Science of The Total Environment
June 2022, Volume 827, Pages 154236 (10p.)
https://doi.org/10.1016/j.scitotenv.2022.154236
https://archimer.ifremer.fr/doc/00754/86558/

Cost-effectiveness of measures to reduce ship strikes: A case study on protecting the Mediterranean fin whale

Sèbe Maxime [1, 2], Kontovas Christos, A. [3, *], Pendleton Linwood [4], Gourguet Sophie [4]

[1] Centre de Recherche en Gestion, Ecole Polytechnique, Paris, France
[2] Aix Marseille Univ., Université de Toulon, CNRS, IRD, MIO UM 110, Marseille, France
[3] Liverpool Logistics, Offshore and Marine Research Institute (LOOM) and School of Engineering, Liverpool John Moores University, Liverpool L3 3AF, United Kingdom
[4] University of Brest, Ifremer, CNRS, UMR 6308, AMURE, Unité d'Economie Maritime, IUEM, Plouzané, France

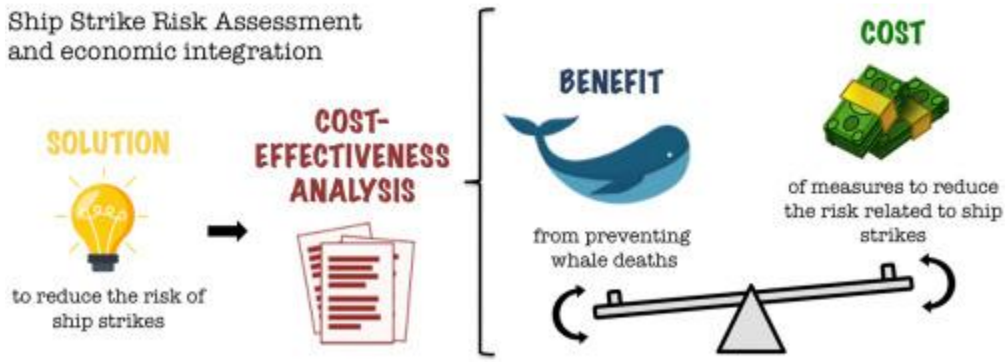
* Corresponding author : Christos A. Kontovas, email address : c.kontovas@ljmu.ac.uk

maxime.sebe@polytechnique.edu ; linwood.pendleton@univ-brest.fr ; Sophie.Gourguet@ifremer.fr

Abstract :

Collisions between ships and whales can pose a significant threat to the survival of some whale populations. The lack of robust and holistic assessments of the consequences of mitigation solutions often leads to poor compliance from the shipping industry. To overcome this, several papers support a regulatory approach to the management of whale-ship collisions through the International Maritime Organization (IMO), the UN agency responsible for maritime affairs. According to the IMO risk assessment approach, in order to compare the costs of implementing mitigation solutions and their benefits, there is a need well-defined risk evaluation criterion. To define a risk evaluation criterion for whales, we have used an ecological-economic framework based on existence values and conservation objectives. As an illustration, we applied our framework to the Mediterranean fin whale (Balaenoptera physalus) population and determined the cost of averting a whale fatality as a proxy for the societal benefits. More precisely, we have estimated a 'Value of averting a Mediterranean fin whale fatality' of 562,462 (in 2017 US dollars); this corresponds to 637,790 USD when converted to 2021 US dollars. The societal benefits of solutions that reduce the risk to whales could therefore be weighed against the costs of shipping companies to implement such measures. This can lead to assessments that are more transparent and the introduction of mandatory measures to reduce ship strikes.

Graphical abstract



Highlights

► Lack of assessments of solutions to collisions leads to poor compliance from ships. ► Societal benefits should be weighed against private costs to implement solutions. ► A dollar value of the benefits of averting a whale fatality could be placed. ► Our work can lead to more transparent whale-ship collision risk assessments.

Keywords : whale-ship collision, risk evaluation criterion, Formal Safety Assessment, cost of averting a whale fatality, cost-effectiveness analyses.

1. Introduction

Collisions between ships and whales are a major threat to some populations' survival (Ritter and Panigada, 2019). Analysis by Winker et al. (2020), based on the International Whaling Commission (IWC) Ship Strike Database, found that most reported collisions involved fin whales (*Balaenoptera physalus*, n=189, 20.2%), followed by humpback whales (*Megaptera novaeangliae*, n=163, 17.5%) and sperm whales (*Physeter macrocephalus*, n=102, 10.9%).

In the Mediterranean Sea, main collision hotspots have been identified in Greece for sperm whales, and in the North-Western basin for fin whales (Avila et al., 2018; Cates et al., 2016; Winkler et al., 2020). Often deadly, the source of the threat lies in the overlap between whale habitats and ship corridors (Dransfield et al., 2014) and the low detection of whales by ships, especially at night (Caruso et al., 2021). Some species are also extremely vulnerable due to their size and behaviour. For fin whales, in particular, their large body size and surface behaviour, i.e., longer surface time compared with other cetaceans, makes them the ones risking the most to collide with ships (Grossi et al., 2021). In the Mediterranean sea, most marine mammal strandings related to collisions concern fin whales (e.g., ~ 82.2% in France; Peltier et al., 2019); these events are also observable in Italy (Panigada et al., 2006) and Spain (Manuel and Ritter, 2010). Depending on the study period, between 6% and 21% of fin whales in the Pelagos sanctuary show collision marks (i.e., scars, propellers marks, cut dorsal fins or flukes; Panigada et al., 2020). Overall, it is expected that the increase of marine traffic and the increased speed capabilities of the new generation of ships will intensify the collision threat in the coming years (Pirotta et al., 2018; Silber et al., 2012).

The literature proposes a number of measures (or solutions) to reduce the risk of collisions. On the one hand, operational measures, such as speed reduction or avoidance of whale high-density areas, are considered to be the most effective ones (Sèbe et al., 2021; Vanderlaan et al., 2009; Vanderlaan and Taggart, 2009). On the other hand, technical measures, such as detection systems that use radio waves (e.g., Radar - radio detection and ranging) or sound propagation (e.g., Sonar - sound navigation and ranging), tagging and telemetry, or passive acoustic detection (e.g., using passive acoustic sensors, like hydrophones), have been tested; see Sèbe et al (2019) for a list of technical measures to avoid whale collisions. However, many of these systems, especially due to technical difficulties, have rarely met expectations (Silber et al., 2008).

Compliance from the shipping industry with the above-mentioned mitigation measures – whether operational or technical – is often limited (Chion et al., 2018a; Freedman et al., 2017; Sèbe and Gourguet, 2022). The lack of robust assessments has been highlighted as a contributing factor for the industry's low compliance (Firestone et al., 2008; World Shipping Council, 2006). Low compliance leads to low applied effectiveness, despite the high theoretical effectiveness of the proposed measures. In the case of whale-ship collisions, the effectiveness of a mitigation measure is rarely considered in associations with the costs and benefits associated with it. This lack of a holistic view impedes decision-maker recommendations, government enforcement, or industry willingness to act (Sèbe et al., 2020, 2019).

Recently, the application of a risk assessment framework introduced by the International Maritime Organization (IMO), namely the Formal Safety Assessment (FSA), has been conceptualized for the case of whale-ship collisions to overcome the lack of a holistic approach (Sèbe et al., 2019). The IMO, the United Nation's agency responsible for regulating shipping, introduced FSA as *"a rational and systematic process for assessing the risk related to maritime safety and the protection of the marine environment and for evaluating the costs and benefits of IMO's options for reducing these risks"* (IMO, 2018). Addressing environmental issues through the use of FSA is relatively recent (Kontovas and Psaraftis, 2009; Sèbe et al., 2019).

Formal Safety Assessment (FSA) follows the rationale of risk assessment techniques and recommends a five-step approach, consisting of Hazard Identification (Step 1), Risk Assessment (Step 2), proposing mitigation solutions – that is Risk Control Option (RCO) in the FSA terminology – (Step 3), performing a Cost-Benefit assessment (Step 4) and, finally providing recommendations for decision making (Step 5). The penultimate step (i.e., Cost-Benefit assessment) is probably the most important given that potential recommendations to decision-makers are based on this analysis. This step aims at identifying and comparing the benefits and costs associated with the implementation of mitigation measures. The definition of this step in the FSA guidelines is quite fuzzy, and has been subject to several discussions in the literature (Kontovas and Psaraftis, 2009; Psaraftis, 2012).

According to the FSA Guidelines, the cost-benefit assessment step may consist of different stages, with amongst others *"estimate and compare the cost-effectiveness of each option, in terms of the cost per unit risk reduction by dividing the net cost by the risk reduction achieved* *as a result of implementing the option"* (IMO, 2018). While Step 4 is entitled *"Cost-Benefit assessment"*, in practice, the FSA guidelines describe a Cost-Effectiveness assessment (CEA); see Kontovas, 2011). Costs should be expressed in terms of life cycle costs and may include initial (purchase) costs, as well as costs related to operation and maintenance, training, inspection, certification, etc., and benefits may include the expected reduction of lives lost or of pollution. In the context of whale-ship collisions, the most relevant benefits are that of avoided property damage (damage to the vessel itself), reduction in injuries/deaths of whales and, to a lesser extent, carcass management (Couvat et al., 2016; Mayol, 2012; Sèbe et al., 2020).

