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Seismic surveys and marine turtles: An underestimated global threat?

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ABSTRACT

Seismic surveys are widely used in marine geophysical oil and gas exploration, employing airguns to produce sound-waves capable of penetrating the sea floor. In recent years, concerns have been raised over the biological impacts of this activity, particularly for marine mammals. While exploration occurs in the waters of at least fifty countries where marine turtles are present, the degree of threat posed by seismic surveys is almost entirely unknown. To investigate this issue, a mixed-methods approach involving a systematic review, policy comparison and stakeholder analysis was employed and recommendations for future research were identified. This study found that turtles have been largely neglected both in terms of research and their inclusion in mitigation policies. Few studies have investigated the potential for seismic surveys to cause behavioural changes or physical damage, indicating a crucial knowledge gap. Possible ramifications for turtles include exclusion from critical habitats, damage to hearing and entanglement in seismic survey equipment. Despite this, the policy comparison revealed that only three countries worldwide currently include turtles in their seismic mitigation guidelines and very few of the measures they specify are based on scientific evidence or proven effectiveness. Opinions obtained from stakeholder groups further highlight the urgent need for directed, in-depth empirical research to better inform and develop appropriate mitigation strategies. As seismic surveying is becoming increasingly widespread and frequent, it is important and timely that we evaluate the extent to which marine turtles, a taxon of global conservation concern, may be affected.

1. Introduction

Natural underwater sound in marine habitats consists of a combination of acoustic sources, both abiotic and biotic in origin (Au and Hastings, 2008; Hildebrand, 2009). Travelling approximately five times faster in water than in air and covering much greater distances at higher amplitude levels, sound is an efficient method of propagating energy through the marine environment (Hildebrand, 2009; Jung and Swearer, 2011; Bouton et al., 2010). As a result, it is used by many marine organisms to communicate, navigate and locate food (Castellote et al., 2012; Codarin et al., 2009; Janik and Sayigh, 2013; Leis et al., 2011; Bouton et al., 2010). However, noise-generating activities, such as shipping and oil and gas exploration, are transforming the marine soundscape (Compton et al., 2008; Hatch and Wright, 2007). In particular, there is growing concern over the potential impacts of airgun sound emitted during seismic surveys on marine fauna (Lavender et al., 2014; Weir and Dolman, 2007). This method uses sound waves to search for oil and gas deposits beneath the sea bed using cylinders of compressed air (airguns) which are suspended in the water column. The simultaneous firing of these airguns generates bubbles, the expansion and collapse of which creates sound waves (see Figs. 1; A.1 for Glossary). Individual seismic surveys vary enormously in source size, shot interval, operation duration (both the length of individual lines and total operational activity per day) and spatial scale, depending on the type of survey, geographic area and other parameters. However, a 'typical' 3D seismic survey uses a source consisting of 20 to 40 individual airguns that are fired simultaneously at shotpoint intervals of 18.75 or 25 m as the vessel moves along a predetermined line at a towing speed of approximately 4.2 knots. The time taken to complete individual survey lines may be short (<1 h) or may exceed 24 h, but typically is of several hours duration followed by a cessation of operations for 2 to 3 h as the vessel turns to the subsequent line. Seismic surveys may continue within an area for several months when a prospect is particularly large, and sometimes require more than one source vessel operating concurrently.

To date, much of the research on this topic has focused on marine mammals due to their known reliance on sound (Caldwell, 2004; Gordon et al., 2003; Weilgart, 2007). More recently, fish and invertebrates have begun to receive greater levels of attention (André et al., 2011; DeSoto et al., 2013; Lillis et al., 2013; Popper et al., 2005; Radford et al., 2014; Simpson et al., 2015). One important taxon has, however,

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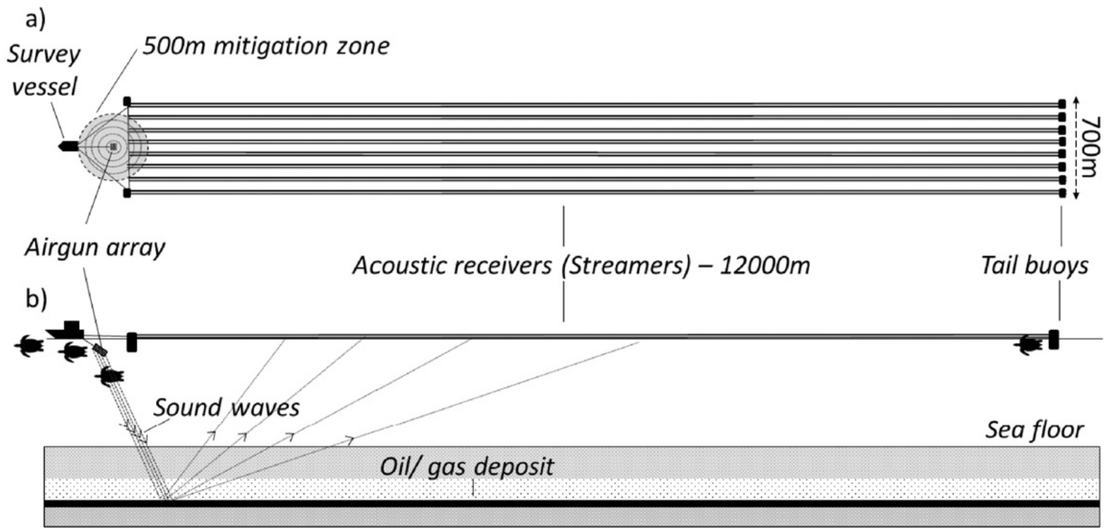

Fig. 1. Schematic showing seismic vessel towing survey equipment and potential impact zones for turtles: a) aerial and b) horizontal views. Not to scale, for illustration purposes only.

so far been over-looked. Seven species of marine turtle are present in nearly all of the world's oceans, occupying a diverse range of habitats throughout their various life-stages (Wallace et al., 2011). Most species are highly migratory, moving periodically between pelagic, neritic and terrestrial environments to forage and breed, often aggregating in key areas (Godley et al., 2010). As a result of the many anthropogenic stressors facing marine turtles, such as fisheries bycatch, habitat loss, climate change, and pollution, they are of global conservation concern.

Acoustic disturbance from seismic survey activities may lead to the interruption of normal behaviours (such as feeding or breeding) and avoidance, leading to displacement from the area and exclusion from critical habitats — an effect that has been documented for a number of cetacean species, particularly mysticetes (baleen whales) and delphinids (Castellote et al., 2012, 2010; Goold, 2009; Richardson et al., 1990; Weller et al., 2002). Additionally, startle responses, such as increased swim speeds and altered dive durations, have been observed in fish and marine mammals (Boeger and Pie, 2006; Robertson et al., 2013) possibly leading to physical damage (and mortality) such as decompression sickness and strandings (Gordon et al., 2003; Jepson et al., 2013; Mann et al., 2010; Wright et al., 2007). A reduction in hearing sensitivity may be observed as a result of damage to auditory organs and structures, such as sensory hair cells (Gordon et al., 2003; McCauley et al., 2003). Noise may also cause stress which in turn can lead to a depressed immune function (Anderson et al., 2011). Bouton et al. (2010) suggested that noise-dependent stress might affect reproductive and growth processes in fish and DeSoto et al. (2013) found that scallop (*Pecten novaezelandiae*) larvae exposed to playbacks of seismic pulses displayed significant developmental delays.

In addition to the noise-induced issues, the firing of airguns during seismic surveys may cause rapid changes in pressure, an occurrence that is known to cause barotrauma in fish, whereby tissues and organs are damaged (Carlson, 2012; Casper et al., 2013; Popper et al., 2014). Another potential risk to turtles is entanglement in seismic equipment, such as tail buoys and their associated attachment materials, towed behind the survey vessel, (Figs. 1 & 2), possibly leading to injuries or mortality (Ketos Ecology, 2009).

Seismic surveys employing airgun arrays have the potential to cause harm to various marine taxa (Gordon et al., 2003; McCauley et al., 2000) yet despite this, there is a lack of knowledge concerning the potential impacts for marine turtles (DeRuiter and Larbi Doukara, 2012; Lavender et al., 2012; Piniak et al., 2012b; Weir, 2007). Given their conservation status, there is a need to assess the degree of threat posed by oil and gas exploration, especially as it is increasing worldwide, both in terms of frequency and distribution (McBarnet, 2014).

The purpose of this study was to: (1) examine the potential effects of seismic surveys on marine turtles, (2) assess the availability and adequacy of current policy (statutory guidelines) and mitigation techniques, and (3) identify areas requiring further research and development. To address these, a mixed-methods approach was employed, involving a systematic review, policy comparison and stakeholder analysis.

2. Materials and methods

2.1. Systematic review

We reviewed all relevant literature with the aim of understanding how seismic surveys may affect marine turtles. Studies carried out on marine mammals and fish were also examined. A broad primary question was formulated: '*What are the potential impacts of seismic surveys on marine turtles*?' This was then broken into a number of components: *behavioural responses to sound*; *physical impacts*; *monitoring* and *the effectiveness of mitigation measures*.

