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FTOWDG SAFESIMM Marine Mammal Noise Impact Assessment – Seals, bottlenose dolphins and harbour porpoises (Seagreen Firth of Forth Offshore Windfarm – Phase 1)

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1 Introduction

Pile driving during the construction of offshore wind turbines has the potential to produce levels of noise in the marine environment which may have a detrimental effect on marine animals. SMRU Ltd were contracted by the Forth and Tay Offshore Developers Group to assess the potential impacts of pile driving at multiple development sites on local marine mammal populations during the construction of wind farms in the region.

A detailed description of the potential effects of pile driving noise on marine mammals is outwith the scope of this report; this assessment is only concerned with two main types of impact. The first is a reduction in hearing ability (permanent and temporary threshold shift) and the second is the elicitation of behavioural responses to sound which may result in animals being displaced away from areas around the piling activities.

The assessment approach combines three key pieces of quantitative information to estimate the number of animals likely to be affected by each type of impact: 1) the predicted spatial pattern and extent of underwater noise produced by piling activities, 2) the spatial pattern of abundance of marine mammals across the area of potential impact, and 3) the way in which animals are predicted to move in response to sound.

This report presents the results of these modelling exercises for both species of seal (harbour seal and grey seal), for bottlenose dolphins and for harbour porpoise for pile driving at the Firth of Forth site at two locations (Alpha and Bravo) and two sets of engineering parameters (drive-only and drive-drill-drive). This report also presents results for piling at the Firth of Forth site concurrent with piling at the two Scottish Territorial Waters offshore wind farm sites within the Forth and Tay region; Inch Cape and Neart na Gaoithe.

2 Methodology

SAFESIMM (Statistical Algorithms For Estimating the Sonar Influence on Marine Megafauna) is a software tool for estimating the potential effects of anthropogenic noise on marine fauna. SAFESIMM can also be used to compare the effectiveness of different strategies for mitigating the effects of anthropogenic sound by determining the risk associated with these strategies under a range of scenarios. For example, a proposed sound producing activity can be analysed with SAFESIMM to determine the likely effects of changes in operational parameters (such as the activity location and time of year, or the source level, frequency and duty cycle of the sound production) on the risk to marine mammals (please see Appendix One for full details of the algorithm).

2.1 Physical Effects

The main physical effect on marine mammals that is likely to occur as a result of turbine construction is Permanent Threshold Shift (PTS). This involves a permanent impairment in hearing sensitivity at a particular frequency caused by exposure to excessive sound levels. There have been no direct experiments on marine mammals to determine what sound levels may cause PTS. Rather, these levels have been estimated by determining what sound levels are required to cause a temporary threshold shift (TTS) and then estimating what additional sound exposure would be required to cause PTS by inference from the results of experiments with small mammals. Southall *et al*. (2007) used this approach to derive interim recommendations of the sound levels that could cause PTS in different groups of marine mammals. They also developed a series of weighting functions (M-weightings) that could be used to take account of the hearing sensitivities of four different marine mammal groups (low frequency cetaceans, mid-frequency cetaceans, high frequency cetaceans and pinnipeds). The authors recommend the following values for the onset of PTS based on M-weighted Sound Exposure Levels (SELs) for both pulsed (such as those produced during pile driving) and non-pulsed sounds (such as vessel noise or that produced during cable laying):

Cetaceans = Pulsed (198dB), Non-pulsed (215dB)
Pinnipeds = Pulsed (186dB), Non-pulsed (203dB)

They also recommended a similar set of values for the onset of TTS:

Cetaceans = Pulsed (183dB), Non-pulsed (195dB)
Pinnipeds = Pulsed (171dB), Non-pulsed (183dB)

However, exposure to SELs at or above these levels does not mean that an animal is certain to experience TTS or PTS, because the onset of threshold shift is a probabilistic phenomenon. The data from Finneran *et al.* (2005) that were used by Southall *et al.* (2007) to develop the TTS values for mid-frequency cetaceans indicate that ~18-19% of exposures to an SEL of 195 dB re 1 $\mu Pa^2.s^{-1}$ resulted in measurable TTS. SAFESIMM therefore uses a series of dose-response relationships derived from Finneran *et al.*'s work to determine the likely effect of sound exposure on the different marine mammal groups. These dose-response relationships are shown in Figure 1. In these relationships, the probability that an animal which is exposed to an SEL equivalent to the threshold values recommended by Southall *et al.* (2007) will experience PTS or TTS is set at 0.18, and that probability increases as the SEL increases.

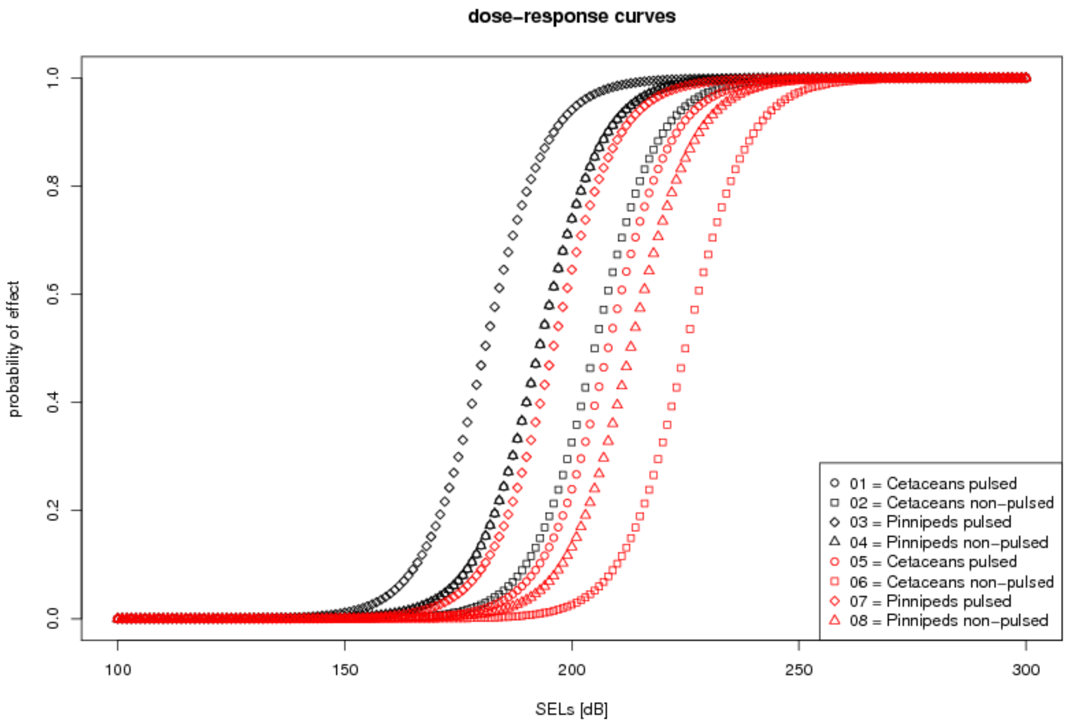

Figure 1 Dose-response curves used within SAFESIMM to relate the probability of Temporary Threshold Shift (black curves) and Permanent Threshold Shift (red curves) to M-weighted Sound Exposure Level (SEL) for cetaceans and pinnipeds exposed to pulsed and non-pulsed sounds.

SAFESIMM provides estimates of the number of animals of each species of marine mammal that may experience PTS and TTS from a particular sound field by simulating the three dimensional movements of thousands of simulated animals through this field, based on known characteristics of the diving and swimming behaviour of each species, and recording the cumulative SEL of each simulated individual. The species-specific PTS and TTS dose-response curves are then used to convert each individual's SEL into a probability that it will experience PTS or TTS. The initial locations of these simulated animals are chosen at random, although the density of simulated animals in any grid cell is proportional to the expected density provided by the animal density data. The actual number of animals predicted to experience PTS and TTS at individual locations is then calculated by scaling these simulated values using estimates of the expected densities of all marine mammal species at each location.

The density data for grey seals and harbour seals used in the simulations were provided by the Sea Mammal Research Unit at a resolution of 5km x 5km (Sparling et al. 2011: FTWODG seal baseline report)(Figure 2 and Figure 3). This grid was converted into a 0.083 degree grid for incorporation into SAFESIMM. The density estimate for bottlenose dolphins was derived from Quick and Cheney (2011) and was applied over all 0.083 degree grid cells which overlapped with the areas surveyed. This resulted in a uniform density estimate of 0.35 dolphins/km^2 (Figure 4). For harbour porpoises, density estimates were derived from the integrated analysis of cetacean density currently being carried out under a contract between SMRU Ltd and the FTOWDG. This analysis integrates data from a number of different surveys across the FTOWDG area (the separate boat surveys of the three windfarm areas by the individual developers and the aerial survey of the whole Forth and Tay region carried out by WWT and funded by The Crown Estate). A figure for this density surface is not yet available; the full methodology and results from this analysis will be reported separately but this analysis uses the generated density surface integrated over all surveys and averaged over all seasons and years.

