

1 Sound exposure in harbour seals during the installation of an
2 offshore wind farm: predictions of auditory damage

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19 **Summary**

- 20 1. With ambitious renewable energy targets, pile driving associated with offshore wind
21 farm construction will become widespread in the marine environment. Many proposed
22 wind farms overlap with the distribution of seals and sound from pile driving has the
23 potential to cause auditory damage.
- 24 2. We report on a behavioural study during the construction of a wind farm using data
25 from GPS/GSM tags on 24 harbour seals *Phoca vitulina* L. Pile driving data and acoustic
26 propagation models, together with seal movement and dive data allowed the prediction
27 of auditory damage in each seal.
- 28 3. Growth and recovery functions for auditory damage were combined to predict
29 temporary auditory threshold shifts in each seal. Further, M-weighted cumulative
30 Sound Exposure Levels [cSELS(M_{pw})] were calculated and compared to permanent
31 auditory threshold shift exposure criteria for pinnipeds in water exposed to pulsed
32 sounds.
- 33 4. The closest distance of each seal to pile driving varied from 4.7 to 40.5 km and predicted
34 maximum cSELS(M_{pw}) ranged from 170.7 to 195.3 dB re $1\mu\text{Pa}^2\text{-s}$ for individual seals.
35 Comparison to exposure criteria suggests that half of the seals exceeded estimated
36 permanent auditory damage thresholds.
- 37 5. Prediction of auditory damage in marine mammals is a rapidly evolving field and has a
38 number of key uncertainties associated with it. These include how sound propagates in
39 shallow water environments, and the effects of pulsed sounds on seal hearing; as such,
40 our predictions should be viewed in this context.
- 41 6. *Policy implications.* We predicted that half of the tagged seals received sound levels from
42 pile driving that exceeded auditory damage thresholds for pinnipeds. These results
43 have implications for offshore industry and will be important for policy-makers
44 developing guidance for pile driving. Developing engineering solutions to reduce sound
45 levels at source, or methods to deter animals from damage risk zones, or changing
46 temporal patterns of piling could potentially reduce auditory damage risk. Future work
47 should focus on validating these predictions by collecting auditory threshold
48 information pre- and post-exposure to pile driving. Ultimately, information on
49 population-level impacts of exposure to pile driving is required to ensure that offshore
50 industry is developed in an environmentally sustainable manner.

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53 Introduction

54 Ambitious renewable energy targets have been developed to mitigate potential impacts of
55 climate change (Jay 2010; Toke 2011). This has led to the proposed installation of several
56 thousand wind turbines throughout coastal areas of Europe. Proposed wind farms are often
57 located on offshore sandbanks, which are also important habitats for marine mammals. For
58 example, harbour seals *Phoca vitulina* L. exhibit at-sea movements that overlap extensively with
59 proposed wind farm locations in the North Sea (Sharples *et al.* 2012; Russell *et al.* 2014) and
60 their distribution has been shown to be clustered around features such as offshore banks
61 (Thompson 1993). This co-occurrence has led to concerns about the potential impacts of wind
62 farms on marine mammals; concerns derive primarily from the production of intense impulsive
63 sounds over periods of several months during impact pile-driving of turbine foundations (e.g.
64 Madsen *et al.* 2006).

65 Underwater sound from pile driving has been measured in a limited number of studies (e.g.
66 Bailey *et al.* 2010; Brandt *et al.* 2011); pulsed sounds are produced approximately every 1-2
67 seconds with predicted source levels ranging up to 250 dB re 1 $\mu\text{Pa}_{(\text{peak-peak})}$ @ 1m (Bailey *et al.*
68 2010). The mammalian auditory system is likely to be vulnerable to damage from intensive
69 sounds such as these and studies of auditory systems in mammals have shown that exposure to
70 intensive pulsed sounds has the potential to cause elevated hearing thresholds (Henderson &
71 Hamernik 1986; Kryter 1994; Finneran *et al.* 2000; Yost 2000; Finneran *et al.* 2002). Such
72 threshold shifts can be described as either temporary (TTS) or permanent (PTS) depending on
73 the capacity for post-exposure recovery (for review see: Clark 1991).

74 A number of studies on the effects of sound on the auditory system of harbour seals have been
75 carried out (Kastak *et al.* 1999; Kastak *et al.* 2005; Kastelein *et al.* 2012). For example, Kastak *et al.*
76 (1999) exposed harbour seals to 20 minutes of continuous octave band white noise with
77 centre frequencies of 100, 500, 750, and 1000 Hz, at source levels 60 dB above the harbour seal
78 hearing threshold (at the centre frequency); this resulted in an average 4.8 dB temporary
79 decrease in hearing sensitivity (Kastak *et al.* 1999). Similarly, harbour seals exposed to octave-
80 band white noise centred at 4 kHz (bandwidth 2.8–5.7 kHz) exhibited statistically significant
81 TTS (>2.5 dB) when exposed to unweighted source levels of 136 dB re 1 μPa for 60 minutes and
82 148 dB re 1 μPa for 15min (Kastelein *et al.* 2012).

83 After a TTS, the time to recovery depends on the level of shift incurred; in general, the greater
84 the shift, the longer the recovery period (Carder & Miller 1972; Mills, Gilbert & Adkins 1979).
85 For example, the auditory sensitivity of a harbour seal with mean TTSs of 2 to 12 dB as a result
86 of exposure to octave band white noise with a centre frequency of 2,500 Hz and net exposure
87 durations of 22 min at 137 dB re 1 μPa @1m (which is equivalent to 80 dB above the hearing
88 threshold of the seal at the centre frequency), and durations of 25, and 50 min at 152 dB re 1
89 μPa @1m (which is equivalent to 95 dB above the hearing threshold of the seal at the centre
90 frequency), recovered fully within 24 h (Kastak *et al.* 2005). In a more recent study, a harbour
91 seal was exposed for 60 minutes to an octave band white noise centred around 4 kHz with a
92 considerably higher sound pressure level (SPL) of 163dB re 1 μPa (corresponding to 22–30 dB
93 above levels causing TTS exceeding 2.5dB). This elicited a TTS of 44dB which only recovered
94 after 4 days (Kastelein, Gransier & Hoek 2013).

