Journal of Applied Ecology
British Ecological Society

Journal of Applied Ecology 2009 doi: 10.1111/j.1365-2664.2009.01648.x

Gear-based fisheries management as a potential adaptive response to climate change and coral mortality

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Summary

1. Climate change is emerging as one of the greatest threats to coral reef ecosystems. Climate-induced warming events trigger coral bleaching and mortality, which can indirectly affect coral reef fishes. Managing fisheries across coral mortality events is expected to influence the persistence of species and reef recovery potential. The most common management recommendation has been to prohibit fishing using fisheries closures, but this response often has limited support from resource users.

2. Here, we explore an alternative of managing fishing gear commonly used in artisanal coral reef fisheries. We examined fisheries landing data from 15 sites in Papua New Guinea and Kenya to explore whether or how specific gears select for: (i) species that depend on coral reefs for feeding or habitat and are likely to be susceptible to the loss of coral, and (ii) different functional groups of fishes.

3. Only 6% of the fishes targeted by fishers were susceptible to the immediate effects of coral mortality; however, loss of habitat structure following coral mortality is expected to affect 56% of targeted species.

4. Importantly, 25% of target species had feeding characteristics (i.e. reef scrapers/excavators and grazers) that contribute to the recovery of coral reef ecosystems, and gears differed considerably in catches of these species.

5. Spear guns and traps target a high proportion of species likely to be affected by bleaching and key for the recovery of corals. These gears are strong candidates for management restrictions in reefs with high coral mortality. In contrast, line fishing catches the lowest proportion of susceptible and recovery-enabling species and is preferential for increasing recovery rates on coral reefs.

6. *Synthesis and applications*. Fisheries managers will require a range of tools to meet the novel challenges posed by climate change. This study presents a way to help reduce the negative impacts of climate change and potentially increase resilience of marine ecosystems by managing fishing gear. Specific gears used by artisanal fishers differentially target fish functional groups. In the coral reefs that we studied, traps and spear guns targeted a high proportion of species highly susceptible to coral mortality and critical to coral reef resilience through their top-down control. Given that full fisheries closures are not always practical, selectively banning or restricting fishing gears is a potentially powerful tool for reducing the detrimental ecosystem effects of climate change disturbances.

Key words: adaptive management, coral bleaching, climate change, herbivory, coral reef, artisanal fishery

Introduction

Climate change is emerging as one of the greatest threats to the ecological integrity of coral reefs (Hoegh-Guldberg *et al.* 2007). Climate-induced warming events trigger coral bleaching (Brown 1997; Glynn 1993), which is one of the principal causes for the global decline of coral cover (Goreau *et al.* 2000; Gardner *et al.* 2003; Bruno & Selig 2007). Coral degradation also has significant effects on reef fishes, especially to those species that depend on corals for food, shelter, and recruitment

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(Wilson *et al.* 2006), and may be expected to have longer-term effects on coral reef fisheries (Graham *et al.* 2007). Some fish have key ecological roles on reefs because their feeding activities help to prevent or reverse phase shifts to algal-dominated reefs (Bellwood, Hughes & Hoey 2006a; Hughes *et al.* 2007), or control species that prey on corals (Dulvy, Freckleton & Polunin 2004). Removal of these fishes can compromise the systems' resilience, with detrimental consequences for long-term sustainability of coral reef ecosystems.

Climate-induced coral bleaching and the associated degradation of reef habitats have the potential to affect coral reef fishes targeted by artisanal reef and reef-related fisheries through several key mechanisms (reviewed by Pratchett *et al.* 2008). However, fishes have varying levels of susceptibility to bleaching and coral mortality, with those species directly dependent on live coral for food, settlement, and shelter experiencing the most negative effects (Jones *et al.* 2004; Pratchett *et al.* 2008). Species associated with reef structure will experience declines associated with the gradual erosion of dead coral skeletons (Sano, Shimizu & Nose 1987), potentially leading to reduced fisheries yields (Westmacott *et al.* 2000; Graham *et al.* 2007). The effects of bleaching are initially restricted to the small proportion of species that obligately depend on live corals in areas where structural complexity is retained independent of coral cover (Munday *et al.* 2008).

Fundamental changes in the structure of benthic reef habitats may have consequences for a wide range of species in the long term, due to declines in availability of prey resources, loss of refugia, and adverse effects on critical settlement cues (Jones *et al.* 2004). The early response of herbivore abundance to coral mortality can be positive (Wilson *et al.* 2006), but an increase in late-successional 'fleshy' algae can reduce the abundance of herbivores that prefer early successional 'turf' algae (McClanahan *et al.* 2000) in favour of species that eat late-successional algae (Fox & Bellwood 2008). Thus, changes in the benthos brought about by disturbance can lead to shifts in the fish community and function, without necessarily affecting total abundance and diversity (Bellwood *et al.* 2006b).