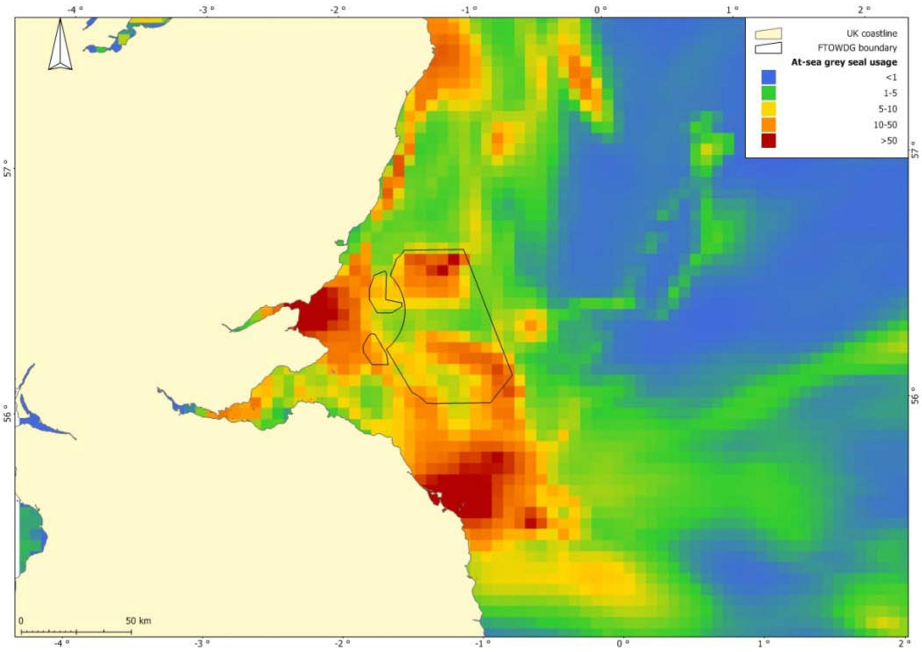

Figure 2. Grey seal density surface used in the simulations (from Sparling et al. 2011)

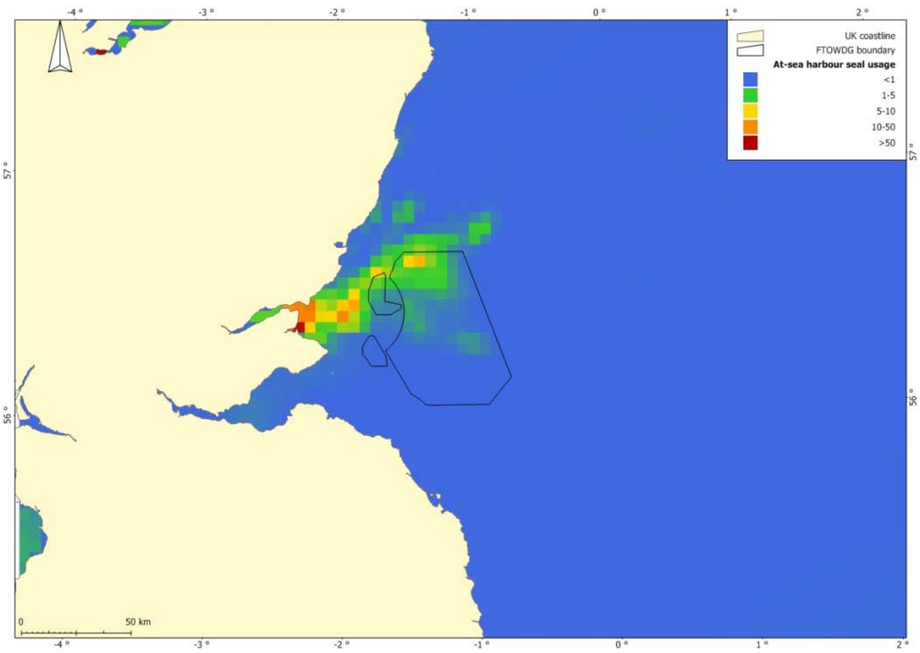

Figure 3. Harbour seal density surface used in the simulations (from Sparling et al. 2011)

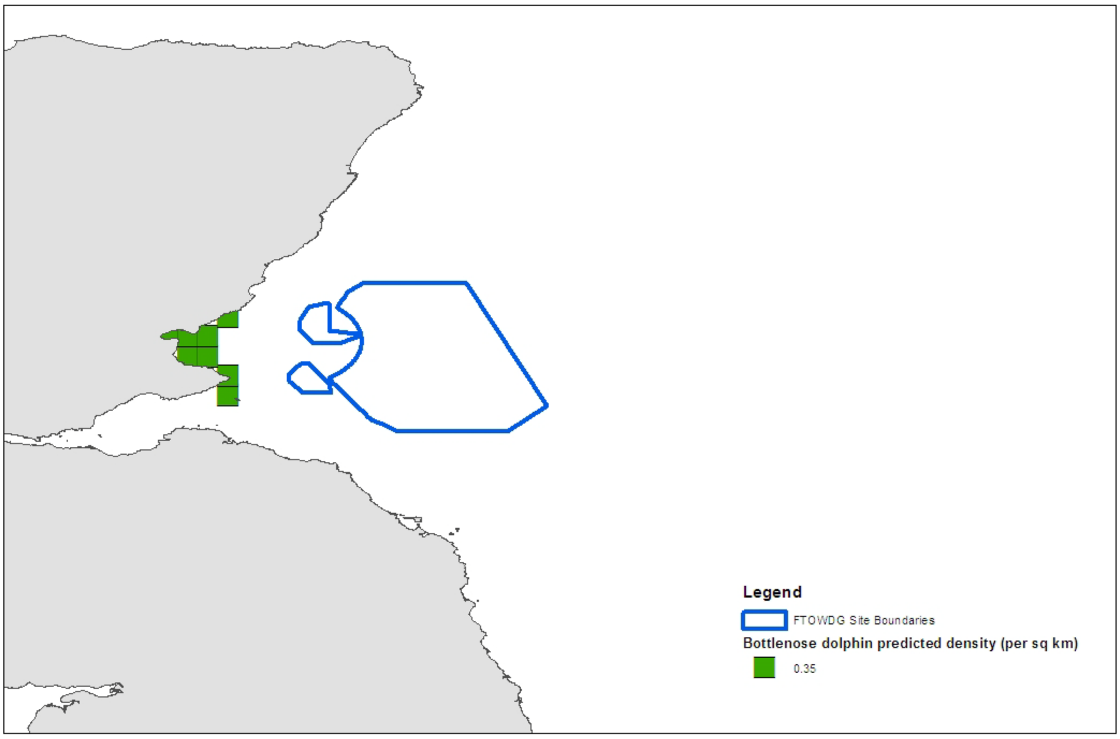

Figure 4. Bottlenose dolphin density surface used in the simulations (derived from Quick and Cheney, 2011).

2.2 Behavioural Effects

SAFESIMM has the capability to simulate known behavioural responses of marine mammals to sound exposure. Incorporating behavioural responses where animals move away or towards the sound source provides not only another metric for assessment, but may also have an important bearing on the number of individuals predicted to experience physical injury. Unless otherwise specified, animals are predicted to follow a correlated random walk. However, they can be programmed to move towards or away from the sound source, both horizontally and/or vertically, if the received level of sound is above a given threshold. For the purposes of this assessment, an individual's movement in response to sound was determined probabilistically using a dose-response curve based on the seal assessment framework (Thompson et al., 2011; Figure 5) which predicts the proportional change in the occurrence of harbour porpoises with distance from a piling event and is based on data from changes in the detection rates during piling at the Horns Rev 2 wind farm from Brandt et al (2011). In the absence of empirical data from other species, this curve has been adopted in this assessment for seals and bottlenose dolphins. It should be highlighted that the Seal Assessment Framework uses dBht as a metric to predict behavioural response; however, to simplify the incorporation of a behavioural response in SAFESIMM, an M-Weighted SEL dose response curve based on Thompson et al's (2011) work was used. Comparison of the single hammer blow SEL's with the equivalent calculated dBht in the Moray Firth demonstrated that at a given distance from the piling location, the predicted instantaneous SEL and predicted dBht for that location resulted in the same probability of behavioural avoidance, providing confidence that the metrics were comparable.

At each time step in the simulation, the probability that each simulated individual will respond to the instantaneous M-weighted SEL experienced at its location is determined by this dose-response curve. The response simulated is a movement directly away from the sound source (i.e. a flight response). The speed at which grey and harbour seals move was determined from unpublished telemetry data collected in the FTOWDG region by SMRU. This gave a minimum speed of $0.01 m.s^{-1}$ for both species and maximum speeds of $2.6 m.s^{-1}$ for grey seals and $2.3 m.s^{-1}$ for harbour seals. The minimum and maximum values of $0.01 m.s^{-1}$ and $5.6 m.s^{-1}$ for bottlenose dolphins and $0.01 m.s^{-1}$ and $3.5 m.s^{-1}$ for harbour porpoises were obtained from an extensive literature search.

The total numbers of individuals that respond in this way over the course of the scenario is documented by SAFESIMM and provided as an output. However, this metric does not distinguish between individuals that respond many or only a few times throughout the simulation, or how far they move away, or how long they stay away. It simply counts the number of animals that received a sound dose high enough to cause them to swim away from the sound at least once during the simulation . This is unlikely to provide a realistic estimate of displacement from an area as a result of piling activity. Any predicted behavioural responses needs to be carefully interpreted in light of the likely spatial and temporal variation in abundance and likely motivation for being in a given area.

