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Bycatch rates in fisheries largely driven by variation in individual vessel behaviour

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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 incidental catch 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, they should also have differing abilities to avoid bycatch. We analysed 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 cases, including species that represent high or low costs to fishers or have economic value as potentially targeted byproducts. Encouragingly, we found high-target and low-bycatch operators in all five sectors, including gears known for high bycatch mortality worldwide. These results show that there is untapped opportunity to reduce negative environmental impacts of fisheries with interventions targeting specific performance groups of individuals, supporting an alternative perspective towards managing global fisheries.

Incidental catch of marine animals in fishing gear ('bycatch') has been recognized as a serious problem for biodiversity and for fisheries' profitability for several decades[1]. 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[2–4]. The most common approaches to reducing bycatch are command-and-control measures implemented across the entire fleet or industry, such as technology requirements or total allowable catch for particular bycatch species[5,6]. These conventional approaches have been successful in certain contexts, such as requiring turtle excluder devices in prawn trawls and bird-scaring lines in some pelagic longline fisheries[1,7,8]. However, they are far from universally successful and often perform worse in practice than models and trials suggested, even when the same approach is translated to a similar fishery[7,9–11].

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. An operator'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 record, such as vessel and gear maintenance, selection of bait, and manoeuvring the vessel to quickly set and haul gear[12]. 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 fisheries[13–16]. Yet, numerous studies show consistent variation in target catch rates among anglers, skippers or fishing vessels that is not explained by environmental variables, characteristics of the boat itself or other economic inputs such as amount of fuel and distance travelled[13,17–19]. This includes technically advanced and homogeneous fleets where operator skill would seemingly be less important[20].

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 the 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 with information about both target and bycatch. We use fisheries scientific observer data from five Australian Commonwealth fisheries sectors to answer three key questions. First, is there significant and predictable variation among operators in their target-to-bycatch ratios? We hypothesize that characteristics at the operator level lead some vessels to consistently perform worse than others and that these characteristics are an important factor driving variations in bycatch across fishing fleets. Second, does the pattern hold across species, gear types and fisheries? We expect to find high-performing operators that avoid bycatch while maintaining high target catch, irrespective of the bycatch context. Third, does skipper skill transfer across species? We posit that certain bycatch types 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 threatened species bycatch. Instead of a random event across a fishery, it may be an issue of particular low-performance operators. In this case, measures aimed directly at those individuals could be more effective at reducing threatened species bycatch than common whole-fishery solutions.

Results

To explore patterns in bycatch among individual fishing vessels, we analysed 17,030 fishing events (setting and hauling the gear) from 297 vessels between 2001 and 2017 (Supplementary Table 1). The observer datasets are from five fisheries with different gear types and geographic areas: prawn trawls, tuna longlines, set gillnets,

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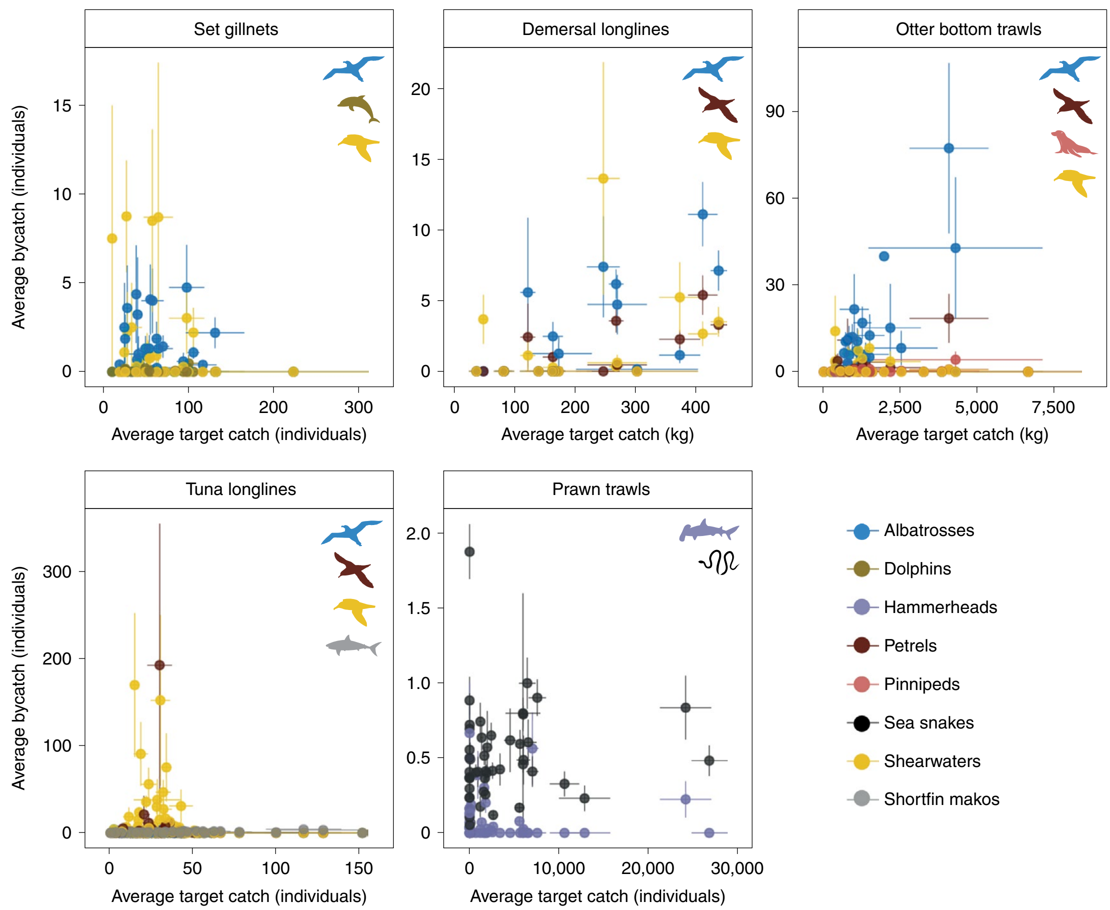

