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Climate change vulnerability of cetaceans in Macaronesia: Insights from a trait-based assessment

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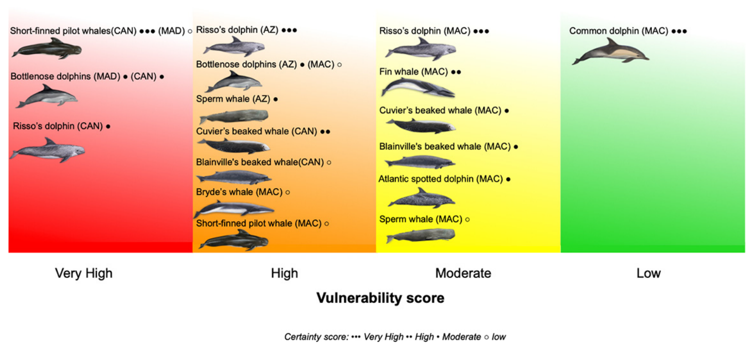
HIGHLIGHTS

- A climate vulnerability assessment was applied to cetaceans in Macaronesia
- Very High to High vulnerability scores for 62% of species management units
- Very High to Moderate certainty scores for 67% of units
- High potential for climate-related responses for over 50% of units
- Further research on trait-based approaches is needed to support decision-makers

GRAPHICAL ABSTRACT



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ABSTRACT

Over the last decades global warming has caused an increase in ocean temperature, acidification and oxygen loss which has led to changes in nutrient cycling and primary production affecting marine species at multiple trophic levels. While knowledge about the impacts of climate change in cetacean's species is still scarce, practitioners and policymakers need information about the species at risk to guide the implementation of conservation measures. To assess cetacean's vulnerability to climate change in the biogeographic region of Macaronesia, we adapted the Marine Mammal Climate Vulnerability Assessment (MMCVA) method and applied it to 21 species management units using an expert elicitation approach.

Results showed that over half (62%) of the units assessed presented Very High (5 units) or High (8 units) vulnerability scores. Very High vulnerability scores were found in archipelago associated units of short-finned pilot whales (*Globicephala macrorhynchus*) and common bottlenose dolphins (*Tursiops truncatus*), namely in the Canary Islands and Madeira, as well as Risso's dolphins (*Grampus griseus*) in the Canary Islands. Overall, certainty scores ranged from Very High to Moderate for 67% of units.

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Over 50% of units showed a high potential for distribution, abundance and phenology changes as a response to climate change.
With this study we target current and future information needs of conservation managers in the region, and guide research and monitoring efforts, while contributing to the improvement and validation of trait-based vulnerability approaches under a changing climate.

1. Introduction

Over the past two decades, an increase in greenhouse gas emissions and subsequent global warming has strongly affected the world's ocean through rapid physiochemical changes (IPCC, 2007, 2014). The rate of ocean warming has more than doubled since the 1970's, and marine heat-related events have increased in frequency, duration and intensity, being projected to continue as such in the future (IPCC, 2019). Since the 1980's, the ocean pH has declined 0.017–0.027 units per decade due to the absorption of 20–30% of total anthropogenic CO2 emissions (IPCC, 2019). Oxygen loss, together with the expansion of oxygen minimum zones, has increased by 3–8% between 1970 and 2010 (IPCC, 2019). Additionally, sea level rise is increasing globally due to ocean thermal expansion, glacier mass loss and increasing rates of ice loss from the Greenland and Antarctic ice sheets (Leuliette and Nerem, 2016). These observed and projected changes in the ocean's physical–chemical properties contribute to changes in the seasonality, abundance and distribution of marine species. Beyond its impact on cetaceans (such as reducing reproductive success (Kershaw et al., 2021), these changes affect ecosystem services with relevant ecological, economic and social impacts on human wellbeing (IPCC, 2019; Pecl et al., 2017).

To help predict and possibly minimize the negative impacts of climate change on ecosystems, conservation scientists, managers and practitioners need to develop a set of approaches to estimate species vulnerability to climate change. Accordingly, in the last decade an increasing number of assessments on the vulnerability of biodiversity to a changing climate have been carried out. The main goal of these assessments is to identify species that are at higher risk and support policymakers in identifying and prioritizing adaptation management options (Foden and Young, 2016; Foden et al., 2019; Pacifici et al., 2015).

There are three general types of approaches that can be used to assess the vulnerability of species to climate change: (1) trait-based approaches (Foden et al., 2013); (2) trend-based approaches, namely mechanistic and correlative models (Jeschke and Strayer, 2008; Kearney et al., 2010; Monahan, 2009); and (3) combined approaches, that result from the association of the first two approaches (Willis et al., 2015). Trend-based approaches focus on modelling tools, either correlative models (considering the observed distribution range of species and anticipating potential climate suitable areas) based on future climate projections or mechanistic models (which incorporate biological processes and interactions, such as species physiological tolerances or energy balance equations and are generally used to determine species' extinction risk) (Pearson et al., 2014). Additionally, trait-based approaches provide ranks of species vulnerability by integrating species biological characteristics (sensitivity and adaptive capacity) with exposure to climate change based on climate projections of relevant environmental variables (Foden et al., 2019; Stortini et al., 2015).

Trait-based indexes have the advantage of providing rapid assessments of multiple taxa when relevant data on species traits is available. They have low requirements for detailed information on species distribution, or extensive knowledge of modelling techniques (Foden and Young, 2016; Foden et al., 2019; Pacifici et al., 2015). For such reasons, they have been increasingly used by the marine ecology community, and the number of related publications has more than doubled from 2010 to 2016 (Beauchard et al., 2017). Indeed, trait-based indexes have been widely developed and applied to marine invertebrates, fishes and coral reefs (Chin et al., 2010; Crozier et al., 2019; Hare et al., 2016; Pecl et al., 2014), and some studies also integrate social-ecological factors related to ship traffic disturbance (Fliessbach et al., 2019), fishing communities (Greenan et al., 2019) or fish farming (Soto et al., 2019).

As for marine mammals, trait-based vulnerability assessments are a recent topic, with new indexes being developed in the last few years (Ferrara, 2017; Hauser et al., 2018; Sousa et al., 2019). Earlier attempts at marine mammal climate vulnerability assessments were developed for arctic species through the quantification of sensitivity indicators (Laidre et al., 2008) that were latter extended to other cetacean species by Simmonds and Smith (2009). Globally, the assessment of marine mammals' vulnerability to climate change has highlighted the loss of functional diversity, as well as the associated impacts on the ecosystem from the potential extinctions of marine mammals (Albouy et al., 2020). Regional efforts have also been carried out to develop vulnerability indexes for marine mammal stocks in the Western North Atlantic, Gulf of Mexico, Caribbean, Pacific and Arctic regions (Lettrich et al., 2019), as well as for cetacean species in the Madeira Archipelago (Sousa et al., 2019).

However, trait-based indexes present a number of limitations related to different sources of uncertainty, such as the choice of traits, knowledge gaps, unknown thresholds for each trait, and the links between species traits and the impacts of climate change (Lankford et al., 2014). Because of such uncertainties, and the relatively recent nature of these indexes, trait-based methods require further development and validation (Foden and Young, 2016; Foden et al., 2019; Pacifici et al., 2015).

The present study aims to contribute to the development and validation of such methods by assessing the vulnerability of cetaceans to climate change in the biogeographic region of Macaronesia. Results are intended to be used to support informed decision-making and effective conservation under a changing ocean. This was accomplished by adapting and applying the methodology developed by Lettrich et al. (2019) for marine mammals in the United States (US) and expanding the index developed by Sousa et al. (2019) to the entire Macaronesia region.

