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Managing fishing gear to encourage ecosystem-based management of coral reefs fisheries

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Abstract. We present fisheries landing data from two tropical countries, Papua New Guinea (PNG) and Kenya, and show that each gear type causes a unique and consistent partitioning of the species and functional groups it targets. Partitioning by gear can be used to influence ecological processes and biodiversity on coral reefs and to respond to disturbances such as coral bleaching. Hook and line capture a higher proportion of top carnivores and piscivores and target species with low susceptibility to coral bleaching. Traps, drag nets, and spearguns capture mostly herbivores and omnivores and target the highest proportion and number of fish species that are moderately susceptible to the effects of coral bleaching. We argue that the use of specific gears can be actively managed to encourage the recovery of select functional groups and adaptively manage for reducing high erect algae cover and sea urchin dominance, increasing coral cover, and reducing detrimental effects of coral bleaching. We present a simulation and conceptual model that describes the effects of gear and effort on fisheries yields and suggest a mechanism for practically implementing this model. Spearguns are predicted to have the highest diversity and yields of catch, but can also result in decline in herbivorous fishes, which has serious consequences for recovery and resilience of the ecosystem. Further understanding of fishing gear effects on specific fish functional groups at a broader selection of reef locations will be valuable in developing adaptive gear-based management in a changing climate.

Key words: Climate change, coral reef model, ecological effects, fisheries yields, herbivory, trophic cascades

Introduction

Coral reef ecosystems are complex and therefore difficult to manage from a holistic systems approach when social conditions do not facilitate the use of large fisheries closures. Suggestions for management based on an understanding of coral reef ecology are a useful first step but their implementation often depends on complex and challenging socioeconomic considerations (McClanahan et al. 2008). Finding appropriate ways to implement management measures that can be adopted by fishing cultures with resultant desired ecological consequences is perhaps one of the greatest challenges for ecosystem-based management of coral reefs. Management of fishing gear can potentially achieve this goal in areas where fisheries closures are impracticable. Gears are selective in their catch and are a management option mostly accepted by fishers and managers (McClanahan et al. 2005).

The impact of climate change and coral mortality on reef ecology, fish, and fisheries are multiple and complex. Hence, there is a need to evaluate fishing and gear-use scenarios with ecological models based on a holistic view of the ecosystem and existing field data. These models can assist researchers in testing and predicting outcomes and encourage an adaptive management program for coral reef ecosystems. Current understanding of coral reef fisheries has focused on the potential effects of the loss of grazers and invertebrate-eating carnivores (McClanahan 2006). Many investigators believe that the protection of coral reef grazers will be important for maintaining the recovery of coral reefs after disturbances (Hughes et al. 2003; Bellwood et al. 2004; Mumby et al. 2006). Additionally, coral-eating invertebrates, such as Crown-of-Thorns starfish and algae grazing sea urchins can become pests and compromise ecological processes and recovery potential in some reef environments (McClanahan et al. 2002; Dulvy et al. 2004). These aspects of management were previously examined in an ecosystem model assuming choice of functional groups by fishers (McClanahan 1995).

The objective of the present paper is to examine the potential benefits of gear management strategies to maintain selected ecological processes and enhance reef recovery after coral depleting disturbances. We analyze the composition of fish catches in artisanal fisheries in two countries with different gear uses and levels of fishing effort and evaluate the effects of gear–specific fishing intensity on functional groups of reef fishes.

Materials and methods

The study examines fishing gear and catches in two countries that represent a low to moderate level of fishing (Papua New Guinea; PNG), and moderate to high level of fishing, (Kenya; Cinner and McClanahan 2006; McClanahan et al. 2008). We evaluate the species and functional group selectivity of gear used in artisanal fisheries (net, speargun, beach seine, line and trap) in these two countries and use these data to calibrate an ecosystem simulation model. Model simulations are then used to forecast catch and stock status of selected functional groups under increasing fishing pressure for the different gears.

