Variation in fisher skill is a major determinant of bycatch rates across species, gears, and fisheries

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Abstract

Fisheries bycatch continues to drive the decline of many threatened marine species such as seabirds, sharks, marine mammals, and sea turtles. Management frameworks typically address bycatch with fleet-level controls on fishing. Yet, individual operators differ in their fishing practices and efficiency at catching fish. If operators have differing abilities to target species, they should also have differing abilities to anti-target bycatch species. We analyse variations in threatened species bycatch among individual operators from five industrial fisheries representing different geographic areas, gear types, and target species. The individual vessel is a significant predictor of bycatch for 15 of the 16 species-fishery interactions, including species that represent high or low costs to fishers, or have economic value as potentially targeted byproducts. Encouragingly, we found high performance operators in all five fishing sectors, including gears known for high bycatch mortality globally. These results show the potential to reduce negative environmental impacts of fisheries with incentive-based interventions targeting specific performance groups of individuals.

Management of threatened species bycatch

Incidental catch of marine animals in fishing gear ("bycatch") has been recognized as a serious problem for several decades. Despite widespread efforts to address it, bycatch remains one of the most pressing issues in fisheries management today, especially for threatened or protected species such as sea turtles, seabirds, elasmobranchs, and marine mammals^{1,2}. The most common approaches to reducing bycatch have been command-and-control measures implemented across the entire fleet or industry, such as technology requirements or total allowable catch for particular bycatch species^{3,4}. These conventional approaches have been far from universally successful, and have often performed worse in practice than models and trials suggested, even when the same approach is translated to a similar fishery⁵.

The Skipper Effect

Managing bycatch is a problem of fishing efficiency. Although management frameworks typically treat fishing fleets as a unit, several studies suggest that the skill of individual operators (the "skipper effect") could be a driver of important and unexplained variations in fishing efficiency. A skipper's skill is some combination of managerial ability, experience and knowledge of the environment, ability to respond to rapidly changing information and conditions at sea, and numerous other factors that are difficult to describe or record⁶. There is ongoing debate about the key components of operator skill and its importance in different contexts, such as different gears or technical advancement of fisheries⁷⁻¹⁰. Yet, numerous studies show consistent variation in target catch rates among anglers, skippers, or fishing vessels that is not explained by environmental variables or economic inputs^{7,11-13}. This includes technically advanced and homogeneous fleets where a skipper's skill would seemingly be less important¹⁴.

Previously, the skipper effect has been explored in relation to fishing efficiency and profitability (effort and target catch). However, if fishers have differing abilities to catch species they want, it follows that they would also have variable skill at avoiding unwanted species. Untangling the skipper effect is difficult without very detailed data, which are often not available for target catch and are extremely rare for bycatch. We capitalize on a rare opportunity to compare multiple high-resolution fisheries datasets that have information about both target and bycatch. We use fisheries observer data from five Australian Commonwealth fisheries sectors to answer three key questions: 1) Is there significant and predictable variation among operators in their target to bycatch ratios? We hypothesize that there are characteristics at the operator level that lead some vessels to perform worse than others on a consistent basis, and that operator skill is an important factor driving variations in bycatch across fishing fleets; 2) Does the pattern hold across species, gear types, and fisheries? We predict that, irrespective of the bycatch context, there are high performing operators that are able to avoid bycatch while maintaining high target catch; and 3) Does skipper skill transfer across species?" We posit that certain types of bycatch are inherently more difficult to avoid but expect to find correlations between bycatch rates, indicating that a skipper's ability to avoid one species extends to other types of bycatch.

If these hypotheses hold true, then there exists untapped potential to reduce bycatch without imposing additional controls on fishing effort and gear. This would support an alternative approach to framing management questions such as those around threatened species bycatch. It may be that it is not a random event across a fishery, but in fact is an issue of particular low performance operators. In this case, measures aimed directly at those individual operators could be an opportunity to make considerable progress towards reducing threatened species bycatch, at potentially much lower cost than common whole-of-fishery solutions.

Introduction

Management of threatened species bycatch

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considerable progress towards reducing threatened species bycatch, at potentially much lower cost than common whole-of-fishery solutions.

Results

To explore patterns in bycatch among individual fishing vessels, we analysed 17,030 fishing events ("shots") from 297 vessels between 2001 and 2017. The observer datasets are from five fisheries with different gear types and geographic areas: prawn trawls, tuna longlines, set gillnets, demersal longlines, and otter bottom trawls. First, we explored the relationship between catch and bycatch. If bycatch were an inevitable consequence of fishing effort, then bycatch should increase with increasing target catch volume. Yet, we found considerable heterogeneity among vessels in their bycatch to target catch ratios in all five fisheries (Figure 1). Several operators with the highest average target catch had some of the lowest average bycatch rates (e.g., seabirds in tuna longlines), and conversely the highest bycatch rates were from operators with lower target catch (e.g., shearwaters in set gillnets). Thus, there is not necessarily a positive correlation between target and bycatch rates, even for species that associate with target species.

Our primary aim was to isolate the marginal effect of the individual operators that is not captured in tactical variables such as location and timing of fishing, while accounting for factors affecting the catchability of bycatch (e.g., depth, association with target species). To do this, we built a base model for bycatch rates that captures fishing practices and environmental variables, including a targeting cluster variable to capture unrecorded fishing métiers such as bait type or gear orientation. Overall, the models performed well and explained anywhere from 12 to 95% of the deviance in bycatch (Table 1, Table S1). The individual vessel was significant in 15 out of 16 species-fishery models and explained anywhere from 5 to 67% of the expected deviance in those models (Table 1). We expected that time and location would be the dominant drivers of bycatch variability, yet, the individual vessel had the highest (or tied for the highest) importance score for 14 of the 16 models (Table S1). Year was the second most important factor (judged by the importance estimates and frequency of occurrence in the best model) because there were substantial changes in the regulation of fishing practices and fleet structure in all sectors over the time period, as well as changes in the availability of bycatch species. Tactical and environmental factors that were significant for some bycatch contexts included geographic location, month, time of day, depth, and type of operation (only relevant to the tuna longlines). Volume of target catch was included in 9 of the 16 models but, interestingly, was not included in the best model for the species most known to associate (e.g., seabirds and tuna, where fishers often use seabirds to locate the tuna), although it was within two AIC points of all best models for seabirds. This could be explained by shifting fishing practices to avoid seabird bycatch, such as adoption of bird scaring lines, night setting, and area closures¹⁵. Surprisingly, targeting cluster was only included in four of the 16 models. However, environmental factors do capture aspects of targeting, and are also related to operator skill because skippers make decisions about where and when to fish.