2. Methods

The method used to assess the vulnerability of cetacean species to climate change in Macaronesia was largely adapted from the Marine Mammal Climate Vulnerability Assessment (MMCVA) developed by the US National Oceanic and Atmospheric Administration (Lettrich et al., 2019). The MMCVA developed a more robust approach than the one previously developed for the Madeira archipelago (Sousa et al., 2019), including a broader geographic range and the contributions of a larger expert working group in the design and test of the methodology, over a period of 3 years. The MMCVA method was established to assess the vulnerability of marine mammal stocks to climate change in US waters, considering species' biological and ecological traits as sensitivity attributes, and climate variables as exposure factors. Then, the method uses expert judgment to evaluate such attributes and factors and produces estimates of species vulnerability to climate change – for detailed information on the MMCVA method see (Lettrich et al., 2019). The present study also takes the work of Sousa et al. (2019) forward by using an optimized approach and extending the assessment of cetacean species conducted in Madeira to the entire Macaronesia region (i.e., the Azores, Canary Islands and Madeira), including a larger number of species and consulted experts in the assessment.

In the present work, the climate change vulnerability assessment consisted of three main steps: 1) definition of scope and scale; 2) scoring process for sensitivity attributes, exposure factors and data quality; and 3) calculation of vulnerability scores and data analysis. Modifications to the MMCVA method were exclusively made on the selection of exposure factors to best reflect the species under study and on the scoring bins of two sensitivity attributes (habitat specificity and site fidelity) to suit our study area specificities (see *Sensitivity attributes and climate exposure factors*). Details on the methodological aspects of each step are provided in the following sub-sections.

3. Definition of scope and scale

3.1. Study area

The biogeographic region of Macaronesia comprises two Portuguese archipelagos, the Azores and Madeira, and the Spanish archipelago of the Canary Islands (Fig. 1). Azores is the northernmost archipelago of Macaronesia encompassing nine islands. Madeira lies approximately 840 km SE of the Azores and 630 km NW of the African continent and is composed of two main islands (Madeira and Porto Santo). The Canary archipelago is situated about 400 km south of Madeira and 115 km off the West African mainland and is composed of seven main islands (Fig. 1).

There has been an ongoing debate on whether the Macaronesia biogeographic region should include the archipelago of Cape Verde (Vanderpoorten et al., 2007). Studies have showed that the marine biota community structure and biogeographic relationships in Cape Verde differ from the remaining North Atlantic archipelagos (Freitas, 2014; Freitas et al., 2019). Indeed, the Azores, Madeira and Canary Islands were considered a single marine ecoregion in the Lusitanian province whereas Cape Verde is biogeographically within the West African Transition province (Spalding et al., 2007). For these reasons, in the present study only the archipelagos of Azores, Canary Islands and Madeira were considered.

The Macaronesian islands have an exclusively volcanic origin with complex oceanographic and topographic features facilitated by the narrow continental shelfs and the occurrence of great depths (over 1500 m) relatively close to shore (Geldmacher et al., 2000; Santos et al., 1995; Valdés and Déniz-González, 2015). The main ocean currents influencing this dynamic region are the Azores and the Canary Currents, which form two of the boundaries of the North Atlantic Gyre, together with the Gulf stream along the East Coast of the United States (Barton, 2001; Cropper, 2013). Furthermore, islands create oceanographic disturbances of oceanic flow, known as the “island mass effect”, which result in the presence of lee eddies, island wakes and upwelling features (Caldeira and Reis, 2017). These conditions foster a high number of cetacean species in each archipelago (over 20 species; Alves et al., 2018; Carrillo et al., 2010; Silva et al., 2014), contributing to the classification of Macaronesia as a world biodiversity hotspot (Myers et al., 2000).

3.2. Experts selection and consultation

In order to support the development of the climate vulnerability assessment, and further validate it, six experts on cetacean ecology with knowledge and expertise on both the overall study area and on each of the archipelagos of Macaronesia (two experts per archipelago) participated in the present study.

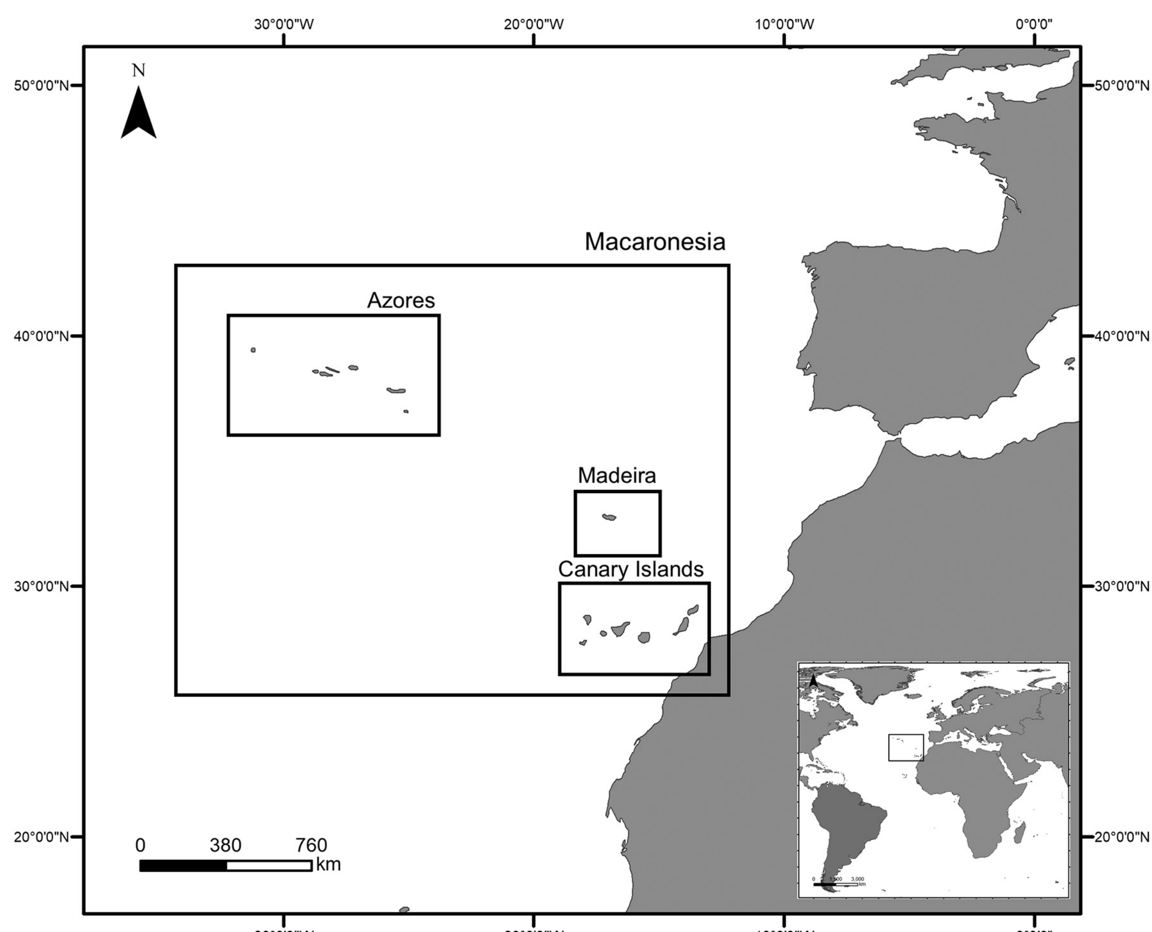

Fig. 1. Map of the Macaronesia biogeographic region, showing the archipelagos of Azores, Madeira and Canary Islands.

The participatory process took place for four months, between February and July 2020, in a full online format because of travel restrictions related to the COVID-19 pandemic. A total of six on-line workshops were performed. In the first workshop (February 19, 2020) experts were consulted to select cetacean species and management units for the assessment (see *species selection* below), and to validate sensitivity attributes and exposure factors in order to ensure their adequacy for cetacean species in Macaronesia.

Experts were then given time to individually score each units' exposure factors and sensitivity attributes. Once the individual scores were collected, preliminary results from archipelago-associated management units were discussed in three dedicated workshops, one for each archipelago (May 4, 2020 – Madeira; May 14, 2020 – Azores; June 2, 2020 – Canary Islands), with the participation of the corresponding archipelago experts. Similarly, preliminary results for Macaronesia management units were discussed in a workshop with all six experts (May 22, 2020).

