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Trade-offs among Catch, Bycatch, and Landed Value in the American Samoa Longline Fishery

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Conservation Biology

Contributed Paper

Trade-offs among Catch, Bycatch, and Landed Value in the American Samoa Longline Fishery

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Abstract: *The interspecific preferences of fishes for different depths and habitats suggest fishers could avoid unwanted catches of some species while still effectively targeting other species. In pelagic longline fisheries, albacore (*Thunnus alalunga*) are often caught in relatively cooler, deeper water (*>100 *m) than many species of conservation concern (e.g., sea turtles, billfishes, and some sharks) that are caught in shallower water (*<100 *m). From 2007 to 2011, we examined the depth distributions of hooks for 1154 longline sets (3,406,946 hooks) and recorded captures by hook position on 2642 sets (7,829,498 hooks) in the American Samoa longline fishery. Twenty-three percent of hooks had a settled depth *<100 *m. Individuals captured in the 3 shallowest hook positions accounted for 18.3% of all bycatch. We analyzed hypothetical impacts for 25 of the most abundant species caught in the fishery by eliminating the 3 shallowest hook positions under scenarios with and without redistribution of these hooks to deeper depths. Distributions varied by species: 45.5% (*$n = 10$*) of green sea turtle (*Chelonia mydas*), 59.5% (*$n = 626$*) of shortbill spearfish (*Tetrapturus angustirostris*), 37.3% (*$n = 435$*) of silky shark (*Carcharhinus falciformis*), and 42.6% (*$n = 150$*) of oceanic whitetip shark (*C. longimanus*) were caught on the 3 shallowest hooks. Eleven percent (*$n = 20{,}435$*) of all tuna and 8.5% (*$n = 10{,}374$*) of albacore were caught on the 3 shallowest hooks. Hook elimination reduced landed value by 1.6–9.2%, and redistribution of hooks increased average annual landed value relative to the status quo by 5–11.7%. Based on these scenarios, redistribution of hooks to deeper depths may provide an economically feasible modification to longline gear that could substantially reduce bycatch for a suite of vulnerable species. Our results suggest that this method may be applicable to deep-set pelagic longline fisheries worldwide.*

Keywords: Albacore, longline, nontarget species, observer data, sea turtles, sharks, trade-offs

Compensaciones entre Captura, Captura Accesoria y Valores Asentados en la Pesquera de Línea Larga de Samoa Americana

Resumen: *Las preferencias interespecíficas de los peces por diferentes profundidades y hábitats sugieren que los pescadores podrían evitar capturas no deseadas de algunas especies mientras se enfocan efectivamente en otras. En las pesqueras pelágicas de línea larga, las albacoras (*Thunnus alalunga*) se capturan más frecuentemente en aguas relativamente más frías y más profundas (*>100 *m) que muchas especies de preocupación para la conservación (p. ej.: tortugas marinas, peces vela y algunos tiburones) que se capturan en aguas más someras (*<100 *m). De 2007 a 2011, examinamos las distribuciones de profundidad de anzuelos para 1154 conjuntos de línea larga (3, 406, 946 anzuelos) y registramos las capturas por posición de anzuelo en 2462 conjuntos (7, 829, 498 anzuelos) en la pesquería de línea larga de Samoa Americana. El 23% de los anzuelos tuvieron una profundidad establecida *<100 *m. Los individuos capturados en las 3 posiciones de anzuelo más someras representaron el 18.3% de toda la captura accesoria. Analizamos los impactos hipotéticos de 25 de las especies más abundantes en la pesquería al eliminar las 3 posiciones más someras de anzuelos bajo escenarios con y sin redistribución de estos anzuelos a mayores profundidades. Las distribuciones variaron por especie: 45.5% (*$n = 10$*) de las tortugas marinas (*Chelonia mydas*), 59.5% (*$n = 626$*) de los peces espada (*Tetrapturus angustirostris*), 37.3% (*$n = 435$*) de los tiburones (*Carcharhinus falciformis*) y 42.6% (*$n = 150$*) de otra especie de tiburones (*C. longimanus*) fueron capturados en los 3 anzuelos más someros. El 11% (*$n = 20, 435$*) de todo el atún y 8.5% (*$n = 10, 374$*) de albacoras fueron capturados en los 3 anzuelos más*

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someros. La eliminación de anzuelos redujo el valor asentado por 1.6–9.2% y la redistribución de los anzuelos incrementó el promedio anual del valor asentado en relación con el status quo por 5–11.7%. Con base en estos escenarios, la redistribución de los anzuelos a mayores profundidades puede proporcionar una modificación económica factible al equipo de línea larga que podría sustancialmente reducir la captura accesoria para una cantidad de especies vulnerables. Nuestros resultados sugieren que este método puede ser aplicable a conjuntos profundos de pesquerías pelágicas de línea larga a nivel mundial.

Palabras Clave: Albacora, compensaciones, datos de observador, especies no-objetivo, línea larga, tiburones, tortugas marinas

Introduction

The development of industrial fisheries has been driven largely by economic and technological forces rather than by ecological concerns (Hall et al. 2000). Bycatch—animals that are discarded due to economic (no value, small size, damaged) or regulatory (e.g., small size, seabirds, marine mammals and sea turtles) reasons—is one side-effect of this industrialization, and the ecological impacts of bycatch are of increasing concern (Kelleher 2005). Bycatch has been implicated as a threat to approximately half of marine mammal and seabird species, the majority of elasmobranch species (Žydelis et al. 2009) and all 7 sea turtle species (Wallace et al. 2010). The global issue of bycatch has not only altered ecological relationships, but bycatch regulations have also affected the operations, economics, and technology of commercial fishing. Such complexities dictate that bycatch reduction efforts not only assess the direct ecological efficacy of mitigation measures, but also assess the inherent trade-offs for different stakeholders.