In order to assess measures based on an economic assessment, several indices to express the cost-effectiveness in relation to risk reductions have been introduced in the FSA guidelines, especially related to human safety. Lately, environmental risk evaluation criteria have been incorporated into the FSA focusing on the prevention of oil spills from ships (Kontovas et al. 2010; Psaraftis, 2012) or even proposed for ship air emissions (Kontovas and Psaaraftis, 2010; Vanem, 2012). Based on the IMO guidelines several methods can be used to derive such criteria, including the following:

- (a) Observations of the willingness to pay to avert a fatality;
- (b) Observations of past decisions and the costs involved with them; and
- (c) Consideration of societal indicators.

Following the same rationale used to assess safety-related measures that result in injuries and human life losses, this paper aims at defining a risk evaluation criterion for mitigation solutions in the context of whale-ship collisions (also known to as 'ship strikes'). This is done, here, in accordance with methodology (a), through what we should refer to as the *'Cost of Averting a Whale Fatality' (CAWF)*. In the event of a ship collision, the benefits of risk reduction to whales should be assessed; this is where assessing the monetary value of averting a whale fatality is relevant.

To our knowledge, our study is the first attempt to incorporate considerations related to whale-ship collisions into FSA. In Section 2, we introduce the general approach of valuation of the risk of whale mortality, and in Section 3, we apply this approach to the case of Mediterranean fin whale. We, then, discuss the use of the cost of averting a whale fatality as a risk evaluation criterion within maritime safety assessment. Finally, Section 5 presents the conclusions and some proposals for further research.

2. Valuation of the risk of whale mortality

2.1 Valuation of protecting a whale population

When deciding whether or not to introduce a safety measure, a quantitative approach (like in the case of FSA) generally requires decision-makers to consider its financial cost, as well as its benefits in terms of saving of lives, preventing oil spills or, in our case, reducing whale-ship collisions. Therefore, to determine whether the measure is worth introducing, a value should be placed on preventing a whale fatality. Placing a monetary value on non-market 'goods' is actually well-studied in the field of environmental economics (e.g., Lipton et al., 2014; Obeng et al., 2020). Following similar studies that place a monetary value on environmental 'goods', there is a number of methods that we could use to define the value of a single whale or a whale population in the literature; see for example (Gerber et al., 2014; Knowles and Campbell, 2011). These studies mainly use contingent valuation (CV) methods to assess the unitary willingness to pay (WTP) of people to conserve a whale population (Lew, 2015), and apply this WTP to the number of people in the study site (Bosetti and Pearce, 2003; Loomis, 2006). However, because contingent valuation methods are time-consuming and expensive, benefit transfer studies emerged to overcome these limitations (Amuakwa-Mensah, 2018; Richardson and Loomis, 2008). Benefit transfer is a methodology used to estimate the non-market value of a species in a locality of interest, based on a value already estimated in one or several other study sites (U.S. EPA, 2014). Of course, the estimations performed using with the benefit transfer method are less accurate compared to those of the original study (e.g., using contingent valuation, travel cost etc), as the original studies are not tailored to the policy site.

Several studies have tried to derive the economic value of one whale (i.e., placing a monetary value on a whale life). For example, Knowles and Campbell (2011) attempted to estimate this value for whales in Australia using the total expenditure value of whale watching. Other studies have tried to assess the value of whales through a market approach in order to encourage conservation (Eiswerth and van Kooten, 2009; Gerber et al., 2014), or rather the opposite, to promote whaling (Amundsen et al., 1995). Whatever the method, these estimations of the monetary value of a whale's life have often been criticized for ethical reasons. Notably, Babcock (2013) argues that whales have an intrinsic right to live; it is, therefore, amoral to put a monetary value on them. This ideology is built on the notion of moral values of biodiversity (e.g., pathocentrism, which refers to the viewpoint that primarily considers the suffering of animals as morally significant; see Wiegleb, 2002). Same concerns have been also expressed on placing a monetary value on human lives; nevertheless, the FSA Guidelines contains some indicative values relating to assessing the risk to human life, i.e., the value of averting (or preventing) a fatality.

Following the same rationale, we investigate a way to derive such a value to be used for the assessment of measures that reduce the risk of ship strikes. This is a necessary step in performing a comparison between the cost of implementing reduction measures and the benefit, which includes, in monetary terms, the benefit of averting whale fatalities. To define the 'Cost of Averting a Whale Fatality' (CAWF), we first need to define the value of protecting a whale population. We derive this value from the WTP per person – or household – to protect a whale population, through contingent valuation or using the benefit transfer method. The application of the unitary WTP per person – or household – to the inhabitants of the policy site to calculate the value of protecting an animal population is often debated in the literature. For endangered species, some authors apply the unitary WTP to all the inhabitants of the policy site – regardless of the study site size (Beaumont et al., 2008; Wakamatsu et al., 2018). Wallmo and Lew (2015), for instance, did not observe a significant difference between the WTP value for endangered species at a policy site level and of that at national level. In other words, in their study, the WTP of a person living near the policy site is the same as that of someone living far away from that.

In our study, we use a more spatialized approach by implementing a distance-decay relationship to calculate the value of protecting a whale population (Bateman et al., 2006; Loomis, 2000) as follows:

$$V = v \times nb \times \gamma \qquad (1)$$

where, V is the value of protecting a whale population at the policy site; v is the WTP to protect the whale population estimated per person – or household – at the policy site based either on a dedicated survey (e.g., contingent valuation) or a benefit transfer study; nb is the number of inhabitants – or households – at the policy site; and γ is the Loomis' (2000) WTP distance-decay relationship described in Figure 1.

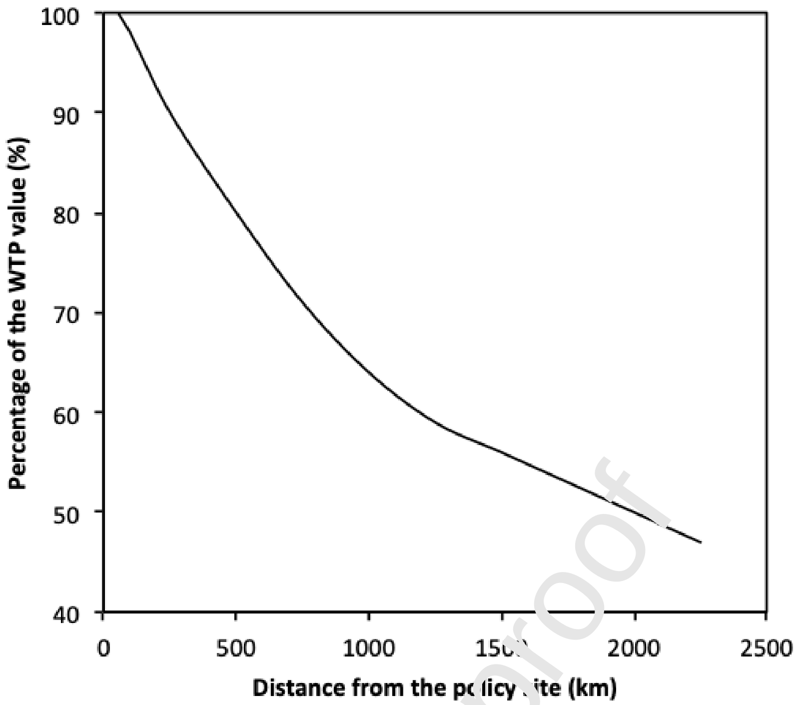


Figure 1. Willingness To Pay (WTP) distance-decay relationship for threatened and endangered species. Source: Loomis (2000)

Most of the contingent valuations – and the related benefit transfer functions – are based on the endangerment status, and not on the abundance of the endangered species population, as lack of data often hinders the use of this latter parameter. We believe that the value of protecting a whale population depending on abundance is required to assess changes in this value due to the mortality of whale individuals. As illustrated in Fig. 2a, we assume that the unitary willingness to pay v – and, by consequence, the population value V – increases when the endangerment status worsens. This decay in status is most likely due to a decrease in abundance[1] (Amuakwa-Mensah, 2018; IUCN, 2012; Martín-López et al., 2008; Richardson and Loomis, 2008). We, therefore, choose to calculate the population value V_{pop_t} at time t, based on the following linear equation:

$$V_{pop_t} = \frac{(V_{min} - V_{max})}{K} \times N_t + V_{max} \qquad (2)$$

[1] Other factors can also contribute to changes in the endangerment status (e.g., reduction of habitat), but to simplify the approach, we choose to focus on the abundance factor. For more information on the other factors, the interested reader may refer to the IUCN guidelines (IUCN, 2012).

where

- N_t the whale abundance of the population at time t
- K the whale carrying-capacity of the population (i.e., the maximum number of individuals that the population can sustain).
- V_{max} the maximum population value – related to $v_{\max}$ the maximum willingness to pay– which we assume related to the marginal WTP to conserve the last whale of a population (i.e., v is equal to $v_{\max}$ is when there is only one whale remaining in the population; Gerber et al., 2014). It should be noted that, at one point, v will not increase, even if the state of the population keeps decreasing (choke price; Amuakwa-Mensah, 2018; Colléony et al., 2017; Martín-López et al., 2008; Richardson and Loomis, 2008). V_{max} is calculated using Eq. 1.
- V_{min} the minimum population value – related to the minimum willingness to pay $v_{\min}$ – which we assume will never tend toward zero, because of the non-use value unrelated to the extinction. This is particularly true for charismatic species, which have a high existence value independently of their endangerment status (Bulte and Van Kooten, 1999; Colléony et al., 2017). In other words, when a population is close to its carrying-capacity K, the v_{min} (and V_{min}) will still be higher to zero. V_{min} is calculated using Eq. 1.

