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Article Impact statement: A cost-effectiveness approach to mitigate dolphin and whale bycatch is cheaper and provides greater benefits over traditional conservation methods.

Abstract

Globally, fisheries bycatch threatens the survival of many whale and dolphin species. Strategies for reducing bycatch can be expensive. Management is inclined to prioritize investment in actions that are inexpensive, but these may not be the most effective. We used an economic tool, return-on-investment, to identify cost-effective measures to reduce cetacean bycatch in the trawl, net, and line fisheries of Australia. We examined 3 management actions: spatial closures, acoustic deterrents, and gear modifications. We compared an approach for which the primary goal was to reduce the cost of bycatch reduction to fisheries with an approach that aims solely to protect whale and dolphin species. Based on cost-effectiveness and at a fine spatial resolution, we identified the management strategies across Australia that most effectively abated dolphin and whale bycatch. Although trawl-net modifications were the cheapest strategy overall, there were many locations where spatial closures were the most cost-effective solution, despite their high costs to fisheries, due to their effectiveness in reducing all fisheries interactions. Our method can be used to delineate strategies to reduce bycatch threats to mobile marine species across diverse fisheries at relevant spatial scales to improve conservation outcomes.

Introduction

Fisheries bycatch is a serious direct threat to cetaceans; dolphin and whale bycatch during the 1990s exceeded 300,000 annually (Read et al. 2006). In addition to threatening the survival of many species globally, bycatch also has negative economic impacts on fisheries, for example by damaging or destroying gear (Alverson 1994; Dunn et al. 2011). Continued human population growth and industrialization of fisheries have led to intensification of fishing effort in many regions, increasing the likelihood of fisheries bycatch (Lewison et al. 2014). Requirements to reduce interactions between cetaceans and fishing gear exist in the national legislation of many countries (e.g., U.S. Marine Mammal Protection Act). Despite new technologies and industry recognition of the problem, monitoring and management can be costly and ineffective (Dolman et al. 2016).

Lethal effects of cetacean interactions with fishing gear include strangulation, increased drag, lacerations, infection, and loss of limbs (Cassoff et al. 2011). Sublethal effects of entanglement in fisheries gear may reduce an individual's fitness and ability to successfully reproduce, catch prey, and avoid predation (Moore & Van der Hoop 2012). The slow reproductive cycles and long life histories of large whales, and limited rates of increase for most small cetaceans, reduce the ability for many cetacean populations to recover from localized population reductions resulting from fatal fisheries interactions. The need to reduce fisheries interactions is urgent as evidenced by the bycatch-related extinction of the baiji (*Lipotes vexillifer*) (Turvey et al. 2007) and the imminent extinction of vaquita (*Phocoena sinus*) and the North Atlantic right whale (*Eubalaena glacialis*) (Harcourt et al. 2019; Taylor et al. 2017).

Solutions to mitigate cetacean bycatch have targeted specific fisheries and gears (e.g., longline [Hamer et al. 2012]; gill net [Trippel et al. 1999], trawl [Hamer et al. 2008], trap [How et al. 2015]) or individual species (e.g., Hamer et al. 2008; Leaper 2016). Such targeted management can be effective if interactions only occur between a particular population and gear type or fishery. Most dolphin and whale populations, however, face incidental capture from multiple fisheries and gears, particularly highly mobile species that have large geographic ranges. Accordingly, broad-scale spatial approaches to mitigation are needed to address bycatch across multiple fisheries at the scale at which species occur.

Strategies to reduce bycatch can be costly to implement and monitor, constraining management's capacity to act across multiple fisheries. Strategies also differ in their effectiveness across species. For instance, spatial closures effectively reduce interactions between marine species and multiple fisheries but can be prohibitively expensive due to lost fishery revenue. An inherent conflict exists therefore between maximizing conservation outcomes of bycatch mitigation versus ensuring economic viability of fisheries (Wilcox & Donlan 2007). This conflict may hinder the ability of managers to make effective decisions that meet both conservation and fisheries management objectives. Simultaneously considering the costs and benefits of multiple threat-management actions leads to an understanding of where to expect the greatest conservation benefit while ensuring economic objectives are met (Wilson et al. 2007). Although research exists on the costs and benefits of bycatch measures (e.g. Gjertsen et al. 2014), no one has addressed bycatch in multiple fisheries of multiple marine megafauna species at appropriate spatial scales.

Decision theory is a rational systematic framework for choosing between different strategies and optimizing decisions with uncertain consequences (Possingham et al. 2001). Integration of economic techniques into decision theory to efficiently solve conservation problems allows the explicit inclusion of costs. Techniques such as return-on-investment (ROI) are increasingly used to explore trade-offs in prioritizing conservation investment on land (Auerbach et al. 2014). Conservation ROI analysis quantitatively measures the costs, benefits, and risks of investments so decision makers can rank or prioritize actions. Successful examples include removing introduced species to maximize native species persistence (Auerbach et al. 2014) and trading off land conversion and acquisition with habitat loss (Murdoch et al. 2010). Cost-effectiveness analysis, a form of ROI, provides a measure of efficiency for alternative courses of action based on their monetary costs and their often nonmonetary outcomes or effects. These analyses are increasingly used in conservation to help managers choose between different mitigation actions given financial constraints by trading off benefits to species (Hughey et al. 2003; Murdoch et al. 2007), thereby allowing managers to identify where the highest rate of conservation return will be (i.e., greatest benefit to biodiversity) for the lowest cost. Until now, ROI approaches have not been applied to mitigating fisheries bycatch despite the obvious benefits of using economic techniques to achieve multiple objectives and visualize the costs and benefits of different decisions.