O'Keefe et al. (2013) provide relevant considerations to different stakeholders involved in decisions regarding bycatch mitigation: intended bycatch reduction, impacts to target catch, impacts to other non-target species or sizes, and economic impacts to fleets. Morzaria-Luna et al. (2012) used a comprehensive ecosystem model to assess fishery closures aimed at recovery of the critically endangered vaquita (*Phocoena sinus*) and determined that the economic impacts of such closures would be detrimental to multiple sectors of the local fleets. Several other studies have examined fishery closures designed specifically to minimize the economic impacts from reduced target species catches while maximizing reduction of bycatch species or sizes (e.g., juvenile tuna bycatch [Harley & Suter 2007]; shark and sea turtle bycatch [Watson et al. 2009]). Similarly, gear modifications have been assessed based on their efficacy for bycatch reduction and their ability to sustain target species catches (e.g., sea turtle and shark bycatch [Gilman et al. 2007]; sea turtle, teleost, and elasmobranch bycatch [Brewer et al. 1998]; elasmobranch and teleost bycatch [Beverly et al. 2009]).

Perhaps the more difficult prediction of O'Keefe et al.'s (2013) to make is the impact a bycatch mitigation measure may have on other species, whether those species are of no commercial value or are the target of adjacent fisheries. For example, in the Bering Sea, fishing effort that was reallocated by fishery closures aimed at protecting red king crab (*Paralithodes camtschaticus*) resulted in increased bycatch of Pacific halibut (*Hippoglossus stenolepis*), yielding economic impacts on an adjacent fishery (Abbott & Haynie 2012). The best-known example of such unintended consequences on other species, however, may be in the eastern Pacific Ocean tuna purse seine fishery. In this fishery, successful efforts to reduce the bycatch of marine mammals ultimately led to increased bycatch of dozens of species of elasmobranchs and teleost fishes, including juvenile tunas whose incidental mortality reduced their economic value (Hall 1998). Such examples highlight the importance of including trade-offs in bycatch mitigation and the difficulty in optimizing the catch to bycatch ratio (Lewison et al. 2009) for all species in a habitat.

Despite the rich biodiversity of many marine environments, fishers have long targeted individual species or species groups, ultimately optimizing the catch to bycatch ratio by exploiting the disparate capture vulnerabilities of fish species. For example, longline fishers use the behavioral differences among pelagic species by setting hooks shallow (<100 m) to target yellowfin tuna (*Thunnus albacares*) and billfishes and deep (>100 m) to target albacore (*Thunnus alalunga*) and bigeye tuna (*Thunnus obesus*; Suzuki et al. 1977). Such depth-specific catchability has been documented for target and nontarget species captured in longline fisheries (e.g, Nakano et al. 1997; Ward & Myers 2005; Bigelow & Maunder 2007), and studies have demonstrated the potential to reduce nontarget catch rates by altering setting practices or gear accordingly (e.g., Boggs 1992; Beverly et al. 2009).

In the western and central Pacific Ocean, green sea turtles (*Chelonia mydas*; Rice & Balazs 2008), silky sharks (*Carcharhinus falciformis*) and oceanic whitetip sharks (*Carcharhinus longimanus*, Musyl et al. 2011) spend the majority of their time relatively near the ocean surface (<100 m) and are more likely to interact with longline gear when it is set shallower than 100 m or when hooks pass through shallow water during setting or retrieval. In contrast, albacore in this area primarily inhabit deeper, cooler waters from 150 to 250 m (Domokos et al. 2007). Accordingly, redistributing longline gear to focus effort on the preferred vertical habitats of target species such as albacore instead of the shallower depths of non-target species should provide a feasible method for reducing bycatch without reducing target catch.

Beverly et al. (2009) tested preferential depth distributions as a bycatch mitigation measure by fishing 90 longline sets (45 paired control and experimental sets). They found that catch rates were significantly less for 4 epipelagic species on experimental sets where all hooks were deeper than 100 m and 3 kg weights were deployed on the mainline. The experimental nature of Beverly et al.'s (2009) work established the ecological precedent for shallow hook removal, but they were unable to address the commercial-scale feasibility of such a gear modification and did not address the ecological or economic trade-offs that would be required for its implementation.

In the western and central Pacific Ocean, several shark and sea turtle species are caught as bycatch in albacore-targeted longline fisheries (Williams et al. 2009; WPRFMC 2012). The U.S. longline fishery based in American Samoa landed from 2268 to 5171 t of albacore and about 227 t of nontuna species annually from 2007 to 2011 (WPRFMC 2007, 2008, 2009, 2010, 2011). The National Oceanic and Atmospheric Administration implemented an observer program in this fishery in 2006 to monitor fish catches and interactions with protected species, primarily Pacific green sea turtles.