Table 1: Best model summaries for 16 species-fishery interactions. Vessel was included as a random effect unless the fixed effect (fe) model had a lower AIC score. If the random effect was not significant, the vessel term was excluded from the best model. Delta deviance explained is the difference in deviance between the best model with versus without the vessel term. Target catch is volume or number of individuals. Target clust=targeting cluster. Op. type=fishing operation for pelagic longlines (e.g., standard operations or bycatch mitigation trial). % in light=percent of shot in daylight. Shot dur=duration of shot in hours. Each model is offset with a metric of fishing effort so that it is bycatch per unit effort.

Model	Target catch	Year	Month	Lat/Lon	Target clust.	Depth	Op. type	% in light	Shot dur.	Vessel	Dev. %	Delta Dev.
Set gillnets												
Albatrosses				x		x	–	–	–	x	20.0	15.0
Shearwaters		x	x	x			–	–	–		12.0	0.0
Dolphins	x	x		x			–	–	–	x	72.3	66.5
Demersal longlines												
Albatrosses	x	x	x	x		x	–	–	–	x	27.0	27.0
Petrels	x	x		x	x	x	–	–	–	x	44.2	9.4
Shearwaters			x				–	–	–	x	16.1	16.1
Otter bottom trawl												
Albatrosses	x	x	x			x	–	–	–	x	51.3	14.3
Petrels	x	x					–	–	–	x	70.3	25.5
Shearwaters	x	x	x	x			–	–	–	x	66.8	16.2
Pinnipeds	x		x	x		x	–	–	–	x	46.3	15.8
Tuna longlines												
Albatrosses		x	x	x		–	x	x		x	52.3	9.2
Petrels		x	x	x		–	x	x		x	84.1	13.8
Shearwaters		x	x	x	x	–	x	x		x	82.5	9.6
Shortfin mako	x	x	x	x	x	–	x	x	x	x (fe)	25.3	5.2
Prawn trawl												
Hammerheads		x	x	x		x	–	–	–	x (fe)	95.4	35.2
Sea snakes	x	x	x	x	x		–	–	–	x (fe)	84.8	62.2

Including a random effect for the vessel allowed us to test whether the population of vessels differ in their bycatch rates across fishing events. In order to evaluate the differences among specific vessels and identify vessels with particularly high or low bycatch rates, we shifted from a random effect for vessels to a fixed effect in cases where the random effect significantly improved the model. To indicate the direction and strength of the relationship between the vessel and the amount of bycatch, we assessed the regression coefficients for individual vessels in each of the 15 models where the vessel was significant (Figure 2). The regression coefficients indicate that in each fishery, specific vessels are significant predictors of high bycatch shots, and others predictably have lower than average bycatch. Overall, there is evidence of three broad patterns in bycatch avoidance skill. The majority of the models have a roughly bimodal pattern of coefficients (e.g., all species in demersal longlines), indicating the fleet is split fairly evenly between low and high bycatch operators. Gradients in the regression coefficients indicate a range of avoidance skill levels, such as shearwaters in otter bottom trawls and petrels in tuna longlines. Large gaps in the spread of positive regression coefficients suggest potential targeting behaviour, such as dolphins and potentially hammerheads. Conversely, clusters of very negative coefficients suggest groups of skilled bycatch avoiders, such as sea snakes and shortfin makos. However, individual regression coefficients for vessels in the otter bottom trawl, tuna

longlines, and prawn trawl are not significant and have large standard errors, meaning there is high uncertainty around how specific vessels drive bycatch variability in those sectors (Figure 2, Supplementary Figure 1).

To explore the relationships between species bycatch within each fishery, we used correlation tests of bootstrapped estimates of vessels' regression coefficients. All but one species pair (hammerheads and sea snakes in the prawn trawl) were positively correlated (Figure 3). In most cases, we found stronger correlations between bycatch species that are logically related. For instance, bycatch of different seabird species in tuna longlines was more strongly correlated than seabirds and shortfin makos, and all seabird species showed strong correlation in demersal longlines. The pattern in the set gillnet and otter bottom trawl sectors was less intuitive, with strong correlations between marine mammals and certain seabird species, but weaker correlations between most seabird groups. One possible explanation is that different diving and foraging behaviours of seabird species—and intra-specific interactions when multiple species are present—affects their catchability and attraction to viscera and waste disposed from the boat¹⁶. The interaction between bycatch species and fishing location is likely important as well. The flesh footed shearwater (*Ardenna carneipes*) dominates the shearwater bycatch in the four gears that interact with seabirds, whereas the petrel and albatross groups vary in species composition across the fishing regions. Exploration at greater taxonomic resolutions would help resolve the correlation in bycatch rates between different species groups. Overall, these results suggest that operators in most fisheries have fairly consistent avoidance skill (or lack thereof) across similar types of bycatch.

Finally, we explored operators' bycatch to target ratios over the timespan of the data to evaluate whether the variability among operators persisted over time. Overall, improvements in bycatch were variable across fisheries (Figure 4), although it is difficult to compare bycatch ratios among rare and common species. Following a series of regulatory changes and bycatch mitigation programs, the observer data shows a dramatic reduction in seabird bycatch in the tuna longlines from a fleet-wide average of over 100 birds per shot in 2001 down to zero in 2015. These very high averages are likely inflated by bycatch mitigation trials in the early 2000s that were not normal operations, but logbooks and recent electronic monitoring data corroborates a significant improvement in seabird bycatch overall^{17,18}. The set gillnets, demersal longlines, and otter bottom trawls also underwent a series of regulatory changes related to bycatch¹⁹, and the most recent years of observer data indicate seabird catch rates may be declining. Compared to seabirds, cetacean and pinniped interactions are relatively rare and it is difficult to detect a trend in the observer data, but bycatch of these species remains a major concern^{20,21}. As expected, catch rates of shortfin mako—a byproduct species with a catch limit per fishing trip—do not decrease like seabird catch rates. There is no evidence of reduction in hammerhead bycatch in the prawn trawl, but sea snake bycatch rates may be decreasing. However, these trends could be driven by changes in abundance of bycatch species as opposed to fishing practices. Most importantly, patterns in the observed bycatch ratios indicate that variability among operators persisted over time in all fisheries, indicating that there remains opportunity for further reduction in bycatch rates.

Discussion

Controlling for factors affecting bycatch availability, targeting tactics, and changes in fleet structure and management over time, we find that characteristics of the individual operators have a significant effect on bycatch levels across a range of species and fishing methods. We detect the pattern of operator variability over a relatively long period of time and across five observer data sets known to have good accuracy²². Thus, our results support our hypothesis that anti-targeting (avoiding) is a skill just as targeting is. We posit three main drivers of the variable anti-targeting performance: 1) Anti-targeting may be inherently more difficult for some gears and species and therefore require greater skill; 2) Bycatch species differ in how much they affect the fishing operation, so there are likely differences in motivation to avoid it across species and gears; and 3) There are incentives to catch some byproduct species, potentially making them clandestine targets. Notably, even in gears known to catch a wide range of bycatch species (e.g., gillnets and demersal trawls), we find that a small group of operators are able to simultaneously anti-target a range of bycatch species (including valuable byproducts) while still maintaining high target species catch. These high-performance operators present an untapped opportunity to greatly improve the environmental performance of fisheries, without necessarily mandating additional gear modifications or other command and control regulations.