We propose a new approach to strategically and efficiently target reductions in bycatch of whales and dolphins across fisheries. We applied decision-theoretic bioeconomic techniques to inform the reduction of cetacean bycatch in a case study of Australian fisheries. We defined bycatch as the accidental capture of nontarget species in active fishing gear, versus interactions with inactive or floating fishing gear. We modeled ROI by comparing the level of investment in a bycatch-mitigation action and the expected conservation outcome (i.e., bycatch reduction for affected cetaceans). We examined where cetaceans are most vulnerable to potential bycatch,   the most cost-effective actions, where actions should be targeted to best mitigate cetacean bycatch, and the trade-offs between an ROI approach to fisheries bycatch mitigation and traditional conservation approaches that maximize benefits to species.

Methods

Fisheries bycatch data and ROI steps

The commercial fisheries we examined are managed by the Australian Commonwealth Government and occur within Australia's Exclusive Economic Zone (EEZ). Inshore commercial fisheries that occur in Australian State and Territory managed waters <3 nautical miles from the coast were not included. Spatial data on bycatch for cetaceans was obtained from the Australian Fisheries Management Authority (AFMA) for 2001-2015. Data from fisheries logbooks were provided at a quarter-degree grid-cell resolution and included bycatch information on species, fishery and gear type, status of individual (dead or alive), and date and location of interaction (latitude and longitude). We combined bycatch into three categories of fisheries based on gear type: net, trawl, and line. Information on fisheries effort at quarter-degree grid-cell resolution for 2001– 2015 was also provided by AFMA.

We followed Auerbach et al.'s (2014) steps of applying ROI analysis in a conservation decision framework (: define objectives and biodiversity benefits, identify actions and costs, and solve the problem by combining information on expected benefits and costs.

Define objectives

We aimed to find the most cost-effective management strategies on a site-by-site basis across Australia to reduce bycatch to cetacean species in Australian fisheries. We sought to maximize net expected benefit of actions taken to mitigate threats from fisheries gear bycatch and ensure fisheries management costs are minimized by choosing cost-effective actions.

Define benefits to biodiversity

We considered all cetaceans involved in reported entanglement incidents a priority for conservation. Twenty-seven species have historical entanglement records (V.T. data), including 9 species listed under the Environment Protection and Biodiversity Conservation (EPBC) Act 1999 as migratory, threatened, or vulnerable (Supporting Information). The EPBC Act is the Australian Government's key environmental legislation covering environmental protection and biodiversity conservation.

We collated species' spatial distributions from data collected at biologically important areas ; Species of National Environmental Significance range maps; Atlas of Living Australia (ALA 2012); and state-based sightings data (Supporting Information). We used these data to define the full range of each species. Due to spatial data deficiencies for several species, we grouped species by habitat into 4 categories – baleen whales, deep-diving toothed cetaceans, offshore toothed cetaceans, and inshore toothed cetaceans (Supporting Information).

We divided the Australian EEZ into a grid of one-quarter-degree management sites (*i*) corresponding to the resolution of the fisheries effort data provided by AFMA. We identified 11,217 sites across the region and joined all species distribution data to the sites. We rescaled all distribution data to range 0 from 1 to create consistency across data sets; combined individual species data within each category (Supporting Information); and used maximum likelihood of occurrence within each category to derive an occurrence metric by site and species group and identify areas of high (likelihood of occurrence 1) and low (likelihood of occurrence 0) bycatch risk. Because the presence of migratory baleen whales in Australian waters is seasonal, we developed distribution metrics for winter (May to October) and summer (November to April). A single metric was used for each of the other species groups.

Our benefit function was based on the assumptions that the region consists of 11,217 sites (*i*); the region contains 4 species groups ($j = 1, ..., 4$) (baleen whale, deep diving, offshore or inshore toothed cetacean); and

there are 3 types of threatening fishing gear ($g = 1, ..., 3$) (line, net, trawl).

To represent spatial heterogeneity of each fishery and variability in vulnerability of a species to the three fisheries, we defined total benefit of mitigating bycatch (B) at each site *i* for each species group *j* and each gear *g* as a function of the presence of each fishery *t*, vulnerability of or risk to that species group from each threat *v*, and presence of that species group in each site *i*. The benefit of mitigation action to each species group by season *s* is thus

$$B^{s}_{gij} = \sum_{k=1}^{n} v_{gij} \cdot a^{s}_{ij} \cdot t_{gik} , \qquad (1)$$

where B^{s}_{gij} is the total biodiversity benefit of action *g* in site *i* for species group *j* for each season *s*, a^{s}_{ij} is the presence of species group *j* representing areas of high susceptibility to bycatch in site *i* by season (derived from the species distribution), v_{gij} is the vulnerability of species *j* to gear *g* at site *i* (1, highly vulnerable; 0, not vulnerable) based on the results of a risk assessment (Supporting Information), and t_{gik} is the presence of individual threats (or fisheries) *k* by gear type in site *i* (0-1) populated by rescaling the fisheries effort to a value from 0 to 1 so as to put them on a single, unitless scale to allow direct comparison. The expected benefit of acting to abate bycatch in gear *g* from each fishery to species *j* at site *i* is thus >0 if a species is vulnerable to that bycatch and 0 if it is not vulnerable. For each species group, we multiplied the consequence value by the proportion of listed species in that gear and species subgrouping.