The linear function in line with Bulte and Van Kooten (1999). We derive a function of the population value depending on abundance; see Fig. 2b. Following the linearity assumption, the function can be defined based on two point estimates, i.e. $(0, V_{max})$ and (K, V_{min}). The value of protecting a population V_{pop_t} of abundance N_t, at the time *t*, is calculated using Eq. 2 (Fig. 2c).

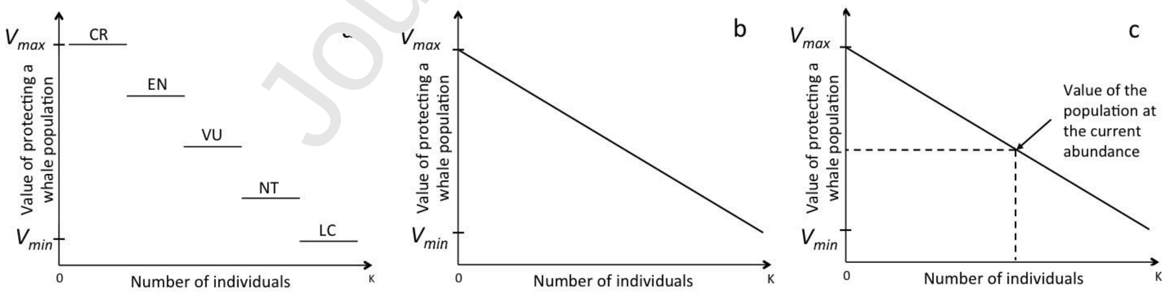


Figure 2. Conceptual illustration of the population value depending on the abundance.
(a) represents the dependence between the population value and the endangerment status;
(b) the linearity between the value and the abundance – assuming the link between the endangerment status and the abundance (Bulte and Van Kooten, 1999; IUCN, 2012);
(c) the calculation of the population value depending on the abundance at time *t*.
IUCN status: CR = Critically endangered; EN = Endangered; VU = Vulnerable; NT= Near-threatened; LC = Least concern. K stands for carrying-capacity.

2.2 Assessing the 'Cost of Averting a Whale Fatality' (CAWF)

To define the cost of averting a whale fatality, we estimate the difference in the theoretical value of protection between a population where a management rule is respected, and that of a population where the rule is not respected (Fig. 3). This difference converts the situation where the population's survival is not threatened by human activities versus the one where it is threatened. Management rules correspond to *"removal thresholds to undesirable population or ecosystem states"* (Curtis et al., 2015). In our study, we use the most common and conservative management rule, the Potential Biological Removal (PBR). Potential Biological Removal refers to *"the maximum number of animals, not including natural mortalities, that may be removed from a marine mammal stock while allowing that stock to reach or maintain its optimum sustainable population"* (Wade, 1998). For a given whale population, it takes the form of $PBR = 0.5\, N_t\, r\, F_r$, where N_t is the abundance of the population, F_r is the recovery factor (Taylor et al., 1997); r is the intrinsic rate of increase of the population (Taylor et al., 2007).

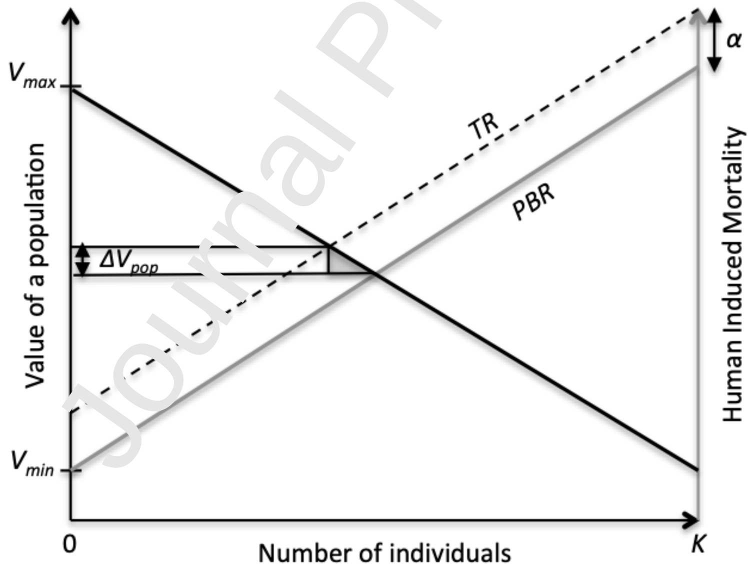


Figure 3. Conceptual illustration of the difference in value between a population where the $\mathrm{PBR_t}$ is respected and a population where the $\mathrm{PBR_t}$ is not respected ($\mathrm{TR_t}$). For simplicity, the PBR is here represented as a linear function of the number of individuals in the population. In reality, the PBR follows an exponential curve.

Consequently, the cost of averting a whale fatality is calculated as follows:

$$\varphi_{t+1} = \frac{\Delta V_{t+1}}{\alpha_t} = \frac{\Delta V_{t+1}}{TR_t - PBR_t} \qquad (3)$$

where φ_{t+1} is the 'Cost of Averting a Whale Fatality' (CAWF); α_t is the difference between the total removals TR_t – not including natural mortalities – in the population and the removals *authorized* by the management rule PBR_t; ΔV_{t+1} is the difference in value between a population where the PBR_t is respected and a population where the PBR_t is not respected (TR_t). To calculate each value ($\Delta V_{t+1,}$), we replace N_t by N_{t+1} in Equation 2. The abundance of the whale population at time t+1 (N_{t+1}) is calculated using a marine mammal's population dynamic model (Taylor & DeMaster, 1993), as follows:

$$N_{t+1} = N_t + r\, N_t \left[1 - \left(\frac{N_t}{K}\right)^{\theta}\right] - R_t \qquad (4)$$

where θ is the shape of the biological function; r is the growth rate of the population, and R_t is the number of removals at time *t*. This variable takes either the value of TR_t or PBR_t.

3. Case study: Mediterranean Fin Whales

3.1. Case study description

The Mediterranean fin whale population (*Balaenoptera physalus*) is composed of maximum ~2,500 individuals (ACCOBAMS, 2021; Laran et al., 2017; Panigada et al., 2021). A significant decrease trend of the population is suspected (Panigada et al., 2021). In addition, its resilience to disturbances is assumed to be low, as the semi-enclosed basin characteristic limits exchanges with populations outside of the Mediterranean (Notarbartolo di Sciara et al., 2016). For these reasons, the fin whale population is listed as "*Endangered"*, according to the IUCN Red List (Panigada et al., 2021).

As mentioned earlier, fin whales are among the species that are known to be severely affected by ship strikes. The shipping-related threats on this Mediterranean population are exacerbated by one of the world's highest ship density, with 13% of the world sea trade in the Mediterranean (Equasis, 2017; IWC-ACCOBAMS, 2012; Panigada et al., 2006).

The risk of ship strikes involving Mediterranean fin whales, especially in the North-Western Mediterranean Sea, has been much analysed in the literature (Panigada et al., 2006; Winkler et al., 2020). More than 3,000 near-miss events occur each year in the Pelagos sanctuary (Jacob and Ody, 2016); 210 fin whale individuals are at risk of collision offshore France in the summer (David et al., 2011); and the risk of collision offshore Spain is real while apparently less frequent (David et al., 2022). Panigada et al. (2006) estimated that the number of deaths by collisions in the Pelagos sanctuary and surrounding waters could reach 40 deaths per year.

Mitigation solutions to reduce ship strikes have been studied in this region. For example, David et al. (2011) and Ham et al. (2021) assessed the spatial distribution of the potential for collisions in the North-Western Mediterranean Sea and discussed various risk mitigation solutions, including reduction of ship speed and avoidance of areas of high whale concentration. They concluded that vessel speed reduction is more practical than other measures such as re-routing vessels.

It is also worth noting that other human-induced indirect impacts (e.g., pollution, climate change) threaten the Mediterranean fin whales population (Panigada et al., 2021).

3.2. Benefit transfer analysis

To our knowledge, there is no study that defines the WTP to protect the Mediterranean fin whale population. We therefore built a benefit transfer function based on the databases of Amuakwa-Mensah (2018) and the USGS Benefit Transfer Toolkit (Sèbe, 2020). These databases contain an extensive number of studies on the definition of the WTP for various animals. The parameters used for the benefit transfer function and the calculation of the CAWF are based on the literature; see Table 1.