Limitations of observer data

We assume the data provides an accurate representation of fishing activities, although observer data are known to have biases and inconsistencies and typically only cover a small fraction of the fishing effort^{23,24}. Implementation of electronic monitoring and quality-checked logbooks opens doors to much larger datasets. This can help resolve some of the uncertainties in how individual operators drive bycatch rates, correlations between different types of bycatch, and interactions between the individual operator and other aspects of fishing practices. For instance, there may be groups of operators that consistently fish in high bycatch areas but still have variable bycatch rates that are independent of the location. We also suspect there is a strong observer effect, where operators may behave better and avoid known bycatch areas when observers are present (e.g., islands with large seabird colonies). Overall, we expect these results underestimate the variability in anti-targeting skill because low-performing vessels and high-bycatch fishing events are likely underrepresented in our sample.

The individual operator effect

The vessel effect in our analysis represents the unknown elements of operator skill and decision making that are not captured in other factors relating to fishing tactics, including managerial skills, knowledge of species or habitats, gear configuration, and ability to manoeuvre the vessel and haul gear. It might be that the low-bycatch operators are more conscientious about using their gear (e.g., the various types of bycatch reduction devices), or that they have developed subtle innovations in their fishing practices, for instance, changing the depth or orientation of their gear in response to changing environmental conditions at sea^{25,26}. Our results suggest there are characteristic groups of operators in each fishery, with more obvious delineations in some sectors. High performers are skilled at avoiding bycatch while maintaining high target catch while low performers have above average bycatch and below average target catch. In between these extreme contexts is a range of skill levels, as well as important ecological and geographic factors. For example, low target and low bycatch could indicate unskilled operators who choose generally unproductive geographic areas. High target and high bycatch operators could be fairly adept at catching target species, but the large catch and subsequent large offal disposal attracts many bycatch species. It could be that these high bycatch operators have not developed innovations or invested in bycatch mitigation techniques such as offal holding tanks to avoid discharging while gear is in the water.

Avoiding different types of bycatch—such as seabirds versus sharks—likely demands different types of skills from operators. Observer coverage was not sufficient for a comprehensive analysis of how individual operators performed across multiple bycatch species over time, especially for the rarer species. However, we find evidence of relationships between certain types of bycatch; for instance, the same tuna longline operators seem to have high bycatch of all seabird species, but these are not always the same vessels with high shortfin mako catch. Further exploration of individual vessels would be useful to detect operators that performed particularly well for certain species, but poorly for others. It may be that these are in fact skilled operators, but are more inclined to avoid certain types of bycatch.

Incentives to avoid bycatch

There is a range of incentives to avoid different species, including safety hazards, damage to gear, lost opportunity to catch target species, or bycatch penalties, as well as perverse incentives to catch some bycatch, such as species with market value. Our results suggest that some incentives may be more salient to fishers than others. For instance, the dramatic decrease in seabird bycatch in the tuna longlines suggests that bycatch mitigation measures were effective, and likely worked in tandem with changing attitudes within the fishery. There was a strong incentive to reduce seabird bycatch because they have no market value, cost time, and waste a hook that could have caught a tuna. Management measures further strengthened the inherent incentive to avoid catching seabirds by imposing a hefty financial penalty, where the region of the fishery with high bycatch rates was closed to fishing if the bycatch rate exceeded 0.05 birds per 1000 hooks²⁷. Since the penalty was imposed across the fleet, presumably there was also hidden social pressure within the fisher network²⁶. In contrast, seabird bycatch reduction measures have been less successful in the otter bottom trawl, demersal longline, and set gillnet sectors¹⁷. This could be because the seabird bycatch mitigation equipment for these gears is more difficult to operate effectively, or because there

was less incentive to do so. Input controls were introduced in these sectors (e.g., mandating the use of at least one approved bycatch mitigation device on trawls), but were not coupled with the high bycatch penalty as in the tuna longlines¹⁹.

The significant variability in bycatch levels among operators suggests that management frameworks that account for individual performance could be more effective at reducing overall bycatch levels, while not punishing operators who are profitable and environmentally efficient (low impact on bycatch species per unit of production). In the tuna longline fishery, a small number of vessels were responsible for the majority of seabird bycatch, but the strict penalty is imposed across the fleet. This type of approach can have unanticipated negative effects at the macro scale. For example, fleet-wide caps on sea turtle bycatch in the Hawaiian swordfish longline fishery resulted in a three-year fishery closure, which allowed less-regulated fleets from other countries to increase their effort and likely had a detrimental effect on overall sea turtle bycatch²⁸. Fleet-wide controls can also reduce target catch, stymie innovation and customization to each context, and fail to encourage continuous improvement beyond the regulatory minimum^{3,29-31}.

Although the input controls in the tuna longline fishery ultimately had very positive outcomes for seabirds, our findings suggest that management measures directed at low performing operators could further reduce overall bycatch levels. Individual standards have been successfully applied in a few cases, such as the multilateral dolphin conservation program for tuna purse seine fisheries in the Pacific, which assigns individual dolphin mortality limits in addition to other measures^{3,26}. In the Commonwealth, increasing concern over dolphin bycatch in set gillnets resulted in the complete closure of a large area in 2011, which significantly impacted the profits of the entire gillnet fleet. The strategy was recently revised so that the maximum interaction rates and the penalties for exceeding them are applied to individual vessels, but the results have not yet been released³².

Latent potential for improvement

Even where these measures are aimed at individuals, a bycatch limit is essentially a total allowable catch that sets an acceptable amount of species mortality, and thus would not be expected to drive bycatch rates to zero. Bycatch may still threaten the viability of seriously endangered populations even if limits are based on sustainability criteria³³. We found that variation among individual operators in their bycatch to target catch ratios persisted over time, even as regulatory conditions changed and many low-performing operators exited the fisheries³⁴. This suggests there remains latent potential to reduce bycatch to very low levels while still maintaining target catch. The next step is to use knowledge of variability among individuals to design interventions that encourage continued innovation towards zero bycatch. Positive incentives (often in combination with some sort of penalty) can encourage continuous improvement, and have been successfully applied to bycatch in a few fisheries³, as well as other environmental problems such as littering and marine debris³⁵.

