Received: 6 December 2020 | Revised: 7 June 2021 | Accepted: 23 June 2021

DOI: 10.1111/csp2.494

CONTRIBUTED PAPER

Conservation Science and Practice
A journal of the Society for Conservation Biology
Open Access

WILEY

Estimating economic losses to small-scale fishers from shark conservation: A hedonic price analysis

Hollie Booth[1,2] | Dale Squires[3] | Irfan Yulianto[4] | Benaya Simeon[2] | Muhsin[2] | Luky Adrianto[4] | Eleanor Jane Milner-Gulland[1]

[1]The Interdisciplinary Centre for Conservation Science, Department of Zoology, University of Oxford, Oxford, UK

[2]The Wildlife Conservation Society, 2300 Southern Boulevard, Bronx, New York, USA

[3]Southwest Fisheries Science Centre, National Oceanic and Atmospheric Administration, San Diego, California, USA

[4]Bogor Agricultural University, Faculty of Fisheries and Marine Sciences, Bogor, Jawa Barat, Indonesia

Correspondence
Hollie Booth, The Interdisciplinary Centre for Conservation Science, Department of Zoology, University of Oxford, 11a Mansfield Rd, Oxford OX1 3SZ, UK.
Email: hollie.booth@ozoo.ox.uk; hbooth@wcs.org

Funding information
Oxford-NaturalMotion, Grant/Award Number: 1175470; Pew Charitable Trusts, Grant/Award Number: 00028268; Shark Conservation Fund

Abstract

Understanding wildlife markets is central to effective conservation: it can help managers and policy-makers to predict how interventions might influence supply and demand of wildlife products, and economic welfare of wildlife users; and thus, design interventions which have better outcomes for wildlife and people. Here we apply a revealed preference method of economic valuation—hedonic price analysis (HPA)—to understand shark markets and explore the economic costs of shark conservation for small-scale fishers. We focus on a targeted semi-commercial shark fishery in Indonesia—which poses a threat to some shark species, but provides important economic and subsistence value for a coastal community in an impoverished region of Indonesia—and use HPA to estimate market prices and welfare measures for threatened and CITES-listed sharks. This represents a pertinent case study with practical implications because Indonesia is the world's largest shark fishing nation, where management interventions to reduce shark fishing mortality are needed. However, such interventions will create short-term socio-economic trade-offs for fishing communities, which may hamper cooperation and compliance, and raise concerns regarding the fairness and equity of conservation. Our results give significant marginal price estimates for five species of conservation and commercial importance. Dusky sharks (*Carcharhinus obscurus*) and bottlenose wedgefish (*Rhynchobatus australiae*) have the highest implicit marginal prices, at US$ 157 and US$ 144, respectively. Our estimates suggest that conservation measures, such as catch limits for endangered and CITES-listed species, could have significant economic opportunity costs (i.e., 3.4–17.6% revenue foregone) for low-income fishers. Innovative policy instruments are required to transform shark markets and fisheries—to effectively reduce threats to endangered species and implement CITES, whilst doing no harm to vulnerable coastal communities. Methods from econometrics can help conservation scientists to better understand wildlife markets, and make management decisions which create better outcomes for wildlife and people.

KEYWORDS

CITES, economic valuation, elasmobranchs, endangered species, equity, fisheries management, welfare, wildlife trade

1 | INTRODUCTION

Overexploitation for commercial trade can threaten wildlife (Broad, Mulliken, & Roe, 2002; IPBES, 2019), with high market prices driving overexploitation and extinction risk for many species of megafauna (McClenachan, Cooper, & Dulvy, 2016). However, wildlife trade regulations and conservation interventions often fail to consider the economic realities of wildlife use, which can lead to ineffective interventions with perverse socio-economic consequences (Booth, Clark, et al., 2021; Challender, Harrop, & MacMillan, 2015; Wright et al., 2016). Economic methods can help to address this, and offer important insights for conservation science. Firstly, understanding wildlife market dynamics can reveal important information on trade-driven extinction risk and drivers of exploitation (Challender et al., 2015; McClenachan et al., 2016; McNamara et al., 2016). Secondly, this information can be used to design cost-effective management interventions, such as: identifying leverage points within supply chains (McNamara et al., 2016; Nuno et al., 2018; t′ Sas-Rolfes, Challender, Hinsley, Veríssimo, & Milner-Gulland, 2019); weighing-up costs and benefits of different interventions, and their distributional impacts (Ban & Klein, 2009; Naidoo et al., 2006; Visconti, Bakkenes, Smith, Joppa, & Sykes, 2015); and identifying least-cost or market-based solutions, such as incentives or compensation (Booth, Arlidge, & Squires, 2021; Lubchenco, Cerny-Chipman, Reimer, & Levin, 2016; Travers, Clements, & Milner-Gulland, 2016). Finally, market signals can also serve as indicators of market distortions or responses to regulations, to monitor the impacts of interventions (Booth, Pooley, et al., 2020; Challender et al., 2015). These insights can help to design conservation interventions that are socio-economically feasible and robust to market forces.

We demonstrate this by applying consumer theory to wildlife market transactions. According to consumer theory, the utility of heterogeneous goods (and thus their price) is derived from the utility of their implicit attributes (Lancaster, 1966). For example, in property markets, the utility of a house is determined by number of bedrooms and proximity to amenities (Anderson, 2018). Similarly, the value of wildlife goods are determined by attributes such as size, color, texture, species, quality and sustainability (Hau, Ho, & Shea, 2016; Hinsley, Verissimo, & Roberts, 2015; Roheim, Bush, Asche, Sanchirico, & Uchida, 2018). Hedonic price analysis (HPA) is based on this theory. It is a revealed preference method of economic valuation, which can be used to estimate the implicit value of different attributes of heterogenous goods (Lancaster, 1966; Rosen, 1974; Taylor, 2003). Most environmental applications of HPA have been based on property markets (Taylor, 2003) and seafood sales (Hammarlund, 2015; Kristofersson & Rickertsen, 2004; Roheim et al., 2018), though to our knowledge it has not been applied to traded wildlife products.

Indonesia's shark markets provide a policy-relevant case study for applying HPA to a conservation science problem. Many species of cartilaginous fish (Class Chondrichthyes, herein sharks) are threatened by over overexploitation, primarily due to high levels of fishing mortality in target and by-catch fisheries (Dulvy et al., 2014, 2017; Pacoureau et al., 2021). For some species, fishing pressure is driven in part by the high economic value of their fins. For example, dusky shark (*Carcharbinus obscurus*) and wedgefish (Rhinidae spp.) fins sell for US$ 400–500 per kilogram in China and Hong Kong (Hau, Abercrombie, Ho, & Shea, 2018; Wu, 2016). As the world's largest shark fishing nation and a major fin exporter Indonesia is a global priority for shark fisheries and trade management (Dent & Clarke, 2014; Dulvy et al., 2017). Moreover, as a Party to the Convention on the International Trade of Endangered Species (CITES), Indonesia is required to ensure that international trade is sustainable for the 46 species listed on CITES Appendix II (Booth, Pooley, et al., 2020; UNEP-WCMC, 2020).

However, some Indonesian fishers are highly dependent on sharks for food and income, and regulation of shark fishing and trade can result in direct costs (i.e., out-of-pocket expenses) and opportunity costs (i.e., profits foregone) to these fishers, who are often economically vulnerable (Booth, Squires, & Milner-Gulland, 2019b; Jaiteh, Loneragan, & Warren, 2017; Lestari et al., 2017). This raises practical challenges for shark conservation in Indonesia, since high socio-economic costs may hamper fishers' willingness to comply with regulations, and increase the cost of monitoring and enforcement (Margavio & Forsyth, 1996); and ethical concerns, since conservation should respect the rights of local communities and "do no harm" to vulnerable people (Balmford & Whitten, 2003; Newing & Perram, 2019; Poudyal et al., 2018). As such, management measures need to be adapted to the socio-economic realities of shark fishing (Booth, Squires, & Milner-Gulland, 2019b; Dulvy et al., 2017).

Estimating the economic costs of shark conservation for fishers requires understanding the supply-side value of conservation-priority species. However, sharks are typically captured and sold as mixed-species bundles, with a single price at the ex-vessel level that does not differentiate by species and their implicit attributes (Fahmi, Sarmintohadi, & Mustika, 2013; Ichsan, Simeon, Muttaqin, Ula, & Booth, 2019). This makes it difficult to tease apart the values of different species within the catch. We use HPA to tackle this issue. We first show that species is implicit in price, then develop a hedonic price function to derive implicit marginal prices for a range of threatened, CITES-listed and commercially important shark species. We then use the marginal price estimates and hedonic price function to estimate the short-term economic opportunity costs of plausible management scenarios for selected threatened and CITES-listed species, which would be borne by local fishers. Finally, we explore the management implications of our findings, with a focus on how to maximize shark conservation outcomes while minimizing cost to local people.

2 | METHODS

2.1 | Study site

We used data on shark catches and market prices collected from Tanjung Luar in East Lombok, West Nusa Tenggara Province (Figure 1). Tanjung Luar is a landing site and auction facility for a small-scale semi-commercial targeted shark fishery, which primarily operates in the Indian Ocean and Makassar Straight (Fisheries Management Area [FMA] 573 and 713), with occasional trips to the Java Sea (FMA 712) (Figure 1) (Yulianto et al., 2018). At least 1,000 small-scale vessels operate from Tanjung Luar, with around 50 specialized vessels (Figure 1(c)) and 132 fishers using bottom and surface longlines to target a mixture of sharks and rays, predominantly large pelagic species (Yulianto et al., 2018). Sharks are landed whole, and the entire animal is sold and used. Fins are traded on to international markets, while non-fin products, particularly meat, are consumed locally and domestically. The shark industry is more profitable than non-shark fisheries, and shark fishers report high dependency on shark fishing, limited occupational diversity and low adaptive capacity for shifting into other fisheries (Lestari et al., 2017). This suggests there are significant socio-economic barriers to regulating shark fishing, with high potential opportunity costs to fishers.