By examining these multi-year data from at-sea observers in the albacore longline fishery, we determined whether pelagic longline gear can be modified to avoid the preferred depths of bycatch species while targeting tuna species. Our approach allowed us to examine each of O'Keefe et al.'s (2013) considerations because we addressed intended bycatch reduction, impacts to catches of targets species, potential impacts to nontarget species, and potential economic impacts. Our specific objectives were to use time-depth recorders (TDRs) to quantify the vertical distribution in depth of hooks deployed in the American Samoa longline fishery; characterize distribution in catch rates of target albacore and incidental (retained, nontarget) and bycatch (discarded) species by hook position; examine hypothetical trade-offs between bycatch reduction and the loss of target and incidental catch under a suite of scenarios in which the shallowest hook positions were modeled as vacant with and without redistributing the vacated hooks to deeper positions in added longline sections; and estimate effects on fishery revenue from 2007 to 2011 under these hypothetical gear modifications.

Methods

TDR Data

Observers in the American Samoa albacore fishery monitored an average of 15.9% (range 7.1–33.3%) of longline trips annually from 2007 to 2011 (Pacific Islands Regional Observer Program (PIROP) 2008, 2009, 2010, 2011, 2012). During this period, observers boarded 108 longline trips and recorded the species and disposition (retained or discarded) of each fish caught. Fish, including albacore, are sometimes discarded because they are small or damaged. Other species are often discarded because they have little commercial value. Species protected under U.S. law (e.g., sea turtles) must be released (discarded) using handling guidelines designed to enhance postrelease survival (NMFS 2013).

TDRs (Lotek model LTD 1110) were deployed as in Bigelow et al. (2006) during 40 longline trips with observers onboard from 25 February 2007 to 22 September 2011 to obtain depth and temperature profiles of the fishing gear. Most of the longline sets (88.5%) were deployed in the American Samoa Exclusive Economic Zone (EEZ, ca. 11°S–14°S and 170°W–175°W), and the remaining sets were deployed in the neighboring Cook Islands EEZ or international waters to the north.

Depth profiles were obtained for 1154 longline sets that deployed 3,406,946 hooks total. Depth profiles were truncated to remove gear deployment and retrieval, which typically occurred within the first and last 30 min of each set. Sharp vertical movements within an individual profile typically corresponded to a fish being hooked adjacent to a TDR, and such anomalous sections were removed to provide a settled TDR depth for analyses. The length of the branchline connecting each hook to the mainline was added to the settled TDR depth to estimate the settled hook depth for the deepest hooks (Fig. 1 & Supporting Information), and the depths of all additional hooks were interpolated with an average ratio of 0.73 between the depth of an intermediate (middle) position on a longline catenary and the settled TDR depth at the deep position (Boggs 1992). Hooks were numbered such that hook 1 was the shallowest (closest to the surface) and hook 18 was the deepest. The deepest hook position was in the middle of each section of hooks, so hook numbers were symmetrical, thereby increasing from hook 1 adjacent to the float to the deepest hook (Fig. 1).

Hook Elimination Scenarios

Observers recorded hook position for 99% of the fish caught. Fishing effort (number of hooks) and the amount of catch (retained) and bycatch (discarded) were calculated for each species by hook position. Six gear-modification scenarios were investigated based on catch rate by hook number to evaluate the effects of eliminating hooks adjacent to longline floats during a simulated typical 3000 hook set. The number of hooks between floats (hbf) ranged from 23–36; thus, the relative impact of eliminating a hook fluctuated (e.g., eliminating one hook from 23 hbf gear had a greater impact than eliminating one hook from 36 hbf gear). We calculated a weighted average of catch rates for each hook position from each

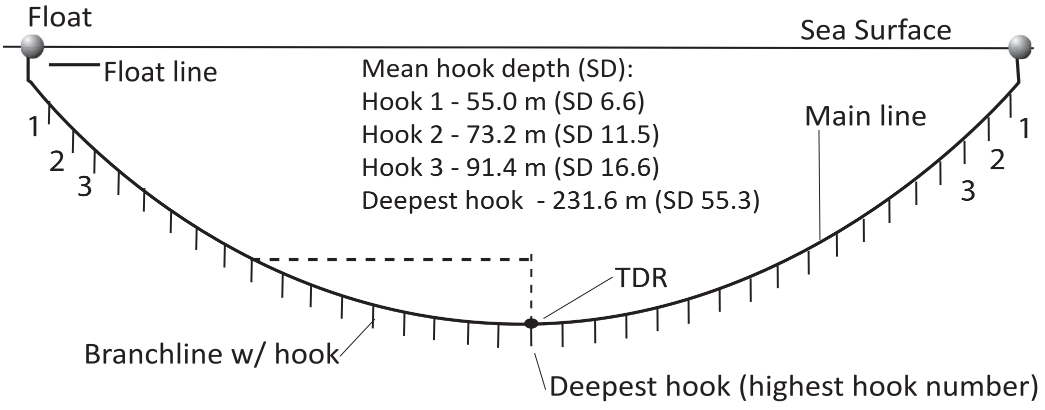

Figure 1. Illustration of one section (typically 23-36 hooks between floats) of a longline set, repeated in many sections (up to ~100 times). The catenary is drawn to scale with the exception of branchline lengths, which were doubled for the purpose of illustration. Hook numbering scheme, time-depth recorder (TDR) location, and average settled hook depths (1 SD) are shown. The intersecting dashed lines illustrate the relationship of the intermediate horizontal position along the catenary with a depth 0.73 times that of the deepest position along the catenary.

of the different hbf configurations and then simulated fishing based on 31 hbf gear (mean hbf configuration observed; Supporting Information for actual distributions of catch rates by number of hbf). Scenarios included elimination of hook1, hooks 1–2, and hooks 1–3, applied to both ends of each section and thus representing the elimination of 2, 4, and 6 hooks per section, respectively (Fig. 1). In 3 scenarios, hooks were eliminated from the shallow positions, and in the other 3 scenarios, hooks were hypothetically redistributed to deeper positions by extending the number of sections with additional mainline and floats. Therefore, if hooks 1–3 were eliminated, they were redeployed at the depth of position 4 and deeper. When catches from redistributed hooks were estimated, the catch rates were based on the mean catch rates for all hooks deeper than the removed hooks.