Management implications

The appropriate combination of incentives and penalties will vary for different bycatch contexts. For instance, sea snake bycatch may not incur enough costs or trigger social norms adequately enough to lead fishermen to avoid compared to seabirds, and thus may be an issue primarily of lack of effort as opposed to lack of skill. Bycatch that associates with offal disposal or target species, such as dolphins in the gillnet fishery, may elicit a stronger response to environmental social norms but could require more ingenuity and skill to avoid. Understanding the incentives and behaviours underlying bycatch contexts is especially pertinent for byproduct species that have high per unit value in legal or illegal markets, such as many elasmobranchs. There may also be rare bycatch incidents that are truly accidental and unpredictable; for example, there was one blue whale entanglement in the demersal longline sector over ten years of observer data. However, our results indicate this is not the norm, and that fishers do possess untapped knowledge and innovation in reducing threatened species bycatch, even for globally problematic bycatch interactions. For example, sea snakes and dolphins both associate with target species and are caught in high-bycatch gears (trawls and gillnets), yet there was significant variability among operators that explained a large proportion of the deviance in bycatch rates of these species.

Ultimately, the goal is to move from identifying patterns of high and low performing vessels, to understanding the underlying processes and using that knowledge to inform actions. Insights into the biophysical drivers of catch and bycatch (e.g., sea surface temperature, frontal systems, isothermal layer depth) likely help explain some aspects of how high-performing operators are fishing³⁶. However, certain elements of operator skill—such as managerial skills or reacting to dynamic conditions at sea—are not captured in biophysical variables or in data from logbooks, observers, or electronic monitoring. Therefore, it is essential that scientists and managers collaborate directly with fishers—and facilitate peer-to-peer learning and communication among fishers—to understand the more nuanced skills and behaviours that characterize good operators and spread that optimal performance across the fishery^{26,37-39}. This level of engagement is expensive and time consuming but would be a worthwhile investment in the long term. Enforcement is the largest expense for fisheries management globally, and increasing voluntary compliance would greatly reduce those costs^{40,41}. In this context, voluntary compliance could mean shifting from bycatch limits and technology requirements with an underlying enforcement program to a focus on innovation at the individual level, supported by incentives.

Our results suggest that some fishers already voluntarily avoid bycatch of species that do not incur a penalty or major cost to their fishing operations, and are able to do so without compromising their economic performance. The appropriate set of incentives and management interventions could encourage further innovation from fishers, and potentially improve bycatch rates beyond what currently seems feasible. The importance of variable skills and behaviour of individual operators could extend beyond threatened species bycatch to management of other environmental impacts, such as gear abandonment and waste discharge. Increased uptake of bycatch avoidance skills and other positive environmental behaviours across fishing fleets would be a monumental gain for management agencies and for biodiversity at a pivotal moment in the trajectory of ocean sustainability.

Methods

Description of fisheries and datasets

We use observer data provided by the Australia Fisheries Management Authority (AFMA) for five federally managed fishing sectors in Australia: Northern Prawn Fishery ("prawn trawl"), Eastern Tuna and Billfish Fishery ("tuna longlines"), and three sub-sectors of the Southern and Southern and Eastern Scalefish and Shark Fishery (SESSF), referred to here as demersal longlines, otter bottom trawls, and set gillnets (Figure 5).

Northern Prawn Fishery (prawn trawl)

The Northern Prawn Fishery extends across most of northern Australia and is the country's most valuable trawl fishery. It is essentially two distinct fisheries; a banana prawn fishery and a tiger prawn fishery, which operate during different time periods and in mostly distinct regions of the management area, and also use slightly different types of trawl gear^{42,43}. White banana prawns (*Fenneropenaeus merguensis*) are mostly caught during the day on the eastern side of the Gulf of Carpentaria offshore from mangrove forests, where they form dense aggregations ("boils") near the surface that are often located using spotter planes (Figure 5). Red-legged banana prawns (*F. indicus*) are mainly caught in the western region of the management area, whereas tiger prawns (mainly *Penaeus esculentus* and *P. semisulcatus*) are usually caught at night closer to the seafloor and near coastal seagrass beds in the central portion of the management area⁴⁴.

Prawn trawls are known to have high environmental impact, including high bycatch rates⁴⁵ (Kelleher, 2005). Yet, the Northern Prawn Fishery received Marine Stewardship Council accreditation in 2012, largely due to the extensive effort to incorporate a range of biological and bioeconomic models into an active management framework⁴⁶. The fishery has been restructured over several decades through a series of management measures and buyback programs of less-efficient vessels, including a reduction from about 250 to 50 vessels⁴⁴. In 2000, the prawn trawl introduced the compulsory use of approved turtle excluder devices (TEDs) and bycatch reduction devices (BRDs), allowing operators to select their desired combination of devices⁴². Overall, the TEDs and BRDs have substantially reduced catches of larger animals such as sea turtles and large elasmobranchs

—although sawfish are an important exception—but have been much less effective for smaller animals such as seahorses and sea snakes^{47,48}. The scientific observer program covers about 2% of fishing days⁴⁹.

Eastern Tuna and Billfish Fishery (tuna longlines)

The Eastern Tuna and Billfish Fishery is a pelagic longline fishery operating year-round in the EEZ and adjacent High Seas off Australia's East Coast (Figure 5). The main targets are yellowfin (*T. albacares*), bigeye (*T. obesus*), albacore (*T. alalunga*), and southern bluefin tuna (*T. maccoyii*), and broadbill swordfish (*Xiphias gladius*)⁵⁰. Structural readjustments and new harvest strategy policies over the past two decades have reduced the number of vessels from 150 to about 40 currently active vessels, with the more economically efficient vessels remaining³⁴. Several management interventions have aimed to reduce bycatch of protected species (seabirds, sea turtles, and marine mammals); for example, requirements to carry line cutters and de-hookers, use bird-scaring lines, and deployment of gear at night³⁴. Wire leaders were banned in 2005 to reduce shark bycatch, although vessels are permitted to retain up to 20 individuals per trip—meaning they are actually byproduct as opposed to bycatch³⁴. Seabird bycatch mitigation has been very successful but there is still concern about catch of other species, such as shortfin mako sharks (*Isurus oxyrinchus*), which were recently upgraded to Endangered on the IUCN Red List and are the most common protected species caught in the tuna longline fishery, and leatherback turtles, which are much rarer occurrences but are listed as Critically Endangered in the Western Pacific^{34,51}. The tuna longline fishery has had a scientific observer program since 2001, which has ranged from 3.5-8% of fishing effort⁵².