After the workshops, experts were given time to independently analyze results and change their scores if desired (this way ensuring impartiality and avoiding peer-pressure to reach a consensus). The final scores from all units were collected, and further discussed and validated in a final workshop with all six experts (July 23, 2020).

3.3. Species selection

The process of species selection was initiated using a list of indicator species created specifically for the Macaronesia region with the purpose of assessing the Good Environmental Status (GES) of European marine waters under the Marine Strategy Framework Directive (MSFD) (MISTIC SEAS, 2016). These indicator species were classified into management units, defined as "animals of a particular species in which management of human activities are performed" (ICES, 2014).

To ensure that other relevant species were not excluded from our study, the list of indicator species was crosschecked with species that are known to be relevant for the whale watching industry in Macaronesia (i.e., species identified as being frequently encountered by those vessels), and species that can be used as indicators of climate-related range changes (e.g., species whose northern distribution range limit is in at least one of the Macaronesian archipelagos) (MacLeod, 2009).

The final list of selected species was then classified into four management units, namely the "Macaronesian unit" and three "archipelago-associated units" (Azores, Canary Islands and Madeira).

Species in the Macaronesian unit correspond to individuals that use the entire region as a single habitat, but that are seen in archipelagic waters during a short period of time (days to weeks), based on long-term data such as photo-identification.

Classification of species into archipelago-associated units was defined as individuals that are resident (or island-associated) or exhibit multi-year and year-round site fidelity to one archipelago.

Overall, this classification distributed 10 individual cetacean species into 21 species management units – 10 Macaronesia units (MAC) and 11 archipelago-associated units (Table 1).

The 11 archipelago-associated units were scored by the two experts from each archipelago and the 10 Macaronesia units were scored by all six experts.

3.4. Sensitivity attributes and climate exposure factors

All 11 sensitivity attributes defined in the MMCVA (Lettrich et al., 2019) were used. From those, two attribute scoring bins description (Site fidelity and Habitat specificity) were slightly modified to suit the study area (S. M. Table 1). In the case of site fidelity, the description of scoring bins was adapted to fit the different geographic scales of our study area, from the Macaronesia region to the archipelagos level, and to the island-specific level. Habitat specificity was modified to consider the reliance on features vulnerable to climate conditions in all life stages

Table 1
Selected species included in the climate change vulnerability assessment and their classification into species management units: Macaronesia unit (MAC) and the archipelago-associated units of Azores (AZO), Canary Islands (CAN) and Madeira (MAD).

Common name	Scientific name	Species management unit
Atlantic spotted dolphin	*Stenella frontalis*	MAC
Bryde's whale	*Balaenoptera edeni*	MAC
Fin whale	*Balaenoptera physalus*	MAC
Short-finned pilot whale	*Globicephala macrorhynchus*	MAC, MAD, CAN
Short-beaked common dolphin	*Delphinus delphis*	MAC, AZO
Sperm whale	*Physeter macrocephalus*	MAC, AZO
Risso's dolphin	*Grampus griseus*	MAC, AZO, CAN
Common bottlenose dolphin	*Tursiops truncatus*	MAC, AZO, CAN, MAD
Blainville's beaked whale	*Mesoplodon densirostris*	MAC, CAN
Cuvier's beaked whale	*Ziphius cavirostris*	MAC, CAN

since there were no differences in the habitat used in specific life stages for cetacean species in Macaronesia.

Five of the original nine exposure factors presented in Lettrich et al. (2019) were used in this study (S.M.1 Table 1). Excluded factors were air temperature, precipitation, ice cover and sea level rise. The first three factors were considered not to directly affect cetaceans in Macaronesia given that in the original MMCVA they were defined as mainly relevant for pinnipeds, some ice-associated or coastal cetacean populations (i.e., bowhead, killer whales, belugas) (Lettrich et al., 2019). Sea level rise is a relevant factor mainly for some particular shoreline habitats and areas with extended continental shelfs. It was therefore not considered to be relevant for Macaronesia where coastal waters tend to exceed depths of 1500 m (Geldmacher et al., 2000; Santos et al., 1995; Valdés and Déniz-González, 2015).

Primary productivity was included as an additional exposure factor due to its direct effect on the distribution, diversity and abundance of cetacean species in Macaronesia (Correia et al., 2020; García et al., 2018; Tobeña et al., 2016).

4. Scoring process for sensitivity attributes, exposure factors and data quality

Each sensitivity attribute and exposure factor selected was scored individually by experts. The scoring process consisted in the attribution of five tallies across four scoring bins: Low (=1); Moderate (=2); High (=3) and Very High (=4) (S.M.1 Table 1). For sensitivity attributes' scoring, experts distributed their tallies according to available evidence from the literature and their own knowledge and experience on the selected cetacean units. When considering exposure factors, scores were attributed according to the degree of change projected for each factor (based on climate projection maps) within the distribution range of each cetacean unit (the latter was assessed by experts through literature review).

Climate projection maps used to determine exposure scores were obtained from the Earth Systems Research Laboratory (ESRL) web portal (ESRL, 2014). These maps were scaled to fit the criteria of the scoring bins, allowing for a clearer visualization and interpretation of each exposure factor (S.M.2 Fig. 1). The North Atlantic region was selected in order to encompass the potential distribution range of all considered cetacean species (Silva et al., 2013). "Circulation" was the only exposure factor for which projections were not available, hence information from literature and expert judgment were used to score it.

For comparability purposes, and following the original method by (Lettrich et al., 2019), this study used the Representative Concentration Pathway (RCP) 8.5 scenario and a short to mid-century timeframe (2006–2055). The choice of RCP 8.5 is also justified as it is the climate change pathway that allows to capture the high-end tail of the uncertainty envelope associated with climate impacts (Riahi et al., 2011). Given the level of uncertainty surrounding the ecological and biological effects of climate change on cetacean species and the lack of substantial change in the magnitude of projected potential climate changes we adopted the precautionary principle by selecting the RCP 8.5 (Foden et al., 2019). The short to mid-century timeframe was selected for similar reasons, but also because the final aim of this study was to assist decision-making processes and support adaptation measures that target species' conservation. Despite the intrinsic value of analyzing the effect of climate change on cetaceans until the end of the century, the combination of increasing uncertainties in longer time frames and the need to produce salient information for conservation decisions taken now dictated the choice (Foden and Young, 2016).

Each sensitivity attribute and exposure factor were classified regarding the quality of the evidence underpinning the experts' choices. Data quality values ranged from zero to three, supporting the degree of evidence available to assign the distribution of tallies in the scoring bins: 0 = No data; 1 = Expert judgment only; 2 = Limited data; 3 = Adequate data (Lettrich et al., 2019). Regarding exposure factors, only the quality of the information on the distribution range of each cetacean unit was assessed by the experts, not the quality of the climate models used, as in Lettrich et al. (2019).

5. Calculation of vulnerability scores and data analysis

5.1. Climate vulnerability

Climate vulnerability scores were calculated through a three-step approach, following the methods of Hare et al. (2016) and Lettrich et al. (2019). First, each Attribute or Factor Weighted Means (AFWM) were calculated for each attribute/factor, based on the distribution of experts tallies in the scoring bins, as follows:

$$AFWM = \frac{((B_1 \times 1) + (B_2 \times 2)(B_3 \times 3)(B_4 \times 4))}{(B_1 + B_2 + B_3 + B_4)}$$

where B_n is the number of tallies in scoring bin n.

Each exposure factor was scored for both a change in mean and a change in variability. The highest factor weighted mean value (either from a change in mean or a change in variability) was the one considered as the mean score for that factor (Lettrich et al., 2019).

