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Seals and shipping: quantifying population risk and individual exposure to vessel noise

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Summary

1. Vessels can have acute and chronic impacts on marine species. The rate of increase in commercial shipping is accelerating, and there is a need to quantify and potentially manage the risk of these impacts.

2. Usage maps characterising densities of grey and harbour seals and ships around the British Isles were used to produce risk maps of seal co-occurrence with shipping traffic. Acoustic exposure to individual harbour seals was modelled in a study area using contemporaneous movement data from 28 animals fitted with UHF global positioning satellite telemetry tags and automatic identification system data from all ships during 2014 and 2015. Data from four acoustic recorders were used to validate sound exposure predictions.

3. Across the British Isles, rates of co-occurrence were highest within 50 km of the coast, close to seal haul-outs. Areas identified with high risk of exposure included 11 Special Areas of Conservation (SAC; from a possible 25). Risk to harbour seal populations was highest, affecting half of all SACs associated with the species.

4. Predicted cumulative sound exposure level, cSELs(M_{pw}), over all seals was 176·8 dB re 1 μPa^2 s (95% CI 163·3–190·4), ranging from 170·2 dB re 1μPa^2 s (95% CI 168·4–171·9) to 189·3 dB re 1 μPa^2 s (95% CI 172·6–206·0) for individuals. This represented an increase in 28·3 dB re 1 μPa^2 s over measured ambient noise. For 20 of 28 animals in the study, 95% CI for cSELs(M_{pw}) had upper bounds above levels known to induce temporary threshold shift. Predictions of broadband received sound pressure levels were underestimated on average by 0·7 dB re 1 μPa (±3·3).

5. *Synthesis and applications*. We present a framework to allow shipping noise, an important marine anthropogenic stressor, to be explicitly incorporated into spatial planning. Potentially sensitive areas are identified through quantifying risk to marine species of exposure to shipping traffic, and individual noise exposure is predicted with associated uncertainty in an area with varying rates of co-occurrence. The detailed approach taken here facilitates spatial planning with regard to underwater noise within areas protected through the Habitats Directive, and could be used to provide evidence for further designations. This framework may have utility in assessing whether underwater noise levels are at Good Environmental Status under the Marine Strategy Framework Directive.

Key-words: acoustic propagation, AIS, *Halichoerus grypus*, marine stressor, MSFD, noise pollution, *Phoca vitulina*, spatial overlap, telemetry, uncertainty

Introduction

Major shipping routes converge around populated coastlines with relatively high densities of ships accessing ports. Coastal regions serve as important habitats (e.g. for breeding, foraging) for many species of marine mammals leading to the potential for interactions with ships in these areas. Marine mammal habitats are often conserved through protected areas or other spatial planning measures. There is a perceived requirement for effective

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spatial planning where shipping traffic and marine mammals share the same environment (Erbe *et al.* 2014; Williams *et al.* 2015), but the level of management required will depend to a large extent on the scale and intensity of interactions and the effects these have on the behaviour and welfare of the species of interest. Injury due to collisions with vessels is widely recognised as a serious risk for large cetaceans and sirenians (Beck, Bonde & Rathbun 1982; Panigada *et al.* 2006). Trauma ascribed to ship strikes has also been identified in a proportion of both live stranded (Goldstein *et al.* 1999) and dead stranded seals in the United States (Swails 2005), suggesting that mortality resulting from these collisions may pose a risk, albeit lower, for pinnipeds. However, difficulties in observing these unpredictable events mean that mortality rates are still poorly understood.

Shipping traffic is a major component of underwater low-frequency ambient noise in the oceans, and has increased by 10 dB since the mid-1960s in monitored areas of the Pacific (Andrew *et al.* 2002). A focus of the Marine Strategy Framework Directive (MSFD, 2008/56/EC; European Commission 2008) requires EU member states to ensure that noise levels do not adversely affect the marine environment. Phocid seals rely on sound for communication (van Parijs *et al.* 1997), and potentially navigation and predator–prey detection, and have good low-frequency hearing from a few hundred Hz to 70–80 kHz (Cunningham & Reichmuth 2016). Vessel noise is likely to be audible to seals at relatively long ranges and has the potential to lead to a range of chronic effects. For marine mammals, these include avoidance of important habitats (Morton & Symonds 2002), changes in behaviour such as interference with vocalisations (Payne & Webb 1971) and auditory damage (Southall *et al.* 2007), which may pose a significant risk of detrimental long-term population consequences (Tyack 2008). Reviewing previous studies of auditory damage in marine mammals, Southall *et al.* (2007) proposed sound pressure level [SPL; dB re: 1 μPa (peak) (flat)] and sound exposure level (cSEL; dB re 1 μPa^2 s), a measurement of cumulative acoustic energy over time, as noise assessment metrics for auditory damage in marine mammals. Hearing loss can be characterised as permanent threshold shift (PTS) in hearing sensitivity that is unrecoverable over time, or a temporary threshold shift (TTS) where hearing recovers completely over a specified time. For pinnipeds exposed to non-pulse underwater sounds, cSEL was predicted as 203 dB re 1 μPa^2 s and 183 dB re 1 μPa^2 s for the onset of PTS and TTS, respectively.

Potential impacts of exposure to shipping noise are likely to increase concomitantly with growth in the commercial shipping industry (Hatch *et al.* 2008). Despite this, little is known about the levels of noise exposure from shipping in relation to the distribution, movements or behaviour of pinnipeds. Shipping traffic is known to disturb seals from haul out sites (Jansen *et al.* 2015), but there is little published information using at-sea movements of seals in relation to vessel activity (Chen *et al.* 2016). Several studies have called for monitoring of areas where there is high incidence of shipping traffic (Merchant *et al.* 2012; Williams *et al.* 2015) so that acute and chronic impacts on marine species can be addressed. It is important to identify areas of greatest risk within the marine environment (Erbe, MacGillivray & Williams 2012; Erbe *et al.* 2014), and to develop techniques to assess long-term sound exposure (Merchant *et al.* 2012).