Changes in the relative abundance of species are expected to influence fisheries yields, species composition of catches, and the resultant economic value of coral-reef fisheries (Westmacott *et al.* 2000). The full consequences of climate change and coral reef degradation for reef-based fisheries are, however, not known, but it is expected that coral mortality will further reduce the sustainable harvest levels for impacted reefs (Westmacott *et al.* 2000; Hoegh-Guldberg *et al.* 2007). It is critical therefore, that contemporary fisheries management incorporates strategies that will reduce the extent to which fishing compounds the effects of climate change (Pratchett *et al.* 2008).

Since root causes of coral bleaching cannot be controlled locally, managers have few possible responses (Mumby & Steneck 2008; Marshall & Shuttenberg 2006). The default management strategy currently used to minimize long-term consequences of climate-induced coral bleaching is to prohibit all fishing activities within designated areas, referred to as No-Take Areas (NTAs) (Hughes *et al.* 2003; Game *et al.* 2008; Mumby & Steneck 2008). The rationale for this is twofold: (i) by minimizing all direct anthropogenic effects, NTAs maximize the capacity for coral reef ecosystems to withstand, and recover from periodic bleaching events; (ii) NTAs also limit harvesting of key functional groups (specifically herbivorous fishes) that directly contribute to coral recovery by keeping algae cropped (Hughes *et al.* 2007; Mumby, Hastings & Edwards 2007). However, regional-scale assessments of the effectiveness of NTAs in promoting resistance to and recovery from bleaching events in the western Indian Ocean suggest limited success probably due to the initial placement of NTAs in areas highly susceptible to bleaching and possibly the small size or weak management of regional NTAs (Maina *et al.* 2008; Graham *et al.* 2008).

Many coral reefs are located in poor, developing countries (Donner & Portere 2007) where fishing restrictions can undermine local livelihoods and are, therefore, difficult to justify and enforce (McClanahan, Hicks & Darling 2008). Total prohibitions on fishing, while perhaps ideal from an ecosystem-management perspective, may pose an unrealistically difficult burden on fishing communities and can, consequently, receive little support or compliance (McClanahan *et al.* 2006). There is a need to explore alternatives that have greater potential for adoption in poor tropical countries (Mumby & Steneck 2008).

Fishers are generally more supportive of restrictions on specific types of fishing gear compared to outright closure of fishing grounds (McClanahan, Maina & Davies 2005). Despite this preference, no studies have explored the use of gear restrictions to adaptively manage coral reef ecosystems facing climatic disturbances. Artisanal coral reef fishers use a range of gears, each of which target specific sizes and species of fishes (McClanahan & Mangi 2004). In the case of coral mortality, specific gears are also likely to differentially target fishes with varying levels of susceptibility to climate-induced coral mortality. Consequently, identifying species most affected by coral mortality and restricting gears that target them might prove to be an effective management option to reduce additional pressure on those fish species. Additionally, the resilience of coral reef ecosystems might be increased by restricting the use of gear types that target guilds of fishes critical to the recovery of benthic habitats (McClanahan & Cinner 2008).

The aims of this study were to: (i) explore the relationship between gear types and fish catch functional groups thought to be critical to the recovery of corals and those species susceptible to coral mortality, and (ii) examine gear selectivity as a basis for managing coral reef fisheries in the face of climate change and increased coral mortality. We used fish catch data from two countries: Kenya and Papua New Guinea (PNG), both of which had about an order of magnitude variation in fishing pressure between study sites (Cinner & McClanahan 2006a,b).

Materials and methods

We used data on species composition of fisheries catches from small-scale artisanal fishers in five sites in PNG (Cinner & McClanahan 2006;

McClanahan & Cinner 2008) and 10 sites in Kenya (McClanahan *et al.* 2008). These study sites encompass a wide range of social, economic, and demographic conditions, but in both countries, fishing was generally undertaken in shallow-water (<20 m depth) coral reef and seagrass ecosystems. PNG data were collected over 2–3 weeks in each village during a period between October 2001 and June 2002 (Cinner & McClanahan 2006a). Kenyan data were collected between October 2004 and May 2008 with a lesser amount collected in 1998.

GEAR AND ANALYSES

PNG data were collected from landing sites or local markets where fish sellers knew the fishers and their gear (Cinner & McClanahan 2006a). We opportunistically examined fish landings at all times of the day and night by approaching and asking permission from fishers when they returned from fishing activities. The methods to sample fish catch in the two countries were slightly different. In PNG, we photographed fish with a digital camera (Sony DSC P-1, 3·3 megapixels) and recorded the gear used to capture each fish (Cinner & McClanahan 2006a). When multiple gears were used in a single trip, we separated the catch by gear type. The length, abundance, and composition of catch were recorded. A variety of fishing gears and techniques were used throughout Papua New Guinea, but three main gear types were widespread and used in sufficient numbers to be important for management and were comparable, namely line fishing, gill nets, and spear guns. The infrequent use of other fishing methods (including weirs, traps, and fish poison) made comparisons among these gears across study sites difficult.