Fig. 1 | Vessel bycatch and target catch. Bycatch compared with target catch per individual vessel for species in five fishing sectors, averaged across all fishing events recorded for each vessel. Bycatch includes individuals that were caught or landed as well as interactions where the animal escaped. The lines show standard errors for target and bycatch for each vessel. Species icons adapted from flaticon.com (albatross and petrel), vecteezy.com (shearwater) and thenounproject.com (shortfin mako, hammerhead, dolphin and sea snake).

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 (Fig. 1 and Supplementary Fig. 1). Several operators with the highest average target catch had some of the lowest average bycatch rates (for example, seabirds in tuna longlines), and conversely, the highest bycatch rates were from operators with lower target catch (for example, 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 (for example, depth and association with target species). 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 (for example, bait type and gear orientation). Overall, the models performed well and explained anywhere from 12% to 95% of the deviance in bycatch (Table 1 and Supplementary Table 2).

We expected that time and location would be the dominant drivers of bycatch variability. Instead, the individual vessel (which was significant in 15 of 16 bycatch–fishery models) consistently had the highest important score and explained anywhere from 5% to 67% of the expected deviance in the models (Table 1 and Supplementary Table 2). Year was also an important factor 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 bycatch species availability[21]. Tactical and environmental factors that were significant for some bycatch contexts included geographic location, month, time of day, depth and type of operation (relevant only to the tuna longlines). The 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 (for example, seabirds and tuna, where fishers often use seabirds to locate the tuna), although it was within two Akaike information criterion (AIC) points of all best models for seabirds. This could be explained by shifting fishing practices to avoid seabird bycatch, such as the adoption of bird-scaring lines, night setting and area closures[21]. Surprisingly, targeting cluster was included in only 4 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. Including a random effect for the vessel allowed us to test whether the population of vessels differed in their bycatch rates across fishing events. 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. 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 (Fig. 2). The regression coefficients indicate that in each fishery, specific vessels are significant

Table 1 | Best model summaries for 16 species–fishery interactions

Model	Target catch	Year	Month	Latitude/longitude	Targeting cluster	Depth	Operation type	Percentage in light	Shot duration	Vessel	Deviance explained (%)	ΔDeviance
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 (f.e.)**	25.3	5.2
Prawn trawl												
Hammerheads		x	x	x		x	–	–	–	**x (f.e.)**	95.4	35.2
Sea snakes	x	x	x	x	x		–	–	–	**x (f.e.)**	84.8	62.2

Factors with 'x' were included in the best model. Factors with '–' were not applicable to that model. Target catch is the volume or number of individuals. Depth represents the depth of fishing gear (either the start or end of the set, depending on the dataset). Operation type represents the fishing operation for pelagic longlines (for example, standard operations or bycatch mitigation trial). Percentage in light represents the percentage of the fishing event in daylight. Shot duration represents the duration of the fishing event in hours. Vessel was included as a random effect unless the fixed effect (f.e.) model had a lower AIC score. If the random effect was not significant, the vessel term was excluded from the best model. ΔDeviance is the difference in deviance between the best model with and without the vessel term. Each model is offset with a metric of fishing effort so that it is bycatch per unit effort.

predictors of high-bycatch fishing events, and others predictably have lower-than-average bycatch. Overall, there is evidence of three broad patterns in bycatch avoidance skill. Most of the models have a roughly bimodal pattern of coefficients (for example, demersal longlines), indicating that the fleet is split evenly between low- and high-bycatch operators. Gradients in the regression coefficients indicate a range of operator avoidance performance (for example, shearwaters in otter bottom trawls and petrels in tuna longlines). Large gaps in the spread of positive regression coefficients suggest potential targeting behaviour (for example, dolphins and potentially hammerheads). Conversely, clusters of very negative coefficients suggest groups of skilled bycatch avoiders (for example, sea snakes and shortfin makos). However, individual regression coefficients for vessels in the otter bottom trawl, tuna longline and prawn trawl sectors are not significant and have large standard errors, meaning that there is high uncertainty around how specific vessels drive bycatch variability in those sectors (Fig. 2 and Supplementary Fig. 2).