Southern and Eastern Scalefish and Shark Fishery (SESSF)

The SESSF is a multispecies, multigear, and multisector fishery with a management area covering almost half of Australia's fishing area and has the largest catch volumes of any Commonwealth fishery³⁴. Many SESSF stocks were overfished (and some remain overfished); thus, it was one of the first fisheries targeted by the Commonwealth government's structural adjustment programs to reduce fishing effort and improve economic efficiency³⁴. The SESSF observer program focuses on discarded fish species¹⁹. Identification of morphologically similar bycatch species (e.g., many shearwaters, albatrosses, and petrels) may not be as reliable as the tuna longline observer program, which has a strong seabird focus and far fewer catch species to identify. Overall, observer coverage has increased since the program was implemented in 1992, with required coverage varying according to the sub-sector and area (e.g. 100% observation is required near certain marine mammal colonies and closure areas)⁵³.

We focus on three gear types used in SESSF fishing sub-sectors: bottom set gillnets, otter bottom trawls, and auto-demersal longlines (referred to here as "demersal longlines"—"auto" refers mainly to how the hooks are baited) (Figure 5). The gillnet sector mainly targets sharks—primarily gummy sharks (*Mustelus antarcticus*), sawsharks (Pristiophoridae), and elephant fish (Callorhynchidae)—whereas the otter bottom trawls predominantly target eight teleost species or genera and the auto-demersal longline subsector primarily targets four deep-water teleosts⁵⁴⁻⁵⁶. However, all three sectors catch and retain hundreds of other teleosts and elasmobranch species, most of which are not directly monitored or managed under a quota system⁵⁶. In addition to these byproduct species, the SESSF sectors also catch a variety of protected species groups, including marine mammals (cetaceans and pinnipeds), seabirds, seahorses and pipefish, and large sharks (e.g., shortfin makos and hammerheads, *Sphyrna* spp.). Bycatch of pinnipeds and cetaceans is frequently cited as a major environmental concern for the SESSF¹⁹.

Fisheries observer data

The observer programs were instated at different times for the five fisheries. We obtained scientific observer data from 2001-2015 for the tuna longlines, 2007-2017 for the prawn trawl, 1992-2017 for the set gillnets and demersal longlines, and 1992 to 2016 for the otter bottom trawl. The scientific monitoring program for the latter three sectors was originally designed to collect data on target species, and the focus only expanded to TEP species in the early 2000s⁵⁷. Thus, we excluded the early years from the analysis because almost no bycatch records appeared in the observer data prior to 2007 for the demersal longlines and set gillnets, and prior to 2004 in the otter bottom trawl. Since 2015, electronic monitoring systems are slowly replacing at-

sea observers in these Commonwealth fisheries. In order to sample the range of operators as best as possible, we included all observer trips within our timeframes in the analysis and did not set a threshold for observer coverage per vessel. Fisheries managers from AFMA advised that observer coverage is not random because observers preferentially sample vessels that are more comfortable and have friendlier crews. Although AFMA has not analysed the correlation between observer coverage and vessel performance, the managers' perception is that their least compliant and least efficient vessels have less observer coverage. Thus, we suspect our data has more complete coverage of high-performing compared to low-performing vessels.

In order to account for species-specific dynamics that affect bycatch availability, we maintained the highest possible taxonomic resolution in the analysis of bycatch. Species-level identification by scientific observers is generally accurate for easily identified species (e.g., shortfin makos) and to the genus or family level for common species (e.g., shearwaters), but is less reliable for rare or similar looking species (e.g., different species of shearwaters)²⁷. We identified candidate bycatch groups of seabirds (albatrosses, petrels, and shearwaters), elasmobranchs (shortfin makos, hammerhead and winghead sharks, and sawfish), sea turtles, seahorses and pipefish, and marine mammals (pinnipeds and dolphins). The majority of the dolphin bycatch records are for common dolphins (*Delphinus delphis*), and the pinnipeds are primarily Australian fur seals (*Arctocephalus pusillus doriferus*).

Statistical Analyses

Targeting cluster analysis

Fishers in multispecies fisheries often use different fishing tactics to target subgroups of target species⁵⁸. Sometimes the targeting practices are well-understood by fisheries managers (e.g., in the ETBF, swordfish are targeted with shallow night sets, often using fluorescent sticks attached to the lines)⁵⁹. These different tactics affect the catchability of bycatch species but can be difficult to define and record. We used model-based clustering of the target species recorded in the observer data to define subgroups of target species and assign a targeting cluster to each fishing event. The cluster analysis was done in the R statistical language⁶⁰ using the mixtools package⁶¹, which uses a mixture of beta distributions to describe the probability of each target species occurring in a single fishing event. An advantage of the mixtools infrastructure, compared to other tools for finite mixture modelling, is that it considers the ratio of target species counts in each shot, as opposed to just the frequency of each species. We fit the mixture model using the expectation-maximization algorithm, limiting it to a maximum of 15 clusters, and compared models of increasing complexity, selecting the model that corresponded to the first minimum in AIC values⁶². For the SESSF sectors, which have many targets, we selected candidate target species first by selecting the 15 species with the highest total catch volumes and then by the most non-zero catches (how frequently that species is caught). We compared the AIC values to select the cluster model that best describes the data. We then used the best fitted model to classify each fishing event as one of the targeting types, assigning it randomly in the case of ties.

Exploring the relationship between catch and bycatch

For the measure of target catch, we used the sum of the number of individuals of the target species from each shot. For the SESSF sectors, which do not have a defined list of targets, we used all retained catch as the target catch (recorded as number of individuals for the set gillnet sector and as weights for the otter bottom trawl and demersal longlines). For the ETBF, we included only the five main target species (albacore, bigeye, yellowfin, and southern bluefin tuna, and broadbill swordfish) in the count of target catch. We combined the retained and discarded shortfin mako catch because they are a byproduct species. All bycatch is recorded as counts. Our focus was on exploring whether operators could avoid bycatch interactions altogether; therefore, we measured bycatch as animals that interacted with the gear but escaped as well as animals that were caught (this mostly applies to seabirds).

To explore the relationship between catch and bycatch, we first examined the data graphically using a generalised additive model (GAM) implemented in the mgcv package in R⁶³. This exploratory analysis indicated different relationships between bycatch and target catch depending on the species and fishery. In most cases the relationship appeared to be monotonic, but

not always linear or in the same direction. For some species-fisheries interactions, there was no evidence of a correlation between target catch and bycatch.

To evaluate the factors driving variations in bycatch, we used a GAM with a Tweedie distribution, which handle very zero inflated data well because they are a mixture of Poisson and Gamma distributions⁶⁴. We incorporated the targeting type as a factor, as well as environmental and tactical factors that could affect the availability of bycatch, including year, month, depth of the fishing activity, latitude, longitude, and their interaction, time of day (percent of the fishing activity duration in daylight hours), and type of operation for the tuna longlines (whether it was a standard fishing trip or an experimental project such as testing bycatch mitigation technologies). Not all variables were available or relevant to all fisheries. We parameterized latitude and longitude as a smoothed spatial surface across the fishing area, but did not include an interaction term for the vessel and the fishing location because observer coverage was uneven across vessels. Information on the skipper and observer IDs was available for one fishery, but we did not test the interaction between the vessel, skipper, and observer because observer coverage was insufficient to include it in the model. Usually there is one skipper per vessel, although occasionally a boat would be decommissioned, and the skipper would move to a new vessel. Each model included an offset for fishing effort, measured as thousands of hooks deployed for the tuna longlines and the duration of the fishing event for the other fisheries (number of hooks was not available for the demersal longlines).