95 Southall *et al.* (2007) developed an approach for evaluating the effects of anthropogenic sound
96 on marine mammals. They developed a series of weighting curves based on the hearing
97 characteristics of five functional marine mammal species groups and reviewed auditory damage
98 studies to provide initial exposure criteria for pulsed and non-pulsed sounds. They predicted
99 that for pinnipeds exposed to pulsed sounds underwater, the onset of PTS would occur at
100 weighted cumulative sound exposure levels (cSELs) of 186 dB re 1 $\mu\text{Pa}^2\text{-s}$ (M_{pw}). For pinnipeds
101 exposed to non-pulse sounds underwater, the predicted PTS onset threshold was at a weighted

102 cSEL of 203 dB re 1 $\mu\text{Pa}^2\text{-s}$ (M_{pw}) (Southall *et al.* 2007). It is important to highlight that, due to
103 the paucity of data on the effects of sound on marine mammal hearing, these preliminary
104 exposure criteria of Southall *et al.* (2007) are based on assumed relationships between the
105 relative levels of TTS and PTS which, in turn, involve proxy data from other species, and are
106 intentionally conservative; further, they do not include the more recent data on auditory
107 damage described above (e.g. Kastelein *et al.* 2012; Kastelein, Gransier & Hoek 2013).

108 Although hearing studies highlight the potential risks to marine mammals from acoustic
109 exposure to pile driving, there is currently no empirical information on the at-sea proximity or
110 the durations of exposure to pile driving, or movements and dive behaviour of seals during pile
111 driving. Such information is critical to understanding the true risk of pile driving sound to seals.
112 To address this gap, we carried out a harbour seal behavioural study during the construction of
113 a wind farm in the North Sea. Our study used data from 24 animal-borne tags collected between
114 January and July 2012. These tags provided location and dive data which, in combination with
115 records of individual pile driving blows, allowed us to predict the potential for auditory damage
116 in each seal.

117

118 **Materials and methods**

119 **Study Area**

120 The Lincs offshore wind farm is located on a submerged sandbank approximately 8 km off the
121 coast of southeast England (53° 11.5' N, -0° 29.5' E). On completion, the wind farm consisted of
122 seventy-five turbines located in water depths of approximately 8 to 20 m, and covering an area
123 of approximately 39 km². As part of the wind farm construction, foundations (5.2m diameter
124 steel monopiles) were installed between 14 May 2011 and 11 May 2012.

125 **Pile driving**

126 Throughout the period of this study (2 January–11 May 2012), 31 monopiles were installed
127 using pile driving. Installation was carried out using a jack-up vessel with an MHU 1900S
128 hydraulic hammer. The temporal pattern of pile driving was characterised by intermittent
129 piling periods (~4–5 hours in length) followed by gaps from a few hours to a few days (Figure
130 1). Within individual pile installations, the median inter-strike interval was 2 seconds (SD=12
131 seconds) and the maximum blow energy was ~2,000 kJ per strike. A ramp-up procedure was
132 carried out during all installations; in general, there was an increase from 100 to 700 kJ over the
133 first 60 minutes before increasing to 2,000 kJ for the remaining installation. A total of 77,968
134 piling strikes were carried out during our study.

135 **Telemetry**

136 To measure the movements and proximity of seals at sea to pile driving, GPS/GSM tags
137 (McConnell *et al.* 2010) were deployed on 25 harbour seals in January 2012. Of these, three tags
138 collected data for less than 2 days (and were therefore excluded from the dataset) with the
139 other 22 collecting data for between 49 and 171 days (Table 1). Furthermore, two seals tagged
140 during a concurrent study approximately 200 km to the south moved into the study area during
141 pile driving and were included in the dataset. Therefore, data from 24 seals were used for
142 further analyses.

143 Seals were captured whilst hauled out on intertidal sandbanks and were anaesthetised with
144 Zoletil® or Ketaset® in combination with Hypnovel®. The tags were attached to the fur at the
145 back of the neck using Loctite® 422 Instant Adhesive. Capture and handling procedures are
146 described in more detail by Sharples *et al.* (2012). All procedures were carried out under Home
147 Office Animals (Scientific Procedures) Act licence number 60/4009.

148 The tags are data loggers that attempt to record the location of a seal at regular intervals using a
149 hybrid GPS (Fastloc®) system. Stored location and dive data are opportunistically relayed
150 ashore by means of an embedded mobile phone (GSM) modem. These tags provided seal
151 locations approximately every 15 minutes. The data were cleaned and erroneous locations
152 removed using thresholds of residual error and number of satellites; tests on land using these
153 thresholds showed 95% of the cleaned locations had an error of <50m (Russell, Matthiopoloulos
154 & McConnell 2011). Further, dive data were provided as nine depth points distributed equally in
155 time throughout each dive. During periods of pile driving, tracks of seals were interpolated
156 linearly between successive GPS locations to provide estimated locations at one second
157 intervals. Similarly, dive depths at each of these locations were estimated through linear
158 interpolation between successive measured dive depths. These provided estimated 3D
159 locations of each seal at one second intervals throughout periods of pile driving.

160 **Acoustic exposure**

161 To predict the acoustic exposure from pile driving for each seal, the source characteristics of the
162 pile driving were derived from existing literature and a series of acoustic modelling approaches
163 were carried out; these are described in Appendix S1 in the Supporting Information. Effectively,
164 a median peak-to-peak source level estimated during previous pile driving at the same wind
165 farm (Nedwell, Brooker & Barham 2011) was used as a source level for pile driving in this

166 study; this value was then corrected for changes in pile driving hammer blow energy by relating
167 individual piling stroke blow energy information (provided by the windfarm developer) with
168 peak-to-peak received levels from recordings made with an autonomous moored sound
169 recorder (DSG-Ocean Acoustic Datalogger; Loggerhead Instruments, FL, USA). This recorder
170 was moored at a range of 4,900 m from the pile driving location. This information, together
171 with information on the mean duration of a pile driving pulse and the mean difference between
172 the peak-to-peak and root mean square sound pressure levels (SPL), was used to derive the
173 Sound Exposure Level (SEL) of a pile driving single-pulse. Using these approaches, the pile
174 driving was estimated to have a maximum single-pulse SEL of 211 dB re 1 $\mu\text{Pa}^2\text{-s}$ at the
175 maximum blow energy of 2,000kJ.