2.2 | Data collection

Shark landings data were collected by three trained enumerators from the Wildlife Conservation Society Indonesia Program (WCS-IP). Landings and auction

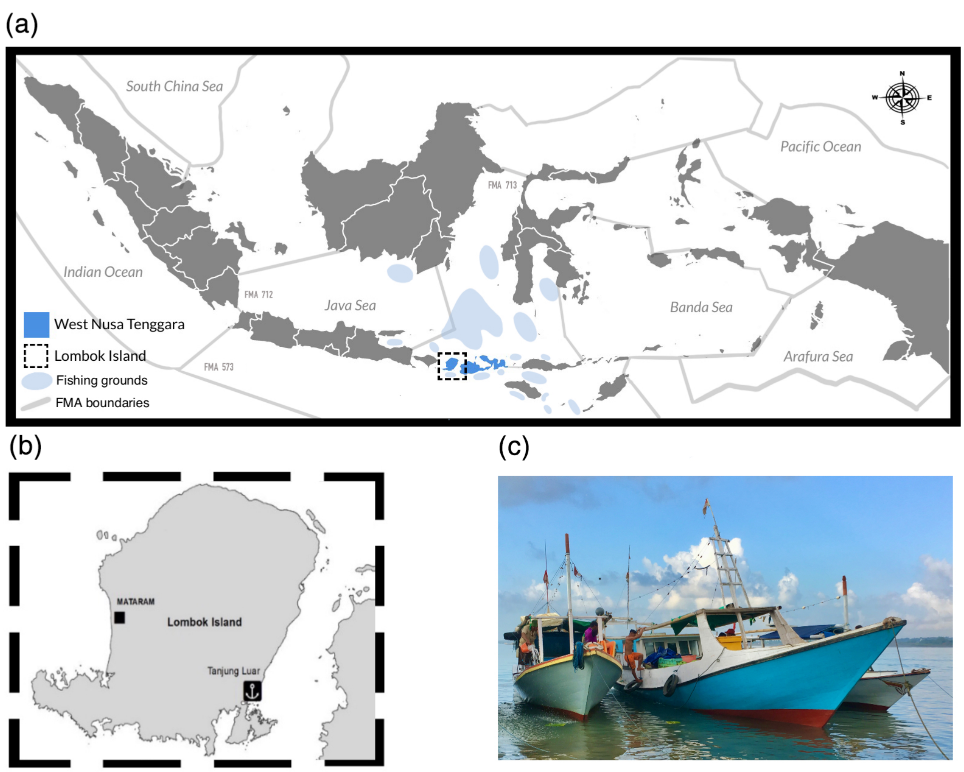

FIGURE 1 Study site: Tanjung Luar shark fishery. (a). Location of Lombok Island, West Nusa Tenggara, and Tanjung Luar fishing grounds in Indonesia (FMA = Fisheries Management Area, only those which are relevant to Tanjung Luar are numbered); (b) Lombok Island; (c) Vessels used to target sharks

prices were recorded every morning at the Tanjung Luar shark auction facility between 5 a.m. and 10 a.m. from January 2017 to December 2018. Data collection methods follow established international protocols (Jaiteh, Hordyk, Braccini, Warren, & Loneragan, 2017; SEAFDEC, 2016; Yulianto et al., 2018), with data recorded on operational variables, catch composition and the final auction price of total catches from each vessel/trip (Appendix S1, S1). This dataset was collected under a Memorandum of Understanding (MoU) and Technical Cooperation Agreement (TCA) between the WCS-IP and the Ministry of Environment and Forestry (MoEF), Ministry Marine Affairs and Fisheries (MMAF) and the Marine and Fisheries Agency (MFA) of West Nusa Tenggara Province. This research was conducted under a foreign research permit for the lead author (No. Surat Izin: 407/E5/E5.4/SIP/2019), with ethical review and approval from the University of Oxford Medical Sciences Interdivisional Research Ethics Committee (MS IDREC) (ref. R66416/RE001).

2.3 | Data preparation

We calculated total catch (number of individuals) and estimated total weight [based on empirical total length measurements and published length-weight relationships taken from FishBase (Froese & Pauly, 2021)] per vessel per trip. We also calculated the species composition of the catch, in terms of numbers of individuals per species per trip; and estimated total weight per species per trip. We grouped species into conservation-priority species and other species. We define conservation-priority species as Endangered or Critically Endangered species according to the IUCN Red List of Threatened Species (IUCN, 2020); internationally regulated species [i.e., those listed on CITES appendices (UNEP-WCMC, 2020)]; and commercially important species [additional species which made up more than 1% of the total catch, or are of particularly high value in international markets (Fields et al., 2018; Hau et al., 2016, 2018; Wu, 2016)] (Table 1). This left 31 “other” species, predominantly consisting of small rays (family Dasyatidae) and small requiem sharks (family Carcarhinidae), which together made up just under 6% of total catch for 2017–2018 (Table 1). The data were not balanced across all species: catch is dominated by silky sharks (*Carcharhinus falciformis*), which make up almost 50% of total catch, followed by tiger sharks (*Galeocerdo cuvier*, 8.3%), scalloped hammerhead sharks (*Sphyrna lewini*, 7.2%), and blue sharks (*Prionace glauca*, 6.3%) (Table 1).

2.4 | The hedonic pricing method

2.4.1 | Method background and justification

We adopted HPA to first test the hypothesis that taxonomic composition is implicit in catch auction prices, and then obtain marginal implicit prices and welfare estimates for conservation-priority taxa. The principle of HPA is that the utility provided by heterogeneous goods is based upon the utility yielded by their various attributes (Lancaster, 1966; Rosen, 1974; Taylor, 2003). In general, a class of heterogeneous goods (X) can be broken down in to a number of valued attributes $(X_1, X_2, ..., X_n)$. A combination of these attributes, and the external factors that affect the goods, determines the price (Equation (1)).

$$\text{Price} = f(X_1, X_2, ..., X_n) \quad (1)$$

where, X_i ($i = 1$ to n) is the amount of any one of the valued attributes describing a composite good.

HPA can be used to empirically estimate the implicit price of each attribute, by regressing market prices against a vector of explanatory variables representing the bundle of attributes. The regression analysis derives a hedonic price function, which indicates how much the price of the composite good will change as the quantity of each attribute (e.g., X_1) changes, holding all other attributes (X_{-1}) constant (Appendix S1, S2). The implicit price function for a given attribute (e.g., X_1) is the partial derivative of the hedonic price function with respect to X_1 ($\delta P/\delta X_1$). In a regression analysis, this is given by the linear model co-efficient for X_1. The value of the co-efficient represents the buyer's marginal willingness-to-pay to acquire an additional unit of attribute X_1, all other things equal, which is equivalent to the marginal price of the attribute (Day, 2001; Rosen, 1974; Taylor, 2003) (Appendix S1, S2).

In this study, total catches per trip represent the heterogeneous composite goods for which there is a total auction price. Prices are based upon the utility yielded from the marketable attributes derived from the catches, including fins, meat, skin and liver oil. These attributes will vary depending on taxonomic composition. Using HPA, we regressed total auction price per trip (in US$, using a conversion rate of 1 IDR = 0.00007 US$) against various iterations of catch composition and control (i.e., non-taxonomic) attributes. This enabled us to test whether taxa are implicit in auction prices, understand the influence of catch composition on auction price, and use model co-coefficients to estimate implicit marginal prices for different taxa in the fishery.

The linear models take the following form, where we focus on estimating β, a vector of coefficients indicating

TABLE 1 Species groupings and justifications

Family	Species: Common name	Species: Scientific name	>1% of total recorded catch	EN or CR	CITES	International commercial value[a]	Contribution to total catch (2017–2018): *n*	Contribution to total catch (2017–2018): %
Aetobatidae	Longheaded eagle ray	*Aetobatus flagellum*		EN		None	1	<0.1
Alopidae	Pelagic thresher	*Alopias pelagicus*	✓	EN	II	Moderate[2]	196	1.5
	Bigeye thresher	*Alopias superciliosus*			II	Moderate[2]	90	0.7
Carcharhinidae	Silvertip shark	*Carcharhinus albimarginatus*	✓			Moderate[2]	185	1.4
	Grey reef shark	*Carcharhinus amblyrhynchos*	✓			Moderate[2]	305	2.3
	Spinner shark	*Carcharhinus brevipinna*	✓			Moderate[2]	775	5.9
	Silky shark	*Carcharhinus falciformis*	✓		II	Moderate[2]	6,282	47.5
	Blacktip shark	*Carcharhinus limbatus*	✓			Moderate[2]	275	2.1
	Oceanic whitetip shark	*Carcharhinus longimanus*		EN	II	High[1]	5	<0.1
	Dusky shark	*Carcharhinus obscurus*	✓	EN		High[1]	392	3.0
	Sandbar shark	*Carcharhinus plumbeus*	✓			High[1]	135	1.0
	Spot-tail shark	*Carcharhinus sorrah*	✓			Moderate[2]	197	1.5
	Tiger shark	*Galeocerdo cuvier*	✓			Moderate[2]	1,103	8.3
	Blue shark	*Prionace glauca*	✓			High[1]	830	6.3
Lamnidae	Longfin mako shark	*Isurus oxyrinchus*	✓	EN	II	High[1]	180	1.4
	Shortfin mako shark	*Isurus paucus*		EN	II	High[1]	12	0.1
Mobulidae	Shortfin devil ray	*Mobula kuhlii*			II	Moderate[2]	1	<0.1
	Giant devil ray	*Mobula mobular*		EN	II	High[1]	21	0.2
	Chilean devil ray	*Mobula tarapacana*		EN	II	High[1]	13	0.1
	Bentfin devil ray	*Mobula thurstoni*		EN	II	Moderate[2]	26	0.2
Dasyatidae	Jenkins whipray	*Pateobatis jenkinsii*	✓			None	127	1.0
Rhinidae	Bowmouth guitarfish	*Rhina ancylostoma*		CR	II	High[1]	16	0.1
	Bottlenose wedgefish	*Rhynchobatus australiae*	✓	CR	II	High[1]	280	2.1
Sphyrnidae	Scalloped hammerhead shark	*Sphyrna lewini*	✓	CR	II	High[1]	947	7.2
	Greater hammerhead shark	*Sphyrna mokarran*		CR	II	High[1]	15	0.1
Stegostomatidae	Zebra shark	*Stegostoma tigrinum*		EN		None	17	0.1
Other	[31 non-priority species]						784	5.9

