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Circle Hooks for Pacific Longliners: Not a Panacea for Marlin and Shark Bycatch, but Part of the Solution

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Abstract.—Blue marlin *Makaira nigricans*, striped marlin *Tetrapturus audax*, and pelagic sharks (e.g., blue shark *Prionace glauca*) are commonly caught as bycatch by longline fisheries in the central North Pacific Ocean. Recently, concern has increased about depletion of these species. Modifications in longline gear may offer one solution. Here, we test the use of circle hooks, rather than the conventional tuna-style hooks, on longlines using an ecosystem model of the central North Pacific Ocean. The simulations considered span a range of reasonable circle hook catchability and survival rates for released fish. The results suggest that if circle hooks have higher catchability than the currently used tuna-style hooks, switching to circle hooks depletes marlin biomass by 25–40% and shark biomass by 15–35% over 30 years. However, these depletions do not occur if circle hook catchability is equal to or lower than that of tuna-style hooks. When the effects of catch-and-release requirements for marlins and sharks were also considered, we found that regardless of assumptions about circle hook catchability and survival rates, a combined policy of using circle hooks and releasing sharks and marlins leads to net increases in marlin and shark abundance. The simulations show a trade-off between the abundance of marlins and sharks and their prey items, yellowfin tuna *Thunnus albacares* and small blue sharks. There is also evidence of trophic trade-offs between yellowfin tuna and small blue sharks and their prey, small scombrids (*Auxis* spp.) and mahi mahi *Coryphaena hippurus*. The results illustrate the importance of understanding catchability and survival rates for circle hooks compared with those for tuna-style hooks and encourage further research in this area.

In a recent, highly visible review, Myers and Worm (2003) asserted that pelagic longline fisheries have had large and global effects on the populations of tunas, billfishes, and sharks, causing declines to 10–20% of prefishery abundances. Although the magnitude of these assertions has been questioned (Walters 2004), there is little doubt that fisheries have had major effects on these apex predators. Removal of apex predators is often seen as a major cause of change in food web composition (Pauly et al. 1998; NMFS 1999), and this has led to calls for restoration of ecosystem function through renewal and conservation of apex predator stocks (Jackson et al. 2001). Two recent symposia (Alaska Sea Grant 1996; Lucy and Studholme 2002) called for a reduction in bycatch of nontarget species, including blue marlin *Makaira nigricans*, striped marlin *Tetrapturus audax*, and an assemblage of pelagic sharks (e.g., blue shark *Prionace glauca*, thresher shark *Alopias superciliosus*, shortfin mako *Isurus oxyrinchus*, and oceanic whitetip shark *Carcharhinus longimanus*). These apex predators are often caught incidentally by pelagic longline vessels, the majority of which currently operate in international waters with few restrictions on catch, effort, or gear. Recent efforts to reduce the fishing mortality on shark and marlin (Shark Finning Prohibition Act 2000; ICCAT 2005) have raised the level of interest in conservation measures such as modifications to longline gear and catch–release.

Changing the gear and fishing practices of longline vessels offers one promising way to reduce the bycatch of apex predators while minimizing the economic impact to fishermen. This approach is feasible because of vertical separation in the habitats of target versus bycatch species (Hanamoto 1974; Boggs 1992, and Nakano et al. 1997); because most bycatch species are not as valuable as target species (Ito and Machado 2000); and because approximately 50–75% of bycatch species are alive when brought aboard (Hoey 1996; Jackson and Farber 1998; Cramer 2000, Lee and

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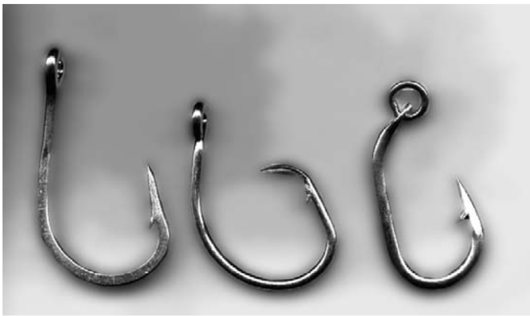

FIGURE 1.—Longline hooks (from left, the J hook, circle hook, and tuna-style hook). The tuna-style hook is the one most commonly used in Pacific fisheries at present. (Photo courtesy of the National Marine Fisheries Service, Pacific Islands Fisheries Science Center, Honolulu, Hawaii).