Second, using the obtained AFWM values, scores for sensitivity and exposure components were calculated using the logic model developed by Hare et al. (2016). The overall vulnerability to climate change of each cetacean unit was thus calculated by multiplying sensitivity and exposure component scores. Component scores varied from Low (=1) to Moderate (=2), High (=3), and Very High (=4), and the crossing between both component scores provided a vulnerability category for each unit (Fig. 2).

5.2. Certainty and data quality

Data quality was calculated for each sensitivity attribute and exposure factor, and vulnerability score, as an average of all experts' scores.

Certainty in sensitivity, exposure and vulnerability scores were calculated with a bootstrap analysis (Hare et al., 2016), using R software. The bootstrap analysis resampled the aggregate of all experts' scores and created simulated samples from the original dataset. Scores attributed by experts were drawn 10,000 times randomly with replacement and the proportion of outcomes was counted for each scoring bin, resulting in the correspondent certainty scores. Calculated scores for attributes, factors, and vulnerability were compared against predicted bootstrap scores, resulting in a metric to evaluate certainty. Certainty scores were classified as very high (>95%), high (90–95%), moderate (66–90%) or low (<66%).

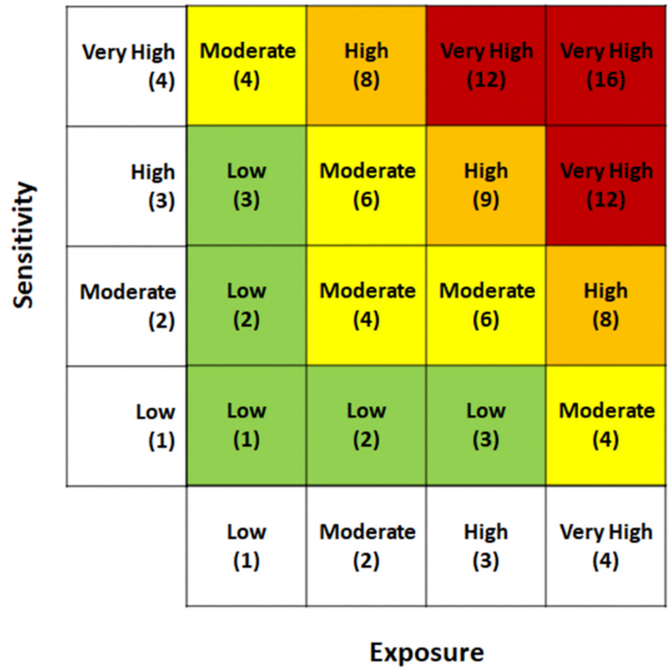

Fig. 2. Vulnerability matrix from Lettrich et al., 2019, showing the component scores of sensitivity/adaptive capacity and exposure to obtain the overall vulnerability score. Numbers in parenthesis indicate the component scores of sensitivity and exposure and the vulnerability score resulting from multiplying sensitivity and exposure [Low vulnerability (1–3), Moderate vulnerability (4–6), High vulnerability (8–9), Very High vulnerability (12–16)].

5.3. Sensitivity analysis

To investigate which attributes and factors were the most influential in determining vulnerability for each unit, a sensitivity analysis was performed following Hare et al. (2016). The analysis consisted of removing one attribute or factor at a time and re-calculating the overall vulnerability score.

5.4. Potential for distribution, abundance and phenology changes

The potential for changes in distribution, abundance and phenology was assessed based on the relation of each sensitivity attribute to potential responses in a unit's geographic distribution, abundance or phenology. These responses were calculated considering only the sensitivity attributes that showed a relationship with each response category (Lettrich et al., 2019). The response scores and respective certainty were calculated similarly to the overall vulnerability scores.

6. Results

From the 21 species management units that were assessed, over half (62%) presented Very High (5 units) or High (8 units) vulnerability scores. From these, 10 units were archipelago-associated and only three were Macaronesian. At the lower range of the vulnerability scale, eight species management units have Moderate (7 units) to Low (1 unit) vulnerability scores, and of these nearly all (7 units) are Macaronesian (Figs. 3 and 4).

Certainty scores show that 29% of the species management units fall under the High to Very High certainty category (>90%), 38% in the Moderate (66–90%), and 33% in the Low category (<66%) (Figs. 3 and 4). Overall, the actual vulnerability scores were very similar (20 out of 21) to the predicted bootstrap vulnerability scores (S.M.3 Fig. 2c). Data quality scores for exposure factors were higher than for sensitivity attributes.

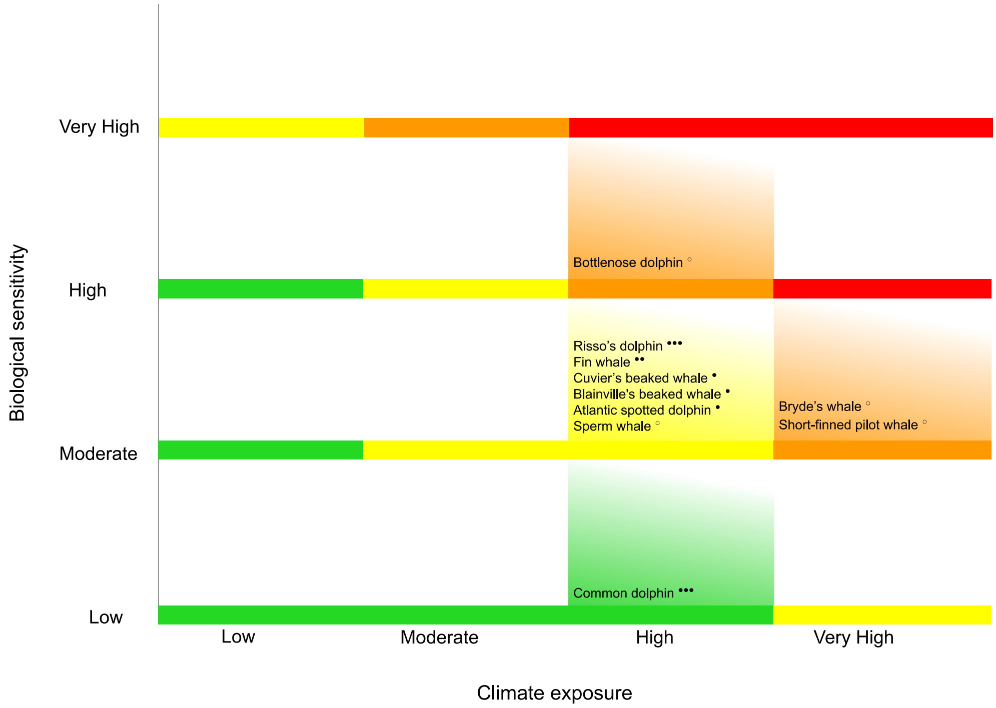

Fig. 3. Climate vulnerability scores which result from the combined biological sensitivity and climate exposure scores for the Macaronesia (MAC) species management units. Colors indicate vulnerability scores: Very High (red), High (orange), Moderate (yellow) and Low (green). Symbols indicate certainty scores: ••• very high certainty (>95%); •• high certainty (90–95); • moderate certainty (66–90%) and ○ low certainty (<66%).

However, neither these nor the combined data quality scores show a general relation with higher or lower attributes, factors, or vulnerability scores (S.M.4 Table 2).