[a]Key: 1 = For sharks, high-grade/first choice fins in international markets; for mobulids, large high-value gill plates. 2 = For sharks, second-grade fins in international markets; for mobulids, smaller lower-value gill plates. Grading as per FAO classifications (Vannuccini, 1999).

how catch composition is associated with catch prices (from β we can estimate the marginal implicit price of taxa included in the model):

$$P_{i,t} = f\left[\alpha + (\beta \times \text{catch}) + (\gamma \times \text{other})\right] \quad (2)$$

where, P is the price of total catch per trip i sold at auction at time t; catch is a vector of variables describing the taxonomic composition (attributes) of the total catch per trip; and other is a vector of non-taxonomic explanatory control variables, such as year and total catch volume.

2.4.2 | Model estimation and selection

We used a linear functional form, in which regression coefficients represent implicit marginal prices (Benoit, 2011; Melichar, Vojáček, Rieger, & Jedlička, 2009; Taylor, 2003), and tested various iterations of the catch composition vector. We investigated biologically and economically meaningful catch composition attributes, based on published literature. These attributes are inter-related, since fins (sharks) and gill plates (mobulid rays) constitute 25–35% of the total value of an individual (despite making up <5% of the total weight) (Clarke et al., 2006; Wu, 2016); and the economic value of fins and gill plates are determined by size, yield of fin needles, color, and texture, which in turn vary by taxa (Hau et al., 2016, 2018; Wu, 2016). We used catch per vessel per trip as the unit of analysis, since price variation occurs at the vessel/trip level (Appendix S1, S3). We compared model fits using Adjusted R-squared and ΔAIC (Akaike Information Criterion).

We first explored the relative benefit of expressing taxonomic composition in terms of numbers of individuals (n) or weight (kg). Our preliminary results indicated that catch in numbers is a better predictor of price than catch in weight (Appendix S1, S3). This makes market sense since fins and gills are the highest value derivative products (Clarke et al., 2006; Wu, 2016). Using numbers of individuals also reduced potential measurement bias. We then explored the relative benefit of increasing taxonomic specificity for explaining variation in price, by first using clade (i.e., shark rand ray) then families, then species as explanatory variables. Our preliminary results indicated that more taxonomic specificity in the explanatory variables improved the explanatory power of the model (Appendix S1, S3). For the final the regression analyses we grouped some species into biologically and economically meaningful groups (Table 2). For example, hammerhead sharks and thresher sharks were grouped by family, since there are no major species-specific distinctions within these groups in international markets. However, silky sharks, dusky sharks and tiger sharks could not be grouped with all carcharhinids, since there is enough fin variation to warrant different prices for different species (Vannuccini, 1999; Wu, 2016).

We included non-taxonomic control variables: total catch [in terms of numbers of total weight in kg (TW) and number of individuals (TC)], to control for total catch volume; a categorical time trend (TEMP) to control for temporal trends such as seasonal price trends and general increases in price within the broader economy; and vessel ID (V-ID) as a random effect, to account for variations in relationships between vessels and buyers which might affect prices, as well as exogenous vessel-related factors such as vessel size, engine size, crew number, and gear type (Table 2). For final model selection we included all taxonomic variables, and tested the impact of removal of non-taxonomic variables and inclusion of TC versus TW on R-squared and ΔAIC (Appendix S1, S3).

We tested linear model assumptions (including linearity, normality of residuals, homogenous variance, and influence/sensitivity to data) and robustness using visual inference, based on diagnostic plots, and several statistical tests. These tests included Granger causality and Durban–Wu–Hausman to test for endogeneity (i.e., confirm that catch causes price, and is not simultaneously determined with price), Breusch–Pagan Lagrange multiplier (LM) to test for panel effects (auto-correlation/homogenous variance across entities), and Hausman to test for random versus fixed effects for vessel ID (Colonescu, 2016; Torres-Reyna, 2010) (Appendix S1, S4).

Prior to analysis, all data rows were checked for errors, with abnormal data points clarified or removed. We removed trips which made negative profits and/or caught fewer than 10 sharks in total, as these can be considered "failed trips" (based on informal discussions with fishers, indicating that they aim to capture at least 20–30 sharks before returning to port, to at least cover operating costs). The resulting dataset contained 581 market transactions, of which 43 were removed due to missing data, resulting in 538 observations used in final model estimation. Taxonomic groups with less than 60 catch records (<0.5% of total catch) were not included as independent model variables, to ensure sufficient statistical power.

All data manipulation, statistical analyses and graphical outputs were prepared in R Studio (RStudio Team, 2020), using packages "skimr," "dplyr," "plyr," and "readr" for data preparation; "lme4" for mixed-effects modeling; "ggplot2" for plots; and packages "AER," "MuMIn," "lmerTest," and "performance" for testing linear model assumptions.

2.5 | Estimation of economic opportunity costs

Based on the results of the HPA we use welfare measurement methods (Day, 2001; Taylor, 2003) to estimate the economic opportunity costs of various plausible policy scenarios to reduce fishing of conservation-priority species. For this part of the analysis we focused only on conservation-priority taxa for which statistically significant co-efficient estimates were obtained in the HPA.

2.5.1 | Cost per average trip

We use price (p) multiplied by quantity (q) calculations to estimate economic welfare changes associated with changes in the supply of conservation-priority taxa per average trip. The model co-efficients from the HPA are used as a shadow price (i.e., an estimated price for something that is not normally priced or sold in the market) per unit (p), which is valid for localized, marginal changes (Taylor, 2003). The mean catch per trip for each taxon (across all recorded trips) is used to estimate the change in quantity supplied per trip (q). We use average catch per vessel per trip, so that the changes in supply remain small (i.e., they approximate marginal changes). These are estimates of average economic opportunity

TABLE 2 Explanatory variables (attributes) included in the hedonic pricing regression analysis

Var type	Code	Description	Data type
Taxa	ALO	Number of thresher sharks (family Alopidae, 2 species)	Numeric
	ALS	Number of silvertip sharks (*Carcharhinus albimarginatus*)	Numeric
	FAL	Number of silky sharks (*Carcharhinus falciformes*)	Numeric
	DUS	Number of dusky sharks (*Carcharhinus obscurus*)	Numeric
	TIG	Number of tiger sharks (*Galeocerdo cuvier)*	Numeric
	LAM	Number of mako sharks (family Lamnidae, 2 species)	Numeric
	MOB	Number of devil rays (family Mobulidae, 4 species)	Numeric
	DHJ	Number of Jenkins whipray (*Pateobatis jenkinsii)*	Numeric
	RCS	Number of bottlenose wedgefish (*Rhynchobatus australiae*)	Numeric
	CAR	Number of "other"[a] carcharhinids (family Carcarhinidae, 6 species)	Numeric
	SPH	Number of hammerhead sharks (family Sphyrnidae, 2 species)	Numeric
Non-taxa	TW/TC	Total catch expressed as weight in kg (TW)/ number of individuals (TC)	Numeric
	TEMP	Categorical time trend, by season [4 seasons: East (June–September), transition II (October–November), West (December–March), transition I (April–May)] by year (2 years: 2017 and 2018); 8 levels in total	Categorical
	V-ID	Unique ID for each vessel, included as random effect	Categorical

[a]Not threatened, CITES-listed, or of species-specific commercial importance.

costs, based on several assumptions (Appendix S1, S5), with similar methods previously applied to labor markets to estimate the value of statistical life (Taylor, 2003).

2.5.2 | Total change in economic welfare

For non-marginal changes in economic welfare (ΔW), such as estimating the economic cost of large changes in quantities of taxa supplied across the entire Tanjung Luar fishery, the total change in welfare (across all vessels per year) is forecast using the hedonic price function (Equation (3)).

$$\Delta W = \sum\nolimits_{i=1}^{N} P_i\left(X_{1i}^1, X_{2i}^0, \ldots, X_{ni}^0\right) - P_i\left(X_{1i}^0, X_{2i}^0, \ldots, X_{ni}^0\right) \quad (3)$$

where, ΔW is the total change in welfare, or in this case net opportunity cost, summed across all (N) vessels for a given year; $P_i(X_{1i}, X_{2i}, \ldots, X_{ni})$ is the ex-ante hedonic price function, predicted across the attributes of the ith fishing trip (per vessel per time category) in the initial (i.e., current) state and the new state.

We applied this equation using the estimated hedonic price function, first to predict the hedonic price and total value of average catches per vessel per time category in the current state [i.e., the baseline/business as usual (BAU) scenario], and then predict the hedonic price and total value of average catches per vessel per time category under three new hypothetical states based on plausible policy scenarios to reduce fishing of three conservation-priority species (bottlenose wedgefish, dusky sharks, and silky sharks). We summed and compared the annual value of the BAU and new hypothetical states, based on 2018 predictions only, to estimate a total annual value and ΔW associated with each scenario. This method assumes no transaction costs, and estimates an upper bound of the welfare change associated with the attribute change (Taylor, 2003). This does not consider potential adaptation or substitution by fishers, however does consider concurrent changes in total weight associated with changes in quantities of taxa.