To view the benefit function spatially, we developed maps showing where fishing pressure (2001-2015) overlapped with cetacean distributions. We mapped benefits across all cetacean groups for each fishing gear and season and calculated the maximum benefit across all gears.

Identifying actions and costs

We reviewed the literature to determine mitigation strategies trialed or used by commercial fisheries to reduce entanglements in Australia and internationally and assessed how successful each mitigation strategy was at reducing cetacean entanglements (Supporting Information). Our review was not comprehensive; others provide detailed evaluations of gear modifications (e.g., Werner et al. 2006). Based on gears associated with cetacean interactions in Australian fisheries and information on mitigation effectiveness, we evaluated a subset of mitigation actions : spatial closures, acoustic deterrent devices (pingers), and cetacean excluder devices (CEDs) (trawl fisheries only).

We calculated costs of funding each mitigation strategy over 5 years (C) (Supporting Information). Costs were only for future outlays and accounted for differing life-spans of each strategy derived from manufacturers and users. We determined costs by site weighted by the average threat level in each site:

$$C_{gim} = \sum_{k=1}^{n} P_{gk}^{m} \left({t_{gik}}/{T_{gk}} \right) \quad , \qquad (2)$$

Where P_{gk}^{m} is the cost of each mitigation strategy *m* for each gear *g* (calculation of *P* by strategy in Supporting Information), T_{gk} is the total fishing effort from each fishery *k* by gear type *g*, and C_{gim} is the total cost of the mitigation strategy *m.* Costs for spatial closures were based on lost fishing effort and associated revenue in each site, whereas costs for pingers and CEDs were based on individual costs of each device or gear modification based on number of vessels operating in each fishery (Supporting Information). By including cost formulation in proportional effort for each fishery in each site, we apportioned costs of implementing each action across the region relative to the amount of fishing in each site.

Solve the problem with ROI

We calculated the cost-effectiveness (CE) of each mitigation strategy *m* for the 4 species groups and 3 gear types by site and season by dividing benefits by costs:

$$\mathrm{CE}_{im}^{s} = \sum_{g=1}^{3} \left(\frac{\sum_{j=1}^{4} B_{gij}^{s} \cdot f_{gjm}}{C_{gm}} \right), \qquad (3)$$

where f_{gjm} is the effectiveness of each action by gear *g* to species group *j*. The effectiveness of each action (i.e., probability the action would successfully mitigate cetacean bycatch) was estimated as a value from 0 to 1 for each species group based on the literature review (Supporting Information).

To evaluate the utility of ROI as a spatial prioritization tool for fisheries bycatch mitigation relative to alternative approaches, we measured the increase in conservation benefit we expected to achieve when investing more funds in each action across the EEZ and ranked sites accordingly for three different objectives. First, we ranked all sites in order of cumulative cost-effectiveness (CE_{im}^{s}) for each action to demonstrate the ROI approach. Second, we maximized biodiversity benefits (traditional conservation approach), whereby we ranked all sites by their cumulative benefit B_{gij}^{s} to all species for each action (highest benefit to lowest benefit). Finally, we minimized costs (typical fisheries management objective), whereby we ranked all sites by their costs for each strategy (C_{gm}) (cheapest to most expensive). We plotted the cumulative expected benefit against the cumulative cost for each objective to explore ROI as sites were added according to their rank and compared curves for each objective (minimize cost, maximize benefits, maximize cost-effectiveness).

To solve the problem of choosing where to implement each management action, we selected the best management strategy (i.e., the highest and quickest benefits for a given budget based on results of ROI approach). The best management strategy was chosen by finding the action with the maximum CE value in each site.

Results

Species vulnerability to bycatch

Driven largely by fisheries effort and risk to each species group, hotspots of cetacean bycatch were identified throughout the eastern waters of Australia and patches of high vulnerability were scattered across offshore waters of Western Australia and South Australia (Fig.1). Average effort varied considerably between fisheries. The majority from 2001 to 2015 was concentrated in eastern and western regions of the EEZ. Tuna longline effort was relatively high compared with average effort for net fisheries. These differences were also reflected in the spatial distribution and extent of fishing effort for each gear type; line fisheries effort extended across 43% of the Australian EEZ compared with a substantially lower fisheries footprint for trawl and net fisheries, which extended across 23% and 10% of the EEZ respectively. Total effort differed between seasons; greater effort across all fisheries occurred during summer than winter. There was no fishing effort recorded across 46% of the EEZ, including substantial portions of offshore waters in southern and northern Australia. There were differences in the spatial distribution of species groups (Supporting Information) relative to fishing effort. Areas of high cetacean occurrence in the northwest and along the southern and western coastline were devoid of recent fishing effort. This resulted in a lower vulnerability ranking than those areas in the east and west, where fishing effort was substantially higher.