We used correlation tests of vessels' regression coefficients to explore the relationships between bycatch types within each fishery. All but one species pair (hammerheads and sea snakes in the prawn trawl sector) were positively correlated (Fig. 3). In most cases, we found stronger correlations between logically related bycatch groups. For instance, bycatch of different seabird groups in tuna longlines was more strongly correlated than that of seabirds and shortfin makos, and all seabird species showed strong correlations in demersal longlines. The patterns in the set gillnet and otter bottom trawl sectors were less intuitive, with strong correlations between marine mammals and certain seabird species, but weaker correlations between most seabird groups. A likely explanation is that different diving and foraging behaviours of seabird species within our broad seabird groups—and interspecific interactions when multiple species are present—affect their catchability and attraction to viscera and waste disposed from the boat[22,23]. Exploration at greater taxonomic resolutions would help resolve the correlations in bycatch rates between different bycatch 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 evaluated variability among operators over time and found variable improvements in bycatch-to-target ratios across fisheries (Fig. 4), although it is difficult to compare rare and common bycatch. Following a series of regulatory changes and bycatch mitigation programmes, the observer data show a dramatic reduction in seabird bycatch in the tuna longlines from a fleet-wide average of over 100 birds per fishing event in 2001 down to zero in 2015 (Fig. 4). These very high averages are probably inflated by bycatch mitigation trials in the early 2000s that were not normal operations, but logbooks and recent electronic monitoring data corroborate a significant improvement in seabird bycatch overall[24]. The set gillnet, demersal longline and otter bottom trawl sectors also underwent a series of regulatory changes related to bycatch[21], and the most recent years of observer data indicate that seabird catch rates may be declining. Compared with seabirds, cetacean and pinniped interactions are rare, and it is difficult to detect a trend in the observer data, but bycatch of these species remains a major concern[25]. As expected, catch rates of shortfin mako—a byproduct species with a catch limit per fishing trip—did not decrease like seabird catch rates. The trends for hammerheads and sea snakes are unclear, and changes could be driven by changes in the abundance of bycatch species as opposed to fishing practices. Most importantly, variability among operators persisted over time in all fisheries, indicating that there remains opportunity for further reduction in bycatch rates.

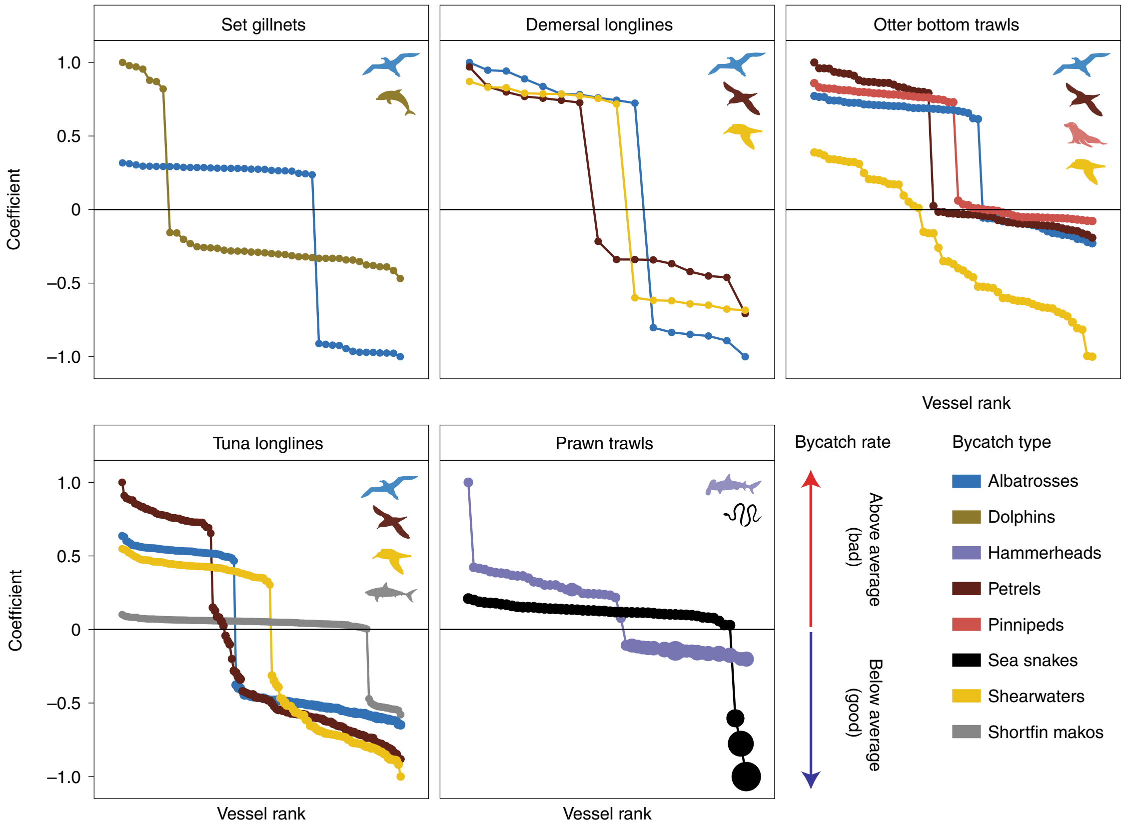

Fig. 2 | Regression coefficients for individual vessels. Vessel was tested as a fixed effect for the 15 models where the vessel factor was significant. The coefficients were rescaled from −1 to 1 across all species in each fishery using the magnitude of the highest coefficient value in that fishery. The coefficients were calculated using deviation contrasts instead of the default treatment contrasts and are ordered by descending coefficient value for each species ('Vessel rank': vessels with the highest predicted bycatch rates are on the top left, and those with the lowest predicted bycatch rates are on the bottom right). The dot size corresponds to the magnitude of the standard error for each coefficient estimate (larger dots indicate larger standard errors). Species icons adapted from flaticon.com (albatross and petrel), vecteezy.com (shearwater) and thenounproject.com (shortfin mako, hammerhead, dolphin and sea snake).