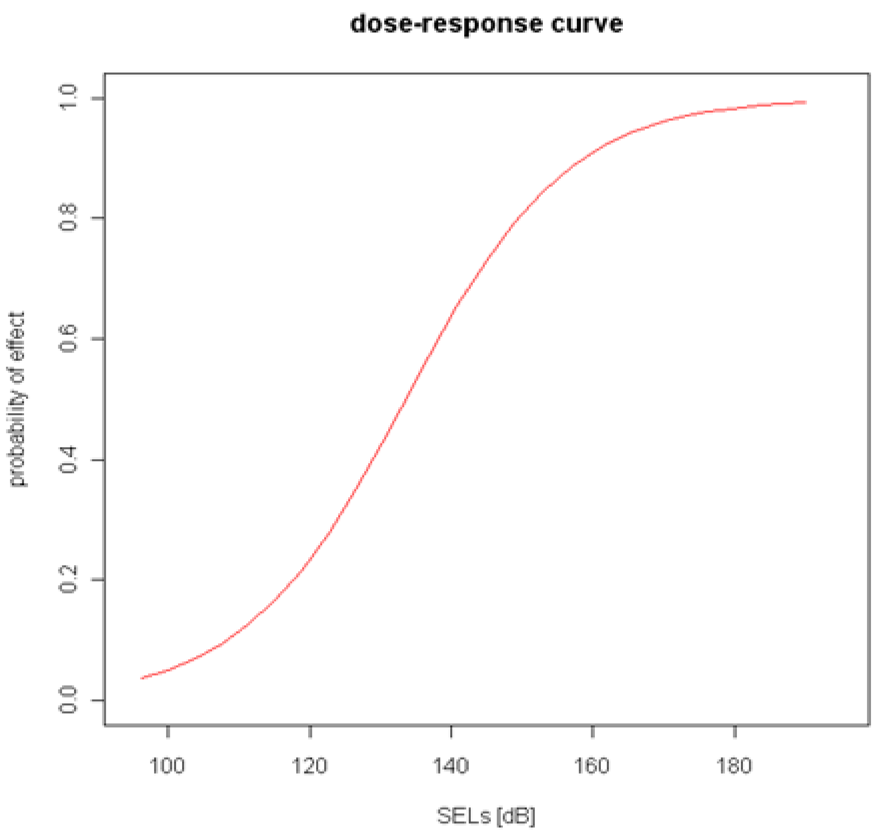

Figure 5. Dose-response curves used within SAFESIMM to relate the probability of behavioural displacement to M-weighted Sound Exposure Level (SEL – calculated over a single hammer blow) for cetaceans and pinnipeds exposed to pile driving noise.

2.3 Parameters modelled

Subacoustech provided SMRU Ltd with the outputs of sound propagation models for each pile driving scenario in the format of a calculated M-weighted SEL for a single hammer blow (of 0.5 sec duration) for each blow energy used during the piling event, on 96 transects 3.75^{o} apart radiating from the source location. The predicted SEL was provided at range steps of 100m along each transect. SAFESIMM then carried out a simulation of animal exposure over the whole piling duration using parameters for duration and strike rate provided by Seagreen (Appendix Two). Where ramp ups were included in the engineering scenarios, Subacoustech provided a separate sound field for each different blow force used – SAFESIMM cycled through these in accordance with the duration of each step in the ramp up. The details of the engineering scenarios and piling locations can be found in Appendix Two and are summarised in Table 1. There are uncertainties relating to the effect of breaks in piling. For the Seagreen drive-drill-drive scenarios, initial tests concluded that incorporating the drilling period in the simulations did not change the predictions of injury. As a result, these simulations were run with only the driving portion of the sound included in the simulations.

Table 1. Summary of the piling scenarios assessed – these represent the activity required to install one pin pile at the stated location.

Scenario	Pile diameter	Location	Description	Piling duration (mins)	Max blow energy (kJ)
S1a GM1	2m	Alpha	Drive only	51	1425 (95%)
S1b GM1	2m	Bravo	Drive only	51	1425 (95%)
S3a GM3	2m	Alpha	Drive-Drill-Drive	32	900 (75%)
S3b GM3	2m	Bravo	Drive-Drill-Drive	32	900 (75%)
C01	2m	Alpha & Bravo	Drive only	51	1425 (95%)
C02	2m	Alpha & Bravo	Drive-Drill-Drive	32	900 (75%)
C06	2m 2.5m	Alpha +Inch Cape	Drive-Drill-Drive Drive only	32 180	900 (75%) 1200
C07	2m 2.4m	Alpha +Neart na Gaoithe	Drive-Drill-Drive Drive-Drill-Drive	32 200	900 (75%) 996 (83%)
C08	2m 2.4m 2.5m	Alpha +Inch Cape +Neart na Gaoithe	Drive-Drill-Drive Drive only Drive-Drill-Drive	32 180 200	900 (75%) 1200 996 (83%)

3 Results

3.1 Firth of Forth Site scenarios

Between 76 and 144 grey seals were predicted to experience PTS as a result of cumulative exposure to piling noise, depending on the location of the piling and the engineering parameters adopted (Table 1). Between five and 16 individual harbour seals were predicted to experience PTS. The difference between the two species is a consequence of the much larger numbers of grey seals predicted to be present in the area, this is the case across all scenarios. However, when expressed as relative to the number of animals predicted to be in the area however, the relative numbers of harbour seals predicted to experience PTS is higher than for grey seals. For example, for the drill-drive-drill scenario at Alpha, the number of grey seals predicted to experience PTS (77) represents 1% of the abundance in the area of calculation (AOC[1]), whereas the number of harbour seals (9) represents 3% of the predicted number in the AOC.

Similarly the proportion of harbour seals responding behaviourally throughout the simulation was higher than grey seals, although the absolute numbers of animals affected were lower. 17-25% of the grey seals in the AOC, and 30-45% of the harbour seals were predicted to respond to the noise at least once during the simulation (Table 3).

No bottlenose dolphins were predicted to experience PTS or TTS in any of the Firth of Forth scenarios (Table 2). Between 5 and 48 bottlenose dolphins were predicted to respond behaviourally during the simulation (Table 3), this represents between 4 and 38% of the number in the AOC.

Between two and six harbour porpoises were predicted to experience PTS as a result of cumulative exposure to piling noise, depending on the location of the piling and the engineering parameters adopted (Table 2). Between 666 and 1126 harbour porpoises were predicted to respond behaviourally throughout the simulation (Table 3), this represents between 21 and 35% of the number in the AOC.

For grey seals the predicted impacts were similar regardless of whether piling was at Alpha or Bravo, this is likely as a result of grey seal density being relatively similar in the vicinity of both locations. In contrast, for both injury and behaviour metrics, piling at Alpha resulted in higher level of impacts for harbour seals across all engineering parameters than piling at Bravo (Table 2 and Table 3). This is probably due to the closer proximity of the Alpha piling location to areas of higher density of harbour seals. The spatial pattern of predicted impact on seals can be seen in Figure 7.

For harbour porpoises the impacts were slightly higher when piling at Bravo compared to piling at Alpha (Table 2, Table 3 and Figure 8). This reflects the relative densities of porpoises around these locations.

[1] The abundance in the area of calculation (AOC) is not intended to provide an indication of a biologically meaningful reference population against which to assess impacts. Although the numbers do reflect the relative abundances of the species involved, it is used here to provide a basic metric for comparison between scenarios and species in terms of relative magnitude of impact.

In general, across all species, predicted impacts were lower for the drive-drill-drive scenarios than the drive-only scenarios. Across all species, the numbers predicted to experience PTS (Table 2) under the drill-drive-drill parameters were approximately half those for the drive only scenario. This is likely to be a result of the overall lower blow energies and shorter piling durations in the drive-drill-drive scenarios compared to the drive only scenarios. The reduction in the numbers of animals responding to the noise was relatively lower than the reduction in injury metrics, with a reduction of approximately 20% in the number of harbour and grey seals responding between the drive only and drive-drill-drive scenarios.

Spatially, the areas of highest impact were generally centred on the piling locations (Figures 6-8) and areas of high marine mammal density (also see Figure 2 and Figure 3).

Table 2. The number of grey seals, harbour seals and bottlenose dolphins predicted to experience physical (PTS) effects and temporary hearing effects as a result of the different piling scenarios at the Firth of Forth site. The number of animals predicted to be at-sea within the area of calculation was 8969 grey seals, 337 harbour seals, 126 bottlenose dolphins and 3205 harbour porpoises.

Construction scenario	Description	Harbour seal		Grey Seal		Bottlenose dolphin		Harbour porpoise	
		TTS	PTS	TTS	PTS	TTS	PTS	TTS	PTS
S1a GM1	Drive only, Alpha 2m	62	16	655	144	0	0	43	5
S1b GM1	Drive only, Bravo 2m	38	10	646	142	0	0	51	6
S3a GM3	Drill-Drive, Alpha 2m	34	9	331	77	0	0	21	2
S3b GM3	Drill-Drive, Bravo 2m	17	5	330	76	0	0	25	3

Table 3. The number of grey seals, harbour seals, bottlenose dolphins and harbour porpoises predicted to respond behaviourally during the simulations of different piling scenarios at the Firth of Forth. The number of animals predicted to be at-sea within the area of calculation was 8969 grey seals, 337 harbour seals, 126 bottlenose dolphins and 3205 harbour porpoises.

Construction scenario	Description	Harbour seal	Grey Seal	Bottlenose dolphin	Harbour porpoise
S1a GM1	Drive only, Alpha 2m	152	2281	48	1020
S1b GM1	Drive only, Bravo 2m	125	2166	26	1126
S3a GM3	Drive-Drill-Drive, Alpha 2m	120	1663	18	666
S3b GM3	Drive-Drill-Drive, Bravo 2m	102	1571	5	744