Three separate literature searches were carried out, one for each group of marine animals — *turtles*, *marine mammals* and *fish*. Google Scholar and ISI Web of Science were searched for the terms *seismic*, *airgun*, *noise*, *sound* or *hearing* along with the taxa. The first 100 results were viewed, spurious hits were ignored and all relevant references

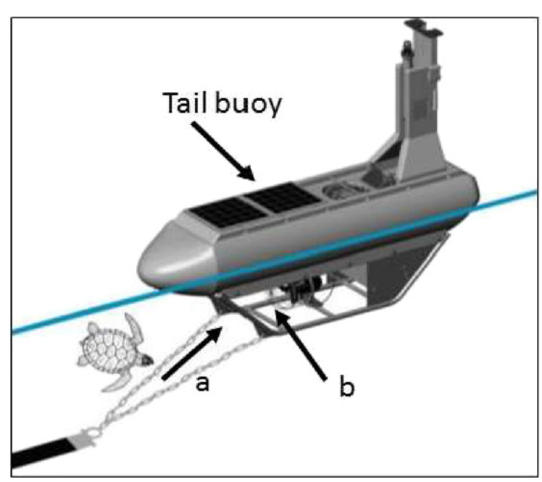

Fig. 2. Schematic of a turtle that has startle-dived in response to an approaching tail buoy. Turtles may become trapped (a) in front of the under-carriage in the area between the buoy and chains or (b) inside the under-carriage structure.

were recorded. For turtles, every article was read in full and the findings collated. The number of references published each year between 1983 and 2013 were recorded and plotted using *R* statistical software (R Development Core Team 2013) to compare the levels of research attention among the taxa.

2.2. Policy comparison

A list of all countries with current statutory mitigation guidelines was obtained through the International Association of Geophysical Contractors (IAGC) website (www.IAGC.org; last accessed 26 June 2014). All guidelines for areas within turtle distribution ranges (71°N to 47°S; Eggleston, 1971, Carriol and Vader, 2002) were obtained and reviewed. They were each compared for their consideration of turtles and the degree of mitigation recommended using similar methods to those used for marine mammals by Weir and Dolman (2007). Note, this does not include measures implemented by individual Environmental Impact Assessments.

2.3. Stakeholder analysis

During the period 1–30 June 2014, an online questionnaire survey (hosted by www.surveymonkey.com; last accessed 1 July 2014) was conducted to investigate three main topics of interest; 1) *attitudes towards degree of threat*, 2) *guidelines and mitigation*, and 3) *research*.

Twenty questions of both open- and closed-responses were developed to encompass a range of elements regarding the seismic industry and marine turtles (see Fig. A.2). Effort was made to avoid wording them in a manner that might lead respondents or bias answers. As such, open-response questions were used where respondents were asked for their opinions. The questionnaire was divided into four sections: 1) *general* (included demographic information such as work sector and location), 2) *guidelines* (only to be answered by respondents who were familiar with mitigation guidelines for their region(s) of activity), 3) *research* (applicable to all respondents), and 4) *offshore observations* (applicable only to those who have experience of working on offshore seismic vessels).

Potential participants were identified by compiling a list of stakeholder groups with an interest in the research question i.e., those involved in the seismic industry and those working with marine fauna, particularly those with knowledge of industry policies and the issues facing marine turtles (Figs. A.3 & A.4). Reviewing literature and communicating with experts aided this process. The stakeholder groups identified were; *government agencies*, *oil and gas companies*, *seismic operators*, *marine mammal observers*, *marine ecologists/consultants*, *conservation NGOs*, *marine turtle scientists/academics* and *marine acousticians.*

Due to the potentially sensitive nature of the survey, it was necessary to allow the respondents to take part anonymously. As such, the questionnaire was emailed to respondents using a uniform resource locator (URL) link which allowed for the identity of the participant to remain undisclosed. To counter any difficulty in attaining an appropriate number of representatives from certain groups through direct contact, snowball sampling was employed, whereby existing contacts were requested to recruit additional participants from among their colleagues and peers (Heckathorn, 2011; Illenberger and Flötteröd, 2012). Open-response answers were manually coded by the same author (SN), whereby key words within the responses were assigned numerical values, to allow for quantitative comparison (see Newing et al., 2011).

3. Results

3.1. Systematic review

During the search process, 29 references were found for marine turtles, the majority of which were peer-reviewed studies (n = 22) but due to the lack of material, some grey literature reports were also included. In comparison, a total of 414 references were recorded for marine mammals and 187 for fish (Fig. A.5), illustrating that these groups have received much greater research attention than marine turtles. The number of studies (concerning the five search terms) published per year for all taxa has generally increased over time (Fig. 3). We discuss the main findings that are specific to seismic surveys and marine turtles below.

3.1.1. Behavioural responses to sound

Behavioural studies fall into two categories: (1) experimental studies using captive animals (n = 4), and (2) observational studies of wild animals (n = 4) (Table 1). A number of experimental studies have found that exposure to sound elicits a behavioural response in turtles. For example, Lenhardt (1994) found that loggerhead turtles

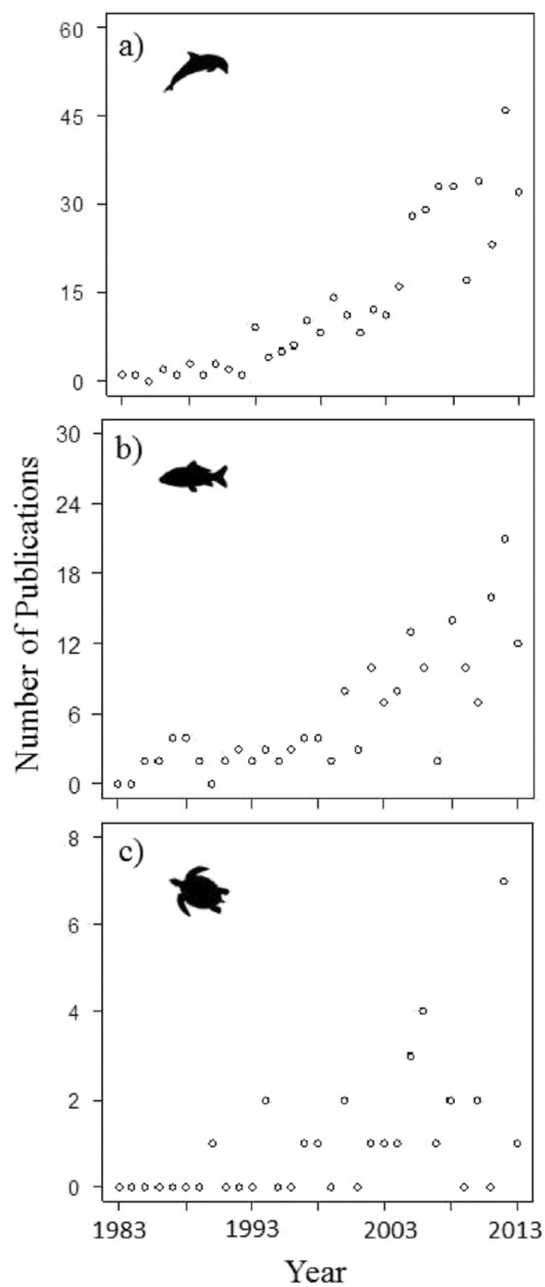

Fig. 3. Number of publications per year (between 1983 and 2013) returned from literature search using the five search terms (seismic, airgun, noise, sound and hearing) for: a) marine mammals, b) fish, and c) turtles. Note different scales on y-axes.

Table 1
Summary all of turtle behavioural studies found through systematic review process.

Species	Location	Method	Setting	Sample size	Result	Constraints	Source
Caretta caretta	USA	Experimental	Captive (turtles of wild origin)	9	Inconclusive	Confined setting – results cannot be applied to open-water situations	O'Hara and Wilcox, 1990
	USA	Experimental	Captive	10	Turtles showed avoidance during initial trials but then apparent habituation behaviour	Confined setting – results cannot be applied to open-water situations	(Moein et al., 1994)
	USA	Experimental	Captive	2	Both turtles always responded to low frequency sound by swimming. No animal returned to the bottom or stopped swimming	Small sample size. Confined setting – results cannot be applied to open-water situations	Lenhardt, 1994
	Mediterranean sea (off Algerian coast)	Observational (at-sea)	Wild	164	Of the 86 turtles whose dive behaviour were observed 57% dove and 43% did not	No controls for effects of vessel presence	DeRuiter and Larbi Doukara, 2012
Caretta caretta & *Chelonia mydas*	Australia	Experimental	Captive	2	Turtles displayed 'alarm' response at an estimated 2 km from an operating seismic vessel and behaviour indicative of avoidance estimated at 1 km	Small sample size. Confined setting – results cannot be applied to open-water situations	McCauley et al., 2000
Chelonia mydas & *Eretmochelys imbricata*	Brazil	Observational (at-sea)	Wild	16	Inconclusive	Limited sampling window and small sample size	Gurjão et al., 2005
Dermochelys coriacea	Trinidad	Bio-logging technology	Wild	3	Inconclusive	Small sample size and technical difficulties	Eckert et al., 1998
Lepidochelys olivacea, *Dermochelys coriacea*, *Caretta caretta* & unidentified	Off Angolan coast	Observational (at-sea)	Wild	240	Inconclusive	No controls for effects of vessel presence	Weir, 2007

(*Caretta caretta*) exposed to low frequency sound in a tank responded by swimming to the surface and remaining there or staying slightly submerged, possibly because received sound levels were lower at the surface. McCauley et al. (2000) observed caged green (*Chelonia mydas*) and loggerhead turtles while they were exposed to increasing levels of sound generated by airguns. Turtles noticeably increased their swim speed when airgun levels exceeded 166 dB re 1 μPa rms. Their behaviour became more erratic, potentially indicating that they were in an agitated state, when airgun levels increased to above 175 dB re 1 μPa rms. Experimental studies, however, are often carried out in artificial surroundings and as such, the results may not be representative of real, open-water situations where the propagation of sound differs and the turtle is able to move away (Lenhardt et al., 1994; O'Hara and Wilcox, 1990).