Discussion

Controlling for factors affecting bycatch availability, targeting tactics and changes in fleet structure and management over time, we found that individual operators have a significant effect on bycatch levels across a range of species and fishing methods. We detected operator variability over a relatively long period and across five observer datasets known to have good accuracy[26]. Our results thus support our hypothesis that bycatch avoidance is a skill much like targeting. We posit three main drivers of the variable avoidance performance: (1) avoidance may be inherently more difficult for some gears and species and therefore require greater skill[27,28]; (2) different types of bycatch differ in their effect on fishing operations, so the motivation to avoid probably differs across species and gears[29,30]; and (3) there are incentives to catch some byproduct species, potentially making them clandestine targets[30,31]. Notably, even in globally high-impact gears known to catch a wide range of bycatch (for example, gillnets and demersal trawls)[32], we found that a small group of operators can avoid a range of bycatch types (including valuable byproducts) while still maintaining high target species catch, challenging the long-standing assumption that reduction of bycatch necessitates reduction of target catch[4]. These high-performance operators present an untapped opportunity to greatly improve the environmental performance of fisheries, without necessarily mandating additional gear modifications or other restrictions on fishing effort.

Limitations of observer data. We assume that the data provide an accurate representation of fishing activities, although observer data are known to have biases and inconsistencies and typically cover only a small fraction of the fishing effort[33,34]. We suspect that there is an observer effect, where operators may behave differently and avoid known bycatch areas when observers are present (for example, islands with large seabird colonies). However, these scientific observer programmes were entirely research-focused, and the observers had no enforcement power, so their presence should have less influence on fisher behaviour. Overall, we expect that we underestimate the variability in bycatch avoidance skill because low-performing vessels and high-bycatch fishing events are probably underrepresented in our sample. The implementation of electronic monitoring and quality-checked logbooks opens doors to much larger datasets. This can help resolve uncertainties around the extent of the observer effect, what characteristics of the vessel and crew drive bycatch rates, correlations between different types of bycatch, and interactions between the individual vessel and other aspects of fishing practices (for example, there may be groups of operators that consistently fish in high-bycatch areas but still have variable bycatch rates).

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. It might be that the low-bycatch operators are more conscientious about using their gear (for example, 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 conditions at sea)[10,35]. Our results suggest that there are characteristic groups of operators in

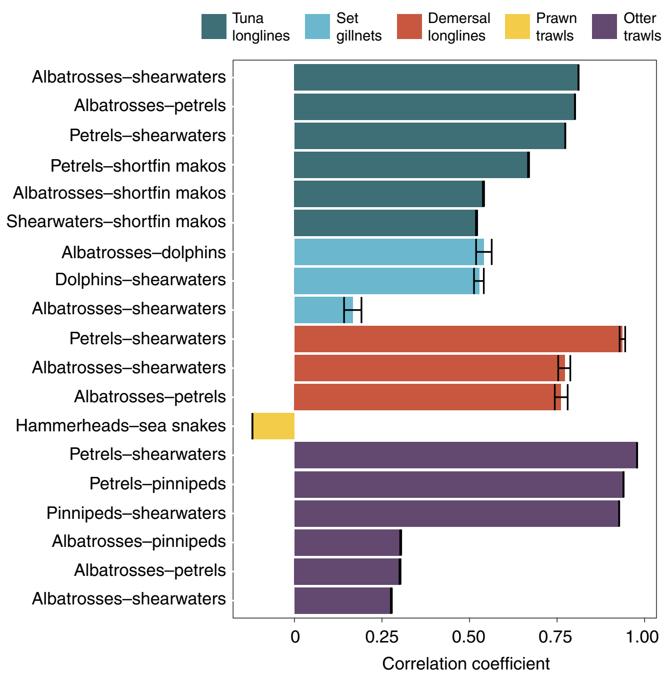

Fig. 3 | Correlations between bycatch types. Mean correlation coefficient for 19 bycatch type pairs in the five fisheries, calculated from 1,000 bootstrapped estimates of each vessel's regression coefficient. The error bars show the minimum (0% quantile) and maximum estimates (100% quantile). Values closer to −1 or 1 indicate stronger correlations between bycatch rates.

each fishery, with more obvious delineations in some sectors. High performers have below-average bycatch while maintaining high target catch; low performers are the opposite. Between these extreme contexts is a range of skill levels, as well as important ecological and geographic factors. For example, high-target and high-bycatch operators could be fairly adept at catching target species, but the large catch and subsequent large offal disposal attract many bycatch species. These operators may not have developed innovations or invested in bycatch mitigation techniques such as offal holding tanks to avoid discharging while gear is in the water[8].