Sensitivity analysis showed that the most influential sensitivity attributes, common to all units, are migration, generation length, and habitat specificity. Regarding exposure factors the same analysis showed that

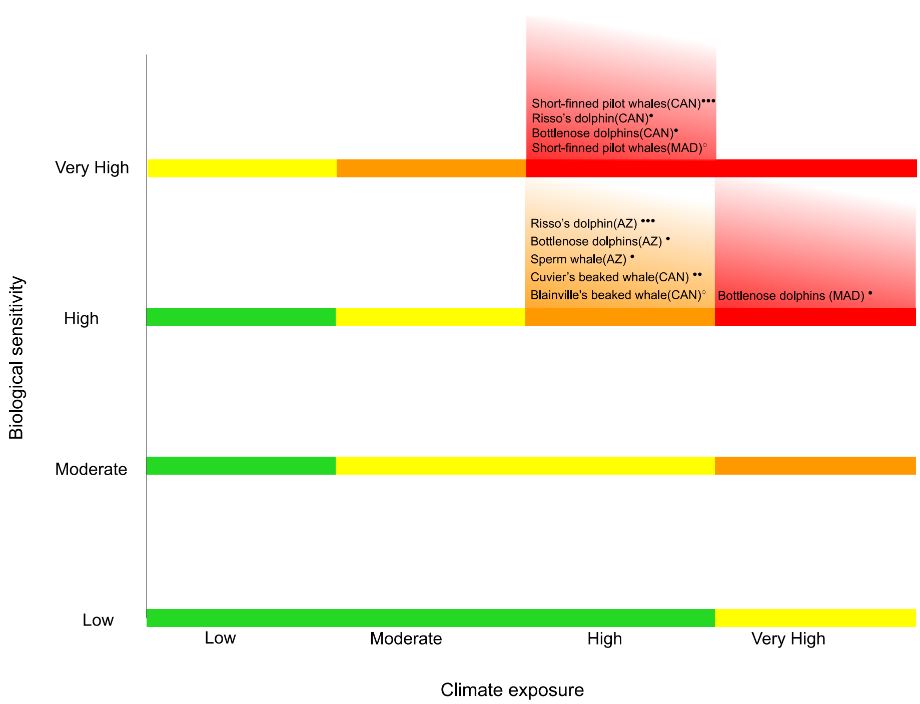

Fig. 4. Climate vulnerability scores which result from the combined biological sensitivity and climate exposure scores for the archipelago-associated species management units of Azores (AZ), Canary Islands (CAN) or Madeira (MAD). Colors indicate vulnerability scores: Very High (red), High (orange), Moderate (yellow) and Low (green). Symbols indicate certainty scores: ••• very high certainty (>95%); •• high certainty (90–95); • moderate certainty (66–90%) and ○ low certainty (<66%).

sea surface temperature (mean), ocean acidification (mean) and dissolved oxygen (mean) were the most influential in determining vulnerability (S.M.2 Fig. 1a, e, i). In general, the variance in sensitivity attributes scoring was higher than for exposure factors (S.M.5 Figs. 3c, d, 4c, d). Sensitivity attributes for archipelago-associated species management units showed a higher variance in scores when compared to Macaronesia (S.M.5 Figs. 3c, 4c).

Overall, results show a high potential for changes in distribution, abundance, and phenology, with all three categories typically scoring higher for archipelago-associated species management units than for Macaronesian (Fig. 5). In general, no clear relationship between climate vulnerability scores and potential changes in distribution, abundance, or phenology was found (S.M.6 Table 3).

6.1. Macaronesia units

The majority (6 out of 10) of Macaronesia species management units presented a Moderate vulnerability score, while covering the full range of certainty scores (Fig. 3). Bottlenose dolphin, Bryde's whale and short-finned pilot whale showed a High vulnerability to climate change, with a low certainty score (<66%). Bryde's whale and short-finned pilot whale displayed Moderate sensitivity and Very High exposure, while the Bottlenose dolphin exhibited High sensitivity and High exposure. The common dolphin had the lowest vulnerability score as a result of its Low sensitivity and High exposure values, with a Very High certainty score (>95%).

The most influential attributes determining vulnerability in Macaronesia were generation length, habitat specificity and migration (S.M.5 Fig. 3c). The only exposure factors that contributed to changes in vulnerability scores were sea surface temperature (mean), ocean acidification (mean) and dissolved oxygen (mean) (S.M.5 Fig. 3d).

Macaronesia species management units showed High (50%) and Moderate (50%) potential for changes in distribution, with most certainty scores in the Very High range (Fig. 5).

Most units exhibited a Moderate potential for changes in abundance, except for common dolphin, Atlantic spotted (hereafter referred as spotted dolphin) and common bottlenose dolphin (hereafter referred as bottlenose dolphin), which showed a Low potential (Fig. 5).

Spotted dolphin, fin whale and Bryde's whale presented a High potential for phenology changes, while the bottlenose dolphin presented a Low phenology response score, and a low certainty score (Fig. 5).

6.2. Archipelago-associated units

The most vulnerable archipelago-associated species management units, with a Very High vulnerability score, were the short-finned pilot whale and the bottlenose dolphin in the Canary Islands and Madeira, and the Risso's dolphin in the Canary Islands (Fig. 4). All the above units scored Very High in sensitivity attributes and High in exposure factors, with the exception of bottlenose dolphin in Madeira with High sensitivity and Very High exposure. In general, the units of Madeira and the Canary Islands showed a higher vulnerability to climate change than the Azores units. The majority of units showed a Moderate certainty in vulnerability scores. The lowest vulnerability and certainty scores were attributed to the common dolphin in Azores.

The most influential attributes determining vulnerability in archipelago-associated units were migration, site fidelity and home range (S.M.5 Fig. 4c). Prey/diet specificity and habitat specificity were the attributes that showed a higher variability in scoring (S.M.5 Fig. 4c).

Sea surface temperature (mean) and ocean acidification (mean) were the two most influential exposure factors contributing to the vulnerability scores, followed by dissolved oxygen (S.M.5 Fig. 4b, d).

The majority of archipelago-associated species management units displayed a High potential for distribution change. The certainty of these results varied from Very High to Moderate.

Most units exhibited a High potential for changes in abundance except for the common dolphin in the Azores which showed a Moderate potential (Fig. 5).

Most archipelago-associated units scored High for potential changes in phenology, with a Very high to Moderate certainty scores. The exceptions were Blainville's beaked whale in the Canary Islands (Moderate potential) and the sperm whale in Azores (Low potential) (Fig. 5).

7. Discussion

7.1. Climate vulnerability of cetacean species in Macaronesia

The assessment conducted for cetaceans in Macaronesia identified the sensitivity attributes and exposure factors that contribute to each species management unit's vulnerability to climate change. The most influential sensitivity attributes explaining vulnerability in all units were: (a) migration; (b) generation length (c) site fidelity; (d) habitat specificity and (e) home range (S.M.5 Figs. 3c, 4c).

Migratory baleen whale species undertake extensive movements between tropical breeding grounds in winter and high latitude foraging areas in summer. For example, fin whales migrate every year to North Atlantic feeding grounds, mostly in springtime (Carrillo et al., 2010; Silva et al., 2013) or undertake shorter migrations, both in space and time (Valente et al., 2019). Sperm whales also migrate but vary their movements according to sex and age. While adult females and immature individuals move mostly within the Macaronesia (i.e., travel between different islands or even archipelagos, every year or season), adult males are known to perform long-range movements, and generally live at higher latitudes returning periodically to warmer waters for reproductive purposes (Clarke, 1956; Whitehead, 2003; Steiner et al., 2012).

Using migratory behavior as a proxy for the ability of a species to disperse, migratory species may have a greater ability to adapt to changing conditions and seek areas with suitable conditions compared to non-migratory species (Gardali et al., 2012; ZSL, 2010).

Nevertheless, migratory species can still be affected by environmental changes across their entire range (Ramp et al., 2015). Archipelago-associated species management units are known to have stronger residency patterns, with more restricted movements. For example, Risso's dolphins in the Azores or in the Canary Islands, form resident groups that exhibit strong habitat preferences (Hartman et al., 2015; Sarabia-Hierro and Rodríguez-González, 2019). However, information available to accurately comprehend and evaluate the movements of archipelago-associated units is currently insufficient. Nonetheless, some archipelago-associated units were recently found to move to neighbouring archipelagos. Examples include a core resident group of short-finned pilot whales in Madeira (i.e., the group with more photographic-captures, seen year-round during at least 17 years) that made a round trip to the Azores (Alves et al., 2018) or the case of seasonal visitors of the same species in Madeira that were also captured in the Canary Islands (Alves et al., 2019). Similarly, bottlenose dolphins' migrant individuals in Madeira ($n = 14$), equivalent to regular or occasional visitors in this study, were seen in Azores (n = 1) and in the Canary Islands ($n = 13$) (Dinis et al., 2021).