Brown 1998). Modeling studies of Pacific ecosystems have also suggested that slight changes in fishing gear or fisherman behavior can dramatically increase abundances of bycatch species such as marlins and sharks. Kitchell et al. (2004) simulated the ecological and economic outcomes of moving all longline hooks to a depth greater than 120 m. This modification produced a substantial reduction in the catch of blue and striped marlins. As a result, simulated blue marlin populations increased almost threefold and other billfish abundance approximately doubled compared with that expected under no gear change. Increased predation mortality was expressed in the reduced abundance of their major prey, especially yellowfin tuna *Thunnus albacares*. Hinke et al. (2004) used the Cox et al. (2002b) model of the central North Pacific food web to evaluate the ecological outcomes of longlining in this system and compared those with results from a model of the eastern tropical Pacific Ocean (Olson and Watters 2003; Watters et al. 2003). They found that in both systems, eliminating both shallow longlining and the finning of sharks led to higher marlin and shark stocks than if fishing mortality from longlining were cut by 50%.

Circle hooks are one alternative gear that might reduce longline hooking mortality (Hoey 1996; Falterman and Graves 2002; Skomal et al. 2002) compared with traditional “J” or “tuna-style” hooks (Figure 1). Much of the motivation for using circle hooks comes from recreational rod-and-reel fisheries, where circle hooks have been demonstrated to catch fish more often in the jaw or mouth rather than the gut or gills, and therefore lead to lower mortality for catch-and-release fisheries (Lucy and Studholme 2002). In addition, recent results from longline fisheries in the Atlantic Ocean demonstrate that circle hooks significantly reduce bycatch and mortality of endangered sea turtles (Garrison 2003; Watson et al. 2005); for this reason, circle hooks have been mandated for U.S. longliners in both the Atlantic and Pacific Oceans (NMFS 2004a, 2004b). If gear changes were implemented for all Pacific longliners and combined with catch-and-release practices (Boggs 1992; Alaska Sea Grant 1996), these mitigation measures might make major contributions toward enhancing the current stocks of marlin and shark species. In addition, implementation of these mitigation measures should raise questions about food web effects caused by altered populations of these apex predators.

In this short paper we employ a well-documented ecosystem model of the central North Pacific Ocean (CNP; Cox et al. 2002a, 2002b) to simulate (1) longline fishery adoption of circle hooks rather than the commonly used tuna-style hook, (2) release of marlin and shark, and (3) potential trophic expression of these changes in fishing policy in an ecosystem context. Our goals are to evaluate both the direct effects on target species and the indirect effects expressed in the CNP food web.

To address uncertainty about circle hook catch rates and the survival of released sharks and marlins, we consider multiple scenarios that encompass the range of catchability and survival rates reported in field studies. The results illustrate the utility of circle hooks in conjunction with mandated catch-and-release; the importance of research to identify catchability of circle hooks relative to tuna-style hooks; and strong tradeoffs between the abundance of predators such as marlins and sharks, and their prey such as yellowfin tuna.

Methods

This analysis employed an Ecopath-Ecosim model (Christensen and Pauly 1992; Walters et al. 2000) developed for the CNP pelagic ecosystem, which is bounded by the equator to the south, the Transition Zone (about 40°N latitude) to the north, and longitudes of 130°E to 150°W. The Hawaiian islands are in the east-central region of this ecosystem. The model includes 25 biological groups, including target species of the Pacific fisheries, their predators, and prey, linked by a nonlinear predation response (Walters et al. 2000). Cox et al. (2002a, 2002b) provide a complete description of the model, the parameters describing life history characteristics, biomass, production rates, mortality rates, and predator–prey linkages for all system components. We will not duplicate those here, except to note that the system component “other billfish” represents the life history characteristics of striped marlins, sailfish *Istiophorus platypterus*, and

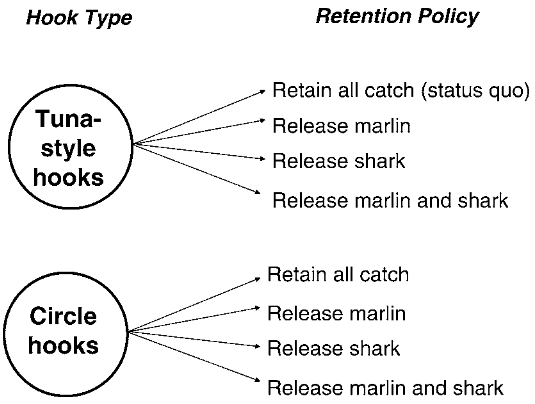

FIGURE 2.—Hook type and retention policy combinations included in policy simulations. For fishing policies involving the use of circle hooks, we considered scenarios with low, medium, and high catchabilities. For fishing policies involving the release of marlins or sharks from tuna-style hooks, we considered high and low postrelease survival rates. For fishing policies involving the release of marlins only, we considered scenarios with high and low rates of survival at haulback.

shortbill spearfish *Tetrapturus angustirostris*. Because striped marlins dominate the biomass of that group, for ecological purposes the "other billfish" component is striped marlins. The base model includes fishing mortality from longline fleets that primarily use tuna-style hooks.