The results of our risk assessment highlighted differences in the level of risk to cetacean groups between Australian fisheries (Table 1). Highest risk overall across all fisheries was estimated for offshore toothed whales and dolphins ($b = 20.84$). Risk for inshore dolphins and baleen whales across all fisheries was substantially lower ($b = 13.74$ and $b=12.84$ respectively).

Actions and costs

Overall estimated costs for the mitigation strategies varied markedly. The most expensive mitigation strategy over 5 years was spatial closures. Average cost/quarter-degree grid was ~AU$3700. Total costs if implemented across the entire region were >AU$82 million for trawl (Table 2), AU$24 million for line, and AU$6 million for net fisheries. Costs of implementing pingers across the entire region was <5% that of spatial closures for the same period for all gears. Although pingers are relatively cheap (~AU$100-150US), they must be recharged every 3 months, which drives up their overall cost (Supporting Information). The cheapest mitigation strategy was CEDs (~AU$16/grid for implementation, AU$363,000 total for implementation across the region over 5 years). The low cost of CEDs arose from the smaller spatial footprint of trawl fisheries and the longevity of pelagic trawl nets (useful life of at least 5 years).

Solve the problem

When management sites for spatial closures were selected based on their cost-effectiveness rank, approximately two-thirds of the total expected benefit to cetaceans was achieved from spending ~AU$13 million in the EEZ over 5 years (<20% of total spatial closure cost across the EEZ) (Fig. 2). This arises from the steep ROI curves for initial cumulative investment and diminishing returns from greater investment (Fig. 2). Similar improvements in benefits were observed for CEDs when choosing sites based on their cost-effectiveness.

When sites were ranked according to their benefit to species, ROI was lower than when choosing sites based on their cost-effectiveness (Fig. 2). Particularly for spatial closures, expensive sites where fishing activity was high drove costs up with very little gain in expected benefits for species. For CEDs, benefits were linearly related to investment when sites were ranked by benefits or costs (linear regression model $R^2 > 0.99$, $p < 0.001$). In contrast, more optimal returns were observed for implementing pingers when ranking sites by cost and then choosing the cheapest sites to implement the strategy first (Fig. 2b).

The ROI for CEDs was always higher in summer than winter. However, when management sites were selected based on their cost-effectiveness, ROI was ~10% higher for winter spatial closures with an investment of <AU$10 million, but benefits were higher in summer with an investment of >AU$13 million for spatial closures (Fig. 2). Similar trends were observed for pingers (ROI for summer greater than winter once investment was >AU$800,000).

The spatial distribution of expected benefits were similar between pingers and spatial closures, but differed considerably from CEDs, which were largely driven by the distribution of trawl fishing effort (Fig. 3). There were some areas of congruence between the spatial distribution of cost-effectiveness values and benefit values for all actions, particularly in the southern offshore waters of Australia, which were consistently highlighted as high benefit and high cost-effectiveness for spatial closures and pingers.

Mapping the spatial distribution of cost-effective sites for management action enabled identification of high priority areas for managing bycatch with spatial closures, pingers, or CEDs (Fig. 4). Pingers were the most cost-effective action for offshore waters of the east, south, and west coasts; optimal use was in summer for western waters but predominantly winter in eastern and southern waters from South Australia to the border of New South Wales. Use of CEDs in both summer and winter were identified as the optimal strategy in the north across the Gulf of Carpentaria and extending to northwestern Australia. Winter spatial closures were identified as optimal for coastal waters across the east coast and deeper offshore waters of southern and western Australia, whereas summer closures were never optimal (Fig. 4).

Discussion

We demonstrated the utility of a spatial ROI approach for mitigating cetacean bycatch across multiple fisheries at a national scale. The approach is easily accessible and translatable to stakeholders because it identifies the most cost-effective actions for investment and is spatially explicit. As such, it improves on traditional conservation hotspot approaches that do not account for costs or effectiveness of actions (Tulloch et al. 2015) and provides an alternative method for managers seeking to optimize mitigation actions for many species distributed across large areas that are affected by threats from multiple fisheries. Although our vulnerability mapping identified risks to cetaceans from bycatch across almost the entire EEZ, we were able to target optimal cost-effective mitigation at a fine spatial resolution with ROI. Spatial approaches to risk mitigation are powerful for highly mobile marine species (Grech et al. 2008), and our method allows managers to prioritize locations and apply different management strategies for multiple fisheries to reduce cetacean bycatch. As such, it may be a useful tool for managers and decision makers to guide more cost-effective allocation of funding towards mitigation at a national scale, offering potential beneficial outcomes for protected species and fisheries.