Table 1. Parameters and variables used in this study

Parameter (at t)	Code	Definition	Value	Source/Comments
Abundance	N_t	Abundance refers to the relative representation of a species in a particular ecosystem and is usually measured as the number of individuals.	2,500	The abundance value from Laran et al. (2017). This value describes the abundance of fin whales in the North-Western part of the Mediterranean. Since then, a dedicated survey performed by the Agreement on the Conservation of Cetaceans of the Black Sea, Mediterranean Sea and contiguous Atlantic Area (ACCOBAMS) estimated that less than 2,500 individuals inhabit the entire Mediterranean Sea (ACCOBAMS, 2021).
Carrying Capacity	K	The maximum population size of a species that can be sustained by the specific environment.	12,178	The carrying-capacity is defined as 70% of the pre-whaling abundance (Wade, 1998). The worldwide current fin whale abundance is considered to be 14.37% of the pre-whaling abundance (Pershing et al., 2010).
Intrinsic rate of increase	r	The theoretical growth rate of the population (Malthusian parameter).	0.04	The intrinsic rate of increase was selected from Taylor *et al.*, (2007) and represents a pre-disturbance value.
Shape of the biological function	θ	Parameter θ defines the shape of the biological function; see Eq.4.	1	We assume linearity i.e. a logistic model (Gilpin et al., 1976)
Average Length (m)	L	Average length of one fin whale individual	22	(Shirihai and Jarrett, 2007)
Average Weight (kg)	W	Average weight of one fin whale individual	43,900	(Shirihai and Jarrett, 2007)
Recovery factor	F_r	It is set by decision-makers to adjust the value of the PBR for a specific conservation situation (see Section 2.2).	Variable	The recovery factor is here expressed as F_r =0.1+0.4N_t/K, so it cannot exceed 0.5 for a conservative effect on the model (Gerber et al., 2014)
Total Removal	TR_t	Total number of individuals	Variable	The total removal is a variable of the model.

		removed from the population (I;e., killed), excluding natural mortality		

A regression model was applied to these attributes in the databases to build the benefit transfer function following Amuakwa-Mensah' (2018) rationale, expressed as follows:

$$\ln v\ (2017\$) = \beta_0 \pm \beta_1 Trend \pm \beta_2 StudyFormat \pm \beta_3 SurveyMode \pm \beta_4 PaymentVehicle \pm \beta_5 PaymentFrequency \pm \beta_6 RespondentUnit \pm \beta_7 \ln IncomeProxy \pm \beta_8 EndangermentStatus \pm \beta_9 SpeciesClassification \pm \beta_{10} \ln Length \pm \beta_{11} \ln Weight \qquad (5)$$

where

- $\ln v\ (2017\$)$ is the natural log of the WTP (in 2017 US dollars)
- *Trend* is the protection objective expected, which is characterized by tow levels: 'increase' or 'no diminution'. The 'increase level' conveys a willingness to restore a population, whereas the 'no diminution' level conveys a willingness to have at least no more depletion of the said population – aka conservation (*stricto sensus*).
- *StudyFormat* is the way the study is administered – e.g. by mail, face to face, internet, mixed, or phone.
- *SurveyMode* describes the type of method used for the valuation study – contingent valuation (CV), choice experiment (CE), or hybrid.
- *PaymentVehicle* is the way the payment of the WTP is proposed in the original study.
- *PaymentFrequency* is the frequency of payment of the WTP proposed in the original study.
- *RespondentUnit* describes the scale at which the WTP is expressed – per person or household.
- *IncomeProxy* is represented by the gross domestic product based on the purchasing power parity (GDP-PPP) of the country in which the survey takes place – using data from the World Bank.
- *EndangermentStatus* is defined by two levels: endangered or not endangered. The endangered status corresponds to the Vulnerable (VU), Endangered (EN) and critically endangered (CR) statuses as defined by the IUCN, and of the endangered and threatened status as per the U.S. Marine Mammal Protection Act.
- *SpeciesClassification* is composed of eight levels describing the belonging of the studied species to the animal reign (e.g., bird, marine mammal).
- Finally, the size and weight of the species studied are defined by their average *Length* and *Weight*, respectively.

Note that as our benefit transfer analysis considered studies that took place in different countries and years the values of the original sources differ in terms of currency and purchasing power. Therefore, all values were converted to United States (US) dollars to the base year of 2017 using the US-Consumer Price Index (CPI). The studies used were published in recent times, the latest being in 2017; thus, our results are presented in 2017 US dollar figures. It is straightforward to convert these figures to 2021 values. To bring 2017 USD WTP values to 2021 values, one can use the cumulative rate of inflation (based on CPI) of 13.4%.

The values of the coefficients of the benefit transfer function (Eq. 5) are expressed in Table 2.

Table 2. Benefit transfer function coefficients.

Coef.: coefficient value; SE: for the standard error of the coefficient;
CV: contingent valuation; GDP-PPP: gross domestic product based on the purchasing power parity.

Attributes	Model	
	Coef	SE
Constant	0.518	1.805
PROTECTION OBJECTIVE (ref=Increase)		
NoDiminution	-0.274#	0.162
STUDY PARAMETERS		
STUDY FORMAT (ref=Mail)		
FaceToFace	1.276***	0.306
Internet	0.229	0.2[illegible]9
Mixed	-0.777#	0.399
Phone	0.787#	0.398
SURVEY MODE (ref=CV)		
Choice experiment	-0.635*	0.244
Hybrid	-0.2[illegible]1	0.455
PAYEMENT VEHICLE (ref=Tax)		
TrustFund	-1.292***	0.189
Bill	-0.[illegible]9#	0.349
Unspecified	-0.929*	0.376
Membership	-1.243***	0.309
PAYMENT FREQUENCY (ref=Annually)		
Monthly	-2.593***	0.323
Once	-1.2***	0.21
Unspecified	-2.593*	0.323
RESPONDENT UNIT (ref=perHousehold)		
PerPerson	-0.554*	0.278
SITE PARAMETERS		
INCOME PROXY		
ln(GDP PPP)	0.475**	0.151
SPECIES CHARACTERISTICS PARAMETERS		
ENDANGERMENT STATUS (ref=Endangered)		
NotEndangered	-0.223	0.189
SPECIES CLASSIFICATION (Ref=Marine Mammal)		
Bird	-0.185	0.344
MarineFish	-0.71*	0.323
FreshwaterFish	-1.178**	0.446
FreshwaterMammal	-0.558	0.755
DiadromousFish	-0.349	0.306
MarineReptile	-0.079	0.308
TerrestrialMammal	0.039	0.252
SIZE		
Ln(Length)	0.326	0.233
Ln(Weight)	-0.11	0.083
Observation	112	
R-squared	0.859	
Adj. R-squared	0.816	

*** p<0.001, ** p<0.01, * p<0.05, # p< 0.1

3.3. Value of averting a Mediterranean fin whale fatality

Here, we can define the value of averting a Mediterranean fin whale fatality by using the benefit transfer function. It should be noted that $v = e^{\ln WTP}$. For our case study, we, therefore, applied the reduced form of the benefit transfer function (Equation 6) to the selected population parameters (see Table 1) in order to estimate the minimum (v_{min}) and maximum (v_{max}) WTP per person, per year, through a tax fee for the conservation of the fin whale population. To calculate the difference between v_{min} and v_{max}, we attributed the level of 'NotEndangered' to define v_{min} and 'Endangered' to define v_{max} in Eq. 6.

$$v = e^{0.518-0.274\text{Trend} -0.554\text{PerPerson}+0.475 \ln \text{GDP PPP}-0.223\text{EndangermentStatus} + \ln 22 + \ln 43900} \quad (6)$$

To calculate the minimum V_{min} and maximum V_{max} value of protecting the Mediterranean fin whale population, we plug the estimated values of v_{min} and v_{max} (derived using Equation 6) into Equation 1 (see Fig. 4 for the values that can be used). We calculated V_{2017} by using Equation 2 with $N_t = 2{,}500$ individuals (ACCOBAMS, 2021; Laran et al., 2017). We finally assessed the 'Cost of averting a whale fatality' using Equation 3 by assuming that $TR_t = PBR_t + 1$ (one death over the PBR). Based on the above calculations (see summary in Table 3), we arrived at a "Value of averting a Mediterranean fin whale fatality" of 562,462 USD (in 2017 values) ; this corresponds to 637,790 USD when converted to 2021 US dollars.

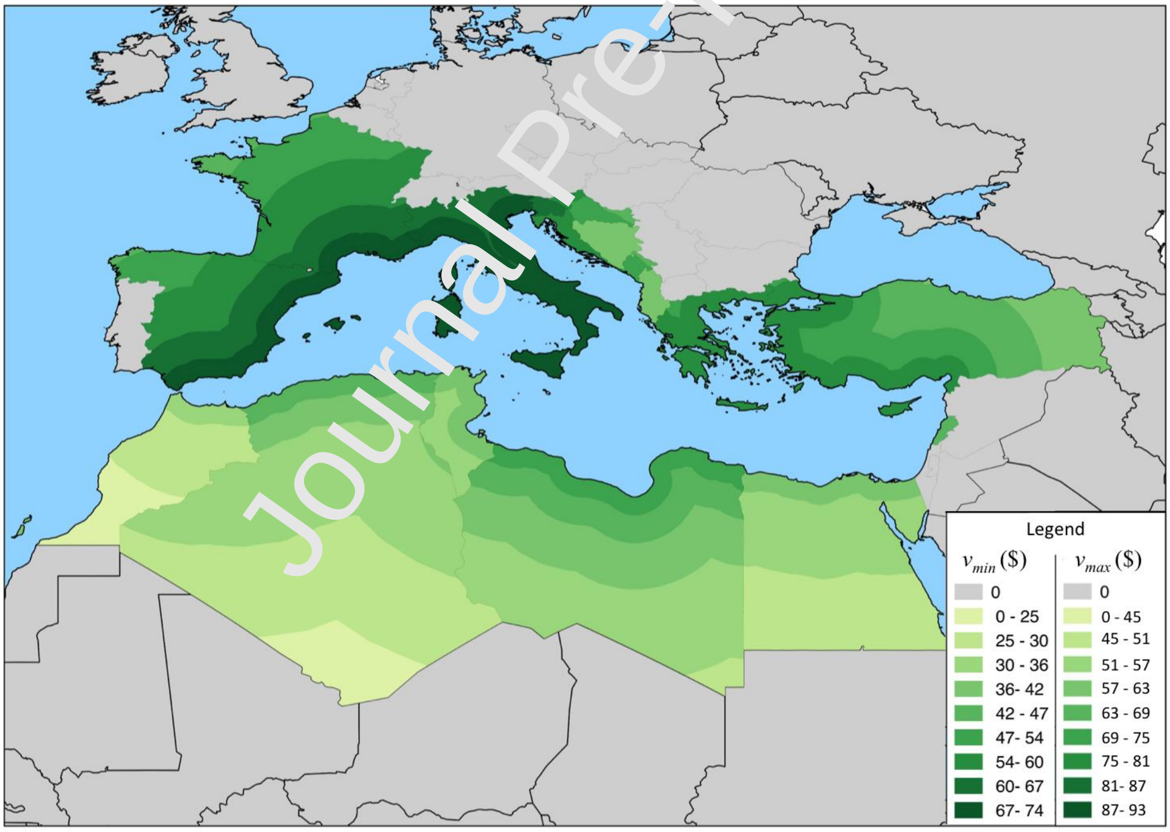


Figure 4. Minimum and maximum willingness to pay values v_{min} and v_{max} (US dollars per person) to protect the Mediterranean fin whale population depending on the responder's location.