Size data were insufficient for estimating the average sizes of commercially valuable species for determining their value and estimating landed value. Instead, percent changes to catches in numbers of fish from each scenario were applied to the average annual landed values reported for each species (WPRFMC 2007, 2008, 2009, 2010, 2011).

Results

Hook and Catch Distributions

The average depths of hooks 1, 2, and 3 were 55.0 m (SD 6.6), 73.2 m (SD 11.5), and 91.4 m (SD 16.6), respectively (Fig. 1 & Supporting Information). Before elimination of any hooks, 23.1% of all hooks settled within the upper 100 m of the water column, while elimination of hooks 1, 1–2, and 1–3 shifted this distribution to 17.7%, 11.5%, and 6.7% of hooks within the upper 100 m, respectively. The majority of the hooks were distributed from 160 to 400 m (Supporting Information); mean settled depth was 231.6 m (SD 55.3) for the deepest hook.

Distributions of catch by hook position were generated from 2642 observed sets that monitored 7,829,498 hooks. A total of 246,031 individuals representing 69 fish, marine mammal, and sea turtle species were available for analysis. Many species were rarely encountered, and we considered only the 25 most abundant species (Table 1). A portion of the catch of each species, including albacore, was discarded, and a portion of the discards for each species was caught on the shallowest 3 hooks (Table 1). During the study period, 29.4% of all individuals were discarded, including 55.7% of all nonalbacore and 81.3% of all nontuna (those other than albacore, skipjack [*Katsuwonus pelamis*], yellowfin or bigeye tuna).

Among all discarded fish (Fig. 2 & Supporting Information), 18.3% were caught on the 3 shallowest hooks; 5.3%, 6.2%, and 6.8% on hook 1, 2, 3, respectively. Among the discarded albacore, 1.5%, 3.3%, and 4.9% were caught on hook 1, 2, and 3, respectively. Of the nonalbacore bycatch, 5.4%, 6.3%, and 6.9% of individuals were caught on hook 1, 2, and 3, respectively. Among all the discarded individuals that were not tunas, 5.3%, 5.6%, and 6.1% were caught on hook 1, 2 and 3, respectively. Twenty-two green sea turtles and 1 olive ridley turtle (*Lepidochelys olivacea*) were captured on observed trips, and 48% of these sea turtles (10 green and 1 olive ridley) were caught on the shallowest 3 hooks.

Hook Elimination Scenarios

Hypothetical hook elimination and redistribution scenarios revealed substantial changes to species catches (Fig. 3). For most species, catches decreased when shallow hooks were eliminated, with the exception

Table 1. Fishery data for 25 of the most abundant species captured on 2636 observed longline sets in the American Samoa longline fishery.

Common name	*Species name*	*Catch rate (per 1000 hooks)*	*Total number caught*[a]	*Number discarded (percentage of total catch)*[b]	*Number discarded from hook 1-3 (percentage of total catch)*[c]
Albacore tuna	*Thunnus alalunga*	15.65	122050	3173 (2.6)	308 (0.3)
Skipjack tuna	*Katsuwonus pelamis*	4.54	33552	12750 (38)	3697 (11)
Yellowfin tuna	*Thunnus albacares*	2.69	20446	3946 (19.3)	608 (3)
Wahoo	*Acanthocybium solandri*	1.64	12046	4300 (35.7)	1462 (12.1)
Bigeye tuna	*Thunnus obesus*	1.2	9730	3396 (34.9)	241 (2.5)
Slender mola	*Ranzania laevis*	1.09	8349	8316 (99.6)	1289 (15.4)
Escolar	*Lepidocybium flavobrunneum*	0.88	6907	6859 (99.3)	809 (11.7)
Longfin escolar	*Scombrolabrax heterolepis*	0.84	6850	6823 (99.6)	232 (3.4)
Pelagic stingray	*Pteroplatytrygon violacea*	0.67	5192	5171 (99.6)	372 (7.2)
Longnose lancetfish	*Alepisaurus ferox*	0.57	4624	4624 (100)	384 (8.3)
Blue shark	*Prionace glauca*	0.29	2189	2189 (100)	438 (20)
Blue marlin	*Makaira mazara*	0.28	1934	1383 (71.5)	532 (27.5)
Dolphinfish	*Coryphaena spp.*	0.22	1624	417 (25.7)	221 (13.6)
Great barracuda	*Sphyraena barracuda*	0.22	1613	995 (61.7)	549 (34.1)
Snake mackerel	*Gempylus serpens*	0.18	1365	1351 (99)	228 (16.7)
Shortbill spearfish	*Tetrapturus angustirostris*	0.17	1200	1054 (87.8)	626 (52.2)
Silky shark	*Carcharhinus falciformis*	0.16	1167	1166 (99.9)	435 (37.3)
Sickle pomfret	*Taractichthys steindachneri*	0.1	888	591 (66.6)	14 (1.6)
Oilfish	*Ruvettus pretiosus*	0.07	520	512 (98.5)	18 (3.4)
Swordfish	*Xiphias gladius*	0.06	478	285 (59.6)	67 (14)
Oceanic whitetip	*Carcharhinus longimanus*	0.05	353	352 (99.7)	150 (42.5)
Shortfin mako	*Isurus oxyrinchus*	0.03	268	267 (99.6)	37 (13.8)
Striped marlin	*Kajikia audax*	0.04	264	206 (78)	103 (39)
Sailfish	*Istiophorus platypterus*	0.02	188	131 (69.7)	73 (38.8)
Bigeye thresher	*Alopias superciliosus*	0.02	142	141 (99.3)	14 (9.8)