Grey (*Halichoerus grypus*) and harbour (*Phoca vitulina*) seals are abundant around much of the UK coastline; they are central-place foragers spending the majority of their time within 50 km of the coast (Jones *et al.* 2015). With similar but asynchronous lifecycles, they haul out on land (to rest, breed and moult) and spend time at-sea travelling to their foraging grounds and moving between haul out sites. Important areas for both species are protected under Annex II of the Habitats Directive (JNCC 2010) and Special Areas of Conservation (SAC) have been designated around the British Isles to protect their terrestrial breeding habitats.

We propose a generalisable framework to characterise co-occurrence between seals and shipping on a broad spatial scale (i.e. nationally). Predicted exposure to shipping noise on individual seals is then investigated in an area where an SAC is designated and where varying spatial overlap occurred.

Materials and methods

SPATIAL CO-OCCURRENCE

To characterise spatial overlap between seals and shipping traffic, two modelled data sources were used: seal at-sea usage maps (Jones *et al.* 2015) and ship usage maps (MMO 2014). Rate of co-occurrence was calculated to quantify spatial overlap between seals and ships in each grid cell. This was defined as the daily number of co-occurrences between seals and ships in each 5 km × 5 km grid cell, *i*, described as S_iB_i, where S_i = mean number of seals in *i*; B_i = mean daily number of vessel transits in *i*. The resolution of the co-occurrence maps was not explicitly linked to the spatial scale of potential auditory damage. Rather, the scale was chosen so that broad-scale analysis could be produced to identify potentially acoustically sensitive areas around the British Isles.

Seal at-sea usage maps for grey and harbour seals around the British Isles were produced at a 5 km × 5 km resolution (Appendix S1: Fig. S1, Supporting Information). Methodology to generate usage maps from Jones *et al.* (2015) is summarised: Usage was estimated using a combination of terrestrial counts of seals at haul out sites and animal-borne telemetry data from 259 grey seals and 277 harbour seals. Animals were tagged with satellite relay data loggers (SRDL) or global positioning satellites (GPS) phone tags between 1991 and 2013. A series of data processing protocols removed observations with null, missing or duplicated data. SRDL data were speed filtered at a maximum of 2 ms^{-1} and Kalman filtered to correct for positional errors. Occasional outliers in the GPS data were excluded using thresholds of residual error and number of satellites (Russell *et al.* 2015). To account for sampling bias, telemetry locations were regularised to 2-hourly intervals. Locations were kernel-smoothed into continuous spatial surfaces to represent the proportion of time animals spent in different areas. Tagged seals did not haul out in some areas, but terrestrial surveys showed that animals were present. To complete the usage maps in these areas, a null model was fitted using all telemetry data to model usage as a function of distance from haul out site. Local usage maps were scaled to local population estimates for 2013. Telemetry-based maps were aggregated with predictions from the null model to create a usage map for the area of the study. Uncertainty was propagated by combining variance in onshore counts with variation between spatial usage of haul outs to produce confidence intervals of usage estimates.

Ship usage maps showing the distribution of vessels around the British Isles in 2012 were developed using automatic identification system (AIS) ship tracking data, available to download from the Marine Management Organisation (https://data.gov.uk/dataset/mmo1066-vessel-density-grid-2012). Due to international maritime legislation on the requirement for use of AIS (IMO 1974), vessels greater than 299 gross tonnes and all passenger vessels in British Isles waters over the study period were represented in the data. Where available, smaller vessels that carried AIS (but were not required to) were also included in the data. Positional data were supplied by the Maritime and Coastguard Agency, collected by their network of ground-based receiving stations around the British Isles. Methodology to generate ship usage at a resolution of 2 km × 2 km from MMO (2014) is summarised: Due to computational constraints, AIS data were sampled over 42 days throughout 2012 (3–9 January, 1–7 March, 1–7 May, 1–7 July, 1–7 September and 1–7 November) to remove seasonality. Positional data were translated into vessel transits to produce a continuous track. A transit began when speed over ground (SOG) exceeded 0·5 knots and normally ended when SOG stayed below 0·2 knots for more than 5 min (or other specified threshold; Appendix S1: Table S1). Density was defined as the number of vessel transits in a grid cell rather than the number of times a vessel transited across a grid cell. Data processing to translate raw AIS locations into a usage surface is summarised in Appendix S1: Table S2. AIS data had maximum locational error of 50 m (Russell *et al.* 2015), so uncertainty in locations around mean usage was not considered. Vessels were categorised into 11 groups: cargo vessels (48%), tankers (18%), passenger (9%), fishing (8%) and the other groups (unknown, non-port and port service, dredging, high-speed craft, military and sailing craft) comprised the remaining usage (Appendix S1: Table S3). To calculate rates of co-occurrence, all vessel types were used to create ship usage, defined as the mean daily number of vessel transits in each grid cell at the same 5 km × 5 km resolution as the seal usage maps (Appendix S1: Fig. S2).

ACOUSTIC EXPOSURE

A study area including high rates of co-occurrence (≥100 per day) was identified. Located 57.5°N to 58.6°N and 2.2°W to 4.4°W, the area was centred on the Moray Firth, north-east Scotland (Fig. 1a), and encompassed the Dornoch Firth and Morrich More SAC where harbour seals were a primary reason for site selection. Harbour seals spend time around haul out sites and foraging in offshore areas in the Moray Firth (Thompson *et al.* 2013). The study area has a mean depth of 54 m (max = 202 m) and sediment in the area is primarily sand, with a mixture of gravel and mud. A series of acoustic propagation approaches were used to predict exposure to shipping noise for individual harbour seals.

Seal telemetry data were collected using Fastloc© GPS Ultra High Frequency tags (Pathtrack Ltd, Leeds, UK). Over 2 years, 35 tags were deployed on harbour seals. Of these, 28 tags transmitted sufficient information to be analysed, between 19 May–17 August 2014 and 6 January–2 August 2015 (Table 1). Seals were captured whilst hauled out and anesthetised with intravenous Zoletil100® (Virbac, Bury St Edmunds, UK) at a dose rate of 0·5 mg kg^{-1}. Tags were attached to fur on the back of the neck using Loctite® 422 (Henkel, Hemel Hempstead, UK) Instant Adhesive. All procedures were carried out under Home Office Animals (Scientific Procedures) Act licence number 70/7806. Data from each tag were uploaded to one of five archiving UHF receiver base stations positioned at locations around the Moray Firth (Fig. 1a). Data transfers were made when animals surfaced or hauled out within range (line-of-sight) of a receiver station. High-resolution movement data were generated by sampling animal locations every 3 min. Erroneous locations were removed using thresholds of residual error and number of satellites (Russell *et al.* 2015). Locations were interpolated and sub-sampled to estimate noise exposure every 15 min and at-sea locations were retained.

