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Multi-criteria decision analysis to select metrics for design and monitoring of sustainable ecosystem restorations

M. Convertino[a,b,*], K.M. Baker[c], J.T. Vogel[c], C. Lu[d], B. Suedel[e], I. Linkov[e,f]

[a] Department of Agricultural and Biological Engineering, University of Florida, Gainesville, FL, USA
[b] Florida Climate Institute, c/o University of Florida, Gainesville, FL, USA
[c] Badger Technologies contractor with the U.S. Army Corps of Engineers, Risk and Decision Science Team, Environmental Laboratory, Engineer Research and Development Center (ERDC), Concord, MA, USA
[d] Department of Civil and Environmental Engineering, Environmental and Water Quality Program, Massachusetts Institute of Technology, Cambridge, MA, USA
[e] Risk and Decision Science Team, Environmental Laboratory, Engineer Research and Development Center (ERDC), U.S. Army Corps of Engineers, Vicksburg, MS, USA
[f] Department of Engineering and Public Policy, Carnegie Mellon University, Pittsburgh, PA, USA

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ABSTRACT

The selection of metrics for ecosystem restoration programs is critical for improving the quality and utility of design and monitoring programs, informing adaptive management actions, and characterizing project success. The metrics selection process, that in practice is left to the subjective judgment of stakeholders, is often complex and should simultaneously take into account monitoring data, environmental models, socio-economic considerations, and stakeholder interests. With limited funding, it is often very difficult to balance the importance of multiple metrics, often competing, intended to measure different environmental, social, and economic aspects of the system. To help restoration planners and practitioners develop the most useful and informative design and monitoring programs, we propose the use of multi-criteria decision analysis (MCDA) methods, broadly defined, to select optimal ecosystem restoration metric sets. In this paper, we apply and compare two MCDA methods, multi-attribute utility theory (MAUT), and probabilistic multi-criteria acceptability analysis (ProMAA), for a hypothetical river restoration case study involving multiple stakeholders with competing interests. Overall, the MCDA results in a systematic, quantitative, and transparent evaluation and comparison of potential metrics that provides planners and practitioners with a clear basis for selecting the optimal set of metrics to evaluate restoration alternatives and to inform restoration design and monitoring. In our case study, the two MCDA methods provide comparable results in terms of selected metrics. However, because ProMAA can consider probability distributions for weights and utility values of metrics for each criterion, it is most likely the best option for projects with highly uncertain data and significant stakeholder involvement. Despite the increase in complexity in the metrics selection process, MCDA improves upon the current, commonly-used ad-hoc decision practice based on consultations with stakeholders by applying and presenting quantitative aggregation of data and judgment, thereby increasing the effectiveness of environmental design and monitoring and the transparency of decision making in restoration projects.

1. Introduction

In the context of ecosystem restoration projects, metrics are measurable system properties that characterize the system and quantify the impact of restoration activities, possibly at different life stages of restorations (Allen et al., 1997; U.S. Army Corps of Engineers, 1999; Nienhuis et al., 2002; Reichert et al., 2007; Seager et al., 2007; Martine and Cockfield, 2008; McKay et al., 2011). Thoughtful, appropriate metrics selection is key to effectively characterizing the system, selecting a restoration strategy or a single restoration among a set of restoration alternatives, and understanding the effects of project actions on the system (Ehrenfeld, 2000). Appropriate, clearly defined metrics should reduce uncertainty, increase knowledge of the system and assess the usefulness of applied restoration alternatives by creating a targeted, effective means of evaluation. The evaluation of a restoration alternative can occur both pre- and post-execution (Holmes, 1991), and it is certainly important considering the variability of climate and other anthropic factors (Palmer et al., 2008). For example, a monitoring plan based on sound metrics can demonstrate progress and

* Corresponding author at: Department of Agricultural and Biological Engineering and Florida Climate Institute, Frazier Rogers Hall, Museum Road, PO box 110570, 32611-0570, USA. Tel.: +1 781 645 6070; fax: +1 352 392 4092.
E-mail address: mconvertino@ufl.edu (M. Convertino).

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the degree to which objectives of a restoration are being met to leadership, stakeholders, and future project sponsors, increase the depth and breadth of understanding about the effects of ecosystem restoration practices, contribute to expanding knowledge about ecosystems, and guide management decisions on the most effective, efficient, and cost-effective courses of action (Kondolf, 1995; Thom and Wellman, 1996; U.S. Army Corps of Engineers, 1999; Grootjans et al., 2002; Rohde et al., 2004). The same considerations are true for design plans that aim to change the configuration of environmental systems at the initial or intermediate steps of ecosystem restorations.

The complexity of ecological systems and restoration objectives gives rise to a multitude of potential ecosystem monitoring metrics. Extensive lists of monitoring metrics provide hundreds of potential options, often with numerous choices for just one specific ecosystem characteristic (Thayer et al., 2005; Faber-Langendoen et al., 2006). For example, NOAA's Tools for Monitoring Coastal Habitats provides fifteen different metrics to monitor whether a mangrove habitat "supports a complex trophic structure" alone, including biological, geographical, hydrological, and chemical metrics as well as others (Thayer et al., 2005). However, with limited funding, it may only be possible to effectively measure, estimate, or otherwise use a few metrics, so it is critical to select the metrics that can most clearly indicate the state of the system and changes in relation to project goals.