Table 3 below presents the minimum (V_{min}) and the maximum (V_{max}) values of protecting the Mediterranean fin whale population at the policy site (calculated using Eq. 1), the value of protecting the total whale population V_{2017} in 2017 USD (using Eq. 2 and assuming a population of N_t=2,500 individuals), and, finally, the Cost of Averting a Whale Fatality' (CAWF; φ_{2017}) (using Eq.3).

Table 3. Estimated values

Value	**(US$2017)**
Minimum value of protecting the Mediterranean fin whale population (V_{min})	20,128,050,428
Maximum value of protecting the Mediterranean fin whale population (V_{max})	26,977,790,662
Value of protecting the Mediterranean fin whale population in 2017 (V_{2017})	25,532,058,838
Value of averting a Mediterranean fin whale fatality in 2017 (φ_{2017})	562,462

4. Using the value of averting a Mediterranean fin whale fatality

4.1. CAWF as a risk evaluation criterion

Within maritime risk assessments, risk evaluation criteria are used to evaluate the acceptability of risk (IMO, 2018). The FSA guidelines propose in Step 4 to assess the cost-effectiveness ratio of the proposed solutions (i.e., measures to control the relevant risks), in order to assess their efficiency and to guide decision-makers' recommendations (Step 5). As mentioned before, despite its title, the above approach is in reality a Cost-Effectiveness Analysis (CEA). Cost-Effectiveness Analysis is considered a particular form of Cost Benefit Analysis (CBA), where the benefits are usually not monetized, and therefore, net benefits cannot be calculated (Mishan and Quah, 2020). This approach avoids the ethical concerns of placing a monetary value on human lives or the lives of mammals. In the CEA context, measures that reduce the risk below a certain threshold, namely a risk evaluation criterion, are considered cost-effective and should be proposed for recommendation. As per the FSA guidelines, a risk control measure is considered to be cost effective if the expected cost of the measure is less than the expected benefit – this is actually in line with a cost-benefit assessment approach. To calculate the benefit, one has to estimate the expected societal cost before applying the risk control measure, and after its application.

In the FSA-related literature, the risk evaluation criteria approach has been used to assess risks related to human safety; see the 'Net Cost of Averting a Fatality' (NCAF) criterion and the 'Cost of Averting a Fatality (ICAF)' threshold value. Following the same rationale, similar ratios and thresholds have been proposed to address the risk of environmental pollution from ship air emissions, see the 'Cost of Averting a Ton of CO2 equivalent Heating effect' (CATCH; Eide et al., 2009) and to oil spills, see the so-called 'Cost to Avert one

Tonne of Spilled oil' (CATS; Psarros et al., 2011). A proposal has actually been submitted to the IMO for the latter to be included in the Formal Safety Assessment guidelines. This has sparked much debate leading to the introduction of environmental risk evaluation criteria on prevention of oil spills; see Psaraftis (2012) for more discussion on the debate and Appendix 7 of the IMO FSA guidelines for the actual criteria. At the end, a non-linear cost function in line with, for example Kontovas et al. (2010), has been incorporated into the FSA Guidelines.

Following this rational, Sèbe et al. (2019) conceptualized a cost-effectiveness ratio to be used within FSA studies that address ship strikes, by defining the 'Net Cost of Averting a Whale Fatality' (NCAWF) as follows:

$$NCAWF = \frac{\Delta C - \Delta B}{\Delta R} \tag{7}$$

where, ΔC is the cost per ship of the solution under consideration; ΔB is the economic benefit per ship resulting from the implementation of the solution; ΔR is the risk reduction induced by the RCO (i.e., the mitigation measure under evaluation), expressed as the number of whale fatalities averted.

To calculate the monetary benefit to the society of reducing the risk to whales, we need to place a value on preserving whales. Although, more research is required on this area, we propose an approach to estimating such a value (Section 2.1) and we derive a risk evaluation criterion λ for the Mediterranean fin whales (Section 2.2), i.e., $\varphi_{2017} = \$562{,}462$ (US\$2017).

4.2. Cost-Effectiveness of measures to reduce ship strikes

In the Mediterranean Sea, one of the major measures proposed to reduce the risk associated with ships strikes is the Real-Time Plotting of Cetaceans System (REPCET). This system creates a network between ships to communicate and share information on whales' sightings in order to avoid collisions (Couvat et al., 2016). The REPCET system costs $120,000 over the ship's lifetime, which is assumed to be 25 years (Couvat, 2015). Note that these costs are underestimated as they do not take into account operational costs caused by actions to avoid whales based on information provided by REPCET, such as additional fuel costs, or costs due to delays in ports of call (Kite-Powell and Hoagland, 2002). Collisions lead to between 7.9 and 40.1 deaths within the fin whale population annually (ICMMPA, 2019; Panigada et al., 2006; Ritter and Panigada, 2019). As REPCET is not a perfect system, we here assume that it can help reduce the annual expected fatalities by 20%; therefore, between 1.6 and 8 expected whale fatalities annually (or 40-200 during the lifetime of 25 years). The cost-effectiveness ratio of the REPCET solution is estimated between \$600 and \$3,000 per whale fatality averted.

Based on our estimated cost of averting a whale fatality ($\lambda = \varphi_{2017} = \$562{,}462$ for Mediterranean fin whales), the specific risk control option (i.e., the REPCET system) has a cost effectiveness ratio well below the threshold. Note that not all cost components are taken into account (such as the annual operating expenses) and that there is also much uncertainty related to the mortality rate that we have used in the above example. This rudimentary example illustrates though the way that the 'Cost of Averting a Whale Fatality' value could be used within risk assessments related to whale strikes. At the same time, it looks like solutions like REPCET are cost-effective – even if, in practice, the total costs are way higher than the 120,000 USD figure which is mentioned in the literature. The costs are still way lower than the benefits.

The comparison between the risk evaluation criterion and the rough calculations of the costs of REPCET exposes a possible low economic impact of mitigation solutions for shipping companies. However, as mentioned earlier, the literature shows that the compliance to these solutions is often low (e.g., Chion et al., 2018; Freedman et al., 2017). We feel that the main reason is that *"a failure to assign a dollar value to the benefits effectively assigns them a zero value or a zero weight in the calculation of net benefits, implying that changes in those services will not be incorporated into the net benefit calculation"* (Epstein, 2003); see Kontovas (2011) for more. By not having a monetary value assigned on the societal benefit of averting the risk of whale fatalities it does not make any economic sense, at least following the 'cost-benefit analysis' rationale, to implementing any measure that reduces the risk of ship strikes as the cost will always be greater than the benefits, which are equal to zero. Two other factors can be highlighted as reasons for this noncompliance with inexpensive solutions. First, even if the solutions are inexpensive, their implementation might be challenging due to logistical factors (e.g., port call loss). Second, the potential loss of competitiveness can be highlighted as a contributing factor (Gritsenko and Yliskylä-Peuralaht, 2013).

We therefore hope that our preliminary work as outlined above, especially if it is to be incorporated in risk assessment methodologies such as the Formal Safety Assessment, will lead to a better understanding of the associated societal benefits of reducing the risk of ship strikes. This can encourage the adoption of measures to reduce the risks associated with ship-strikes and will be beneficial both for vessels and the mammals.

5. Conclusions and Future research

In our study, we estimated the cost of averting a Mediterranean fin whale fatality, which could be used as a risk evaluation criterion. The adoption by the IMO of a whale risk-related 'evaluation criterion' will help decision-makers to evaluate solutions that reduce collisions – or other whale-ship related interactions. This will encourage the adoption of reduction measures; currently the benefits are not clear since the environmental damages are not much considered. This criterion might lead to win-win solutions both for the shipping companies and the society through the benefits associated with whale preservation (Makina and Luthuli, 2014). We should also highlight here the recent research on the carbon capture potential of whales; with the International Monetary Fund (IMF) placing a monetary value of a great whale at $2 million each, mainly as protecting whales can limit greenhouse gases and global warming (Chami et al., 2019).