Ship tracking data were provided by MarineTraffic (www.marinetraffic.com) for all vessels with operational AIS transmitters in the Moray Firth. AIS data mostly extended over the same spatio-temporal range as the seal telemetry data to enable acoustic exposure of seals to be modelled in the context of surrounding ship traffic (19 May–17 August 2014 and 11 March–2 August 2015). Information was provided on individual vessel name, type, length and width. The sampling rate was set to 2-min intervals and true speed at each vessel location was derived from the on-board vessel log system. Course, heading, date and time were also recorded. Data were cleaned and locations with missing attributes or stationary vessels (speed = 0 knots) were removed. Vessel data were grouped to the same 15-min intervals as the seal data, and one location for each vessel present by interval was selected randomly. Data from 1689 vessels were retained (Table 2).

Predictions of acoustic exposure were made. Source levels (SPLs referenced to 1 m; dB re 1 μPa at 1 m) were estimated for each ship by date and time within one-third octave bands (centre frequencies: 12·5 Hz to 20 kHz) based on ship length and speed, using the 'Research Ambient Noise Directionality' model (Breeding *et al.* 1996; Table 2; Appendix S2). Transmission losses (dB) and associated uncertainty were estimated using spherical and cylindrical spreading models (Marsh & Schulkin 1962; Urick 1983), based on empirical measurements in shallow water in the frequency range 0·1–10 kHz. In coastal waters, estimations of ship noise need to account for the dependence of sound wave attenuation on highly variable local environmental factors (Jensen *et al.* 2011), and so seabed depth and sediment type were incorporated into acoustic modelling. Bathymetric metadata and Digital Terrain Model data products were derived from the European Marine Observation and Data Network (EMODNet) Bathymetry portal (http://www.emodnet-bathymetry.eu) released August/September 2015, and were based on the seabed depth at the Lowest Astronomical Tide (LAT).

Skip distance (H; km) represents the distance at which sound waves make first contact with either the sea floor or surface, where (D; m) is the water depth (Schulkin & Mercer 1985).

$$H = [2D/3]^{1/2} \qquad \text{eqn 1}$$

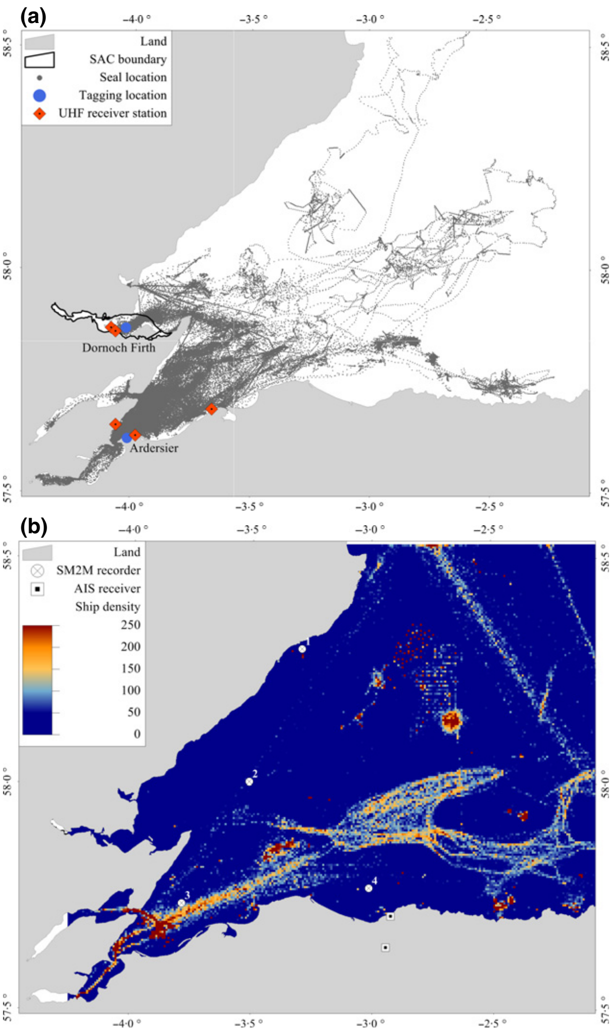

Fig. 1. (a) At-sea telemetry locations from 28 tagged seals, regularised to 15-min intervals (grey points), tagging locations (blue points), UHF GPS receiver stations (orange diamonds), and boundary of Dornoch Firth and Morrich More SAC (black outline); (b) AIS shipping density over the study period at 0·5 × 0·5 km resolution, AIS receiver stations (squares), and labelled SM2M recorders (circles with cross). Global Self-consistent, Hierarchical, High-resolution Geography Database (GSHHG) shoreline data version 2.2.2 from NOAA were used to represent land, available from http://www.soest.hawaii.edu/pwessel/gshhg/.

Transmission loss (TL; dB) was calculated using the distance between source (ship location) and receiver (seal location), range (R; km), absorption coefficient in seawater (α; dB km^{-1}) where $\alpha = 0{\cdot}036 f^{1{\cdot}5}$ with each one-third octave band centre frequency (f; kHz; Richardson *et al.* 1995), near-field anomaly (k_L; dB) and shallow water attenuation coefficient (a_T; dB).

