Ecosystem Services 8 (2014) 1–15

Contents lists available at ScienceDirect

Ecosystem Services

journal homepage: www.elsevier.com/locate/ecoser

Comparison of methods for quantifying reef ecosystem services: A case study mapping services for St. Croix, USVI

Susan H. Yee*, John A. Dittmar, Leah M. Oliver

US Environmental Protection Agency, Office of Research and Development, National Health and Environmental Effects Research Laboratory, Gulf Ecology Division, Gulf Breeze, FL 32561, USA

ARTICLE INFO

Article history:
Received 9 January 2013
Received in revised form
26 October 2013
Accepted 6 January 2014
Available online 31 January 2014

Keywords:
Coral reef
Ecological integrity
Fishing
Natural products
Recreation
Shoreline protection

ABSTRACT

A key challenge in evaluating coastal and watershed management decisions is that monitoring efforts are largely focused on reef condition, yet stakeholder concerns may be more appropriately quantified by social and economic metrics. There is an urgent need for predictive models to quantitatively link ecological condition of coral reefs to provisioning of reef ecosystem goods and services. We investigated and compared a number of existing methods for quantifying ecological integrity, shoreline protection, recreational opportunities, fisheries production, and the potential for natural products discovery from reefs. Methods were applied to mapping potential ecosystem services production around St. Croix, U.S. Virgin Islands. Overall, we found that a number of different methods produced similar predictions. Furthermore, areas predicted to be high in ecological integrity also tended to be high in other ecosystem services, including the potential for recreation, natural products discovery, and fisheries production, but this result depended on the method by which ecosystem services supply was calculated. Quantitative methods linking reef condition to ecosystem goods and services can aid in highlighting the social and economic relevance of reefs, and provide essential information to more completely characterize, model, and map the trade-offs inherent in decision options.

Published by Elsevier B.V.

1. Introduction

Ecosystem function and services are inextricably linked to human well-being, yet are often overlooked or taken for granted in social and economic decision-making (MEA (Millennium Ecosystem Assessment), 2005). A key challenge is that environmental assessments typically focus on ecological endpoints, failing to consider the social and economic values of stakeholders (Arvai and Gregory, 2003). A key to bridging ecological and socio-economic concerns is the concept of ecosystem goods and services (Wainger and Boyd, 2009).

In particular, coral reef ecosystems provide the ecological foundation that supports multi-billion dollar reef fishing and tourism industries vital to coastal and island economies (Burke and Maidens, 2004; C. I. (Conservation International), 2008; Pendleton, 2008). However, reef ecosystem goods and services are threatened by a rapidly growing regional human population, climate change, and serial over-exploitation (Waddell and Clarke, 2008; Wilkinson, 2008). Policies to protect coastal resources will be more effective if they account for the social and economic concerns of stakeholders in the watershed, and are responsive to potential tradeoffs among coastal resources or with other economic sectors such as agriculture or industry (Productivity Commission, 2003; Roebeling, 2006; Thomas et al., 2012). A key challenge is that reef monitoring efforts are largely focused on indicators of reef condition, such as coral cover and diversity, yet stakeholder concerns may be more appropriately quantified by health, social, or economic measures of factors such as subsistence from fisheries, opportunities for tourism or recreation, or coastal protection of property or lives during storm events (Cesar et al., 2003; Burke and Maidens, 2004). A quantitative link between attributes of reef condition and potential supply of ecosystem services will help identify meaningful indicators to compare decisions or monitor the success of their implementation, contribute to a conceptual link between coral condition and socio-economic relevance, and provide greater clarity in decision-making, including being able to estimate the potential consequences of alternative decisions on key stakeholder objectives (Yee et al., in press).

Insufficient scientific information can make it challenging to be able to estimate the consequences of potential management options. Coral reef modeling efforts to date have typically focused on the link between stressors and ecosystem condition, modeling a limited number of stressors such as land-based activities (Wolanski and De'ath, 2005), fishing pressure (Ault et al., 2005), or climate change (Buddemeier et al., 2008), and a few components of the ecosystem, such as reef fish or stony coral (e.g., McClanahan et al. (2007), Wakeford et al. (2008)). Other models

* Corresponding author. Tel.: +1 850 934 9397.
E-mail address: yee.susan@epa.gov (S.H. Yee).

2212-0416/$ - see front matter Published by Elsevier B.V.
http://dx.doi.org/10.1016/j.ecoser.2014.01.001

have included more ecosystem interactions, including interactions between coral, algae, herbivorous fish, and mangroves (Ault et al., 2003; McClanahan and Branch, 2008; Mumby and Hastings, 2008) and incorporate multiple stressors (Melbourne-Thomas et al., 2011). To be useful for decision-makers, however, the ecological endpoints of these models must be linkable to things stakeholders and decision-makers recognize as valuable (Wainger and Boyd, 2009). For coral reefs, development and application of production function methods is an essential step in the integration of models describing threats, coral reef dynamics, ecosystem services production, and socio-economic benefits (e.g. van Cesar (2004), Chang et al. (2008), Thomas et al. (2012)).

Two types of functional relationships are required to translate ecosystem state into human benefits: ecological production functions (EPF) and ecosystem services valuation functions (Wainger and Boyd, 2009; Compton et al., 2011). EPFs quantify the relationships between metrics of ecosystem condition and the supply of ecosystem goods and services. While ecosystem production functions describe the supply or provisioning of ecosystem services, the realized value of these benefits will depend on human demand for them (Wainger and Boyd, 2009). Ecosystem services valuation functions (EVF) relate characteristics of society, such as demand, accessibility, or substitutability, to derive value for ecosystem services (Compton et al., 2011). Numerous studies have developed and applied methods for estimating economic values for benefits received from coral reefs (reviewed in C. I. (Conservation International) (2008), Pendleton (2008)). Here, we evaluate methods for translating reef ecosystem condition into potential production of ecosystem goods and services.