TABLE 3 Best-fit hedonic model

Variables		Co-efficient	Standard error	Significance
Taxon-related	Thresher sharks (ALO)	34.31	22.17	
	Silvertip sharks (ALS)	89.44	32.67	**
	Silky sharks (FAL)	55.06	4.75	***
	Dusky sharks (DUS)	157.45	25.38	***
	Tiger sharks (TIG)	54.04	11.74	***
	Mako sharks (LAM)	58.42	40.57	
	Devil rays (MOB)	−4.21	80.11	
	Jenkins whiprays (DHJ)	−40.78	41.82	
	Bottlenose wedgefish (RCS)	143.99	33.73	***
	Other carcharhinids (CAR)	−42.78	10.89	***
	Hammerheads (SPH)	13.71	12.40	
Non-taxonomic (control)	Total weight (TW)	0.74	0.10	***
	Temporal (TEMP)	✓		
	2017/transition I	−21.49	145.41	
	2017/transition II	134.84	169.21	
	2017/west	−4.36	147.69	
	2018/east	329.41	127.11	**
	2018/transition I	−224.11	143.21	
	2018/transition II	935.60	140.39	***
	2018/west	89.83	145.92	
	Vessel ID (V-ID) (as random effect)	✓		
Adjusted R-squared		0.652		
AIC		8,274.1		

Note: Significance codes: *** <.001, ** <.01, * <.05. Standard error at 95% confidence intervals. Model checked for linear model assumptions and robustness (Appendix S1, S4).

3 | RESULTS

3.1 | Model outputs

Including taxonomic composition variables improves the explanatory power of price models, in comparison to modelling price against catch volume (Table 3; Appendix S1, S3). The modelling process also indicated that total weight and year were important as control (i.e., non-taxonomic) variables, with weight as a better variable to control for total catch volume than number of individuals (Appendix S1, S3).

The lowest AIC/highest R-squared model was a linear mixed-effects model including all taxa, plus total weight, a time trend and vessel-ID as a random effect (Table 3; Appendix S1, S3). Significant marginal prices were estimated for silvertip sharks, silky sharks, dusky sharks, bottlenose wedgefish and other carcharhinids (Table 3). The model was a relatively good fit to the data (adjusted R-squared = 0.65), and met model assumptions as per diagnostic plots and tests (Appendix S1, S4). The standard errors reflect what would be expected, given the proportion of species in the catch and sample size (Table 3; Appendix S1, S3), that is, the confidence intervals are tightest for the species groups with the largest catches. However, unlike the other most frequently caught species, the co-efficient for hammerhead sharks was insignificant.

3.2 | Price functions per taxa

Conditional plots can be derived for each variable in the model. Each plot represents the hedonic price function for a given taxa, which demonstrate the relationship between total catch price (US$) and quantity of taxon supplied, other things equal. The gradient of these plots (i.e., the linear model co-efficients) can be interpreted as the implicit marginal prices for each taxonomic group included in the model that is, the marginal increase in

TABLE 4 Interpretation of hedonic models in marginal price terms

	Priority criteria		Marginal price (US$)			
Taxa	Threat status	CITES	Estimate	Sig	High	Low
Bottlenose wedgefish	CR	II	144	***	177	110
Dusky shark	EN		157	***	182	132
Silvertip shark	VU		89	**	122	56
Silky shark	VU	II	55	***	59	50
Mobula rays	EN		−4		75	−84
Thresher sharks	EN	II	34		56	12
Hammerhead sharks	CR		14		26	1
Tiger shark	NT	II	54	***	65	42
Mako sharks	EN		58		99	17
Jenkins whipray	VU		−41		1	−82
Other Carcharhinids	NT/VU		−43	***	−31	−53

Note: Marginal price shows the additional value of a catch with the addition of one individual of the given taxonomic group. High and low estimates are based on standard errors at 95% confidence intervals. Significance codes: *** <.001, ** <.01, * <.05.

total auction price (δP) (in US$) associated with adding one additional individual of that taxon (δQ_i) (Appendix S1, S6).

Based on this we can estimate the marginal economic value per shark per taxon per trip. The models show that wedgefish, dusky sharks, silvertip sharks and silky sharks are amongst the highest value species in the fishery (Table 4, Figure 2). For example, the marginal price of a critically endangered wedgefish in the Tanjung Luar shark fishery can be estimated at US$ 110–177, relative to the average shark ($p < .001$). Similarly, the marginal price of an endangered dusky shark is estimated at US$ 132–182 ($p < .001$). On the other hand, other carcharhinids (which includes *Carcharhinus plumbeus*, *C. sorrah*, *C. limbatus*, *C. amblyrhynchos*, and *Pricona glauca*) have negative marginal values relative to the average shark ($p < .001$) (Table 4, Figure 2).

3.3 | Estimating the economic opportunity costs of shark conservation

These price estimates allow for exploration of the economic welfare costs (and potential benefits) of plausible management scenarios (Table 5, Figure 3).

3.3.1 | Cost per trip

On average, 2.3 (SD 1.6) bottlenose wedgefish were landed per trip in Tanjung Luar during the survey period. This species is critically endangered and CITES-listed, therefore a plausible policy scenario could be a total catch ban. Based on a shadow price of US$ 144 per individual, the expected economic welfare loss of a catch ban for bottlenose wedgefish would be US$ 325 per trip (13% of average revenue per trip), all other things equal (Table 5). By volume, silky sharks make up the majority of Tanjung Luar's shark catch with 16.7 (*SD* 13.4) individuals landed per trip. Management measures such as catch quotas are needed to implement CITES for this species. At an implicit marginal price of US$ 55, a quota requiring a 33% reduction in catches could reduce revenue by US$ 304 or 12% per trip (Table 5), all other things equal.

3.3.2 | Total change in economic welfare

Ex-ante predictions using the hedonic price function estimate that a 33% reduction in silky shark catches could lead to a US$ 59,798 economic opportunity cost per year across the fishery against a 2018 baseline of US $ 770,959 (Figure 3). This represents a 7.8% loss. Similarly, a dusky shark ban could cost US$ 47,886 (6.2%) while a wedgefish ban could cost US$ 27,730 (3.4%) across the fishery (Figure 3). Combining all of these policies would create a combined opportunity cost of US$ 135,414; a 17.6% loss to the total value of the fishery against the 2018 baseline.

3.4 | Non-taxonomic explanatory variables

As well at the taxa-specific explanatory variables, total weight, temporal trend and vessel-ID were important variables. The total weight co-efficient (0.74) suggests that the marginal price of an extra kilogram of catch is US$ 0.74. The temporal variable indicates that auction price is typically lower in Transition I and West seasons, and higher in Transition II and East Season in 2018 ($p < .001$), with East season in 2017 as the reference year.

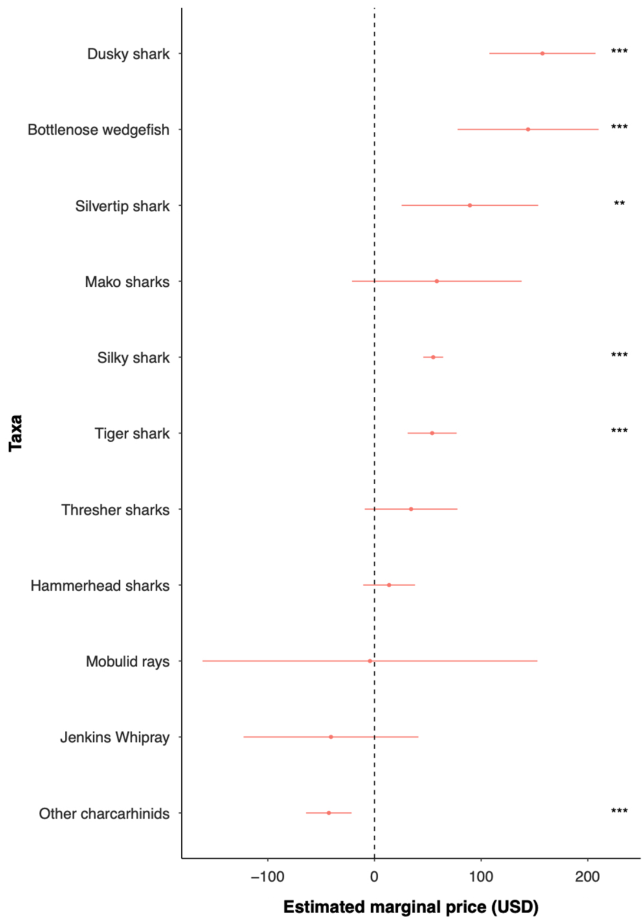

FIGURE 2 Plots of taxa co-efficients from best-fit hedonic models, where co-efficients represent marginal implicit prices per taxa (i.e., US$ per individual shark)

4 | DISCUSSION

We used HPA to estimate implicit market prices and welfare measures for threatened and CITES-listed sharks in Indonesia. The results have important implications for understanding the economic opportunity costs of shark conservation to small-scale fishers, and how we might consider these costs to communities when designing management interventions.

4.1 | Model interpretation and validation in the context of international shark trade

The price estimates from the hedonic models directionally reflect what we would expect, given the state of international shark and ray markets at the time of data collection, which supports the external validity of our method and results. For example, fins from bottlenose wedgefish and dusky sharks are two of the most highly-valued in international markets (Hau et al., 2018; Wu, 2016). Dusky shark fins belong to a specific category (Hai Hu Fin [海虎翅]) and can fetch US$ 240–430 in China and Hong Kong (Clarke et al., 2006; Wu, 2016). Similarly, fins from shark-like batoids (order Rhinipristiformes) are categorized as Qun chi (群翅/裙翅), and recognized as "king of shark fins" due to their high quality and fin-needle yields (Hau et al., 2018; Jabado, 2019). Processed Qun chi are sold for US$ 560/kg on average, and can fetch over US$ 1,600/kg (Hau et al., 2018). Silky shark "*Gou*" (i.e., caudal) fins are also moderately valuable, sold for US$ 26–591 in China and Hong Kong (Wu, 2016), and the most frequently traded fins, based on Hong Kong retail market surveys (Fields et al., 2018).