Using the Cox et al. (2002a) model, we simulated eight fishing policies that would mandate the use of either circle hooks or tuna-style hooks combined with the release of bycaught marlins, sharks, or both marlins and sharks (Figure 2). Making these projections required three key assumptions, namely, those pertaining to (1) the catchability of circle hooks relative to that of tuna-style hooks, (2) the survival of sharks and marlins at haulback (i.e., when the longline gear is retrieved), and (3) the survival of marlins and sharks released alive. We ran each fishing policy under assumptions of high, medium, or low circle hook catchability, high or low survival at haulback, and high or low postrelease survival. The bases for these assumptions are described below.

The exact catchability of circle hooks for pelagic longliners is uncertain and is the focus of ongoing research in the Pacific Ocean. Until such results are available, we are forced to use data from Atlantic fisheries. Hoey (1996) and Falterman and Graves (2002) reported that circle hooks produced higher catch than J or tuna-style longline hooks. For a high catchability scenario, we incorporated Hoey's (1996) circle hook catch rates of 32.9 fish/set for circle hooks and 25.5/set for tuna-style hooks, expressing the fishing mortality rate for all species with circle hooks as 1.29 times the fishing mortality rate with tuna-style hooks. Hoey's report was based on observer data from 352 longline sets (~2,000 hooks/set) from the Gulf of Mexico, where the species composition was similar to that observed in the CNP, although bait type and other fishing practices differ. Alternatively, for medium catchability scenarios, we set catchability (fishing mortality rate) of circle hooks equal to that of tuna-style hooks, following the lack of significant difference between hook types reported by Kerstetter and Graves (2006) for 85 sets in the fall Mid-Atlantic Bight/Northeast Distant fishery and the spring Gulf of Mexico/Caribbean fishery. Although Kerstetter's study compared circle hooks to J hooks, for these scenarios we assume that tuna-style hooks have catchability similar to J hooks, based on their similarity in shape. Finally, for low catchability scenarios, we set catchability (fishing mortality) of circle hooks equal to 0.9× the rate for tuna-style hooks. Lower catch rates for circle hooks have been observed for swordfish *Xiphias gladius* (Watson et al. 2005; Kerstetter et al. 2006). Another motivation for including lower catchability was that fishermen in the Pacific Ocean generally continue to use tuna-style hooks rather than circle hooks, possibly because of observed differences between catching power of the different hook types.

The fishing policies that involved release of sharks and marlins required an assumption about survival at haulback. We considered one set of scenarios with low marlin survival rates of 51% for circle hooks and 47% for tuna hooks, based on Hoey (1996). We also considered another set of scenarios with a higher 76% survival-at-haulback for marlins, based on Cramer (2000; $n = 2{,}992$ billfish recorded for 1998). Data from the most recent study year (1998) reported by Cramer summarized 10,099 sets from the Grand Banks, northwest and southwest Atlantic coasts, offshore southwest Atlantic Ocean waters, Gulf of Mexico, and Caribbean, with more of the fisheries using dead bait than in Hoey's study. Dead bait generally leads to lower rates of hook ingestion and fatal internal injury. Cramer (2000) did not specify hook types, and we therefore used the 76% marlin survival-at-haulback for both tuna-style and circle hooks. In all cases, we set the shark survival-at-haulback rate at 73%, the rate reported by Hoey (1996). This is between the 78% and 67% rates recently reported by Diaz and Serafy (2005) for blue sharks off the U.S. Atlantic East Coast and the Grand Banks. Cramer (2000) also found a 75% survival rate ($n = 47{,}778$ sharks in 1998).