In Kenya, we sampled catches from artisanal coral reef fishers at landing sites. Where possible, the entire catch was sampled; when this was not possible, a sub-sample was taken, ensuring that each gear used at each site was sampled and each species landed was recorded. In both countries, each fish was identified to species (Randall 1997). In Kenya, we recorded two gears frequently used that were not used in PNG: traps and beach seine nets. Traps were generally woven from locally available material, hexagonal shaped with a funnel entry, and had gauge sizes ranging from ~3–5 cm. Beach seine nets are small gauge nets (1–2 cm) that are used to encircle fish in shallow (~3 m deep) areas and are hauled in by a crew of up to 25 fishers (see McClanahan & Mangi 2004 for a description of Kenyan gears). Eliminating other gear types and fishes that were unidentifiable reduced the number of fishes to 2154 in PNG and 4205 in Kenya.

Plots of the number of species by the number of individuals were used to ensure that a sampling asymptote was reached and our sampling size of reef fish was adequate (Cinner & McClanahan 2006a). We used published literature (Wilson *et al.* 2006; Pratchett *et al.* 2008; Froese & Pauly 2008) and expert opinion to group species found in catch records from both these fisheries into three categories: (i) those that settle, dwell, or feed on the reef, (ii) those that are associated with the reef structure, and (iii) those that are not associated with the reef (list available in Supporting Information, Table S1). Species were also (separately) categorized into the following functional groups based on their diet (Froese & Pauly 2008): piscivore, invertivore, grazer, scraper/excavator (parrotfish that remove calcium carbonate while grazing), detritivore, and planktivore. In addition, we classified fishes as key species if they were known to have a direct effect on recovery of reefs or in preventing major shifts in habitat (Supporting Information, Table S1). These were: *Platax* spp. (Bellwood *et al.* 2006a), members of the family Siganidae (Mantyka & Bellwood (2007), *Kyphosus* spp. (Choat, Robbins & Clements 2004; Cvitanovic & Bellwood in press), *Cheilinus undulatus* (Sadovy *et al.* 2003), *Bolbometopon muricatum* (Bellwood, Hoey & Choat 2003; Sadovy *et al.* 2003), and *Balistapus undulatus* (McClanahan 1995).

ANALYSIS

First, selectivity of each gear type was examined by visually comparing plots of the proportion of catch from each gear by functional groups and strength of coral association. Secondly, we visually examined how location (at both the country and site level) and gear type were related to coral association and guild of captured species using ordination plots generated by correspondence analyses. Thirdly, chi-square (χ^2) and logistic regression analyses were used to validate these visual assessments. Fourthly, chi-square of gear selectivity were tested against a random distribution and four logistic regression models to examine if the coral association of fishes could be predicted by gear type, location, country or fishing intensity. Lastly, two multinomial logistic regression models were used to compare the selectivity of gear types between all sites in our study (one model for coral association and one model for functional group). This required removing gears that only occurred in Kenya (trap and beach seine) because it was not possible to carry out the analysis with no variance in the country. Two additional multinomial logistic regression models that integrated comparable published data on fishing effort by gear type were used to examine the potential effects of fishing intensity on gear selectivity that was available for five sites in PNG and three sites in Kenya (from Cinner & McClanahan 2006a,b). Since comparable fishing pressure was available for only eight of the sites, we conducted a separate set of analyses including fishing intensity. For these analyses, we converted fishing effort by gear type from the published studies into three ordinal categories, based on natural breaks in the data: low (0–7·5 fishing trips^{-1} day^{-1} km^{-2}, $n = 7$), medium (7·6–15 fishing trips^{-1} day^{-1} km^{-2}, $n = 6$), and high (>15·1 fishing trips^{-1} day^{-1} km^{-2}, $n = 4$). Fishing intensity for each gear type at each site was used, and thus, a single site may contain more than one case or replicate.

DIFFERENCES IN GEAR SELECTIVITY, DESTRUCTION, AND PROFITS

Gear selectivity, damage to habitat, and profitability to fishers were integrated into a figure to conceptualize some of the trade-offs among gears used in Kenya. Data on the differential damage of each gear to coral habitats (Mangi & Roberts 2006), the levels of profitability to fishers (Mangi, Roberts & Rodwell 2007), and the differential selectivity of gear for species that are highly and moderately associated with corals was plotted. Profitability was reported separately for crew and owners using gill nets and beach seine nets as described by Mangi *et al.* (2007).