Turtle behaviour is difficult to interpret (DeRuiter and Larbi Doukara, 2012) and many observational data are often somewhat qualitative. This makes comparing response results among studies problematic. For example, observations from one seismic survey reported no signs of panic or distress and "behaviour consisted of either 'steady swimming' or 'diving' to avoid the vessel" (Pendoley, 1997). However, similar studies have categorised diving as a potential startle response or avoidance behaviour. A promising approach was employed by Eckert et al. (1998) who sought to use bio-logging technologies to measure leatherback (*Dermochelys coriacea*) turtle movements at sea in response to airgun sounds. Unfortunately, technical problems meant that only limited data were gathered and no quantitative examination of turtle responses was possible. The validity of the method, however, stands.

Aside from issues with interpreting behaviour, in-situ observational studies often encounter additional limitations including difficulties in visually detecting animals (due to sea conditions and the small amount of time turtles spend at the surface) and issues distinguishing between the effects of airgun sound versus presence of the survey vessel (Weir, 2007). For example, in a study where turtle responses were observed during a seismic survey, a lack of controls meant that it was not possible to determine whether the behaviour observed was due to sound exposure or the presence of the vessel and towed equipment (DeRuiter and Larbi Doukara, 2012).

3.1.2. Physical impacts

Studies measuring turtle hearing sensitivity have found that all species investigated (loggerhead, green, leatherback and Kemp's ridley; *Lepidochelys kempi*) are able to detect low frequency acoustic stimuli (Bartol and Ketten, 2006; Lavender et al., 2012; Martin et al., 2012; Moein et al., 1994; Piniak et al., 2012b; Ridgway et al., 1969), indicating that their hearing ranges overlap with the peak amplitude, low frequency sound emitted by seismic airguns (10 Hz–500 Hz; Parente et al., 2006; Stone and Tasker, 2006; DeRuiter and Larbi Doukara, 2012). Whether airgun sound has the potential to cause hearing damage remains to be investigated, as do any subsequent ecological effects.

Although underwater explosions have the potential to cause tissue damage and can be lethal to some marine fauna (Gordon et al., 2003), only a single study looked specifically for evidence of turtle mortality due to seismic surveys (Gurjão et al., 2005). A marine and terrestrial monitoring programme recorded 16 observations of turtles (eight alive observed in the sea, and eight dead, four of which were in the sea and four stranded on land). Of the dead turtles, five showed signs of interactions with fishing activities/human consumption of turtle meat (Gurjão et al., 2005). The authors do not suggest what may have caused the deaths of the remaining three nor do they specify whether further investigation into the cause of death (such as necropsies) was carried out. No link with the seismic survey was confirmed.

In addition to damage from airgun sound, a further potential physical impact for sea turtles from seismic surveys is entanglement in equipment, either towed by a vessel (Fig. 1) or deployed on the seabed (Weir, 2007). While no peer-reviewed literature documenting such incidences

Table 2
Summary of all mitigation guidelines examined during policy comparison.

Location	Includes turtles?	Duration of pre-shoot watch	Soft start/ramp-up	Mitigation/exclusion/safety zone (m)	Soft-start delay for turtle(s) within mitigation zone	Airgun shut-down for turtle(s) within mitigation zone?	Night-time/poor visibility airgun use	Time/area restrictions?
Australia	No	–	–	–	–	–	–	–
Brazil	Yes	30 min	20–40 min	Safety area of 500 m and warning area between 500 m and 1000 m	30 min	Yes	Not allowed to *start* shooting air guns	Yes
Canada	Yes[a]	30 min	Minimum of 20 min	500 m	30 min	Yes[a]	Recommends PAM for detecting cetaceans. No recommendations for turtles	Yes[a]
Ireland	No	–	–	–	–	–	–	–
New Zealand	No	–	–	–	–	–	–	–
UK	Yes[b]	30 min	20–40 min	500 m	20 min	No	Recommends PAM for detecting cetaceans. No recommendations for turtles	None
USA (Gulf of Mexico)[c]	Yes	30 min	20–40 min	500 m	30 min	No	Prevents ramp-up if minimum source level drops below 160 dB re 1 μPa-m (rms)	None

[a] Specifies only those listed on Schedule 1 of the 'Species at Risk Act' — leatherback turtles.
[b] Designed for marine mammals but states 'whilst the appropriate mitigation may require further investigation, the soft-start procedures for marine mammals would also be appropriate for marine turtles and basking sharks'.
[c] These mitigation measures apply to geophysical activities conducted under lease terms, for all seismic survey operations conducted in waters deeper than 200 m (656 ft).

was encountered during the literature search, the authors have received anecdotal reports (unpublished) of turtle entrapments in tail buoys (Fig. 2) and airgun strings during several offshore seismic surveys off the west coast of Africa. Additionally, a recent incident where eight olive ridley turtles (*Lepidochelys olivacea*) became entangled in Ocean Bottom Cable (OBC) gear off Gabon has been reported in the media.

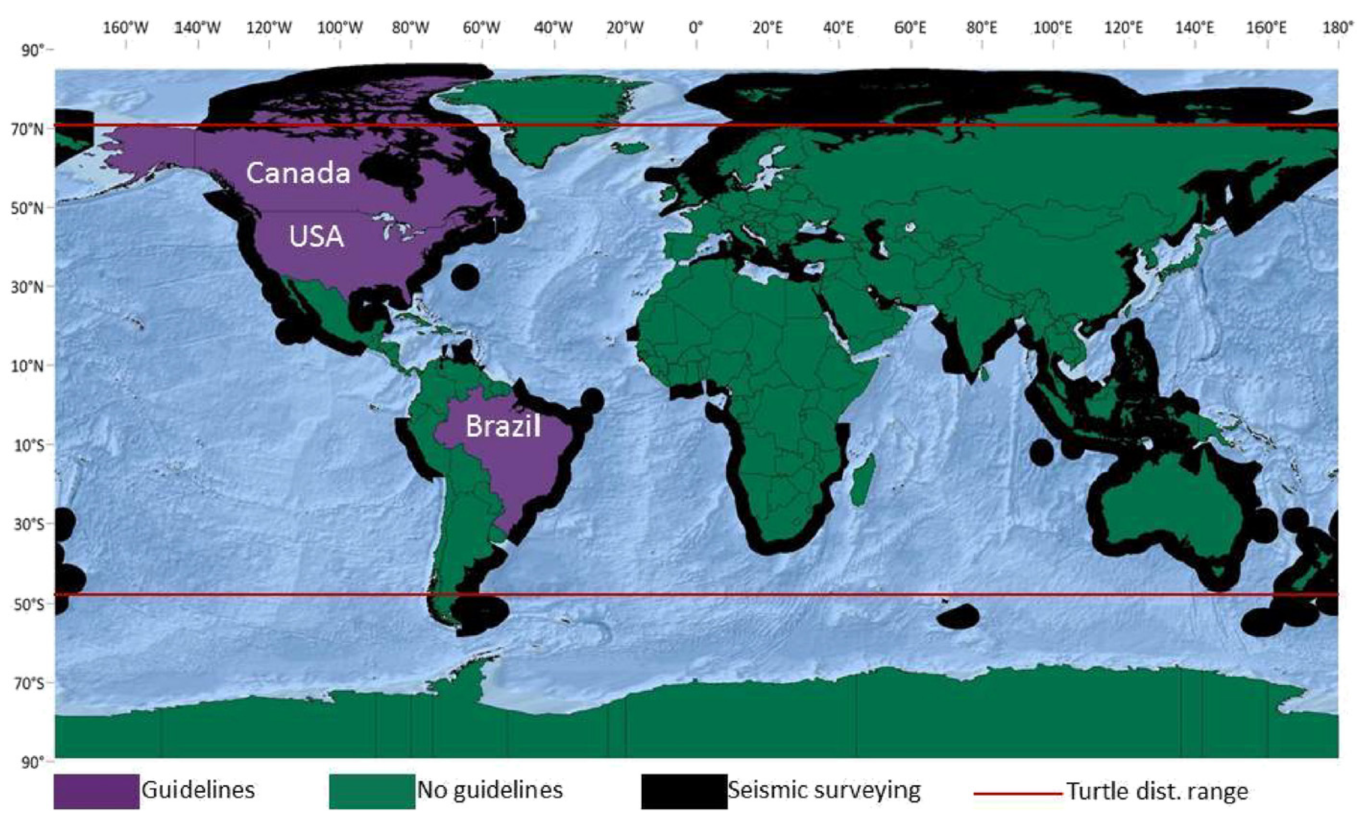

Fig. 4. Global presence of turtle-specific mandatory mitigation guidelines in relation to the distribution of oil and gas exploration (www.offshore-technology.com/projects) and turtle distribution ranges (71°N to 47°S; Eggleston, 1971; Carriol and Vader, 2002). Countries whose guidelines include turtles are Brazil, Canada and USA. Black areas show exclusive economic zones (EEZ) of countries who allow oil and gas exploration in their waters (n = ~50), 47 of which do not consider turtles in their mitigation guidelines (Algeria, Angola, Argentina, Australia, Azerbaijan, Bermuda, Bulgaria, China, Congo, Cote d'Ivoire (Ivory Coast), Denmark, Egypt, Equatorial Guinea, Gabon, Germany, Ghana, Greece, India, Indonesia, Iran, Ireland, Israel, Italy, Kazakhstan, Malaysia, Mauritania, Mexico, Mozambique, Myanmar, Namibia, Netherlands, New Zealand, Nigeria, Norway, Peru, Philippines, Qatar, Russia, Saudi Arabia, South Africa, Tanzania, Thailand, Tunisia, Turkey, United Arab Emirates, United Kingdom, and Venezuela). Note: does not depict exact location of exploration or amount of area covered — illustration only.