We considered two possible rates of postrelease survival. In one set of scenarios, we assumed 100% postrelease survival for both circle hooks and tuna-style hooks. This is based on pop-up satellite archival tag studies of Kerstetter et al. (2003), who found that survival rates for longline-caught blue marlins were relatively high—at least seven of nine tagged fish were alive when the tags released 5–30 d after tagging. All but one of these nine fish were caught on J hooks. In a second set of scenarios, we assumed 100% postrelease survival for circle hooks, but only a 65% postrelease survival rate for tuna-style hooks. This was based on data from recreational fisheries for white marlin *Tetrapturus albidus* in the Atlantic Ocean (Horodysky and Graves 2005) and assuming that the tuna-style hooks used in the Pacific Ocean had postrelease survival rates similar to J hooks. A study by Domeier et al. (2003) similarly found a 75% postrelease survival of striped marlins from recreational gear, and less gut hooking with circle hooks than with J hooks. We believe that our scenarios bracket reasonable expected differences between circle hooks and tuna-style hooks.

Because of the inherent uncertainty in complex ecosystem models, we established a cautionary guideline that a change in abundance of about 10% would be the minimum realistic outcome worthy of interpretation, similar to that adopted by Kitchell et al. (2004). In addition, like the Kitchell et al. analysis, we expected major changes in the target populations of marlins and sharks, but lesser effects in the CNP food web because these systems are dominated by tuna species. Although marlins and sharks are at the apex of the food web, they represent a relatively minor percentage of fish biomass at that trophic level. Each simulation was run to cover 30 years with a constant fishing mortality rate determined by the hook type, catchability and survival assumptions, and catch-and-release policy. A new equilibrium developed in response to each manipulation within the 30 years.

Results

For each species, the results of the simulation were compared against the standard case by calculation of the ratio of the biomass 30 years after implementation of the policy change to the corresponding biomass with a status quo fishery. The status quo for the longline fishery in the Pacific Ocean is to use tuna-style hooks and to retain all marlins and sharks. "Retaining" sharks usually means they are finned and their carcasses are dumped at sea (McCoy and Ishihara 1999). Results of all the simulated alternative policies are summarized in Table 1. Figures 3–7 illustrate a key subset of the results, for simplicity omitting simulations where only marlins or only sharks were released.

Scenarios that assumed continued use of tuna-style hooks or circle hooks with catchability equal to that of tuna-style hooks (following Kerstetter and Graves 2006), show the potential for catch-and-release of marlins and sharks to increase the abundance of these species (Figure 3). Depending on the survival rate at haulback and after release, blue marlins and other billfish (striped marlin) increased to 1.7–4.0 and 1.3–2.1 times their biomass under the status quo, respectively. Adult blue sharks, large sharks, and brown sharks increased from 1.3 to 2.7 times the status quo, depending on the postrelease survival rate. The abundance of large yellowfin tuna decreased by 20–50% as a consequence of increases in predation by marlins (Table 1; Figure 4). Similarly, the abundance of small blue sharks declined by 35–45% because of increased predation by large sharks (Table 1; Figure 5). Mahi mahi and small scombrids (*Auxis* spp.), two prey items of yellowfin tuna and small blue sharks, increased to as much as 1.15 and 1.25 times the biomass under the status quo. Catch–release of marlins and sharks generally led to a slightly lower recovery of marlins than release of marlins only (Table 1), because sharks are a major predator of marlins. This held true regardless of assumptions about catch rates and survival rates.

Scenarios that assumed circle hook catchability of 1.29 times the catchability of tuna-style hooks (following Hoey 1996) primarily reflected the higher catch rates on these hooks. Important changes occurred when tuna-style hooks were replaced by circle hooks, with no release of bycatch (Figure 6; Table 1). Billfish, sharks, and bigeye tuna declined to between 0.6 and 0.85 times the biomass under a status quo fishery. Yellowfin tuna and small blue sharks both increased as a consequence of reductions in their predators. Increased predation by yellowfin tuna and small blue sharks led to 10% declines in small scombrids. Releasing sharks and marlins more than counterbalanced the effect of increased circle hook catch rate: release of these species led to increases of 1.5–3.6 times the biomass under the status quo. Assuming a fixed survival at haulback (either low or high), this recovery was above what we predicted for catch–release with tuna-style hooks and low postrelease survival, but less than that predicted for tuna-style hooks and high postrelease survival (Table 1).

Scenarios that assumed circle hook catchability of 0.9 times that for tuna-style hooks primarily reflected the lower fishing mortality. With no release of bycatch (Figure 7; Table 1), all apex predator biomasses increased, except for yellowfin tuna, which declined because of increased predation by marlins, and small blue sharks that declined because of predation by large sharks. Release of sharks and marlins led to levels of abundance higher than any comparable catch–release policy using tuna-style hooks. The resulting predation by sharks and

TABLE 1.—Shark and marlin biomass 30 years after new fishery practices are adopted relative to a status quo scenario in which tuna-style hooks are used and all catch is retained. Assumptions refer to catchability (low [L], medium [M], or high [H]); postrelease survival from tuna-style hooks (low [L] or high [H]); and marlin survival at haulback (low [L] or high [H]), in that order. The letter X indicates an assumption that is not relevant for that fishing policy (e.g., an assumption about survival at haulback or postrelease survival when all catch is retained). Medium catchability with high postrelease survival could derive from continued use of tuna-style hooks or circle hooks (Kerstetter et al. 2003; Kerstetter and Graves 2006).