176 Transmission loss across the study area was then estimated using range dependent acoustic
177 models (Collins 1993); these are described in detail in Appendix S1 in the Supplemental
178 Information. This was calculated along 5 degree radii from each of the pile driving source
179 locations out to a range of 200 km. At each 1-km interval, transmission loss at a series of water
180 depths was estimated; these were one metre and each 5 metre depth interval from 5 to 110
181 metres depth (the maximum seal dive depth during the study). The acoustic models were
182 validated using boat based recordings during the installation of one of the piles; these
183 recordings covered the full range of pile driving blow energies. Recordings were made using a
184 Reson TC 4014 hydrophone with a Brüel and Kjaer amplifier (type 2635) and a calibrated
185 Avisoft Ultrasoundgate 416 digital acquisition system at a sample rate of 192 kHz. Recording
186 locations varied between 1,000 and 9,500 m from the pile driving.

187 **Prediction of auditory damage**

188 To predict the potential for auditory damage in each seal, received SELs for each pile driving
189 pulse were estimated at the location of each of the seals using the approach described above;
190 seal locations and depths were matched to the transmission loss estimates at the associated
191 location and depth for each individual pile driving pulse to estimate received SELs (Figure 2 and
192 3).

193 Auditory damage was predicted in individual seals using two approaches. These were based on
194 1) results from previous studies of TTS onset, growth (during exposure), and recovery (post
195 exposure) in harbour seals (e.g. Kastak *et al.* 2005; Kastak *et al.* 2007), and 2) the approach
196 developed by Southall *et al.* (2007) for evaluating the likelihood of PTS in marine mammals
197 exposed to anthropogenic sound (Figure 4).

198 The first approach required summing individual pulse SELs for each period of pile driving to
199 calculate the cSEL and to integrate published TTS growth and recovery functions for harbour
200 seals with the cSELs. The growth of TTS was modelled (Equation 1) as described by Kastak *et al.*
201 *et al.* (2005); the best fit parameter values for the harbour seal tested in their study were used to
202 construct the growth curve in the present study. In the absence of data for harbour seals on
203 recovery from TTS, recovery was modelled using a -8.8 dB per log(min) relationship for
204 California sea lions *Zalophus californianus* L. (Kastak *et al.* 2007). It is important to highlight
205 that predictions of auditory damage made here for pulsed sounds are based on TTS onset and
206 recovery functions derived from exposure to octave-band (continuous) noise for varying
207 durations.

208 (Equation 1)

$$TTS = (10m1)\log_{10}(1 + 10^{((SEL-m2)/10)})$$

209 where $m1$ is 2.0 and corresponds to the slope of the linear portion of the curve relating SEL to threshold
210 shift (Kastak *et al.* 2005);

211 m_2 is 183.1 and corresponds to the x intercept of the extrapolation of the linear portion of the
212 curve (considered the onset of TTS (Kastak *et al.* 2005));

213 The second approach was to weight the SELs according to the auditory M-weighting function for
214 pinnipeds in water (M_{pw}) formulated by Southall *et al.* (2007). For pile driving pulses, this
215 effectively reduced individual pulse SELs by 1.6 dB re 1 $\mu\text{Pa}^2\text{-s}$. M-weighted individual pulse
216 SELs were then summed for each period of pile driving to calculate the cSEL (M_{pw}). Permanent
217 auditory injury onset thresholds at a cSEL of 186 dB re 1 $\mu\text{Pa}^2\text{-s}$ (M_{pw}) for pinnipeds exposed to
218 underwater pulsed sound within a 24-hour period were proposed by Southall *et al.* (2007); we
219 therefore adopted this approach and calculated cSEL (M_{pw}) in each 24-hour period from the
220 start of piling. In addition, Southall *et al.* (2007) propose an unweighted peak SPL of 218 dB re
221 1 μPa as an alternative permanent auditory injury onset threshold. We therefore present
222 predicted received peak SPLs (calculated as predicted SPL_(peak-peak) minus 6dB) for each seal.

223 Given that the acoustic propagation model validation recordings were only made to ranges of
224 ~10 km from the pile driving, there is greater uncertainty in the SELs and the characteristics of
225 the signals (e.g. frequency, duration, rise time) received at seals beyond this range. To account
226 for this, auditory damage predictions are summarised for cases where seals were within 10 km
227 and beyond 10 km from the pile driving location.

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230 **Results**

231 **Telemetry**

232 Throughout the study, all seals moved between haul out sites and areas offshore. During
233 transits offshore, seals travelled within 20 km of the wind farm site. All seals spent time
234 offshore during at least one pile driving event; the closest distance of individual seals to active
235 pile driving locations while at sea varied between individual seals from 4.7 to 40.5 km.

236 **Acoustic exposure**

237 The results of the validation recordings suggested that the modelling approaches provided a
238 relatively accurate means of predicting received levels from pile driving; overall mean error in
239 the predictions of unweighted single pulse SELs was +2.3 (SD = 1.8) dB up to ranges of ~10 km
240 from the source.

241 Maximum predicted unweighted single pulse SELs at individual seals varied from 146.1 to 166.5
242 dB re 1 $\mu\text{Pa}^2\text{-s}$. In general, predicted received levels increased with dive depth; the maximum
243 single pulse SEL was 166.5 dB re 1 $\mu\text{Pa}^2\text{-s}$ for seal 'pv42-277-12' at a range of 6.9 km and a dive
244 depth of 17.1 m.

