Exploring cost-effective management measures for reducing risks to threatened species in a targeted shark longline fishery

Abstract

Many shark and ray species (Class Chondrichthyes, herein 'sharks') are threatened by overfishing. Tackling this requires implementation of context-specific fisheries management measures, which are both technically effective and socio-economically feasible. Here we explore the cost-effectiveness of various input-oriented management measures for mitigating capture of seven priority shark taxa (i.e., threatened and CITES-listed species) in a small-scale longline mixed-species shark fishery in Indonesia, where there is a need to balance difficult trade-offs between conservation and socio-economic objectives. We apply Boosted Regression Trees (BRT) to analyse five years of landings and profit data, to identify and assess the relative influence of different plausible management measures (e.g., effort restrictions, gear restrictions, spatio-temporal closures). We then use predictive models to inform a semi-quantitative assessment of the hypothetical cost-effectiveness of these management measures, based on the estimated conservation benefits (reduced risk of capture of priority taxa) and socio-economic cost (relative profit foregone). Our results show that fishery closures in January-March, depth limits at <100m, hook limits at <500 hooks, and gear restrictions on bottom longlines could have the greatest relative conservation impact for lowest profit foregone. However, there are clear trade-offs between taxa, with these measures primarily benefiting Critically Endangered bottlenose wedgefish (*Rhynchobatus*

Australiae) and scalloped hammerheads (*Sphyrna lewini*), while potentially increasing pressure on Vulnerable silky sharks (*Carcharhinus falciformis)* and Endangered mako sharks (*Isurus* spp.). When shark fishing is important for economic welfare, and entire fishery closures or buy-outs are unfeasible, managing small-scale shark fisheries for multiple outcomes may require hard choices. This may require prioritising slow-growing Critically Endangered taxa for protection – by restricting fishing during seasons and at depths in which they are most susceptible to capture – while faster-growing taxa can continue to provide benefits for coastal communities.

Key words: elasmobranchs, marine conservation, endangered species, fisheries management, risk management, cost-effectiveness

1. Introduction

Sharks and their cartilaginous relatives (Class Chondricthyes, herein ‘sharks’) are one of the world’s most threatened taxa. Over one third of described shark species are at risk of extinction, with population declines of more than 70% for some taxa over the past 50 years (Dulvy et al., 2021; IUCN, 2021; Pacoureau et al., 2021). These declines are primarily driven by overfishing for human use, in both targeted and bycatch fisheries, which in turn is driven by a range of socio-economic factors including general expansion of global fishing fleets and valuable markets for shark-derived commodities such as fins, meat and liver oil (Dulvy et al., 2021; IUCN, 2021; Pacoureau et al., 2021). In a move to address this, international policy mechanisms for sharks have been strengthened in the past decade. For example, under various Regional Fisheries Management Organisations (RFMOs), the Convention on Migratory Species (CMS), and the Convention on International Trade of Endangered Species (CITES), there are provisions relating to catch, retention and/or international trade of over 40 of the most threatened and commercially-important shark species (UNEP-WCMC, 2020). However, conservation outcomes in terms of population recoveries remain elusive for most species and places, hampered by policy complexity, socio-economic trade-offs and inadequate fisheries management (Booth et al., 2019a; Davidson et al., 2016; Dulvy et al., 2017; Lack and Sant, 2011). In particular, evidence-based fishery management plans, which can translate high-level policies into sustainability outcomes, and the effective implementation thereof, remain limited for most of the world’s shark population (Simpfendorfer and Dulvy, 2017). As such, population declines and species extirpations continue (Kyne et al., 2019; MacNeil et al., 2020; Pacoureau et al., 2021; Yan et al., 2021).

Indonesia is the world’s largest shark fishing nation, and therefore a global priority for tackling unsustainable shark fishing (Dent and Clarke, 2014; Dulvy et al., 2017). Large-scale closures (e.g. ‘shark sanctuaries’ in several island states) appear to be effective for maintaining healthy shark populations in some places (MacNeil et al., 2020; Ward-Paige, 2017; Ward-Paige et al., 2013), however these measures are unfeasible for fishery-dependent nations like Indonesia. Sharks have been captured in Indonesian waters for centuries, as a source of food and income (Tull, 2014). Today, thousands of coastal communities remain highly dependent on marine resources, including sharks and rays, for income, livelihoods and food security, such that overly restrictive conservation measures can result in unacceptable socio-economic trade-offs (Booth et al., 2021b; Lestari et al., 2017; Selig et al., 2018). Management measures need to carefully consider these trade-offs, in order to design approaches which are effective and socially just (Booth et al., 2019a). Moreover, sharks are a highly diverse species group, which are not uniformly vulnerable to overexploitation; some shark fisheries can be sustainable if they operate within evidence-based management plans (Simpfendorfer and Dulvy, 2017). As such, nuanced approaches to managing shark catches are needed, which can protect the most at-risk species from overexploitation, whilst allowing for sustainable use of more resilient and faster-growing species (Dulvy et al., 2017; Simpfendorfer and Dulvy, 2017). The Indonesian government has already shown strong commitment to implementing CITES, for example through protecting manta rays and developing a robust Non-Detriment Finding (NDF) study for silky sharks (Booth et al., 2020b, 2020a; LIPI, 2018). However, implementing adequate fisheries management for other threatened and CITES-listing species whilst minimising negative socio-economic impacts of such regulations on vulnerable coastal communities, particularly in the context of ubiquitous small-scale mixed-species fisheries, remains challenging.

Acknowledging these needs and challenges, we explore the cost-effectiveness of potential management measures for mitigating risks to threatened and protected species in a small-scale semi-commercial mixed-species targeted shark fishery (Tanjung Luar in East Lombok, West Nusa Tenggara). More specifically we aim to answer the following research questions:

1. Which variables related to fishing operations create the greatest risk to priority (i.e., threatened and CITES-listed) shark and ray species?
2. Based on these variables, which technical management measures (e.g., spatial closures, temporal closures, gear restrictions and effort restrictions) could have the largest relative conservation benefits for priority species, in terms of reduced risk of capture?

3. What is the relative socio-economic feasibility of these mitigation measures, based on estimated economic opportunity costs to fishers (i.e., profit foregone)?
4. Overall, which fisheries management measures might be most cost-effective and feasible, in terms of minimising risks to priority species with minimal economic welfare losses to fishers?