It is perhaps surprising that mobulid rays were one of the less valuable taxa. However, there is a large standard error around the estimate, which makes it statistically indistinguishable from zero. This is likely due to the

TABLE 5 Estimates of the economic costs of shark management scenarios for priority species

Taxa	Priority criteria		Hypothetical policy scenario	Mean catch per trip	Estimated marginal price (US$)			Estimated economic opportunity cost per trip of policy scenario (US$)		
	IUCN	CITES			High	Estimate	Low	High	Estimate	Low
Silky shark	VU	II	Reduce catch by 33%	16.7 (*SD* 13.4)	60	55	50	330	304 (12%)	277
Dusky shark	EN		Catch ban	2.5 (*SD* 2.1)	183	157	132	451	388 (16%)	326
Bottlenose wedgefish	CR	II	Catch ban	2.3 (*SD* 1.6)	178	144	110	401	325 (13%)	249

Note: Estimated marginal prices are derived from significant model co-efficients and standard error at 95% confidence intervals (Table 3), estimated economic cost per trip is calculated based on marginal revenue (i.e., $q * p$).

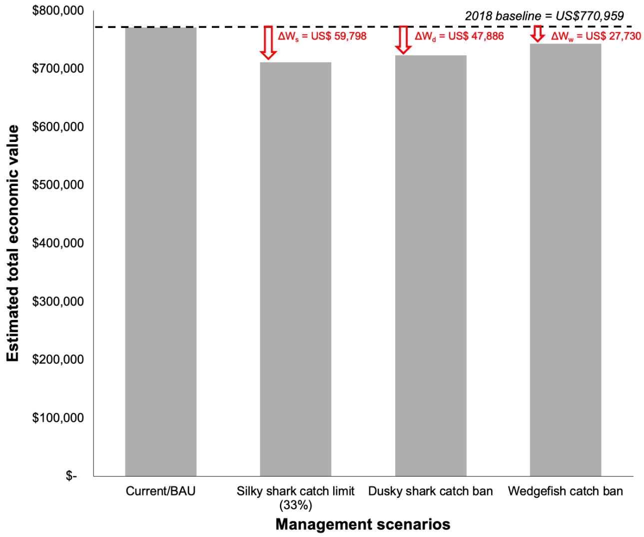

FIGURE 3 Estimated annual opportunity costs of policy scenarios across the entire fishery

small number of market transactions, yielding limited explanatory power; and the need to combine four different species, leading to aggregation bias. For example, larger mobulid gills typically fetch higher values (Hau et al., 2016), such that larger devil ray species (e.g., *Mobula mobular*, which can reach up to 5.2 m disc width) are likely to be more valuable than smaller species (e.g., *Mobula thurstoni*, which typically only reach 1.8 m disc width). In international markets, devil ray gills sell for US$ 73–350/kg, depending on the size and quality, though average at US$ 87/kg (Wu, 2016). Wu (2016) also noted that some market retailers consider mobulid ray gills a "low-price" tonic ingredient. The listing of all mobulids on CITES Appendix II, and the full protection of manta rays in Indonesia in 2014, may have also impacted market prices. A species-specific assessment may reveal more accurate and diverging prices for different species, should sufficient data be available in the future.

Mako sharks, hammerhead sharks and thresher sharks make up a relatively small proportion of the international fin trade (Fields et al., 2018). While previous studies have claimed that hammerhead and mako sharks are classified amongst the top grade fins (Vannuccini, 1999), more recent studies suggest these species are not specifically recognized or valued amongst retailers in Hong Kong. For example, Wu (2016) found one hammerhead fin in Hong Kong valued at US$ 134/kg, while no specific categorization was noted for mako or thresher sharks. The fins from these species are also, on average, smaller than those from dusky sharks, silky sharks, and wedgefish (Clarke et al., 2006) and therefore represent lower fin needle yields. As with mobulids, CITES-listings of hammerhead sharks and thresher sharks in 2016 may have impacted market values, though further investigation in to broader market dynamics would be required to confirm this.

The other carcharhinids had negative marginal prices, while the marginal price of the Jenkins whipray is not statistically different from zero. However, individuals from these taxa do not have no or negative absolute market value. Rather, these prices represent marginal values holding all other variables equal. Jenkins whipray have little-to-no commercial value (other than for local meat trade) and smaller carcharhinids fetch lower values in the fin trade. If these species are captured, they create an opportunity cost by taking up hold space and therefore reducing the number of other more valuable species that could be caught and sold. However, in the absence of other catches, they would still be worth transporting to market for sale. We also note that informal discussions with shark fishers suggests there is an informational asymmetry between fishers and traders, in which the fishers are not aware of the relative market values of the different taxa, which may also be obscured by the "bundling" of the catch. As such, fishers may be unlikely to discard these catches for high-grading purposes.

The inclusion of total weight in the model also indicates that total catch volume is important as well as catch composition. A higher volume lowers unit transaction costs through economies of scale, thereby increasing profits. However, the marginal value per kilogram is low (US$ 0.74), which reflects the low value attributed to non-fin commodities that are volume-dependent, such as meat. This also means that species which are larger on average, such as tiger sharks, dusky sharks and hammerhead sharks, will add additional marginal value to the auction price by virtue of their extra weight. For example, a 100 kg tiger shark will add an extra US$ 74 on top of its marginal taxa-specific value.

The co-efficients for the temporal variables may be explained by seasonal fluctuations in supply and demand, leading to price signals. Adverse weather during the West monsoon and Transition I seasons (December to May) may impact catch supply and therefore auction prices (Yulianto et al., 2018). Transition II season (October to November) in 2018 appears to be associated with particularly high prices ($p < .001$), which may be indicative of a change in supply–demand dynamics over time. Observations of mean total catch per trip over the time periods suggests a small but significant general decline in total catch over time. This reduced supply may be driving a long-term increase in auction price, particularly since the Tanjung Luar shark fishery is the only targeted shark fishery in WNT province, and is therefore not closely integrated by price or commodity flows with other shark markets. This would also fit with the results of the

Granger causality test, which implied that catch Granger-causes (i.e., predictably forecasts) price (Appendix S1, S4).

The inclusion of Vessel ID in the linear model may be an indicator of debt and power relationships between boat owners and buyers (Lestari et al., 2017), and differences in skipper skill, vessel characteristics, and handling for quality. That this effect is random suggests vessel-specific characteristics are relatively widely felt and diffuse across the fishery.

Finally, it is worth noting that while the model explains a considerable amount of the variation in price (adjusted $R^2 = 0.65$) some variation remains unexplained. This may be due to variables that were not collected or included in the model, such as within-taxon variation in sizes and variation in catch quality.

4.2 | The costs and benefits of managing shark fisheries

We provide a first estimate of the potential economic opportunity costs of shark conservation in a small-scale fishery, and the results have implications for displacement effects, market distortions, and the interplay between conservation and social justice.

In terms of displacement, assuming perfect species substitutability, such that it is possible for fishers to switch between conservation-priority and non-priority species, fishers might need to catch 110–150% more vulnerable tiger sharks or silvertip sharks per trip (current mean value per trip = US$ 217 and US$ 293, respectively) to make up for economic losses from a 33% reduction in silky shark catches. Similarly, average economic losses of US$ 325 per trip from a bottlenose wedgefish ban could cause even greater displacement effects on other taxa. This raises concerns regarding unintended consequences of wildlife policies, which can induce shifts toward other damaging activities, or on to other vulnerable species and ecosystems, with potentially perverse outcomes (Booth, Mardhiah, et al., 2020; Booth, Clark, et al., 2021; Suuronen, Jounela, & Tschernij, 2010). As such, any restrictions on shark fishing should come with clear adaptation and transition plans that can move fishers toward sustainable practices.

In the absence of displacement or adaptation, fisher households may lose significant portions of their income. To put our results in to context, the estimated opportunity costs per trip are higher than the average monthly income of shark fishers (crew) in Tanjung Luar (US$ 233) and 2–4 times the minimum monthly wage for manual workers in West Nusa Tenggara Province (US$ 133 per month) (Lestari et al., 2017; WageIndicator, 2020). This raises ethical concerns regarding who should bear the costs of shark conservation, as well as compliance management issues, whereby unacceptable social costs or large financial incentives for non-compliance may render policies unfavorable and unimplementable (Keane, Jones, Edwards-Jones, & Milner-Gulland, 2008; Margavio & Forsyth, 1996; Smith & Anderson, 2004). These estimates provide a first indication of some of the socio-economic trade-offs that might result from management measures for threatened and CITES-listed sharks, and can inform least-cost policy formulation, through understanding how much conservation can be achieved per unit cost (Booth, Squires, & Milner-Gulland, 2019a; Squires & Garcia, 2018).

On the other hand, these values also provide an economic argument for sustainably managing shark populations. Given declines in shark populations worldwide (MacNeil et al., 2020; Pacoureau et al., 2021), it is unlikely that many of these species can sustain current catch levels in the long-term, particularly in the absence of careful management. As such, while reduced catches may represent a short-term opportunity cost of foregone catches while stocks re-build, they could provide long-term financial benefits through a continued well-managed fishery for faster-growing species (Simpfendorfer & Dulvy, 2017). This may be feasible for blue and silky sharks, for example, which are relatively faster-growing and more abundant, and for which some examples of sustainable fisheries exist (Bonfil, 2009; LIPI, 2018; Simpfendorfer & Dulvy, 2017). However, this may be more challenging for critically endangered species such as wedgefish, which require more stringent catch and trade limits due to their extremely high extinction risk (Kyne et al., 2020).