A number of methods have been developed for linking biophysical attributes of reef condition, such as reef structural complexity, fish biomass, or species richness, to provisioning of ecosystem goods and services (Principe et al., 2012). We investigated the feasibility of using existing methods and data for mapping production of reef ecosystem goods and services. We applied these methods toward mapping potential ecosystem goods and services production in St. Croix, U.S. Virgin Islands (USVI). Spatially explicit methods are needed to quantify ecosystem services because supply and demand for ecosystem services are inherently spatially explicit and may differ geographically, such that mapping becomes a useful tool for communicating and supporting decision-making (Crossman et al., 2013).

Although coral reefs provide numerous economic benefits, to maximize the potential for transferability between locations, we focused on four categories of ecosystem services that are commonly identified as the four most valuable economic benefits: shoreline protection, tourism and recreation opportunities, fisheries production, and natural products potential (Principe et al., 2012). These were also key objectives of stakeholders identified in workshop discussions in the U.S. Virgin Islands, Florida, and Puerto Rico (Rehr et al., 2013; Carriger et al., 2013; Yee et al., In review). In addition to direct and indirect economic benefits from reefs, stakeholders also identified maximizing reef ecosystem integrity as a key objective (Carriger et al., 2013). Therefore, we also investigated metrics of reef ecosystem integrity, or how well the ecosystem is functioning, which may contribute to non-use values such as existence value, cultural value, or option value (Cesar, 2000; Principe et al., 2012). Finally, we examined the overall suite of ecosystem goods and services metrics to evaluate comparability across the different methods and to assess the extent to which different categories of ecosystem services produce similar spatial patterns.

2. Methods

Methods for linking reef condition to provisioning of ecosystem services have been described in a number of ways, including anecdotally, statistical analysis, bio-physical models, and surveys of stakeholder preferences (reviewed in Principe et al. (2012)). For each of the five categories of ecosystem services, we chose a suite of models and indices for estimating potential production based on relative ease of implementation, consisting of well-defined parameters, and likely availability of input data, to maximize potential for transferability to other locations. For each method, we assembled the necessary reef condition and environmental data as spatial data layers for St. Croix (Table 1). The coastal zone surrounding St. Croix was divided into 10×10 m grid cells, and production functions were applied to quantify ecosystem services provisioning in each grid cell.

2.1. Ecosystem services production functions

2.1.1. Ecosystem integrity

A number of indicators have been proposed for measuring reef integrity, defined as the capacity to maintain healthy function and retention of diversity (Turner et al., 2000). The Simplified Integrated Reef Health Index (SIRHI) combines four attributes of reef condition into a single index:

$$\mathrm{SIRHI} = \sum_i G_i \tag{I1}$$

where G_i are the grades on a scale of 1 to 5 for four key reef attributes: percent coral cover, percent macroalgal cover, herbivorous fish biomass, and commercial fish biomass (Table 2; Healthy Reefs Initiative, 2010). An alternative, but similar, indicator for reef ecological integrity (van Beukering and Cesar, 2004) defines the state of the reef as

$$\text{State of the Reef} = \sum_i w_i R_i \tag{I2}$$

where the R_i are the relative quantity of coral cover, macro-algal cover, fish richness, coral richness, and fish abundance, standardized to reflect the range of conditions at the location being evaluated (in this case, St. Croix). The w_i give the weighted contribution of each attribute to reef condition based on expert judgment, originally developed for Hawaii, which were $w_{\mathrm{coral\_cover}}=0.30$, $w_{\mathrm{algae\_cover}}=0.15$, $w_{\mathrm{fish\_richness}}=0.15$, $w_{\mathrm{coral\_richness}}=0.20$, and $w_{\mathrm{fish\_abundance}}=0.20$ (van Beukering and Cesar, 2004). Ideally, these values would be developed to reflect local knowledge and concerns for the Caribbean or St. Croix. Changes in the state of the reef are expected to have consequences for dive and snorkeling tourism, the value of homes and hotels in the vicinity of the reef, the reef's existence value or scientific value, and the probability of a bio-prospecting discovery (van Beukering and Cesar, 2004).

2.1.2. Shoreline protection

Shoreline protection as an ecosystem service has been defined in a number of ways including protection from shoreline erosion, storm damage, or coastal inundation during extreme events (UNEP-WCMC (United Nations Environment Programme, World Conservation Monitoring Centre), 2006; WRI (World Resources Institute), 2009), but is often quantified as wave energy attenuation, an intermediate service that contributes to shoreline protection by reducing rates of erosion or coastal inundation (Principe et al., 2012). Perhaps the simplest method to estimate shoreline protection is by defining the relative contribution of different habitat types to wave energy attenuation (Mumby et al., 2008). For each grid cell, we estimated the contribution of coral reefs to wave energy dissipation as the overall weighted average of the magnitude of wave energy dissipation across habitat types within that grid cell:

$$\text{Relative wave energy dissipation} = \sum_i c_i M_i \tag{S1}$$

where c_i is the fraction of area within each grid cell for each habitat type i (dense, medium dense, or sparse seagrass, mangroves, sand,