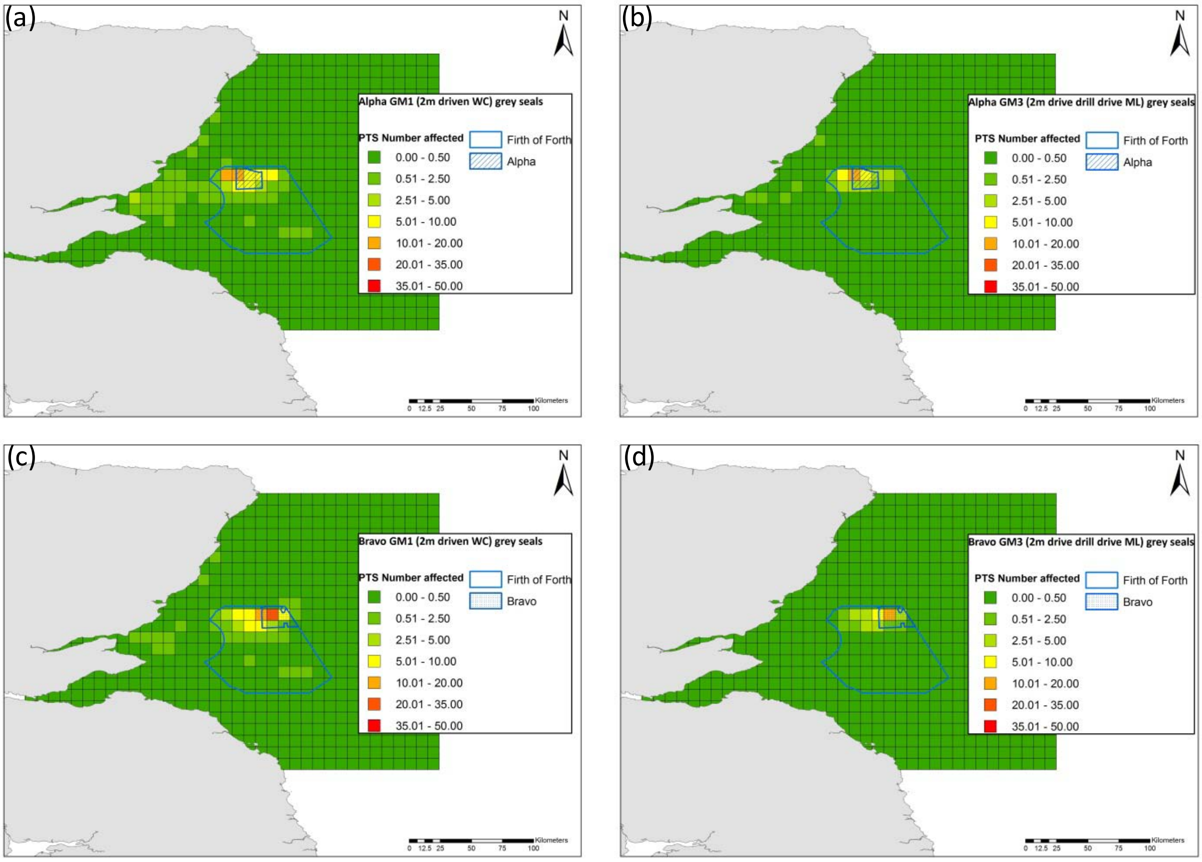

Figure 6. The number of grey seals predicted to experience PTS per 0.083 deg grid cell within the area of calculation (boundary of green area) for (a) Alpha drive only, (b) Alpha drive-drill-drive, (c) Bravo drive only, and (d) Bravo drive-drill-drive.

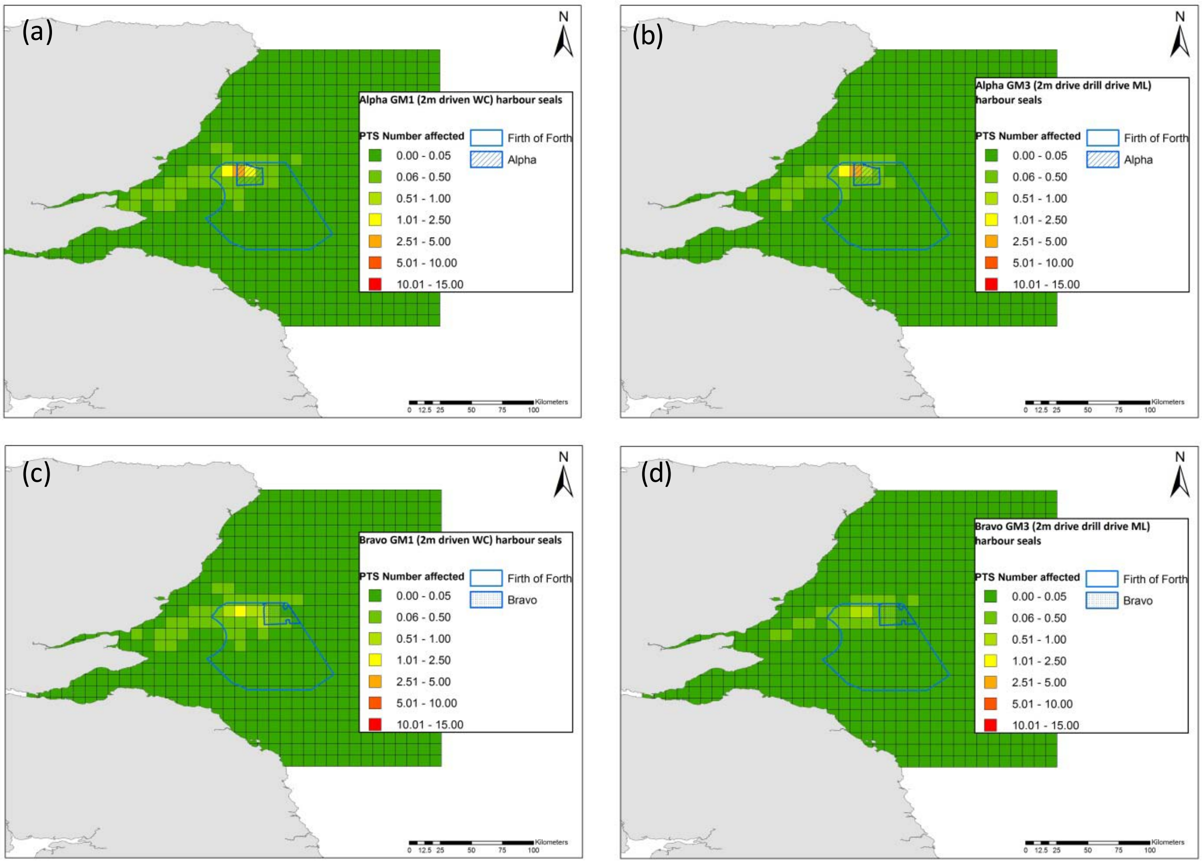

Figure 7. The number of harbour seals predicted to experience PTS per 0.083 degree grid cell within the area of calculation (boundary of green area) for (a) Alpha drive only, (b) Alpha drive-drill-drive, (c) Bravo drive only, and (d) Bravo drive-drill-drive.

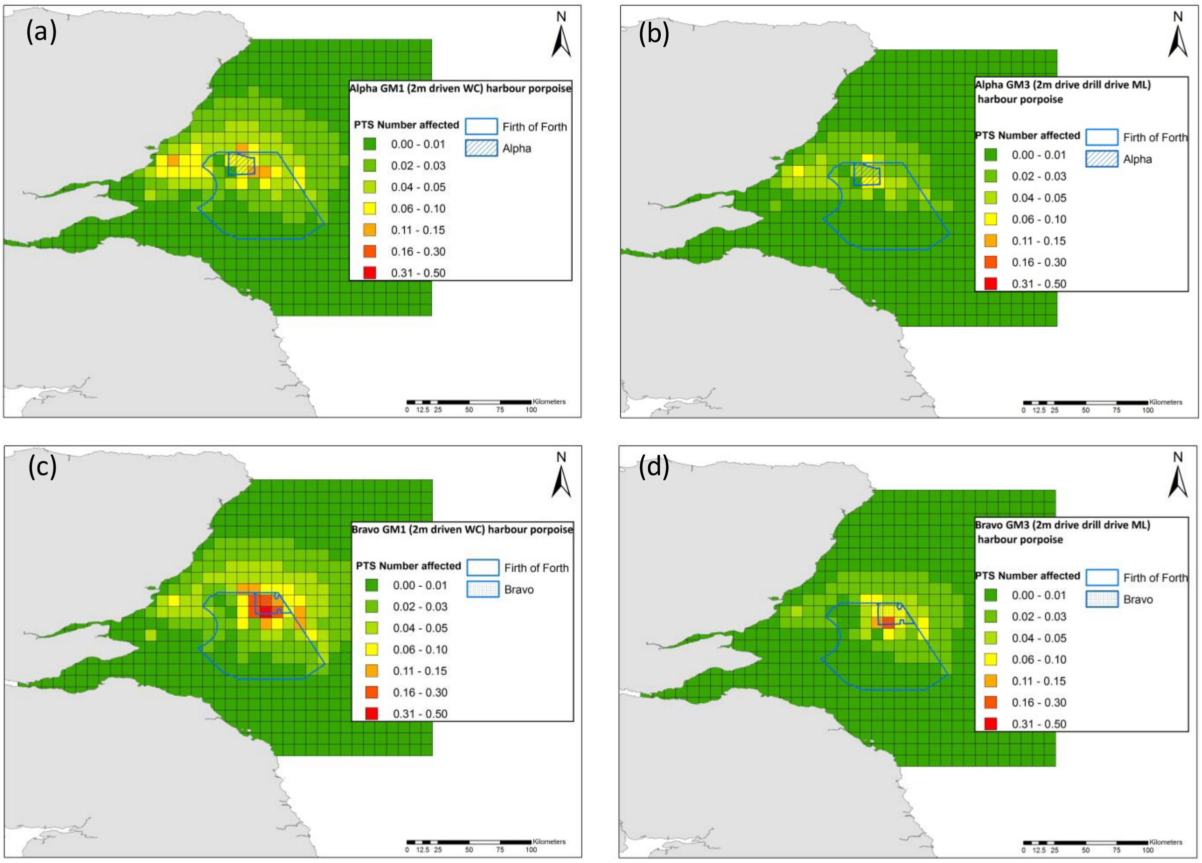

Figure 8. The number of harbour porpoises predicted to experience PTS per 0.083 deg grid cell within the area of calculation (boundary of green area) for (a) Alpha drive only, (b) Alpha drive-drill-drive, (c) Bravo drive only, and (d) Bravo drive-drill-drive.

3.2 Cumulative scenarios

Increasing the number of sites at which piling occurred concurrently increased the predicted impacts, for both injury and behaviour. As was the case with the single location predictions, predictions of impact were higher for drive only scenarios than for drive-drill-drive scenarios (Table 4 and Table 5).

