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Methods

Can the concept of ecosystem services be practically applied to improve natural resource management decisions?

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ABSTRACT

Applying ecosystem service valuation principles to natural resources management has the potential to encourage the efficient use of resources, but can decision support systems built on these principles be made both practical and robust? The limitations to building such systems are the practical limits on managers' time to develop or learn tools and the state of the science to support decision-making components. We address this question by applying a cost-effectiveness analysis framework and optimization model to support the targeting of restoration funds to control an invasive grass (*Bromus tectorum*) in agro-ecosystems. The optimization aims to maximize benefits derived from a suite of ecosystem services that may be enhanced through site restoration. The model combines a spatially-varying cost function with ecosystem service benefit functions that are risk-adjusted to capture the probability of successful restoration. We demonstrate that our approach generates roughly three times the level of ecosystem service benefits (as measured through indicators) compared to the current management strategy of selecting restoration sites that are superlative producers of one ecosystem service. The results showed that spatial (GIS) data and ecosystem understanding were sufficient to formally capture the managers' informal decisions and that cost-effectiveness of restoration could be improved by considering the ability of sites to jointly produce multiple ecosystem services and adjusting expected benefits by the probability of success.

1. Introduction

1.1. Use of Ecosystem Services in Decision-making

The ecosystem services framework is promoted as an approach capable of integrating ecological and economic outcomes in a manner useful for making tradeoffs in natural resource management (Barbier, 2007; Carpenter et al., 2006, NRC, 2005; Polasky, 2008; Tallis et al., 2009; Wainger and Boyd, 2009). Ecosystem services are variously defined, but here we define them as the benefits derived from nature for which people can express preferences that allow tradeoffs to be evaluated (see Wainger et al., 2001 for further discussion). This definition primarily distinguishes valued end uses (e.g., preventing flood damage) from the ecosystem processes from which they are derived (e.g., hydrologic regulation). The ultimate goal of using ecosystem services is to balance competing interests when deciding how best to manage and allocate natural resources. Yet, in applying an ecosystem services approach, particularly to local natural resource management, the devil, truly, is in the details.

The management decisions potentially aided by the ability to tally changes in ecosystem services include a range of land and resource management choices, including prioritizing investments in restoration, land set-asides, judging equivalency of market credits, or conservation easements. To date, the question of how to choose among land protection options has received the most attention (see Egoh et al., 2007 for review), but the approach is equally appropriate for targeting incentives for best management practices, controlling invasive species, or other management choices that can co-occur with developed uses of the land or water. Yet, despite development of many such tools, examples of application by public land managers are rare (Newburn et al., 2005).

1.2. Invasive Species Management Decisions

The ecosystem services approach has particular relevance to managers of public rangelands who are increasingly urged to manage these systems as "agro-ecosystems," i.e., create integrated systems that produce agricultural commodities, while simultaneously providing ecosystem services for other services, including those derived from wildlife habitat, hydrology, and fire management (Fischer et al., 2008; Maresch et al., 2008; Swinton et al., 2006). Rangeland managers make a variety of decisions that affect the production of ecosystem services on public lands, but a growing concern is the management of

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invasive plant species. Rangelands, grasslands and pasture, which comprise 26% of US land area (USDA ERS, 2009), are increasingly under threat from non-native invasive plants that harm the ability of lands to support agricultural production and habitat goals alike (DiTomaso, 2000; D'Antonio and Vitousek, 1992; Mack, 1981). According to the Bureau of Land Management (BLM) and the US Forest Service (2009), "Each year, the BLM inventories over 10 million acres [of rangeland] for invasive and noxious weeds; treats weeds on over 300,000 acres; and monitors and evaluates nearly 500,000 acres of weed treatments." This spending represents a major public expenditure and managers of such funds can benefit from a streamlined approach to prioritising response options.

Because invasive species control is expensive and because ecosystem service benefits can conflict as invasive species are controlled, a decision framework, either formal or informal, can help to assess tradeoffs and use allocated funds efficiently to promote public welfare. While cost-effectiveness analysis is used widely in allocation decisions, restoration choices are often *ad-hoc* and data-limited (e.g., Palmer et al., 2007). Where ecosystem service decision-support systems have been created, they typically capture a great deal of the understanding of environmental features and processes, but may miss information on costs and risks that can inform tradeoffs between different types of services (e.g., ICBEMP, 2000; Chan et al., 2006). Costs are typically estimated in ways that ignore important differences between sites (e.g., Denne, 1988), and performance risks are often ignored completely. Few systems capture the probability that the restoration will succeed in restoring ecosystem services, yet, as we will show, this short-coming can profoundly affect expected benefits for invasive species management. This inattention to costs and risks of different actions can prevent agencies from getting the most "bang for the buck" when allocating funds to land purchase or restoration.