Field studies of catch by gear

Catch data are based on six fishing sites in PNG (Cinner and McClanahan 2006) and ten fish landing sites in Kenya (McClanahan et al. 2008). Landing sites were selected to represent a wide range of social, economic, and demographic conditions. The fisheries were typical tropical artisanal fisheries where catch was derived from shallow-water coral reef and seagrass ecosystems. Analyses of catch data are based on 4205 and 2154 fish specimens from Kenya and PNG, respectively.

Methods to sample fish catch in the two countries differed slightly. In both countries we opportunistically examined fish landings at all times of the day and night by approaching and asking permission from fishers as they returned from fishing activities and the whole catch was measured whether the catch was for market or home use. Abundance and taxonomic composition were recorded to species level (Lieske and Myers 1994; Randall et al. 1997). In PNG, we photographed the fish using the methods of Cinner and McClanahan (2006) and recorded the gear used to capture each fish. When multiple gears were used in a single trip, we separated the catch by gear type. In Kenya, catches were identified, counted, and measured to the nearest centimeter using a fixed marker rule on a flat board. Where possible the entire catch was sampled, alternatively a sub sample was measured, ensuring that each gear used at each site was adequately sampled and each species landed was recorded.

Although a variety of fishing gears and techniques were used throughout PNG, three main gear types were widespread and used in sufficient numbers to be useful for management and comparison; line fishing, gill nets, and spearguns. In Kenya, these three gears were also commonly used along with beach seines and traps. The infrequent use of other fishing methods (weirs, poisons, bombs, and derris root) did not allow for sufficient data to make comparisons.

Catch and gear analyses

We used expert opinion to group species into the following functional groups, based on their diet: piscivore, macro piscivore-invertivore, plankivores, macro and micro invertivores, grazer (micro-turfs), macrograzers (seagrass and large erect algae), scraper/excavator (parrotfish that remove coralline algae and calcium carbonate while grazing), and detritivores. We also classified species particularly important for ecological processes as a “key-species”, i.e. batfish and red-lined triggerfish (McClanahan 2000, Bellwood et al. 2006). We used ordination plots generated by correspondence analyses to examine how nation and gear were related to the above functional guilds and species.

Simulation model development

A coral reef computer-based simulation model was developed to specifically run scenarios for fisheries management using the above gear types. This model, which has been given the acronym CAFFEE (Coral-Algae-Fish-Fisheries Ecosystem Energetics), is a system-dynamic model of a coral reef ecosystem based on the transfer of energy implicit in interactions between functional groups. The model is an expansion and improvement on a previous model (McClanahan 1995).

CAFFEE was developed in STELLA to represent a conceptualized reef food-web that integrates 17 functionally distinct groups across four trophic levels, including 6 primary producers, 8 primary consumers, 2 secondary consumers and 1 tertiary consumer (Fig. 1). Interactions between functional groups were modeled using an energy-based approach that considered metabolism and biological processes (production, consumption, assimilation, respiration, excretion), as well as ecological factors such as resource competition, density-dependent consumption, and group-specific rates of capture by different fisheries. A detritus-cycle including benthic and pelagic DOM and POM was also incorporated. Calibration used parameters obtained from the literature or derived from datasets provided by collaborating scientists (a full list of references is available on request). A fuller presentation of the model's equations and calibration is forthcoming.

Simulations in the absence of fishing effort ('pre-fisheries' conditions) were allowed to run until a steady state was achieved (i.e. until the values of all stock variables had less than 0.1% of annual variation). The standing stock of each functional group at this stage was taken to be the 'pre-fisheries stock' and these values were used as initial or steady-state stock values (30 to 50 years of simulation) for determining the effect of all further fisheries simulations.

Steady-state stocks of functional groups were compared at different levels of fishing effort with 'pre-fisheries stocks' for different fisheries in order to identify gear-based management strategies likely to enhance reef recovery after disturbance. The model's program increases the catch rates of different gear types at 1 fisher per km^2 intervals and the effect on the stocks on key functional groups were taken and plotted. Gear and catch data from the PNG and Kenya landing sites were used to calibrate the fisheries parameters of the model and here we focus on the effects of effort and gear use on total yields and grazer abundance.