[a] *Retained and discarded combined.*
[b] *Discarded as bycatch.*
[c] *The 3 shallowest hooks (hook 1 is shallowest).*

of sickle pomfret (*Taractichthys steindachneri*), oilfish (*Ruvettus pretiosus*), and longfin escolar (*Scombrolabrax heterolepis*), which were virtually unaffected (<2% change in catch) by elimination of shallow hooks. Elimination of the first 3 hooks decreased catches of albacore, skipjack, yellowfin, and bigeye tuna by about 7%, 30%, 14%, and 5%, respectively. Meanwhile, hypothetical reallocation of all 3 shallow hooks to deeper positions increased the catch of albacore and bigeye tuna by more than 14% and 23%, respectively. Catch declines were still observed after effort reallocation for skipjack, wahoo (*Acanthocybium solandri*), blue marlin (*Makaira mazara*), mahi mahi (*Corphyaena* spp.), great barracuda (*Sphyraena barracuda*), shortbill spearfish (*Tetrapturus angustirostris*), silky shark, shortfin mako (*Isurus oxyrinchus*), striped marlin (*Kajikia audax*), and sailfish (*Istiophorus platypterus*). Minimal changes (<5%) in catches were observed with hook reallocation for slender mola (*Ranzania laevis*), blue shark (*Prionace glauca*), and snake mackerel (*Gempylus serpens*); swordfish changed by a similarly small 8.5%.

Species that showed decreased catches under both hook elimination and redistribution scenarios (Fig. 3 & Supporting Information) had significant negative linear relationships between hook position and catch rate ($P < 0.01$). Species for which catch increased or remained virtually unchanged during hook redistribution scenarios showed significant quadratic relationships between catch rate and hook number except for bigeye thresher (*Alopias superciliosus*), shortfin mako, and snake mackerel. Sickle pomfret, longfin escolar, and oilfish catches were unaffected by hook elimination, but catches increased with hook redistribution, and their catch rates were linearly related ($P < 0.05$) with hook number.

Hypothetical impacts on landed value based on hook elimination without redistribution (Table 2) showed that elimination of hooks 1, 1–2, and 1–3 reduced the landed value in the longline fishery by 1.6%, 4.8%, and 9.2%, respectively. Over half of lost value was from decreased albacore catch. Redistribution of hook 1, 1–2, and 1–3 increased value by about 5.0%, 8.8%, and 11.7%, respectively, with the latter accounting for a net increase of ex-vessel value of nearly $U.S.1.4 million annually. Fishery landed value recovered by hook redistribution resulted from increased catches of albacore and bigeye tuna caught on deeper hooks, whereas fishery value for non-tuna species remained depressed despite redistribution of shallow hooks.

The contribution of each species to the overall change in value (Table 2) was consistent with changes in catch from hook elimination and redistribution scenarios (Fig. 3

