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Using an Ecosystem Model to Evaluate Fisheries Management Options to Mitigate Coral Bleaching on Western Indian Ocean Coral Reefs

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Abstract—A coral reef ecosystem simulation model, CAFFEE, developed to evaluate the effects of fisheries management measures on coral reef ecosystem services and functioning, was applied to these parameters independently and taking the effects of coral bleaching into account. We present model outputs for temporary fishing closures and the switching of fishing gears on fish biomass, fisheries yield and coral recovery after bleaching events to exemplify the types of simulations available. CAFFEE was calibrated to simulate Kenyan coral reef ecosystems and fisheries based on long-term observational data. Temporary closure simulations benefited hand line fisheries, with an increase in total annual catch over time unlike gill net fisheries. Closures in gill net fisheries resulted in less trophic level effects on hard coral than closures in hand line fisheries, and corals recovered faster in the gill net fishery after a simulated bleaching event. The use of spear guns or gill nets after bleaching aided coral recovery and promoted greater fisheries yields, whereas hand line fishing promoted sea urchins by reducing their predators, resulting in reduced coral recovery. Ecosystem models combined with empirical surveys can thus assist managers to evaluate the effects of fisheries management options on ecosystem services where climate change mitigation is required.

INTRODUCTION

Small-scale artisanal fisheries are major contributors to the total fish catch in western Indian Ocean countries, yet scientific information on these fisheries is considered inadequate and management strategies are in need of improvement (Jiddawi & Öhman, 2002; van der Elst *et al.*, 2005; McClanahan *et al.*, 2008). These management strategies generally need to address a complex array of economic, social and conservation objectives, an undertaking which is further complicated when mitigation of climate change impacts is needed (Cinner *et al.*, 2009a, b). Addressing multiple objectives and balancing trade-offs will require evaluation and comparison of the performance and feasibility of alternative

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options, and appropriate tools would assist managers with the task of assessing the potential outcomes of implementing different strategies.

Over the last two decades, computer model simulations of the dynamics of marine ecosystems have become established as valuable tools in the development of ecosystem-based fisheries management approaches (Pauly *et al.*, 2000). These models are based on mathematical representations of the trophic relationships between groups of marine organisms and consequent effects on their stocks and productivity. More recently, emphasis has been laid on the incorporation of complete food webs and the integration of biotic-abiotic linkages at all trophic levels, including human and climate change impacts, in end-to-end models to assess direct and indirect effects of climate and fishing on ecosystem dynamics (Travers *et al.*, 2007).

The present paper provides a brief introduction to CAFFEE (Coral-Algae-Fish-Fisheries Ecosystem Energetics), a process-based ecosystem model for coral reefs designed to test different scenarios of fisheries management and coral bleaching in the western Indian Ocean. CAFFEE simulates the ecosystem trophodynamics of coral reefs and includes features such as detrital pathways and the coupling of benthic abiotic processes, thus aligning it with current efforts to develop end-to-end models. The objective of CAFFEE is to provide a platform for managers and scientists to evaluate the effects of alternative management options on ecosystem function and stability, and the performance of ecosystem services, independently and taking the effects of coral bleaching into account. Analysis of CAFFEE simulations may be used to fill gaps in knowledge on the effects of artisanal fisheries and provide managers and policy makers with recommendations on conservation or fisheries management objectives.

We present a few examples here of the applicability of CAFFEE in addressing fisheries management questions in the context of climate disturbances that are likely to occur with climate change. Computer simulations were used to investigate three scenarios: a) the effects of temporal closure on fish catches in gill net and line fisheries; b) the effects of temporary closures in gill net and line fisheries on the recovery of corals after bleaching; and c) the effects of switching fisheries gear on fisheries yield and fish stocks after a severe bleaching event.

MATERIALS and METHODS

The CAFFEE (Coral-Algae-Fish-Fisheries Ecosystem Energetics) model simulates processes that drive the biomass and benthic cover dynamics of 27 functional groups, representing typical components of coral reef ecosystems in the western Indian Ocean. Trophic interactions between the functional groups are synthesised in a food web (Fig. 1) integrating four types of benthic macrophytes (turf, foliose and calcifying algae; seagrass), two types of hard coral (branching/foliaceous and massive/submassive forms), microplankton, zooplankton, four categories of detrital matter (reef and pelagic particulate and dissolved organic matter), four types of invertebrates (algivores, corallivores, detritivores and micro-invertebrates), and 11 fish guilds (macro- and micro-grazers, scraper-excavators, corallivores, macro- and micro-detritivores, planktivores, macro- and micro-invertivores, piscivores and pisci-invertivores). The model also simulates selective fish harvesting in five categories of artisanal fisheries common in the region with distinct gear characteristics (fish traps, beach seines, spear guns, gillnets and hand lines) and associated gear-guild catch ratios. Light and nutrients are the implicit energetic drivers in the model.