3.1.3. Monitoring and the effectiveness of mitigation

We were unable to locate any studies that evaluated the effectiveness of mitigation measures (see Section 3.2 for types of measures) put in place to protect turtles. However, three studies have been published using data collected by observers on seismic vessels that were relevant to assessing whether visual methods are an effective manner of detecting turtles in order to implement real-time mitigation measures. Three out of eight turtles observed by Gurjão et al. (2005) were recorded at distances of 6–8 m from the ship (the distances to the others were not stated). Parente et al. (2006) noted that most of the 46 sea turtle sightings off Brazil occurred within 50 m of the ship and in 'calm' sea conditions. For 240 turtle sightings off Angola, Weir (2007) reported that detection rates was significantly higher during very calm sea conditions of Beaufort 0 or 1 and noted that visual detection was ineffective in Beaufort sea states >1. A review by Fisheries and Oceans Canada revealed that the difficulties of visually detecting turtles means that mitigation measures that are designed for marine mammals (but applied to turtles) may not be effective, highlighting the need for a full examination of their efficacy (DFO, 2004).

3.2. Policy comparison

At the time of writing, seven (14%) of the approximately 50 countries who allow seismic surveys in their waters have developed mandatory mitigation guidelines relating to marine wildlife, comprising Australia, Brazil, Canada, Ireland, New Zealand, United Kingdom (UK) and the United States of America (USA; Gulf of Mexico). These were examined and compared for a number of criteria (below) (see Table 2).

3.2.1. Inclusion of turtles

Only three (6%) countries who allow seismic testing in their waters have developed mandatory mitigation guidelines which include turtles (Fig. 4). These are Brazil (IBAMA, 2005), Canada (DFO, 2007) and USA (BOEM, 2012). The Brazilian and USA guidelines include all turtle species (although USA guidelines are only applicable to the Gulf of Mexico (Outer Continental Shelf Region) and turtles are exempt from some mitigation measures — see below). The Canadian guidelines make recommendations only for turtle species listed as endangered or threatened on Schedule 1 of the Species at Risk Act (leatherback turtles). Additionally, the UK's guidelines (JNCC 2010) make a generalised statement acknowledging that "…other protected fauna, for example turtles, will occur in waters where these guidelines may be used" and that "…whilst the appropriate mitigation may require further investigation, the soft-start procedures for marine mammals would also be appropriate for marine turtles…". However, no mandatory mitigation measures for turtles are included by JNCC (2010). Comments referring to 'all guidelines' beyond this point pertain only to those three sets of guidelines that specifically include mitigation measures for marine turtles.

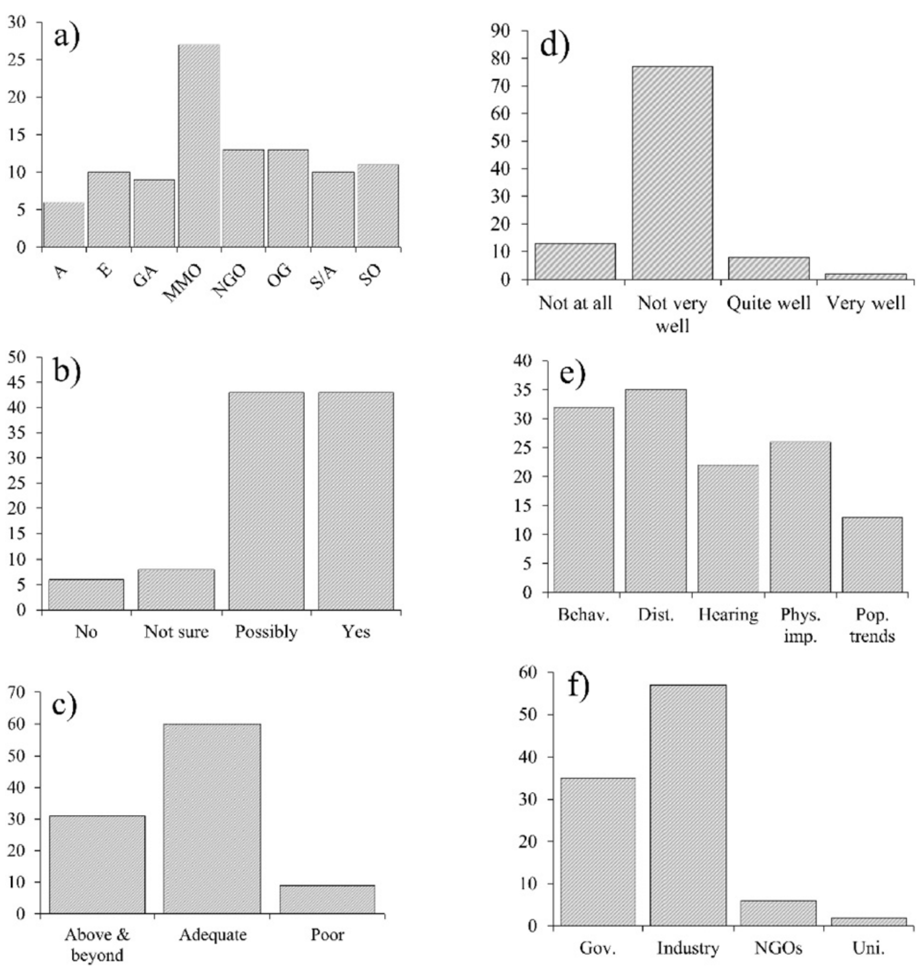

Fig. 5. Responses from stakeholder questionnaire survey; a) percentage of survey participants from each stakeholder group (A = acoustician, E = ecologist/consultant, GA = government agency, MMO = marine mammal observer, NGO = non-governmental organisation, OG = oil and gas company, S/A = scientist/academic, SO = seismic operator); b) percentage of participants who answered 'Yes', 'Possibly', 'No' or 'Not sure' when asked if seismic surveys could pose a threat to turtles; c) percentage of participants who selected 'Poor', 'Adequate' or 'Above and beyond' when asked how well the seismic industry complies with recommended mitigation measures; d) percentage of participants who selected 'Not at all', 'Not very well', 'Quite well' or 'Very well' when asked how well understood are the impacts of seismic operations on turtles; e) the frequency of the top five research topics as suggested by the participants: distribution, behaviour, physiological impacts, hearing and population trends; f) percentage of participants who felt that governments, industry (seismic operators/oil and gas companies), NGOs and universities should fund research into the impacts of seismic surveys on turtles.

3.2.2. Pre-shoot watch

All guidelines recommend a pre-shoot watch period of 30 min to allow for a visual search for turtles by marine mammal observers (MMOs). However, none offer mitigation for turtles at night when visual watches are not viable.

3.2.3. Soft-start/ramp-up

All guidelines specify that soft-starts should last for a minimum duration of 20 min, to provide marine organisms with the opportunity to leave the vicinity of the airguns before full power is reached. All except Canada recommend a maximum soft start period of 40 min to minimise the duration of airgun sound in the marine environment.

3.2.4. Mitigation/exclusion/safety zone

All guidelines recommend a zone around the airguns of 500 m in which mitigation measures should be implemented if a marine turtle is sighted. The Brazilian guidelines also recommend an additional 'warning area' that has a 1 km radius around the seismic source.

3.2.5. Soft-start delay

All three recommend a delay to gun use of 30 min if an animal is observed within the 500 m mitigation zone prior to airguns firing. The Brazilian guidelines define a 1000 m zone for delays to soft start.

3.2.6. Shut-down

Brazilian guidelines state that if a turtle enters the 500 m safety zone, firing should be suspended immediately. Canadian guidelines state that operations must be shut down immediately if the safety zone is entered by: i) a turtle listed as endangered or threatened on Schedule 1 of the Species at Risk Act (leatherbacks); or ii) a turtle species that has been identified by the Environmental Impact Assessment process as being adversely affected by the operations. Guidelines for the USA Gulf of Mexico (GoM) only require a shut-down for whales and no shut-down is implemented for turtles.

3.2.7. Night-time/poor visibility airgun use

No guidelines prohibit airgun use during the hours of darkness or poor visibility when turtles are unlikely to be visually detected. Both the Brazilian and USA GoM guidelines recognise the difficulties of monitoring the mitigation zone in these situations and so do not allow start-up of airguns during darkness or inclement weather. However, both allow night-time power downs (to sound levels of 160 dB re 1μPa-m) during line changes to avoid delays to shooting while waiting for daylight, followed by a gradual ramp up back to full volume. Canada requires the use of passive acoustic monitoring (PAM) to allow for acoustic detection of vocalising marine mammals when the full mitigation zone is not visible but makes no recommendations with regard to turtles.

3.2.8. Operational stoppages in gun use

Airguns may be temporarily deactivated for maintenance or operational purposes. The Brazilian guidelines state that any breaks in firing longer than 5 min duration will require a full 20 min soft start. The USA GoM guidelines allow guns to resume at full power after breaks in firing of up to 20 min, on condition that visual observations have been maintained and no turtles seen. The Canadian guidelines require a full soft start unless a single source element (this is not defined) is kept activated and a visual watch for animals maintained (and none seen within the mitigation zone).

3.2.9. Time–area closures

Only the Brazilian guidelines make relatively clear and specific recommendations for avoiding sensitive areas and times of year by advising that those planning seismic surveys should consult scientific literature and industry guidelines for information on species distributions. The surveys should then be planned "to avoid overlapping the reproduction periods". The Canadian guidelines also recommend consideration for spatio-temporal sensitivities. They do not, however, specify how operators should access this information.