We used a series of steps to select the best model. First, we compared two global models—with all factors included, along with a term for the vessel, as either a fixed or a random effect—to a null model of each bycatch species. We used the dredge function from the mumin package in R⁶⁵ to compare all possible combinations of factors in the best global model (with vessel and observer as either fixed or random effects), then selected the model with the lowest AIC as the best model. If there were multiple models within a 95% confidence interval of the best model, we selected the simpler one with fewer factors. We assessed the final model to verify the data were not over-dispersed and that the model captured the important patterns in the data. We excluded several species groups due to rarity of bycatch records: sea turtles in the tuna longlines and prawn trawl, marine mammals in the tuna longlines, seahorses and pipefish in the otter bottom trawl, and sawfish in the prawn trawl. The final analysis included 16 models of species or species-groups for the five fisheries. There is no way to directly quantify the effect size of each GAM parameter; therefore, to indicate the relative importance of each variable in explaining the variation in bycatch, we first calculated the difference in the deviance explained by the best model with and without the vessel. We then estimated the importance of each variable from the models in the dredge analysis using the importance function (which sums model weights for each variable across all combinations) from the mumin package⁶⁶.

Exploring the vessel effect

If the best model includes the vessel factor as a random effect, this tells us that something about the individual vessels help explain variations in bycatch. To further explore the vessel effect, we moved to a fixed effect, which tells us which individual vessels matter. However, the fixed effect is very data hungry because it requires estimation of a coefficient for each vessel, instead of estimating the population level variation as in the case of the random effect. We re-ran all the best models that included a vessel effect with the vessel as a fixed effect using a deviation contrast coding. The default in R is to use treatment contrasts to translate categorical factors to a set of variables, where each variable level is compared to a random reference level (meaning any one of the individual vessels). Instead, we used deviation coding (also called sum coding), which compares each level of the vessel variable to the grand mean, thereby providing a better picture of the vessels driving high or low bycatch.

Finally, we explored the relationship between different types of bycatch. Since all the vessels are anonymized, our aim was not to identify particular vessels that had better or worse bycatch rates. Instead, we were interested in correlations between different bycatch species across the individual vessels in each fishery; for instance, if vessels with higher hammerhead bycatch also catch more sea snakes. To generate more robust estimates of the regression coefficients for each vessel, we bootstrapped each estimate 1000 times and then calculated the correlation coefficient between each species pair in the five fisheries.

Declarations

Data Availability

All of the figures and tables in this manuscript have associated raw data from five scientific observer datasets. These databases are confidential access was granted by the Australian Fisheries Management Authority (AFMA), following the terms of a Deed of Confidentiality. The key provisions of the Deed prohibit release of the data, and prohibit any outputs that identify individual vessels. In line with these restrictions, the data needed to recreate the figures and tables in the manuscript will be made freely available in a public GitHub repository.

Code Availability

The code needed to reproduce the figures and tables in this manuscript will be made freely available as R Markdown files in a public GitHub repository.

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Competing Interests

The authors declare no competing interests.

References

- 1 Gray, C. A. & Kennelly, S. J. Bycatches of endangered, threatened and protected species in marine fisheries. *Reviews in Fish Biology and Fisheries* **28**, 521-541, doi:10.1007/s11160-018-9520-7 (2018).
- 2 Soykan, C. U. *et al.* Why study bycatch? An introduction to the Theme Section on fisheries bycatch. *Endangered Species Research* **5**, 91-102, doi:10.3354/esr00175 (2008).
- 3 Lent, R. & Squires, D. Reducing marine mammal bycatch in global fisheries: An economics approach. *Deep-Sea Research Part II: Topical Studies in Oceanography* **140**, 268-277, doi:10.1016/j.dsr2.2017.03.005 (2017).
- 4 Smith, M. D. The New Fisheries Economics: Incentives Across Many Margins. *Annual Review of Resource Economics* **4**, 379-402, doi:10.1146/annurev-resource-110811-114550 (2012).
- 5 Gladics, A. J. *et al.* Fishery-specific solutions to seabird bycatch in the U.S. West Coast sablefish fishery. *Fisheries Research* **196**, 85-95, doi:10.1016/j.fishres.2017.08.015 (2017).
- 6 Squires, D. & Kirkley, J. Skipper skill and panel data in fishing industries. *Canadian Journal of Fisheries and Aquatic Sciences* **56**, 2011-2018, doi:10.1139/f99-135 (2011).
- 7 Hilborn, R. Fleet Dynamics and Individual Variation: Why Some People Catch More Fish than Others. *Canadian Journal of Fisheries and Aquatic Sciences* **42**, 2-13, doi:10.1139/f85-001 (1985).
- 8 Russell, S. D. & Alexander, R. T. The skipper effect debate: Views from a Philippine fishery. *Journal of Anthropological Research* **52**, 433-460, doi:10.1086/jar.52.4.3630296 (1996).
- 9 Tidd, A., Brouwer, S. & Pilling, G. Shooting fish in a barrel? Assessing fisher-driven changes in catchability within tropical tuna purse seine fleets. *Fish and Fisheries* **18**, 808-820, doi:10.1111/faf.12207 (2017).