There have been many studies and reviews exploring the availability and effectiveness of different fisheries management approaches to reduce mortality of threatened sharks (BMIS, 2021; Booth et al., 2019b; Fowler, 2016; Molina and Cooke, 2012; Shiffman and Hammerschlag, 2016). However, the costs and cost-effectiveness of different management measures are rarely considered. As such, this represents the first attempt to operationalise a least-cost approach to shark conservation (Booth et al., 2019a, 2019b). This is particularly important for the case study fishery - Tanjung Luar – since shark fishers exhibit high economic dependency on threatened and declining shark populations, with limited occupational diversity and adaptive capacity (Milner-Gulland et al., 2020). As such, management measures need to effectively reduce risks to priority taxa whilst also being cognizant of socio-economic realities, if they are to be effective and socially-just (Booth et al., 2019a). We also adopt a Boosted Regression Tree (BRT) method in our analysis - which offers an innovative and flexible approach for coping with non-linear relationships and the influence of a range of co-variables (De’ath, 2007; Elith et al., 2008; Froeschke and Froeschke, 2011). BRTs are therefore well suited to assessing the operational predictors of shark catches, yet while they have been used to model shark distribution (Espinoza et al., 2014; Juhel et al., 2018) application of BRTs to shark fisheries management remains under-utilised. Our approach, findings and lessons learned can be used to understanding and improve the sustainability of problematic mixed-species fisheries with multiple stakeholders and management objectives, and cross-taxa conflicts, including our case study fishery and beyond (Gilman et al., 2019; Smart et al., 2020).

2. Methods

To identify and assess cost-effective management measures for Tanjung Luar we implemented a multi-stage process for making evidence-based management decisions to reconcile trade-offs between shark conservation and fisheries objectives, as proposed by Booth et al. (2019b) and implemented by Gupta et al. (2020). This process includes: 1) Define the problem, 2) Explore management measures, 3) Assess hypothetical (cost) effectiveness of management measures, 4) Make a management decision, 5) Implement, monitor, and adapt. This study primarily focuses on steps 1-3, which we describe in turn below. We then interpret the results of the semi-quantitative cost-effectiveness assessment, and combine them with additional sources of contextual and market knowledge from other published literature (Booth et al., 2021b; Lestari et al., 2017; Milner-Gulland et al., 2020) to offer some potential management recommendations and implementation needs (i.e. for steps 4 and 5) in the Discussion.

2.1. Defining the problem

Defining the problem entails defining the fishery and the taxa of management concern, understanding the various technical and socio-economic risks to the taxa of concern (e.g., extinction risk of taxa, markets, constraints), and setting management goals (Booth et al., 2019b).

2.1.1. Study fishery

We focused on Tanjung Luar - a small-scale semi-commercial shark fishery in East Lombok, West Nusa Tenggara Province, Indonesia (Figure 1) – as our study fishery, and reviewed available data on the fishery (WCS-IP, 2019; Yulianto et al., 2018) and it’s socio-economic context (Booth et al., 2021b; Lestari et al., 2017; Milner-Gulland et al., 2020) to inform our assessment.

There are roughly 50 specialised shark vessels operating from Tanjung Luar, all of which are <10GT capacity, which is classified as small-scale according to the Indonesian Ministry of Marine Affairs and Fisheries (Yulianto et al., 2018). The vessels use longlines to target a range of shark species, though some vessels use bottom longlines and others use surface longlines. Each vessel is crewed by 3-4 people, including a captain, and they spend an average of 12 days at sea, with at least two days spent travelling to/returning from fishing grounds (Yulianto et al., 2018). Sharks are landed whole and sold at auction as an entire aggregated catch (Booth et al., 2021b).

This is an important case study for operationalising a least-cost approach to shark conservation, since targeted shark fishing in Tanjung Luar is both legal and profitable, yet it creates a direct threat to several taxa of conservation concern (Booth et al., 2021b; Yulianto et al., 2018). However, most shark fishers are economically vulnerable, with high dependence on shark fishing and limited adaptive capacity, such that strict regulations may result in unacceptable socio-economic costs and non-compliance (Booth et al., 2019a; Milner-Gulland et al., 2020; Oyanedel et al., 2020). Therefore, there is a need to balance trade-offs between conservation objectives and socio-economic objectives in fisheries management measures for Tanjung Luar. The fishery also represents a rare example of relatively data rich small-scale fishery.

Figure 1 Location of Tanjung Luar fishery and fishing grounds in Indonesia (FMA = Fisheries Management Area, only those which are relevant to Tanjung Luar are numbered)

2.1.2. Study taxa

Previous studies show that over 70 species of sharks and rays have been recorded at Tanjung Luar (Yulianto et al., 2018). We conducted preliminary exploration of available landings data (WCS-IP, 2019) to define the species of management concern, with a focus on 'priority taxa', which we defined as species which are: 1. Subject to regulation under domestic or international policy frameworks (e.g. Indonesian law and/or listed on one of the CITES Appendices); and/or 2. Classified as Endangered or Critically Endangered according to the IUCN Red list of threatened species. There are 20 species captured in Tanjung Luar which fit this definition (S1). We then grouped some species into higher taxonomic groups and removed any taxa which made up less than 1% of total catch to ensure sufficient statistical power for further analysis. Based on these groupings seven priority taxa were defined as the taxa of management concern for further analysis: thresher sharks (*Alopias spp.)*; silky shark (*Carcharhinus falciformis)*; mako sharks (*Isurus spp.*); mobula rays (*Mobula spp.*); bottlenose wedgefish (*Rhynchobatus australiae)*; hammerhead sharks (*Sphyrna spp.)*; and dusky shark (*Carcharhinus obscurus*).

2.1.3. Management goal

The remainder of the analysis focused on identifying potential management measures for the Tanjung Luar fishery which could achieve the goal of reducing risks to the seven priority taxa whilst minimising economic losses to fishers.

2.2. Exploring management measures

Exploring management measures entails understand which management levers are available for achieving the management goal. To do so we analysed available daily landings data collected by the Wildlife Conservation Society Indonesia Program during 2014-2018 (WCS-IP, 2019; Yulianto et al., 2018) using Boosted Regression Trees (BRTs).

2.2.1. Landings Data

The landings data used for this analysis were collected by three experienced enumerators, following the Southeast Asian Fisheries Development Centre (SEAFDEC) standard operating procedures (Ahmad et al., 2019; Yulianto et al., 2018). The enumerators were trained, assessed, and mentored in species identification, with records verified using photo-ID in cases of uncertainty or ambiguity. Landings were recorded every morning at the Tanjung Luar shark auction facility at 5am – 10am from January 2014 to December 2018. Data were recorded on catch composition per trip via direct observation (i.e., numbers of each species that were caught); fishing operations during the trip via direct observation and brief post-trip interviews with captains (i.e., date, trip length, fishing location, gear type); and the final auction price of total catches from each vessel, along with trip operating costs, which allowed net profit to be calculated (WCS-IP, 2019; Yulianto et al., 2018).

2.2.2. Analysis using Boosted Regression Trees

We modelled all management-relevant predictors of catch of priority taxa for which data were available (Table 1). These included: month of fishing trip (managed through temporal closures), set depth of fishing gear (managed through depth restrictions), gear type used (managed through gear restrictions), number of hooks used (managed through hook limits), trip length in days (managed through trip limits), and fishing zone (managed through spatial closures) (Table 1). We modelled the relative influence of each predictor/ management measure on 1) the likelihood of catching each priority taxon during a fishing trip (as an indicator of hypothetical mortality risk that could be avoided); and 2) trip profit (as indicator of socio-economic cost, in terms of which types of operational fishing practices tend to lead to higher/lower profits overall) using boosted regression trees (BRTs).