Overall, impacts were highest when piling was occurring at all three wind farm sites concurrently (Firth of Forth (FoF), Neart na Gaoithe (NNG) and Inch Cape (IC)). Predicted impacts for seals and bottlenose dolphins were higher when piling at Firth of Forth (Alpha) was concurrent with piling Neart na Gaoithe than when piling at Firth of Forth (Alpha) was concurrent with piling at Inch Cape (Table 4 and Table 5; Figures 9-12). For harbour porpoises the predicted impacts differed little between the two double site scenarios (Table 4 and Table 5; Figure 12).

Spatially, the areas of highest impact were generally centred on the piling locations, in a similar way to the single site simulations. However, when there was concurrent piling at other wind farm sites which were closer to the shore, increased levels of impact were predicted in coastal areas. This was particularly the case for seals and bottlenose dolphins (Figures 9-12). Predictions of auditory injury in seals were particularly high around the mouth of the Tay and Eden Estuary (Figure 9 and 10). This is likely to be a result of particularly high seal density in these areas (Figure 2 and Figure 3). Seals do have the option of hauling out at these locations during periods of low tide when the sandbanks are exposed, and thus preventing any further exposure to underwater noise. However haul out behaviour is not currently incorporated into the simulations. For harbour porpoises, impacts were highest around the Bravo location when piling was concurrent at Alpha and Bravo. When piling at the other FTWODG sites was included with piling at Alpha, impacts were comparatively higher around the other sites (Figure 12).

Predictions of injury for bottlenose dolphins in the cumulative scenarios are, inevitably, restricted to the known range of the species in this region (see Figure 4). The simulations assumed a uniform density of dolphins across this range, but actual density may be lower in the part of the range closest to the NNG site given that there are relatively few sightings here, particularly in the winter months (Quick and Cheney, 2011). These cells, which are at the southern extreme of the dolphins' predicted range, have the highest predicted risk of auditory injury (Figure 11). It should be recognised that bottlenose dolphins probably occur outside the range assumed here, but we currently have no data with which to quantify this.

Table 4. The number of grey seals, harbour seals, bottlenose dolphins and harbour porpoises predicted to experience physical (PTS) effects as a result of the different piling scenarios at the Firth of Forth site, Inch Cape (IC) and Neart na Gaoithe (NNG).

Scenario	Description	Harbour seal		Grey Seal		Bottlenose dolphin		Harbour porpoise	
		TTS	PTS	TTS	PTS	TTS	PTS	TTS	PTS
C01	Drive only, Alpha and Bravo	75	21	983	236	1	0	72	9
C02	Drive-Drill-Drive, Alpha and Bravo	52	12	621	131	0	0	35	4
C06	Drive-Drill-Drive, Alpha & IC	129	33	1410	308	5	1	71	9
C07	Drive-Drill-Drive, Alpha & NNG	170	47	2017	506	26	4	70	9
C08	Drive-Drill-Drive, Alpha, IC & NNG	192	59	2267	609	27	4	99	13

Table 5. The number of grey seals, harbour seals, bottlenose dolphins and harbour porpoises predicted to respond behaviourally during the simulations of different piling scenarios at the Firth of Forth site, Inch Cape (IC) and Neart na Gaoithe (NNG).

Construction scenario	Description	Harbour seal	Grey Seal	Bottlenose dolphin	Harbour porpoise
C01	Drive only, Alpha and Bravo	153	2426	50	1207
C02	Drive-Drill-Drive, Alpha and Bravo	123	1807	19	789
C06	Drive-Drill-Drive, Alpha & IC	268	3579	103	1031
C07	Drive-Drill-Drive, Alpha & NNG	313	5640	124	1464
C08	Drive-Drill-Drive, Alpha, IC & NNG	316	5756	124	1473

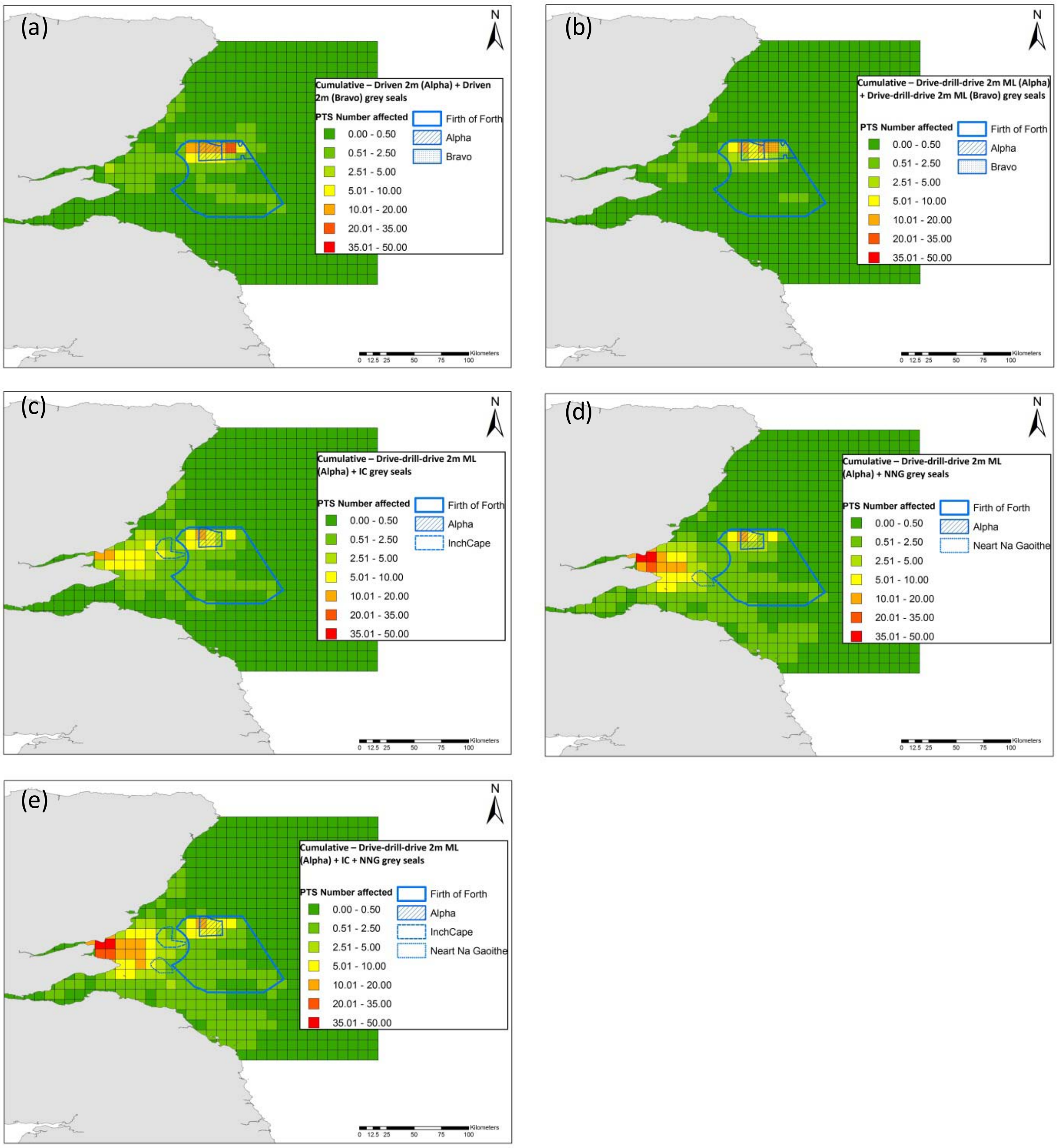

Figure 9. The number of grey seals predicted to experience PTS per 0.083 deg grid cell within the area of calculation (boundary of green area) for (a) Alpha and Bravo drive only, (b) Alpha and Bravo drive-drill-drive, (c) Alpha drive-drill-drive and Inch Cape, (d) Alpha drive-drill-drive and Neart na Gaoithe, and (e) Alpha drive-drill-drive, Inch Cape and Neart na Gaoithe.

