Global Environmental Change 38 (2016) 58–69

Contents lists available at ScienceDirect

Global Environmental Change

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

Simulating the outcomes of resource user- and rule-based regulations in a coral reef fisheries-ecosystem model

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ARTICLE INFO

Article history:
Received 27 March 2015
Received in revised form 15 February 2016
Accepted 26 February 2016
Available online xxx

Keywords:
Adaptive capacity
Common-pool resource
Indian Ocean
Social-ecological systems
Tanzania

ABSTRACT

Many political ecology debates hinge on the roles and outcomes of resource user regulation versus those arising from governance rules. Because of the difficulties of empirically testing theories of resource regulation, we evaluated the alternatives using a simulation modeling approach developed for East African coral reef fisheries where four scenarios of fisheries regulation on fish catch rates and resource ecology were evaluated. These scenarios were (1) a control simulation where fishing practices were held constant, (2) fishing that gradually incorporates fishers' self-reported behavioral responses to declining resources, (3) rapid change where illegal gears were not allowed and effort was equally partitioned among the legal gears, and (4) gradual change where legal gears or exiting were adopted as yields decline. The model indicates that at moderate fishing effort (5 fishers/km^2), the gradual behavioral change scenarios two and four produced the highest per fisher yields and maintained the highest fish biomass compared to the other two strict-control options. At high fisher numbers (10 fishers/km^2), the rapid ban of illegal gear in scenario 3 had more similar ecological outcomes to gradual behavioral response scenarios 2 and 4. The model assumed no changes in behavior coming from outside the system or over longer periods of time that could potentially undermine or change the stated behavioral responses. The simulations show the difficulty of developing resource use regulations because of the complex interactions between numbers of fishers, behavioral responses, management decisions, and feedbacks to the resource. Nevertheless, the simulations indicate that at moderate fisher densities, governance strategies that allow resource users to respond to changing resources can produce better yield and resource outcomes than rigid control. Ecosystem models that do not incorporate fisher's behavioral choices may overestimate their detrimental impacts.

1. Introduction

The capacity of people to respond to changes in their environment is critical to the sustainability of social-ecological systems. Some responses to environmental change can reinforce the consequences of environmental disturbance, often called maladaptation (Barnett and O'Neill, 2010), whereas other responses can be adaptive and prevent a further loss or degradation of resource (Cinner et al., 2011). Understanding how people's responses to change can lead to positive or negative ecosystem outcomes is a critical challenge for sustainably managing natural resources (Costanza, 1987; Steneck et al., 2011). Fisheries provide an interesting example of this kind of social-ecological linkage because of the complex interactions that arise between management, feedbacks with ecosystem processes that influence resource changes over time, and people's response to change (Jentoft and Chuenpagdee, 2009; Schluter et al., 2012; Basurto et al., 2013).

Fisheries management can constrain how resource users respond to changing resources. For example, some fisheries management regulations can constrain fishers' ability to switch between gears or fishing grounds (Aguilera et al., 2015). In other cases, a lack of or poor enforcement of these regulation allows fishers to respond in ways that are ultimately harmful for the ecosystem; for example, by responding to declining fish stocks by employing gears that are destructive to the habitat and target juveniles (Pauly, 1990; McClanahan et al., 2008; Cinner, 2011). Additionally, fisheries management may also seek to encourage behavioral responses, but guide them towards more sustainable outcomes. Critically, fisheries management is often embedded in social processes that seek to negotiate socioeconomic issues of

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http://dx.doi.org/10.1016/j.gloenvcha.2016.02.010
0959-3780/

power, incentives, costs, and the distribution of fisheries benefits which, if ignored, can undermine viable governance (McCay and Jentoft, 1998; Hilborn, 2007; Bene et al., 2009). Thus, some management decisions have to be implemented gradually to monitor and evaluate social-ecological outcomes.

What might be the consequences of different management decisions and behavioral responses when social-ecological feedbacks are present, such as in fisheries? Empirically comparing outcomes of different behavioral responses and management decisions are difficult because finding replicate and comparable social organizations and controls is unlikely. Nor, will most research or adaptive management programs have the resources to measure the full ecological consequences of the decisions and actions over an ecologically relevant period of time (McLain and Lee, 1996; Westgate et al., 2013). An alternative approach is therefore to pose these questions to ecological simulation models where social-ecological attributes are sufficiently represented to evaluate the potential temporal responses of a full series of fisheries decisions. Social-ecological simulation models can be used to test and compare various scenarios of behavioral responses and management decisions. While models assume a deterministic and averaged response that is unrealistic in the face of stochastic, external and rare events, and heterogeneous natural processes, they do provide a useful heuristic for evaluating complex systems and to assist management decisions (Ludwig et al., 1993; Walters and Martell, 2004).