Assumptions	Hook type and fishing policy	Blue marlin	Other billfish	Large sharks	Brown sharks	Large blue shark	Small blue shark
MXX	Either hook type, all catch retained	1.00	1.00	1.00	1.00	1.00	1.00
MLL	Tuna-style hook, marlins released	1.78	1.40	1.03	1.00	1.00	1.00
MLX	Tuna-style hook, sharks released	0.96	0.95	1.83	1.46	1.33	0.64
MLL	Tuna-style hook, marlins and sharks released	1.72	1.34	1.87	1.46	1.32	0.64
MHL	Either hook type, marlins released	2.40	1.66	1.06	1.00	0.99	0.99
MHX	Either hook type, sharks released	0.94	0.93	2.56	1.78	1.64	0.56
MHL	Either hook type, marlins and sharks released	2.27	1.55	2.62	1.78	1.63	0.55
MLH	Tuna-style hook, marlins released	2.51	1.71	1.06	1.00	0.99	0.99
MLH	Tuna-style hook, marlins and sharks released	2.42	1.64	1.90	1.47	1.32	0.64
MHH	Either hook type, marlins released	4.18	2.25	1.13	1.01	0.98	0.99
MHH	Either hook type, marlins and sharks released	3.95	2.11	2.72	1.79	1.62	0.55
LXX	Circle, all catch retained	1.16	1.09	1.14	1.07	1.05	0.93
LXL	Circle, marlins released	2.75	1.79	1.21	1.07	1.04	0.92
LXX	Circle, sharks released	1.10	1.02	2.65	1.80	1.66	0.55
LXL	Marlins and sharks released	2.62	1.68	2.72	1.81	1.65	0.55
LXH	Circle, marlins released	4.30	2.27	1.28	1.08	1.03	0.92
LXH	Circle, marlins and sharks released	4.08	2.14	2.81	1.81	1.64	0.54
HXX	Circle, all catch retained	0.62	0.76	0.64	0.82	0.86	1.16
HXL	Circle, marlins released	2.15	1.58	0.70	0.82	0.85	1.15
HXX	Circle, sharks released	0.57	0.69	2.30	1.71	1.55	0.57
HXL	Circle, marlins and sharks released	2.01	1.45	2.38	1.71	1.54	0.56
HXH	Circle, marlins released	3.85	2.19	0.76	0.82	0.84	1.14
HXH	Circle, marlins and sharks released	3.59	2.02	2.46	1.72	1.53	0.56

marlins led yellowfin tuna and small blue sharks to decline by as much as 50%. In response to a decline in predation by yellowfin tuna and small blue sharks, mahi mahi and small scombrids increased to 1.15 and 1.3 times their respective biomasses under the status quo.

Conclusions

Though evidence from recreational fisheries has led to a general advocacy of circle hooks as a means for reducing bycatch mortality, it is not clear whether the use of circle hooks by longliners will reduce marlin and