These observations support the notion that archipelago-associated individuals can be, at times, part of their respective Macaronesia species management unit and that, conversely, transient individuals will also spend time in archipelagos and may occasionally be a part of their respective species management units (Alves et al., 2013, 2019).

Longer generation lengths together with other traits such as shorter lifetime reproductive potential and lower reproductive plasticity provide little opportunity for rapid evolutionary adaptation under a changing climate (Lettrich et al., 2019; Silber et al., 2017).

Obtaining information on generation length is especially onerous for cetaceans, because of their remote oceanic habitats, their extended

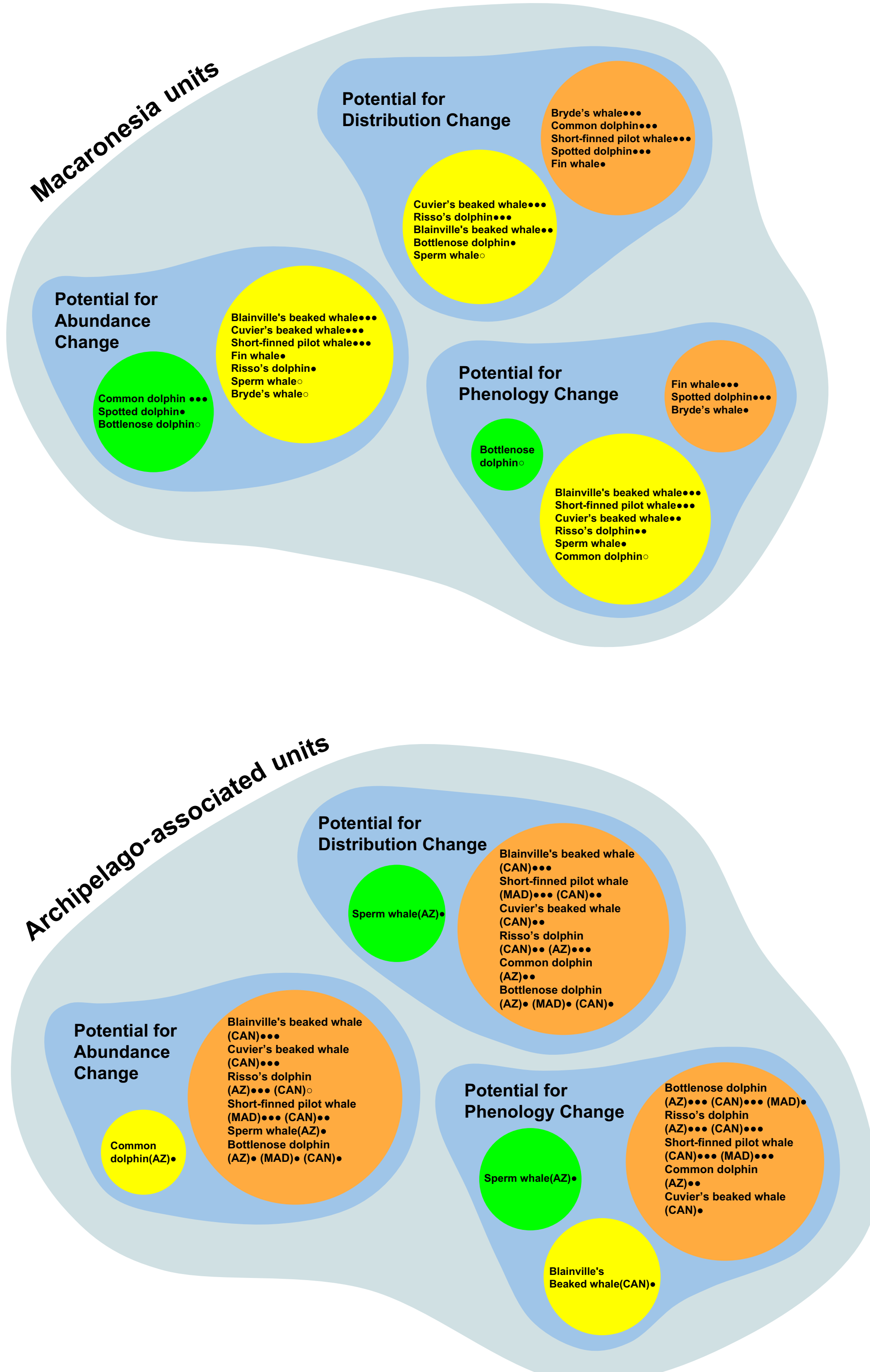

Fig. 5. Vulnerability scores and potential distribution, abundance and phenology responses for the Macaronesia (MAC) and archipelago-associated species management units of Azores (AZ), Canary Islands (CAN) or Madeira (MAD). Colors indicate Very High (4; red), High (3; orange), Moderate (2; yellow) and Low (1; green) potential for changes. Symbols indicate certainty scores: ••• very high certainty (>95%); •• high certainty (90–95); • moderate certainty (66–90%) and ○ low certainty (<66%).

longevity, and the difficulties in obtaining age specific data (Taylor et al., 2007). Several methods have been used to overcome this lack of data, such as: (i) extrapolate generation length estimates for a given species using life-history and demographic data of other species, based on the general patterns of taxonomic relatedness and body size (Cooke et al., 2018); (ii) use a demographic model to estimate both the percentage of mature individuals of the current population and the generation length of a pre-disturbed population (Cooke et al., 2018); or (iii) use data from captive animals to extrapolate age for wild populations, although this approach has associated problems, as conditions for species in captivity and in the wild differ substantially (Cooke et al., 2018).

Bottlenose dolphins have a general generation length of approximately 20 years (Pacifici et al., 2014), which also accounted for its higher sensitivity score. However, due to the previously mentioned difficulties in obtaining age specific data (Taylor et al., 2007), these scores should be considered with caution, even if the expert's judgment about the overall data quality of the sensitivity attributes found in the literature is high. Data quality scores presented refer to the average sensitivity attributes and not to individual attribute scores (S.M.4 Table 2).

The habitat specificity attribute considers a units' reliance on physical features that are more or less resilient to climate conditions. If a habitat tends to be less affected by climate change, its populations are also expected to be less affected. The Macaronesia region is characterized by a high density of volcanic peaks, some of them rising up as oceanic islands (Morato et al., 2013). Oceanographically, the presence of a submarine peak or an island will disturb the ocean currents and produce perturbations that ultimately have biological consequences (Caldeira et al., 2014; Caldeira and Reis, 2017). These disturbances known as "island wakes", are areas with intense eddy activity that influence the availability and transport of organic matter in the ocean. They can have an effect on the biological productivity and concentration of prey, particularly if connected with oceanic fronts (Barton, 2001). Macaronesia is a region where bathymetric and oceanographic features interact in complex ways, providing the habitat that supports the many cetacean species recorded in the area.

Risso's dolphins in the Canary Islands have a higher sensitivity than in the Azores. Coastal population of Risso's dolphins in the eastern Canary Islands have been reported to be highly habitat specific and exhibit a high site fidelity (Sarabia-Hierro and Rodríguez-González, 2019). Due to the limited studies focusing on this area, the residency patterns described may be a result of sample bias, therefore not excluding the possibility of a lower degree of site fidelity. In Azores, results off Pico island show relatively restricted home ranges for Risso's dolphins (Hartman et al., 2015) and specific habitat conditions for groups with new-borns and calves (Hartman et al., 2014). Differences in sensitivity scores between these two species' units are an example of how habitat specificity and site fidelity can contribute to influence overall vulnerability.