245 **Prediction of auditory damage**

246 Using the TTS growth and recovery functions established for exposure to continuous noise
247 (Kastak *et al.* 2005; Kastak *et al.* 2007), it was predicted that all seals received SELs sufficient to
248 cause TTS during pile driving. Predicted maximum threshold shifts for individuals ranged from
249 1.6 to 23.0 dB (Figure 5 and Table 1). Predicted cSELs (M_{pw}) (Southall *et al.* 2007) from pile
250 driving varied between individual seals; the seal with the lowest exposure had cSELs (M_{pw})
251 ranging from 132.8 to 190.6dB re 1 $\mu\text{Pa}^2\text{-s}$ (M_{pw}), and the seal with the highest exposure had
252 cSELs (M_{pw}) ranging from 147.2 to 195.3 dB re 1 $\mu\text{Pa}^2\text{-s}$ (M_{pw}) (Figure 6 and Table 1). In total,
253 twelve (50%) of the seals were predicted to receive cSELs (M_{pw}) that exceeded the estimated
254 PTS onset threshold of 186 dB re 1 $\mu\text{Pa}^2\text{-s}$ (M_{pw}) for pinnipeds in water exposed to pulsed
255 sounds (Southall *et al.* 2007). The number of times these twelve seals exceeded the threshold
256 varied between one and nine (Table 1).

257 Out to ranges where the acoustic propagation models were formally validated (~10 km), a total
258 of five seals were present during pile driving with closest approaches ranging from 4.7 to 9.8 km
259 from the pile driving location. Predicted maximum threshold shifts for these five seals ranged
260 from 0.8 to 24.5 dB (Table 1). Of these five seals, three (60%) were predicted to exceed the
261 estimated PTS onset threshold for pinnipeds in water exposed to pulsed sounds (Southall *et al.*
262 2007) between one and nine times (Table 1).

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265 **Discussion**

266 This study used animal movement and dive data to predict the long-term acoustic exposure
267 history of a marine mammal during the construction of an offshore wind farm. The results
268 showed that all 24 tagged seals were present at sea and showed diving behaviour during pile
269 driving at some stage during the study; we therefore predicted that each received acoustic
270 exposure from the piling. The closest distance that each seal came to active pile driving
271 locations varied between 4.7 and 40.5 km, and a total of 5 (~20%) of the seals moved within 10
272 km of pile driving.

273 Predicted received SELs were frequently relatively high and led to auditory damage predictions
274 using both the approaches taken here. By integrating auditory damage growth and recovery
275 functions established for exposure to continuous, octave-band noise (Kastak *et al.* 2005; Kastak
276 *et al.* 2007), all seals were predicted to receive cSELs sufficient to cause TTS; although this was
277 relatively low in three of the seals (<6 dB), the majority of seals (21 out of 24) were predicted to
278 get TTS greater than 6dB, and two seals were predicted to get high levels of TTS (>20dB).

279 Using the M-weighted cSELs and the PTS onset criteria for pulsed sounds (Southall *et al.* 2007),
280 half of the seals were predicted to gain PTS; furthermore, this was a relatively frequent
281 occurrence (up to nine occasions) for some of the seals. The accurate prediction of auditory
282 damage in this study is reliant on the thresholds being appropriate for pile driving sound; there
283 are a number of important caveats and uncertainties that need to be considered with respect to
284 this. The PTS onset thresholds as derived by Southall *et al.* (2007) are based upon assumed
285 relationships between relative levels of TTS and PTS and are intentionally conservative. In their
286 study, PTS was predicted if the auditory threshold was increased by ≥ 40 dB (i.e., 40 dB of TTS)
287 (Southall *et al.* 2007). Although few studies of PTS in harbour seals exist, one study supports
288 this assumption (Kastak *et al.* 2008). In their study, Kastak *et al.* (2008) twice exposed a single
289 harbour seal to a 4.1 kHz pure tone with a maximum received SPL of 184 dB re 1 μ Pa for a
290 duration of 60 s (SEL=202 dB re 1 μ Pa²s). This led to a threshold shift in excess of 50 dB at 5.8
291 kHz, and an apparent PTS of 7 to 10 dB evident after more than two months following exposure
292 (Kastak *et al.* 2008). In contrast, more recent work showed despite a high SPL exposure that
293 resulted in 44 dB TTS in a harbour seal, full hearing recovery occurred within four days
294 (Kastelein, Gransier & Hoek 2013). Thus, our predictions of PTS following Southall *et al.* (2007)
295 will need further investigation once PTS thresholds for harbour seals are more fully understood.

296 TTS growth and recovery functions (Kastak *et al.* 2007) were derived from TTS measurements
297 as a result of exposure to continuous sound. For these to be appropriate for pulsed sounds, we
298 have assumed that TTS follows the equal energy hypothesis (Burns & Robinson 1970), i.e. that
299 fatiguing sounds with equal SELs are predicted to induce the same TTS. However, recent results
300 suggest that this may not be an optimal model for predicting TTS in harbour seals; both Kastak
301 *et al.* (2005) and Kastelein *et al.* (2012) show that different levels of TTS may result from
302 exposure to sounds with similar SELs, but consisting of different duration/level combinations.
303 Kastelein, Gransier and Hoek (2013) suggest that their results are more in line with the
304 hypothesis of Henderson *et al.* (1991) that hearing loss depends on the interaction of several
305 factors including exposure level and duration, rise time, and repetition rate (Henderson &
306 Hamernik 1986; Henderson *et al.* 1991). Similarly, studies of terrestrial mammals generally
307 conclude that impulse noise is more hazardous than continuous noise with respect to hearing
308 damage (e.g. Sulkowski & Lipowczan 1982; Dunn *et al.* 1991). For example, chinchillas exposed
309 to pulsed noise showed substantially more threshold shift than a control group exposed to
310 continuous pink noise (where signals were matched by exposure duration and SPL_(RMS)) (Dunn
311 *et al.* 1991). Furthermore, Buck (1982) examined the effect of impulse rate on Guinea pigs *Cavia*
312 *porcellus* and showed that TTS was greatest at a presentation rate of 1 per second and could be
313 reduced by either increasing or decreasing this rate (Buck 1982). Price (1974; 1976) measured
314 TTS in the domestic cats *Felis catus* after exposure to intermittent and continuous tones; results
315 showed that recovery of TTS began within milliseconds of the end of exposure and continued

316 for several hours. However, the presentation of tones intermittently effectively disrupted the
317 recovery mechanism and led to longer recovery post exposure compared to continuous
318 exposure (Price 1976).