Short-range $R \leq H$ $$\mathrm{TL} = 20\log_{10} R + \alpha R + 60 - k_L \quad \text{eqn 2}$$

Mid-range $H \leq R \leq 8H$ $$\mathrm{TL} = 15\log_{10} R + \alpha R + a_T\left(\frac{R}{H} - 1\right) + 5\log_{10} H + 60 - k_L \quad \text{eqn 3}$$

Long-range $R \geq 8H$ $$\mathrm{TL} = 10\log_{10} R + \alpha R + \alpha T\left(\frac{R}{H} - 1\right) + 10\log_{10} H + 64{\cdot}5 - k_L \quad \text{eqn 4}$$

Sand was the predominant sediment in the study area [seabed sediment data (BGS Geology: marine sediments 250k) used with permission of the British Geological Survey, http://www.bgs.ac.uk, and available to view on Maremap, http://www.maremap.ac.uk/index.html], and estimates of k_L and a_T in shallow water with sand sediment were used in eqns (2)–(4), where sea state was assumed to be 2 on the Beaufort scale (Appendix S2: Table S4).

Uncertainty in transmission loss was modelled using data of error estimates at selected frequencies and ranges (Appendix S2: Table S5). A linear model was produced with a response variable of standard deviation and explanatory covariates of range and frequency (up to 2·85 kHz). The maximum standard deviation predicted from the model was used for higher frequencies (up to 20 kHz). Received SPLs (dB re 1 μPa$_{(RMS)}$) were calculated by subtracting transmission loss from source levels and integrating over frequency to produce broadband received SPL at each seal location. For analytical purposes, sound sources (vessels) and receivers (seals) were assumed to be located at the mid-point of the water column. Uncertainty in transmission loss was propagated through the acoustic models: Parametric bootstrapping was used to create a set of realisations, sampling from transmission loss mean and standard deviation. Estimated mean ambient noise in the study area (see Acoustic validations below) was used as a minimum threshold for predictions of SPL. Mean SPL was calculated by seal for each 15-min interval. Based on the tracks of seals through predicted sound fields, and using the M-weighting function for pinnipeds in water (Southall *et al.* 2007), cSEL (M$_{pw}$) was calculated every 15-min for each individual over each 24 h period. Mean cSEL(M$_{pw}$) for ambient noise (see Acoustic validations below) was used as a minimum threshold for the predictions. Using bootstrapped data, estimates of mean cSEL(M$_{pw}$) and 95% CI were produced for each 15-min interval over 24 h for individual animals and as an aggregation over all individuals.

ACOUSTIC VALIDATIONS

Predictions from the acoustic models were compared to field measurements of underwater sound made using remote acoustic recorders deployed on the seabed. Four recorders (Wildlife Acoustics SM2M recorders; Maynard, MA, USA) with a sample rate of 96 kHz and gain of 12 dB were deployed within the study area and were set to record on a 33% duty cycle (10 min on, 20 min off) (Fig. 1b). Recordings were available from 27 June to 17 August 2014, overlapping the study period by 53 days. Details of the data analysis procedure are given in Merchant *et al.* (2016); the monitoring data selected for comparison were resolved to one-second resolution in one-third octave bands between 25 Hz and 1 kHz. Broadband received SPL over this frequency range were calculated at the same 15-min intervals used in the predictive model. SPL mean and variance were calculated if there was more than one observation within an interval. Daily ambient noise at each receiver location was calculated as a median SPL (Merchant *et al.* 2016).

Table 1. Animals used to predict acoustic exposure

Animal ID	Year	Tagging site	Sex	Mass at capture (kg)	Tag duration (days)	Number of days used in analysis
65170	2014	Ardersier	M	74·8	57·9	56
65180	2014	Ardersier	M	77·8	92·3	86
65181	2014	Ardersier	M	83·6	59·9	53
65184	2014	Ardersier	M	81·8	39·4	36
65185	2014	Ardersier	M	88·8	73·2	70
65186	2014	Ardersier	F	90·2	35·9	35
65187	2014	Ardersier	M	60·6	39·1	38
65190	2014	Ardersier	M	51·8	50·4	36
65194	2014	Ardersier	M	90·6	67·8	52
65196	2014	Ardersier	F	74·2	66·0	59
65198	2014	Ardersier	F	82·0	45·5	40
65145	2015	Ardersier	M	77·3	61·5	60
65202	2015	Ardersier	M	57·2	156·7	154
65204	2015	Ardersier	M	87·2	97·5	79
65206	2015	Ardersier	F	82·7	96·6	96
65207	2015	Ardersier	M	89·7	131·8	107
65209	2015	Ardersier	M	79·1	145·8	120
65212	2015	Ardersier	M	87·1	98·3	92
65213	2015	Ardersier	F	94·3	91·0	89
65214	2015	Ardersier	F	79·7	89·7	82
65217	2015	Ardersier	M	85·1	111·0	106
65219	2015	Ardersier	F	80·3	98·2	95
65220	2015	Ardersier	M	87·7	114·2	109
65226	2015	Dornoch Firth	M	90·3	37·9	37
65233	2015	Dornoch Firth	M	65·5	131·9	126
65234	2015	Dornoch Firth	M	88·5	38·6	33
65255	2015	Dornoch Firth	M	62·7	84·1	79
65258	2015	Dornoch Firth	F	72·7	20·9	15

Table 2. Moray Firth AIS data summarised by vessel group (italicised sub-totals)