Table 1 Description of management-relevant input-oriented predictors of catch considered in this study

Management-relevant operational predictors	Description	Potential management measure
Month	Categorical variable describing the month in which the fishing trip occurred (Jan – Dec)	Temporal closures
Fishing depth (m)	Numerical variable describing the depth at which the gear is set (12m - 250m)	Depth restrictions
Gear type	Categorical variable describing the gear type used (bottom longline or surface longline)	Gear restrictions
Number of hooks	Numerical variable describing the	Hook limits

	number of hooks used (3 – 600)	
Trip length (days)	Numerical variable describing the number of days at sea (1 – 25)	Trip limits
Fishing zone	Categorical variable describing one of three broad provincial jurisdictions in which the fishing took place (West Nusa Tenggara (NTB) waters, East Nusa Tenggara waters (NTT) or other)	Spatial restrictions

BRTs are a machine-learning method for data exploration and analysis (De’ath, 2007; Elith et al., 2008), which were well suited to our exploratory research aims. BRTs are non-parametric, and therefore require no prior distributional assumptions or data transformations; rather, they fit complex, non-linear relationships using algorithms, which learn the relationship between the response and its predictors, and are trained iteratively on random partitions of the data (Breiman 2001). As such, BRTs can handle skewed and multi-modal data, and different types of predictor variables and response types, as well as interaction effects between predictors. They have also been proven to handle non-linear relationships, unbalanced data, missing values and higher-order interactions among many variables (all of which are characteristics of the available fisheries data for Tanjung Luar) more robustly than many other modelling methods (Pennino et al., 2013; Soykan et al., 2014). Accordingly, BRTs have been increasingly used in ecology, conservation biology and fisheries science during the past decade (De’ath, 2007; Elith et al., 2008; Froeschke and Froeschke, 2011), and provided a suitably flexible method for exploring the influence of management measures (i.e., rather than building a predictive model of shark catches based on all possible environmental, operational, and socio-economic predictors). Unlike conventional models, BRTs do not produce confidence intervals or p-values. Rather, they use relative influence (RI) to characterize the contribution of each explanatory variable to the model, and mean receiver operating characteristic (ROC) from 0 to 1 as a measure of a model's explanatory power, where values of more than 0.7 indicate acceptable performance of the model and values of >0.8 indicate excellent performance (De’ath, 2007; Elith et al., 2008).

For each priority taxa we constructed a BRT model with risk of capture as the response variable, and used a Bernoulli distribution (i.e., a binary 0/1 response variable) to model the influence of the different predictors/management measures on the presence/absence of priority taxa within each catch per trip. For the BRT model for profit, we used a Gaussian distribution to model the influence of the different operational predictor variables on total profit per trip (Elith et al., 2008). We used a learning rate of 0.001, tree complexity 5, and bag fraction 0.5, which were selected to minimize holdout residual deviance (a measure of the error remaining in the tree after construction) (De’ath, 2007; Elith et al., 2008). This resulted in a total of 8 models, which explored the degree to which the predictors/management measures influenced risk of capture for each of the 7 priority taxa, and trip profit.

To interpret the model outputs, fitted models were used to generate RI plots and partial dependence plots (PDPs) with 90% confidence intervals. RI indicates the influence of a given predictor variable on the response variable, with the RIs for each variable in a model scaled so that the sum adds to 100, such that higher numbers indicate stronger influence relative to other variables included in the model. PDPs show the effect of a predictor variable on the response variable after accounting for the average effects of all other variables in the model (De’ath, 2007; Elith et al., 2008). Together, these two outputs indicate how and to what degree a given predictor/management measure affects a response variable. We then selected the predictors/management measures with the highest RIs for further analysis.

2.3. Assessing the hypothetical cost-effectiveness of management measures

Assessing the hypothetical cost-effectiveness of management measures entails estimating the degree to which each potential management measure could technically reduce risks to taxa of management concern (i.e., conservation benefit), and the associated costs (in this case, the opportunity costs of reduced profits).

2.3.1. Predicting benefits and costs of management measures

Based on the outputs of the BRT models we developed prediction datasets for likelihood of capture for all priority taxa and total trip profit under a range of imputed plausible values for each operational variable, and across all possible combinations of those values. The values included: each of the twelve months (January - December); five fishing depths (10m, 20m, 50m, 100m and 200m); each of the two gear types (bottom and surface longline); five representative values of hook numbers (50, 100, 150, 300 and 500); two fishing zones (West Nusa Tenggara and East Nusa Tenggara); and three representative values of fishing effort (trip lengths of 10, 15 and 20 days), which could be managed via trip limits. This gave a total of 3,601 combinations of operational variables, each with a predicted catch risk (0-1) for each taxon, and a predicted total profit. This prediction dataset allowed us to assess the conservation benefits and socioeconomic costs of different ranges of plausible input-oriented management measures associated with those values, where conservation benefits were assumed to be proportional to the reduction in capture risk for each taxon, if that range of operational variables were restricted and socio-economic cost was assumed to be proportional to the reduction in total trip profit.

2.3.1. Deriving an overall semi-quantitative cost-effectiveness score

The prediction data then informed a semi-quantitative assessment of the overall cost-effectiveness of each type of management measure across all priority taxa, whilst also considering differences in conservation need for each taxon. Where the risk of capture for a given taxon and a given set of operational values was predicted to be above average, these values were classified as a potential set of operational restrictions (i.e., management measures) which could have conservation benefits for that taxon. Within this set of potential management measures, we identified the single set of operational values associated with the highest overall conservation benefit for each taxon, which we gave a score of 3. The next 4 operational values were scored 2, and the rest of the above-average values were scored 1. The scores for each management measure for all taxa were then combined into an assessment of overall conservation benefit, with weighted scores for each taxon based on their threat status according to the IUCN Red List of Threatened Species.

For weighting, we followed conventions from previous studies which used IUCN Red List categories for species conservation priority scoring, where each threat category represents a doubling of conservation need (Dickman et al., 2015). In this study, all priority taxa were classified as Vulnerable (VU) or above, therefore VU species = 1, Endangered (EN) species = 2 and Critically Endangered (CR) species = 4, which is equivalent to the weightings that would be computed through geometric scaling. Where a taxon included multiple species with different threat categorisations (i.e., for *Alopias* spp. and *Mobula* spp.) we used the highest threat level to adopt a precautionary approach. We recognize this scoring system to be inherently subjective and values-based, and emphasize that other weights could be transparently applied for other studies and sites, to represent the conservation values of different taxa in different contexts. Acknowledging this, we also tested two other scoring systems: one with no weighting based on threat category and one with linear progression (i.e., VU = 1, EN = 2, CR = 3) to demonstrate other scoring options and explore the sensitivity of the results to different value judgements (S2).