Our spatial mapping highlighted substantial variation in the location of optimal cost-effective management strategies. High costs estimated for spatial closures due to potential lost fishing revenue resulted in the lowest average cost-effectiveness value for this strategy, but this strategy is also highly effective because it reduces the chance of bycatch in the area to zero. Because of this, substantial regions of Australian waters were chosen as optimal locations for spatial closures. In reality, closing large areas to fishing may not be a practical solution, but the results could be used as a guide to highlight areas where fishing effort reductions may improve bycatch outcomes for cetaceans, especially during certain seasons. Because the analysis was conducted at a national scale and strategies were split across 2 seasons, we were able to account for the seasonal migratory patterns of far-ranging baleen whales and target mitigation toward those areas and seasons where higher densities of cetacean species are present. Hence, higher benefit overall was afforded to regions along the east and west coast seasonally, corresponding to the migratory patterns of humpback whales, and in southern waters, where endangered southern right whales breed over winter. The high risk to offshore species as opposed to coastal dolphins largely reflects the distribution of effort of federally managed fisheries in Australia, which are not active in coastal state waters, and because of this, expansion of this model to include state fisheries would likely result in quite different spatial priorities.

We demonstrated the advantages of using cost-effectiveness to prioritize sites for action by comparing alternative objectives (e.g., minimize cost by choosing the cheapest sites first or maximize biodiversity outcomes by choosing sites with the highest species benefits first). With sites chosen by their cost-effectiveness rank, it was possible to achieve greater benefits to whales and dolphins by implementing CEDs and spatial closures with only small increases in expenditure. In contrast, an approach prioritizing sites for management based on conservation outcomes for species alone results in a worse ROI for all management strategies. Our approach helps visualize associated trade-offs between the benefits and costs of multiple management actions. We show that managers allocating funds based on benefits alone may prioritize unsuitable areas for management by using scarce resources inefficiently (Balmford et al. 2000), resulting in lost opportunities to achieve conservation goals (Naidoo et al. 2006).

The ROI approach demonstrated here depends on a number of assumptions. Outcomes will vary depending on the amount, accuracy, and resolution of species distribution information; coarser or fewer data will result in solutions driven largely by fisheries effort, rather than the location of species. We aggregate species into groups but species vulnerability to different mitigation actions is still uncertain and can vary by area and within gear types (e.g., mesh size and net position for gillnets), which will also affect action cost-effectiveness values. Gear modifications and deterrent devices have produced equivocal results for cetaceans (Supporting Information) (Hamer et al. 2008; Northridge et al. 2005). Although pingers have become an integral part of bycatch reduction strategies in a numbers of fisheries worldwide (e.g,. North American gillnet fisheries [Carretta et al. 2008], Australian shark control programs [Reid et al. 2011]), there is insufficient evidence that pingers reduce cetacean interactions with fisheries (Harcourt et al. 2014; Pirotta et al. 2016); thus, effectiveness values used in the ROI were best estimates only. Areas identified as more cost-effective for pingers were driven largely by their low cost (Fig. 2). Because of these uncertainties, results of the ROI for pingers in particular should be used as a general guide. Should this approach be used to inform actual fisheries management, further refinement through sensitivity tests that explore bounds of effectiveness uncertainty are warranted.

Our main objective was to demonstrate the utility of bioeconomic tools such as ROI for guiding efficient investment in bycatch-mitigation actions. Some Australian fisheries, however, are already managed through bycatch and discarding work plans informed by ecological risk assessments. For example, temporal and spatial closure arrangements were implemented in the midwater trawl sector of the small pelagic fishery in 2015 to prevent dolphin mortalities. By explicitly incorporating fishing effort into the benefit function, we assume that some of these management strategies already in place are accounted for in the spatial analysis. There are also many places where bycatch is high, but spatial data is poor, or risk assessments have not been conducted. Our approach can be modified by deriving a measure of risk based on historical bycatch of whale and dolphin species in the region or by removing the spatial component to simply compare ROI of different actions that could complement new scientific tools specifically designed to inform marine mammal mortality in bycatch for data-poor regions (https://www.lenfestocean.org/pt/research-projects/developing-recommendations-to-estimate-bycatch-for-the-marine-mammal-protection-act). Rather than evaluate all possible bycatch-mitigation strategies, we demonstrated the utility of an ROI approach that can evaluate trade-offs between the costs and benefits of implementing three commonly used strategies. Realistically, however, managers will implement multiple strategies to mitigate bycatch. For example, the gillnet sector of the Commonwealth Southern and Eastern Scalefish and Shark Fishery, which has a history of high common dolphin mortality, employs a number of strategies to reduce bycatch, including area closures, gear restrictions, and a dolphin strategy that provides a targeted management response to any dolphin mortality (AFMA 2014). The ROI could be expanded to evaluate different combinations of mitigation methods to aid in the selection of the best suite of solutions, rather than just one in each site (e.g. Auerbach et al. 2014). A range of other mitigation strategies we did not evaluate could also be included that might be highly effective, including fishery closures in association with bycatch trigger limits, effort reduction, and time and area closures. However, such actions would require reliable estimates of cetacean populations within each fishery management boundary and population models that inform appropriate limits. Dynamic ocean management is emerging as an effective method of generating responsive spatial strategies to address bycatch (Hazen et al. 2018). The ROI is based on static distribution information and average fisheries effort over time, but could be modified to account for spatial and temporal variation to derive dynamic fishing responses, such as updating the species occurrence parameters and threat parameters dynamically to reflect real-time whale distribution and fisheries effort accordingly, if such information were readily available for Australian waters.