Avoiding different types of bycatch—such as seabirds versus sharks—probably demands different types of skills. Observer coverage was not sufficient for an analysis of individual operator performance across multiple bycatch types over time, especially for rarer species. However, we found evidence of relationships between certain bycatch types. 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. These operators might be skilled but 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 and bycatch penalties, as well as perverse incentives to catch some bycatch, such as species with market value[5,30]. Our results suggest that some incentives may be more salient to fishers than others. For instance, the dramatic decrease in seabird bycatch in tuna longlines in Australia indicates that bycatch mitigation measures were effective (independent of changes in seabird abundance)[36] and probably worked in tandem with changing attitudes within the fishery[37]. Seabirds have no market value, cost time and waste a hook. Management measures strengthened the inherent avoidance incentive by imposing a hefty financial penalty, where fishing areas with high bycatch rates were closed if the bycatch rate exceeded the threshold[36]. Since the penalty was imposed across the fleet, presumably there was also hidden social pressure within the fisher network[35]. In contrast, seabird bycatch reduction measures have been less successful in the otter bottom trawl, demersal longline and set gillnet sectors[21], perhaps because seabird bycatch mitigation equipment for these gears is more difficult to operate effectively, or because there is less avoidance incentive. Input controls were introduced in these sectors (for example, mandating at least one approved bycatch mitigation device on trawls) but were not coupled with the high-bycatch penalty as in the tuna longlines[21].

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 (with a 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, reduce target catch, stymy innovation and customization to each context, and fail to encourage continuous improvement beyond the regulatory minimum[5,38–40]. Although the input controls in the tuna fishery ultimately had 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 programme for tuna purse seine fisheries in the Pacific, which assigns individual dolphin mortality limits in addition to other measures[5,35]. In Australia, a new strategy to reduce dolphin bycatch in set gillnets applies maximum interaction rates and subsequent penalties to individual vessels, but the results have not yet been released.

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. Even low bycatch rates can threaten the viability of seriously endangered populations[11]. 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 fisheries[41]. This suggests that there remains latent potential to further reduce bycatch 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 penalties) can encourage continuous improvement and have been successfully applied to bycatch in a few fisheries[5,8,42], as well as other environmental problems such as littering and marine debris[43].

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 pressure as much as seabirds, and may be an issue primarily of lack of motivation 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 value in legal or illegal markets, such as many elasmobranchs. There may be rare bycatch incidents that are truly accidental and unpredictable, but our results indicate that these are outliers and fishers do

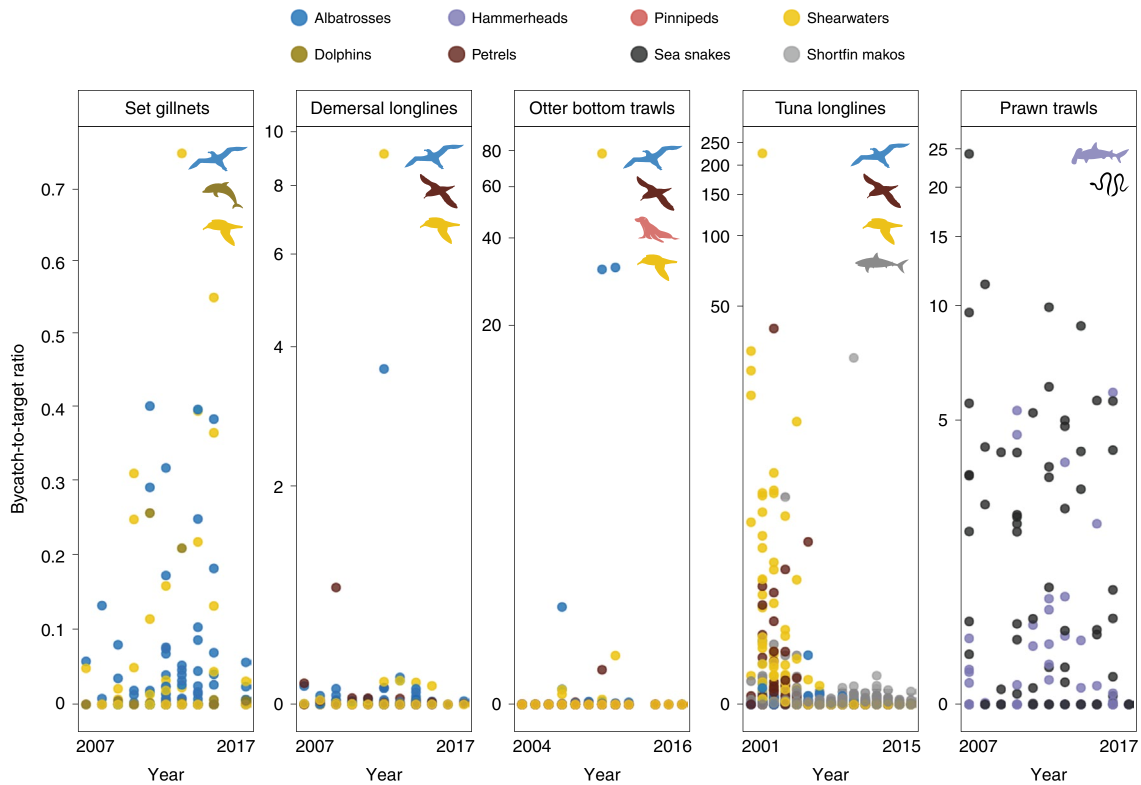

Fig. 4 | Bycatch ratios over time. Ratio of bycatch to target catch for individual vessels in the five fishing sectors, averaged across all fishing events for each vessel each year. Bycatch includes individuals that were caught or landed as well as interactions where the animal escaped. The ratios are the number of individual bycatch animals to the number of individual target animals, or to kg of target catch for otter bottom trawls and demersal longlines. The ratios are shown on a log-transformed scale (except for set gillnets). Species icons adapted from flaticon.com (albatross and petrel), vecteezy.com (shearwater) and thenounproject.com (shortfin mako, hammerhead, dolphin and sea snake).