Based on the total conservation benefit score, each management measure was then categorised in to very high, high, moderate, or low conservation benefit categories, based on which quartile they fell in to. For socio-economic costs we used just two categories due to the relatively low predictive accuracy of the profit model (see Results): where profits at a given set of operational values were predicted to be above the average, these were classified as management measures with 'higher cost', while those which were below average were categorized as 'lower cost'. The overall conservation benefit scores were then compared with the socio-economic cost categorisation, to identify management measures which could have higher overall conservation benefits for lower socio-economic cost.

We emphasise that these scores do not account for potential displacement effects of restrictions, wherein, for example, restricting bottom longlines could have a negative impact on taxa that are more frequently caught with surface longlines, due to bottom longlines fishers switching to that gear type. These scores also assume that each operational variable is fully independent, as opposed to being combined as part of an overall fishing strategy, however that is not necessarily the case. For example, on average, fishers who use surface longlines gears also typically set their gears in shallower waters and use more hooks, while fishers who use bottom longlines gears typically set in deeper waters and use fewer hooks (Yulianto et al., 2018). Nonetheless, there are overlaps in the distribution of all the operational variables. We acknowledge these nuances and draw on additional sources of information about the fishery as part of the management recommendations.

3. Results

3.1. Status of the fishery, and general risks to priority taxa

Vessels typically landed a mixed species catch of 20-30 individual sharks, though there was wide variation in total catches per trip (mean = 24, SD: 17). Silky sharks (*Carcharhinus falciformis*) which are listed on CITES Appendix II and Vulnerable (VU) according to the IUCN Red List are most frequently caught at 40% of total recorded catch (Table 2). Hammerhead sharks (*Sphyrna* spp.) are the next most frequently caught taxa at 8% of total catch, while the other five priority taxa make up lower proportions of total catch at 1-3% (Table 2).

On average each trip earns around US$3,000 in profit (SD: 1,569), though there are extremes: profits can also reach as high as US$6,000 per trip, while for some trips the operational costs can exceed profits resulting in economic losses. Per individual, Dusky sharks (*Carcharhinus obscurus)* and Bottlenose wedgefish (*Rhynchobatus australiae*) are amongst the highest value taxa in the fishery (Booth et al., 2021b).

Table 2 Summary of total catches of priority taxa in Tanjung Luar shark fishery, 2014-2018 (VU = Vulnerable, EN = Endangered, CR = Critically Endangered)

Common name	**Latin name**	**IUCN Red List**	**CITES Appendix**	**Bottom longlines**		**Surface longlines**		**Grand Total**	
				N	**%**	**N**	**%**	**N**	**%**
Silky shark	*Carcharhinus falciformis*	VU	II	775	7	123,63	56	13,138	40
Hammerhead sharks	*Sphyrna spp.*	CR	II	1,178	11	1,761	8	2,939	8
Dusky shark	*Carcharhinus obscurus*	EN		792	7	223	1	1,015	3
Bottlenose wedgefish	*Rhynchobatus australiae*	CR	II	651	6	39	0	690	2
Mako sharks	*Isurus spp.*	EN	II	61	1	764	3	685	2
Thresher sharks	*Alopias spp.*	VU/EN	II	59	1	611	3	465	1
Mobula rays	*Mobula spp.*	VU/EN	II	7	0	160	1	167	1
Other sharks & rays	*Chondrichthyes spp.*			7,230	67	6,303	28	13,533	41
Total				**10,753**		**22,224**		**33,244**	
Priority %				**34**		**72**		**59**	
Other %				**66**		**28**		**41**	

3.2. Potential management measures

The BRT analysis produced models with excellent (ROC >0.8) or acceptable (ROC >0.7) performance for all priority taxa besides hammerheads (the hammerheads model was just below acceptable levels at ROC = 0.6; Figure 2), while the model for profit performed quite poorly (ROC = 0.4). This implies that operational fishing variables alone are not reliable predictors of trip profit, which is unsurprising given that profits typically depend on catch outputs rather than fishing inputs (Booth et al., 2021b). Nonetheless, the model results remain fit for purpose for the aims of this study (i.e., to explore the relative cost-effectiveness of management levers, as opposed to building a predictive model of catch and profit).

The model outputs indicated that the most influential operational predictors for the relative likelihood of catching priority taxa are month, fishing depth, gear type and hook number; while depth, gear type and month are the most influential predictors of profit (Figure 2, Figure 4, Table S1). Fishing zone and fishing effort had low RIs, and therefore were not further considered as potential management measures.

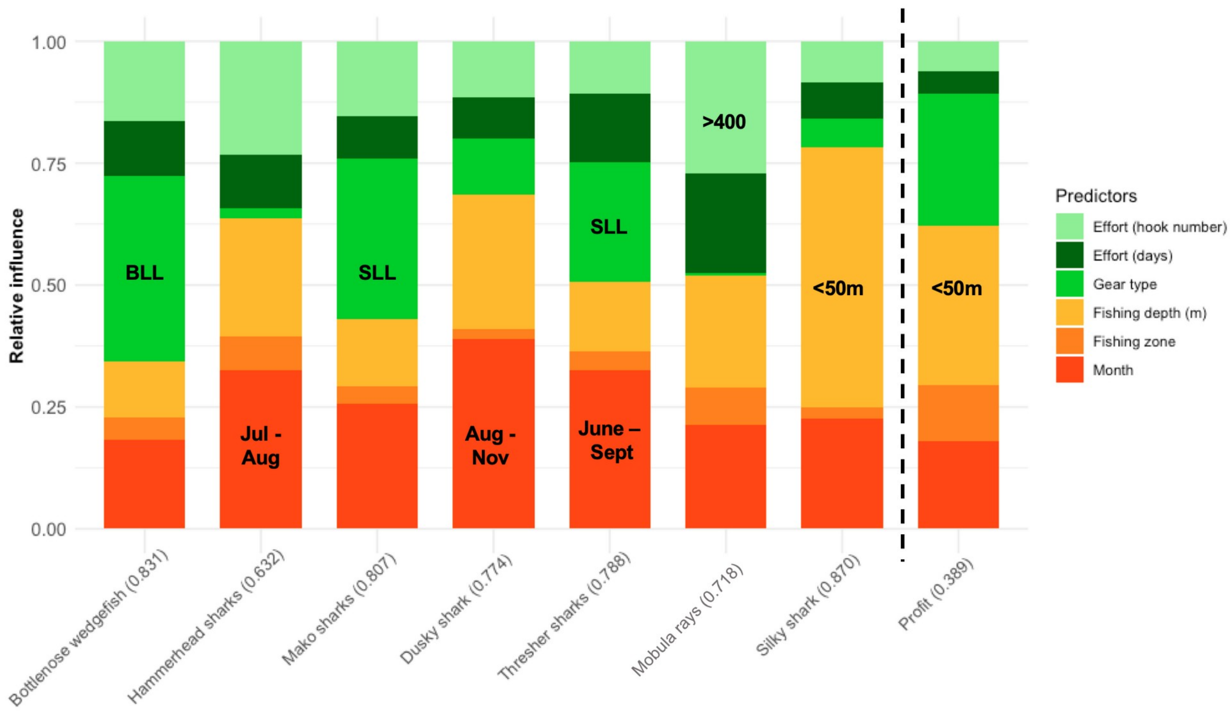


Figure 2 Summary of the relative influence of each management-relevant predictor on the likelihood of catching each priority taxa and total trip profit, based on BRT models. The labels in bold text indicate the highest-risk value for the most influential predictor(s) of risk for a given species group (e.g., for wedgefish, the gear is the most influential predictor, and the highest-risk gear is bottom longline; see Table S1 for details). The numbers in brackets next to each response variable are the mean ROC values for each model, where values above 0.7 indicate an acceptable performance. BLL = bottom longline, SLL = surface longline.