319 The disparity in TTS growth between impulse and continuous noise exposures can also be seen
320 in TTS patterns post exposure. Experiments on monkeys (Luz & Hodge 1970), humans
321 (Fletcher 1970), and chinchillas (Hamernik, Patterson & Salvi 1987) have shown that post-
322 exposure recovery from impulse noise often follows a non-monotonic pattern; i.e. there can be a
323 post-exposure growth in TTS to maximum levels as much as 10 h after exposure (Hamernik,
324 Patterson & Salvi 1987). This recovery pattern is markedly different from the typical log-linear
325 recovery seen following continuous noise exposure (Ward et al., 1959).

326 Prediction of auditory damage is further complicated by uncertainties in the nature of the
327 pulsed sounds of pile driving. First, it is important to highlight that the received levels in this
328 study are derived from a series of acoustic models with associated assumptions; however, the
329 sound propagation models used here have been benchmarked previously (e.g. Matthews &
330 MacGillivray 2013) and are widely employed in the acoustics community. Furthermore, our
331 validation suggests that the models provide an accurate means of predicting received levels out
332 to at least 10 km from the pile driving. Nevertheless, we measured a mean error in single pulse
333 SEL of +2.3 dB re 1 $\mu\text{Pa}^2\text{-s}$ (a positive value represents an overestimate); in terms of auditory
334 damage prediction, if we incorporate this error into the predictions, all seals were still predicted
335 to receive relatively high exposure but the number of seals exceeding the PTS onset threshold
336 for pulsed sounds (Southall *et al.* 2007) reduces from twelve to seven. Similarly, predicted
337 maximum threshold shifts for individuals reduce from between 1.6 and 23.0 dB (Table 1) to
338 between 0.5 and 18.9 dB when this error is incorporated.

339 A second important point is that pulsed sounds are described as brief, broadband, atonal,
340 transients, characterised by a relatively rapid rise time from pressure to maximal pressure
341 (Southall *et al.* 2007). As Southall *et al.* (2007) highlight, a sound that has pulsed characteristics
342 at the source may, as a result of propagation effects, lose those characteristics (e.g. rise time)
343 and could be characterized as non-pulses at some (variable) distance from source. This has
344 implications for the use of the Southall *et al.* (2007) pulsed threshold, particularly for exposures
345 where the seals were a long distance from the pile driving. Rise times for the pile driving signals
346 in our recordings were generally short. but did increase from around 35 to 100 msec between 1
347 and 10 km from the source; these appear to be within the range of rise times previously
348 measured in industrial pulsed sounds (e.g. Žera 2001) and it would therefore seem valid to use
349 the pulsed threshold in our study out to at least 10 km. This would support our prediction that
350 of the five seals within 10 km of pile driving, three exceeded the PTS onset threshold for pulsed
351 sounds (Southall *et al.* 2007). However, at longer ranges, it is arguable that the pile driving
352 signals may no longer be considered impulsive and the nonpulse PTS threshold criteria for
353 pinnipeds (cSEL: 203 dB re: 1 $\mu\text{Pa}^2\text{-s}$) may be more appropriate; using this approach, none of
354 the seals beyond 10 km from the pile driving would have exceeded the PTS threshold.

355 Although there are uncertainties associated with the predictions made here, using current
356 published auditory damage thresholds for pinnipeds exposed to pulsed sounds, half of the seals
357 were predicted to exceed the PTS onset threshold (Southall *et al.* 2007). The biological
358 consequences of a permanent reduction in auditory sensitivity are unclear; however,
359 underwater hearing is likely to be important for seals in a number of behavioural contexts. For
360 example, low frequency vocalisations appear to play a role in reproduction (Van Parijs, Hastie &
361 Thompson 2000) in harbour seals. These are produced by male seals and appear to function in
362 male-male competition or advertisement to females (Hanggi & Schusterman 1994; Van Parijs,
363 Hastie & Thompson 2000). Impairment to auditory sensitivity may therefore affect the
364 detection of vocalisations with implications for reproductive success.

365 In addition to intraspecific communication, detection of underwater sounds is also important
366 during foraging or for predator detection in some species; for example, utilization of prey
367 sounds for hunting has been shown for several fish species (Myrberg 1981), and some cetaceans
368 (Gannon *et al.* 2005) and seals (Stansbury *et al.* 2015) make use of passive listening during
369 foraging. Furthermore, seals acoustically detect and avoid predators such as killer whales
370 (Deecke, Slater & Ford 2002). Overall, based on psychophysical data (e.g. Wolski *et al.* 2003;
371 Bodson *et al.* 2006; Reichmuth *et al.* 2013) and the allocation of resources to the auditory sense
372 (Alderson, Diamantopolous & Downman 1960; Walloe *et al.* 2010) hearing appears to be
373 important to seals and it seems likely that auditory impairment has the potential to impact
374 individual fitness.

375 In summary, although the effects of pulsed sound on the auditory system are highly complex
376 and the prediction of auditory damage in marine mammals is a rapidly evolving field of
377 research, based on current noise exposure criteria (Southall *et al.* 2007), we predict that half of
378 the seals received sound levels sufficient to exceed PTS thresholds during the construction of an
379 offshore wind farm. A critical avenue for future work will be to validate the predictions made
380 here through the collection of auditory threshold information pre- and post- exposure to pile
381 driving; this could be carried out on wild seals using auditory evoked potential measurements
382 (Wolski *et al.* 2003) or in a captive environment using controlled exposures and psychophysical
383 methods (e.g. Kastak *et al.* 2005; Kastelein *et al.* 2012). Furthermore, although all seals
384 remained in the general area during the study, it will be important to determine whether
385 individual seals responded to piling to limit their acoustic exposure. This could potentially
386 occur through spatial avoidance of areas with high received levels, or by animals actively
387 changing hearing thresholds in response to noise to protect their auditory system (as is known
388 from humans, bats and cetaceans: see Nachtigall & Supin 2013). Ultimately however, to
389 estimate the population level impacts of exposure to sounds from activities such as pile driving ,
390 the long term impacts of auditory damage on individual fitness, fecundity, and survival need to
391 be quantified (Thompson *et al.* 2013); such information is required to ensure that the
392 development of offshore industry is carried out in an environmentally sound manner.

