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Analysis

Measuring the contribution of ecological composition and functional services of ecosystems to the dynamics of KwaZulu-Natal coast fisheries

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ABSTRACT

This study extended a bio-economic fishery model to establish an explicit link between coastal and estuarine ecosystems ecological composition (biodiversity) and functional (nutrient supply) attributes and the dynamics and productivity of KZN coastal fisheries. Results confirmed the importance and strong contribution of the tested ecological attributes. In-sample simulation indicates that current fishing efforts and harvest rates are sustainable, but are sensitive to changes in nutrient influx and rainfall. This confirms the need to modify conventional fisheries models to include environmental variables as additional predictors of fish stocks in addition to historical catch records and catch effort for management and control of fishing efforts and permits. This study provided confirmation of the strong linkage between nutrient levels and productivity of coastal fisheries thus enabling investigation of runoff and rainfall related climate change effects on the KZN fisheries.

1. Introduction

Gaps in current scientific knowledge of the interdependence between the coupled socio-ecological systems translate into misinformed decision making and adoption of wrong policies and actions that fundamentally result in unsustainable use of these natural assets and weak willingness to conserve them. Due to this knowledge gap human society recognizes only the value of a subset of services that are directly used as final products for consumption, production or recreation — *provisioning services* (MEA, 2005, 2007; TEEB, 2010). These are tangible products that are usually commercially exploited and traded in functioning markets and in many cases have defined property rights, e.g. food, fiber, water, medicines, etc. Accordingly, the shadow prices of these services are relatively easy to estimate and hence the bulk of the environmental economics work on valuation of ecosystem services had gone into this category of ecosystem services — ES (MEA, 2005; Perrings, 2006; Barbier et al., 2009).

On the other hand, the role and value of other more fundamental services that are not directly used as final products, but are crucial for the functionality of ecosystems and underlie the provision of directly used services, are not well understood and recognized. Examples of *supporting* ecosystem processes forming essential intermediate inputs in the production of final ecosystem goods and services include primary production, nutrient cycling and photosynthesis. Another set of services known as *regulating services* control and normalize ecosystem functioning and thus insures the benefits supplied by ecosystems. In spite of their crucial role as the basis of all other provisions of nature, the literature on valuing such regulating and supporting services is sparse, leaving an important gap in knowledge of sustainable management of ecosystems for human wellbeing (MEA, 2005; Barbier et al., 2009; TEEB, 2010). Efforts to improve our scientific understanding of the complex nature of the involved dynamics of socio-ecological interactions are therefore necessary for prudent ecosystem management and development.

Various formulations and combinations of production function (PF) and bio-economic modeling approaches have been employed to measure marginal contributions of intermediate ES (*supporting and regulating*) to generation of final benefits to human society. Such applications include studies of nutrient cycling in seas and soils (Gren et al., 1997; Nakhumwa and Hassan, 2012; Yerga and Hassan, 2010), biodiversity and carbon sequestration (Boscolo and Vincent, 2003) and pollination services (Ricketts et al., 2004) of tropical forests. Other examples are studies of groundwater recharge for irrigation (Acharya and Barbier, 2000), tropical watershed protection services (Kaiser and Roumasset, 2002), and hydrological functions of wetlands (Jogo and Hassan, 2010). Intermediate ecosystem services in the fishery and coastal ecosystems literature include studies of the role of habitat quality (Acharya and Barbier, 2000; Barbier, 2007; Rodwell et al., 2003) marine reserves (Mardle et al., 2004; Sumaila, 2002) and nutrients (Knowler et al., 2001; Kasulo and Perrings, 2006 and Crafford and Hassan, 2014) among many others.

The present study attempts to adapt a bio-economic fishery model to measure the contribution of regulating and supporting services of the KwaZulu-Natal (KZN) estuaries of South Africa to the dynamics of

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the KZN coastal fisheries. This will be achieved through establishing an explicit link between estuaries' ecological composition (biodiversity) and functional attributes (nutrient supply) and provision of the final service (i.e. fish biomass) harvested for direct consumption. The study will accordingly enable establishing accounting prices for estuaries' ecosystem assets needed for deriving sustainability indicators to evaluate tradeoffs between future benefits of intact estuaries' ecological health and benefits from current and planned coastal management and development regimes in the study area and elsewhere.

The next section presents the analytical approach and how it is extended in this study to control for the effects of ecological attributes of estuaries' ecosystems to coastal fishery dynamics. Section 3 describes the case study area where the developed model is applied to value the regulating and supporting ecosystem service of estuaries in KZN. The empirical model developed for implementing the intended analysis is presented in Section 4. Section 5 presents and discusses empirical estimation results. Simulations are performed in Section 4 and implications for policy and future research are drawn in the concluding Section 5.