CAFFEE simulates the biomass dynamics of the functional groups by time-step computing the energy flows of metabolic and ecological processes in each biomass pool, quantifying the amount of biomass gained as a consequence of production, the amount of organic matter used in metabolic maintenance and the organic matter transferred to higher trophic levels due to consumption. The dynamics of benthic

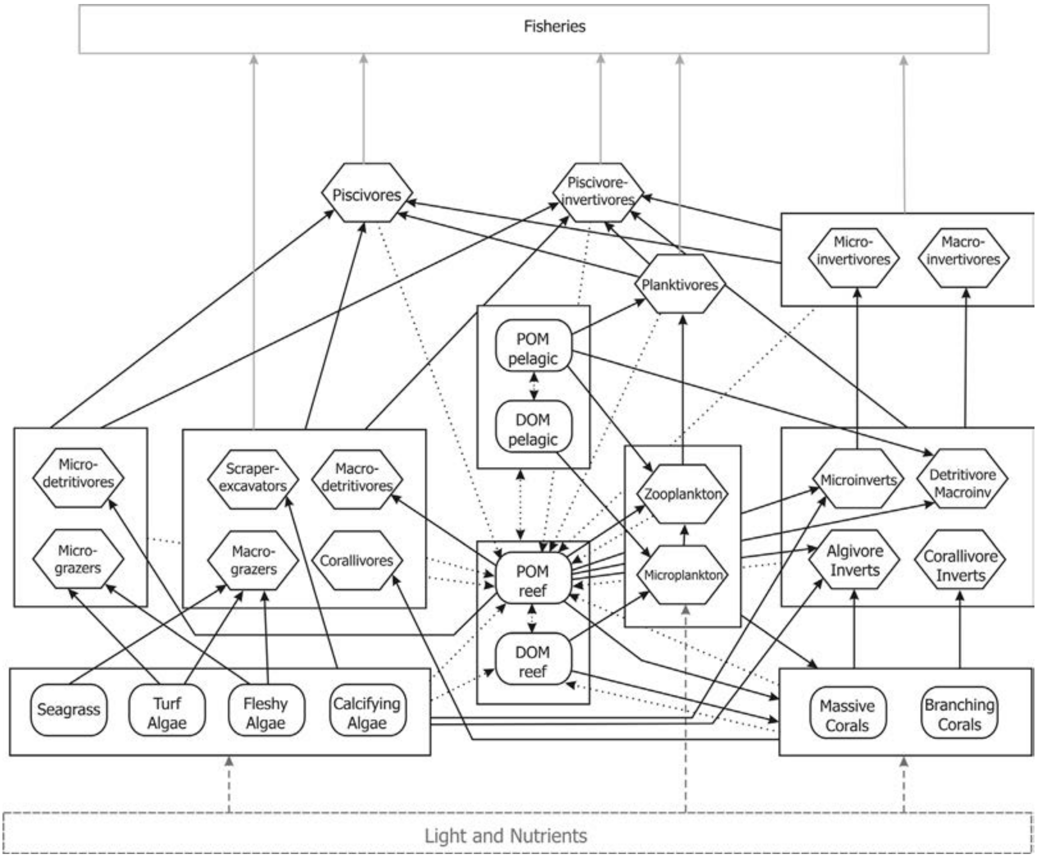

Figure 1. Food web of a coral reef ecosystem as implemented in CAFFEE, including 27 functional groups and their trophic interactions (solid black arrows). Non-trophic transfers of organic matter (e.g. detritus) are indicated by dotted lines. Extraction of pelagic resources by fisheries is indicated by solid grey arrows.

substrata are similarly calculated based on the parameterization of colonization, lateral expansion and cover loss processes, including bioerosion. Reef accretion and erosion are also modelled, based on rates of deposition of calcium carbonate by corals and coralline algae and rates of bioerosion by reef fauna. Ruiz Sebastián and McClanahan (in press) provide a formal mathematical description of the model formulation and its validation; only a brief description of the parameterization of the main processes is thus provided here.