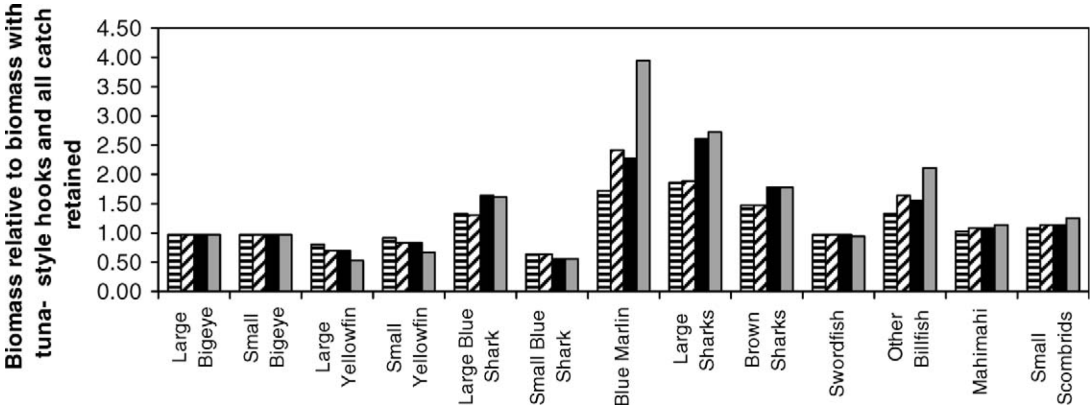

FIGURE 3.—Results from scenarios with tuna-style hooks and the release of marlins and sharks. Shown is the biomass 30 years after circle hooks are adopted relative to a status quo scenario in which tuna-style hooks are used and all catch retained. The horizontally striped bars represent low postrelease survival and low marlin survival at haulback, the diagonally striped bars low postrelease survival and high marlin survival at haulback, the black bars high postrelease survival and low marlin survival at haulback, and the gray bars high postrelease survival and high marlin survival at haulback. These correspond to assumptions MLL, MLH, MHL, and MHH in Table 1. Circle hooks with medium catchability give results identical to those represented by the black and gray bars.

TABLE 1.—Extended.

Assumptions	Large bigeye tuna	Small bigeye tuna	Large yellowfin tuna	Small yellowfin tuna	Swordfish	Mahi mahi	Small scombrids
MXX	1.00	1.00	1.00	1.00	1.00	1.00	1.00
MLL	1.00	1.00	0.83	0.92	0.99	1.03	1.07
MLX	0.98	0.98	0.96	0.99	1.00	1.01	1.01
MLL	0.98	0.98	0.80	0.91	0.98	1.04	1.09
MHL	1.00	1.00	0.73	0.86	0.98	1.06	1.12
MHX	0.97	0.97	0.94	0.98	0.99	1.01	1.02
MHL	0.97	0.97	0.69	0.83	0.97	1.07	1.15
MLH	1.00	1.00	0.72	0.85	0.98	1.06	1.13
MLH	0.98	0.98	0.69	0.83	0.97	1.07	1.14
MHH	1.01	1.02	0.56	0.71	0.96	1.12	1.22
MHH	0.98	0.98	0.52	0.67	0.95	1.14	1.25
LXX	1.18	1.15	0.94	0.98	1.06	1.01	1.05
LXL	1.19	1.16	0.67	0.82	1.04	1.08	1.18
LXX	1.15	1.12	0.89	0.96	1.05	1.02	1.07
LXL	1.16	1.13	0.63	0.78	1.03	1.09	1.20
LXH	1.20	1.18	0.53	0.69	1.03	1.13	1.26
LXH	1.17	1.14	0.50	0.66	1.01	1.15	1.29
HXX	0.61	0.65	1.15	1.02	0.84	0.98	0.89
HXL	0.60	0.64	0.81	0.90	0.83	1.04	1.02
HXX	0.58	0.62	1.08	1.01	0.84	0.99	0.91
HXL	0.57	0.61	0.75	0.87	0.82	1.05	1.05
HXH	0.61	0.65	0.61	0.76	0.82	1.10	1.12
HXH	0.58	0.62	0.57	0.72	0.81	1.11	1.16

shark mortality rates by itself. If we want to be fairly certain of increasing the abundance of marlins and sharks, additional conservation policies are needed. Our results show that across a range of reasonable circle hook catchability and survival rates, catch–release policies combined with circle hook use can bolster populations of marlins and sharks. Implementing catch–release policies would be complex in the international Pacific fisheries, because bycatch species can be a substantial source of income in some fisheries, particularly for crew members (McCoy and Ishihara 1999). However, longliners in the Atlantic Ocean are now required to release all billfish alive at haulback

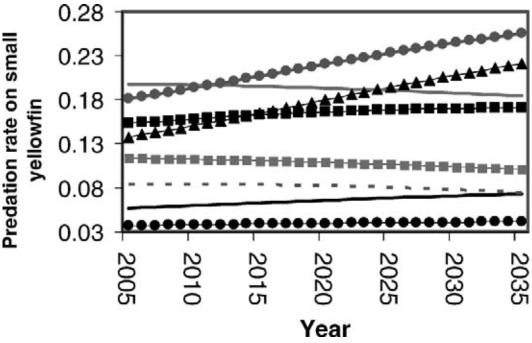

FIGURE 4.—Predation mortality on small yellowfin tuna in a scenario in which tuna-style hooks are used, marlins and sharks are released starting in 2005, and postrelease survival and marlin survival at haulback are high. Shown is predation by other billfish (gray circles), blue marlins (black triangles), swordfish (gray solid line), large albacore (black squares), large bigeye tuna (gray squares), large yellowfin tuna (gray dashed line), large sharks (black line), and brown sharks (black circles). Total predation increases 17%.