- 10 Viswanathan, K. *et al.* Fishing Skill in Developing Country Fisheries: The Kedah, Malaysia Trawl Fishery. *Marine Resource Economics* **16**, 293-314 (2002).
- 11 Marchal, P. *et al.* Improving the definition of fishing effort for important European fleets by accounting for the skipper effect. *Canadian Journal of Fisheries and Aquatic Sciences* **63**, 510-533, doi:10.1139/f05-238 (2006).
- 12 Vázquez-Rowe, I. & Tyedmers, P. Identifying the importance of the "skipper effect" within sources of measured inefficiency in fisheries through data envelopment analysis (DEA). *Marine Policy* **38**, 387-396, doi:10.1016/j.marpol.2012.06.018 (2013).
- 13 Gaertner, D., Pagavino, M. & Marciano, J. Influence of fishers' behaviour on the catchability of surface tuna schools in the venezuelan purse-seiner fishery in the Caribbean Sea. *Canadian Journal of Fisheries and Aquatic Sciences* **56**, 394-406, doi:10.1139/f98-191 (1999).
- 14 Ruttan, L. M. & Tyedmers, P. H. Skippers, spotters and seiners: Analysis of the "skipper effect" in US menhaden (*Brevoortia* spp.) purse-seine fisheries. *Fisheries Research* **83**, 73-80, doi:10.1016/j.fishres.2006.08.022 (2007).
- 15 Commonwealth of Australia. Threat Abatement Plan for the incidental catch (or bycatch) of seabirds during oceanic longline fishing operations (2018). Report No. 9781876934231, (Australia Department of the Environment and Energy, Canberra, 2018).
- 16 Jiménez, S., Domingo, A., Abreu, M. & Brazeiro, A. Bycatch susceptibility in pelagic longline fisheries: Are albatrosses affected by the diving behaviour of medium-sized petrels? *Aquatic Conservation: Marine and Freshwater Ecosystems* **22**, 436-445, doi:10.1002/aqc.2242 (2012).
- 17 Phillips, K., Giannini, F., Lawrence, E. & Bensley, N. Cumulative assessment of the catch of non-target species in Commonwealth fisheries: a scoping study. Report No. 978-1-921192-41-8, 1-42 (Australian Government Bureau of Rural Sciences, Canberra, 2010).
- 18 Emery, T. J., Noriega, R., Williams, A. J. & Larcombe, J. Changes in logbook reporting by commercial fishers following the implementation of electronic monitoring in Australian Commonwealth fisheries. *Marine Policy* **104**, 135-145, doi:10.1016/j.marpol.2019.01.018 (2019).
- 19 Tuck, G., Knuckey, I. & Klaer, N. Informing the review of the Commonwealth Policy on Fisheries Bycatch through assessing trends in bycatch of key Commonwealth fisheries. Report No. FRDC final report 2012/046, (FRDC, Canberra, 2013).
- 20 AFMA. Southern and Eastern Scalefish and Shark Fishery: Management Arrangements Booklet 2019. (Australian Fisheries Management Authority, Canberra, Australia, 2019).
- 21 Tulloch, V. *et al.* Long-term trends and a risk analysis of cetacean entanglements and bycatch in fisheries gear in Australian waters. *Biodiversity and Conservation* **29**, 251-282, doi:10.1007/s10531-019-01881-x (2020).
- 22 Kennelly, S. J. Bycatch Beknown: Methodology for jurisdictional reporting of fisheries discards – Using Australia as a case study. *Fish and Fisheries* **21**, 1046-1066, doi:10.1111/faf.12494 (2020).
- 23 Benoît, H. P. & Allard, J. Can the data from at-sea observer surveys be used to make general inferences about catch composition and discards? *Canadian Journal of Fisheries and Aquatic Sciences* **66**, 2025-2039, doi:10.1139/F09-116 (2009).
- 24 Wakefield, C. B. *et al.* Uncertainty associated with total bycatch estimates for rarely-encountered species varies substantially with observer coverage levels: Informing minimum requirements for statutory logbook validation. *Marine Policy* **95**, 273-282, doi:10.1016/j.marpol.2018.05.018 (2018).

- 25 Cox, T. M. *et al.* Comparing effectiveness of experimental and implemented bycatch reduction measures: The ideal and the real. *Conservation Biology* **21**, 1155-1164, doi:10.1111/j.1523-1739.2007.00772.x (2007).
- 26 Hall, M. A. *et al.* in *By-catch reduction in the world's fisheries*. 235-288 (Springer, 2007).
- 27 Trebilco, R. *et al.* Characterizing seabird bycatch in the eastern Australian tuna and billfish pelagic longline fishery in relation to temporal, spatial and biological influences. *Aquatic Conservation: Marine and Freshwater Ecosystems* **20**, 531-542, doi:10.1002/aqc.1115 (2010).
- 28 Chan, H. L. & Pan, M. Spillover Effects of Environmental Regulation for Sea Turtle Protection in the Hawaii Longline Swordfish Fishery. *Marine Resource Economics* **31**, 259-279, doi:10.1086/686672 (2016).
- 29 Innes, J., Pascoe, S., Wilcox, C., Jennings, S. & Paredes, S. Mitigating undesirable impacts in the marine environment: a review of market-based management measures. *Frontiers in Marine Science* **2**, 1-12, doi:10.3389/fmars.2015.00076 (2015).
- 30 Squires, D. & Garcia, S. The least-cost biodiversity impact mitigation hierarchy with a focus on marine fisheries and bycatch issues. *Conservation Biology* **32**, 989-997, doi:10.1111/cobi.13155 (2018).
- 31 Wilcox, C. & Donlan, J. Compensatory fisheries conflicts mitigation as a solution conservation to. *Ecological Society of America* **5**, 325-331, doi:10.1890/1540-9295(2007)5[325:CMAAST]2.0.CO;2 (2011).
- 32 AFMA. Gillnet Dolphin Mitigation Strategy. (Australian Fisheries Management Authority, Canberra, Australia, 2019).
- 33 Komoroske, L. M. & Lewison, R. L. Addressing fisheries bycatch in a changing world. *Frontiers in Marine Science* **2**, 1-11, doi:10.3389/fmars.2015.00083 (2015).
- 34 Mobsby, D. Australian fisheries and aquaculture statistics 2017. Report No. 9781743234150, (FRDC, Canberra, 2018).
- 35 Hardesty, B. D., Good, T. P. & Wilcox, C. Novel methods, new results and science-based solutions to tackle marine debris impacts on wildlife. *Ocean and Coastal Management* **115**, 4-9, doi:10.1016/j.ocecoaman.2015.04.004 (2015).
- 36 Scales, K. L. *et al.* Fit to predict? Eco-informatics for predicting the catchability of a pelagic fish in near real time. *Ecological Applications* **27**, 2313-2329, doi:10.1002/eap.1610 (2017).
- 37 Johnson, T. R. & Van Densen, W. L. T. Benefits and organization of cooperative research for fisheries management. *ICES Journal of Marine Science* **64**, 834-840, doi:10.1093/icesjms/fsm014 (2007).
- 38 O'Keefe, C. E., Cadrin, S. X. & Stokesbury, D. E. Evaluating effectiveness of time/area closures, quotas/caps, and fleet communications to reduce fisheries bycatch. *ICES Journal of Marine Science* **70**, 883-891, doi:10.1093/icesjms/fst034 (2014).
- 39 Barnes, M. L., Lynham, J., Kalberg, K. & Leung, P. in *Proceedings of the National Academy of Sciences* Vol. 113 6466-6471 (2016).
- 40 Arias, A. Understanding and managing compliance in the nature conservation context. *Journal of Environmental Management* **153**, 134-143, doi:10.1016/j.jenvman.2015.02.013 (2015).
- 41 Mangin, T. *et al.* Are fishery management upgrades worth the cost? *PLoS ONE* **13**, 1-24, doi:10.1371/journal.pone.0204258 (2018).
- 42 Brewer, D. *et al.* The impact of turtle excluder devices and bycatch reduction devices on diverse tropical marine communities in Australia's northern prawn trawl fishery. *Fisheries Research* **81**, 176-188, doi:10.1016/j.fishres.2006.07.009 (2006).