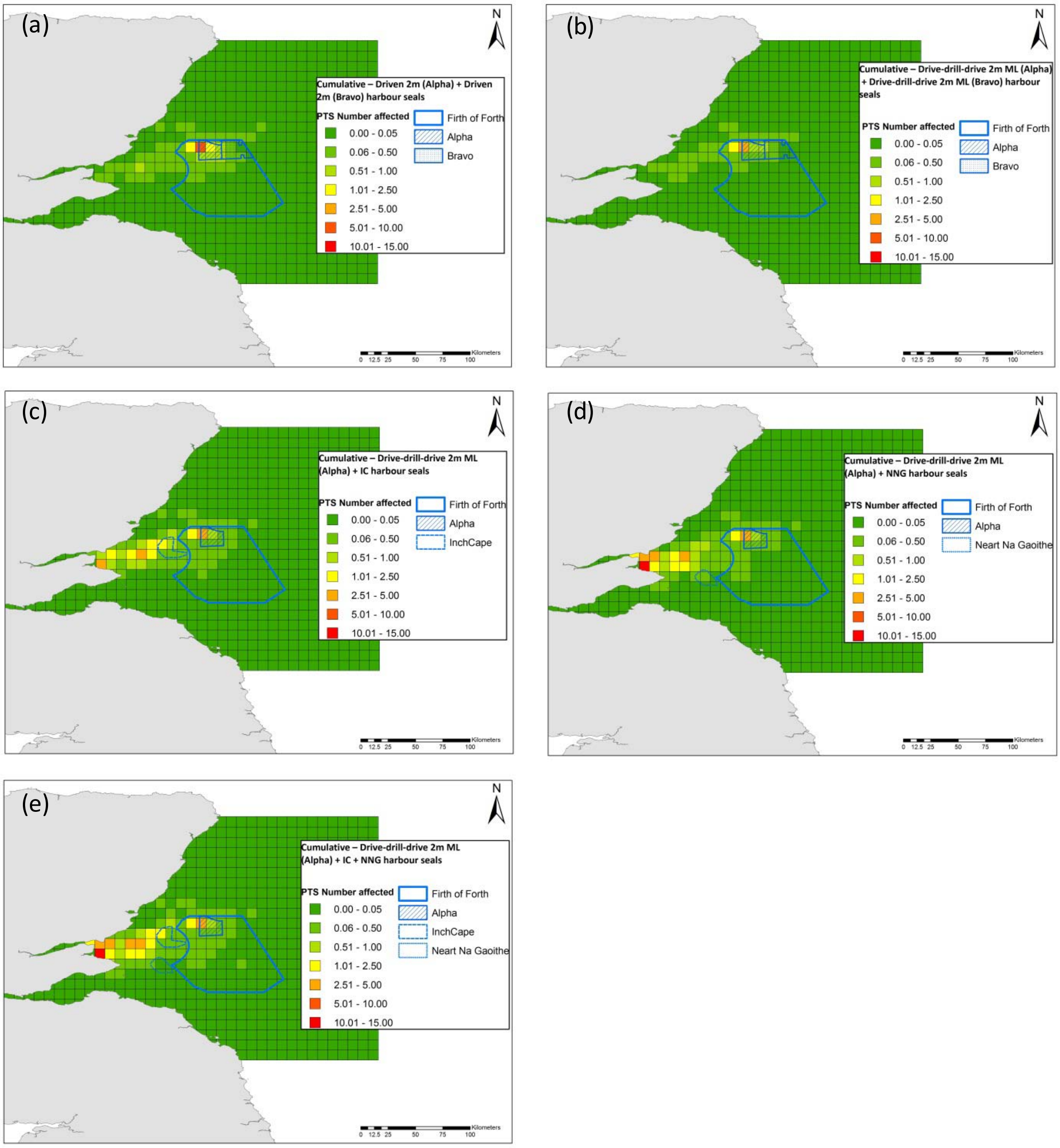

Figure 10. The number of harbour seals predicted to experience PTS per 0.083 deg grid cell within the area of calculation (boundary of green area) for (a) Alpha and Bravo drive only, (b) Alpha and Bravo drive-drill-drive, (c) Alpha drive-drill-drive and Inch Cape, (d) Alpha drive-drill-drive and Neart na Gaoithe, and (e) Alpha drive-drill-drive, Inch Cape and Neart na Gaoithe.

Figure 11. The number of bottlenose dolphins predicted to experience PTS per 0.083 deg grid cell within the area of calculation (boundary of green area) for (a) Alpha and Bravo drive only, (b) Alpha and Bravo drive-drill-drive, (c) Alpha drive-drill-drive and Inch Cape, (d) Alpha drive-drill-drive and Neart na Gaoithe, and (e) Alpha drive-drill-drive, Inch Cape and Neart na Gaoithe.

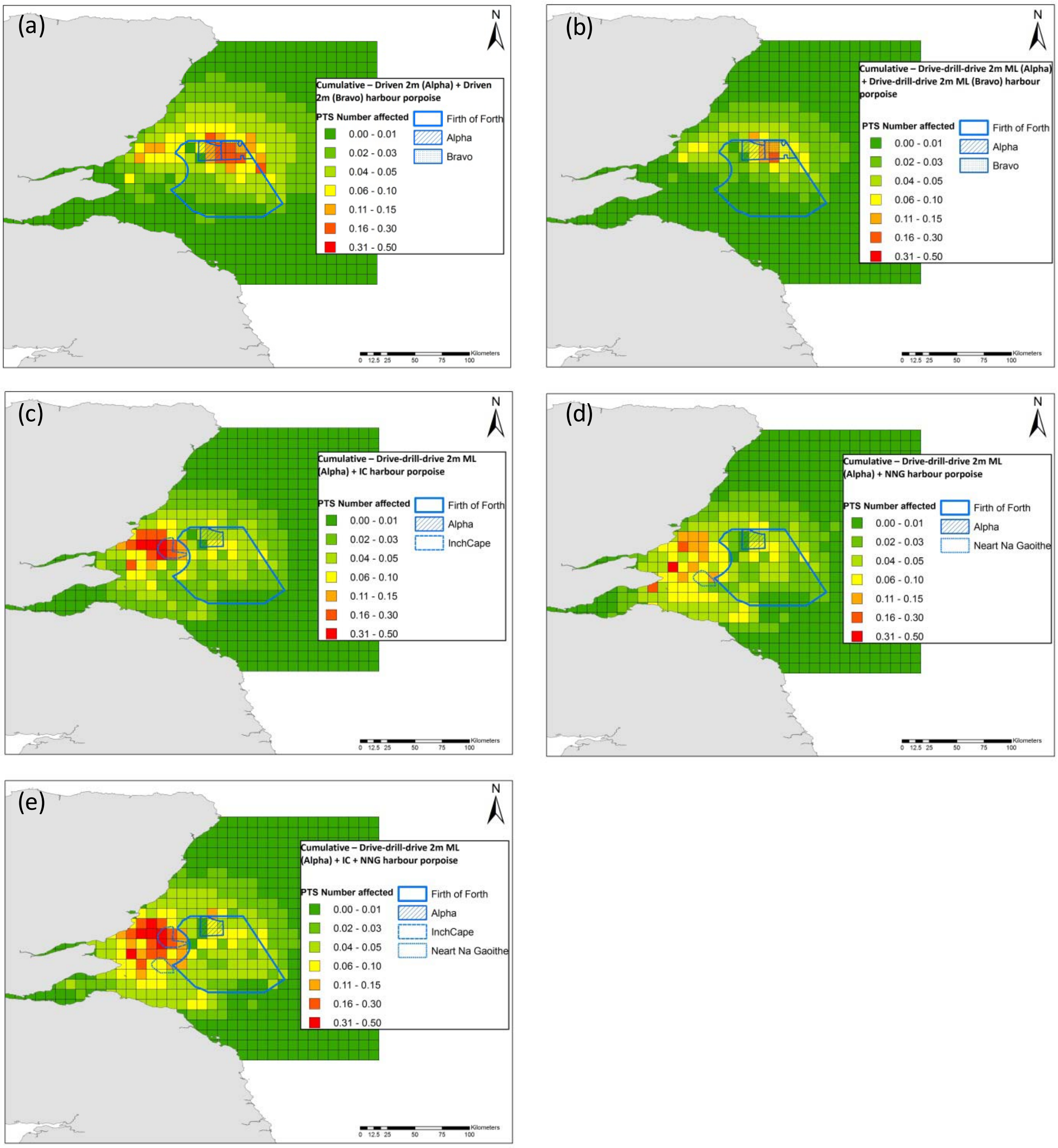

Figure 12. The number of harbour porpoises predicted to experience PTS per 0.083 deg grid cell within the area of calculation (boundary of green area) for (a) Alpha and Bravo drive only, (b) Alpha and Bravo drive-drill-drive, (c) Alpha drive-drill-drive and Inch Cape, (d) Alpha drive-drill-drive and Neart na Gaoithe, and (e) Alpha drive-drill-drive, Inch Cape and Neart na Gaoithe.

4 Discussion

The differences in the number of animals showing behavioural responses between the 'best' and 'worst' scenarios were generally less pronounced than those for injury metrics. This is partly because, the spatial area over which sound levels with the potential to cause a behavioural response occurs is always larger than the spatial area covered by sound levels with the potential to cause injury. Therefore an increase in the number of locations, or an increase in the blow energies (leading to louder piling events) has a greater effect on the total area of impact for injury than for behaviour. In addition, the probability of a behavioural response is determined by the absolute loudness of the sound to which animals are exposed, whereas the probability of injury is determined by the cumulative exposure to sound over time. Absolute loudness levels were more similar between the different scenarios than cumulative exposure levels. Therefore an increase in the number of piling events will increase cumulative sound exposure (and therefore the probability of injury) more than it will increase the number of animals responding behaviourally.

However, the number of animals responding at least once does not reflect the full extent of the behavioural effects of sound exposure. There are likely to be more marked differences between scenarios in the proportion of time individual animals spend responding to sound exposure and the distances they move in response. However, at present, the software cannot provide this information as an output. Furthermore, the current behavioural metric does not provide information on what the consequences of this response may be for the population in the long term. The metric is used here to provide a basic assessment of the scale of the response and how it might differ under different scenarios. Assessment of the long term population consequences will require much more detailed information on the spatial and temporal variability in behavioural response between individual animals. It will also require a number of assumptions regarding how changes in individual behaviour may impact population dynamics. Such an assessment is outwith the scope of this current work, although progress is currently being made on these issues on a number of projects.

These predictions rely on a number of assumptions about the response of animals to noise, the propagation of noise underwater and the underlying distribution and abundance of animals. In particular, the equations used to describe the response of the species considered here to sound exposure have limited empirical basis. A full examination of the sensitivity of the results of these simulations to variations in the assumptions adopted is beyond the scope of this report, but the biggest uncertainties probably relate to the nature and extent of species-specific behavioural responses to piling noise and the onset of auditory injury in relation to the temporal nature of exposure to piling noise.

Nevertheless these results represent an application of the best available information on these factors, along with the best available estimates of spatial variation in abundance in the region to produce the most robust estimates possible of the impact of pile driving in the FTOWDG region.

5 Summary and conclusions

- No bottlenose dolphins were predicted to develop PTS under any of the simulations involving piling at only the Seagreen Firth of Forth sites. A relatively high proportion of seals were predicted to develop PTS, this is likely to be due to their high predicted density in some parts of the area of calculation.
- Relatively high numbers of marine mammals were predicted to experience noise levels with the potential to elicit behavioural responses.
- In absolute terms, more grey seals were predicted to be affected than harbour seals. This is as a result of an overall higher abundance of grey seals in the region. However, the impacts on harbour seals were higher when they were expressed as a proportion of total abundance.
- Drive-drill-drive scenarios resulted in lower predictions of impacts across all species. This is because of the shorter duration of the piling operation and the lower blow energies used.
- Variations in the level of predicted impact between simulations of piling at Alpha and Bravo depended on the predicted underlying distribution of animals. Harbour seals were proportionately more impacted as result of piling at Alpha, whereas harbour porpoises were predicted to be more impacted from piling at Bravo. Grey seal impacts were similar between the two scenarios. In the cumulative scenarios, bottlenose dolphins were predicted to be impacted more when piling was closer to the coast, where they are more likely to be found. These results are sensitive to the assumptions made about the underlying distribution of animals.
- Injury metrics were more sensitive than behavioural responses to differences between scenarios, such as the number of locations and differences in engineering parameters. Although the differences can be largely explained by differences in the duration of piling and blow energies, there is a degree of variability due to stochasticity in animal responses and the probabilistic nature of the responses. Further development of SAFESIMM is required to provide a comprehensive description of the differences, and consequences, in behavioural responses between scenarios.