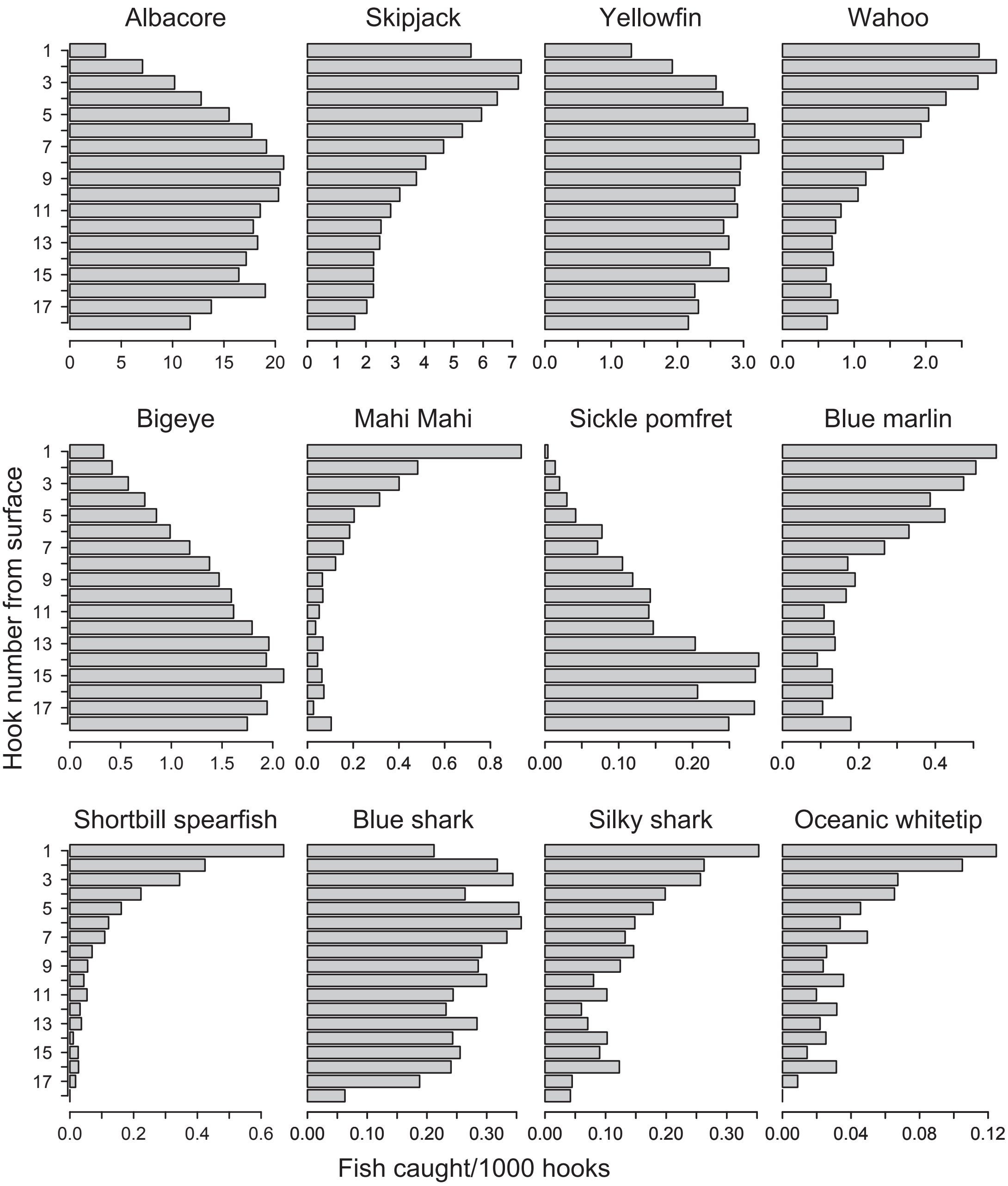

Figure 2. Catch rate by hook number for 12 species. The lower the hook number the closer the hook is to the surface.

& Supporting Information). Of the 25 species examined, 13 had commercial value within the American Samoa longline fishery, and 8 had an average annual landed value that exceeded $U.S.5000. Elimination of shallow hooks reduced the landed value for all 8 of these species.

Discussion

The American Samoa longline fishery, similar to other albacore longline fisheries in the South Pacific Ocean, is characterized by moderate to high levels of discarding (~35–78%) of several marketable species (e.g., bigeye tuna, wahoo, billfishes); other less marketable species have discard rates of 100%. Albacore longline fisheries preferentially use a vessel's fish hold for albacore given the guaranteed cannery market. High amounts of discarding result because domestic markets in American Samoa and other Pacific Islands are easily overwhelmed by nonalbacore landings, given a lack of infrastructure to export fish that are marketable elsewhere.

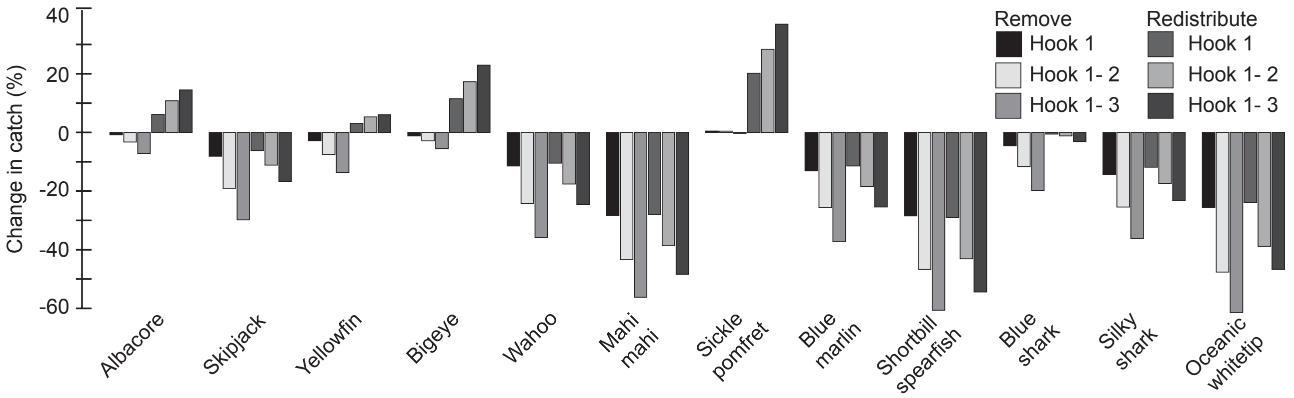

Figure 3. Percent change in catch for each of the different hook removal and replacement scenarios: remove hook 1; remove hook 1–2; remove hook 1–3; remove hook 1 and redistribute effort; remove hook 1–2 and redistribute effort; remove hook 1–3 and redistribute effort. Results presented for 12 of the species with the highest economic value, abundance, or conservation concern.

Table 2. Average annual (2007–2011) landed values ($U.S.) from the American Samoa longline fishery for albacore (*Thunnus alalunga*) and hypothetical changes in value resulting from 6 different hook-removal scenarios.