Where no guidelines exist for turtles, some seismic companies voluntarily implement 'turtle pauses' (also known as 'shot pauses') in order to provide some short-term relief for turtles observed close to an airgun array. They are a temporary cessation of firing for a small number of shots (typically around 8), calculated to remain within survey specification and avoid loss of production. However, this measure is not recommended by any statutory guidelines and its effectiveness has not been investigated.

3.3. Stakeholder analysis

3.3.1. Response rates and demographics

From 125 invitations, 89 full-survey responses were received. However, it is not possible to determine how many of those contacted took part in the questionnaire due to the anonymous nature of the survey and the employment of snow-ball sampling. The proportion of respondents from each stakeholder group is shown in Fig. 5a. In terms of locality, there was a heavy bias towards respondents based in Europe (50%) and North America (28%) followed by Africa (6%), Australia (6%), the Middle East (5%), Central America and the Caribbean (2%), South America (2%) and Asia (1%).

3.3.2. Attitudes towards degree of threat

When asked if seismic activity could pose a threat to turtles, the majority (86%) of the 70 participants answered "yes" or "probably" (Fig. 5b). The most common themes that emerged when respondents were asked to explain their answers to this question were; *potential impacts* ($n = 33$) (such as *physiological damage* ($n = 9$), *damage to hearing* ($n = 8$), *entrapment with survey equipment/collisions with vessels* ($n = 8$), *behavioural changes* ($n = 5$) and *exclusion from habitat* ($n = 3$)) and the *need for further information on impacts and effectiveness of mitigation measures* ($n = 6$). When the respondents who said they have experience of working offshore ($n = 36$) were asked whether they have ever witnessed a turtle being impacted during survey operations, 42% answered 'Yes'. Those who answered 'Yes' were asked to provide a description of their observations. Responses included; *dead turtles* (cause not specified) ($n = 5$), *behavioural responses* ($n = 4$) and *entrapment/collision with survey equipment* ($n = 4$).

3.3.3. Adequacy of guidelines and mitigation

Of the respondents who said they were familiar with the guidelines concerning seismic surveys and marine fauna for their region(s) of activity, 61% felt that the recommended mitigation measures were not adequate for minimising the impact on turtles (excluding those who said they were unsure). This proportion featured representatives from all of the stakeholder groups, but the largest proportion (30%) were MMOs. The most common reason given was the *difficulty of visually detecting turtles at sea* ($n = 10$), especially at night or in bad weather. The advantages and disadvantages of turtle pauses were also discussed ($n = 8$) with the majority ($n = 6$) against their implementation. Other topics such as the *general inadequacy of mitigation measures* ($n = 6$), *lack of evidence and need for further research/monitoring* ($n = 6$) and the *benefits of soft-starts* ($n = 2$) were also articulated. When asked which of the mitigation measures were most effective, *time–area closures* were most frequently selected ($n = 50$). Followed by *soft start/ramp up* ($n = 39$), *delay soft-start* ($n = 37$), *shut down operations if turtle enters mitigation zone* ($n = 32$), *prevent operating at night or during bad weather* ($n = 27$) and finally, *turtle (shot) pauses* ($n = 19$).

Most respondents felt that the industry generally complies well with recommended mitigation measures as specified by the regional guidelines, with the majority selecting '*adequate*' or '*above and beyond*' when questioned (Fig. 5c). However, some respondents felt that compliance levels vary ($n = 5$). Examples given of 'above and beyond' compliance include the implementation of voluntary measures such as '*turtle/shot pauses*' (n = 4). For areas where no turtle-specific guidelines exist, respondents were asked what they feel should happen in terms of mitigation. The primary response was to provide specific measures. These were; *delay soft-starts for turtles* (n = 6), *time–area closures* (n = 5), *shot pauses* (n = 5), *shut down for turtles* (n = 3), *no firing at night* (n = 3), and *turtle guards* (n = 3). A secondary response was to discuss policy development. Specifically, the need for *developing international guidelines to be used as* '*best practise*' (n = 5) and the possibility of *forming new guidelines using pre-existing recommendations* (n = 4). Some suggested *implementing JNCC guidelines* (n = 3) and the same number stated that *turtle-specific guidelines should be developed* (n = 3).

3.3.4. Research

The majority of respondents felt that the impacts of seismic operations on turtles are not very well understood (Fig. 5d). To identify how this might be improved, the respondents were asked to list five topics requiring further research. *Turtle distribution* (n = 35) was the most mentioned research topic, followed by *behaviour* (n = 32), *physiological impacts* (n = 26), *hearing* (n = 22) and *population trends* (n = 13) (Fig. 5e). Other, less common, research topic suggestions included; *entanglement in survey equipment/effectiveness of turtle guards* (n = 5), *bio-logging technologies* (n = 4), *methods of detecting turtles* (n = 5), *autopsy/post mortem* (n = 3), *education* (n = 2), *impacts on different age classes/species* (n = 1) and *modelling of seismic sound propagation* (n = 1). In terms of who should fund this research, most respondents felt that the *industry* (*oil and gas companies/seismic operators*; 57%) should be responsible. Other possible funding sources included *governments* (35%), *environmental organisations/NGOs* (6%) and *universities* (2%) (Fig. 5f).

The respondents were asked, to their knowledge, *what currently happens to observational turtle data collected by MMOs during seismic surveys*? Although many people were *unsure* (n = 12), the most common response was that data are *reported to regulators/government agencies* (n = 14). Other frequently stated answers included *filed/archived* (n = 12) and *nothing/very little/unused* (n = 10). When asked what they would like to see happen to it, the most popular answers were: *collated, analysed and published* (n = 17); *available in a central database* (n = 15); *available to the scientific community and conservation NGOs* (n = 10); *used for further research* (n = 7); *used to develop protocols and inform management decisions* (n = 3); *no change needed, current system is adequate* (n = 3). In terms of the constraints affecting these processes, the most common reasons stated were; *industry ownership of data/intellectual property rights* (n = 21) and *lack of resources* (*funding and time*) (n = 19). *Inaccuracy and lack of turtle data* (i.e. poor species identification and low sample sizes) were also frequently mentioned (n = 11) as well as *lack of cooperation from the industry* (n = 9).

4. Discussion

4.1. Systematic review

The literature review confirmed that marine turtles have received very little research attention when compared to marine mammals and fish. Indeed, historically, turtles were thought to be deaf (Piniak et al., 2012b). However, studies using electrophysiological and behavioural techniques have found that they can detect frequencies between 50 Hz and 1600 Hz (Bartol and Ketten, 2006; Lavender et al., 2014; Martin et al., 2012; Piniak et al., 2012a), indicating that their hearing ranges overlap with the peak amplitude, low frequency sound emitted by seismic airguns (10–500 Hz; Bartol et al., 1999; DeRuiter and Larbi Doukara, 2012; Parente et al., 2006; Stone and Tasker, 2006). Their hearing ability allows them to perceive important biological signals, the proposed functions of which include predator avoidance, navigation, communication and the identification of nesting beaches (Eckert et al., 1998; Ferrara et al., 2014; Lenhardt, 1994; Martin et al., 2012; Piniak et al., 2012a; Ridgway et al., 1969). Hearing damage may lead to a reduced ability to avoid natural and anthropogenic threats, such as fisheries by-catch and vessel collisions, which are major sources of turtle mortality (Hazel and Gyuris, 2006; Wallace et al., 2010). However, due to a lack of research, it is not known what levels of sound exposure (or frequencies) would cause permanent or temporary hearing loss or what effect this may have on their fitness or survival (DeRuiter and Larbi Doukara, 2012).

In addition to potential hearing damage, airgun sound has been found to affect the behaviour of some other marine organisms (Cerchio et al., 2014; Dilorio and Clark, 2010; Fewtrell and McCauley, 2012) with unknown long-term consequences (Gordon et al., 2003). In turtles, acoustic disturbance could potentially lead to exclusion from key habitats, interruption of behaviours, such as those necessary for breeding, foraging or thermoregulation (basking), as well as inciting responses which may compromise their energy budgets, such as changes to foraging duration, swim speed, dive depth and duration, and restricting access to the surface to breath (DeRuiter and Larbi Doukara, 2012). Such alterations may lead to a reduction in individual fitness (through changes to reproductive outputs or foraging rates), potentially causing detrimental effects at a population level (Hall, 2013). Captive experimental studies show that turtles display avoidance and startle responses when exposed to impulse sounds (Lenhardt, 1994; McCauley et al., 2000) but a number of limitations have meant that at-sea observational studies have been unable to confirm whether this occurs in the wild (DeRuiter and Larbi Doukara, 2012; Parente et al., 2006; Pendoley, 1997; Weir, 2007).

It is difficult to observe a direct causal link between physical damage and anthropogenic noise in wild marine animals. A number of studies have suggested a relationship between cetacean and cephalopod strandings and anthropogenic noise (André et al., 2011; Engel et al., 2004; Jepson et al., 2013) and one study reported an observation of a pantropical spotted dolphin (*Stenella attenuata*) apparently exhibiting 'aberrant behaviour' in the proximity of operating airguns (Gray and Van Waerebeek, 2011). However, no literature was found with respect to turtles. Additionally, only one study commented on the potential issue of turtles becoming fatally trapped in survey equipment (Weir, 2007). For seismic surveys in areas where aggregations of turtles occur (such as in proximity to nesting beaches or key foraging areas), entrapment could pose a significant threat.