In the model, benthic organisms have been characterized by two state variables (biomass and benthic cover), and primary production and metabolic processes of corals and macrophytes have been modelled as functions of biomass density. Production, respiration and excretion curves have been derived from productivity and P/R ratios obtained from the literature. Rates of coral heterotrophy on zooplankton, microplankton, particulate and dissolved organic matter were derived from Sorokin (1982), Anthony and Fabricius (2000) and Ferrier-Pagès *et al.* (2003). The prey capture rates by functional consumer groups are dynamically derived in the model from ratio-dependent sigmoidal (type III) functional response equations, where the density of predators, prey and competitors are taken into account (Arditi & Ginzburg, 1989; Abrams & Ginzburg, 2000). Secondary production by consumers was calculated from estimates of assimilation and production efficiencies (e.g. Miller & Mann, 1973), and respiration metabolism was based on rates of basal respiration and activity coefficients (e.g. van Rooij & Videler, 1996).

The dynamics of detrital pools are explicitly modelled in CAFFEE, including consumption by detritivores, passive leakage of soluble components from particulate organic matter (POM), degradation due to photoreactivity and diagenetic processes, sedimentation and detrital export from the system. Reef formation processes are also included, based on calcification rates of corals and calcifying algae that contribute to skeleton deposition, and rates of bioerosion of skeletal structures and reef framework by parrotfishes and urchins (Carreiro-Silva & McClanahan, 2001). Reef benthic complexity is considered in terms of two factors that distinctly affect benthic processes: framework rugosity, a scaling factor between planar and three-dimensional space available for benthic colonization; and surface index, a ratio between the spatial and basal surface area of calcifying organisms. Framework rugosity has been estimated as 1.3 (McClanahan, 1994; Garpe & Öhman, 2003), while surface indices are calculated dynamically in the model based on the amount of skeleton deposited and corresponding to the values published by Holmes (2008).

Reef benthic space is a critical resource for sessile organisms and a determinant of the standing stock and productivity of macrophytes and corals. The main processes that drive benthic cover dynamics are recruitment, lateral expansion and cover loss due to herbivory, corallivory and other interactions. All these processes are simulated in CAFFEE and derived from causative processes (e.g. coral lateral expansion is derived from coral calcification).

Five types of artisanal fisheries common in the western Indian Ocean coastal region (traps, beach seine nets, gill nets, hand lines and spear guns) are modelled in CAFFEE. The different gears used in these fisheries result in catch selectivity, where certain functional groups are caught more frequently than others (Cinner *et al.* 2009b). These catch-guild ratios are dynamically adjusted relative to variation in the fish stock from initial conditions. A theoretical maximum daily catch of 25 kg has been assumed for a fisherman working on previously unfished reefs. Fishing gear was assumed to have no direct effects on benthic cover in these simulations.

Different scenarios of coral bleaching can be simulated in CAFFEE by specifying coral bleaching intensity (as a percentage of corals losing their symbionts), coral recovery rate (the daily rate of symbiont reacquisition) and the frequency of bleaching events. Coral photosynthetic production by unbleached corals is represented by an annual integration of light and symbiont variability. In bleached corals, the photosynthetic production is assumed to be proportional to the percentage of symbionts in coral tissue. Coral heterotrophy plays an important role in bleached corals (Grottoli *et al.*, 2006) and heterotrophy compensation coefficients have been included in the model.

CAFFEE was calibrated to simulate Kenyan coral reef ecosystem dynamics in the scenarios presented in this paper. We used a comprehensive data set of observations on coral reef benthic cover and fish and urchin populations collected by the Wildlife Conservation Society over >20 years to validate this calibration. The data set includes records from sites where fishing has recently or long-since been restricted or stopped, and sites located in long-standing fishery closures or Marine National Parks. A combination of data from these protected sites provided a time-series of fish biomass relative to benthic cover spanning 40 years from the establishment of the first fishing closure. Initial values in this time series were used to represent the starting conditions in 40-year CAFFEE simulations, and the resulting trajectories were compared to the observational series and used to make fine adjustments to the model’s internal parameters until external validation was achieved.