Despite these economic findings, we acknowledge that it may be impractical to reduce catches of conservation-priority species in the absence of an entire fishery closure or large reduced catches of associated species [e.g., due to issues with selectivity, post-release mortality, interactions with other fisheries and economic viability (Smart et al., 2020)]. The temptation for high-grading and discarding might be high, particularly if there is no operationally-feasible adaptation available to avoid catching restricted species. Similarly, reductions in supply may lead to increases in market prices, particularly for species with high prices and inelastic demand (Courchamp et al., 2006). This would further distort incentives, and may drive illegal fishing and trade. Overall, further exploration of supply–demand dynamics and substitutability is required to attain more accurate estimates of opportunity cost, and likely responses of price to market interventions.

4.3 | Future directions

Our results indicate that endangered and CITES-listed species continue to be economically important in small-scale fisheries in Indonesia. This underlines the importance of providing resources for CITES implementation, since meaningful domestic measures must be implemented in major shark fishing nations for CITES to drive conservation impact. Yet many of the world's largest shark fishing nations are also highly dependent on marine resources, necessitating a nuanced and socio-economic approach (Booth, Squires, & Milner-Gulland, 2019a; Golden et al., 2016). A better understand of domestic demand (e.g., for shark meat) and local-level drivers of shark fishing (e.g., for profit vs. subsistence) is needed to inform domestic measures and fisheries management. In parallel, demand-side countries should also play a role in driving changes through the supply chain—for example, through monitoring and enforcing sustainable quotas and permit systems—to further reduce trade-driven over exploitation of sharks. An improved understanding of the entire shark value chain, including domestic and international price leaders, and integration by price and commodity flows with other markets, will be important for identifying future market-based leverage points.

Our findings also contribute to broader debates regarding reconciling biodiversity conservation with social justice and human rights (Newing & Perram, 2019; Shoreman-Ouimet & Kopnina, 2015); and in particular the need to ensure the costs of conservation are equitably distributed, and that conservation interventions "do no harm" (Balmford & Whitten, 2003; Bennett et al., 2019; Giron-Nava et al., 2021; Griffiths, Bull, Baker, & Milner-Gulland, 2019). In small-scale fisheries, one option for simultaneously delivering conservation and social welfare outcomes could be through compensation or payment for ecosystem service schemes, which incentivize fishers to reduce capture of the most threatened species while maintaining their material well-being (Bladon, Short, Mohammed, & Milner-Gulland, 2016; Booth, Arlidge, & Squires, 2021; Wosnick, Da Costa De Lima Wosiak, & Machado Filho, 2020). Given the high value of the shark and ray tourism industry in Indonesia (Mustika, Ichsan, & Booth, 2020; O'Malley, Lee-Brooks, & Medd, 2013), it could be possible to gather funding through tourism taxes or donations, and channel this into conservation, including fisher compensation for economic losses incurred from not catching sharks (Vianna et al., 2018). Similarly, bycatch levies could be introduced for commercial fisheries, with the funds invested in critical habitat conservation and assisting small-scale fishers to adapt (Booth, Arlidge, & Squires, 2021; Gjertsen, Squires, Dutton, & Eguchi, 2014; Pakiding et al., 2020).

Overall, we reiterate the importance of understanding markets, and considering opportunity costs and distributional impacts when designing interventions to reduce overexploitation of traded species. To do so, we encourage other conservation scientists to integrate methods from economics into conservation decision-making, to better understand both supply-side and demand-side drivers of overexploitation, explore the economic and social welfare implications of conservation interventions, and mitigate unintended consequences. This is particularly important for reducing shark fishing mortality in small-scale fisheries, which are influenced by both local-level needs and macro-economic market forces (Booth, Squires, & Milner-Gulland, 2019b; Collins, Bech Letessier, Broderick, Wijesundara, & Nuno, 2020; MacKeracher et al., 2013). Rapid transformations of global markets and local fisheries are needed to save species on the brink of extinction, such as sawfish, wedgefish and hammerhead sharks. Innovative socio-economic interventions and creative institutional arrangements will be required to support these transformations, to effectively change fishing, trading and consumer behavior, and achieve positive outcomes for sharks and people.

ACKNOWLEDGMENTS

Hollie Booth acknowledges the Oxford-NaturalMotion graduate scholarship in Zoology for funding her DPhil studies. EJ Milner-Gulland acknowledges Pew Charitable Trusts, who supported this work through a Pew Marine Fellowship. All authors are grateful to the Shark Conservation Fund, who supported data collection in Tanjung Luar; to the Ministry of Environment and Forestry (MoEF), the Ministry Marine Affairs and Fisheries (MMAF), the Marine and Fisheries Agency (MFA) of West Nusa Tenggara Province and the Tanjung Luar fishing community for permitting and supporting this research, and their cooperation and collaboration throughout.

CONFLICT OF INTEREST

The authors declare no conflicts of interest.

AUTHOR CONTRIBUTIONS

Hollie Booth: Conceptualized and designed the study and analytical methods, conducted the analysis and interpretation, and led on writing the manuscript. **Muhsin:** Conducted and coordinated data acquisition. **Benaya Simeon:** Conducted and coordinated data acquisition. **Irfan Yulianto:** Designed and oversaw data acquisition protocols. **Dale Squires:** Supervised the research, in particular providing intellectual support and insights for the econometric analysis, and critical inputs to draft manuscripts. **EJ Milner-Gulland:** Supervised the research, in particular providing intellectual support and insights for the econometric analysis, and critical inputs to draft manuscripts. **Luky Adrianto:** Supervised the research, in particular providing intellectual support and insights for the econometric analysis, and critical inputs to draft manuscripts.

DATA AVAILABILITY STATEMENT

Summaries of the shark landings data used for this study are freely available online at http://data-ikan.org, which is coordinated and maintained by the Wildlife Conservation Society—Indonesia Program. Raw data is officially owned by the Marine and Fisheries Agency (MFA) of West Nusa Tenggara Province, and may be made available upon reasonable request via a data sharing agreement.

ETHICS STATEMENT

Hollie Booth has undergone comprehensive research integrity and ethics training as per the University of Oxford Central University Research Ethics Committee (CUREC) procedures and the Social Research Association Ethical Guidelines. This research was conducted under a foreign research permit for Hollie Booth (No. Surat Izin: 407/E5/E5.4/SIP/2019), with ethical review and approval from the University of Oxford Medical Sciences Interdivisional Research Ethics Committee (MS IDREC) (ref. R66416/RE001).

ORCID

Hollie Booth https://orcid.org/0000-0003-4339-820X

REFERENCES

Anderson, H. (2018). Value of nature implicit in property prices – Hedonic pricing method (HPM) methodology note.

Balmford, A., & Whitten, T. (2003). Who should pay for tropical conservation, and how could the costs be met? *Oryx*, *37*(2), 238–250. https://doi.org/10.1017/S0030605303000413

Ban, N. C., & Klein, C. J. (2009). Spatial socioeconomic data as a cost in systematic marine conservation planning. *Conservation Letters*, *2*(5), 206–215. https://doi.org/10.1111/j.1755-263x.2009.00071.x

Bennett, N. J., Cisneros-Montemayor, A. M., Blythe, J., Silver, J. J., Singh, G., Andrews, N., … Sumaila, U. R. (2019). Towards a sustainable and equitable blue economy. *Nature Sustainability*, *2*, 991–993. https://doi.org/10.1038/s41893-019-0404-1

Benoit, K. (2011). *Linear regression models with logarithmic transformations*. London: London School of Economics.

Bladon, A. J., Short, K. M., Mohammed, E. Y., & Milner-Gulland, E. J. (2016). Payments for ecosystem services in developing world fisheries. *Fish and Fisheries*, *17*(3), 839–859. https://doi.org/10.1111/faf.12095

Bonfil, R. (2009). The biology and ecology of the silky shark, Carcharhinus falciformis. *Sharks of the Open Ocean: Biology, Fisheries and Conservation*, *2009*, 114–127. https://doi.org/10.1002/9781444302516.ch10

Booth, H., Arlidge, W. N. S., & Squires, D. (2021). Bycatch levies could reconcile trade-offs between blue growth and biodiversity conservation. *Nature Ecology & Evolution*, *5*, 715–725. https://doi.org/10.1038/s41559-021-01444-w

Booth, H., Clark, M., Milner-Gulland, E. J., Amponsah-Mensah, K., Antunes, A. P., Brittain, S., … Williams, D. R. (2021). Investigating the risks of removing wild meat from global food systems. *Current Biology*, *31*(8), 1788–1797.e3. http://dx.doi.org/10.1016/j.cub.2021.01.079.