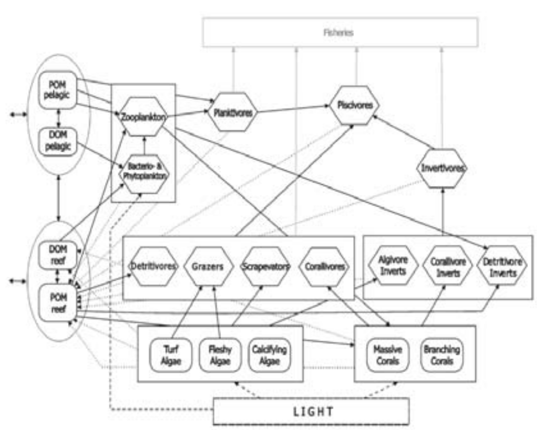

Figure 1. Systems diagram showing the main components and flows of the coral reef ecosystem model used in the gear-use simulation experiments.

Results

Gears were strongly associated with functional groups in both countries (Fig. 2). PNG spearguns caught mostly (micro) grazers, scraper/excavators, detritivores, and planktivores. Kenyan spears, traps, and beach seines caught more grazers (i.e. browsers) and invertivores. Hook and line in both Kenya and PNG captured more carnivores but Kenyan catches had fewer planktivores. Set or gill nets predominantly caught carnivores. Nets in PNG caught piscivores and macro-invertivores, whereas Kenyan nets caught more micro-invertivores and some grazers.

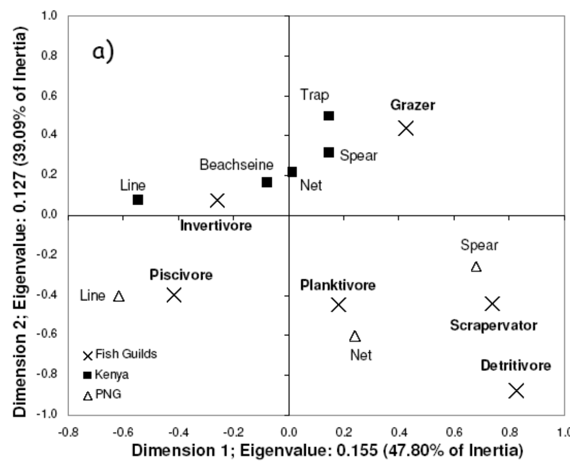

Figure 2. Correspondence analysis plot showing the relationships between functional group catch by gears in the two countries. Scrapervator = scraping and excavating parrotfish.

Model simulations using the calibration for the PNG catch produced three distinct responses for catches by the gear types - spears, nets, and hook-and-line (Fig. 3). Spears produced the highest yield but it was also associated with a collapse in the fisheries beyond the maximum catch, which for this simulation calibration was found at 12 fishers km^{-2}. Nets produced the second highest yields and above 25 fishers km^{-2} did not increase the total yield. Hook and line produced the lowest total yields and declined above 25 km^{-2} for increasing fishing effort, suggesting a constant diminishing catch per fisher. Model outputs calibrated for all gears and pooling all grazers together into a single functional group indicate that spearguns, traps, Kenyan gill nets, and beach seines will reduce grazers to extinction at moderate levels of fishing effort while grazer fish stocks will be able to sustain greater fishing pressure by lines and the nets used in PNG (Fig. 4).

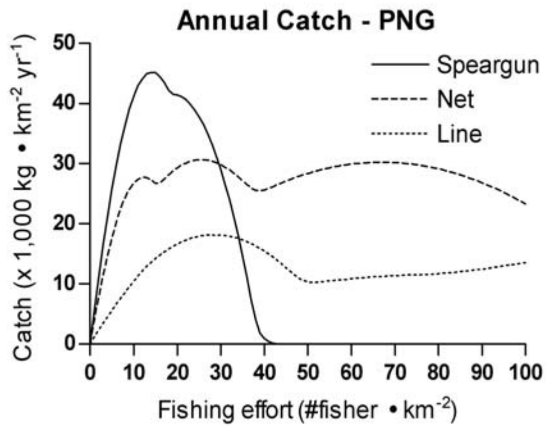

Figure 3. Estimated sustainable annual catch for three gear types from simulation runs based on the Papua New Guinea model calibration.