393

394 **Acknowledgements**

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399 providing pile-driving records. We wish to thank Peter Tyack, Brandon Southall, and Ailsa Hall
400 for valuable comments on the manuscript. We also thank Graham Weatherup for acoustic
401 measurements, SMRU Instrumentation, and everyone who assisted with seal tagging.

402 **Data accessibility**

- 403 - Location and diving data for individual seals are available from the Dryad Digital
404 Repository: doi: 10.5061/dryad.h79q4 Data files: pv42_data (Hastie *et al.* 2015)
- 405 - Pile driving data are the property of Centrica Energy Renewables, Millstream,
406 Maidenhead Road, Windsor, Berkshire, SL4 5GD

407

408 **Supporting Information**

409 Supporting information may be found in the online version of this article.

410 Appendix S1: Estimation of acoustic exposure in seals

411

412

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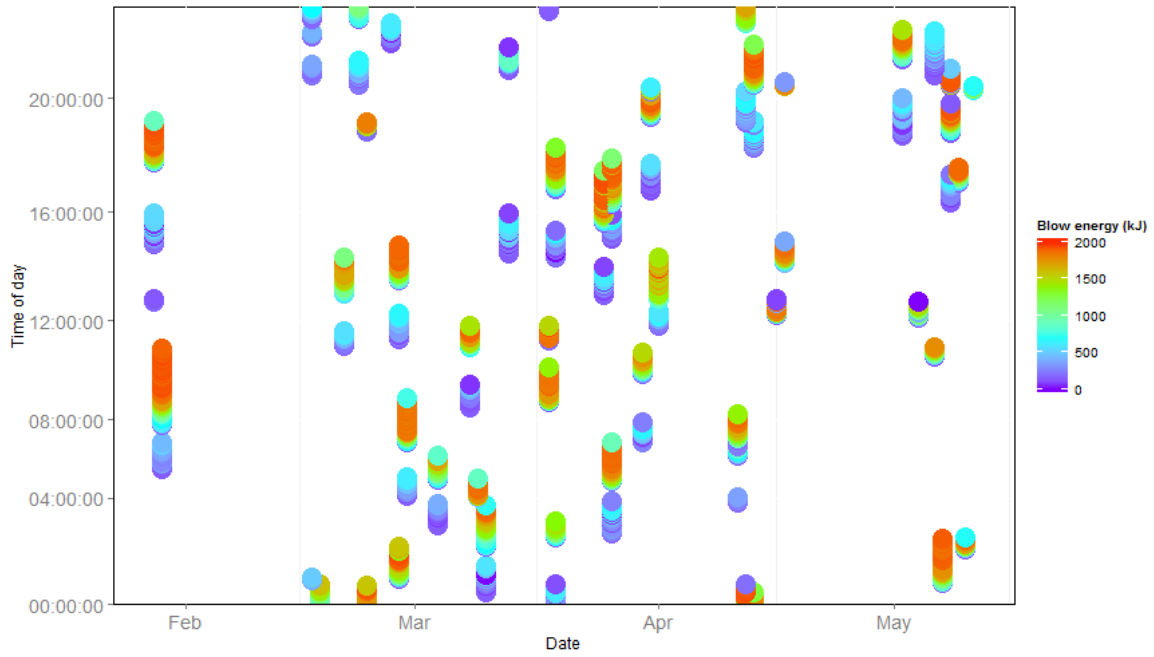
553 **Tables**

554 Table 1: Summary of the predicted auditory damage for the tagged seals, including the maximum cSEL (M_{pw}) (dB re: 1 $\mu\text{Pa}^2\text{-s}$) (Southall *et al.* 2007),
555 the number of piling bouts where the PTS onset threshold was exceeded, and the maximum TTS (dB) predicted from TTS growth and recovery
556 functions (Kastak *et al.* 2005; Kastak *et al.* 2007). Each of the predictions is shown for seals when located less than and greater than 10 km from the
557 piling location

Seal ID	Sex	Age class	Tag duration (days)	Closest range to piling (km)	Maximum RL (dB re 1 $\mu\text{Pa}_{(\text{peak})}$)	Max cSEL (M_{pw}) (dB re: 1 $\mu\text{Pa}^2\text{-s}$)		# of piling bouts exceeding 186 dB re: 1 $\mu\text{Pa}^2\text{-s}$		Max predicted TTS (dB re 1 μPa)	
						<10km	>10km	<10km	>10km	<10km	>10km
pv40-268-12	Female	Adult	135	6.1	179.7	187.8	188.4	3	2	7.9	16.8
pv40-270-12	Male	Adult	91	40.5	171.0	-	178.6	-	0	-	2.9
pv42-162-12	Female	Adult	160	9.8	179.9	170.7	190.0	0	4	0.8	18.3
pv42-165-12	Female	Juvenile	64	6.9	173.5	182.0	185.5	0	0	1.9	8.2
pv42-194-12	Male	Adult	115	27.0	173.8	-	183.1	-	0	-	7.8
pv42-198-12	Male	Adult	131	29.1	179.0	-	187.1	-	3	-	14.0
pv42-220-12	Male	Adult	144	34.3	177.2	-	186.2	-	0	-	11.2
pv42-221-12	Male	Adult	50	26.8	173.3	-	183.6	-	0	-	7.8
pv42-266-12	Female	Adult	84	11.1	177.0	-	185.5	-	0	-	7.8
pv42-277-12	Female	Adult	158	4.7	184.7	193.4	191.3	9	3	24.5	21.2
pv42-287-12	Male	Adult	18	38.8	164.4	-	176.7	-	0	-	1.6
pv42-288-12	Female	Adult	170	15.8	176.1	-	185.5	-	0	-	11.9
pv42-289-12	Male	Adult	79	27.6	172.3	-	183.3	-	0	-	8.1
pv42-290-12	Female	Adult	58	16.9	175.6	-	187.8	-	1	-	9.5
pv42-291-12	Female	Adult	109	15.0	178.0	-	183.8	-	0	-	9.7
pv42-292-12	Male	Adult	105	31.5	174.8	-	184.3	-	0	-	5.2
pv42-293-12	Female	Adult	69	17.1	177.5	-	185.4	-	0	-	10.5
pv42-294-12	Male	Adult	103	29.6	172.7	-	184.0	-	0	-	8.9
pv42-295-12	Female	Adult	69	10.8	181.0	-	190.7	-	1	-	16.4