Computer simulations were run to obtain results for three scenarios in which the initial biomass and benthic cover were those derived from the older protected areas in Kenya, assumed to be close to an ecological steady-state. First, we compared the effects of temporary closures on net and line fisheries in terms of fisheries yield. Simulations were run for ten years at a fishing effort of five fishermen per km^2 and periodic fishery closures were placed at the end of the annual fishing season. Second, we compared the effects of one- to three-month per year temporary closures in the net and line fisheries on coral recovery after a bleaching event. For this scenario, we ran similar simulations for 15 years, with a single coral bleaching event of 80% bleaching intensity five years after the start of the simulations and a symbiont recovery rate of 0.4% per day. Thirdly, we compared the effects on fisheries yield and fish stock of a switch of fisheries gear after a severe bleaching event. The conditions for this simulation were the same as in the second scenario except that, instead of temporary closures, fisheries management consisted of maintaining the same gear (gill nets) or switching gear (spear guns or hand lines).

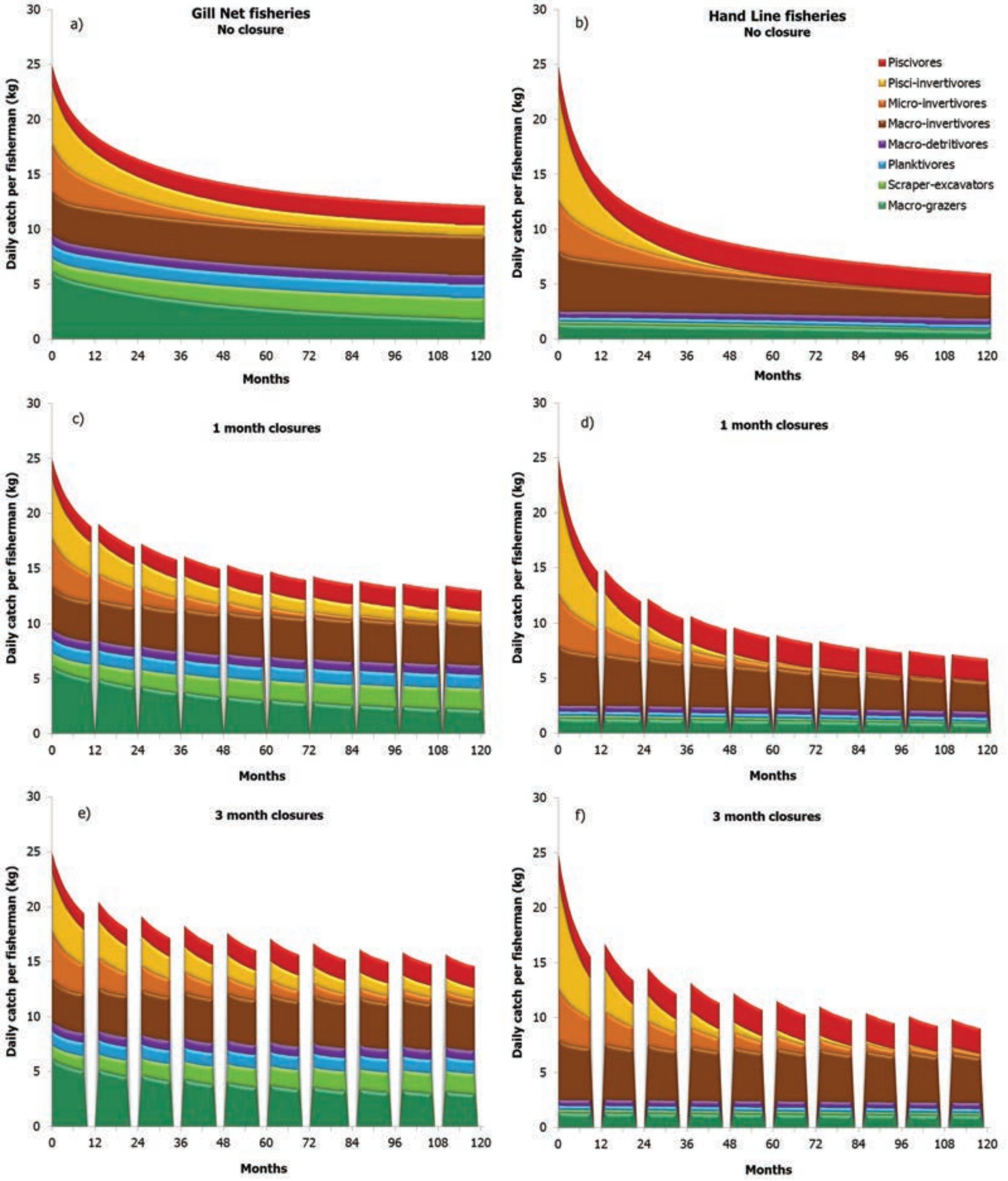

Figure 2. Results of CAFFEE simulations showing the medium-term effects (10 years) of temporary closures on daily catch in gill net (left panels) and hand line fisheries (right panels) with: a, b) no closures; c, d) 1-month closures; or e, f) 3-month closures. The simulations are based on a fishing effort of five fishermen per km^2 and initial conditions corresponding to previously unfished reefs.