Here, we undertake a simulation modeling approach that incorporates fishers' stated behavioral responses to environmental change. We integrate a coral reef ecosystem model (CAFFEE) that was developed for the nearshore African coral reefs (Ruiz Sebastián and McClanahan, 2013), with fisher's stated responses to scenarios of changes in catch (Cinner et al., 2011). We examined how fishers' stated decisions impact ecosystem conditions in a control and three different scenarios relevant to our Western Indian Ocean study region. We simulated fishing effort, yields, and key ecological states at the early (after 1 year of fishing) and late stages (after 10 years) for four different scenarios. These were: (1) a control simulation where fishing effort across all gear types was kept constant, (2) fishers respond to declining yields by changing their fishing behavior according to their stated responses to decline, (3) implementing immediate bans on the commonly illegal gears and partitioning fishers among legal gear, and (4) allowing fishers to either exit or adopt legal gear as their yields decline.

2. Methods

2.1. Fisher decision data

To determine how fishers respond to scenarios of decline, we studied nine coastal communities in Zanzibar and mainland Tanzania (Cinner et al., 2011). We used a systematic sampling design to survey a total of 240 fishing households. The number of surveys per community ranged from 8 to 44 (Appendix A) depending on village population size, the proportion of fishers in the community, and the available time per site. We constructed hypothetical scenarios involving a reduction of catch. Fishers were asked what they would do in response to sustained 10%, 20%, 30%, and 50% declines in their normal catch. Responses were open ended and later coded as either: (1) continue fishing as before (i.e. maintain same fishing effort), (2) move location, (3) change gear, (4) increase their effort, (5) reduce effort, or (6) stopping fishing. For example, fishers that responded that they would put more effort into farming, but not stop fishing entirely was coded as "reduce effort," whereas someone who would put all fishing effort into farming and quit fishing was coded as "stopping fishing." We asked follow up questions, which probed for details about their responses, such as what type of gear they would change to, how they would increase or reduce their effort, such as through changes to labor or capital. We aggregated answers to the response to decline questions by the primary gear types used by fishers. This was determined by asking fishers about the different fishing gears they use and were asked to rank them in order of importance. Gears ranked as most important were considered their primary gear. These resource-user responses were used in our simulation model as likely responses to declining yields and fisheries regulations. Fishers' answers to hypothetical declines were aggregated across all nine studied villages.

2.2. Scenarios details

We designed scenarios based on the common multi-gear traditional fishing communities found in the western Indian Ocean. The first control scenario, referred to as 'Unregulated without response', represents a fixed number of fishers using each type of fishing gear, where fishing intensity by gear is maintained constant for each simulation regardless of variations in the volume of fish capture over time. This scenario is typical of behaviorally or socially naïve ecological models where fishing effort is held constant for each model run and effort changed between model runs. The usual behavioral responses of changing gears, moving locations, or implementing other behavioral responses were not allowed. This scenario is, therefore, meant to simulate a control situation where resource user behavior is inflexible or governance rules and incentives constrain fishers' ability to respond to changing resources. The second scenario ('unregulated with behavioral response') incorporates the interviewed fisher's stated responses to decreasing fish catch. Integrating these responses into the model results in changing levels of fishing intensity for different gears as the catch crosses a series of thresholds. For our simulation modeling, we viewed behavioral responses that would dampen environmental change as exiting the fishery and moving location, while responses such as changing gears, continuing to fish, and fishing harder would amplify environmental degradation. In the third scenario, named 'immediate gear ban', beach seines and spearguns [which are illegal but commonly used in East Africa (McClanahan et al., 2005)] are declared illegal and enforced before the start of the simulations and the fisher using those gears were partitioned equally among the three remaining legal gears. In this scenario, fishers can change fishing behavior as stated in interviews but can only chose among the three remaining legal gears. In the fourth and last scenario, 'gradual gear ban', the two illegal fishing gears are not immediately abandoned by fishers, but they cannot be adopted when fishers decide to change gears. We believe the last two scenarios represent realistic scenarios of interactions and negotiations typical of fisheries rule development and compliance in the region (McClanahan et al., 2008).

2.3. Modeling

The coral-algae-fish-fisheries-ecosystem-energetics (CAFFEE) coral reef ecosystem model developed by Ruiz Sebastián and McClanahan (2013) was used to run 10-year computer simulations of the scenarios described above. The CAFFEE model simulates the main processes driving the ecosystem dynamics in western Indian Ocean coral reefs and can be used to test hypotheses on the effects of management options on ecological indicators. The full formal mathematical description of the model can be found elsewhere but uses Stella software and difference equations representing the gains and losses derived from proposed social and ecological interactions (Ruiz Sebastián and McClanahan, 2013). The large number of variables, including factors that change continuously, such as the calcium carbonate balance, results in a model that does