possess untapped knowledge and innovation to reduce bycatch, even for globally problematic bycatch interactions.

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 management actions. Insights into the biophysical drivers of catch and bycatch (for example, sea surface temperature, frontal systems and isothermal layer depth) probably help explain some aspects of how high-performing operators are fishing[44]. 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. We observe the phenomenon of a strong vessel effect but can only hypothesize what underlying mechanisms are responsible. We refer to these mechanisms collectively as the 'skipper effect', although they probably vary across fisheries and may not always be driven by the skipper. For example, in many tuna fleets the ultimate decision power lies with a 'Master Fisher' who is in constant communication with the boat owner[45].

It is essential that scientists and managers collaborate directly with fishers—and facilitate peer-to-peer learning and communication among fishers and managers—to understand what characterizes high-performing vessels and spread that optimal performance across the fishery[35,46–48]. This level of engagement is expensive and time-consuming but would be a worthwhile long-term investment. Enforcement is the largest expense for fisheries management globally, and increasing voluntary compliance would greatly reduce those costs[49,50]. In this context, voluntary compliance could mean shifting from bycatch limits and technology requirements to using social and economic incentives to encourage innovation at the individual level—for example, triggering peer pressure by reporting vessel bycatch rates back to the fleet or rewarding low-bycatch operators using bonds, insurances or quotas[8,38,51].

We found evidence of variable bycatch performance among operators from a range of fisheries and suspect that this is a general pattern that exists in many contexts, including non-industrial and recreational fisheries and other geographic regions. If so, we should approach bycatch management with the expectation of variable bycatch avoidance performance, instead of treating it as a fleet-level problem. Our results suggest that some fishers already voluntarily avoid bycatch even if it does not incur penalties or major costs to their operations, and they 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 global bycatch rates beyond what currently seems feasible[8]. The importance of variable skills and behaviours of individual operators could extend beyond threatened species bycatch to the management of other environmental impacts, such as gear abandonment and waste discharge. Increased uptake of bycatch avoidance strategies 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 used observer data provided by the Australian Fisheries Management Authority (AFMA) for five federally managed fishing sectors in Australia: Northern Prawn Fishery (prawn trawls), Eastern Tuna and Billfish Fishery (tuna longlines) and three subsectors of the Southern and Eastern Scalefish and Shark Fishery (SESSF), referred to here as demersal longlines, otter bottom trawls and set gillnets (Supplementary Table 1 and Supplementary Figs. 3 and 4).

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 periods and in mostly distinct regions of the management area, and use slightly different types of trawl gear[52,53]. Prawn trawls typically have high environmental impact, including high bycatch rates[2]. Yet, the Northern Prawn Fishery received Marine Stewardship Council accreditation in 2012, largely due to its proactive and science-driven management framework[54]. The fishery has been restructured over several decades through a series of management measures and buyback programmes of less-efficient vessels, with a reduction from about 280 to 52 vessels[55]. In 2000, prawn trawls required approved turtle excluder devices and bycatch reduction devices, allowing operators to select their desired combination of devices[52]. Overall, the turtle excluder devices and bycatch reduction devices have substantially reduced catches of larger animals such as sea turtles and large elasmobranchs—although sawfish (Pristidae) are an important exception—but have been much less effective for smaller animals such as seahorses and sea snakes[28,56]. The scientific observer programme covers about 2% of fishing days[57].

The Eastern Tuna and Billfish Fishery is a pelagic longline fishery operating year-round in the exclusive economic zone and adjacent high seas off Australia's East Coast (Supplementary Figs. 3 and 4). Structural readjustments and new harvest strategies over the past two decades have reduced the number of vessels from 150 to about 40 active vessels, with the more economically efficient vessels remaining[41]. 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 deploy gear at night in some areas[41]. Wire leaders were banned in 2005 to reduce shark bycatch, although vessels are permitted to retain up to 20 individuals per trip—meaning that they are actually byproduct as opposed to bycatch[41]. Seabird bycatch mitigation has been successful, but there is still concern about other species. Shortfin mako sharks (*Isurus oxyrinchus*) were recently upgraded to Endangered on the IUCN Red List and are the most common protected species caught in the tuna longline fishery[21]. Leatherback turtles (*Dermochelys coriacea*) are much rarer occurrences but are listed as Critically Endangered in the Western Pacific[21]. The tuna longline fishery has had a scientific observer programme since 2001, which has ranged from 3.5% to 8% of fishing days[58].