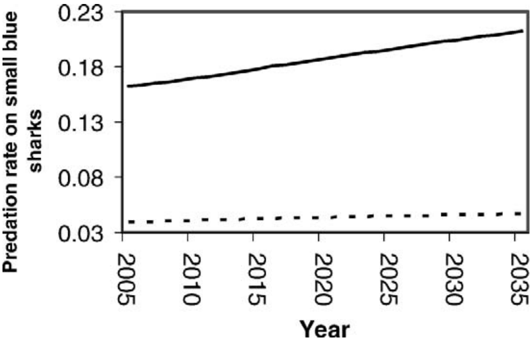

FIGURE 5.—Predation mortality on small blue sharks in a scenario in which tuna-style hooks are used, marlins and sharks are released starting in 2005, and postrelease survival and marlin survival at haulback are high. The solid line represents predation by large sharks, the dashed line predation by large blue sharks. Total predation mortality increases 28%.

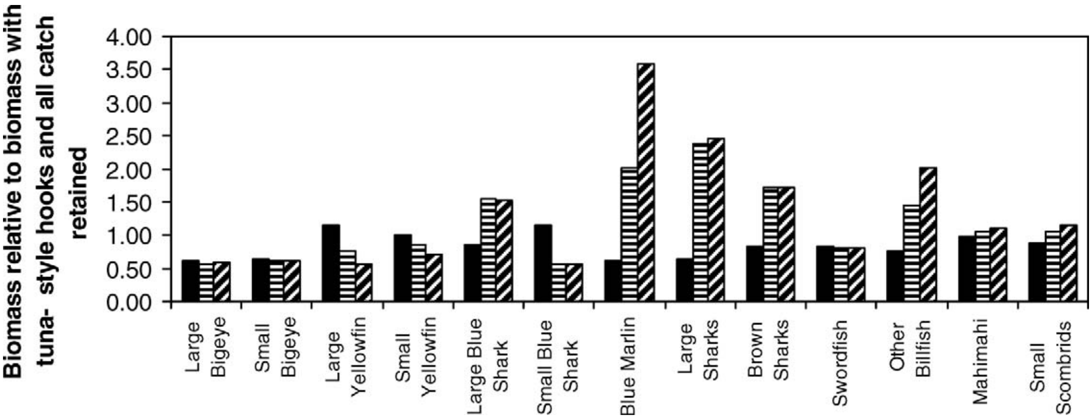

FIGURE 6.—Results from scenarios with circle hooks with high catchability. Shown is the biomass 30 years after circle hooks are adopted relative to a status quo scenario in which tuna-style hooks are used and all catch is retained. The black bars represent the scenario in which all catch is retained, the horizontally striped bars the scenario in which marlins and sharks are released with low marlin survival at haulback, and the diagonally striped bars the scenario in which marlins and sharks are released with high marlin survival at haulback. These correspond to scenarios HXX, HXL, and HXH in Table 1.

(ICCAT 2005), and we advocate similar regulations in the Pacific Ocean.

In these scenarios we highlighted the uncertainty about circle hook catch rate for marlins and sharks. This is in direct contrast to results for the endangered leatherback turtles *Dermochelys coriacea* and loggerhead turtles *Caretta caretta*. For these turtle species, Watson et al. (2005) and Garrison (2003) found that circle hooks can drastically reduce bycatch rates. Therefore, circle hook use in the future may arise out of concerns about these sea turtles, with unintended consequences on marlin and shark mortality. These consequences can be ameliorated by conservation measures such as catch–release policies.

Our primary goal was to evaluate the changes in food web structure that might occur from changes in hook types and the additional effects that would stem from catch-and-release policies for selected species. The model predicted two direct trophic effects of the fisheries manipulations. The first was a trade-off between abundances of billfish and yellowfin tuna. In all scenarios where billfish were released, the biomass of blue marlins and other billfish increased. Predation by these groups on small yellowfin tuna increased, leading to lower yellowfin tuna abundance. Converse-