The high sensitivity of bottlenose dolphin relates to their distribution which is directly or indirectly linked to the habitat they occupy, and the availability and distribution of prey. Resident individuals of bottlenose dolphins (all archipelago units) tend to be coastal, with potential spatial overlaps with human coastal development. Their home range can vary from small to large displacements (Ballance, 1992; Robinson et al., 2012) depending on food availability, reproductive cycle, season and calf care (Bearzi and Politi, 1999; Würsig et al., 1991). Bottlenose dolphins in the Canary Islands are highly mobile within the archipelago (Tobeña et al., 2014). However, and despite the current insufficient information to identify any ecotypes, there might be individuals with relatively small home ranges, showing mainly local movements, which are dependent on specific conditions more sensitive to climate change. In additon, insufficient ecological and genetic data on bottlenose dolphins in the Canary Islands (Carrillo et al., 2010) limits the knowledge available to score this unit. On the contrary, common dolphins in the Azores are sighted year-round in the entire archipelago and occur in a wide range of environmental conditions (González Garcia, 2019; Silva et al., 2014). This unit was therefore expected to be less sensitive than other archipelago associated units with more specific preferences, a characteristic that is supported by our results.

In addition, the Macaronesia unit of common dolphin, has the lowest sensitivity score of all assessed units. They show a very seasonal occurrence pattern in Madeira, with more sightings during the first semester of the year, peaking in spring (Alves et al., 2018). A similar pattern, but with a wider temporal distribution, occurs in Azores, where the species is sighted all year around, but declines during summer months (Silva et al., 2014). Moreover, the species is generally associated with cold and productive regions, occupying a wide area in the proximity of the islands or seamounts (Fernandez et al., 2018; Tobeña et al., 2016). Therefore, they might move through the archipelagos following productive water masses, but with a high degree of plasticity. In fact, in other areas the species has been documented to have an opportunistic feeding behavior, with a wide range of potential preys (Santos et al., 2013).

The exposure factors that were most influential to species' vulnerability across all units were: (i) sea surface temperature; (ii) ocean acidification; and (iii) dissolved oxygen. These were also the factors for which the highest magnitude of change is projected.

Bryde's whale, short-finned pilot whales and Bottlenose dolphin (Canary Islands unit) exhibited the highest exposure score of all units because their distribution overlaps with areas of high projected climate changes, when compared to the remaining units (S.M.2 Fig. 1). The first two species are known to have a tropical and warm-temperate distribution (Kato and Perrin, 2018; Olson, 2018), with their northern, central and eastern Atlantic limit at the latitude of Azores (Steiner et al., 2008; Alves et al., 2019). In Madeira, Bryde's whales were only first recorded in 2003 (Freitas et al., 2012) but since 2005 are amongst the most encountered species in the region (Alves et al., 2018). In the Azores, it was first sighted in 2004, and since then, occasional occurrences have been reported in the archipelago, with some exceptional years where Bryde's whales were observed in several consecutive months (Azevedo et al., 2018).

7.2. Comparison with other climate change vulnerability assessments

Exploring and comparing results from multiple trait-based indexes is an important step to further advance and validate vulnerability assessments for marine species under changing climates.

When comparing the results of our work with recently published studies, similarities and differences were found, namely in taxonomic groups, study areas and/or methodologies. The main differences identified were related to: (1) the full list of species selected, and management units defined; (2) the overall study area; (3) the sensitivity attributes and exposure factors considered (even in the cases of similar climate modelling approaches like the use of projection maps from ESRL); (4) the definition of scoring bins for each indicator; and (5) the computation of results (e.g., the use of logic models).

Results show that the overall climate vulnerability scores differ from the previous assessment for the Madeira archipelago (Sousa et al., 2019). In that study, sperm whales and fin whales were identified as the most vulnerable species, being highly scored for both exposure and sensitivity, whereas in the present study most vulnerable species corresponded to the archipelago-associated units of bottlenose dolphins (Canary Islands and Madeira), Risso's dolphins and short-finned pilot whales (both in the Canary Islands). Still, some similarities could be found, namely for island associated (or archipelago-associated) individuals of bottlenose dolphins in Madeira which showed a lower sensitivity than island associated individuals of short-finned pilot whales in both studies. Common and spotted dolphins also showed a low vulnerability in both studies. Differences between both studies can be related with the number and type of sensitivity attributes and exposure factors considered, as well as their definition and scoring categories. For example, Genetic variability and IUCN Status were attributes only considered in Sousa et al., 2019 while Generation Length and Habitat specificity were only considered in this study (S.M.1 Table 1). Also, Diet diversity was defined in Sousa et al., 2019 in three scoring categories (One prey type comprises >20% of a species diet – Score = 3; Two prey types comprise >20% of a species diet – Score = 2; Three or more prey types comprise >20% of a species diet – Score = 1) different from the ones defined in this study (S.M.1 Table 1). Additionally, the present study defined

Macaronesia and archipelago-associated species management units, while Sousa et al. (2019) considered the North Atlantic populations of 7 cetacean species and island associated individuals of short-finned pilot whales and bottlenose dolphins.

When comparing the results of our approach to a similar expert-based scoring method developed by Hare et al. (2016) to assess the vulnerability to climate change, of 82 marine fish and invertebrate species in the Northeast U.S, we found a similar high potential for changes in species distribution (over 50% of analysed species management units). In our study, we found certainty scores for distribution response to be high for 43% of units, while vulnerability certainty scores varied from Moderate to Low. Whereas Hare et al. (2016) found that certainty results for distribution change potential were low (<66%) when compared to the certainty in vulnerability results. Results also differ when comparing climate vulnerability scores with species potential for distribution change. Hare et al. (2016) found that climate vulnerability was negatively correlated to potential for a distribution shift, meaning that species which are highly vulnerable to climate change also have a lower potential to change their distribution and vice versa, something not found in our study. Differences between both studies may indicate that, contrary to fish and invertebrate species, cetaceans are more likely to have a high potential for distribution change due to their high mobility and endothermicity despite their vulnerability to climate change. Cetacean species have a broader range of temperature tolerance compared to fish, making them more resilient to changes in climate. However, due to their lack of isotherm tracking behavior, their responses to potential changes in food resources are also less predictable (Silber et al., 2017).

The recently developed method applied in our study was also used to assess the vulnerability of marine mammal stocks in the Northwest Atlantic, Gulf of Mexico and Caribbean. In that study, Lettrich et al. (in preparation) found greater vulnerability to be correlated with greater potential for distribution change and that most stocks scored high for distribution change. Potential for abundance change and phenology change were directionally similar to distribution change (i.e., greater vulnerability correlated to greater likelihood of change), but the correlation was not as strong as for distribution.

In our study we found a high potential for distribution, abundance and phenology change but none showed a relation with high vulnerability.

Poleward shifts in the distribution of different marine species have been recorded since the 1950's with an average range shift of 52 ± 33.3 km per decade (IPCC, 2019) and at a rate six time faster than in terrestrial species (Lenoir et al., 2020). The rate and direction of distribution changes result from the interaction of climatic factors such as local temperature, ocean currents and oxygen gradients across depth, latitude and longitudinal gradients and non-climatic factors such as fishing (IPCC, 2019; Poloczanska et al., 2013).

For cetacean species, an increase in species richness has been predicted from tropical regions to higher latitudes above 40° (Kaschner et al., 2011; Whitehead et al., 2008). This redistribution of species was predicted to affect 88% of cetacean species globally due to changes in water temperature driven by climate change (MacLeod, 2009).

In mid-latitude regions, evidence for climate change impacts in cetacean species is generally documented by range shifts with range contractions of cold-water species such as the minke whale, northern bottlenose whale and white-beaked dolphin, and a northwards expansion of warmer water species such as striped dolphin, short-beaked common dolphin, and Cuvier's beaked whale (Evans, 2020; Lambert et al., 2014).