Results

Catch data was comprised of 223 different species in PNG, and 127 species in Kenya. The predominant fishing methods used in PNG were: (i) line fishing, where fishers used a single baited hook attached to nylon line; (ii) gill nets, where fishers used monofilament nets in shallow coral reef or seagrass habitats; and (iii) spear guns, where fishers dove with home-made spears (generally fashioned from bicycle spokes, wood, and an inner tube for propulsion). Spear fishing targeted the

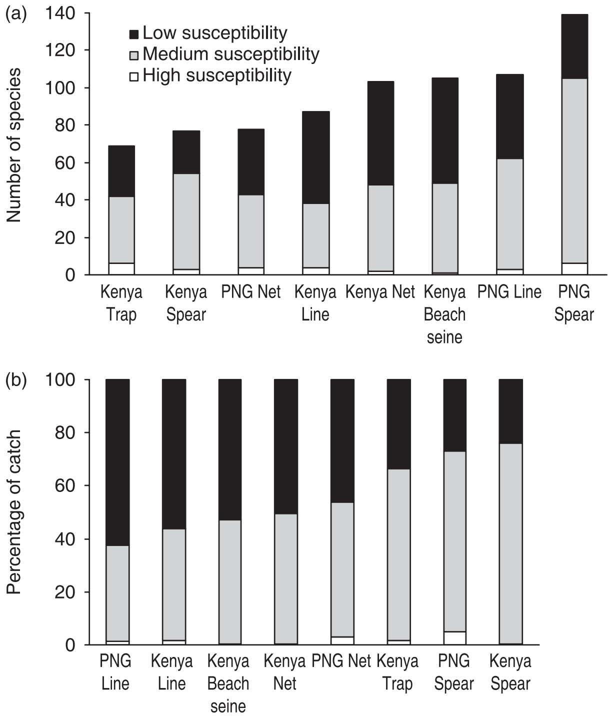

Fig. 1. Coral association of the species captured by each gear as: (a) the total number of species from each classification, and (b) proportion of the catch.

highest number of species in PNG, while net fishing targeted the highest number of species in Kenya (Fig. 1a).

Species that live or feed on live corals comprised <6% of the catch from any specific gear (Fig. 1b). However, line, net, and spear guns in PNG targeted a slightly higher proportion of highly susceptible fishes than the same gears in the heavily exploited Kenyan fishery (Fig. 1b). There was considerable variation in how different gears targeted the proportion and number of species that were moderately susceptible to bleaching. More than 40% of the catch from all gears was comprised of species moderately susceptible to bleaching, but spear guns in both PNG and Kenya, and traps in Kenya targeted a majority of fish that were moderately susceptible to bleaching (Figs 1b, 2a). Line fishing in both countries targeted >58% of fish with low susceptibility to bleaching. Gill net fishers and beach seine net fishers caught approximately equal proportions of catch from the low coral-association category (46–53%) and the medium reef-associated category (47–51%).

Correspondence analyses show that at both the country and landing site level, there were significant trends in the selectivity of gear for species based on their coral association (Fig. 2a,b), although trends tended to be stronger at the site level (Table 1). When data were pooled by gear type at the country level, there were significant differences in the observed data ($\chi^2 = 547{\cdot}9$, d.f. = 14, $P < 0{\cdot}001$). No gear types were associated with highly susceptible fish species at the country level (Fig. 2a). In PNG there was, however, considerable spatial variation in the species of fishes that nets target and highly coral dependent fish were susceptible to nets at one site in this country (Fig. 2b). Correspondence analysis explained all of the variation in these data with two axes (the sum of the two percentages of inertia). There were also significant trends when the data were examined at the landing-site level ($\chi^2 = 969{\cdot}1$, d.f. = 78, $P < 0{\cdot}001$, Fig. 2b).