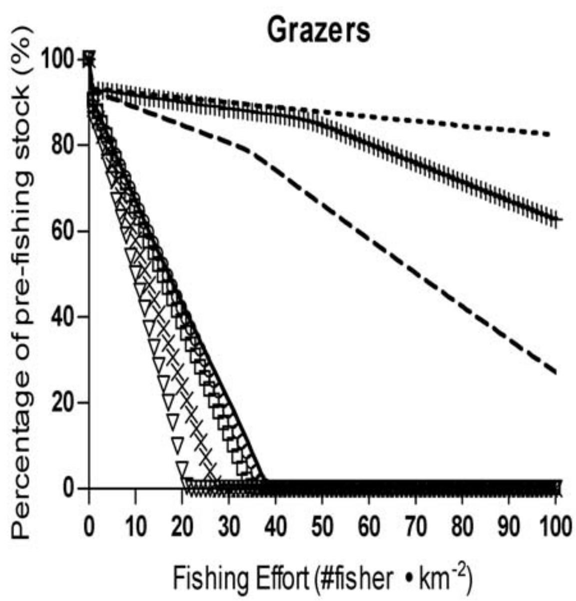

Figure 4. Long-term effects of the common gear types on the grazer functional groups. Legend: (-) line PNG, (+) line Kenya, (—) net PNG, (•) spear PNG, (°) net Kenya, (□) beach seine Kenya, (×) spear Kenya, (∇) trap Kenya.

Discussion

Field data on fish catches by gear in the two countries indicates strong associations between the functional groups of caught fish and types of gear used with some differences in the two nations. We expected the effect of "nation" due to the different levels of fishing intensity and history in the two countries. Kenya has higher numbers of fisher and fishing intensity than PNG. With regard to fisheries yield, the main difference between Kenya and PNG was the high amount of grazers, particularly macro-grazers, caught by spearguns, beach seines, and set nets in Kenya. Many of these macro-grazers feed in and on seagrass and erect algae, and national differences are likely a result of greater use of seagrass ecosystems and greater fishing pressure in Kenya (McClanahan et al. 2008).

Spearguns largely catch herbivores of various kinds in both countries, and a considerably high diversity of other species, as demonstrated by catch-biodiversity studies (McClanahan and Cinner 2008). This high diversity of catch is likely to explain the rapid decline in catch at high levels of effort found in speargun simulation models. The high diversity of catch allows more resources to be utilized but the ultimate consequence of this versatility is a potential for total fisheries collapse at high levels of fishing effort. Fisheries involving gear with low catches of grazers did not collapse but the catch per fisher is extremely low at high levels of effort for PNG nets and hook and line. It is likely that fishers will switch to more effective gear as yields drop, and this may lead to greater use of beach seines and spearguns, with associated losses of grazers (Pauly et al. 1989; McClanahan et al. 2008). Catching fish higher in the food web may not result in the loss of grazers and may help conserve corals, but it is also associated with lower yields. These yields are, however, more stable and less likely to collapse. Lower, yet sustainable, yields are indicative of the types of trade offs required in managing fisheries.

It would appear that gears effective at catching reef grazers should be avoided in order to prevent their population collapse and possible degradation of reefs associated with low grazing. This has not occurred in Kenyan reefs because grazing sea urchins have largely occupied the niche of grazing fish (McClanahan 2008). The catch of reef grazers has also been stable in Kenya, as most catch is now derived from seagrass ecosystems that appear less likely (or possibly slower) to collapse or to become dominated by sea urchins (Heck and Valentine 2007; McClanahan et al. 2008). Where overfishing effects are not buffered by seagrass and sea urchins, we may expect to see degradation of coral reef ecosystems and collapses of fish populations at lower levels of effort, especially where the most effective or destructive gear are not controlled. We suggest that knowledge of fishing gear effects can be used to develop a conceptual basis for adaptive ecosystem-based coral reef management. Knowledge of functional groups and their effects on reef processes can be utilized to develop a feedback between the state of the reef ecosystem and choices of gear use (McClanahan and Cinner 2008).

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