To our knowledge this is the first approach on addressing risk related to ship strikes using the IMO FSA procedure and also assigning a monetary value to the benefit of reducing the fatality risk of Mediterranean fin whales. For the latter, we use a widely applied methods, which has however some limitations. The method relies on the willingness of individuals to pay for the preservation of a whale. Now, there is a difference between what people state they are willing to pay, and what they would really pay if they had to (Garrod et al., 2012; Stithou and Scarpa, 2012). In addition, our study assessed the value of protecting the Mediterranean fin whale population, disregarding the sperm whales (*Physeter macrocephalus*), another at-risk population in the Mediterranean (Frantzis et al., 2015; Rendell and Frantzis, 2016). If the two populations were to be considered as one unit (e.g., the Mediterranean large cetacean stock), the value of protecting the stock would increase, as sperm whales' individuals would be added to the 2,500 fin whales individuals. Besides the technical issues related to the method that we have adopted in this study, we understand that placing a monetary value on whales, in general, has attracted much criticism (Babcock, 2013). There are however many approaches that could be considered in future research. The ecosystem services (ES) or the nature contribution to people (NCP) approaches have been advocated to overcome the monetization philosophical – and technical – limitations (Beaumont et al., 2008). For instance, Cook et al. (2020) recently listed the contribution of whales to human well-being and continued work in this direction could be crucial for our approach (see also Chami et al., 2019). Gerber et al. (2014) also applied an ecological-economic framework to whale conservation, but created a market between conservationists and whalers, which triggered a lot of criticisms (Smith et al., 2014). Beyond philosophical concerns, research needs to investigate the ecological-economic approaches using existence value for whales as this value might be one of the highest of the animal realm (Amuakwa-Mensah, 2018; Christie et al., 2006).

Finally, there is a limitation related to the use of a constant risk evaluation criterion. When calculating the cost of averting a whale fatality, which is used as the threshold value in the risk evaluation criterion, we assume a linear relationship between the endangerment status and the WTP in line with Bulte and Van Kooten (1999). However, as it has been shown in the literature, this linearity is an oversimplification (Amuakwa-Mensah, 2018; Colléony et al., 2017; Martín-López et al., 2008; Richardson and Loomis, 2008), mainly due to the diminishing marginal returns or the increasing marginal value of scarcity (Richardson and Loomis, 2008; U.S. EPA, 2014). As a result of this oversimplification, the risk evaluation criterion defined in our study is constant. Though, the more the population is in danger, the higher the value of a whale should be (Amuakwa-Mensah, 2018; Colléony et al., 2017; Martín-López et al., 2008; Richardson and Loomis, 2008). Using constant criteria in cost-effectiveness analyses, such as the ones used for oil spills or gas emissions, has been criticized by Kontovas (2011). Further research is therefore required to examine a non-linear function in line with what has been done for oil spills; see for example Kontovas et al. (2010). To that effect, our research can hopefully contribute to open-up new venues of research in this area.

Acknowledgements

This work has been partially supported by the “Laboratoire d'Excellence” LabexMER (ANR-10-LABX-19) at the European Institute of Marine Sciences (IUEM), by the Région Bretagne, and by the Université de Bretagne Occidentale through an allocation to The Marine & Coastal Sciences Doctoral School.

We would like to thank the Editor and the two anonymous reviewers for their constructive suggestions and comments, which have improved the work.

REFERENCES

ACCOBAMS, 2021. Estimates of abundance and distribution of cetaceans, marine mega-fauna and marine litter in the Mediterranean Sea from 2018-2019 surveys. By Panigada S., Boisseau O., Canadas A., Lambert C., Laran S., McLanaghan R., Moscrop A. Ed. ACCOBAMS - ACCOBAMS Sur.

Amuakwa-Mensah, F., 2018. Deriving a benefit transfer function for threatened and endangered species in interaction with their level of charisma. Environments 5, 1–31. https://doi.org/10.3390/environments5020031

Amundsen, E.S., Bjørndal, T., Conrad, J.M., 1995. Open access harvesting of the Northeast Atlantic minke whale. Environ. Resour. Econ. 6, 167–185. https://doi.org/10.1007/BF00691682

Avila, I.C., Kaschner, K., Dormann, C.F., 2018. Current global risks to marine mammals: Taking stock of the threats. Biol. Conserv. 221, 44–58. https://doi.org/10.1016/j.biocon.2018.02.021

Babcock, H.M., 2013. Putting a price on whales to save them: What do Morals have to do with it. Environ. Law 33, 1–33. https://doi.org/10.2307/43267663

Bateman, I.J., Day, B.H., Georgiou, S., Lake, I., 2006. The aggregation of environmental benefit values: Welfare measures, distance decay and total WTP. Ecol. Econ. 60, 450–460. https://doi.org/10.1016/j.ecolecon.2006.04.003

Beaumont, N.J., Austen, M.C., Mangi, S.C., Townsend, M., 2008. Economic valuation for the conservation of marine biodiversity. Mar. Pollut. Bull. 56, 386–396. https://doi.org/10.1016/j.marpolbul.2007.11.013

Bosetti, V., Pearce, D., 2003. A study of environmental conflict: The economic value of Grey Seals in southwest England. Biodivers. Conserv. 12, 2361–2392. https://doi.org/10.1023/A:1025809800242

Bulte, E.H., Van Kooten, G.C., 1999. Marginal valuation of charismatic species: Implications for conservation. Environ. Resour. Econ. 14, 119–130. https://doi.org/10.1023/A:1008309816658

Caruso, F., Hickmott, L., Warren, J.D., Segre, P., Chiang, G., Bahamonde, P., Español-

Jiménez, S., Li, S., Bocconcelli, A., 2021. Diel differences in blue whale (Balaenoptera musculus) dive behavior increase nighttime risk of ship strikes in northern Chilean Patagonia. Integr. Zool. 16, 594–611. https://doi.org/10.1111/1749-4877.12501

Cates, K., DeMaster, D.P., Brownell, R.L.J., Silber, G., Gende, S., Leaper, R., Ritter, F., Panigada, S., 2016. Strategic plan to mitigate the impacts of ship strikes on cetacean populations: 2017-2020, IWC/66/CC20 - CC Agenda Item 5.2.

Chami, R., Cosimano, T., Fullenkamp, C., Oztosun, S., 2019. Nature's solution to climate change - A strategy to protect whales can limit greenhouse gases and global warming. Finance Dev. 56, 1–5.

Chion, C., Turgeon, S., Cantin, G., Michaud, R., Ménard, N., Lesage, V., Parrott, L., Beaufils, P., Clermont, Y., Gravel, C., 2018a. A voluntary conservation agreement reduces the risks of lethal collisions between ships and whales in the St. Lawrence Estuary (Québec, Canada): From co-construction to monitoring compliance and assessing effectiveness. PLoS One 13, 1–26. https://doi.org/10.1371/journal.pone.0202560

Chion, C., Turgeon, S., Cantin, G., Michaud, R., Ménard, N., Lesage, V., Parrott, L., Beaufils, P., Clermont, Y., Gravel, C., 2018b. A voluntary conservation agreement reduces the risks of lethal collisions between ships and whales in the St . Lawrence Estuary (Que Canada): From co-construction to monitoring compliance and assessing effectiveness. PLoS One 1–26. https://doi.org/10.1371/journal.pone.0202560

Christie, M., Hanley, N., Warren, J., Murphy, K., Wright, R., Hyde, T., 2006. Valuing the diversity of biodiversity. Ecol. Econ. 58, 304–317. https://doi.org/10.1016/j.ecolecon.2005.07.034

Colléony, A., Clayton, S., Couvet, D., Saint Jalme, M., Prévot, A.C., 2017. Human preferences for species conservation: Animal charisma trumps endangered status. Biol. Conserv. 206, 263–269. https://doi.org/10.1016/j.biocon.2016.11.035

Cook, D., Malinauskaite, L., Davíðsdóttir, B., Ögmundardóttir, H., Roman, J., 2020. Reflections on the ecosystem services of whales and valuing their contribution to human well-being. Ocean Coast. Manag. 186, 1–12. https://doi.org/10.1016/j.ocecoaman.2020.105100

Couvat, J., 2015. Le système repcet: pour la tranquillité des cétacés en Méditerranée... Press release.

Couvat, J., Dhermain, F., Mayol, P., 2016. Comment couler une baleine ? Etude de faisabilité pour l'IMMERsion raisonnée des carcasses de grands cétacés en Méditerranée française, Projet IMMERCET, Convention de partenariat 14-027 GIS3M, Par national de Port-Cros.

Curtis, K.A., Moore, J.E., Boyd, C., Dillingham, P.W., Lewison, R.L., Taylor, B.L., James, K.C., 2015. Managing catch of marine megafauna: Guidelines for setting limit reference points. Mar. Policy 61, 249–263. https://doi.org/10.1016/j.marpol.2015.07.002

David, L., Alleaume, S., Guinet, C., 2011. Evaluation of the potential of collision between fin whales and maritime traffic in the North-Western Mediterranean Sea in summer, and mitigation solutions. J. Mar. Anim. Their Ecol. 4, 17–28. https://doi.org/1911-8929

David, L., Arcangeli, A., Tepsich, P., Di-Meglio, N., Roul, M., Campana, I., Gregorietti, M., Moulins, A., Rosso, M., Crosti, R., 2022. Computing ship strikes and near miss events of fin whales along the main ferry routes in the Pelagos Sanctuary and adjacent west area, in summer. Aquat. Conserv. Mar. Freshw. Ecosyst. 1–15. https://doi.org/10.1002/aqc.3781

Dransfield, A., Hines, E., McGowan, J., Holzman, B., Nur, N., Elliott, M., Howar, J., Jahncke, J., 2014. Where the whales are: Using habitat modeling to support changes in shipping regulations within national marine sanctuaries in central California. Endanger. Species Res. 26, 39–57. https://doi.org/10.3354/esr00627

Eide, M.S., Endresen, Ø., Skjong, R., Longva, T., Alvik, S., 2009. Cost-effectiveness assessment of CO2 reducing measures in shipping. Marit. Policy Manag. 36, 367–384. https://doi.org/10.1080/03088830903057031

Eiswerth, M.E., van Kooten, G.C., 2009. The ghost of extinction: Preservation values and minimum viable population in wildlife models. Ecol. Econ. 68, 2129–2136. https://doi.org/10.1016/j.ecolecon.2009.02.009

Equasis, 2017. The World Merchant Fleet in 2017 - Statistics from Equasis.