Booth, H., Mardhiah, U., Siregar, H., Hunter, J., Giyanto, Putra, M. I. H., … Yulianto, I. (2020). An integrated approach to tackling wildlife crime: Impact and lessons learned from the world's largest targeted manta ray fishery. *Conservation Science and Practice*, *3*, 1–18. https://doi.org/10.1111/csp2.314

Booth, H., Pooley, S., Clements, T., Putra, M. I. H., Lestari, W. P., Lewis, S., … Milner-Gulland, E. J. (2020). Assessing the impact of regulations on the use and trade of wildlife: An operational framework, with a case study on manta rays. *Global Ecology and Conservation*, *22*, e00953. https://doi.org/10.1016/j.gecco.2020.e00953

Booth, H., Squires, D., & Milner-Gulland, E. J. (2019a). The neglected complexities of shark fisheries, and priorities for holistic risk-based management. *Ocean & Coastal Management*, *182*, 104994. https://doi.org/10.1016/j.ocecoaman.2019.104994

Booth, H., Squires, D., & Milner-Gulland, E. J. (2019b). The mitigation hierarchy for sharks: A risk-based framework for reconciling trade-offs between shark conservation and fisheries objectives, *21*, 269–289. https://doi.org/10.1111/faf.12429

Broad, S., Mulliken, T., & Roe, D. (2002). The nature and extent of legal and illegal trade in wildlife. In S. Oldfield (Ed.), *The trade in wildlife regulation for conservation*. London, UK: Earthscan Ltd.. https://doi.org/10.4324/9781849773935-11

Challender, D. W. S., Harrop, S. R., & MacMillan, D. C. (2015). Understanding markets to conserve trade-threatened species in cites. *Biological Conservation*, *187*, 249–259. https://doi.org/10.1016/j.biocon.2015.04.015

Clarke, S. C., McAllister, M. K., Milner-Gulland, E. J., Kirkwood, G. P., Michielsens, C. G. J. J., Agnew, D. J., … Shivji, M. S. (2006). Global estimates of shark catches using trade records from commercial markets. *Ecology Letters*, *9* (10), 1115–1126. https://doi.org/10.1111/j.1461-0248.2006.00968.x

Collins, C., Bech Letessier, T., Broderick, A., Wijesundara, I., & Nuno, A. (2020). Using perceptions to examine human responses to blanket bans: The case of the thresher shark landing-ban in Sri Lanka. *Marine Policy*, *121*, 104198. https://doi.org/10.1016/j.marpol.2020.104198

Colonescu, C. (2016). *Principles of econometrics with R*. Retrieved from https://bookdown.org/ccolonescu/RPoE4/RPoE.pdf

Courchamp, F., Angulo, E., Rivalan, P., Hall, R. J., Signoret, L., Bull, L., & Meinard, Y. (2006). Rarity value and species extinction: The anthropogenic allee effect. *PLoS Biology*, *4*(12), e415. https://doi.org/10.1371/journal.pbio.0040415

Day, B. H. (2001). The theory of hedonic markets: obtaining welfare measures for changes in environmental quality using hedonic market data. Research report. CSERGE Publications. Centre for Social and Economic Research on the Global Environment (CSERGE), London, UK. Retrieved from https://discovery.ucl.ac.uk/id/eprint/17583/1/17583.pdf

Dent, F., & Clarke, S. C. (2014). *State of the global market for shark commodities*. Rome, Italy: FAO.

Dulvy, N. K., Fowler, S. L., Musick, J. A., Cavanagh, R. D., Kyne, P. M., Harrison, L. R., … White, W. T. (2014). Extinction risk and conservation of the world's sharks and rays. *eLife*, *3*. https://doi.org/10.7554/eLife.00590

Dulvy, N. K., Simpfendorfer, C. A., Davidson, L. N. K., Fordham, S. V., Bräutigam, A., Sant, G., & Welch, D. J. (2017). Challenges and priorities in shark and ray conservation. *Current Biology*, *27*(11), R565–R572. https://doi.org/10.1016/j.cub.2017.04.038

Fahmi, Dharmadi, Sarmintohadi, & Mustika, C. (2013). A review of the status of shark fisheries and shark conservation in Indonesia. Retrieved from http://www.kkji.kp3k.kkp.go.id2013

Fields, A. T., Fischer, G. A., Shea, S. K. H., Zhang, H., Abercrombie, D. L., Feldheim, K. A., … Chapman, D. D. (2018). Species composition of the international shark fin trade assessed through a retail-market survey in Hong Kong. *Conservation Biology*, *32*(2), 376–389. https://doi.org/10.1111/cobi.13043

Froese, R., & Pauly, D. (Eds.). (2021). *FishBase* (version 0). Retrieved from www.fishbase.org

Giron-Nava, A., Lam, V. W. Y., Aburto, O., Cheung, W. W. L., Halpern, B. S., Sumaila, U. R., & Cisneros, A. M. (2021). Sustainable fisheries are essential but not enough to ensure well-being for the world's fishers. https://doi.org/10.1111/faf.12552

Gjertsen, H., Squires, D., Dutton, P. H., & Eguchi, T. (2014). Cost-effectiveness of alternative conservation strategies with application to the Pacific leatherback turtle. *Conservation Biology*, *28*(1), 140–149. https://doi.org/10.1111/cobi.12239

Golden, C. D., Allison, E. H., Cheung, W. W. L., Dey, M. M., Halpern, B. S., McCauley, D. J., … Myers, S. S. (2016). Nutrition: Fall in fish catch threatens human health. *Nature News*, *534*(7607), 317–320. https://doi.org/10.1038/534317a

Griffiths, V. F., Bull, J. W., Baker, J., & Milner-Gulland, E. J. (2019). No net loss for people and biodiversity. *Conservation Biology*, *33*(1), 76–87. https://doi.org/10.1111/cobi.13184

Hammarlund, C. (2015). The big, the bad, and the average: Hedonic prices and inverse demand for Baltic cod. *Marine Resource Economics*, *30*(2), 157–177. https://doi.org/10.1086/679972

Hau, Y. C. L., Abercrombie, D., Ho, K. Y. K., & Shea, K. H. S. (2018). King of shark fins: A rapid survey on the availability of shark-like batoid fins in Hong Kong SAR and Guangzhou, China Retail Markets. Retrieved from http://www.bloomassociation.org/en/wp-content/uploads/2018/12/King-of-shark-fins-not-quite-sharks.pdf

Hau, Y. C. L., Ho, K. Y. K., & Shea, K. H. S. (2016). Rapid survey of mobulid Gill plate trade and retail patterns in Hong Kong and Guangzhou markets. Retrieved from http://www.bloomassociation.org/en/wp-content/uploads/2016/04/Rapid-survey-of-Mobulid-gill-plate-trade-and-retail-patterns-in-Hong-Kong-and-Guangzhou_Revised.pdf

Hinsley, A., Verissimo, D., & Roberts, D. L. (2015). Heterogeneity in consumer preferences for orchids in international trade and the potential for the use of market research methods to study demand for wildlife. *Biological Conservation*, *190*, 80–86. https://doi.org/10.1016/j.biocon.2015.05.010

Ichsan, M., Simeon, B. M., Muttaqin, E., Ula, S., & Booth, H. (2019). Shark fisheries and trade characteristic in North Maluku, Indonesia. *IOP Conference Series: Earth and Environmental Science*, *348*(1), 012013. https://doi.org/10.1088/1755-1315/348/1/012013

IPBES. (2019). Summary for policymakers of the global assessment report on biodiversity and ecosystem services of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services. Retrieved from https://ipbes.net/system/tdf/ipbes_global_assessment_report_summary_for_policymakers.pdf?file=1&type=node&id=35329

IUCN. (2020). IUCN Red List of Threatened Species. Retrieved from https://www.iucnredlist.org/

Jabado, R. W. (2019). *Wedgefishes and giant guitarfishes: A guide to species identification* (p. 2019). New York, NY: Wildlife Conservation Society.

Jaiteh, V., Hordyk, A. R., Braccini, M., Warren, C., & Loneragan, N. R. (2017). Shark finning in eastern Indonesia: Assessing the sustainability of a data-poor fishery. *ICES Journal of Marine Science*, *74*(1), 242–253. https://doi.org/10.1093/icesjms/fsw170

Jaiteh, V., Loneragan, N., & Warren, C. (2017). The end of shark finning? Impacts of declining catches and fin demand on coastal community livelihoods. *Marine Policy*, *82*, 224–233. https://doi.org/10.1016/j.marpol.2017.03.027

Keane, A., Jones, J. P. G. G., Edwards-Jones, G., & Milner-Gulland, E. J. (2008). The sleeping policeman: Understanding issues of enforcement and compliance in conservation. *Animal Conservation*, *11*(2), 75–82. https://doi.org/10.1111/j.1469-1795.2008.00170.x

Kristofersson, D., & Rickertsen, K. (2004). Efficient estimation of hedonic inverse input demand systems. *American Journal of Agricultural Economics*, *86*(4), 1127–1137. https://doi.org/10.1111/j.0002-9092.2004.00658.x

Kyne, P. M., Jabado, R. W., Rigby, C. L., Dharmadi, Gore, M. A., Pollock, C. M., … Dulvy, N. K. (2020). The thin edge of the wedge: Extremely high extinction risk in wedgefishes and giant guitarfishes. *Aquatic Conservation: Marine and Freshwater Ecosystems*, *30*(7), 1337–1361. https://doi.org/10.1002/aqc.3331

Lancaster, K. J. (1966). A new approach to consumer theory. *Journal of Political Economy*, *74*(2), 132–157. https://doi.org/10.1086/259131

Lestari, W., Sayuti, M., Muhsin B, Akbar, B., Sundari, E., & Isnaini E. (2017). Socio economic study of shark fishers in Tanjung Luar, East Lombok, West Nusa Tenggara. Wildlife Conservation Society–Indonesia Program.