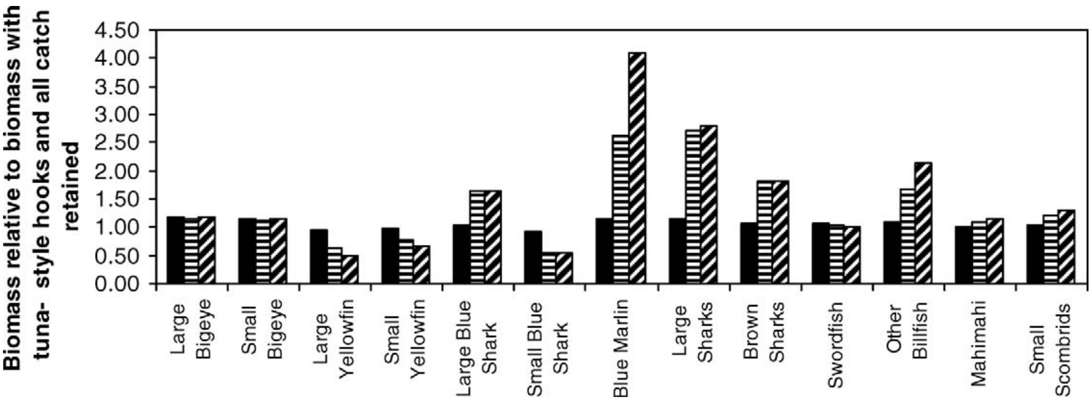

FIGURE 7.—Results from scenarios with circle hooks with low catchability. Shown is the biomass 30 years after circle hooks are adopted relative to a status quo scenario in which tuna-style hooks are used and all catch is retained. The black bars represent the scenario in which all catch is retained, the horizontally striped bars the scenario in which marlins and sharks are released with low marlin survival at haulback, and the diagonally striped bars the scenario in which marlins and sharks are released with high marlin survival at haulback. These correspond to scenarios LXX, LXL, and LXH in Table 1.

ly, in scenarios where billfish biomass decreased, we saw a subsequent increase in yellowfin tuna abundance as they were released from predation. A second trade-off occurred between small blue sharks and their predator, large sharks. The large shark group includes white sharks, oceanic whitetip sharks, and shortfin mako sharks, all of which include small blue sharks as prey. Catch-and-release of marlins and sharks and the subsequent higher predation on small yellowfin tuna and small blue sharks led to a trophic cascade: mahi mahi and small scombrids increased in abundance as they were released from yellowfin tuna and small blue shark predation.

The results presented here are consistent with those of similar analyses that investigated alternative management strategies for Pacific fisheries. Kitchell et al. (2004) and Hinke et al. (2004) used the Cox et al. (2002a) model presented here as well as a model of the eastern tropical Pacific Ocean (Olson and Watters 2003) to investigate the effect of halving marlin fishing mortality by removing longline hooks above 120 m, and of reducing shark mortality by banning shark finning. For both the CNP and eastern tropical Pacific Ocean, this led to billfish and shark recovery similar to what we predict here for circle hook use and catch–release in scenarios with low catchability, or for intermediate catchability and high postrelease survival rates. Trade-offs between marlins and yellowfin tuna, and between yellowfin tuna and small scombrids, were also apparent in the Kitchell et al. (2004) and Hinke et al. (2004) CNP scenarios, but not in the eastern tropical Pacific model. Both the CNP and eastern tropical Pacific models showed slight trade-offs between shark abundance and marlin abundance resulting from predation, similar to what we observed in the recoveries simulated here. Overall, the results to date from the CNP and eastern tropical Pacific models suggest that gear modification and bycatch release are likely to be more effective conservation strategies than a 50% reduction in fishing effort.

We must add the caveat that this model, like most complex food web simulation models, cannot be thoroughly statistically fit to data. We view the parameterization as one of many reasonable approximations of the ecosystem dynamics (Walters and Martell 2004) and view the output as qualitative and less than definitive. Cox et al. (2002a) present in some detail the uncertainties involved in the ecosystem model used here, including data quality and the lack of spatial resolution, oceanographic effects, and migrations. However, we believe that the simple trade-offs between predator and prey abundance, and the straightforward effects of altered fishing mortality, are robust conclusions.

There is a clear need for more extensive trials of circle hook gear and catch–release in the Pacific Ocean. The scenarios here illustrate that the apex predator populations, and their impact in an ecosystem context, are sensitive to the efficacy of circle hooks relative to typical tuna-style hooks, and to a lesser extent to the likelihood of survival for fishes that are released alive after capture. In the Atlantic Ocean, Watson et al. (2005) have conducted experiments assessing the catch rates of circle hooks and J hooks. Similar comparisons of circle hooks and tuna-style hooks are badly needed for pelagic longline gear in the Pacific Ocean. We strongly encourage collaboration with Pacific fishing fleets in this important realm of research endeavor.

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