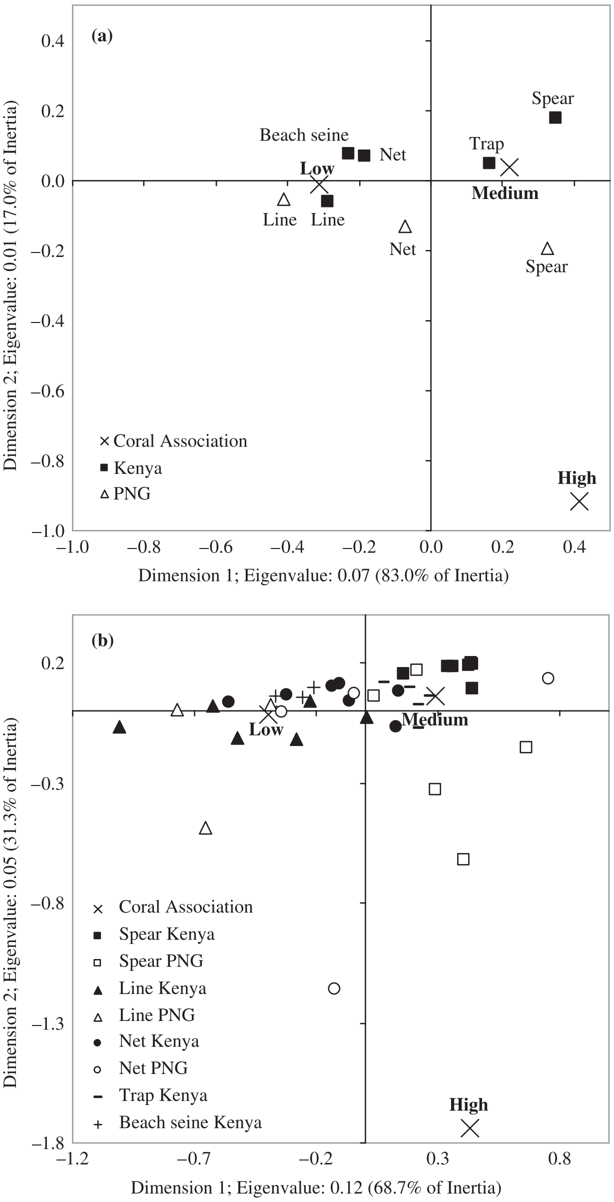

Fig. 2. Ordination plot generated by correspondence analysis, representing the relationship between the coral associations of the taxa caught and the type of gear used for their capture at: (a) the country scale, and (b) the landing- site scale.

Gears differentially targeted fish functional groups (Figs 3, 4a,b). Grazers were primarily targeted by spear guns in both countries and also by traps in Kenya. However, scrapers/excavators were targeted largely by spears and nets in PNG (Figs 3, 4a,b). Line fishing in Kenya targeted invertivores and piscivores, while line fishing in PNG captured more piscivores

Table 1. Factors related to the coral association of fish catch in PNG and Kenya, based on outputs of multinomial ordinal logistic regression models 1 and 2. Model 1 examines the selectivity of the different gear types within and between locations and countries. Model 2 includes secondary data on fishing effort (from Cinner & McClanahan 2006a,b)

Predictor variables	d.f.	Log-likelihood	Chi-square	*P*
Model 1: coral association (no fishing)				
Intercept	2	–3133·93		
Country	1	–3132·85	2·16	0·14
Location	11	–3033·99	197·73	0·00
Gear	3	–2899·90	268·17	0·00
Country × gear	2	–2897·76	4·29	0·12
Location × gear	14	–2845·79	103·94	0·00
Model 2: including fishing				
Intercept	2	–2310·02		
Country	1	–2308·68	2·68	0·10
Location	7	–2207·94	201·48	0·00
Fishing Pressure per Gear	4	–2156·25	103·38	0·00
Country × fishing pressure per gear	0	–2154·25	57·08	0·00
Location × fishing pressure per gear	2	–2153·82	4·85	0·09

Table 2. Factors related to the functional groups of fish catch in PNG and Kenya, based on outputs of multinomial ordinal logistic regression models 3 and 4. Model 3 examines the selectivity of the different gear types within and between locations and countries. Model 4 includes secondary data on fishing effort (from Cinner & McClanahan 2006a,b)

Predictor variables	d.f.	Log-likelihood	Chi-square	*P*
Model 3: fish guilds (no fishing)				
Intercept	2	–3421·58		
Country	1	–3420·22	2·88	0·08
Location	11	–3332·28	252·68	0·001
Gear	3	–3251·82	324·93	0·001
Country × gear	2	–3248·67	4·30	0·11
Location × gear	14	–3240·08	109·17	0·001
Model 4: including fishing				
Intercept	2	–4665·73		
Country	1	–4561·63	4·89	0·07
Location	7	–4347·53	428·18	0·001
Fishing pressure per gear	4	–4315·16	64·75	0·001
Country × fishing pressure per gear	0	–4285·16	45·56	0·001
Location × fishing pressure per gear	2	–4245·87	138·58	0·001