In summary, the potential effects of seismic surveys on marine turtles are diverse and sometimes cryptic. This, coupled with a lack of research, makes understanding the impacts on individuals difficult and the implications for populations almost impossible to decipher. In addition, frequency and duration of exposure to seismic surveys are not discussed in the literature, a topic that is clearly important when determining the level of risk to turtles.

4.2. Policy comparison

Although offshore oil and gas exploration is occurring in the waters of at least 50 countries worldwide (www.offshore-technology.com/projects; last accessed 13 July 2015), regulation at governmental level is lacking. Very few countries have developed mitigation guidelines to minimise the impacts on marine life and only three (6%) of these include specific mitigation measures for turtles.

Of the guidelines examined here, it is surprising that Australia and New Zealand do not consider turtles, particularly as six of the seven species occur in their waters (Gill, 1997; Pendoley, 1997). As leatherback turtles occur in both UK and Irish waters (Doyle, 2007; Witt et al., 2007) and are listed as a European Protected Species (Annexes II and IV of the European Habitats Directive), it would seem appropriate to include them in the development of future guidelines. Statutes and policies, such as the Endangered Species Act in the USA and the Environment Protection and Biodiversity Conservation Act in Australia, may require mitigation to be implemented but measures are usually recommended on a case-by-case basis. Additionally, environmental legislation often has a broad application, usually at population or species level, whereas most mitigation guidelines are specifically aimed at reducing local impacts on individuals/groups of animals. This mis-match indicates a possible source of inconsistency that may result in mitigation recommendations that are unsuitable.

During seismic surveys, visual detection is the most widely-used method of monitoring the mitigation zone for marine fauna and currently represents the only feasible method of detecting turtles (Compton et al., 2008). However, as highlighted by Weir (2007), observing turtles at the surface is unreliable in sea states above Beaufort 1 and detection rates decrease with increased distance from the vessel. Additionally, it is currently not possible to detect turtles below the surface where they might be most vulnerable due to the proximity of the seismic source and other survey equipment (Weir, 2007). As turtles spend the majority of their time subsurface (Hazel and Gyuris, 2006), detection range is low, and calm sea conditions may comprise only a low percentage of the total duration of offshore seismic surveys (Weir, 2007), clear limitations of relying on visual methods to detect turtles exist. Furthermore, the detection of turtles relies on human effort (diligence, skills and concentration), which is subjective and inevitably varies among MMOs, many of whom have little previous experience of detecting and identifying turtles at sea. According to Parente et al. (2006), a lack of training and field experience has a direct impact on the adequacy of mitigation measures implemented. In addition, sources of bias (such as, perception and availability; see Fuentes et al., 2015) may also affect the reliability of observational data and are not usually accounted for by policy. One further important, but mostly unrecognised, issue is that the 500 m or 1000 m radius mitigation zones are simply too extensive for turtle detection to be viable. In modern 3D and 4D seismic surveys, the size of the seismic spread (with the airgun source located several hundred metres astern of the ship) means that a 500 m mitigation zone may be located entirely astern of the ship's bridge where the MMO is typically located (Fig. 1). Effective visual detection of turtles is predominantly limited to within tens of metres of an observer (Parente et al., 2006). However, the furthest part of a 500 m mitigation zone may be some 1000 m astern of the MMO. The potential to visually detect sea turtles anywhere other than in the nearest part of the mitigation zone to the MMO's vantage point is very low.

The three sets of turtle-inclusive guidelines all recommended a 500 m mitigation zone for turtles. However, the appropriateness of this radius in terms of offering protection to turtles is unknown. As noted by Weir and Dolman (2007), defining the radius of a mitigation zone is a fundamental component of the real-time mitigation measures used during seismic surveys, but in most regional guidelines no scientific rationale is provided to support the chosen radius. An appropriate mitigation zone for turtles should take into account data on emitted and received sound levels, turtle hearing ranges and information on the sound levels that are injurious to a sea turtle. However, at present all of this information is lacking. Consequently, the mitigation zones adopted for turtles have simply been selected as the same as those used for marine mammals, and their effectiveness for minimising the potential impacts on turtles from airgun sound is unknown.

Most guidelines recommend a pre-shoot watch of 30 min but whether this is appropriate for turtles has not been evaluated. Some Chelonid species are known to make long resting dives of more than 7 h during the colder months and the longest reported dive duration for leatherbacks is 83.8 min (Fossette et al., 2008; Hawkes et al., 2007). It is therefore unlikely that a 30 min watch duration would detect a high proportion of such animals. Even under normal circumstances, turtles may spend 80% of their time submerged below the water during routine foraging behaviour (Hazel et al., 2009) and therefore are simply not available to a visual observer for the majority of a pre-shoot watch irrelevant of its duration.

Currently, there is no way of detecting turtles at night or in poor weather conditions. The use of PAM is becoming a common method of detecting vocalising marine mammals and many guidelines recommend it either as a requirement or to be used on a trial basis. But as turtles are not known to vocalise (except as hatchlings; Ferrara et al., 2014), PAM cannot be used for their detection. Alternative potential methods of detection (all of which need to be trialled on sea turtles) include night-vision binoculars and heat-sensing cameras (such as thermo-graphic infrared scanners; Weir and Dolman, 2007, Compton et al., 2008, Boebel and Zitterbart, 2013). These methods, however, are designed for large, warm-blooded mammals and are not necessarily suitable for reliably detecting turtles which may emit little heat at the surface.

Although a standard recommendation in most guidelines, the soft-start method and its usefulness as a mitigation measure for marine mammals (for which it was designed) is viewed as a ‘common sense’ measure (Compton et al., 2008; Weir and Dolman, 2007). Nothing is known about how turtles may react and there is little information regarding whether it evokes the appropriate response. For example, turtles may move vertically rather than horizontally (by surfacing or diving), making them more vulnerable to acoustic exposure as well as other impacts that have been suggested for marine mammals, such as decompression sickness and/or increased likelihood of entanglement in survey gear (García-Párraga et al., 2014; Parsons et al., 2009).

A 30 min delay to the soft start for turtle sightings within the mitigation zone was recommended by three sets of guidelines. This delay period is also applied to marine mammals, although the basis for defining that time period is not stated. However, sea turtles may be less mobile than marine mammals, especially given their metabolic differences. In particular, basking turtles may be very slow to respond (if at all) to an approaching ship, reducing their ability to avoid a seismic operation (DeRuiter and Larbi Doukara, 2012; Weir, 2007). The appropriateness of a 30 min delay is therefore unclear and requires further investigation, particularly regarding the effects on turtle swim speeds and directions (vertical and horizontal). Additionally, the vessel tow speed (taking into account that a vessel may slow to minimum speed in the event of a mitigation event) and the size of the mitigation zone are crucial factors in calculating the appropriate length of delay to ensure that a turtle is no longer within the mitigation zone when airgun use resumes, and should be considered on a survey-specific basis.

Currently, only two sets of guidelines (Brazil and Canada) require a shut-down when the mitigation zone is entered by a turtle. Given that the mitigation zone is intended to protect animals from injurious sound levels, a shut-down would seem to represent a suitable precautionary measure. The appropriate duration of the shut-down period should be considered carefully in relation to vessel tow speed and the size of the mitigation zone, as described previously. This is especially important because it is unlikely that turtles will be visually tracked outside of the mitigation zone in practise (due to their short surfacing period and the significant problems in visually detecting them over large distances).

In areas where shut-downs are not required by guidelines, some operators implement a voluntary ‘turtle pause’. However, the effectiveness of this measure has not been investigated. We advise against the use of a ‘turtle pause’, given its short duration (typically around 8 missed shots) and therefore the high potential for error in its implementation. The shot-point interval of a typical 3D seismic survey is either 18.75 m or 25 m, which equates to time intervals of 8.7 and 11.6 s respectively at a typical tow speed of 4.2 knots (2.16 m/s). Eight missed shots (which is likely to be the maximum possible) equates to total ‘pause’ distances of only 150 m (69 s) and 200 m (93 s) respectively. For a pause to provide any protection to a turtle over such a short distance would therefore require the guns to be stopped exactly 75 or 100 m ahead of a turtle and then resumed again at the same distance on the other side. This would require an extremely high level of coordination between MMOs and the seismic crew, and a very well-judged decision by the MMO as to when the guns should be switched off. Given that the guns may be several hundred metres astern of the MMO's vantage point, and that a turtle may well be subsurface and its whereabouts unknown at the time a pause is implemented, it is clear that there are inherent limitations to this procedure and there is a risk of restarting guns at full volume with the turtle in immediate proximity.

Due to the constraints affecting turtle detection during surveys, time–area closures designed to avoid critical habitats when aggregations are known to occur is likely to be the most effective method of mitigating against any adverse effects of seismic surveys on marine turtles at a population level.

4.3. Stakeholder analysis

The purpose of engaging with stakeholders is to understand their attitudes and identify issues requiring attention. Our results found that, irrespective of stakeholder group, there was a clear consensus that seismic surveys could pose a threat to turtles. Additionally, most felt that where mitigation guidelines do exist for turtles, they are not adequate due to the difficulties of detecting turtles and the lack of knowledge surrounding the issue. Reinforcing this attitude was the response that a vast proportion of respondents felt the impacts were not well understood and identified key areas requiring further research; *turtle distribution*, *behaviour*, *direct physiological impact*, *hearing* and *population trends*.