3.2.1. Temporal closures by month

Month is particularly influential for thresher sharks (33%), dusky sharks (39%) and hammerhead sharks (33%) (Figure 2). The likelihood of thresher sharks and hammerhead sharks being caught increases during the middle of the year (June – September and July – August, respectively), while dusky sharks are more likely to be caught during the mid-to-end of the year (August to November) (Figure 4). This suggests that a temporal closure in around July or August could reduce capture of these taxa. This could also be beneficial for mako sharks and mobula rays, though may have no or negative impacts on wedgefish, since wedgefish are at higher risk in January-March. Month is also moderately influential for profit (18%), with profits peaking in June-July and August-September (Figure 2; Figure 4).

3.2.2. Restrictions on fishing depth

Fishing depth is most influential for silky sharks (53%) and has moderate influence for dusky sharks (28%), mobula rays (23%) and hammerheads (24%; Figure 2). The relative likelihood of catch declines with increasing depth for silky sharks, mobula rays, thresher sharks and mako sharks, and increases with increasing depth for dusky sharks, bottlenose wedgefish, hammerhead sharks (Figure 3). In particular, fishing at depths of 0-50m leads to a higher likelihood of catching silky sharks and mobula ray, while fishing at depths greater than 60m and 100m leads to a higher likelihood of catching of dusky sharks and hammerheads, respectively (Figure 3). Depth is also the most influential variable for profit (33%), with higher profits associated with fishing at <50m depth (Figure 2; Figure 4).

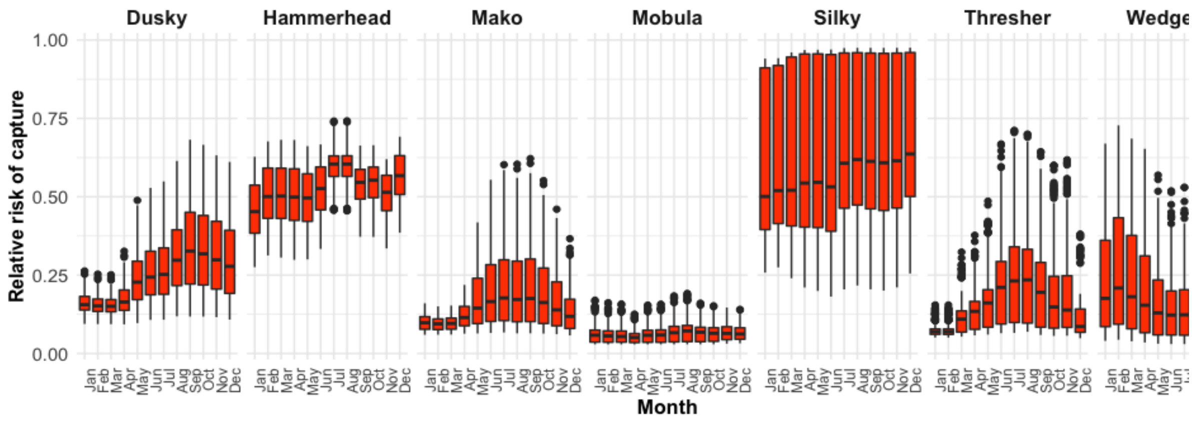
3.2.3. Restrictions on gear type

Gear type has a large influence on capture of wedgefish (38%) and mako sharks (33%), and a moderate influence on thresher sharks (25%) (Figure 3). Surface longlines are highest risk for threshers and makos, while bottom longlines are highest risk for wedgefish (Figure 3). Gear type is also the second most influential variable for profit (27%) with surface longlines associated with higher profit (Figure 2; Figure 4).

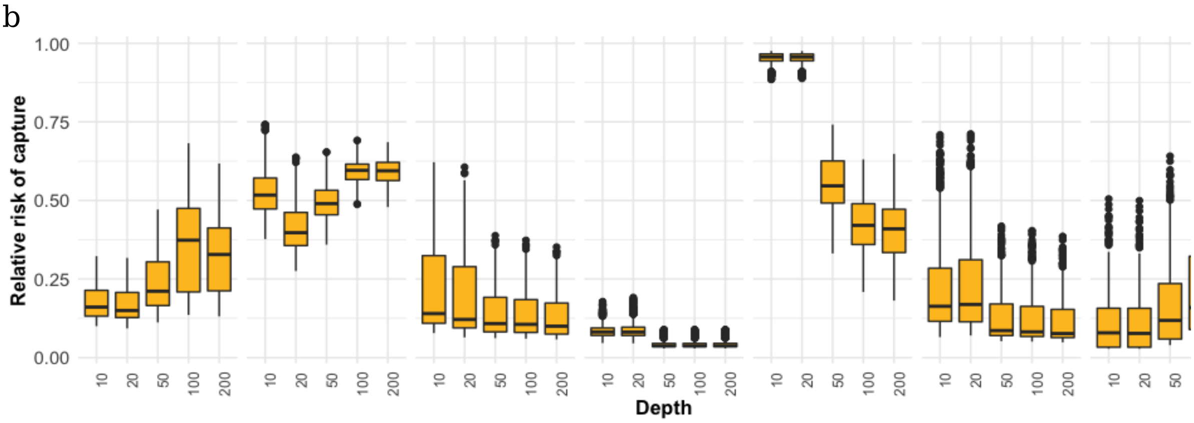
3.2.4. Hook limits

Hook number is the most influential variable for capture of mobula rays (27%; Figure 2). Higher hook numbers are associated with higher catches of mobula rays, particularly above 400 hooks (Figure 3). Hook number has limited influence on profit (6%) (Figure 2; Figure 4).