We focused on observed bycatch only, but recognize the urgent need to address unobserved mortality from fisheries gear interactions. We also recognize the growing problem of marine debris impacts including floating and discarded gear on cetaceans, however a lack of explicit information on the scale and scope of both these problems, as well as issues in identifying the source of the entangling gear or debris, hinders our ability to effectively target mitigation solutions (Tulloch et al. , personal observation). Finally, although our approach may help reduce cetacean mortality within national waters, many far-ranging species move outside of national waters exposing them to bycatch elsewhere. This problem is not unique to the Australian context, but it is pervasive for conservation of most migratory and far-ranging animals, emphasizing the need for complementary programs that can help protect threatened species beyond single-nation boundaries.

Bycatch of whales and dolphins occurs in different and often overlapping fisheries and different gears around Australia and elsewhere, yet mitigation typically focuses on single-species or single-fishery strategies. By using a spatial ROI approach, we devised a solution to a decision problem of multiple threats and associated actions, identifying the most cost-effective locations around Australia for different mitigation actions to reduce bycatch of whales and dolphins across multiple fisheries. This method improves on single-threat mitigation methods by providing an alternative approach for managers wishing to address the issue of cetacean bycatch across multiple gears and fisheries at a national scale. The method and outcomes are also easily translatable and accessible to stakeholders compared with more complex conservation tools (e.g., Chadès et al. 2012) and can be adapted to provide more dynamic solutions if the data permits or modified for data-limited problems. Finally, this approach enables managers to transparently prioritize actions expected to provide the highest ROI for reducing dolphin and whale bycatch and gives industry a concrete set of strategies to improve management and protect species.

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Table 1. Bycatch risk values estimated for each cetacean group and Australian Commonwealth fishery.

Fishery	Gear used	Baleen whales	Beaked toothed cetaceans	Offshore toothed whales and dolphins	Inshore dolphins	Reference
Southern and eastern scalefish and shark fishery (SESSF), commonwealth trawl sector (CTS)	bottom otter trawl	1.80	2.90	2.63	1.00	combination of residual risk assessment of the level-2 productivity susceptibility analysis 2012 and logbook entries
SESSF - gillnet, hook and trap sector (GHAT)	gillnet	1.00	1.00	3.31	1.00	residual risk assessment of the level-2 productivity susceptibility assessment 2012
SESSF -	line	1.00	1.10	1.13	1.00	residual risk assessment of

gillnet, hook, and trap sector (GHAT)						the level-2 productivity susceptibility assessment 2012
Northern prawn fishery (NPF)	trawl	2.92	3.02	3.03	3.04	residual risk assessment of the level-2 ecological risk assessment, species results december 2008
Small pelagic fishery (SPF)	trawl	2.98	3.12	3.12	2.79	residual risk assessment of the level-2 ecological risk assessment, species results, report for the small pelagic fishery – midwater trawl march 2010
Small pelagic fishery (SPF) -	purse seine	3.05	3.14	3.09	3.01	residual risk assessment of level-2 ecological risk assessment,

						species results, report for the small pelagic fishery – purse seine march 2010
Eastern tuna and billfish fishery (EBFT)	pelagic longline and pole and line	1.00	2.63	2.95	1.00	residual risk assessment of the level 2 ecological risk assessment species results march 2009
Western blue fin tuna (WBFT)	pelagic longline and pole and line	1.00	2.63	2.70	1.00	residual risk assessment of the level 2 ecological risk assessment species results november 2009
Total risk		13.74	18.44	20.84	12.84	

Table 2. Total costs and benefits for each cetacean bycatch-mitigation strategy for each gear, and average costs of each strategy among sites.

remove $ from next to numbers;

		Spatial closure (AU$)	Pingers (AU$)	Cetacean excluder devices (AU$)
Total cost all sites	trawl	82,796,119	2,310,842	363,340
	net	5,965,294	245,091	-
	line	24,315,000	372,060	-
Total benefit all sites	trawl	26274.30	1897.34	1373.81
	net	32,979.35	1,984.80	-
	line	8111.45	619.20	-
Average cost per site	trawl	3,690	103	$16
	net	265	10	-
	line	1,083	16	-
Average benefit per site	trawl	1.17	0.08	0.06
	net	1.47	0.09	-

	line	0.36	0.03	-

Figure 1. (a) Areas where fishing effort (2001-2015) in 6 Australian fisheries for which cetacean bycatch data are available overlaps with cetacean presence and distribution (the darker the shading the higher the fishing pressure and abundance of cetaceans).. (b) Average annual fishing effort for all Australian fisheries combined (? need to define combined on figure) per site (values rescaled to 0 to 1 and summed). (c) Combined cetacean species distribution map (average occurrence values summed for each species group in each cell).