Firestone, J., Lyons, S.B., Wang, C., Corbett, J.J., 2008. Statistical modeling of North Atlantic right whale migration along the mid-Atlantic region of the eastern seaboard of the United

States. Biol. Conserv. 141, 221–232. https://doi.org/10.1016/j.biocon.2007.09.024

Frantzis, A., Leaper, R., Paraskevi, A., Lekkas, D., 2015. Update on sperm whale ship strike in the Hellenic Trench, Greece. Pap. Present. to IWC Sci. Committee, San Diego, CA, USA, 22 May–3 June 2015, SC/66a/HIM06 6.

Freedman, R., Herron, S., Byrd, M., Birney, K., Morten, J., Shafritz, B., Caldow, C., Hastings, S., 2017. The effectiveness of incentivized and non-incentivized vessel speed reduction programs: Case study in the Santa Barbara channel. Ocean Coast. Manag. 148, 31–39. https://doi.org/10.1016/j.ocecoaman.2017.07.013

Garrod, G., Ruto, E., Willis, K., Powe, N., 2012. Heterogeneity of preferences for the benefits of Environmental Stewardship: A latent-class approach. Ecol. Econ. 76, 104–111. https://doi.org/10.1016/j.ecolecon.2012.02.011

Gerber, L.R., Costello, C., Gaines, S.D., 2014. Conservation markets for wildlife management with case studies from whaling. Ecol. Appl. 24, 4–14. https://doi.org/10.1890/12-1919.1

Gilpin, M.E., Case, T.J., Ayala, F.J., 1976. θ-selection. Math. Biosci. 32, 131–139. https://doi.org/https://doi.org/10.1016/0025-5564(76)90060-2

Gritsenko, D., Yliskylä-Peuralaht, J., 2013. Governing shipping externalities: Baltic ports in the process of SOx emission reduction. Marit. Stud. 12, 1–21. https://doi.org/10.1186/2212-9790-12-10

Grossi, F., Lahaye, E., Bortoni, A., Rosso, M., Tepsich, P., 2021. Locating ship strike risk hotspots for fin whale (Balaenoptera physalus) and sperm whale (Physeter macrocephalus) along main shipping lanes in the North-Western Mediterranean Sea. Ocean Coast. Manag. 212. https://doi.org/10.1016/j.ocecoaman.2021.105820

Ham, G.S., Lahaye, E., Rosso, M., Moulins, A., Hines, E., Tepsich, P., 2021. Predicting summer fin whale distribution in the Pelagos Sanctuary (north-western Mediterranean Sea) to identify dynamic whale–vessel collision risk areas. Aquat. Conserv. Mar. Freshw. Ecosyst. 1–21. https://doi.org/10.1002/aqc.3614

ICMMPA, 2019. Proceedings of the fifth international conference in marine mammal protected areas.

IMO, 2018. Revised guidelines for Formal Safety Assessment (FSA) for the use in the IMO rule-making process, International Maritime Organization - MSC-MEPC.2/Circ.12/Rev.2.

IMO, 2004. Formal Safety Assessment - Risk evaluation, Submitted by the International Association of Classification Societies (IACS) - MSC 78/19/2. https://doi.org/10.1163/092735209X12499043518304

IUCN, 2012. IUCN Red List categories and criteria, Version 3.1. Second edition. Gland, Switzerland and Cambridge, UK: IUCN. https://doi.org/10.9782-8317-0633-5

IWC-ACCOBAMS, 2012. Report of the joint IWC-ACCOBAMS workshop on reducing risk of collisions between vessels and cetaceans, IWC/63/CC 8 - Agenda item 4.1.

Jacob, T., Ody, D., 2016. Characteristics of maritime traffic in the Pelagos sanctuary and analysis of collision risk with large cetaceans, From the report of Quiet Oceans and Institut EcoOcéans.

Kite-Powell, H.L., Hoagland, P., 2002. Economic aspects of right whale ship stike management measures, Final project report to the National Marine Fisheries Serivce, NOAA Order Number 40EMNF100235, Final Project Report to the National Marine Fisheries Serivce, NOAA Order Number 40EMNF100235.

Knowles, T., Campbell, R., 2011. What's a whale worth? Valuing whales for National Whale Day, a report for the International Fund for Animal Welfare (IFAW), prepared by Economists at Large, Melbourne, Australia.

Kontovas, C.A., 2011. Quantitative risk management framework for maritime safety and environmental protection, PhD Dissertation - School of Naval Architecture and Marine Engineering, PhD Dissertation - School of Naval Architecture and Marine Engineering.

Kontovas, C.A., Psaraftis, H.N., 2009. Formal Safety Assessment: a critical review. Mar. Technol. 46, 45–59.

Kontovas, C.A., Psaraftis, H.N., Ventikos, N.P., 2010. An empirical analysis of IOPCF oil spill cost data. Mar. Pollut. Bull. 60, 1455–1466. https://doi.org/10.1016/j.marpolbul.2010.05.010

Laran, S., Pettex, E., Authier, M., Blanck, A., David, L., Dorémus, G., Falchetto, H., Monestiez, P., Van Canneyt, O., Ridoux, V., 2017. Seasonal distribution and abundance of cetaceans within French waters - Part I: The North-Western Mediterranean, including the Pelagos sanctuary. Deep. Res. Part II Top. Stud. Oceanogr. 141, 20–30. https://doi.org/10.1016/j.dsr2.2016.12.011

Lew, D.K., 2015. Willingness to pay for threatened and endangered marine species: a review of the literature and prospects for policy use. Front. Mar. Sci. 2, 1–17. https://doi.org/10.3389/fmars.2015.00096

Lipton, D., Lew, D.K., Wallmo, K., Wiley, P., Dvarskas, A., 2014. The Evolution of Non-Market Valuation of U.S. Coastal and Marine Resources. J. Ocean Coast. Econ. 2014, 1–26. https://doi.org/10.15351/2373-8456.1011

Loomis, J., 2006. Estimating recreation and existence values of sea otter expansion in California using benefit transfer. Coast. Manag. 34, 387–404. https://doi.org/10.1080/08920750600860282

Loomis, J.B., 2000. Vertically summing public good demand curves: An empirical comparison of economic versus political jurisdictions. Land Econ. 76, 312–321. https://doi.org/10.2307/3147231

Makina, A., Luthuli, A., 2014. Corporate South Africa and biodiversity in a green economy. Int. J. African Renaiss. Stud. - Multi-, Inter- Transdiscipl. 9, 197–212. https://doi.org/10.1080/18186874.2014.987963

Manuel, C., Ritter, F., 2010. Increasing numbers of ship strikes in the Canary Islands: Proposals for immediate action to reduce risk of vessel-whale collisions. J. Cetacean Res. Manag. 11, 131-138.

Martín-López, B., Montes, C., Benayas, J., 2008. Economic valuation of biodiversity conservation: The meaning of numbers. Conserv. Biol. 22, 624–635. https://doi.org/10.1111/j.1523-1739.2008.00921.x

Mayol, P., 2012. Collisions between vessels and large cetaceans in the Pelagos Sanctuary, Souffleurs d’Ecume Report.

Mishan, E.J., Quah, E., 2020. Cost-Benefit Analysis (6th ed.), Routledge. ed. https://doi.org/https://doi.org/10.4324/9781351029780

Notarbartolo di Sciara, G., Castellote, M., Druon, J.N., Panigada, S., 2016. Fin whales, Balaenoptera physalus: At home in a changing Mediterranean Sea? Adv. Mar. Biol. 75, 75–101. https://doi.org/10.1016/bs.amb.2016.08.002

Obeng, E.A., Obiri, B.D., Oduro, K.A., Pentsil, S., Anglaaere, L.C., Foli, E.G., Ofori, D.A., 2020. Current Research in Environmental Sustainability Economic value of non-market ecosystem services derived from trees on cocoa farms. Curr. Res. Environ. Sustain. 2, 1–15. https://doi.org/10.1016/j.crsust.2020.100019

Panigada, S., Azzellino, A., Cubaynes, H., Folegot, T., Fretwell, P., Jacob, T., Lanfredi, C., Leaper, R., Ody, D., Ratel, M., 2020. Proposal to develop and evaluate mitigation strategies to reduce the risk of ship strikes to fin and sperm whales in the Pelagos Sanctuary - Final report. Pelagos Secretariat - Convention No. 2018-04.

Panigada, S., Gauffier, P., Notarbartolo di Sciara, G., 2021. Balaenoptera physalus (Mediterranean subpopulation). The IUCN Red List of Threatened Species 2021: e.T16208224A50387979. https://doi.org/10.2305/IUCN.UK.2021-3.RLTS.T16208224A50387979.en

Panigada, S., Pesante, G., Zanardelli, M., Capoulade, F., Gannier, A., Weinrich, M.T., 2006. Mediterranean fin whales at risk from fatal ship strikes. Mar. Pollut. Bull. 52, 1287–1298. https://doi.org/10.1016/j.marpolbul.2006.03.014

Peltier, H., Beaufils, A., Cesarini, C., Dabin, W., Dars, C., Demaret, F., Dhermain, F., Doremus, G., Labach, H., Van Canneyt, O., Spitz, J., 2019. Monitoring of marine mammal strandings along french coasts reveals the importance of ship strikes on large cetaceans : a challenge for the European Marine Strategy Framework Directive species composition of strandings. Front. Mar. Sci. 6, 1–6. https://doi.org/10.3389/fmars.2019.00486

Pershing, A.J., Christensen, L.B., Record, N.R., Sherwood, G.D., Stetson, P.B., 2010. The impact of whaling on the ocean carbon cycle: Why bigger was better. PLoS One 5, 1–9. https://doi.org/10.1371/journal.pone.0012444

Pirotta, V., Grech, A., Jonsen, I.D., Laurance, W.F., Harcourt, R.G., 2018. Consequences of global shipping traffic for marine giants. Front Ecol Env. 1–9. https://doi.org/10.1002/fee.1987

Psarros, G., Skjong, R., Vanem, E., 2011. Risk acceptance criterion for tanker oil spill risk reduction measures. Mar. Pollut. Bull. 62, 114–127. https://doi.org/10.1016/j.marpolbul.2010.09.003.