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I. Appendix One

Donovan et al. Quantifying the effects of anthropogenic sound on marine mammals.
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A simulation-based method for quantifying and mitigating the effects of anthropogenic sound on marine mammals

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Abstract

The SAFESIMM (Statistical Algorithms For Estimating the Sonar Influence on Marine Megafauna) algorithm is a software tool for estimating the potential effects of anthropogenic noise on marine animals. SAFESIMM can also be used to compare the effectiveness of different strategies for mitigating the effects of anthropogenic sound by determining the risk associated with these strategies under a range of scenarios. For example, a proposed sound producing activity can be analysed with SAFESIMM to determine the likely effects of changes in operational parameters (such as the activity location and time of year, or the source level, frequency and duty cycle of the sound production) on the risk to marine mammals.

Introduction

SAFESIMM is a simulation-based framework for calculating the probable numbers of animals affected by underwater sound; for example active sonar, which has been implicated in recent marine mammal fatalities (Parsons et. al. 2008). SAFESIMM is the culmination of a large, multi-year collaborative project between BAE Systems and the University of St Andrews, specifically the Centre for Research into Ecological and Environmental Modelling (CREEM) and the Sea Mammal Research Unit (SMRU).

The project draws together, into a software tool, results from the latest research on the effects of sound on marine mammals, and data on the distribution, abundance and hearing characteristics of these species. The end result is a simulation-based statistical model that quantifies the probability of physical effects and behavioural responses, along with the expected numbers of occurrences and associated uncertainty in the predictions. The parameters used in each simulation are easily altered, allowing rapid comparison of alternative scenarios.

SAFESIMM is modularized and designed to allow easy modification, in anticipation of the rapid progress being made in this research area. In most situations, new research can be incorporated simply by modifying parameter values or information held in internal databases. More fundamental shifts in our understanding can be incorporated by replacing existing modules with improved versions.

This paper describes:

1. The problem in general terms;
2. The logical high-level solution;
3. The principal questions that must be addressed,
4. The solutions to these based on current knowledge;
5. The framework (SAFESIMM) that combines these.

The problem

The over-arching question is simple: what is the likely effect on marine animals of any activity that involves the generation of relatively large amounts of underwater noise? It is clear from the outset that the answer must be probabilistic due to the inherent uncertainties. For example, the location of all animals relative to the source will never be known with certainty.

The problem is more approachable if it is divided into a series of smaller questions that can be addressed in turn:

1. What is the distribution of the sound source's energy through space and time?
2. What sound exposure histories are likely to be experienced by the different components of the marine fauna?

3. What is the likely effect on this fauna of a given history of sound exposure?

So far, most of the research in this area has focussed on one component of the marine fauna (marine mammals, and particularly cetaceans), because they are perceived (at least by the public) to be the most vulnerable to anthropogenic sound. We have followed this example in SAFESIMM, and the rest of this paper deals primarily with evaluating the potential impacts of such sounds on marine mammals.

The distribution of sound from the anthropogenic source

The underwater propagation characteristics for many anthropogenic sound sources are well known. Indeed, the effectiveness of active sonar depends on knowing how the emissions travel through the aquatic environment. More generally, there are established physics principles governing the transmission of sound waves through water that can be used to model propagation-loss under a particular set of physical conditions (e.g. source spectra, bathymetry, water column temperature profiles, sediment types etc.).

The output from such a two or three-dimensional propagation-loss model can be used to predict the received sound-level, and history of sound exposure, at any point in space and time in the ocean, provided the important oceanographic features and source characteristics are known.

The distribution of animals within the sound field

Although it may be possible to determine the precise locations of individual animals that are detected and tracked, the specific locations of the vast majority of animals within the sound field will never be known. This is, to a large extent because of the limited availability of animals for detection (e.g. at the surface for a visual observer, or vocalising if passive acoustic detection is being used) and the relatively low probability that animals will be detected even if they are available (e.g. animals far from the observer/detector are likely to be overlooked).

However, extensive information is available about the distribution of marine animals, both horizontally and vertically, from surveys and statistical models. Published survey results can be used to identify regions of high or low densities for many species. Similarly, species distribution maps can be constructed using information such as presence/absence, density and habitat preference (Kaschner et. al. 2006, Costello et. al. 2007). Detailed studies of the diving behaviour of marine mammals also provide information about their depth distributions. This can be at a coarse level (such as maximum dive depth and preferred depths) or fine scale (distribution at depth from models of dive patterns or animal tag data). Collectively, this information can be used to predict the distribution of most marine mammals species in three-dimensions, and these models can be used to provide probabilistic predictions for a given area and time.

The likely sound exposure of these animals can be derived from the history of sound exposure for a hypothetical animal as it moves through the sound field. The distribution model described above can be used to provide probable starting points for these hypothetical animals. Then a suitable movement model can be used to provide species-specific sound-exposure histories. These movement models can be parameterised from detailed studies of the behaviour of individual animals fitted with various kinds of telemetry devices. For example, we can use the distribution of swim speeds and dive depths of these animals, with constrained random components to reflect the uncertainties in actual movement.

The range of probable sound-exposure histories for all of the individuals likely to be exposed to the predicted sound field can therefore be found by repeated computer simulations using the species distribution information and movement model. Each simulated animal represents a possible reality of sound exposures. Hence it is possible to calculate probable exposures for all animals, even though their precise locations are unknown.

The effect of sound exposure history

Sound exposure histories form the basis of Health and Safety regulation for humans and elements of this approach can be used to answer similar questions for marine mammals. In terms of physical effects, the most important factor is the accumulated amount of sound energy the subject has been, or is likely to be, exposed to.

For humans, accumulated sound energy is calculated as a function of the received levels through time. These are typically weighted, to give a single numeric measure called the personal exposure level for the period exposed. The weighting assigns less importance to sounds at frequencies to which the human ear is least sensitive. Similar calculations can be performed for marine mammal sound exposure histories, with the weighting provided by a measured or assumed profile of hearing sensitivity. Southall et al (2007b) provide a set of such weightings for different groups of marine mammals.

In the human case, the accumulated sound exposure can be compared to threshold levels which delineate safe and unsafe histories of sound exposure. In general this is based on dose-response curves that predict the probability of a particular response given a particular sound exposure history. For human hearing, the most commonly used responses are temporary and permanent deafness (defined as an unacceptably large upward shift in the threshold for hearing) at particular frequencies.

Dose-response curves, relating sound exposure to the probability of physical effects, have been estimated for some marine mammals through captive studies (e.g. Finneran et. al. 2005, Kastak et. al. 2005).

A general framework for estimating the probable effects of anthropogenic sound

The information discussed above can be combined to estimate the probabilities of any individual marine mammal exhibiting physical effects from sound exposure, and hence the actual numbers that might be affected. The uncertainties associated with these calculations can also be quantified to provide information on the confidence associated with the individual estimates.

Put simply, the sound field produced by the source is simulated, as are the animals that might potentially be affected by it. These simulated animals sample the sound field through time in a realistic way and their sound exposure histories can be used to estimate the probability that they will suffer hearing problems. The simulation process is repeated a large number of times to reflect the uncertainty in the modelled system.

SAFESIMM

SAFESIMM implements the approach described above in such a way that it can be used to simulate the effects of anthropogenic sound in the marine environment anywhere in the world's oceans. It includes a collection of global distribution maps for 115 marine mammal species; a database of information on hearing capabilities, diving and swimming behaviour, reactions to sound and conservation status for each species; parameter sets that define hearing sensitivities and dose response curves; and simulation routines. SAFESIMM can be used with any model providing propagation loss information.

The core code for SAFESIMM is written in the statistical programming environment R (R Core Development Team, 2008). The broad functioning is shown in Figure 8, the module descriptions that follow relate to this flow diagram.

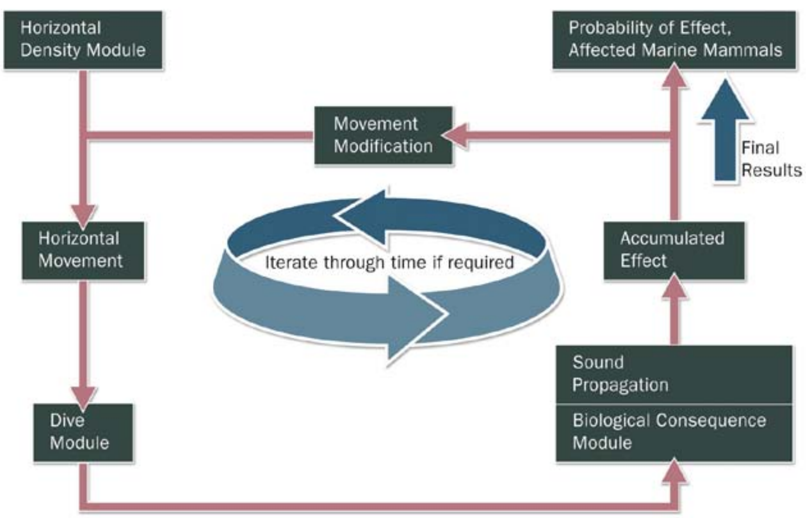

Figure 13: Broad overview of the modular nature of SAFESIMM

The *Horizontal Density Module* determines the horizontal distribution of animals that initializes the simulation process. Currently the data underlying this are species density maps provided as part of the UK Hydrographic Office's Integrated Water Column product but these data can readily be replaced with other density data where available. These are derived from the Relative Environmental Suitability models of Kaschner et. al. (2006), calibrated using published survey data for each species. The data is stored at 0.5°-grid cell resolution and gives both a density estimate and uncertainty measure for all 115 marine mammal species. In the case of 46 species, separate estimates are available for different quarters of the year. Fig. 2 shows the predicted mean densities for Sperm Whales (*Physeter macrocephalus*) about the Hawaiian Islands.