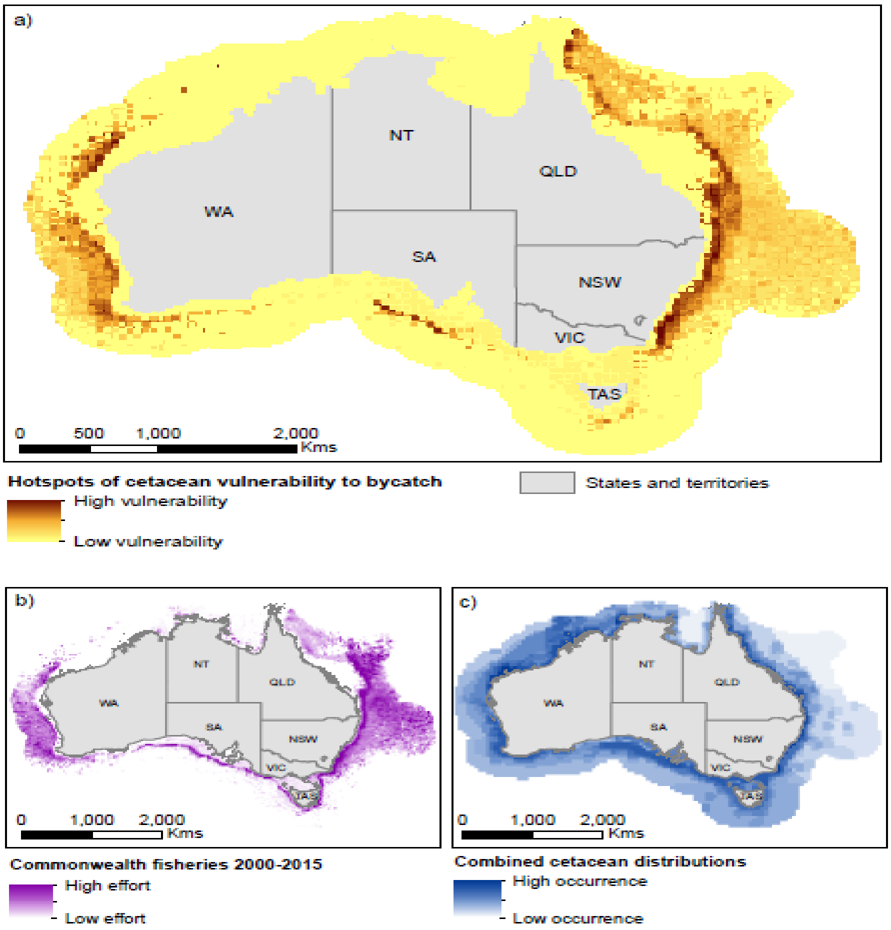

Figure 2. Relationship between investment in each bycatch-mitigation action and the percentage of the total benefit expected to be returned from (a) spatial closures; (b) acoustic deterrents (pingers); (c) cetacean excluder devices for November-April (summer) and May-October (winter) (6-month seasons). Curves show return on investment when sites are ranked by cost-effectiveness (black) compared with choosing sites to minimize cost or and to maximize benefit. Values on x-axes differ.