LIPI. (2018). Non-detrimental findings for silky shark Carcharhinus falciformis. Retrieved from https://cites.org/sites/default/files/ndf_material/DocumentofNDFforSilkySharkinIndonesia.pdf

Lubchenco, J., Cerny-Chipman, E. B., Reimer, J. N., & Levin, S. A. (2016). The right incentives enable ocean sustainability successes and provide hope for the future. *Proceedings of the National Academy of Sciences of the United States of America*, *113*(51), 14507–14514. https://doi.org/10.1073/pnas.1604982113

MacKeracher, T., Mizrahi, M., Bergseth, B., Maung, K. M. C., Khine, Z. L., Phyu, E. T., … Diedrich, A. (2013). Understanding non-compliance in small-scale fisheries: Shark fishing in Myanmar's Myeik archipelago. *Ambio*, *2020*, 572–585. https://doi.org/10.1007/s13280-020-01400-1

MacNeil, M. A., Chapman, D. D., Heupel, M., Simpfendorfer, C. A., Heithaus, M., Meekan, M., … Cinner, J. E. (2020). Global status and conservation potential of reef sharks. *Nature*, *583*, 801–806. https://doi.org/10.1038/s41586-020-2519-y

Margavio, A. V., & Forsyth, C. J. (1996). Caught in the net: The conflict between shrimpers and conservationists. In J. A. Pratt (Ed.), *Kenneth E. Montague series in oil and business history* (7th ed.). Texas, USA: Texas A&M University Press. Retrieved from. http://agris.fao.org/agris-search/search.do?recordID=US19960119059

McClenachan, L., Cooper, A. B., & Dulvy, N. K. (2016). Rethinking trade-driven extinction risk in marine and terrestrial megafauna. *Current Biology: CB*, *26*(12), 1640–1646. https://doi.org/10.1016/j.cub.2016.05.026

McNamara, J., Rowcliffe, M., Cowlishaw, G., Alexander, J. S., Ntiamoa-Baidu, Y., Brenya, A., & Milner-Gulland, E. J. (2016). Characterising wildlife trade market supply-demand dynamics. *PLoS One*, *11*(9), e0162972. https://doi.org/10.1371/journal.pone.0162972

Melichar, J., Vojáček, O., Rieger, P., & Jedlička, K. (2009). Measuring the value of urban forest using the hedonic price approach. *Czech Regional Studies*, *2*, 13–20. Retrieved from. http://www.researchgate.net/profile/Pavel_Rieger/publication/227473980_Measuring_the_Value_of_Urban_Forest_using/links/0c96053522fa73f56e000000.pdf

Mustika, P. L. K., Ichsan, M., & Booth, H. (2020). The economic value of shark and ray tourism in Indonesia and its role in delivering conservation outcomes. *Frontiers in Marine Science*, *7*, 261. https://doi.org/10.3389/fmars.2020.00261

Naidoo, R., Balmford, A., Ferraro, P. J., Polasky, S., Ricketts, T. H., & Rouget, M. (2006). Integrating economic costs into conservation planning. *Trends in Ecology and Evolution*, *21*, 681–687. https://doi.org/10.1016/j.tree.2006.10.003

Newing, H., & Perram, A. (2019). What do you know about conservation and human rights? *Oryx*, *53*(4), 595–596. https://doi.org/10.1017/S0030605319000917

Nuno, A., Blumenthal, J. M., Austin, T. J., Bothwell, J., Ebanks-Petrie, G., Godley, B. J., & Broderick, A. C. (2018). Understanding implications of consumer behavior for wildlife farming and sustainable wildlife trade. *Conservation Biology*, *32*(2), 390–400. https://doi.org/10.1111/cobi.12998

O'Malley, M. P., Lee-Brooks, K., & Medd, H. B. (2013). The global economic impact of manta ray watching tourism. *PLoS One*, *8*(5), e65051. https://doi.org/10.1371/journal.pone.0065051

Pacoureau, N., Rigby, C. L., Kyne, P. M., Sherley, R. B., Winker, H., Carlson, J. K., … Dulvy, N. K. (2021). Half a century of global decline in oceanic sharks and rays. *Nature*, *589*(7843), 567–571. https://doi.org/10.1038/s41586-020-03173-9

Pakiding, F., Zohar, K., Allo, A. Y. T., Keroman, S., Lontoh, D., Dutton, P. H., & Tiwari, M. (2020). Community engagement: An integral component of a multifaceted conservation approach for the transboundary Western Pacific leatherback. *Frontiers in Marine Science*, *7*, 756. https://doi.org/10.3389/fmars.2020.549570

Poudyal, M., Jones, J. P. G., Rakotonarivo, O. S., Hockley, N., Gibbons, J. M., Mandimbiniaina, R., … Ramamonjisoa, B. S. (2018). Who bears the cost of forest conservation? *PeerJ*, *2018*(7), e5106. https://doi.org/10.7717/peerj.5106

Roheim, C. A., Bush, S. R., Asche, F., Sanchirico, J. N., & Uchida, H. (2018). Evolution and future of the sustainable seafood market. *Nature Sustainability*, *1*(8), 392–398. https://doi.org/10.1038/s41893-018-0115-z

Rosen, S. (1974). Hedonic prices and implicit markets: Product differentiation in pure competition. *Journal of Political Economy*, *82*, 34–55. https://doi.org/10.1086/260169

RStudio Team. (2020). *RStudio: Integrated development for R*. Boston, MA.: RStudio. Retrieved from. http://www.rstudio.com/

SEAFDEC. (2016). *Sampling at landing sites SOP*. Bangkok, Thailand: SEAFDEC.

Shoreman-Ouimet, E., & Kopnina, H. (2015). Reconciling ecological and social justice to promote biodiversity conservation. *Biological Conservation*, *184*, 320–326. https://doi.org/10.1016/j.biocon.2015.01.030

Simpfendorfer, C., & Dulvy, N. K. (2017). Bright spots of sustainable shark fishing. *Current Biology*, *27*(3), R97–R98. https://doi.org/10.1016/j.cub.2016.12.017

Smart, J. J., White, W. T., Baje, L., Chin, A., D'Alberto, B. M., Grant, M. I., … Simpfendorfer, C. A. (2020). Can multi-species shark longline fisheries be managed sustainably using size limits? Theoretically, yes. Realistically, no. *Journal of Applied Ecology*, *57*(9), 1847–1860. https://doi.org/10.1111/1365-2664.13659

Smith, R. G., & Anderson, K. (2004). Understanding non-compliance in the marine environment. *Trends and Issues in Crime and Criminal Justice*, *275*, 1–6.

Squires, D., & Garcia, S. (2018). The least-cost biodiversity impact mitigation hierarchy with a focus on marine fisheries and bycatch issues. *Conservation Biology*, *32*(5), 989–997. https://doi.org/10.1111/cobi.13155

Suuronen, P., Jounela, P., & Tschernij, V. (2010). Fishermen responses on marine protected areas in the Baltic cod fishery. *Marine Policy*, *34*(2), 237–243. https://doi.org/10.1016/j.marpol.2009.07.001

t' Sas-Rolfes, M., Challender, D. W. S., Hinsley, A., Veríssimo, D., & Milner-Gulland, E. J. (2019). Illegal wildlife trade: Scale, processes, and governance. *Annual Review of Environment and Resources*, *44*(1), 201–228. https://doi.org/10.1146/annurev-environ-101718-033253

Taylor, L. O. (2003). The hedonic method. In P. A. Champ, K. J. Boyle, & T. C. Brown (Eds.), *A primer on nonmarket valuation. The economics of non-market goods and resources*. Dordrecht: Springer.

Torres-Reyna, O. (2010). *Getting started in fixed/random effects models using R*. Princeton, NJ: Princeton University. Retrieved from. http://dss.princeton.edu/training/

Travers, H., Clements, T., & Milner-Gulland, E. J. (2016). Predicting responses to conservation interventions through scenarios: A Cambodian case study. *Biological Conservation*, *204*, 403–410. https://doi.org/10.1016/j.biocon.2016.10.040

UNEP-WCMC. (2020). CITES trade database. Retrieved from https://trade.cites.org/

Vannuccini, S. (1999). *Shark utilization, marketing and trade*. Rome, Italy: Food and Agriculture Organization of the United Nations.

Vianna, G. M. S., Meekan, M. G., Rogers, A. A., Kragt, M. E., Alin, J. M., & Zimmerhackel, J. S. (2018). Shark-diving tourism as a financing mechanism for shark conservation strategies in Malaysia. *Marine Policy*, *94*, 220–226. https://doi.org/10.1016/J.MARPOL.2018.05.008

Visconti, P., Bakkenes, M., Smith, R. J., Joppa, L., & Sykes, R. E. (2015). Socio-economic and ecological impacts of global protected area expansion plans. *Philosophical Transactions of the Royal Society B: Biological Sciences*, *370*(1681), 230–238. https://doi.org/10.1098/rstb.2014.0284

WageIndicator. (2020). Provincial and regencies minimum wage in West Nusa Tenggara 2019. Retrieved from https://gajimu.com/garment/Salaries-in-Garment/minimum-wage-garment/provincial-and-regencies-minimum-wage-in-west-nusa-tenggara

Wosnick, N., Da Costa De Lima Wosiak, C., & Machado Filho, O. C. (2020). Pay to conserve: What we have achieved in 10 years of compensatory releases of threatened with extinction guitarfishes. *Animal Conservation*, 1–3. https://doi.org/10.1111/acv.12651

Wright, J. H., Hill, N. A. O., Roe, D., Rowcliffe, J. M., Kümpel, N. F., Day, M., … Milner-Gulland, E. J. (2016). Reframing the concept of alternative livelihoods. *Conservation Biology*, *30*(1), 7–13. https://doi.org/10.1111/cobi.12607

Wu, J. (2016). Shark fin and mobulid ray gill plate trade in mainland China, Hong Kong, and Taiwan.

Yulianto, I., Booth, H., Ningtias, P., Kartawijaya, T., Santos, J., Sarmintohadi, K. S., … Hammer, C. (2018). Practical measures for sustainable shark fisheries: Lessons learned from an Indonesian targeted shark fishery. *PLoS One*, *13*(11), e0206437. https://doi.org/10.1371/journal.pone.0206437

SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section at the end of this article.

How to cite this article: Booth, H., Squires, D., Yulianto, I., Simeon, B., Muhsin, Adrianto, L., & Milner-Gulland, E. J. (2021). Estimating economic losses to small-scale fishers from shark conservation: A hedonic price analysis. *Conservation Science and Practice*, *3*(9), e494. https://doi.org/10.1111/csp2.494