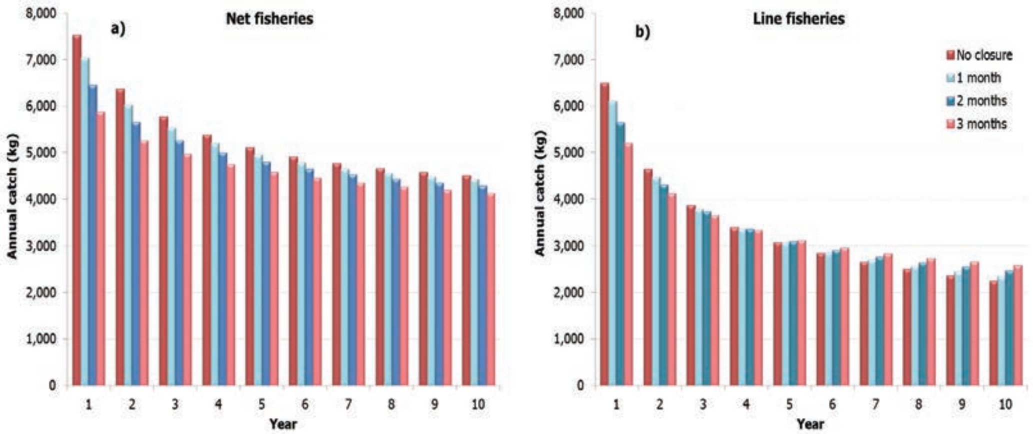

Figure 3. CAFFEE-modelled effect of temporary closures on annual catch in a) gill net and b) hand line fisheries.

RESULTS and DISCUSSION

Scenario 1: Temporary closures

The effects of gear selectivity on total catch in gill net and hand line fisheries resulted in a total daily catch per fisherman of 12.21 kg and 5.99 kg respectively at the end of the ten-year simulation, at a fishing effort of five fishermen per km^2 without temporary closures (Fig. 2a, b). In the case of the hand line fishery, most of the catch comprised carnivorous fish groups and their relative contribution to the daily catch decreased progressively with reduced standing stocks. The stocks of omnivorous predators and micro-invertivores were practically depleted halfway through the simulation. In contrast, the catch of non-carnivorous groups remained almost constant for the length of the simulation and, therefore, comprised an increasing proportion of the total catch. In the gill net fishery, the discrepancy between the capture rate of

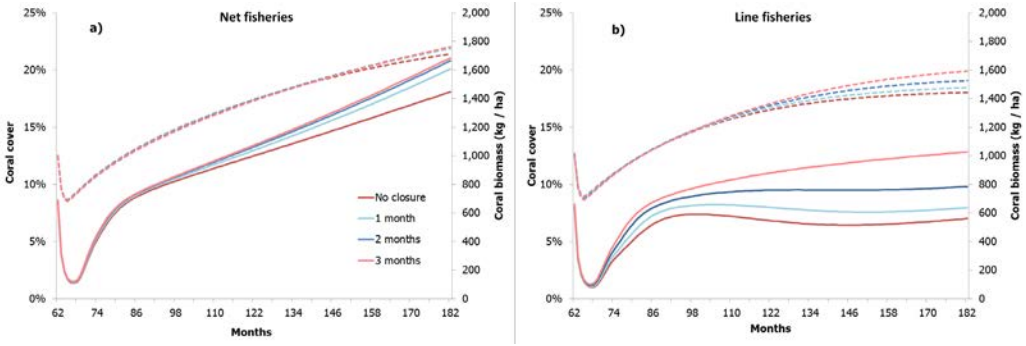

Figure 4. CAFFEE-modelled changes in coral benthic cover and biomass after a severe bleaching event on a reef subjected to a) a gill net or b) a hand line fishery managed with temporary closures. Dotted lines indicate coral cover and solid lines indicate coral biomass. The simulated bleaching event was introduced five years into the simulation and the figure shows only the subsequent ten years to portray differences in coral recovery.

carnivorous and non-carnivorous groups was not as marked, resulting in a more balanced catch composition throughout the simulation.