Group	Vessel type	Number of vessels	Mean vessel length (min, max; m)	Mean vessel speed (min, max; kts)	Mean source level (min, max; dB re 1 μPa at 1 m)	Number of locations (15-min intervals)	Proportion of locations (%)
1	Tug	*82*	*53 (13, 95)*	*6 (0·1, 14)*	*148 (113, 196)*	*22 217*	*8·9*
2	Cargo	526	126 (15, 335)	11 (0·1, 23)	160 (112, 187)	33 409	13·4
	Tanker	110	159 (40, 333)	10 (0·1, 16)	160 (137, 178)	24 979	10·0
		636	*132 (15, 335)*	*11 (0·1, 23)*	*160 (112, 187)*	*58 388*	*23·4*
3	Dredger	13	83 (15, 207)	6 (0·1, 13)	150 (123, 191)	1648	0·7
	Fishing	192	32 (9, 143)	7 (0·1, 65)	144 (113, 202)	73 982	29·7
		205	*35 (9, 207)*	*7 (0·1, 65)*	*144 (113, 202)*	*75 630*	*30·3*
4	Local Vessel	5	24 (15, 28)	6 (0·1, 18)	173 (154, 194)	784	0·3
	Pilot Vessel	1	5	16	144	970	0·4
	Pleasure Craft	126	13 (7, 60)	6 (0·1, 23)	134 (113, 205)	5461	2·2
	Port Tender	1	19	8	137	122	0·0
	Sailing Vessel	323	14 (6, 59)	5 (0·1, 33)	133 (113, 203)	15 018	6·0
		456	*14 (5, 60)*	*5 (0·1, 33)*	*134 (113, 205)*	*22 355*	*9·0*
5	Dive Vessel	*15*	*75 (17, 157)*	*9 (0·1, 21)*	*149 (129, 170)*	*1370*	*0·5*
6	High Speed Craft	8	20 (17, 26)	13 (0·1, 24)	156 (127, 198)	3180	1·3
	Law Enforcement	4	66 (24, 84)	7 (2, 11)	140 (118, 156)	828	0·3
	Reserved	9	41 (11, 92)	7 (0·1, 20)	145 (116, 201)	2168	0·9
	Search and Rescue	32	35 (12, 105)	7 (0·1, 26)	151 (113, 198)	8773	3·5
		53	*36 (11, 105)*	*8 (0·1, 26)*	*150 (113, 201)*	*14 949*	*6·0*
7	Military Operations	*9*	*69 (6, 176)*	*18 (0·1, 102)*	*157 (118, 219)*	*552*	*0·2*
8	Passenger	*75*	*155 (11, 333)*	*12 (2, 24)*	*160 (115, 181)*	*5513*	*2·2*
9	Unclassified	*158*	*69 (2, 208)*	*8 (0·1, 22)*	*151 (113, 204)*	*48 379*	*19·4*
Total		1689	76 (2, 335)	8 (0·1, 102)	149 (112, 219)	249 353	100·0

The acoustic exposure model was run contemporaneously for these four locations at the same temporal resolution. Uncertainty in transmission loss was propagated and mean and variance of SPL were estimated. The minimum predicted SPL in the four locations was used as a threshold of daily ambient noise. Estimates of SPL from the acoustic exposure model were then compared with measurements from the acoustic monitoring data at each of the four locations to validate the noise estimations. Mean ambient noise over all four locations was also calculated by taking an average over median daily values of SPL. To represent ambient noise over a 24-h period, cSEL (M_{pw}) was calculated. These data represented a spatial, temporal and frequency sample, which was assumed to be representative of daily ambient noise over the study area.

Results

SPATIAL CO-OCCURRENCE

Estimated number of daily co-occurrences per grid cell between grey and harbour seals and vessels around the British Isles are shown in Fig. 2. For both species, high spatial overlap (≥100 per day) occured within 50 km of the coast close to seal haul outs. Due to low densities of shipping in the west coast of Scotland, there were relatively low rates of co-occurrence than would be expected given the high usage by both species of seals.

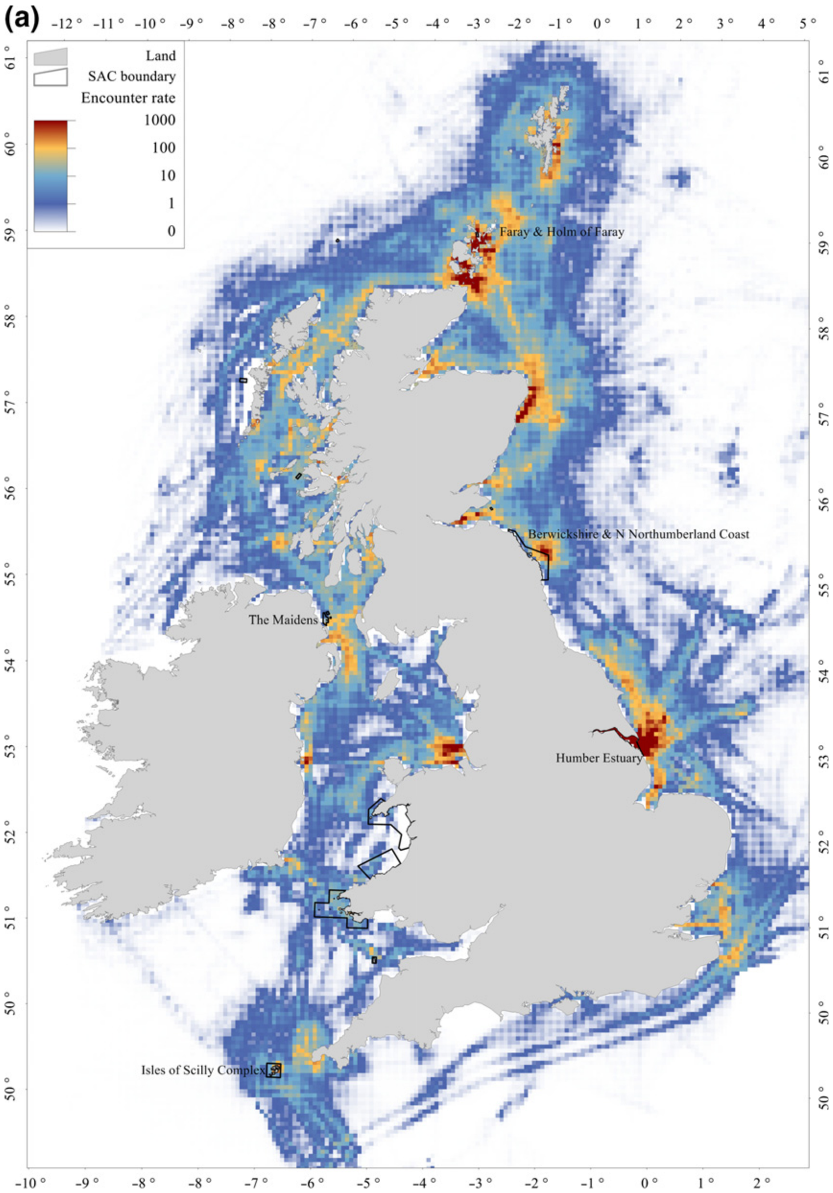

Fig. 2. Estimated number of daily co-occurrences around the British Isles between vessels and (a) grey seals; (b) harbour seals. Boundaries of SACs are shown (black outlines), available to download from http://jncc.defra.gov.uk/protectedsites/SACselection/gis_data/terms_conditions.asp, and are labelled to show where the daily rate of co-occurrence ≥100 (yellow cells) within an SAC.