pv42-316-12	Male	Juvenile	106	5.8	179.1	184.3	187.4	0	1	6.6	13.3
pv42-317-12	Female	Adult	111	17.1	179.6	-	190.6	-	3	-	16.8
pv42-318-12	Female	Adult	139	13.8	180.6	-	195.3	-	7	-	23.0
pv42-319-12	Male	Juvenile	114	27.3	176.6	-	188.9	-	2	-	15.7
pv42-320-12	Female	Adult	106	4.9	182.3	188.7	186.0	1	1	17.3	12.5

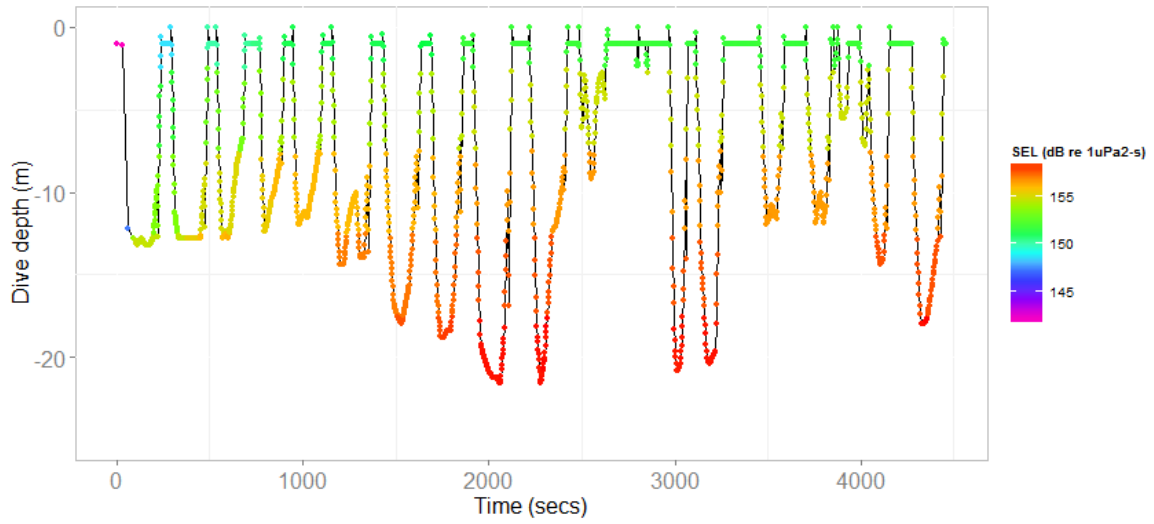
558 **Figures**



559

560 Figure 1: Temporal pattern in pile driving with month along the x-axis and time of day on the y-
561 axis. Each point represents a pile driving pulse which is coloured by the blow energy (kJ) of the
562 piling strike.

