values for attributes. Procedures for estimating attributes and their weights, and reconciling differences in weights among members of a group are discussed by Prato (2003) and Prato and Fagre (2005).

Strong sustainability requires each and every attribute to exceed its corresponding threshold level, namely $a_i \geq T_i$ for i=M, D, and W, where T_i is the threshold value for the ith attribute. Strong sustainability is more restrictive than weak sustainability. Weak sustainability allows higher values of one attribute to offset lower values of another attribute in proportion to the ratio of their weights. This is not the case with strong sustainability. An ecosystem that is strongly sustainable is necessarily weakly sustainable. The converse is not true.

The non-stochastic method for assessing weak and strong sustainability does not account for: (1) errors in measuring attributes, which can result in errors in determining the state of ecosystem sustainability, (2) stochastic variability in attributes (deviations from the mean are not considered in assessing sustainability), and (3) uncertainty regarding the relationship between attributes and states (degrees) of ecosystem sustainability. To illustrate the first limitation, let T=90 and suppose $\bar{E}$=89 based on one set of measurements and $\bar{E}$=91 based on another set of measurements. The ecosystem is not weakly unsustainable for $\bar{E}$=89, but is weakly sustainable for $\bar{E}$=91, even though there may be no real difference in ecosystem sustainability. The strong sustainability method has the same limitation.

The second limitation occurs because average values of attributes mask their variability over time and space. Such variability can have significant implications for ecosystem sustainability. For example, suppose $\bar{E}$ equals 94, 95, 93 and 75 in each of four time periods, and T=90. If these values are

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