- 43 Pascoe, S., Coglan, L., Punt, A. E. & Dichmont, C. M. Impacts of Vessel Capacity Reduction Programmes on Efficiency in Fisheries: The Case of Australia's Multispecies Northern Prawn Fishery. *Journal of Agricultural Economics* **63**, 425-443, doi:10.1111/j.1477-9552.2011.00333.x (2012).
- 44 Patterson, H., Noriega, R., Georgeson, L., Larcombe, J. & Curtotti, R. Fishery Status Reports 2017. Report No. 9781743233559, 547 (Australian Fisheries Management Authority, Canberra, 2017).
- 45 Kelleher, K. Discards in the world's marine fisheries - an update. Report No. 9251052891, 131 (FAO, 2005).
- 46 Pascoe, S. D., Plagányi, É. E. & Dichmont, C. M. in *ICES Journal of Marine Science* Vol. 74 464-474 (2017).
- 47 Abrantes, K. *et al.* Can sawfish bycatch within the Northern Prawn Fishery be mitigated using an electric field? (2020).
- 48 Gourguet, S. *et al.* The Cost of Co-viability in the Australian Northern Prawn Fishery. *Environmental Modeling and Assessment* **21**, 371-389, doi:10.1007/s10666-015-9486-y (2016).
- 49 Laird, A. Northern Prawn Fishery Data Summary 2019. (NPF Industry Pty Ltd, Australia, 2020).
- 50 Emery, T. J., Noriega, R., Williams, A. J. & Larcombe, J. Measuring congruence between electronic monitoring and logbook data in Australian Commonwealth longline and gillnet fisheries. *Ocean and Coastal Management* **168**, 307-321, doi:10.1016/j.ocecoaman.2018.11.003 (2019).
- 51 IUCN. Vol. Version 2020-2 (2020).
- 52 Kirby, D. S. & Ward, P. Standards for the effective management of fisheries bycatch. *Marine Policy* **44**, 419-426, doi:10.1016/j.marpol.2013.10.008 (2014).
- 53 Emery, T., Marton, N., Woodhams, J. & Curtotti, R. Southern and Eastern Scalefish and Shark Fishery. (2020).
- 54 AFMA. *Methods and Gear*, <<https://www.afma.gov.au/fisheries-management/methods-and-gear/longlining>> (2020).
- 55 Wayte, S. *et al.* Ecological Risk Assessment for Effects of Fishing: Report for the otter trawl sub-fishery of the Commonwealth trawl sector of the Southern and Eastern Scalefish and Shark Fishery., 215 (Australian Fisheries Management Authority, Canberra, Australia, 2007).
- 56 Zhou, S., Smith, A. D. M. & Fuller, M. Quantitative ecological risk assessment for fishing effects on diverse data-poor non-target species in a multi-sector and multi-gear fishery. *Fisheries Research* **112**, 168-178, doi:10.1016/j.fishres.2010.09.028 (2011).
- 57 Bergh, M., Gayland, J., Martens, K., Knuckey, I. & Koopman, M. Revised Sampling Regime for the Southern and Eastern Scalefish and Shark Fishery – Final Report, AFMA Project F2008/0627. *Australian Fisheries Management Authority & Fishwell Consulting*, 235, doi:10.13140/RG.2.1.5101.1603 (2009).
- 58 Zhou, S., Campbell, R. A., Hoyle, S. D. & Anderson, E. Catch per unit effort standardization using spatio-temporal models for Australia's Eastern Tuna and Billfish Fishery. *ICES Journal of Marine Science* **76**, 1489-1504, doi:10.1093/icesjms/fsz034 (2019).
- 59 Campbell, R. A. & Young, J. W. Monitoring the behaviour of longline gears and the depth and time of fish capture in the Australian Eastern Tuna and Billfish Fishery. *Fisheries Research* **119-120**, 48-65, doi:<https://doi.org/10.1016/j.fishres.2011.12.006> (2012).
- 60 Team, R. C. R: A language and environment for statistical computing. *R Foundation for Statistical Computing* (2019).

- 61 Benaglia, T., Chauveau, D., Hunter, D. R. & Young, D. S. Mixtools: An R package for analyzing finite mixture models. *Journal of Statistical Software* **32**, 1-29, doi:10.18637/jss.v032.i06 (2009).
- 62 Peel, D. & McLachlan, G. J. Robust mixture modelling using the t distribution. *Statistics and Computing* **10**, 339-348, doi:10.1023/A:1008981510081 (2000).
- 63 Wood, S. *Package 'mgcv'*. (2015).
- 64 Shono, H. Application of the Tweedie distribution to zero-catch data in CPUE analysis. *Fisheries Research* **93**, 154-162, doi:10.1016/j.fishres.2008.03.006 (2008).
- 65 Barton, K. *Package 'mumin'*. (2015).
- 66 Fisher, R., Wilson, S. K., Sin, T. M., Lee, A. C. & Langlois, T. J. A simple function for full-subsets multiple regression in ecology with R. *Ecology and Evolution* **8**, 6104-6113, doi:10.1002/ece3.4134 (2018).

Figures

Figure 1

Vessel bycatch and target catch. Average bycatch compared to target catch per individual vessel for species in five fishing sectors, with standard errors for target and bycatch for each vessel.

Figure 2

Regression coefficients for individual vessels. Vessel was tested as a fixed effect for the 15 models where the vessel factor was significant. Coefficients were rescaled from -1 to 1 across all species in each fishery using the magnitude of the highest coefficient value in that fishery. Coefficients were calculated using deviation contrasts instead of the default treatment contrasts, and ordered by descending coefficient value for each species. Size of dot corresponds to magnitude of standard error for each coefficient estimate (larger dots indicate larger standard error).

Figure 3

Bycatch species correlations. Mean correlation coefficient for 19 species pairs in the five fisheries, calculated from 1000 bootstrapped estimates of each vessel's regression coefficient. Error bars show the minimum (0% quantile) and maximum estimate (100% quantile). Values closer to -1 or 1 indicate stronger correlations between bycatch rates.

Figure 4

Bycatch ratios over time. Annual average ratio of bycatch to target catch for individual vessels in the five fishing sectors. Ratios are the number of individual bycatch animals to individual target animals, or to kg of target catch for the otter bottom trawl and demersal longlines. Ratios are shown on a log transformed scale (except for set gillnets).

Figure 5

Map of the five Australian Commonwealth fisheries. Area shows each fishery's general area of operation, as shown in reports from the Australian Fisheries Management Authority.

Supplementary Files

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