2. Modeling Contributions of Intermediate Estuarine Ecosystems Services to Coastal Fisheries Production

Static fish production functions are typically specified to evaluate impacts of economic efforts on fish harvest and market outcomes. However, the importance of ecological structure and function of coastal and estuarine ecosystems (CEE) for the fishery have been studied and confirmed by many authors (Lynne et al., 1981; Ellis and Fisher, 1987; Barbier and Strand, 1998; Barbier et al., 2011). The said studies modeled the combined effects of economic inputs and ecological attributes of CEE on fish harvest H as follows:

$$H = h(E_i, X(S)) \tag{1}$$

where E_i denotes economic inputs (e.g. effort, costs, etc.) and X measures stock of fish biomass. S is a vector of CEE ecological attributes. Barbier (2003, 2007) used habitat area (coastal wetland or mangrove areas) to represent S. However, in addition to physical characteristics such as habitat area many other ecological components and processes regulate the functioning of CEE. For instance, freshwater flows are known to be a major source of nutrients for primary production supporting key compositional elements (biodiversity) and important underlying ecological processes influencing fish production.

Changes in CEE structure and functionality however, represent stock changes (adjustments in the ecological infrastructure) over time, which cannot be described by static formulations. Accordingly models accounting for the dynamic linkages between changes in CEE stock attributes and harvest over time have been developed. The commonly used dynamic fishery system follows the general form:

$$X_t – X_{t-1} = F(X_{t-1}; St.-1) – h(X_{t-1}; E_{t-1}) \tag{2}$$

which specifies change in fish biomass X as a function of biological growth $F(X_{t-1}, S_{t-1})$ less harvesting $h(X_{t-1}, E_{t-1})$ realized through application of economic efforts E_{t-1}. This model assumes that CEE assets' attributes S_t (structure and function) influence fish stocks X_t through the biological growth function F. Employing the well known Schaefer model (Schaefer, 1954) specification of logistic biological fishery growth (Eq. (3)) and harvest-economic effort fishery yield (production) functions (Eq. (4)):

$$F(X_{t-1}, St._{-1}) = rX_{t-1}[1 - X_{t-1}/K] \tag{3}$$

$$H_t = qX_tE_t \tag{4}$$

where the intrinsic growth rate r, the biological carrying capacity K, and fish density dependent harvesting coefficient q are the drivers of this system. The yield/production function in Eq. (4) is based on the assumption that potential harvesting per unit effort (H_t/E_t) depends on fish biomass (level of X) (Clark, 1985).

Due to the typical problem of lack of appropriate data on fish biomass (i.e. levels and change in X over time are rarely monitored and recorded) the above system has been alternatively specified as function of observable fish catches (annual harvest H_t) and efforts E_t instead (Schnute, 1977). Eq. (4) is therefore used to substitute for the fish biomass variable defined as:

$$X_t = (1/q)(H_t/E_t) = (1/q)c_t \tag{5}$$

Back in the dynamic fishery system in model 2 above will transform the dynamic fishery model into a relationship between catch per unit and effort:

$$(c_t – c_{t-1})/c_{t-1} = r – (r/qK)(c_{t-1}) – qE_{t-1} \tag{6}$$

where c_t measures catch per unit effort (H_t/E_t). Accordingly parameters of the dynamics of the fishery system (r, K and q) can be estimated from a regression of data on fish catches H_t and effort E_t using transformation Eq. (6). This approach is common in the fishery literature and its plausibility has recently been tested (Martell and Froese, 2013). Most model estimates based on above specifications and data used to analyze such dynamic linkages were derived under assumptions of long-run equilibrium of the studied fishery.[1]

Barbier (2007) modeled the effect of coastal ecosystem structure on the fishery through the carrying capacity parameter (K). In his specification of a dynamic coastal habitat-fishery model he made K a function of coastal ecosystem stock attributes S, specifically represented by habitat area:

$$K(S_t) = \alpha \ln S_t, \tag{7}$$

this changes the catch per unit and effort transformed relationship of Eq. (6) to:

$$(c_t – c_{t-1})/c_{t-1} = r – (r/\alpha q)[ct - 1/\ln S_{t-1}] – qE_{t-1} \tag{8}$$

Following Bjørndal and Conrad (1987), Barbier (2007) dynamic habitat-fishery model specified a fishing function that adjusts in response to profits realized in previous periods as follows:

$$E_t – E_{t-1} = \varphi[P * H_{t-1}(X_{t-1}, E_{t-1}) – wE_{t-1}] \tag{9a}$$

Rearranging terms we rewrite relation (9a) as:

$$E_t = \varphi P * H_{t-1}(X_{t-1}, E_{t-1}) – (1 - \varphi w) * E_{t-1} \tag{9b}$$

where H, X, and E as defined above, P and w refer to fish prices and unit cost of fishing efforts, respectively and $\varphi > 0$ is the fishing effort adjustment coefficient.

We adapt the above dynamic fishery system analytical framework to empirically specify the relationship and value the contribution of CEE composition (biodiversity) and functional attributes (nutrient supply) to KZN coastal fishery production in subsequent sections.

3. Study Area Coastal and Estuarine Ecosystem and Coastal Fishery

This study uses data collected on the ecological composition and function of the CEE of the east coast of South Africa within the KZN Bight between Cape St. Lucia and Durban (Fig. 1). This system plays an important functional biodiversity role in connecting terrestrial and estuarine system processes and components to marine-based species dynamics. This CEE consists of approximately 70 estuaries that have sub-tropical characteristics. Since the early 1980s, many researchers

[1] Barbier (2007) discusses key methodological problems with models attempted to value intermediate CEE services under such assumption.