Rendell, L., Frantzis, A., 2016. Mediterranean sperm whales, Physeter macrocephalus: The precarious state of a lost tribe, in: Advances in Marine Biology. Elsevier Ltd., pp. 37–74. https://doi.org/10.1016/bs.amb.2016.08.001

Richardson, L., Loomis, J., 2008. The total economic value of threatened, endangered and rare species : An updated meta-analysis. Ecol. Econ. 68, 1535–1548. https://doi.org/10.1016/j.ecolecon.2008.10.016

Ritter, F., Panigada, S., 2019. Collisions of vessels with cetaceans — The underestimated threat, in: World Seas: An Environmental Evaluation. Elsevier Ltd., pp. 531–547. https://doi.org/10.1016/B978-0-12-805052-1.00026-7

Sèbe, M., 2020. An interdisciplinary approach to the management of whale-ship collisions. Thesis Manuscript. UBO, EDSML, AMURE. https://doi.org/10.13140/RG.2.2.10388.01924

Sèbe, M., Gourguet, S., 2022. To save whales, look to the sky. PNAS 119, 1–4. https://doi.org/10.1073/pnas.2121360119

Sèbe, M., Kontovas, A.C., Pendleton, L., 2019. A decision-making framework to reduce the risk of collisions between ships and whales. Mar. Policy 109, 1–12. https://doi.org/10.1016/j.marpol.2019.103697

Sèbe, M., Kontovas, C.A., Pendleton, L., 2020. Reducing whale-ship collisions by better estimating damages to ships. Sci. Total Environ. 713, 1–7. https://doi.org/10.1016/j.scitotenv.2020.136643

Sèbe, M., Nassiri, A., Pendleton, L., 2021. Using choice experiment designs to evaluate mitigation solutions to reduce whale-ship collisions. Mar. Policy 124, 1–10. https://doi.org/10.1016/j.marpol.2020.104368

Shirihai, H., Jarrett, B., 2007. Guide des mammifères marins du monde: toutes les espèces décrites et illustrées., Delachaux. ed.

Silber, G.K., Bettridge, S., Cottingham, D., 2008. Report of a workshop to identify and asess technologies to reduce ship strikes of large whales, NOAA technical memorandum, NMFS-OPR-42.

Silber, G.K., Vanderlaan, A.S.M., Arceredillo, A.T., Johnson, L., Taggart, C.T., Brown, M.W., Bettridge, S., Sagarminaga, R., 2012. The role of the International Maritime Organization in reducing vessel threat to whales: Process, options, action and effectiveness. Mar. Policy 36, 1221–1233. https://doi.org/10.1016/j.marpol.2012.03.008

Skjong, R., Vanem, E., Endresen, Ø., 2005. Risk Evaluation Criteria, A SAFEDOR report D452, SAFEDOR report D452.

Smith, M.D., Asche, F., Bennear, L.S., Havice, E., Read, A.J., Squires, D., 2014. Will a catch share for whales improve social welfare? Ecol. Appl. 24, 15–23. https://doi.org/https://doi.org/10.1890/13-0085.1

Stithou, M., Scarpa, R., 2012. Collective versus voluntary payment in contingent valuation for the conservation of marine biodiversity: An exploratory study from Zakynthos, Greece. Ocean Coast. Manag. 56, 1–9. https://doi.org/10.1016/j.ocecoaman.2011.10.005

Taylor, B.L., Chivers, S.J., Larese, J., Perrin, W.F., 2007. Generation length and percent mature estimates for IUCN assessments of cetaceans, Administrative Report LJ-07-01 National Marine Fisheries. https://doi.org/doi:10.1.1.530.4789

Taylor, B.L., DeMaster, D.P., 1993. Implications of non-linear density dependence. Mar. Mammal Sci. 9, 360–371. https://doi.org/10.1111/j.1748-7692.1993.tb00469.x

Taylor, B.L., Scott, M., Heyning, J.E., Barlow, J., 1997. Suggested guidelines for recovery factors for endangered marine mammals under the Marine Mammal Protection Act, NOAA-TM-NMFS-SWFSC-354.

U.S. EPA, 2014. Guidelines for preparing economic analyses, National Center for Environmental Economics Office of Policy - U.S. Environmental Protection Agency, National Center for Environmental Economics Office of Policy - U.S. Environmental Protection Agency.

Vanderlaan, A.S.M., Corbett, J.J., Green, S.L., Callahan, J.A., Wang, C., Kenney, R.D., Taggart, C.T., Firestone, J., 2009. Probability and mitigation of vessel encounters with North Atlantic right whales. Endanger. Species Res. 6, 273–285. https://doi.org/10.3354/esr00176

Vanderlaan, A.S.M., Taggart, C.T., 2009. Efficacy of a voluntary area to be avoided to reduce risk of lethal vessel strikes to endangered whales. Conserv. Biol. 23, 1467–1474. https://doi.org/10.1111/j.1523-1739.2009.01329.x

Vanderlaan, A.S.M., Taggart, C.T., 2007. Vessel collisions with whales: The probability of lethal injury based on vessel speed. Mar. Mammal Sci. 23, 144–156. https://doi.org/10.1111/j.1748-7692.2006.00098.x

Vanem, E., 2012. Ethics and fundamental principles of risk acceptance criteria. Saf. Sci. 50, 958–967. https://doi.org/10.1016/j.ssci.2011.12.030

Wade, P.R., 1998. Calculating limits to the allowable human caused mortality of cetaceans and pinnipeds. Mar. Mammal Sci. 14, 1–37. https://doi.org/10.1111/j.1748-7692.1998.tb00688.x

Wakamatsu, M., Shin, K.J., Wilson, C., Managi, S., 2018. Exploring a gap between Australia and Japan in the economic valuation of whale conservation. Ecol. Econ. 146, 397–407. https://doi.org/10.1016/j.ecolecon.2017.12.002

Wallmo, K., Lew, D.K., 2015. Public preferences for endangered species recovery : an examination of geospatial scale and non-market values. Front. Mar. Sci. 2, 1–7. https://doi.org/10.3389/fmars.2015.00055

Wiegleb, G., 2002. The value of biodiversity. Forum Fam. Plan. West. Hemisph. 1–21.

Winkler, C., Panigada, S., Murphy, S., Ritter, F., 2020. Global numbers of ship strikes : An assessment of collisions between vessels and cetaceans using available data in the IWC Ship Strike Database - Report to the International Whaling Commission, IWC/68B/SC HIM09.

World Shipping Council, 2006. Proposed rule to implement speed restrictions to reduce the threat of ship collisions with North Atlantic Right Whales, Comments of the World Shipping Council before the National Marine Fisheries Service - RIN 0648-AS36.

Contribution to the paper:

Maxime Sèbe

Contribution to the paper: Formal analysis; Investigation; Methodology; Validation; Visualization; Writing – original draft; Writing – review & editing.

Christos Kontovas

Contribution to the paper: Formal analysis; Methodology; Validation; Writing – review & editing.

Linwood Pendleton

Contribution to the paper: Funding acquisition; Project administration; Supervision; Validation; Writing – review & editing.

Sophie Gourguet

Contribution to the paper: Formal analysis; Methodology; Validation; Writing – review & editing.

DECLARATION OF INTEREST STATEMENT

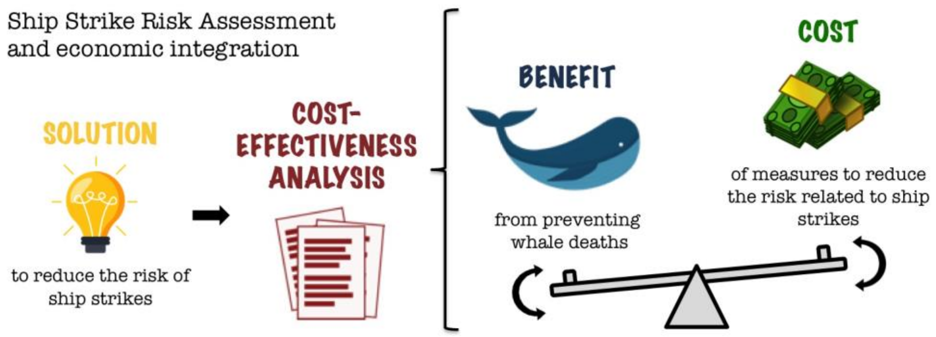
☒ The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

On behalf of the authors,

Christos Kontovas

Corresponding author

18 January 2022



Graphical abstract

Highlights

- Lack of assessments of solutions to collisions leads to poor compliance from ships
- Societal benefits should be weighed against private costs to implement solutions
- A dollar value of the benefits of averting a whale fatality could be placed
- Our work can lead to more transparent whale-ship collision risk assessments