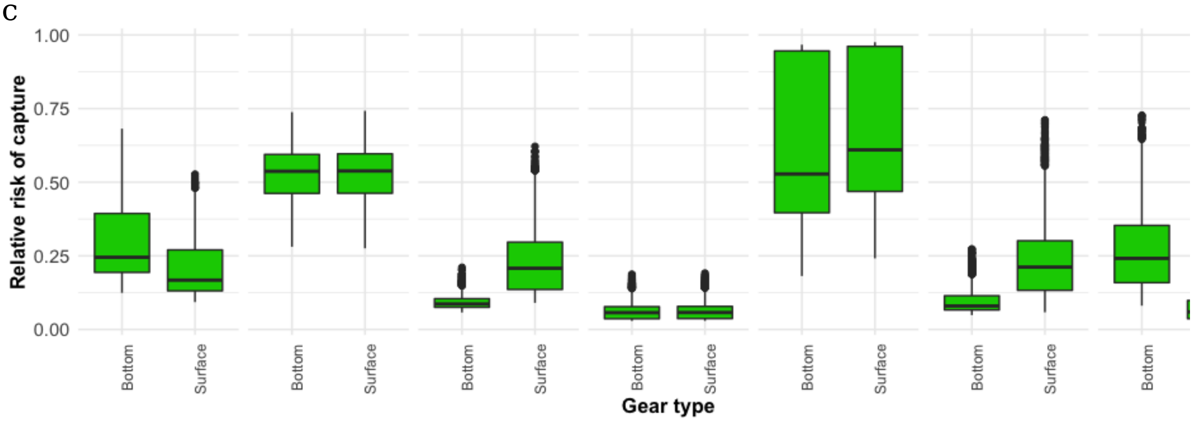
a


Dusky
Hammerhead
Mako
Mobula
Silky
Thresher
Wedge
Relative risk of capture
1.00
0.75
0.50
0.25
0.00
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
Month

b


Relative risk of capture
1.00
0.75
0.50
0.25
0.00
10
20
50
100
200
Depth

c


Relative risk of capture
1.00
0.75
0.50
0.25
0.00
Bottom
Surface
Gear type

d

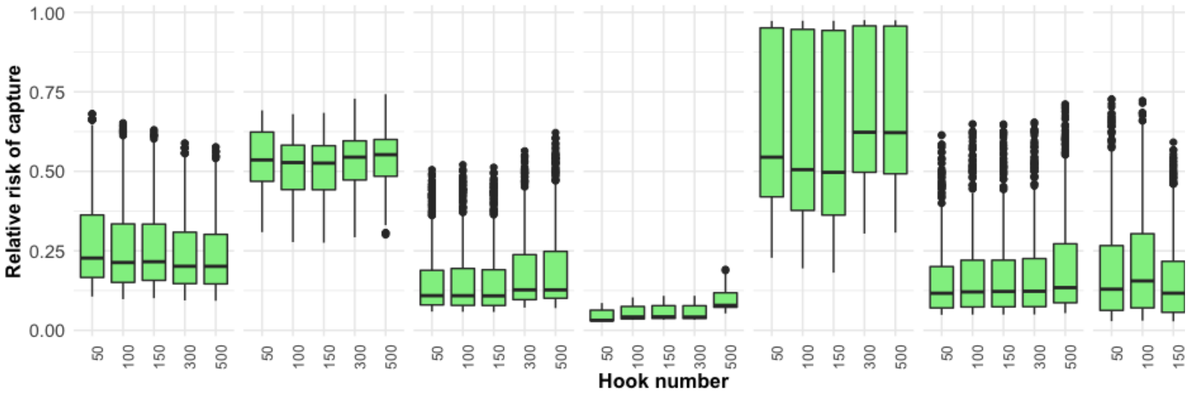


Figure 3 Boxplots showing the relationship between the relative risk of catching each priority taxon and the most influential operational predictors (a. month, b. depth (m), c. gear type and d. hook number)

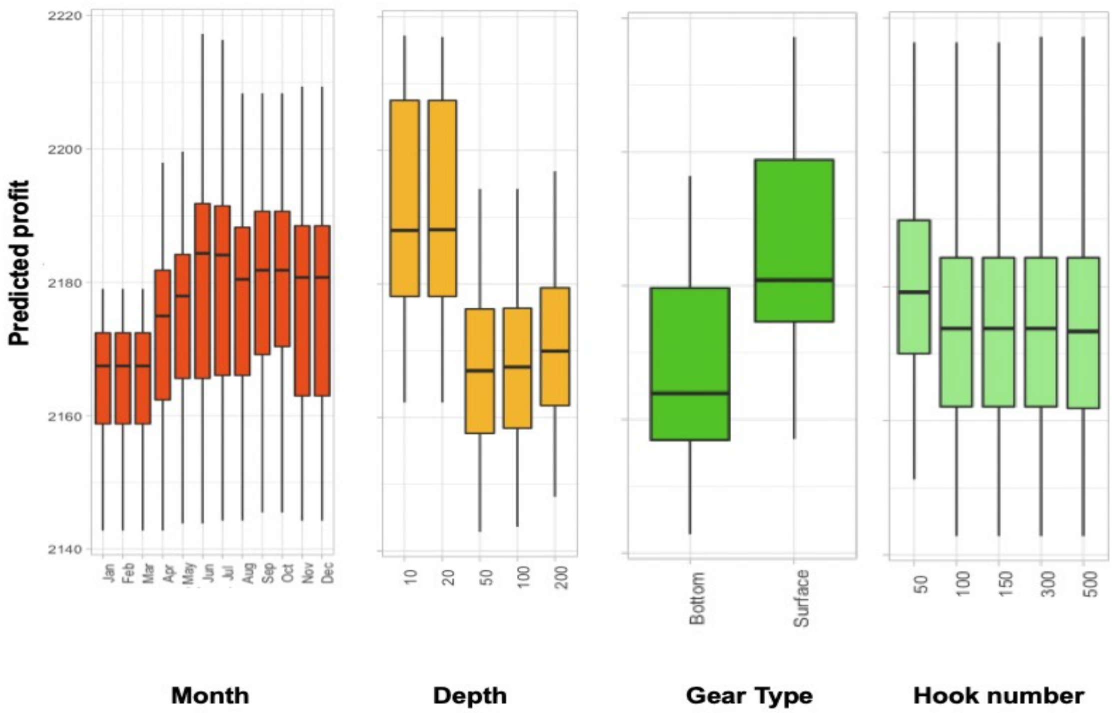


Figure 4 Boxplots showing the relationships between trip profit and the most influential operational predictors

3.3. Hypothetical cost-effectiveness

Based on our semi-quantitative assessment, the most cost-effective management measures – in terms of maximising overall conservation benefits while limiting costs – could be temporal closures in January to March (moderate benefit for lower cost), depth restrictions at >100m (high benefit for lower cost), gear restrictions for bottom longlines (high benefit for lower cost), and hook restrictions at >300 hooks (moderate-to-high benefit for lower cost) (Table 3, S2). These measures could be particularly beneficial for hammerhead sharks, dusky sharks, wedgefish and mobula rays, which are the most threatened species captured in the fishery (Table 3). These measures may, however, provide limited benefits for silky and mako sharks, since capture of these species is more frequent in shallower waters using surface longlines, which is also coupled with trip profit (Figure 3; Figure 4).