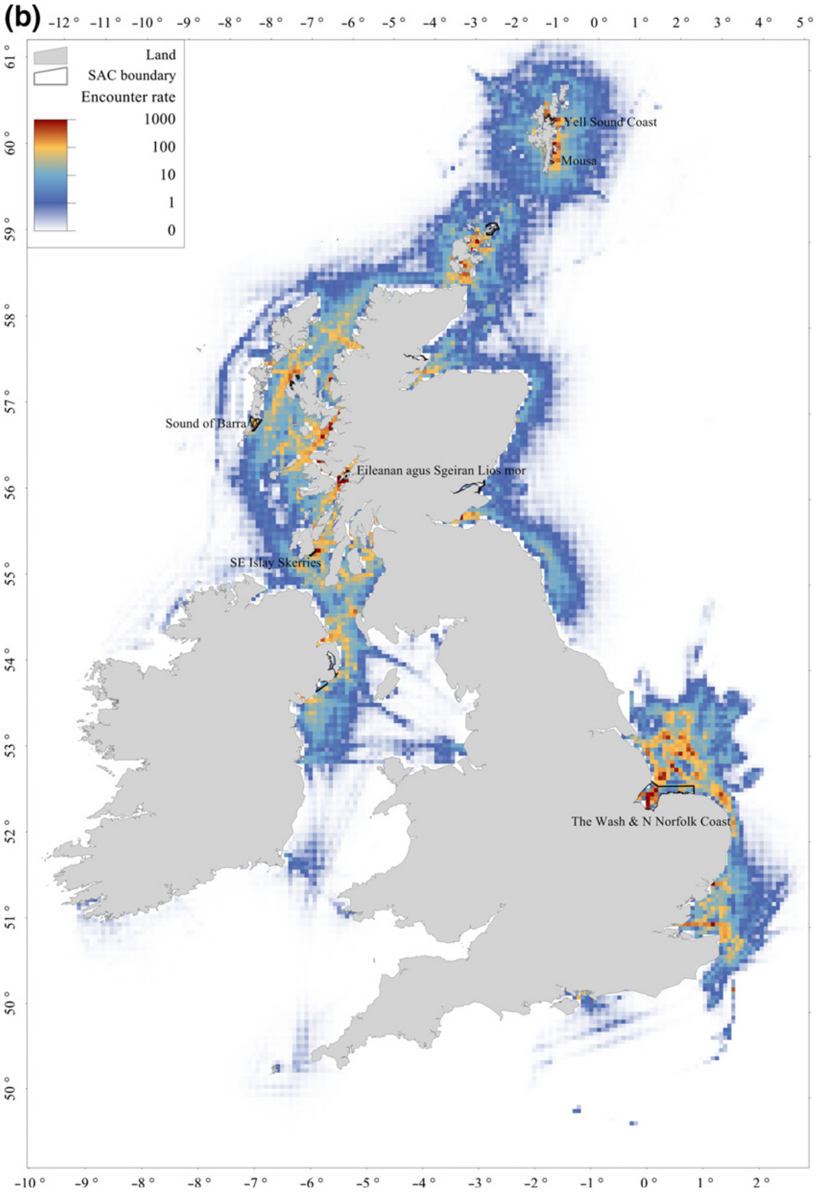

Fig. 2. Continued.

Of the 13 SACs designated for grey seals, five were associated with high co-occurrence, in Orkney (Faray and Holm of Faray), north-east England (Berwickshire and North Northumberland Coast), east England (Humber Estuary), Isles of Scilly off the west coast of England and Northern Ireland (The Maidens) (Fig. 2a). Six of the 12 SACs designated for harbour seals were in areas of high overlap, in west Scotland (South-East Islay Skerries; Eileanan agus Sgeiran Lios mor), Outer Hebrides (Sound of Barra), Shetland (Mousa; Yell Sound Coast) and east England (The Wash and North Norfolk Coast) (Fig. 2b). Fig. 3 shows that variable spatial overlap occurs within the Moray Firth, the detailed study area where acoustic exposure was estimated.

ACOUSTIC EXPOSURE

Locations (corresponding to 2040 seal days) from 28 animals (M = 20; F = 8; Table 1) were combined with locations from 1689 vessels to estimate mean SPL at each seal location and mean cSEL(M_{pw}) for seals over each 24-h period. The majority of location data came from three groups of vessels: fishing and dredging (30·3%), cargo and tankers (23·4%), and unclassified (19·4%) (Table 2).

Mean SPL was estimated for each seal location (Fig. 4). Higher mean SPLs (≥140 dB re 1 μPa) were predicted close to the ports of Nigg in the Cromarty Firth, Inverness in the inner Moray Firth, and Banff. The spatial pattern in mean SPL corresponds well with areas of

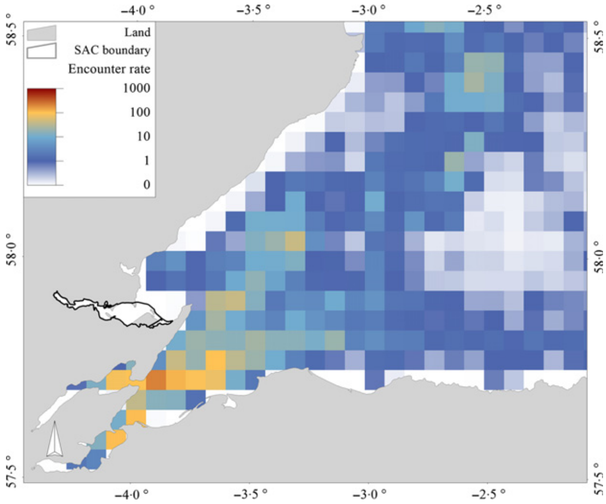

Fig. 3. Estimated number of daily co-occurrences between harbour seals and vessels within the Moray Firth study area. The boundary of Dornoch Firth and Morrich More SAC is shown (black outline).