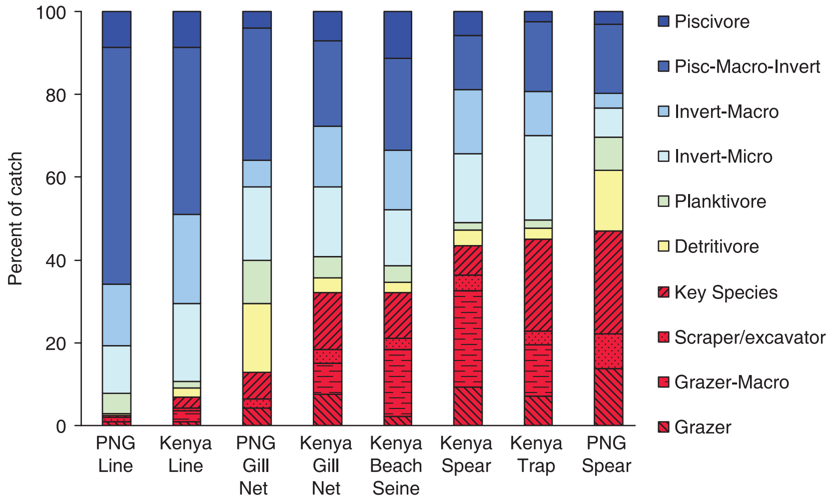

Fig. 3. Catch by gear as a proportion of functional groups targeted. Gears arranged from those that capture the lowest proportion of species and functional groups considered critical for recovery to disturbance on the left to the most on the right. The species in each functional group are listed in Supporting Information, Table S1.

(Figs 3, 4a,b). Both gill nets and beach seine targeted a diverse suite of trophic groups of fish, but there was a moderately high proportion (13–33%) of herbivorous fishes (including grazers of macroalgae) and key species in their catch. There were significant associations in the distribution of functional groups by gear (χ^2 = 261·1, d.f. = 35, $P < 0{\cdot}001$, Table 2). The regression models showed that country did not significantly predict the functional group targeted unless fishing pressure was included (Table 2). Both gears and landing sites could be used to predict the functional group of target species, both with and without fishing pressure included (Table 2).

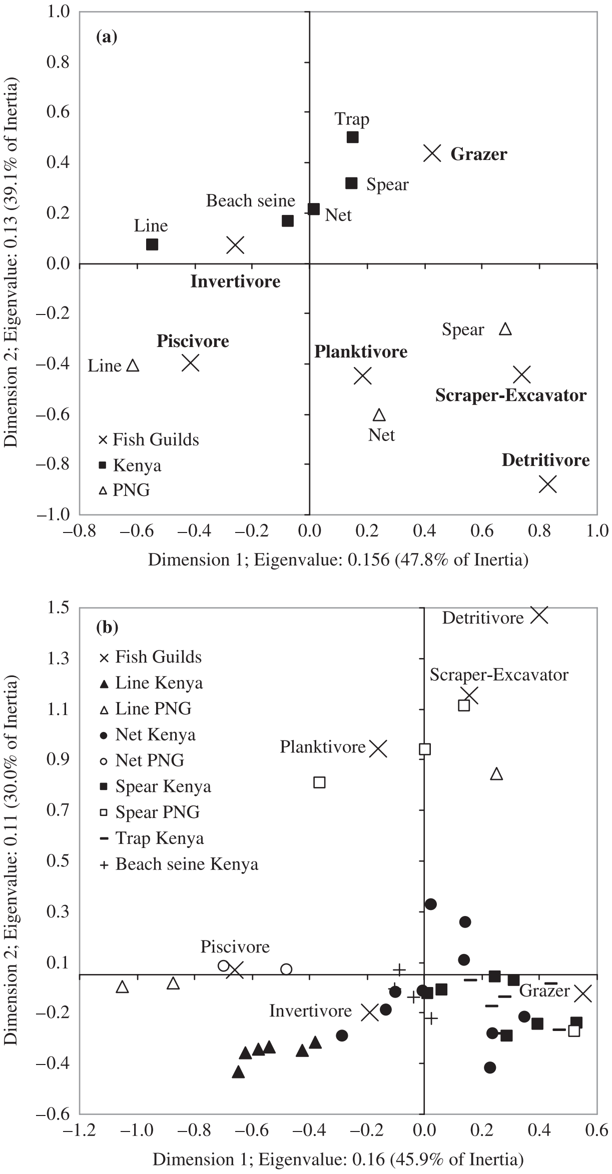

Fig. 4. Ordination plot generated by correspondence analysis, representing the relationship between the fish guild of the specimen caught and the type of gear used for their capture at: (a) the country scale, and (b) the landing-site scale among the landing site level.

When gear profitability and damage to corals were considered with gear selectivity in the Kenyan fishery, spear guns stood out as targeting a high proportion of coral-associated fishes, highly damaging per kilogram of fish caught, but also as being highly profitable (Fig. 5). Conversely, hand lines stood out as having low selectivity for coral-associated fishes, low damage, and moderate profitability. Gill nets and beach seines had relatively low selectivity for coral-associated species and high damage to corals, but their profitability varied considerably between crew and owners, particularly for beach seine nets. Crew members for both types of nets received less than any other gears. Traps had high selectivity, lower profitability than hand lines or net crews, but low damage to corals.