Closure of the fisheries for one month per year allowed some degree of recovery of the fish stocks and, consequently, a higher catch rate after ten years of fishing, yielding 13.0 kg and 6.8 kg per fisherman per day for gill net and hand line fisheries respectively (Fig. 2c, d). An increasing trend in catches with more prolonged closure was confirmed, with an annual three-month closure (Figs. 2e, f) yielding daily catches per fishermen after ten years of 14.6 kg and 9.1 kg respectively. Temporary closures also had a balancing effect on catch diversity by favouring the recovery of the most vulnerable, targeted fish groups.

In the case of the gill net fishery, temporary closures increased catch daily rates that were nevertheless insufficient to compensate for the loss of fish catch during the closure (Fig. 3a) and all closure lengths produced declining trends in total annual catch rates. In the hand

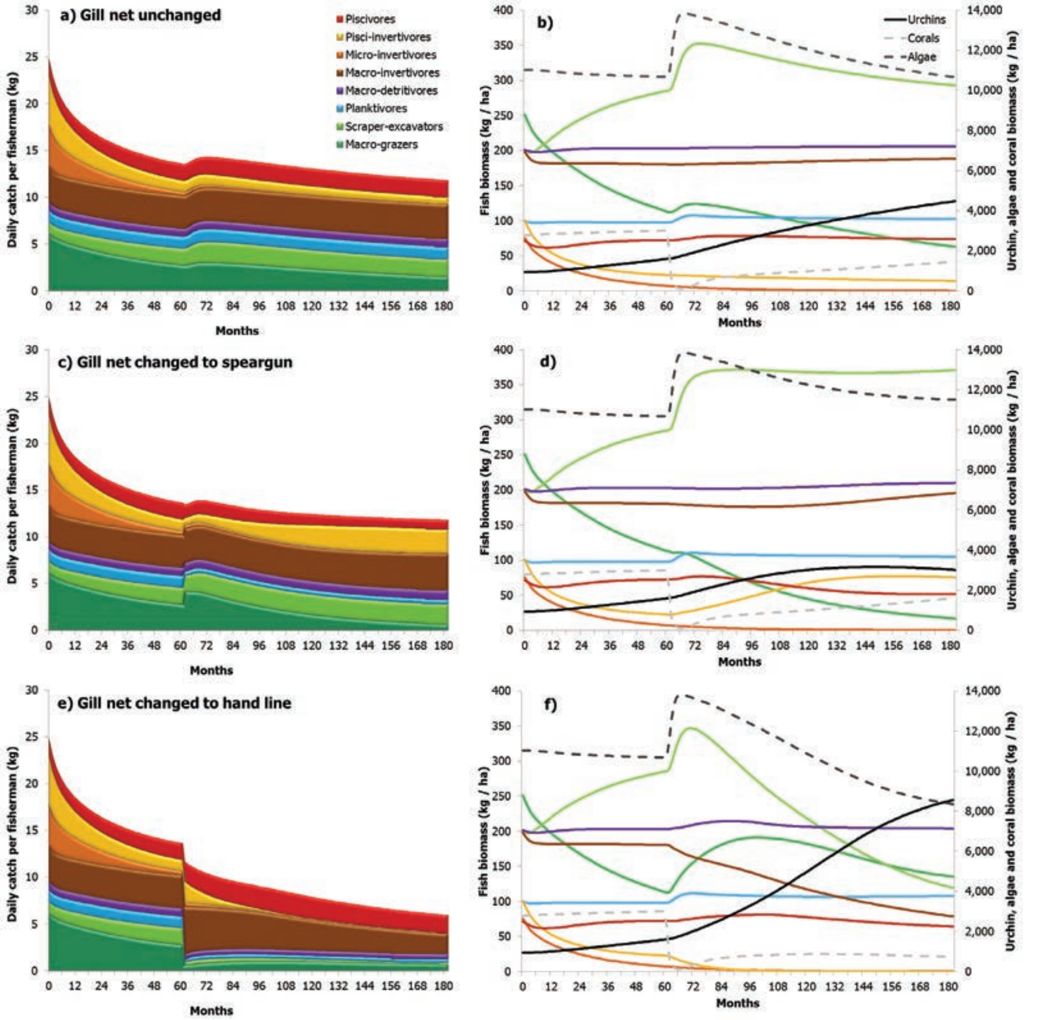

Figure 5. CAFFEE-modelled effects of switching fishing gear after a bleaching event on fisheries catch and fish biomass. The simulations are based on a fishing effort of five fishermen per km^2 on a reef subjected to a single severe bleaching event (80% loss of symbionts) five years into the simulation. Left panels portray daily catch and composition and right panels the biomass of fish, urchins, corals and algae with gill net gear: a, b) unchanged; c, d) changed to spear guns; or e, f) changed to hand lines after the bleaching event.

line fishery, there was a medium- and long-term benefit in the annual catch to the periodic closures (Fig. 3b); this commenced increasing after five years of temporary closures and the increase in fish catch due to stock recovery made up for the catch loss caused by the closure.

Scenario 2: Coral recovery after bleaching

In the second scenario, the rates of recovery of coral cover and biomass were compared in areas with gill net and with hand line fisheries at a fishing effort of five fishermen per km^2. The 80% loss of coral symbionts produced a reduction in coral cover from 28.6% to 8.6% five months after the bleaching event, followed by a gradual recovery in coral cover. Overall, the gill net fishery had less impact on the coral cover than the hand line fishery. Periodic closures had little effect on coral recovery in the gill net fishery but some effect in the hand line fishery. In the gill net fishery, the coral cover improved to 21.4% without and 22.0% with three-month closures (Fig. 4a). In the line fishery, the final coral cover values were 18.0% without and 19.9% with three-month closures (Fig. 4b). The fishing closure effect was greater on coral biomass, especially in the hand line fishery where the final coral biomass after three-month closures was twice that (1,025.8 kg ha^{-1}) of non-closure management (560.6 kg ha^{-1}).