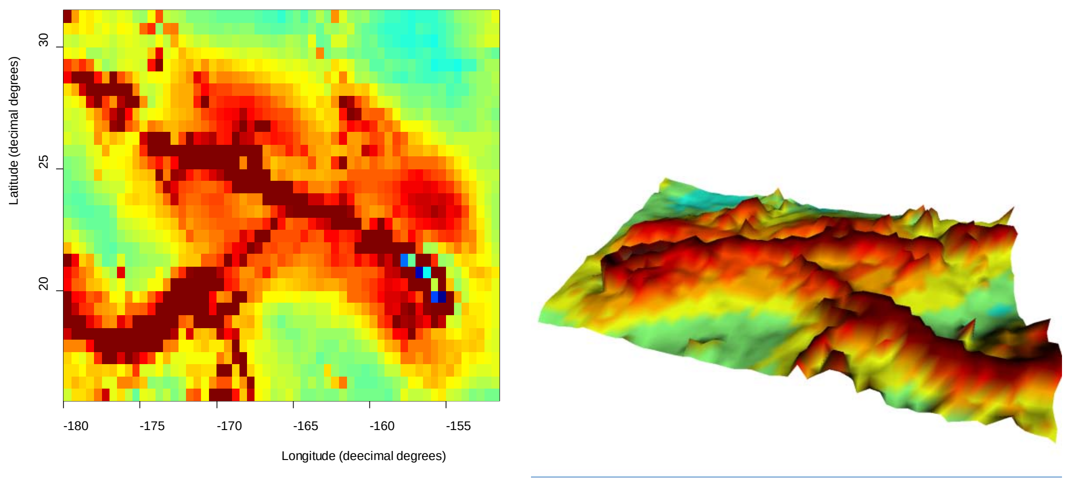

Figure 14: Density maps for sperm whales around the Hawaiian Islands, based on the RES models of Kaschner et. al. (2006) and calibrated against survey data.

The *Horizontal Movement, Dive* and *Movement Modification Modules* determine the movement of the simulated animals. The horizontal and dive movements are based on parameters from an internal database, which was populated from an extensive literature review. For example, specific parameters determine the depth of dives and speed of movement of each species.

The *Movement Modification Module* controls how the animals respond to the received sounds. Although such behaviour may be quite complex, current information on responses is limited, and so the modelled responses are limited to: movement away from the sound source, movement towards the sound source, a cessation of diving, and no response.

The movement of thousands of simulated animals and dozens of species are tracked at 1-minute intervals within the simulation, with received sound levels recorded at each step by reference to the sound field provided by the *Sound Propagation Module*.

At the end of the simulation process, the sound histories for the simulated animals are summarized by their Sound Exposure Levels (SELs). The *Biological Consequence Module* then uses information from the internal databases to determine the probability that this SEL will result in a Temporary Threshold Shift (TTS) in hearing or a Permanent Threshold Shift (PTS) based on the thresholds recommended by Southall et al. (2007). The current summary outputs are the probability, by species, that any animal will suffer PTS and the expected number of animals, also by species, that may are expected to suffer TTS. These values can also be displayed across all species. This information can be summarised for an entire area or displayed at the level of 0.5°grid-cell (or finer depending on resolution of input density data), allowing areas of high and low risk to be identified.

All density estimates have an estimate of uncertainty associated with them. These uncertainties, together with the uncertainty associated with the other parameters used in the simulation process, allow confidence intervals to be provided for any outputs.

Mitigations can be explored by comparing results under different scenarios. For example, deploying the sound source in a slightly different location or at a different time of year. Similarly, a small change in the characteristics of the sound source may have a substantial effect on risk, depending on the hearing sensitivities of the marine mammal species that occur in the region.

Behavioural responses to sound exposure are still poorly understood (Southall et al. 2007c) but, as understanding increases, they can be accommodated within SAFESIMM in two ways. Additional dose-response curves for particular behavioural responses can be included without system modification. The sound exposure and location of simulated animals are monitored at a fine spatial scale. It is therefore possible to record and flag particular high risk events, such as if simulated beaked whales are driven from deep to shallow waters during a simulation, or if a large proportion of a local population is driven out of a particular area.

Summary

SAFESIMM is a flexible algorithm for the calculation of risk to marine fauna from anthropogenic sound. It is currently populated with a large and comprehensive set of data that reflects the current state of knowledge for marine mammals.

The algorithm has been created in an easily modifiable form, so the latest research developments in this rapidly changing field can easily be incorporated.

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II. Appendix Two

Table 6 Engineering parameters modelled at Inch Cape

Estimated Engineering Parameters	Inch Cape (Most Likely)
Pile Diameter (mm)	2438
Total Penetration (m driven below seabed)	50
Hammer Capacity (max blow energy, kJ)	1200
Soft-start duration (mins)	20
Total Piling Duration (hours per pile)	3 hours
Ramp up	Standard ramp up
Strike rate (per s)	1

Table 7 Engineering parameters modelled at Neart na Gaoithe

Estimated Engineering Parameters	NNG (Most Likely)	
Pile Diameter (mm)	2500	
Total Penetration (m driven below seabed)	27.5	
Hammer Capacity (max blow energy, kJ)	1200	
Soft-start duration (mins)	20	
Total Piling Duration (hours per pile)	200 Mins (3 Hours 20 mins)	
Ramp-up Details	Time (minutes at % efficiency)	Efficiency (% of max blow energy)
	20	20
	180	83
Strike rate (per s)	0.5	

Action	Hours
Hammer 1 Pile 1	2
Remove hammer and install drill	4
Perform drilling operations	19.5
Trip out drill string	3
Hammer 2 Pile 1	1.333

Table 8 Scenarios modelled for the Firth of Forth site. The first table in each section provides a summary of the key parameters, the second table provides the detailed piling profile for each scenario broken down in to 10 stages. Total duration of each stage in the operation can be calculated using the cumulative blowcount and the blows per minute which is 45.

Driven Pile Mode

					Axial Capacity				Pile Driveability Assessment								
Scenario	Pile Diameter	Required			Achieved Capacity		Utilisation		Max SRD (kN)	Hammer Size	Driveability Results			Total Blow Count	Duration *	Enthru (kJ)	
		Comp (MN)	Ten (MN)	Required Pile Length (m)	Comp (MN)	Ten (MN)	Compress	Tens			Driveable Pile Length (m)	Max Comp (MPa)	Max Ten (MPa)		(Hour)	Min (15%)	Max (95%)
1	2m	34.07	25.97	27	51.80	27.10	0.66	0.96	78504	IHC-S1800	27	235.23	-24.10	2316	0.9	233	1420

Ground Model	Parameter Model	Pile Diameter (m)	Pile Length (m)	Hammer Model	Efficiency (%)	Depth(m)	SRD (kN)	Blows per meter	Compression (MPa)	Tension (MPa)	Energy (kJ)	Cumulative Blowcount
1	BE	2	27	IHC S1800	15%	0.0	2000	0	0	0	0	0
					15%	6.0	4000	26	86	-51	233	77
					15%	10.0	5000	33	86	-46	233	195
					15%	11.5	5200	35	86	-45	233	246
					35%	14.5	14539	72	122	-31	411	405
					55%	17.5	24205	80	155	-25	644	632

					75%	22.5	40649	87	203	-29	1143	1047
					95%	23.5	70782	228	234	-26	1428	1205
					95%	25.5	74626	274	235	-25	1425	1707
					95%	27.0	78504	335	235	-24	1421	2316

Drive – Drill – Drive Mode

				Axial Capacity					**Pile Driveability Assessment**									
Scenario	**Pile Diameter**	**Required**		**Achieved Capacity**			**Utilisation**		**Max SRD (kN)**	**Hammer Size**	**Driveability Results**			**Total Blow Count**	**Duration**	**Duration ***	**Enthru (kJ)**	
		Comp (MN)	**Ten (MN)**	**Required Pile Length (m)**	**Comp (MN)**	**Ten (MN)**	**Compress**	**Tens**			**Drilled section (m below mudline)**	**Max Comp (MPa)**	**Max Ten (MPa)**		**(Min)**	**(Hour)**	**Min (15%)**	**Max**
3	2m	34.07	25.97	29	34.35	31.48	0.99	0.82	40837	IHC S1200	17	190.28	-63.58	1445	32	0.5	189	916

Ground Model	**Parameter Model**	**Pile Diameter (m)**	**Pile Length (m)**	**Hammer Model**	**Efficiency (%)**	**Depth(m)**	**SRD (kN)**	**Blows per meter**	**Compression (MPa)**	**Tension (MPa)**	**Energy (kJ)**	**Cumulative Blowcount**
3	BE	2	29	IHC S1200	15%	7.5	3263.9	24	80	-64	189	89
					15%	9.5	4509.4	34	80	-59	188	146

					15%	11.5	5632	43	80	-55	188	223
					35%	12.7	14079	52	126	-59	435	280
					35%	14.5	11345	41	126	-68	437	364
					35%	17.5	16676	65	126	-51	434	524
					35%	20.5	22311	85	126	-40	431	750
					55%	23.5	28227	72	161	-43	677	985
					55%	26.5	34407	90	162	-35	673	1228
					75%	29.0	40837	84	190	-32	916	1445