In addition to shifts in distribution, we assessed the potential for abundance and phenology responses to climate change. In general, for all units assessed, we found shifts in abundance and phenology to be High. In the North-East Atlantic, evidence of changes in distribution, abundance, and feeding ecology of cetacean species have been documented (Nøttestad et al., 2015; Víkingsson et al., 2015). Víkingsson et al. (2015) found an increase in the abundance of Central North Atlantic humpback (*Megaptera novaeangliae*) and fin whales (*Balaenoptera physalus*). The increase in fin whale's abundance, together with an expansion of its distribution, may be a response to the increase in the abundance of their main prey (euphausiids). In addition, a decrease in the abundance of minke whales (*Balaenoptera acutorostrata*) in the Icelandic continental shelf may also be a response to changes in the local abundance of sand eel, capelin and euphausiids. In the Norwegian sea, higher densities of toothed whales, killer whales (*Orcinus orca*) and long-finned pilot whale (*Globicephala melas*) were recorded and were potentially linked to elevated average surface temperatures along with a reduction in zooplankton biomass and an increase in abundances of pelagic planktivorous fish (Nøttestad et al., 2015). Changes in phenology were investigated for fin and humpback whales which showed an earlier arrival and departure from their summer feeding ground in the Gulf of St. Lawrence (Canada) over three decades (Ramp et al., 2015). Earlier ice break-up and increasing sea surface temperature, which likely triggered earlier primary production, were strongly related to the earlier arrival trend in both species (Ramp et al., 2015).

The high potential for abundance, distribution and phenology changes found in our study, further highlights that if climate change impacts increase, changes in cetacean species as a response to environmental changes may also become more common in the future. Thus creating a challenge for policy and conservation planning by increasing the need to anticipate species' responses driven by climate change (Evans and Waggitt, 2020; Silber et al., 2017). In addition, non-climate stressors can be exacerbated or modified by climate change as a result of climate driven shifts in human behavior (Alter et al., 2010). For example, increased shipping activities in the arctic as a result of a reduction in sea ice will likely lead to increased mortality or injury events on cetaceans due to ship strikes. In our study area no major local impacts have been currently identified, with the exception of ship strikes from high-speed ferries in the Canary Islands (Carrillo and Ritter, 2010). Nevertheless, other human induced impacts such as an increased reliance on marine species in the future can produce serious knock-on effects leading to changes in prey availability or increased bycatch on cetaceans' populations (Alter et al., 2010; Simmonds, 2017).

Despite differences between the previously mentioned studies, the improved method used in this study, provided an optimized version of the previous work developed for the Madeira archipelago (Sousa et al., 2019) and a solid evolution in the use of this sort of trait-based methods for the assessment of climate change vulnerability.

7.3. Methodological considerations and further research

There are several methodological challenges in addressing the vulnerability of species to climate change. In a recent study from Wheatley et al. (2017) results showed that different vulnerability assessment methods were not consistent with one another because they consider different input variables and combine and measure those variables in different ways. These aspects present a challenge in sorting out the causes of differences in vulnerability rankings (Comte et al., 2019). In addition, there is a high degree of uncertainty about the relationship between species traits and the impact of climate change as well as the limited baseline knowledge on species ecology to carry out such assessments (Foden et al., 2019; Lankford et al., 2014). Another source of uncertainty is the use of expert elicitation which presents a set of bias such as group thinking (i.e., social pressure to minimize individual separation from the group), overconfidence or conservatism (i.e., overestimating or underestimating uncertainties) or anchoring (i.e., the tendency to anchor subsequent scores around an initial estimate) (Kuhnert et al., 2010; Mukherjee et al., 2015, 2016). There are several recommendations to address such uncertainties, namely the use of multiple experts to provide an estimate of the uncertainty based on the aggregation of multiple responses. Nevertheless, expert elicitation methods can be a powerful tool specially when there is limited data available (Kuhnert et al., 2010).

The number of experts assessing archipelago associated units was limited to two per archipelago while for Macaronesia units the assessment was made by all six experts. Generally, gathering cetacean ecology experts in geographically isolated areas such as islands can be a challenging. While we increased the number of experts from the previous assessment (Sousa et al., 2019) a larger expert group would be beneficial in future assessments.

According to Hare et al. (2016), there will never be a complete agreement between expert-based assessments and more detailed, empirical, or process-oriented assessments or approaches. Wheatley et al. (2017) argued that climate vulnerability assessments should not be used interchangeably. Such assessments of vulnerability are proposed to be used more as scoping studies rather than expecting the clear identification of robust priorities for investment (Comte et al., 2019).

Notwithstanding their limitations, trait-based indexes are valuable tools that can help to rapidly assess many taxa and are able to identify specific areas or species in need of more in-depth studies and analysis (Foden et al., 2019; Pacifici et al., 2015).

The question is then how confident we are in a given assessment and if we are making meaningful interpretations that can be useful for conservation practitioners and policymakers? Considering the results from different assessments, the uncertainty in the perceived vulnerability of species to climate change and the potential impact in conservation management decisions, we provide the following suggestions.

Firstly, the communication of the framework used in the assessment and the associated uncertainties helps to provide the context in which results were obtained (e.g., the factors considered, how they were measured, which species and units were defined, and which study area was considered). An effective communication can support the informed use of results in the definition of adaptation strategies for species (Foden et al., 2019).

Secondly, research and monitoring of cetacean species is of uttermost importance in order to increase our knowledge on species' ecological traits. Baseline data on species ecology will help to identify changes in abundance, distribution and phenology and to validate the frameworks being used in the assessment of future climate change impacts. Trait-based vulnerability assessments, such as the one used in this study, can provide guidance for future monitoring and research studies (Hare et al., 2016).

Lastly, studies have advocated the use of different approaches such as the combination of trait-based methods with distribution modelling (Reside et al., 2019; Silber et al., 2017; Willis et al., 2015) and the use of an ensemble of climate vulnerability assessments and scenario planning exercises to produce an array of potential species responses to climate change (Borggaard et al., 2019; Wade et al., 2017). In this particular study and considering the use of climate scenarios, we have used RCP 8.5 that agrees closely with historical total cumulative CO_2 emissions (within 1% for 2005 to 2020) and is especially useful to inform short to mid-century decision-making (Schwalm et al., 2020). Overall, due to the unpredictability of future emissions and variability in historical emissions trends recommendations are to use a wide range of emission scenarios as input to analyses of future climate change (Pedersen et al., 2020).

8. Conclusion

We have built on the previous work for the Madeira archipelago, by applying a recently developed index and extending the study area of the assessment to Macaronesia, while including a larger poll of experts. This study contributed to the assessment of the vulnerability of cetacean in Macaronesia and to the debate on the comparability and agreement of results from different trait-based vulnerability assessments.

This methodology has the advantage of contributing to a systematic evaluation based on the most relevant sensitivity attributes and exposure factors for species under a changing climate. Additionally, it produces a species vulnerability rank that can, together with its underlying attributes, factors and data quality scores, support conservation and monitoring efforts while considering known uncertainties and knowledge gaps.

Further research should focus on the harmonization and validation of trait-based indexes to increasingly provide more comprehensive assessments. We highlight the importance of trait-based indexes as a valuable exploratory method that can provide insights into which species will most likely be affected by climate change.

CRediT authorship contribution statement

A. Sousa: Conceptualization, Methodology, Writing – original draft, Visualization, Writing – review & editing. **F. Alves:** Formal analysis, Validation, Investigation. **P. Arranz:** Formal analysis, Validation, Investigation. **A. Dinis:** Formal analysis, Validation, Investigation. **M. Fernandez:** Formal analysis, Validation, Investigation. **L. González García:** Formal analysis, Validation, Investigation. **M. Morales:** Formal analysis, Validation, Investigation. **M. Lettrich:** Methodology, Software. **R. Encarnação Coelho:** Software, Project administration, Funding acquisition. **H. Costa:** Visualization, Project administration, Funding acquisition. **T. Capela Lourenço:** Writing – review & editing, Project administration, Funding acquisition. **N.M.J. Azevedo:** Writing – review & editing, Supervision. **C. Frazão Santos:** Writing – review & editing, Supervision.

Declaration of competing interest

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.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2021.148652.

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