Table 3 Summary of semi-quantitative cost-effectiveness estimates for each management measure analysed in the BRT models, their potential benefits for each priority taxa, and their total weighted conservation benefit

Mgmt measure	Benefit to priority taxa							Overall conservation benefit	Relative economic cost
	TH (EN)	SY (VU)	DU (EN)	MK (EN)	MB (EN)	WF (CR)	HH (CR)		
Temporal closure in…									
Jan						✓✓		Moderate	Lower
Feb						✓✓		Moderate	Lower
Mar						✓✓		Moderate	Lower
Apr						✓		Low	Lower
May	✓			✓				Low	Higher
Jun	✓✓		✓	✓				Moderate	Higher
Jul	✓✓✓	✓	✓	✓✓	✓		✓✓	Very High	Higher
Aug	✓✓	✓	✓	✓✓	✓✓		✓✓✓	Very High	Higher
Sep	✓	✓	✓✓	✓✓	✓✓		✓	High	Higher
Oct	✓	✓	✓✓	✓	✓		✓	High	Higher
Nov	✓	✓✓	✓✓	✓	✓			Moderate	Higher
Dec		✓✓	✓	✓	✓		✓✓	High	Higher
Depth restrictions at…									
10	✓	✓✓		✓✓	✓✓		✓	High	Higher
20	✓✓	✓✓✓		✓	✓✓			Moderate	Higher
50								Low	Lower
100			✓✓✓			✓	✓✓	High	Lower
200			✓✓			✓✓	✓✓	High	Lower
Gear restrictions for…									
BLL			✓			✓✓✓		High	Lower
SLL	✓✓	✓		✓✓✓	✓			Moderate	Higher

Hook restrictions at...									
50			✓			✓	✓	Moderate	Higher
100			✓			✓		Low	Lower
150			✓					Low	Lower
300		✓		✓			✓	Moderate	Lower
500	✓	✓✓		✓	✓✓✓		✓	High	Lower

TH = thresher, SY = silky, DU = dusky, MK = mako, DV = mobula ray, WF = wedgefish, HH = hammerhead;
VU = Vulnerable, EN = Endangered, CR = Critically Endangered;
(✓) = predicted conservation benefit above average for that taxon, (✓✓) = top five predicted benefit for that taxon, (✓✓✓) = absolute highest predicted benefit for that taxon

When testing different scoring and weighting systems we found that different types of management measures had different sensitivities to changes in taxa weightings (S2). The overall conservation benefit for different hook limits did not change under different weighting systems, while depth restrictions were also relatively consistent – only restrictions at shallower depths became more effective overall (20m became categorised as high, and 10m became categorised as very high under both linear and equal weightings), due to the relative increase in weightings given to silky and mako sharks, which are typically caught in shallower waters. The different potential months for temporal closures were somewhat sensitive to changing in the weight system, though the scores for some months remained consistent. The overall categorisations for the months of April – August (inclusive) and October and December did not change, however the conservation benefit for January – March became relatively lower as the weightings became more equal, and the conservation benefit for September and November became relatively higher (S2). Gear restrictions was the most sensitive to changes in the scoring system, with the overall conservation benefit of bottom longline decreasing, and the overall conservation benefit of surface longline increasing and the weightings became more equal. Again, this is due to the relatively higher risks to silky sharks and makos in surface longlines (S2).

4. Discussion

We applied a multi-stage process and BRT analysis to explore cost-effective management options for reducing risks to threatened and CITES-listed shark species in a small-scale longline fishery of socio-economic importance in Indonesia. The results provide insights into potential management measures for the study fishery which could achieve the management goal of reducing risks to priority taxa whilst minimising economic losses to fishers, and enable transparent assessment of their relative cost-effectiveness and potential cross-taxa trade-offs. Based on the results we offer some management recommendations and related implementation needs; highlight limitations, knowledge gaps and research priorities; and offer some general recommendations regarding managing small-scale shark fishing in challenging socio-economic contexts.

4.1. Management recommendations and implementation needs

Combining and interpreting the results of the BRT analysis with additional sources of knowledge on the study fishery and taxa indicates that depth restrictions and effort limits could provide cost-effective management options for reducing threats to Critically Endangered species, while allowing fishers to continue to benefit from shark fishing (Table 4). Temporal closures could also have conservation benefits but may be difficult to implement due to the opportunity costs of closing the fishery for an entire 2-3-month period, during which fishers would have limited other sources of income. This could be particularly challenging in July and August, when the conservation benefits could be highest, but the socio-economic costs would also be greatest (Table 3). These months fall during Lombok's East Season, when the weather is calm so that fishing effort is typically higher (Yulianto et al., 2018), and thus profit is also higher (Figure 4). Closures during January-March may represent a more socio-economically feasible option. This would fall during West season, when fishers typically reduce their fishing effort due to poor weather conditions (Yulianto et al., 2018), and could be particularly beneficial for Critically Endangered wedgefish, though would still create costs, albeit lower than at other times of year (Table 4). Gear restrictions on bottom longlines could also have high conservation benefits for lower overall cost, but may be inequitable and difficult to implement due to limited inter-changeability between surface and bottom longlines (Table 3). Fishers are typically 'bought-in' to their particular gear, both socially and in terms of skill and capital: they usually learn and inherit from their fathers, and the gears are relatively expensive such that the investment in switching to a different gear would be significant (Lestari et al., 2017). As a result, while the overall cost may be relatively lower, there would be an unequal impact on fishers using bottom longlines. Nonetheless, it may be possible to implement these measures if agreements and compensation schemes are carefully negotiated with fishers, such as conservation payments for profits foregone during closures, vessel buyouts for bottom longlines fishers or financial support for gear swaps (Table 3) (Gleason et al., 2013; Sykes et al., 2018; Wasserman et al., 2013).

Table 4 Overall assessment of different possible management measures, and implementation needs

Potential	Bene	Feasibili	Overall assessment, and implementation

management measure	fit	ty	needs
Complete fishery closure	Very High	Very Low	Would have largest conservation benefit for all species, but highly costly to fishers and is unfeasible within current economic and policy context. Could only be implemented through a negotiated buy-out or compensation scheme.
Temporal closure (July – August)	High	Low	Could have conservation benefits for all species, since all are caught year-round, and particularly for hammerhead, dusky and thresher sharks. Would result in two months of lost income for fishers during the most profitable months of the year, so would require compensation if implemented.
Temporal closure (January - March)	Moderate	Moderate	Could have significant conservation benefits for Critically Endangered wedgefish. Would result in lost income for fishers, but during a less-profitable time of year, which may be more socio-economically acceptable. Would require a compensation scheme if implemented.
Spatial closure	Low	Moderate	Found to have limited influence on risk to priority species, could benefit from further analysis using fine-scale spatially-explicit catch data.
Depth restrictions (no fishing >300m)	High	Moderate	Could have conservation benefits for Critically Endangered taxa (wedgefish, hammerheads). Could result in lost income from reduced wedgefish catches which, while caught less frequently than other taxa, are high value per individual (Booth et al., 2021b). Could have inequitable cost for bottom longline fishers who typically set gears deeper.
Gear restrictions (on bottom longlines)	High	Low	Could have conservation benefits for Critically Endangered taxa (wedgefish), however may have inequitable cost for bottom longline fishers who may not easily switch to surface longline due to differences in skill, equipment and social attachments to fishing practices (Lestari et al., 2017). Would require a buyout or gear swap scheme if implemented.
Effort limit (days)	Moderate	Moderate	Found to have limited influence on risk to priority species, though an overall effort cap on the fishery could reduce mortality for all species.
Effort limit (hooks <150)	Moderate	High	Could have conservation benefits for mobula rays. Could be easy to implement at limited costs to fishers, though may reduce total catch and hence profit per trip.