		Change in value ($U.S.)[b]					
Species	*Average value ($U.S.)*[a]	*Remove hook 1*	*Remove hook 1–2*	*Remove hook 1–3*	*Redistribute hook 1*	*Redistribute hook 1–2*	*Redistribute hook 1–3*
Albacore	9,699,375	−84,385	−322,989	−694,475	578,083	1,018,434	1,374,401
Skipjack	275,781	−22,504	−52,674	−82,652	−18,863	−32,790	−48,455
Yellowfin	1,330,224	−36,980	−95,510	−177,585	38,577	69,704	79,414
Wahoo	287,854	−32,585	−68,480	−101,440	−30,800	−50,576	−69,949
Bigeye	503,736	−6,397	−14,961	−27,957	58,836	87,801	116,061
Blue marlin	36,379	−4,937	−9,415	−13,635	−4,456	−6,934	−9,480
Dolphinfish	30,682	−9,002	−13,616	−17,476	−8,962	−12,260	−15,190
Shortbill spearfish	962	−269	−439	−578	−282	−411	−525
Sickle pomfret	909	4	2	−2	207	281	363
Oilfish	1,570	4	−3	−27	181	290	397
Swordfish	25,483	−1,486	−3,670	−6,154	−573	−1,157	−2,156
Striped marlin	1,385	−245	−482	−650	−252	−420	−536
Sailfish	3,365	−887	−1,380	−1,806	−946	−1,293	−1,614
Summary							
Albacore only	9,699,375	−84,385	−322,989	−694,475	+578,083	+1,018,434	+1,374,401
All tunas	11,809,117	−150,266	−486,134	−982,669	+656,632	+1,143,149	+1,521,422
Nontunas	388,588	−47,813	−94,382	−137,810	−43,076	−67,926	−92,861
Total	12,197,705	−198,079	−580,517	−1,120,479	613,556	1,075,223	1,428,561
Percentage of total		−1.6%	−4.8%	−9.2%	+5.0%	+8.8%	+11.7%

[a] *Annual average landed values from WPRFMC (2007, 2008, 2009, 2010, 2011). Species not listed had no reported commercial value.*
[b] *Three scenarios only remove hooks whereas the other 3 scenarios remove the same hooks and redistribute them by adding additional longline.*

Our results suggest that substantial bycatch reductions are feasible for numerous species by eliminating shallow hooks from longline sets. By redistributing even a small portion of the hooks to deeper depths, target catches and landed values are likely to be retained or increased.

Hook Depths

The median settled depth of the deepest hook position was 234 m, slightly shallower than observed in the Hawaii-based longline fishery (248 m; Bigelow et al. 2006), where deeper-dwelling bigeye tuna are the target species. In the Hawaii-based longline fishery, there are distinct deep and shallow set fisheries targeting tunas and swordfish (*Xiphias gladius*), respectively. In American Samoa, however, there is no shallow set fishery and regulations limit the number of swordfish that a vessel may possess to discourage shallow sets. We estimated that 23.1% of longline effort is within the upper 100 m of the water column, and this effort usually corresponds to the initial 3 hooks adjacent to the float. These 3 shallow hooks accounted for 18.3% of the bycatch, suggesting that more than one-fifth of the effort is fishing at depths where hooks are more likely to become occupied by less marketable fish. Thus redistribution of hooks to deeper depths may reduce bycatch and shift effort to targeted depths of albacore.

Vertical Distributions of Species and Catch Rates

The majority of catches followed 1 of 3 patterns with respect to their vertical distributions in the water column. Catch rates were broadly distributed throughout the water column with highest catch rates at intermediate hook numbers (e.g., Fig. 2, albacore), catch rates decreased with increasing hook number (e.g., Fig. 2, skipjack tuna and wahoo), or less often, catch rates increased with hook number (e.g., Fig. 2, sickle pomfret). These 3 patterns characterized the hypothetical economic and ecological responses of each species to our hook elimination and redistribution scenarios. Similar patterns have been documented elsewhere in the Pacific Ocean for several of the same species (Nakano et al. 1997; Campbell & Young 2012). These findings suggest management focused on hook number, and thereby, depth preference, may be broadly applicable across the region.

Economic Impacts

Species whose catches were broadly distributed throughout the water column (Fig. 2): albacore, yellowfin and bigeye tuna, slender mola, escolar (*Lepidocybium flavobrunneum*), longnose lancetfish (*Alepisaurus ferox*), and bigeye thresher had reduced catch during hook elimination scenarios, but their catches increased when hooks were redistributed to deeper positions (Fig. 3). Three species—albacore, yellowfin, and bigeye tunas—were the most valuable species in the fishery (Table 2); their combined average annual landed values exceeds $U.S.11 million. Because these species were typically caught on deeper hooks, redistribution of hooks 1-3, for example, increased total annual landed value by nearly $U.S. 1.4 million. A caveat is that some of the fish caught on deep hooks may have been captured as a hook was passing through shallower waters during setting or retrieval of gear. Tagging studies show that yellowfin tuna spend the majority of their time in warm surface waters shallower than 100 m (e.g., Brill et al. 1999), and Boggs (1992) reports that about 12% of yellowfin and bigeye tuna were caught on moving hooks during sinking and retrieval. Saito (1973) presented evidence of albacore catch mostly on settled hooks. Thus, the impacts of hook elimination and redistribution on species that are caught when the longline is sinking or being retrieved (e.g., mahi mahi, and billfishes) may not be as predictable as for species generally caught on settled hooks (e.g., albacore and bigeye tuna).

Conservation Benefits

The elimination of shallow longline hooks is associated with ecological benefits for numerous species. Among 25 fish species and sea turtles, billfishes and some shark species would benefit most from elimination of the first 3 hooks. Catch rates of blue marlin, shortbill spearfish, silky shark, oceanic whitetip shark, striped marlin, and sailfish declined by as much as 50%, even after all effort was redistributed. Green sea turtles could also be expected to benefit because shallow hooks accounted for nearly half of all captures.