Cost-effectiveness can form the basis of a formal decision framework, however, many difficulties plague the application of such a framework, including the time required to bring current research and cost-accounting to bear on the decision process and the lack of ecological and economic information. Shortfalls in the ecological research include a lack of quantification of the damage inflicted by invasive species, beyond a few isolated ecosystem services. Shortfalls on the economic side include the lack of quantification of public values and tolerance for irreversible loss of a sufficiently broad range of ecosystem services to inform tradeoffs. Yet, managers make decisions with incomplete information because waiting for complete information is deemed risky, given the ability of invasive species to spread and irreversibly alter ecosystems (e.g., Brooks et al., 2004).

A decision support system cannot overcome all these challenges, but it does present an opportunity to apply the best available data and test effects of uncertainty in order to promote efficient use of limited resources. A key challenge for such systems, given data gaps, is capturing the benefits of enhancing or restoring ecosystem services (see Barton et al., 2009 for discussion). Either monetary (e.g., Holmes et al., 2004; Loomis et al., 2000) or non-monetary metrics (e.g., Boyd and Wainger, 2002; van Wilgen et al., 2008) can be used in an optimization framework aimed at achieving cost-effectiveness, as long as the non-monetary metrics can be meaningfully aggregated across the bundle of services being maximized. However, only monetary metrics can be used to demonstrate net social benefits of an invasive species control strategy, as illustrated in some dynamic optimization models (e.g., Cook et al., 2007; Higgins et al., 1997; Leung et al., 2002; Settle and Shogren, 2002).

1.3. Monetary vs. Relative Measures of Ecosystem Services

Models that monetize benefits of invasive control may be ideal for comparing management strategies, but they are not necessarily useful for prioritizing restoration on a site-by-site basis. Much of the historic valuation literature has failed to meaningfully capture ecosystem functional quality, suggesting that site-specific monetary values (most likely derived through benefit transfer) may not accurately reflect the ecological quality or level of service provided by each site (Spash and Vatn, 2006; Ready and Navrud, 2005). If the monetary value does not capture the ecological productivity of the site when it is required for generating a service, then that value fails to distinguish highly functional parcels (e.g., ones that provide scarce habitat, flood control, etc.) from low functioning parcels (e.g., ones that provide little habitat value and flood control), and can ultimately result in the environment being degraded if such values are used in offsets or trading.

For many decisions, particularly those to avoid, minimize or mitigate harm, the most important information is the *relative* value of services, which can be well-represented with non-monetary metrics. However, to be useful in decision-making, relative benefit indicators must nonetheless capture details relevant in the decision context and focus on changes in human welfare, not just ecological changes (Heal, 2000; Wainger et al., 2001). The metrics for assessing benefits of an ecosystem service should encapsulate the characteristics that would inform a purchase, if ecosystem goods were bought and sold. Namely, metrics should capture how much users need or want that service, how much it costs to access the service, how easily the service may be substituted or replaced, and how reliable that service is over the long term.

1.4. Applying Multi-objective Optimization

Multi-objective optimization (multi-criteria decision analysis and multi-attribute utility analysis) is an increasingly common approach to applying non-monetary metrics (or a mix of monetary and non-monetary metrics) in resource use tradeoffs (see Kiker et al., 2005 for review). The basic optimization approach maximizes the production of a weighted set of objectives, subject to one or more constraints, such as a budget. For example, the objective may be to maximize the change in the benefits derived from a bundle of ecosystem services produced with a given management action. Benefits associated with different services are weighted to reflect their ability to meet management goals, and the weighted sum of benefits is maximized in the optimization algorithm. The ability to use a variety of metrics typically allows a broader set of ecosystem services to be considered and overcomes the problem of having to apply controversial monetary metrics to non-use services that may be better captured through ecological indicators. Furthermore, the multi-objective optimization model is appealing for guiding management decisions because of its ability to mimic real-world goals and constraints and integrate relatively complex information and tradeoffs.

Multi-objective decision methods have been used for decades (Keeney and Raiffa, 1976; Clemen, 1996) but, more recently, have been expanded to include spatially-detailed approaches that apply GIS tools and modelling environments to compare site-specific management actions for their ability to induce systems to produce multiple ecosystem services. Decision support tools, some of which are optimization models, link management actions to outcomes and prioritize the actions that maximize ecosystem services. Many models are produced (e.g., National Oceanographic and Atmospheric Association's Habitat Priority Planner, NatureServe's Vista) but not necessarily published in peer-reviewed literature, making it difficult to summarize the state of the art.

Among spatial decision support models, few apply cost-effectiveness analysis (CEA) or return on investment (ROI) approaches to capture potential efficiency of spending on ecosystem services. Models that have applied CEA or ROI deal with a range of terrestrial and marine ecosystems (Klein et al., 2008; Leslie et al., 2003; Marshall and Homans, 2006; Murdoch et al., 2007; Naidoo and Ricketts, 2006) and the coastal interface (e.g., Stoms et al., 2005). Most of these models are aimed at promoting land conservation through agricultural land