It was widely felt that the industry (oil and gas companies and seismic operators) should be responsible for funding this research. Although there is some uncertainty about the acoustic effects of seismic surveys on turtles, the questionnaire results have revealed a surprising amount of anecdotal evidence for incidences where turtles have become trapped in survey equipment. There was also a good deal of discussion concerning 'turtle pauses'. Although the majority of responses were not in favour of their implementation, and no guidelines recommend using them, they are sometimes adopted as a voluntary measure by seismic operators. However, the uncertainty surrounding their effectiveness, and even potential for causing greater harm, indicates a need for clarification if they are to be implemented as a turtle-specific mitigation measure. This also applies to all other mitigation methods.

4.4. Future work

4.4.1. Behaviour

To date, only a handful of studies have attempted to understand turtle responses to airgun sound and so further research is needed. Effort should be made to study and interpret turtle behaviour so that responses may be categorised in a consistent manner. Furthermore, controlled exposure experiments (CEEs) are a controversial but powerful tool for determining the response of animals to airgun emissions. They have been used for marine mammals and, if designed correctly, have the potential to demonstrate cause and effect (Compton et al., 2008; Gordon et al., 2003; Tyack et al., 2003). For example, migrating humpback whales (*Megaptera novaeangliae*) off Australia were exposed to four different sound levels ranging from a single airgun to a full seismic array and their behavioural responses recorded (Cato et al., 2012). It is possible that a similar technique could be used for turtles and would be best carried out in areas where seismic operations are occurring in areas of high turtle abundance. Such studies would be expensive and logistically challenging, requiring a considerable degree of collaboration and funding from the industry (oil and gas companies and seismic operators) to ensure the necessary resources were in place for an effective, ethical investigation. The use of bio-logging techniques, whereby turtles are fitted with tags prior to a seismic survey taking place in the vicinity, would be extremely useful in observing turtle dive behaviour and underwater movement in response to airgun sound. With recent advances in such technologies, this method has great potential in terms of data acquisition, the benefits of which should not be underestimated.

4.4.2. Physical impacts

Very few data have been recorded with regard to the potential for seismic surveys to cause direct physical injury or death to turtles, either as a result of sound or entanglement/collision. This is partly due to a lack of studies but also the difficulties with detecting such incidences. Observers are usually situated on board the source vessel and their vantage point (the bridge) may be inappropriate to accurately detect dead turtles astern of an airgun array (DeRuiter and Larbi Doukara, 2012; Hirst and Rodhouse, 2000; Weir and Dolman, 2007). To overcome this issue, one study employed an environmental monitoring boat to search the area surrounding the seismic survey for the presence of injured or dead turtles (Gurjão et al., 2005). The use of additional dedicated monitoring boats could be considered on an experimental basis for other seismic surveys occurring in areas of known high turtle density. The results from the stakeholder analysis further highlighted the need to investigate the issue of entrapment in survey equipment, such as the streamer tail buoys (Ketos Ecology, 2009). This issue cannot be monitored by MMOs located on the source vessel as entrapments usually occur subsurface and at considerable distance from the vessel (e.g. tail buoys are usually several kilometres astern). Investigation of the methods and regularity of turtle entrapments in seismic gear requires the encouragement of open reporting by seismic operators. Regular inspections of tail buoys, gun strings and other potential entrapment sites for marine fauna could be made using underwater cameras deployed from the workboat or potentially fitted to the tail buoys themselves. Trials investigating the effectiveness of preventative measures, such as 'turtle guards', should also be conducted (Ketos Ecology, 2009; Weir, 2007). Additionally, to limit the possibility of turtles becoming trapped in non-towed seismic equipment, such as ocean bottom cables (OBCs) which are laid across the seabed, possible preventative measures should be trialled. These include covering rope lanyards with plastic tubing to reduce the likelihood of entanglement, as in the case of the recent olive ridley turtle mortality in Gabon where animals became trapped in lanyards that connect the nodes and pingers to the main cable (A. Formia, 2014, pers. comm.).

4.4.3. Distribution and abundance

For migratory species such as turtles, assessing the level of exposure to any anthropogenic threat requires an understanding of their movements and the spatial overlap with such activities (Witt et al., 2011, Pikesley et al., 2013). The use of satellite telemetry allows for large-scale investigation across ocean basins and has proven successful in identifying the probability of interaction with industries, such as fisheries (Fossette et al., 2014). The analysis of the spatio-temporal distribution and habitat use of turtles and the distribution of seismic surveys will allow for the identification of areas and times of potential overlap to predict the level of risk (Fossette et al., 2014). Furthermore, existing unpublished tracking data should be made available for analysis as this information would not only enhance our species knowledge for conservation purposes, it would also provide empirical evidence with which appropriate policies can be designed. Additionally, aside from the petro-chemical industry, this information could be utilised by other industries such as marine renewables and shipping.

Knowledge of baseline distributions and abundances of turtles is important for measuring change as a result of any human activity. However, no studies have been published where aggregations have been monitored before and after seismic surveys.

4.4.4. Mitigation measures

For real-time mitigation measures to be effective, an ability to reliably locate turtles is essential. However, visual detection techniques are subject to multiple limitations and are not considered to be a reliable method. Many MMOs have very little experience of detecting and identifying turtles and as such, there is a clear need for more comprehensive observer training (Parente et al., 2006). Additionally, detection techniques other than visual methods require further trialling, particularly those with potential to locate turtles underwater. One possible future method may be to use multi-beam echo sounder systems (MBES) which are advancing beyond their original bathymetry applications. Current research into their use for detecting biological features within the water column (such as fish shoals) is being carried out with promising results (Deimling and Weinrebe, 2014). However, their application to detect turtles is currently limited due to the difficulties in acquiring *in situ* reference acoustic data for individual animals/species (e.g. target strength) and the ambiguity in identifying relatively small objects (A. Bicknell, 2014, pers. comm.). Additionally, introducing more (higher frequency) sound into the marine environment raises other conservation concerns, for example potential impacts on cetaceans.

Our findings suggest that time–area closures are much more appropriate than attempting to implement real-time measures during seismic operations. Their value as a mitigation tool has been highlighted by a number of reviews concerning marine mammals (e.g., Castellote, 2007; Parsons et al., 2009; Nowacek et al., 2013) and turtles, particularly with regard to avoiding nesting seasons due to the potential disturbance to breeding females and emerging hatchlings (Parente et al., 2006; Pendoley, 1997; Whittock et al., 2014). Equally important are offshore habitats used by turtles as migration corridors and foraging grounds (Godley et al., 2010). As such, in the absence of strong empirical data, implementing time–area closures should be the primary mitigation measure adopted by governments, seismic operators and environmental management organisations during the planning stages of seismic surveys.

Results from the stakeholder analysis suggest that data collected by on-board marine mammal observers are not routinely made publically available, yet there is a clear desire for it to be so. Sharing of such data, would not only benefit biodiversity monitoring, it would also encourage transparency within the seismic industry as well as increase public confidence (Grech et al., 2013). We therefore recommend the development of a global open-access database of sightings which would greatly help the industry as well as scientists.

4.5. Conclusion

It is clear that further research is urgently needed to generate a greater understanding of the aforementioned issues. This, and collaboration between the various stakeholder groups, particularly the scientific community and the seismic industry, will allow for better management decisions and appropriate policy development. In the meantime, a precautionary approach should be adopted since absence of evidence should not be interpreted as evidence of absence.

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Appendix A

Seismic Survey (marine): A method of using sound waves to search for oil and gas deposits beneath the sea bed (see Fig. 1).

Airgun: A cylinder of compressed air which is suspended in the water column. The firing of the airgun generates bubbles, the expansion and collapse of which creates a sound wave.

Airgun array: A collection of airguns towed behind a survey vessel, typically fired at shot-point intervals of 18.75 or 25 m during 3D surveys.

Hydrophone streamers: Cables containing sound recording equipment that are towed from the ship astern of the airgun array to receive the sound waves as they are reflected back from the sea bed.

Tail buoys: Floating buoys are attached to the termination points of the streamers.

Mitigation/ exclusion/ safety zone: A pre-defined radius around the seismic source where sound levels are considered to be most likely to cause auditory damage to marine organisms (particularly marine mammals) (Compton et al., 2008).

Marine Mammal Observer (MMO): On-board personnel responsible for monitoring the mitigation zone, detecting and identifying marine organisms (species stipulated by guidelines) and implementing appropriate mitigation measures (Compton et al., 2008; Weir and Dolman, 2007).

Passive Acoustic Monitoring (PAM): Method of detecting vocalising marine mammals, often used during hours or darkness or poor weather when visual detection is not possible. Cannot be used for non-vocalising organisms such as turtles.

Pre-shoot watch: Specified duration of monitoring for the presence of marine organisms within mitigation zone by MMOs and PAM Operators prior to commencement of an airgun operation (Weir and Dolman, 2007).

Soft-start: Also known as 'ramp-up', the term refers to the gradual increase in energy emitted by the seismic source. For example, initial firing of a single airgun (usually the smallest) with subsequent gradual activation of multiple, more powerful airguns. The soft start is a 'common sense' mitigation measure, intended to warn marine organisms, allowing them time to move away before full power is reached (Compton et al., 2008; Weir and Dolman, 2007).

Soft-start delay: Occurs if a relevant species is observed within the mitigation zone during the pre-shoot watch. A delay in the commencement of airgun firing is observed for a specified duration or until the animals are seen exiting the area (Weir and Dolman, 2007).

Shut-down: Cessation of airgun operation.