The SESSF is a multispecies, multigear and multisector fishery with the largest catch volumes of any federal fishery and a management area covering almost half of Australia's fishing grounds[41]. Many SESSF stocks were overfished (and some remain overfished); it was therefore one of the first fisheries targeted by the federal government's structural adjustment programmes to reduce fishing effort and improve economic efficiency[41]. The SESSF observer programme focuses on discarded fish species[21]. The identification of morphologically similar bycatch species (for example, many shearwaters, albatrosses and petrels) may not be as reliable as for the tuna longline observer programme, which has a strong seabird focus and far fewer target species to identify. Overall, observer coverage has increased since the programme was implemented in 1992, with required coverage varying according to the subsector and area (from zero coverage up to 100% observation required near certain marine mammal colonies and closure areas)[59].

We focus on three gear types used in SESSF fishing subsectors: bottom set gillnets, otter bottom trawls and auto-demersal longlines (referred to here as 'demersal longlines'—'auto' refers to how the hooks are baited and where the fishery is allowed to operate) (Supplementary Figs. 3 and 4). The gillnet sector mainly targets elasmobranchs, whereas the otter bottom trawl and demersal longline sectors predominantly target bony fish (teleosts)[60,61] (Supplementary Table 1). 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 system[61]. In addition to these byproduct species, the SESSF sectors catch a variety of protected species groups, including marine mammals (cetaceans and pinnipeds), seabirds, seahorses and pipefish, and large sharks (for example, shortfin makos and hammerheads, *Sphyrna* spp.). Bycatch of pinnipeds and cetaceans is frequently cited as a major environmental concern for the SESSF[21].

Fisheries observer data. The observer programmes for the five fisheries are all scientific and not affiliated with enforcement agencies, but they differed in their research objectives and programme design. For example, the scientific monitoring programme for set gillnets, demersal longlines and otter bottom trawls was originally designed to collect data on target species[21], and the focus only expanded to threatened and protected species in the early 2000s. We thus excluded the early years from the analysis because almost no bycatch records appeared in the observer data. To sample the range of operators as best as possible, we included all observer trips within our time frames 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. We therefore suspect that our data have more complete coverage of high-performing than of low-performing vessels. Since 2015, electronic monitoring systems have been slowly replacing at-sea observers in these Commonwealth fisheries.

To account for species-specific dynamics that affect bycatch availability, we maintained the highest possible taxonomic resolution when identifying candidate bycatch groups (Supplementary Table 1). Species-level identification by scientific observers is generally accurate for easily identified species (for example, shortfin makos) and to the genus or family level for common species (for example, albatrosses), but is less reliable for rare or similar-looking species (for example, different species of albatrosses)[36]. Taxonomically vague groups such as shearwaters and petrels are problematic and inconsistent across the observer programmes. We included common or species-specific groups and excluded the most taxonomically vague groups with fewer records (for example, 'petrels, prions and shearwaters'). The flesh-footed shearwater (*Ardenna carneipes*) dominates all shearwater bycatch, whereas the petrel and albatross groups vary in species composition across the five fisheries.

Statistical analyses. For the measure of target catch, we used the sum of the number of individuals of the target species from each fishing event. For the set gillnet, otter bottom trawl and demersal longline sectors, which do not have a well-defined list of targets, we used all retained catch as the target catch (recorded as the number of individuals for the set gillnet sector and as weights for otter bottom trawls and demersal longlines). For the Eastern Tuna and Billfish Fishery, we included only the five main target species (albacore, bigeye tuna, yellowfin tuna, 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; we therefore 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 generalized additive model (GAM) implemented in the mgcv package in R[62]. 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. These distributions handle very zero-inflated data well because they are a mixture of Poisson and gamma distributions[63]. We incorporated 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 (percentage 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. There is usually 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 (the number of hooks was not available for demersal longlines).

In addition to the available parameters, we derived a targeting factor to capture unknown strategies used in multispecies fisheries to target subgroups of target species[64,65]. For example, in the tuna longline fishery, swordfish are targeted with shallow night sets, often using fluorescent sticks attached to the lines[66]. These tactics affect the catchability of bycatch species but can be difficult to define and record. We used model-based clustering (also called 'finite mixture modelling') of the target species recorded in the observer data to define subgroups of target species and assign a targeting cluster to each fishing event[67]. We used the mixtools package in R, which uses a mixture of beta distributions to describe the probability of each target species occurring in a single fishing event[68,69]. An advantage of the mixtools infrastructure—compared with common tools for finite mixture modelling such as mclust—is that it relaxes the assumption of multivariate normality, allowing the fitting of non-parametric models and mixtures of regressions[67,68]. In the context of multispecies fisheries with many and often poorly defined targets, this means that the computational technique considers the ratio of target species counts in each fishing event, 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 values[70]. 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 and used the best-fitted model to classify each fishing event as one of the targeting types, assigning it randomly in the case of ties.

We then 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 or group. We compared all possible combinations of factors in the best global model (with vessel and observer as either fixed or random effects) using the dredge function from the mumin package in R. We 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 ($\Delta AIC < 2$), we selected the simpler one with fewer factors. We assessed the final model to verify that the data were not overdispersed 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 tuna longlines and prawn trawls, marine mammals in tuna longlines, seahorses and pipefish in otter bottom trawls, and sawfish in prawn trawls. 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 package.