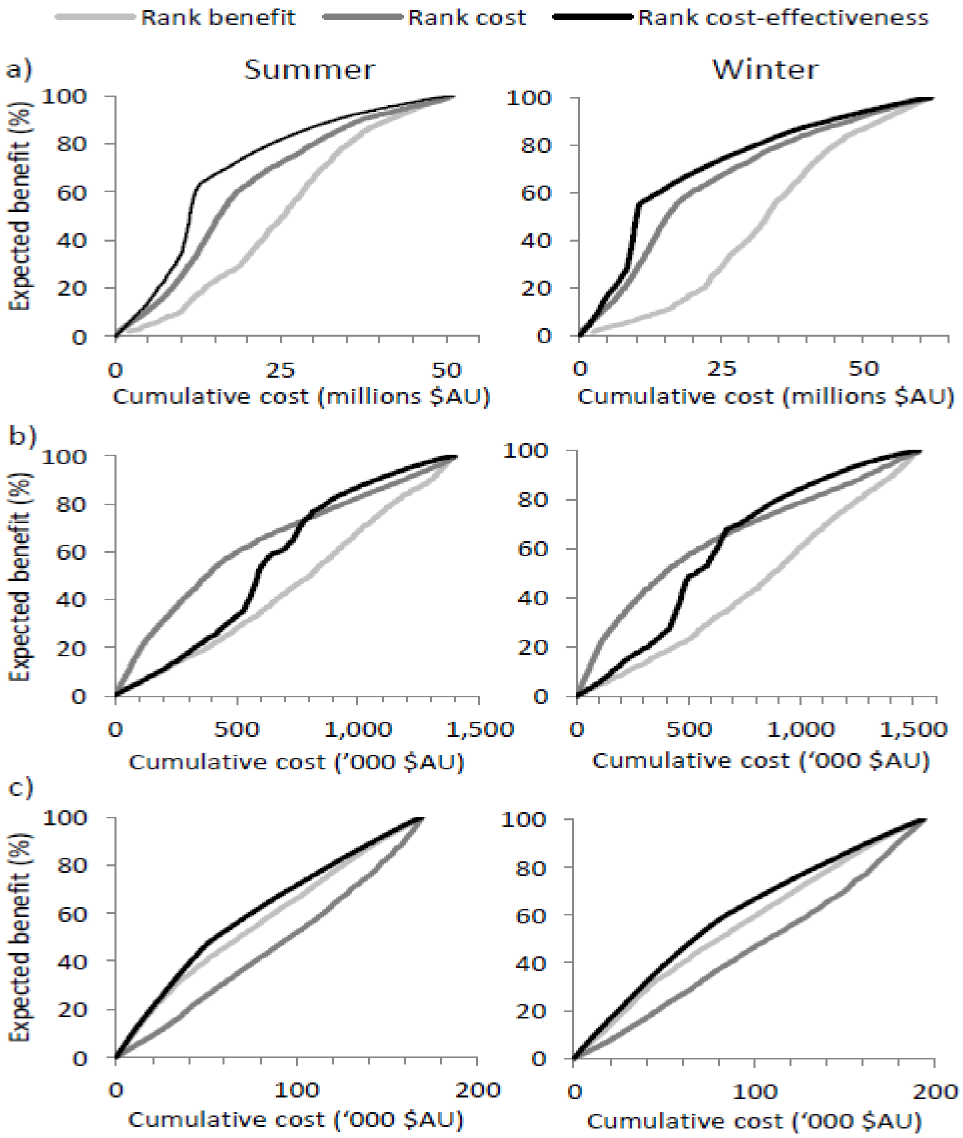

Figure 3. Spatial distribution of the expected benefits of cetacean bycatch mitigation (left, blue) in Australian fisheries and cost-effective locations for managing bycatch (right, red) with (a) spatial closures, (b) pingers, and (c) cetacean excluder devices (CEDs) (summer, November-April; winter, May-October).Data were normalized by dividing every benefit or cost-effectiveness value by the maximum possible summed benefit or cost-effectiveness value, respectively, for each threat. Maps are shaded using geometric intervals based on classes delineated by natural data groupings to yield a balance between highlighting middle and extreme values.

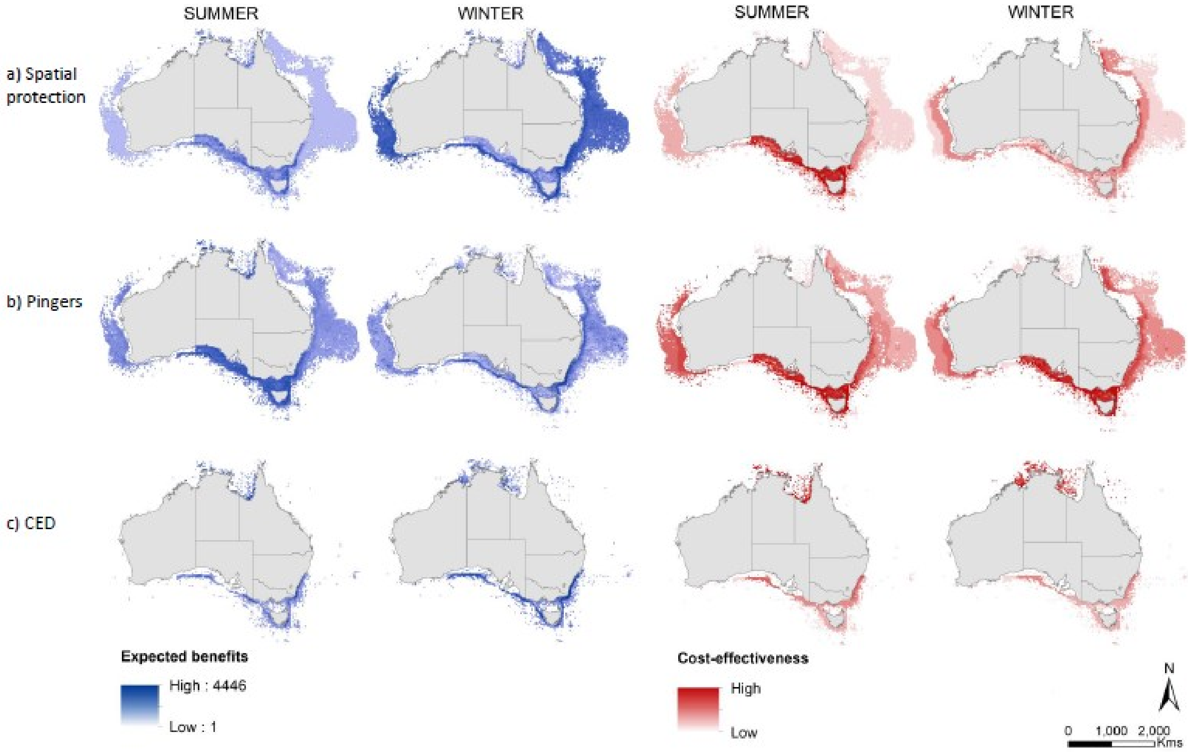

Figure 4. By region and season, the most highly ranked cost-effective strategy to abate dolphin and whale bycatch in Australian fisheries (WA, Western Australia; NT, Northern Territory; QLD, Queensland; NSW, New South Wales; VIC, Victoria; SA, South Australia; TAS, Tasmania).