Metrics selection is thus a challenging process. The optimum choice of metrics will depend on a number of factors including multiple project objectives, technical feasibility, effectiveness, communicability, and stakeholder preferences. Balancing and evaluating these factors with respect to each metric choice is a difficult task that requires a comprehensive, practical metrics selection method. There are a number of commonly used methods for metrics selection, including best professional judgment, historical precedence, conceptual modeling, screening using established criteria sets, and Analytic Hierarchy Process models (AHP) (Saathy, 1980; Dale and Beyeler, 2001; Niemeijer and de Groot, 2008; Linkov and Moberg, 2011; Convertino et al., 2012; Mexas et al., 2012). Here we briefly describe only the most commonly used methods and refer the reader to more extended review papers for additional methodology (see for example Linkov and Moberg, 2011).

The use of *best professional judgment* (BPJ) is generally inexpensive and time-efficient and may be an appropriate metrics selection method for small, well-understood projects. However, metrics selection via this method may exclude or place bias on specific stakeholder values, and becomes exceedingly difficult as project complexity increases. Another weakness of both best professional judgment and historical precedence is lack of transparency, which makes the decision-making more difficult to document and justify (Dale and Beyeler, 2001; Niemeijer and de Groot, 2008).

Historical precedence constitutes selection of metrics that have been previously utilized in similar ecosystem restoration programs (e.g. those with similar objectives, with similar regional or ecological characteristics, that respond to similar disturbances, and/or involve similar stakeholders). Maintaining the use of historical metrics often allows for easy comparison to baseline data and cross-comparison among projects, and may involve lower initial investment than developing new metrics. However, metrics selection via this method may encourage project planners to overlook well-suited and site-specific metrics in favor of less appropriate but more familiar metrics.

As a more transparent alternative or supplement to best professional judgment and historical precedence, restoration project managers may sometimes evaluate or "screen" potential metrics against a set of criteria to identify the most appropriate subset of metrics for a given project. *Screening* is relatively inexpensive and time-efficient, and criteria are well-documented. Screening is a more structured metrics selection method than best professional judgment and historical precedence, but is generally not adequate as a standalone method. Screening does not facilitate formal consideration of a metric's utility within the total collection of its metrics set, as most criteria are meant to apply to metrics individually (Niemeijer and de Groot, 2008). In particular, there is no a quantitative internal structure for determining whether a metrics set is comprehensive.

Analytical Hierarchy Process is a controversial method for alternative selection developed by Saaty, 1980. To the best of our knowledge it was never used in selection of metrics as alternatives of the decision problem. However, AHP has been used in a variety of environmental management problems (Linkov and Moberg, 2011; Huang et al., 2011). Because AHP is based on a subjective pairwise comparison of criteria, rather than using value functions and normalized weights, it has been criticized for its measurement scale, rank reversal, and transitivity of preferences (Gass, 2005; Yatsalo et al., 2007).

To improve the efficacy of ecosystem restoration design and monitoring programs (Linkov and Moberg, 2011), we suggest the application of MCDA, a decision-making analysis based on decision science theory (Keeney and Raiffa, 1976) that can quantitatively evaluate alternatives (i.e. metrics in our case) based on their utility value for stakeholders with respect to defined criteria, and the relative importance of those criteria (Drechsler et al., 2003; Linkov and Moberg, 2011). Applied correctly, MCDA methods will result in the most useful metric set for evaluating stated project priorities, which would enable project managers to make comprehensive, well-informed decisions, and allow researchers and practitioners to improve and update the principles that guide restoration practices. We believe that a formal MCDA-based method is largely useful and needed for the selection of metrics that can be used in evaluating restoration alternatives or monitoring alternatives of restorations. Tsoutsos et al. (2009) provides several reasons that justify MCDA for use in complex decisions with similar factors to consider. MCDA is appropriate for complex decisions because: (a) it enables integration of interests and objectives of multiple players, since all of this information can be accounted for in the form of criteria and weight factors (Pohekar and Ramachandran, 2004; Sigrid, 2004; Loken, 2007; Tsoutsos et al., 2009); (b) it deals with the complexity of having multiple stakeholders by providing easily understandable outputs, and, by virtue of working systematically, is transparent and user-friendly (Georgopoulou et al., 1997; Tsoutsos et al., 2009); and (c) it is well-documented and a large number of different MCDA methods have been applied in a wide range of decisions (Phillis and Andriantiatsaholiniana, 2001; Kaminaris et al., 2006; Diakoulaki and Karangelis, 2007; Tsoutsos et al., 2009; Linkov and Moberg, 2011). Here, we expand the application of MCDA techniques by developing and applying a MCDA framework for evaluating and ranking ecosystem restoration metrics designed to characterize the system and quantify the effects of project actions.

In this paper, we introduce the framework for using MCDA for ecosystem restoration metrics selection and illustrate its application to a hypothetical restoration case study which we call the "Black River Restoration Project". Our case study resembles a realistic ecosystem because we consider all the components typically present in a river ecosystem. The paper is structured as follows. Materials and Methods describe the hypothetical case study and the development of the components of the MCDA models. In the same section we introduce the theoretical background of the deterministic and stochastic multi criteria decision models (MAUT and ProMAA). Results and Discussion present the results of the domination analysis and metric alternative rankings. We also provide a comparative assessment of both MCDA models applied to the case study. The Conclusions section discusses the benefits and