Scenario 3: Switching gear after a bleaching event

After a severe bleaching event, there was a short-term increase in fisheries yield when gill nets were maintained throughout the simulation (Fig. 5a) and when switching from gill nets to spear guns (Fig. 5c), but not when switching from gill nets to hand lines (Fig. 5e). This was to be expected, considering that coral mortality after bleaching is accompanied by an increase in macrophyte cover, making more food available for herbivorous fish. An increase in scraper-excavators was probably the main factor leading to higher catches in gill net and spear gun fisheries, where herbivores make up a substantial portion of the catch. While the increased macrophyte biomass on these reefs was consistent in all simulations, coral biomass was more variable, being reduced in the hand line fishery due to an increase in sea urchins (Fig. 5b, f).

Hand line fisheries capture a much smaller proportion of herbivores and, therefore, an increase in herbivore stocks does not result in an increase in their yield in this fishery. Furthermore, a high proportion of predators is caught in the hand line fishery, driving a rapid depletion in macro-invertivore and pisci-invertivore stocks (Fig. 5f), which releases sea urchin populations from predation and allows them to compete with herbivorous fish in the process. Switching gear from gill nets to spear guns appeared more effective in controlling the increase in the urchin population than maintaining gill nets (Figs. 5b, d), thus reducing fishing pressure on pisci-invertivores that feed on sea urchins. Nevertheless, there was a drastic decline in the biomass of large grazers with this type of fishing as spear guns are effective gear for the capture of this trophic group.

CONCLUSIONS

The above scenarios offer a brief introduction on CAFFEE's potential to investigate the consequences of fishery management options in coral reef ecosystems while simultaneously evaluating the effects of coral bleaching and fishing. The results indicate some of the complexity and unexpected effects of management choices in fishing gear selection and fisheries closure in coral reef ecosystems. The provision of results that can be expected from management policies and recommendations in specific systems will require explicit definition of the relevant scenarios, empirical data on the fisheries and ecosystem in question, and calibration of the model, catch gear, importance of sea urchins and other factors for which data are available in the region. The acquisition of data for further calibration and testing of the model currently forms part of two projects supported by the Western Indian Ocean Marine Science Association (WIOMSA) Marine Science for Management (MASMA) programme.

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