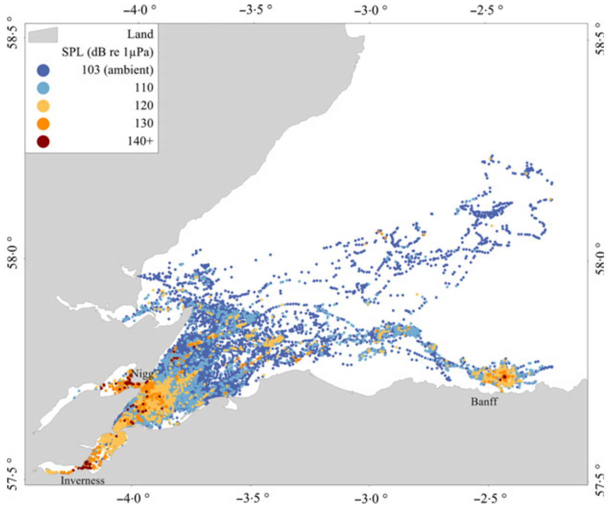

Fig. 4. Predicted mean SPL (higher than ambient levels) for seal locations within the study area, with ascending order of plotting to show locations where highest values occurred.

high co-occurrence previously identified (Fig. 3), with the exception of Banff, which did not feature as an area of high spatial overlap because a single animal spent time there, and therefore it was not representative of seal movement at the population level.

Maximum daily cSEL(M_{pw}) for each individual ranged from 170·2 dB re 1 μPa^2 s (95% CI 168·4–171·9) to 189·3 dB re 1 μPa^2 s (95% CI 172·6–206·0) (Appendix S3: Fig. S3). Figure 5 shows the cSEL(M_{pw}) over all individuals with a maximum of 176·8 dB re 1 μPa^2 s (95% CI 163·3–190·4). Mean cSEL(M_{pw}) based on ambient noise levels was calculated as 150·0 dB re 1 μPa^2 s, suggesting that 26·8 dB re 1 μPa^2 s of sound exposure above this level could be attributed to shipping traffic.

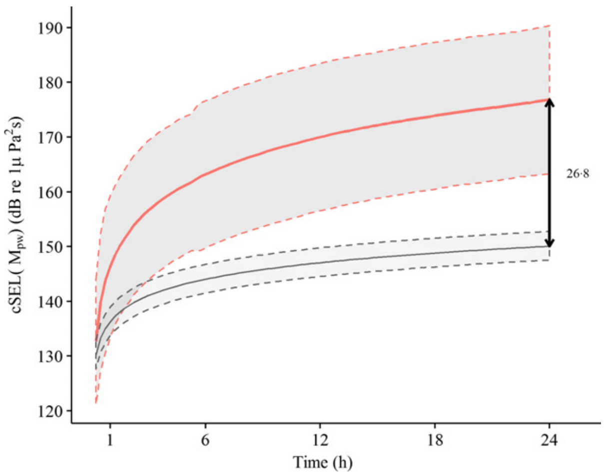

Fig. 5. Predicted mean cSEL (M_{pw}) over all individuals by hour of day (orange line) with 95% CI (dotted orange lines). The maximum elevation above mean ambient noise (grey line) with 95% confidence intervals (dotted grey lines) is 26·8 dB re 1 μPa^{2}s.

ACOUSTIC VALIDATIONS

Predictions from the acoustic exposure model underestimated SPL on average by 0·7 dB re 1 μPa (±3·3) when compared with measurements of underwater sound (Appendix S4: Fig. S4). The four locations (Fig. 1b) varied in prediction accuracy: location 1 (0·9 dB re 1 μPa; ±2·3), location 2 (1·1 dB re 1 μPa; ±2·6) and location 4 (0·6 dB re 1 μPa; ±6·3). Location 3, which had the highest volume of ship traffic in close proximity corroborated to within 0·1 dB re 1 μPa (±2·0) of field measurements.

Discussion

We describe a framework to identify exposure risk to marine species from vessel traffic, and predict acoustic exposure to shipping noise for individuals, validated using measurements of underwater sound. Distributions of seals and shipping traffic around the British Isles were analysed to identify persistent spatial patterns of co-occurrence. Caveats and limitations associated with the analysis of spatial overlap of seals and vessels, and the acoustic exposure approach taken here are discussed in Appendix S5. Both seal and vessel distributions have low stochasticity at a broad spatial scale; seals are central-place foragers, and ships travel on defined shipping routes. Co-occurrence was most intense within 50 km of the coast close to seal haul outs, and given their relatively coastal range (Jones *et al.* 2015), any impacts may affect more of the harbour seal population compared with grey seals. Some offshore areas greater than 50 km from the coast also exhibited high spatial overlap; this was generally limited to areas where seal usage was coincident with offshore shipping lanes. When considering exposure to shipping traffic in isolation, we found no evidence relating declining seal population trajectories with high levels of co-occurrence between animals and vessels. Particularly, counts of harbour seals in east Scotland have decreased (by over 90% between early 2000s and 2015), where there are relatively lower levels of shipping, compared with east England where the harbour seal population is increasing and there are high intensities of vessels (Duck & Morris 2016). Our results show that 11 SACs around the British Isles have high risk of exposure within their boundaries.