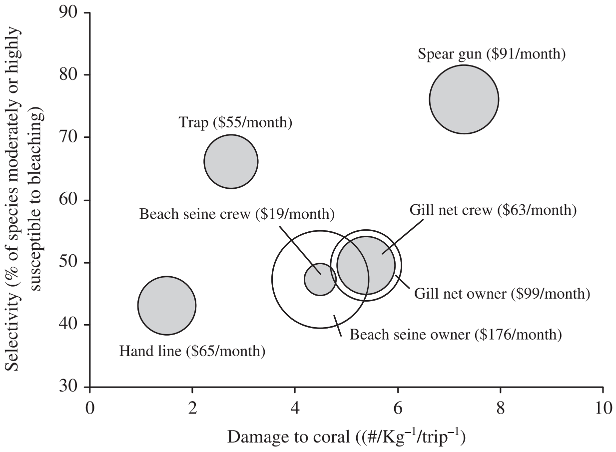

Fig. 5. Plot of damage to coral, selectivity for species with high or moderate coral association, and profitability (indicated by size of bubbles) by gear type. Unshaded circles indicate the variation in profitability between crew and owners (for beach seine nets and gill nets only).

Discussion

This study is the first to examine how artisanal fishing gears target fishes that are likely to be affected by coral mortality and fishes influential in the recovery of coral reef ecosystems. A principal finding is that fishes with strong coral associations currently represent only a small proportion (<6% by number) of artisanal fisheries catches in both PNG and Kenya. Species within this category are often small bodied, and feed, dwell, or settle into live coral (Wilson *et al.* 2006). Most fisheries preferentially target larger species and individuals (Jennings & Polunin 1997). There is the potential that extensive depletion of large piscivorous fishes may increase fishing pressure on smaller benthic-associated fishes (Friedlander & Parrish 1998; Mangi & Roberts 2006). Thus, a fishery may be showing signs of depletion if small-bodied, coral-dependant species represent even a small portion of the catch. When fishing intensity is low, the greatest threat to the smaller fishes comes from widespread habitat degradation, rather than fishing (Wilson *et al.* 2008).

Although species with strong coral affiliations are not a major component of artisanal fisheries, fishes reliant on the reef structure for habitat are heavily targeted (36–76%, depending on the gear type used). Fisheries-landing studies in Seychelles and Kenya before and after coral mortality have indicated that these species are not immediately affected by bleaching events (Grandcourt & Cesar 2003); however, the longer-term erosion of reef structures and subsequent loss of structural complexity can have detrimental effects on their abundance and size structure (Graham *et al.* 2007). Thus, fishes with medium levels of coral association are expected to be vulnerable to longer-term combined effects of coral mortality and fishing.

Fishes such as grazers and scrapers/excavators that have feeding activities thought to be critical to the resilience of coral reefs were identified (Bellwood *et al.* 2004; Mumby *et al.*

2007). These fish are predicted to prevent or reverse phase shifts on reefs (Hughes *et al.* 2007). Hence, identification of fishing gears that preferentially target these species is of great management importance. Overall, key functional groups and species make up about 25% of the total catch, with considerable variation among gears. Spear guns, traps and nets captured a high proportion (>40%) of key species that have been shown to play essential roles in herbivory and predation on sea urchins (e.g. *Echinometra mathaei*, McClanahan 1995) and crown-of-thorns starfish (*Acanthaster planci*) (Power *et al.* 1996; Bellwood *et al.* 2003, 2006; Fox & Bellwood 2008). Of critical importance is that gears that target reef-associated fishes also tend to target key functional groups and species. Perhaps the most pertinent point is that spears and traps captured the highest proportion of moderate to high coral-association species (>60%) and key species and functional groups (>40%). Thus, the use of these fishing gears is expected to compound the ecological effects of bleaching on reef fish and potentially retard the ability of reefs to recover.

Collectively, our analyses suggest that selective banning of gears that target species highly susceptible to bleaching and functional groups key to coral recovery is a potential tool to manage coral reefs experiencing climate change disturbances. Gears such as traps and spears, which target key functional groups and species, are strong candidates for restrictive management in areas where climate disturbances and coral mortality is high. Restrictions could also be implemented as a preventative measure in areas where environmental conditions such as currents, upwellings, and prevailing winds create high susceptibility to climatic events such as bleaching (Donner *et al.* 2005; Game *et al.* 2008; Maina *et al.* 2008). In contrast, line fishing catches the lowest proportion of species susceptible to bleaching and belonging to key functional groups and, from a management perspective, may be the most preferred gear in these environments.