For most measures, there are also clear trade-offs between different taxa, with the most cost-effective measures potentially leading to displacement effects - for example with increases in silky and mako shark catches because of increased fishing effort at times and depths at which they are at higher risk of capture. Of course, a complete closure of the shark fishery would address these cross-taxa conflicts and have the largest conservation benefit but would come at a significant (and arguably unacceptable) cost to the fisher community. If this policy were considered, it would require a negotiated buy-out or compensation scheme, with full free, prior, and informed consent of affected fishers. Based on the sum of total profits from all trips in 2017 and 2018, the total economic surplus from the Tanjung Luar fishery is around US$437,000 – US$830,000 per year, therefore a negotiated buy-out scheme may need to cover these opportunity costs (discounted in perpetuity).

4.2. Limitations and knowledge gaps

There are several limitations to this study, which warrant caution when using the results to inform future management decisions, and potential future research. Firstly, the low receiver operating characteristic (ROC) for the profit BRT model indicates that the model has low performance in terms of explaining and predicting profit per trip. There are several possible reasons for this. 1) Profit data were only collected for 2017 and 2018, meaning there was limited data available to train the model. 2) The management-relevant variables used as predictors for the purposes of this study may not be the most relevant predictors for explaining profit. Since shark catches are sold for their meat and fins, catch outputs (such as total catch and species composition) are likely to be more important for explaining economic value than fishery inputs (Booth et al., 2021b). Profit may also be related to other socio-economic factors, such as skipper skill and capacity (Roberson and Wilcox, 2022), which were not included in this analysis. As such, the profit predictions should be interpreted with caution, with further work needed to gain more accurate measures of the economic opportunity costs of different management measures. Nonetheless, they provide a directional indication of how changes in fishing practices might influence profit, which remains useful for the aims of this study. In the future, more long-term data on trip profit could help to prepare a better model for a more robust assessment, or opportunity costs could be more accurately estimated based on estimated reduced catch ratios of different taxa, provided such data are available.

Secondly, impact on trip profit represents a somewhat simplified indicator of the socio-economic feasibility of management measures, which will also depend on the beliefs, attitudes, norms and values of fishers, as well as management costs and the practicalities of implementation (Booth et al., 2019a; Fulton et al., 2011; Gupta et al., 2020). In the future it will be important to supplement this narrow assessment with social surveys and participatory techniques, to understand the perceptions of fishers and any potential non-monetary values associated with certain fishing practices, such as social capital and personal pride (Milner-Gulland et al., 2014; Woodhouse et al., 2015). While we outline some recommendations in Table 4, any management decisions would need to be made following open discussions and negotiated agreements with fishers, with full respect for their rights and well-being (Gleason et al., 2013; Newing and Perram, 2019). Relatedly, there is a need to understand which types of policies and instruments could help to better align conservation outcomes with socio-economic benefits for fishers in the short and long term. We suggest several options in Table 4, such as compensation/incentive schemes, but note that economic and rights-based instruments have received limited attention in small-scale fisheries and even less so in a shark conservation context (Bladon et al., 2016). In the future, it will be important to use interdisciplinary methods to explore the potential role of such instruments in delivering conservation outcomes for sharks, whilst maintaining the well-being of coastal communities (Booth et al., 2021a; Giron-Nava et al., 2021).

Third, we have quantitatively explored the potential conservation benefits of the different management measures, while only qualitatively acknowledging any potential negative effects due to displacement. In the future, it will be important to understand the likely adaptive responses of fishers so that any unintended consequences – in terms of socio-economic and conservation impacts – can be foreseen and addressed.

Finally, this study only focused on at-sea input-oriented measures to avoid or minimise capture of the priority species, yet a fully integrated conservation strategy should also consider the potential role of post-capture remediation and compensation strategies (Booth et al., 2019b; Dutton and Squires, 2008). This could be especially important for Critically Endangered species like wedgefish and hammerhead sharks, for which completely avoiding fishing mortality can be challenging (Gallagher et al., 2014; Tolotti et al., 2015), and thus alternative approaches to address residual unavoidable mortality may be required. For example, retention bans with live release protocols could provide further cumulative conservation benefits for species within family Rhinidae (i.e., wedgefish), which exhibit relatively high post-capture survivability (Fennessy, 1994; Stobutzki et al., 2002; Wosnick et al., 2020). However, since wedgefish are not legally protected in Indonesia, and are also amongst the highest value species in domestic and international markets (Booth et al., 2021b; Hau et al., 2018), this may require a compensation/incentive scheme to encourage uptake amongst fishers (Booth et al., 2021a). Such programs have proven to be effective for reducing mortality of guitarfishes in small-scale fisheries in Brazil (Wosnick et al., 2020), and these lessons could easily be applied to similar situations in Indonesia. In contrast, live release protocols may be of limited effectiveness for hammerhead sharks, which typically have low survivability (Gallagher et al., 2014). Instead, compensatory approaches, such as protecting and restoring important hammerhead shark habitat (e.g., nursery and pupping grounds) may be needed to maintain population health.

4.3. Concluding remarks, and the future of cost-effective shark conservation

We have used novel methods to explore and identify cost-effectiveness management measures for mitigating mortality of threatened and protected shark species in a small-scale semi-commercial targeted shark longline fishery. We used BRTs to demonstrate which operational fishing variables create the greatest risks to priority taxa; and estimate which input-oriented management measures could have the largest relative conservation benefits and highest socio-economic feasibility, as well as potential implementation needs. These results can be used within participatory management planning processes to design fisheries management interventions that support endangered species conservation and CITES-implementation, whilst mitigating the negative socio-economic impacts of conservation on small-scale fishers.

More broadly, the results show the importance of considering socio-economic costs/feasibility in conservation decision-making, since incorporating this information can result in somewhat different recommendations in comparison to considering absolute effectiveness alone. For example, while temporal closures in July and August and depth restrictions for <10m might have the highest overall conservation benefits, they are also associated with some of the highest socio-economic costs. This could make them ineffective or unfeasible to implement, due to ethical dilemmas regarding causing harm to vulnerable coastal communities, and backlash or non-compliance from communities as a result of these costs (Oyanedel et al., 2020; Semedi and Schneider, 2021). This study also highlights the more general lesson that shark conservation entails hard choices and trade-offs (Gilman et al., 2019; McShane et al., 2011). These manifest as trade-offs between biodiversity conservation and human well-being, and as trade-offs between species and different groups of people. These dilemmas warrant further consideration in the move towards a more effective and ethical paradigm for shark conservation, which can contribute to the Convention on Biological Diversity's vision of "*living in harmony with nature*" by 2050.

Supplementary materials

S1. Total catches of priority taxa in Tanjung Luar shark fishery, 2014-2018

S2. Prediction data and calculations for semi-quantitative cost-effectiveness estimates

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