If the best model includes the vessel factor as a random effect, this tells us that something about the individual vessels helps 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 the estimation of a coefficient for each vessel, instead of estimating the population-level variation as in the case of the random effect. We reran 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 and no information about vessel characteristics was provided, our aim was not to identify particular vessels that had better or worse bycatch rates. Instead, we were interested in correlations between different bycatch types across the individual vessels in each fishery—for instance, whether 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 1,000 times and then calculated the Pearson's correlation coefficient (r) between each species pair in the five fisheries.

Reporting Summary. Further information on research design is available in the Nature Research Reporting Summary linked to this article.

Data availability

All the figures and tables in this manuscript have associated raw data from five confidential scientific observer datasets. Access was granted by AFMA, following the terms of a Deed of Confidentiality between AFMA and the authors. The key provisions of the Deed prohibit release of the data in any form and prohibit any outputs that identify individual vessels or any characteristics of the vessels. In line with these restrictions, the data needed to replicate the statistical analyses cannot be released, but the summarized and fully anonymized data needed to recreate the figures in the manuscript are freely available as CSV files in a public GitHub repository (https://github.com/lroberson/skippersbycatch_pub). The data needed to recreate Table 1 and Supplementary Table 2 (the results of the statistical models) cannot be released because they include fishing locations. Source data are provided with this paper.

Code availability

The code needed to reproduce the figures in this manuscript is freely available as R Markdown files in a public GitHub repository (https://github.com/lroberson/skippersbycatch_pub).

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Author contributions
C.W. conceived the original idea for the study and L.A.R. further developed the concept to its current state. L.A.R. performed the analysis and interpreted the results, with C.W.'s input on both components. L.A.R. wrote the manuscript with editorial contributions from C.W.

Competing interests
The authors declare no competing interests.

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Our web collection on statistics for biologists contains articles on many of the points above.

Software and code

Policy information about availability of computer code

Data collection	No data were collected for this study
Data analysis	All analyses were conducted using the free software R (version 4.1.0) in the RStudio user interface (Version 1.4.1106). The code used to produce the figures and tables will be provided as an R Markdown file in a public GitHub repository.

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- A description of any restrictions on 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.

Field-specific reporting

Please select the one below that is the best fit for your research. If you are not sure, read the appropriate sections before making your selection.

☐ Life sciences ☐ Behavioural & social sciences ☒ Ecological, evolutionary & environmental sciences

For a reference copy of the document with all sections, see nature.com/documents/nr-reporting-summary-flat.pdf

Ecological, evolutionary & environmental sciences study design

All studies must disclose on these points even when the disclosure is negative.

Study description	This study used five scientific observer datasets provided by the Australian Fisheries Management Authority to analyze variability in bycatch rates of threatened, endangered, or protected species among individual fishing vessels.
Research sample	This study used existing datasets collected by scientific fisheries observers. The observer program only covers a small proportion of the total fishing effort, and that proportion varies by fishery and by year. We used as much of the observer data as possible (that was of acceptable quality to include in our models). From the bycatch data, we selected 8 threatened, endangered, or protected species with enough records to include in the analysis (for a total of 16 species-fishery models).
Sampling strategy	Sampling strategy is not relevant to this study. We included all available observer data that met the quality standards for our analysis.
Data collection	The data were collected by scientific observers trained by the Australian Fisheries Management Authority. The requirements for scientific observers vary by fishing sector, but some level of coverage from onboard observers is required in all five fisheries included in this study (or was required during the timeframe of the data).
Timing and spatial scale	We included data from 2001-2015 for the tuna longlines, 2007-2017 for the prawn trawl, set gillnets, and demersal longlines, and 2004-2016 for the otter bottom trawl. The end dates are the most recent data that were made available to us. All spatial records were included, unless spatial information was missing or obviously incorrect (e.g., coordinates on land).
Data exclusions	Records of individual fishing events were excluded if information on key parameters was missing (e.g., date, location, depth, etc). For three of the five datasets (set gillnets, otter bottom trawls, demersal longlines), the dataset began in 1992 but only records from 2007, 2004, and 2007 onwards were included for these sectors, respectively. We chose these thresholds based on available literature about the observer programs and when recording of our focus species began.
Reproducibility	We ran the code several times to ensure reproducibility.
Randomization	Randomization was not relevant to our study. No experiments were conducted in this study.
Blinding	Blinding was not relevant to our study. No experiments involving live subjects were conducted in this study.

Did the study involve field work? ☐ Yes ☒ No

Reporting for specific materials, systems and methods

We require information from authors about some types of materials, experimental systems and methods used in many studies. Here, indicate whether each material, system or method listed is relevant to your study. If you are not sure if a list item applies to your research, read the appropriate section before selecting a response.

Materials & experimental systems

n/a	Involved in the study	
☒	☐	Antibodies
☒	☐	Eukaryotic cell lines
☒	☐	Palaeontology and archaeology
☒	☐	Animals and other organisms
☒	☐	Human research participants
☒	☐	Clinical data
☒	☐	Dual use research of concern

Methods

n/a	Involved in the study	
☒	☐	ChIP-seq
☒	☐	Flow cytometry
☒	☐	MRI-based neuroimaging