There are, however, a number of other factors that should inform gear use and regulation. These include not only their destruction of habitat and their profitability (Fig. 5), but also the ease of adoption, enforceability, and indirect effects on ecosystems (Mangi *et al.* 2007; McClanahan *et al.* 2008). A key trade-off is gear profitability, which is influenced by the catch per unit effort, the value of the species targeted, and the maintenance or operational costs. Fishers are unlikely to adopt gears with reduced profitability without compensation. For example, line fishing has advantages in that it targets few fishes highly susceptible to bleaching, causes little direct damage to habitat and is at least as profitable as many of the commonly used gears (Fig. 5) (Mangi & Roberts 2006; Mangi *et al.* 2007). In Kenya, for example, line fishers make at least as much profit as both beach seine and gill net fishers who do not own their gear, and trap fishers, but less than spear fishers and net owners (Mangi *et al.* 2007). However, line fishing does target a very high proportion (49–66%) of piscivores and piscivores/macro-invertivores. Piscivores can be important in structuring coral reef fish assemblages (Mumby *et al.* 2006; Sandin *et al.* 2008), and thus, although line fishers are targeting fewer fishes that associate with coral, they may still influence the trophic and size structure of the ecosystem.

Likewise, net fishing targets a moderate proportion of fish susceptible to coral bleaching and from key functional groups and species. From this perspective, their use has some advantages over spears or traps, but these advantages must be weighed against other considerations. In particular, beach seine net use can cause considerable conflicts with other gear users because they are destructive to habitat, target a large proportion of juveniles, and tend to exclude other gears types (McClanahan & Mangi 2004; Mangi *et al.* 2007). Furthermore, the majority of beach seine fishers are crew members whose profits are only 25% of the next most profitable gear (Mangi *et al.* 2007). Prohibiting beach seine nets may be one of the most effective management interventions, both to increase overall yield and minimize direct habitat degradation from fishing activities (McClanahan *et al.* 2008). Spear fishing, which captures the highest proportion and causes the most damage per kilogram of fish caught is among the most profitable gears and has a low capital investment (Mangi *et al.* 2007). Management initiatives seeking to ban spear-gun use may have to consider some form of compensation for fishers. There are clear trade-offs to be made between minimizing gear conflict, reducing overfishing, maintaining profits, and protecting species vulnerable to losses of coral and important for reef recovery processes.

Adaptively managing resources in a changing climate is going to depend on the use of pragmatic management tools that can be rapidly implemented. Relatively short windows of opportunity are available for effectively responding to events such as bleaching. Bleaching typically occurs when corals are subjected to abnormally high water temperatures for 5–10 days (Glynn 1996) and coral mortality occurs within the ensuing 40–70 days, but may take up 280 days, depending on coral species (Baird & Marshall 2002). Space vacated by living coral tissue is rapidly colonized by turf algae, which may develop into fleshy erect algae over several months, depending on local nutrient concentrations and grazing intensity (Diaz-Pulido & McCook 2002). Importantly, satellite data can now be used to predict when bleaching events may occur (Liu *et al.* 2005; Game *et al.* 2008) allowing managers a wider window to take precautionary actions.

In places such as PNG and Kenya, local-level management decisions such as banning certain gears can be enacted and implemented on the order of days to months (Johannes 2002; Francis, Nilsson & Waruinge 2002). Rapidly enacting restrictions that are difficult to enforce or are ignored by resource users will, however, be of little use. In the context of small-scale artisanal fisheries, resource users often prefer management of gear over fisheries closures because artisanal fishers often employ a range of fishing gears and have opinions about their sustainability (McClanahan *et al.* 2005). Consequently, gear-based regulations are less likely to threaten fishers' livelihoods than full fishery closures, as long as their alternative gears are still permitted. In some contexts, however, certain gear restrictions may be difficult to enforce and fishers' preference for them may be in part because they can be easy to circumvent.

An important consideration for managers is that variations in fishing pressure and likely gear use can affect gear selectivity. There may be different effects from the same gear even within a single country, as we observed with net use in Papua New Guinea (Fig. 2b). Additionally, concentrating fishing effort on a single gear could cause increased pressure on target species, resulting in a change in selectivity and profits for that gear. Consequently, regularly collected site-specific information on fishing pressure, gear use and selectivity will help mangers to make informed decisions about adaptively managing gear. Managers can use the list of functional groups and susceptibility to coral mortality provided in the Supporting Information (Table S1) to analyse local catch data and assist in developing site-specific management strategies.

Acknowledgements

Research was stimulated by discussions arising from a workshop 'Meso-scale Effects of Coral Bleaching' held between Nov 28 and 30th, 2006 at the Institute of Marine Sciences, Zanzibar that was funded by the World Bank Targeted Research Program on Coral Bleaching. The Packard Foundation and the Wildlife Conservation Society funded fieldwork in Papua New Guinea and Kenya.

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Received 20 October 2008; accepted 2 March 2009
Handling Editor: Chris Frid

Supporting Information

Additional supporting information may be found in the online version of this article:

Table S1. Reef association and functional groups of fish in catches from Kenya and Papua New Guinea.