Predicted exposure levels in the Moray Firth were below those previously estimated to cause PTS (203 dB re 1 μPa^2 s) for pinnipeds in water (Southall *et al.* 2007). However, upper confidence interval bounds of 20 from 28 animals did exceed levels previously shown to cause TTS as a result of 25 min exposure to 2·5 kHz Octave Band Noise with a source level of 152 dB re 1 μPa (183 dB re 1 μPa^2 s) (Kastak *et al.* 2005). When making this comparison, it is important to highlight that shipping noise in the current study was generally below this frequency, but studies investigating TTS have not included lower frequencies. Nevertheless, this demonstrates the importance of propagating uncertainty in predictive modelling of vessel noise, particularly close to the coast where sound propagation can be highly variable. There is a degree of uncertainty in the TTS estimates as published TTS values (Kastak *et al.* 2005) were based on unweighted cSELs, whereas our predicted cSELs were M-weighted; for a discussion of the implications of applying different weighting systems during the data collection and subsequent prediction stages, see Tougaard, Wright & Madsen (2015). However, as the signals used to derive TTS estimates (2·50 and 3·53 kHz) in Kastak *et al.* (2005) were within the functional hearing range of seals as defined by Southall *et al.* (2007), they effectively had an M-weighting of 0 dB, making our comparisons valid. While the definition of injury from exposure to noise is not written into law, guidance regarding European Protected Species (EPS) only refers to permanent shifts in hearing thresholds of cetaceans. TTS would not be considered to be an injury under EPS, and in this context, the definition is transferable to seals. However, where high levels of noise have been identified, the acoustic modelling approach presented here could be used further to test the potential effectiveness of pragmatic mitigation measures. For example, the impact of rerouting shipping lanes or speed restrictions at different levels (Bagočius 2014; Merchant *et al.* 2014) in these areas could be modelled so that predicted sound levels received by individuals (assuming consistent behaviour) are reduced to acceptable limits. Although high spatial co-occurrence was present in the Moray Firth, by comparison with other areas around the British Isles, it has relatively less intense shipping traffic. Predictions of exposure to ship noise are likely to be considerably higher in other areas where very high intensities of spatial overlap occur for one or both species of seals (e.g. daily rate ≥1000) such as Orkney, Shetland, north-east Scotland, east and south-east England, west Scotland and north Wales. The framework could also be used to identify the potential consequences of changes in shipping traffic. This is particularly relevant to areas that currently experience lower levels of anthropogenic noise where ecosystems may undergo relatively large changes if shipping traffic increases.

Auditory masking of biologically significant sounds for seals is a potential risk, defined as the amount by which the audibility threshold for one sound is raised by the presence of another (Moore 1982). This may be particularly important where higher levels of sound above ambient noise are estimated in and around SACs, designated due to their importance for breeding. Vocalisations, which overlap in frequency with shipping noise appear to play a role in harbour seal reproduction, through male–male competition or advertisement to females (Hanggi & Schusterman 1994; van Parijs, Hastie & Thompson 2000). A reduction in the ability of seals to detect these calls has the potential to lead to biologically significant effects. Furthermore, behavioural responses by seals to anthropogenic sound (e.g. Russell *et al.* 2016) have the potential to lead to avoidance of important foraging habitats with possible impacts on energy acquisition by individuals. However, paucity of empirical studies on behavioural responses by seals to shipping noise means that impacts associated with avoidance have not been quantified in the current study. This remains a clear data gap when considering the potential risks posed by shipping to seal populations. Although our results do not suggest an acute effect on individuals, where populations are affected (90% decline in harbour seals in some regions over the last 15 years; Duck & Morris 2016) by other stressors, cumulative impacts may have a significant effect.

Identifying levels of risk of marine stressors for spatial planning is a focus of legislation in the EU (European Commission 2008). EU member states are required to manage the marine environment to ensure ‘Good Environmental Status’ (GES), but given the paucity of information on population or ecosystem level effects of underwater noise (descriptor 11 of MSFD), measuring whether GES is being achieved remains challenging. The framework presented here offers a basis to begin assessing GES by identifying areas where high levels of noise coincide with areas of greatest usage by sensitive species. This provides evidence for further investigation and the application of mitigation measures (Bagočius 2014; Merchant *et al.* 2014). Here, we demonstrate areas where high rates of co-occurrence between seals at-sea and shipping coincide with SACs; designated to protect these species at a population level during important periods of their life history through the Habitats Directive. To manage this risk and develop properly targeted mitigation solutions, there remains a need to improve understanding of the implications of cumulative exposure to elevated ambient noise levels for both individual- and population-level effects.

FUTURE RECOMMENDATIONS

We describe a framework to identify risk of exposure to marine species populations from shipping traffic, through spatially explicitly calculating rates of co-occurrence between animals and vessels. We then predict exposure to individuals using acoustic models to estimate mean SPL and cSEL(M_{pw}) with associated uncertainty. Where there are increasing populations of animals combined with a growing volume of ship traffic, spatial co-occurrence can be used to identify new regions of overlap. In areas where levels of noise exposure to individuals are above acceptable thresholds, the framework could inform mitigation measures to reduce noise to tolerable levels. However, there remains a need to investigate the impact of elevated noise exposure on avoidance behaviour of individuals. To understand the long-term implications of exposure to noise from shipping, targeted studies to assess the effects on individual survival and reproductive parameters in areas with quantified but differing levels of shipping would be useful.

Authors' contributions

E.L.J., S.S., G.D.H., J.O., D.T. conceived the manuscript; E.L.J. drafted the manuscript; J.O. and K.L.B. provided data; E.L.J., G.D.H. and N.D.M. analysed the data. All authors provided intellectual input and editorial content to the manuscript.

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Data accessibility

Ship usage maps are available to download from the Marine Management Organisation, https://data.gov.uk/dataset/mmo1066-vessel-density-grid-2012. Bathymetric metadata and Digital Terrain Model data products were derived from the European Marine Observation and Data Network (EMODNet) Bathymetry portal, available to download http://www.emodnet-bathymetry.eu. Sediment data are available from the British Geological Survey, http://www.bgs.ac.uk and available to view on Maremap, http://www.maremap.ac.uk/index.html. Global Self-consistent, Hierarchical, High-resolution Geography Database (GSHHG) shoreline data version 2.2.2 from NOAA were used to represent land, available from http://www.soest.hawaii.edu/pwessel/gshhg/.

Seal at-sea usage maps, location data for individual seals, locations and source levels for vessels, and SPLs from monitoring data used for acoustic validations are available from the Pure repository, https://doi.org/10.17630/89ac9345-240a-41bb-8f53-b3f14bb114c0. Data files SealAtSeaUsageMaps, SealTelemetryData, SourceLevelData, SoundMonitoringData (Jones *et al.* 2017).

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Supporting Information

Details of electronic Supporting Information are provided below.

Appendix S1. Usage maps.

Appendix S2. Modelling acoustic exposure.

Appendix S3. Sound exposure levels for individuals.

Appendix S4. Validating acoustic predictions with underwater sound measurements.

Appendix S5. Caveats and limitations.

Appendix S6. Spatial co-occurrence using 2011 ship usage maps.