The elimination of shallow hooks is applicable to deep set longline fisheries globally, although the conservation effects are dependent on the magnitude of catch rates within a particular fishery. The technique could be beneficial within longline fisheries incidentally catching overfished Pacific populations of oceanic whitetip sharks (Rice & Harley 2012) and silky sharks (Rice & Harley 2013). Pelagic longlines catch large numbers of billfish, and there is also concern for North Pacific striped marlin (*Kajikia audax*, Piner et al. 2013), overfished Atlantic populations of blue (*Makaira nigricans*) and white marlin (*Kajikia albidus*, ICCAT 2006), and possibly overfished Atlantic sailfish (*Istiophorus platypterus*, ICCAT 2009).

The elimination of shallow hooks may have clear conservation advantages, and redistribution of fishing effort to deeper depths would reduce lost landed value, but trade-offs would still remain. Economic trade-offs would have to be made in the form of lost landed value from species such as wahoo, billfishes, and dolphinfish, though these losses would be likely offset by value from increased tuna catches. Meanwhile, decreased catches of tuna predators, like billfishes, may result in unintended trophic cascades, increasing predation of targeted tuna species (Kitchell et al. 2004; Hunsicker et al. 2012), though the scale of change from this fishery alone may be insufficient to alter trophic cascades. Other ecological impacts include a 20% increase in catch rates of escolar, longfin escolar, sickle pomfret, and oilfish. Further trade-offs may include increased catch rates of deeper dwelling shortfin mako and bigeye thresher sharks, which are particularly vulnerable to overexploitation (Dulvy et al. 2008). In our hook redistribution scenarios, catches increased by as much as 9.2-12.5%; however, their overall catch rates would still be relatively low (<0.04/1000 hooks). Additional incentives may be needed for sustained or further reductions of bycatch among these more vulnerable species, highlighting once more the persistence of trade-offs with each conservation decision.

Feasibility of Hook Elimination

Eliminating shallow hooks (<100 m) can be operationally accomplished by using longer floatlines and branchlines or by not deploying hooks adjacent to the float. The distance between hooks is ~22 m (Supporting Information); therefore, in a new longline configuration, a vessel would deploy 46, 69, or 92 m of mainline before attaching the initial hook to effectively eliminate hook 1, 1–2, or 1–3, respectively, in the current configuration. Redistributing hooks would require longline fishers to extend mainline lengths which would require additional time and gear modifications (e.g., larger spools). If a longline set consists of 3000 hooks with 30 hbf, redistribution of hooks 1–3 (600 hooks) would require approximately 20% more setting and retrieval time. Similarly, redistribution of only hook 1 (200 hooks) would require ~6.7% more setting time. Elimination of hook 1 would reduce landed value by 1.6% (Table 2), whereas redistribution of hook 1 to a deeper position would increase landed value by 5.0%. If fishers were limited only by time constraints, they could expend a portion of that extra 6.7% of time and still be likely to land at least the status quo. Alternatively, hook 1 and 1–2 could be removed with a 4.8% loss of value. Hook 1 alone could be redistributed to recover 5% of value or enable the fisher to return to the economic status quo, while still having favorable impacts on bycatch reduction. Economic implications of hook redistribution were generally positive because greater landed value is predicted. However, we considered economics only in relation to fish value, and a better understanding of net revenue would need to consider cost data (e.g., fuel, labor for gear adjustment, and additional mainline), which was beyond the scope of our study.

Longline catches of some species are uncommon events. We examined more than 2,500 longline sets, and only 10 of the 25 species examined were caught at least once per set on average. The distributions of different species vary across time and space, even within the relatively small EEZ of American Samoa. By examining spatial distributions vertically instead of horizontally and seasonally, we aimed to identify an operational modification that would be relevant fishery-wide and that would minimize the impacts to fishers (e.g., avoiding a time-area closure, catch limits).

Efforts to reduce bycatch are typically characterized by trade-offs (e.g., Harley & Suter 2007; Watson et al. 2009). These trade-offs may come in the form of unintended (increased) bycatch of a different species (e.g., Hall 1998; Gjertsen et al. 2010; Abbott & Haynie 2012), detrimental impacts to target catch, or costs (money or time) of gear modifications or reallocated effort. We have addressed the interests of different stakeholders by examining 25 of the most commonly captured species in the American Samoa longline fishery and trying to understand how bycatch reduction efforts can balance impacts to different species. If shallow hooks are eliminated and the effort is not redistributed, there are likely to be fewer detrimental ecological impacts (although see Kitchell et al. 2004), but the economic consequences would be akin to those of a time-area closure, where the area closed would be the shallowest 100 m of the water column. If hooks are shifted deeper, some species, including valuable tunas and several species of conservation concern, are likely to be captured at greater rates. Although the redistribution of effort may be able to recoup the lost value of not catching shallow caught species, deeper caught species may experience greater fishing mortality which may be a conservation concern.

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Supporting Information

Details of gear configurations (Appendix S1), hook depth distributions (Appendix S2), extensions of Fig. 2 for the remainder of the 25 species (Appendices S3 and S4), tabular data for Fig. 3 (Appendix S5), catch rate illustrations for different numbers of hooks between floats (Appendix S6, S7 and S8), and an extension of Fig. 3 for the remainder of the 25 species (Appendix S9) are available online. The authors are solely responsible for the content and functionality of these materials. Queries (other than absence of the material) should be directed to the corresponding author.

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