Turtle pause: Sometimes adopted as a voluntary measure where shut-downs for turtles are not required by guidelines. Airguns are not fired for a series of shots to allow a silent period as the array passes the last visual location of the turtle. Does not result in lost seismic survey data as would occur with total shut down (Barkaszi et al., 2012)

Time/ area closures: Temporal and spatial restrictions to avoid conducting seismic surveys in sensitive areas or times of year when species aggregations are known to occur. For example, breeding or feeding areas/ seasons (Compton et al., 2008; Weir and Dolman, 2007).

Exclusive Economic Zone (EEZ): 200 nautical mile jurisdiction boundary of coastal countries.

Fig. A.1. Glossary.

Many thanks for agreeing to take part in my survey. I am looking to obtain responses from key stakeholder groups including those who work in the offshore oil and gas industry, seismic policy and regulations, marine fauna and seismic research as well as marine conservation. This questionnaire is voluntary and for research purposes only. All data and answers will remain anonymous in analysis and write-up.

1. **Which of the following best describe your job function?**

- Government agency representative
- Oil and gas company representative
- Seismic operator representative
- Marine Mammal Observer (MMO)
- Marine ecologist/ consultant
- Conservation NGO representative
- Marine turtle scientist/ academic
- Marine acoustician
- Other (please specify)

2. **In which region are you based?**

- Africa
- Asia
- Australasia
- Central America and the Caribbean
- Europe
- Middle East
- North America
- South America
- Other (please specify)

3. **Which ocean basin(s) does your work concern? (Please select all that apply)**

- North Atlantic
- South Atlantic
- North Pacific
- South Pacific
- Mediterranean
- Caribbean
- Gulf of Mexico
- Indian

4. **Are turtles part of the marine fauna in the area(s) in which you work?**

- Yes
- Not sure
- No

GUIDELINES

5. **Are you familiar with the current mitigation guidelines (also known as policy statements or codes of conduct) concerning seismic surveys and marine fauna for your region(s) of activity?**

- Yes (Please use the text box below to indicate which)
- No (skip logic sends respondent to question 11)
- There are none (Please use the text box below to specify where) (skip logic sends respondent to question 11)

GUIDELINES

6. **What mitigation procedures do the guidelines recommend that are specific to turtles? (Please select all that apply)**

- None
- Soft start/ ramp up to allow animals to move away from the source
- Delay soft start if a turtle is observed in the mitigation zone during pre-shoot watch
- Shot pause when turtle is encountered – ‘turtle pause’
- Shut down operations if a turtle is observed within the mitigation zone during firing
- Prevent operating at night or during bad weather when turtles cannot be detected
- Time-area closures to avoid aggregations of breeding/ foraging turtles

7. **Do you feel these measures are adequate for minimising the impact on turtles?**

- Yes
- No
- Not sure

Please explain your answer

Fig. A.2. Questionnaire.

8. Of the mitigation procedures, which do you feel are effective at reducing the impact on turtles? (Please select all that apply)

- None
- Soft start/ ramp up to allow animals to move away from the source
- Delay soft start if a turtle is observed in the mitigation zone during pre-shoot watch
- Shot pause when turtle is encountered – 'turtle pause'
- Shut down operations if a turtle is observed within the mitigation zone during firing
- Prevent operating at night or during bad weather when turtles cannot be detected
- Time-area closures to avoid aggregations of breeding/ foraging turtles
- Other (please specify)

9. Of the mitigation procedures, which do you feel are NOT effective at reducing the impact on turtles? (Please select all that apply)

- None
- Soft start/ ramp up to allow animals to move away from the source
- Delay soft start if a turtle is observed in the mitigation zone during pre-shoot watch
- Shot pause when turtle is encountered – 'turtle pause'
- Shut down operations if a turtle is observed within the mitigation zone during firing
- Prevent operating at night or during bad weather when turtles cannot be detected
- Time-area closures to avoid aggregations of breeding/ foraging turtles
- Other (please specify)

10. Please give details of what you feel should happen in terms of mitigation for areas where there are NO turtle specific guidelines

RESEARCH

11. In terms of scientific research, how well understood are the impacts of seismic operations on turtles?

- Very well
- Quite well
- Not very well
- Not at all
- Not sure

Text box: Option to explain response

12. In your opinion, could seismic activity pose a threat to turtles?

- Yes
- Possibly
- No
- Not sure
- Rather not say

Text box: Please explain your answer

13. In terms of understanding the impacts of seismic surveys on turtles, where should research focus? Please list 5 topics in order of priority (1=highest, 5=lowest).

1.
2.
3.
4.
5.

14. Who do you feel should be responsible for funding the research?

15. To your knowledge, what currently happens to observational turtle data collected by Marine Mammal Observers during seismic surveys?

16. What would you like to see happen to it?

17. Are there any constraints affecting this process?

Fig. A.2 (*continued*).

OFFSHORE OBSERVATIONS

18. Do you have experience of working on an offshore seismic vessel?

- Yes (skip logic send respondent to Q.19)
- No (skip logic sends respondent to Q.21)

19. During your time working offshore, have you ever witnessed a turtle being impacted during survey operations? Includes dead/ unconscious turtle in the vicinity of a survey, turtle becoming trapped in survey equipment etc.

- Yes
- No

If yes, please provide details

20. In your experience, how well does the seismic industry comply with the recommended mitigation measures as specified by the regional guidelines?

- Compliance levels are poor
- Compliance levels are adequate
- Compliance levels go above and beyond guidelines
- Rather not say
- I don't know

Text box: Option to explain response

21. If you would you be happy for me to contact you should follow-up questions to your responses be needed, please provide your email address below (please note, this information will NOT be passed to any third party or published as a result of this survey).

Many thanks for taking the time to complete my survey. Your assistance is very much appreciated.

Fig. A.2 (*continued*).

Stakeholder group	*Involvement in seismic industry*	*Role in seismic industry*	*Influence on seismic industry guidelines*	*Role in influencing seismic industry guidelines*
Government agency	High	Regulatory body involved with seismic survey licencing procedures, handling MMO data and dealing with non-compliance issues.	High	Responsible for developing industry guidelines
Oil and gas company	High	Contracts seismic operator to search for oil and gas deposits beneath sea floor	High	Unknown
Seismic operator	High	Carries out seismic surveys on behalf of the oil and gas company	High	Unknown
Marine Mammal Observer	High	Contracted by either an oil and gas company or a seismic operator (usually via an agency),to carry out on-board marine life observations as specified by mitigation recommendations	Medium	Can advise governing body of issues/ improvements to be made
Marine ecologist/ consultant	Low	May carry out research on the impact of seismic surveys on marine life	Medium	May provide advice and recommendations
Conservation NGO	Low	May carry out research on the impact of seismic surveys on marine life	Medium	May provide advice and recommendation, implement pressure through public support
Marine turtle scientist/ academic	Low	May carry out research on the impact of seismic surveys on turtles	Medium	May provide advice and recommendations
Marine acoustician	Low	May carry out research on the impact of seismic surveys on marine life	Medium	May provide advice and recommendations

Fig. A.3. Stakeholder analysis.

Stakeholder	*Methods of identification*
Government agencies	These were identified as those who have developed industry guidelines for mitigating against the potential impacts of seismic surveys on marine fauna. As such, a total of seven government agencies were contacted.
Oil and gas companies	An internet search was carried out for companies operating offshore and those that appeared in the top 20 results were contacted directly. The Oil and Gas Producers Association, a forum for the oil and gas industry (www.ogp.org.uk) which has 82 members, was also contacted.
Seismic operators	All twelve companies listed as core members on the IAGC website were contacted as well as the IAGC themselves.
Marine Mammal Observers	A URL link to the survey was posted on the MMO Association forum (www.mmo-association.org).
Marine ecologists/ consultants	A small number (four) of individuals were contacted via associations with universities and consultancy companies.
Conservation NGOs	An internet search for relevant marine conservation organisations was carried out and contact was made to twelve of them.
Marine turtle scientists/ academics	First, last and corresponding authors (a total of 30) of all turtle literature collected during the systematic review process were contacted.
Marine acousticians	The process used to identify marine turtle scientists/ academics also encompassed marine acousticians. I.e., first, last and corresponding authors of relevant literature.

Fig. A.4. Stakeholder identification and engagement.

Group	Search terms	No. hits in Google Scholar	No. hits in WoS	Total number of articles found (duplicates removed)	Total number of relevant articles obtained and read
Turtles	Turtles Seismic	8	3	29	29
	Turtles Airgun	4	2		
	Turtles Noise	4	13		
	Turtles Sound	17	15		
	Turtle Hearing	7	11		
	Total	**40**	**44**		
Marine Mammals (ALL)	Marine mammals Seismic	30	8	414	40
	Marine mammals Airgun	5	1		
	Marine mammals Noise	84	37		
	Marine mammals Sound	57	51		
	Marine mammals Hearing	8	9		
	Total	**184**	**106**		
	Cetaceans Seismic	8	3		
	Cetaceans Airgun	0	1		
	Cetaceans Noise	12	13		
	Cetaceans Sound	21	29		
	Cetaceans Hearing	9	20		
	Total	**50**	**66**		
	Whales Seismic	40	11		
	Whales Airgun	8	5		
	Whales Noise	81	37		
	Whales Sound	96	104		
	Whales Hearing	31	39		
	Total	**256**	**196**		
	Dolphin Seismic	11	11		
	Dolphins Airguns	1	1		
	Dolphins Noise	31	22		
	Dolphins Sound	72	76		
	Dolphins Hearing	29	25		
	Total	**144**	**135**		
Fish	Fish Seismic	43	30	187	12
	Fish Airgun	5	3		
	Fish Noise	91	73		
	Fish Sound	333	354		
	Fish Hearing	70	82		
	Total	**542**	**542**		

Fig. A.5. Systematic review results.

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