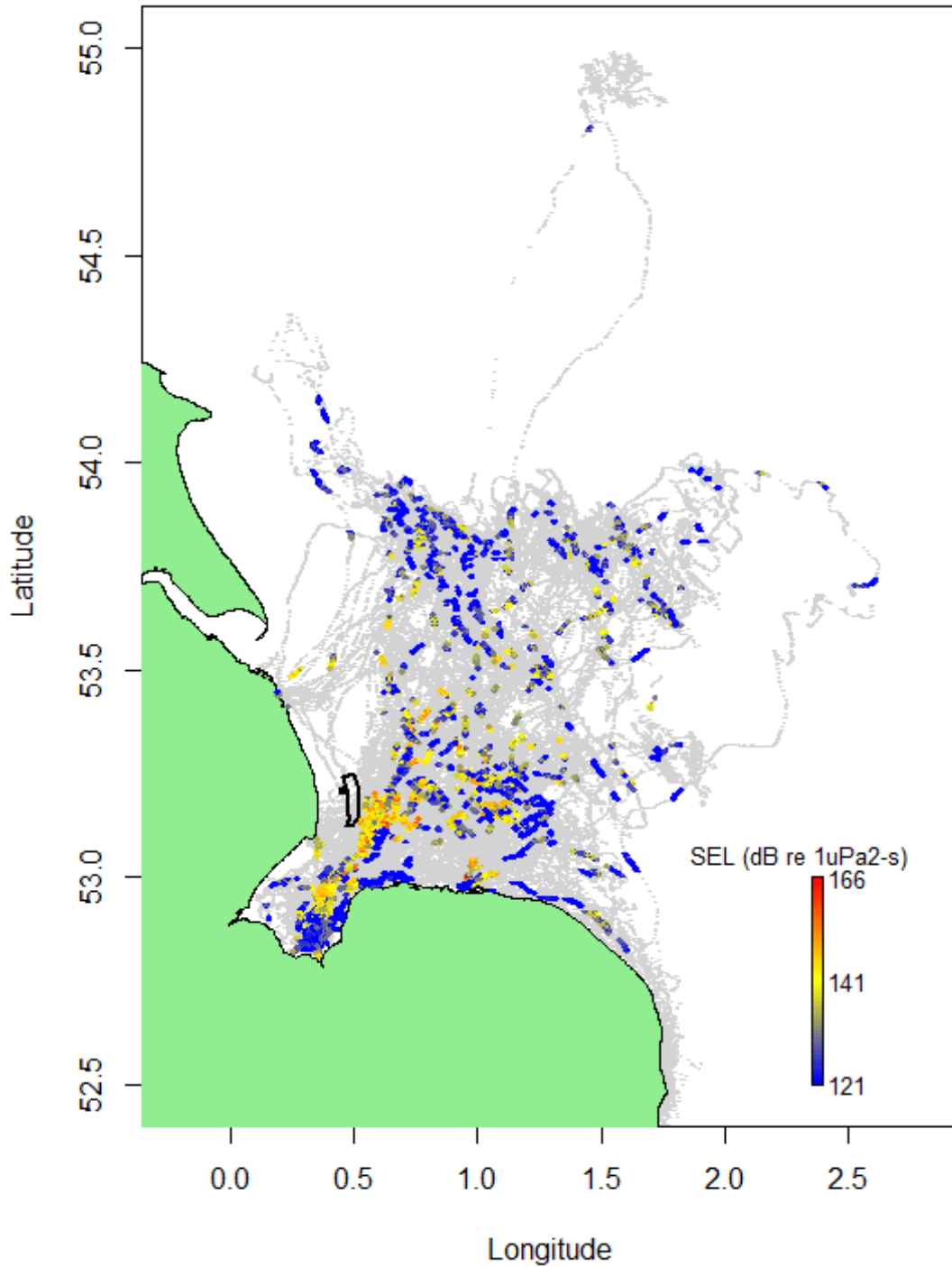
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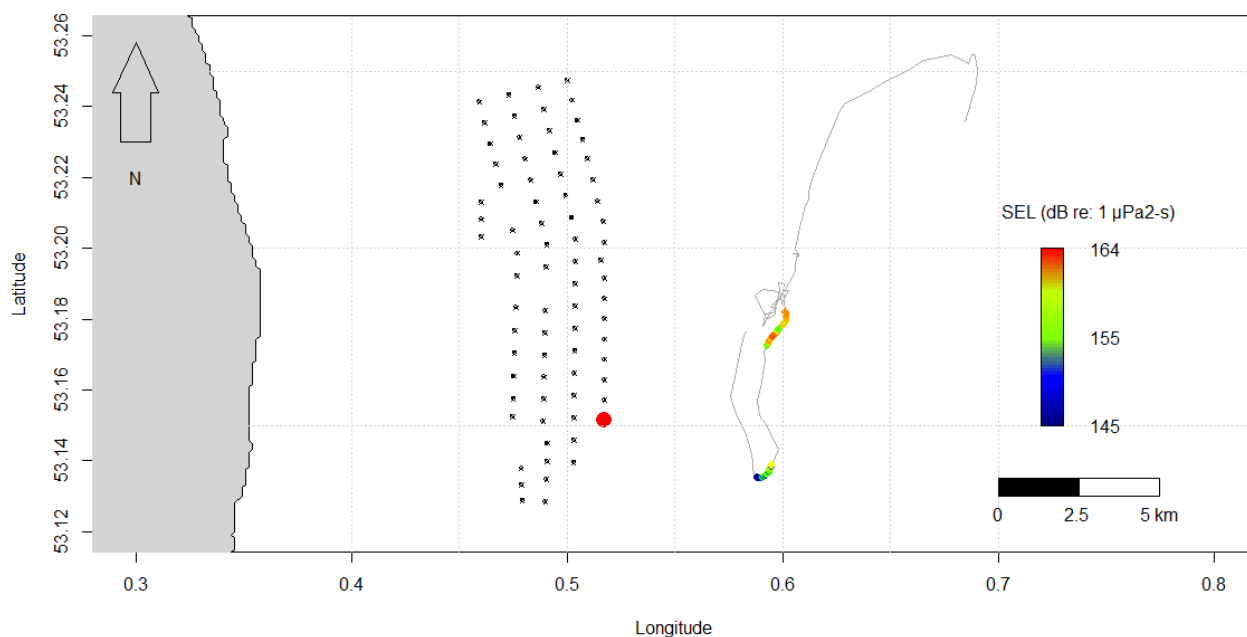
565 Figure 2: Example of a harbour seal dive profile over a period of 75 mins with predicted
 566 unweighted single pulse SELs (dB re: 1 $\mu\text{Pa}^2\text{-s}$) received from pile driving.

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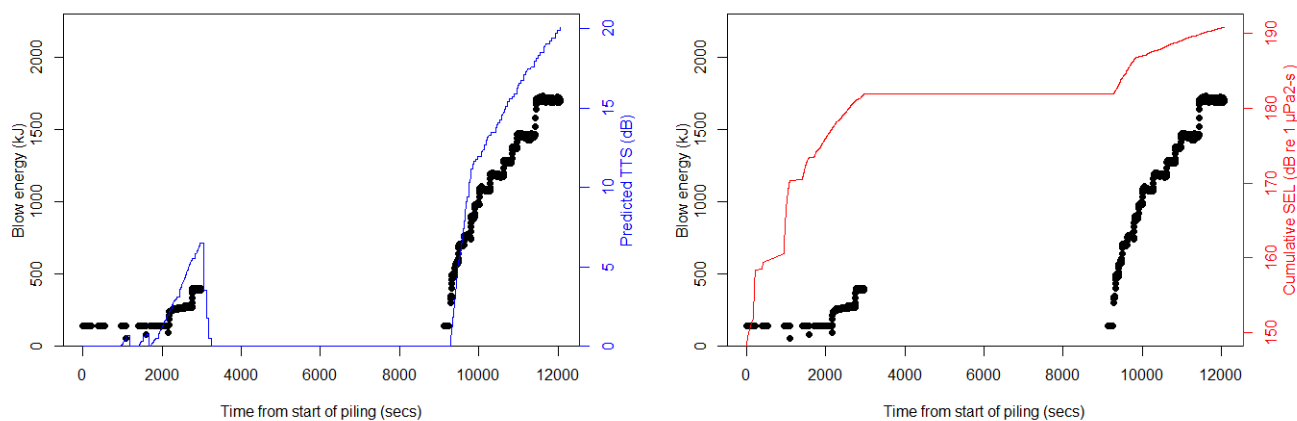


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569 Figure 3: Map of the study area showing all GPS locations of 24 seals with predicted single pulse
 570 SELs (dB re: 1 $\mu\text{Pa}^2\text{-s}$) from pile driving. The figure shows the seal locations when no piling was
 571 taking place (grey points), during piling (coloured points), and the location of the wind farm
 572 (black polygon).



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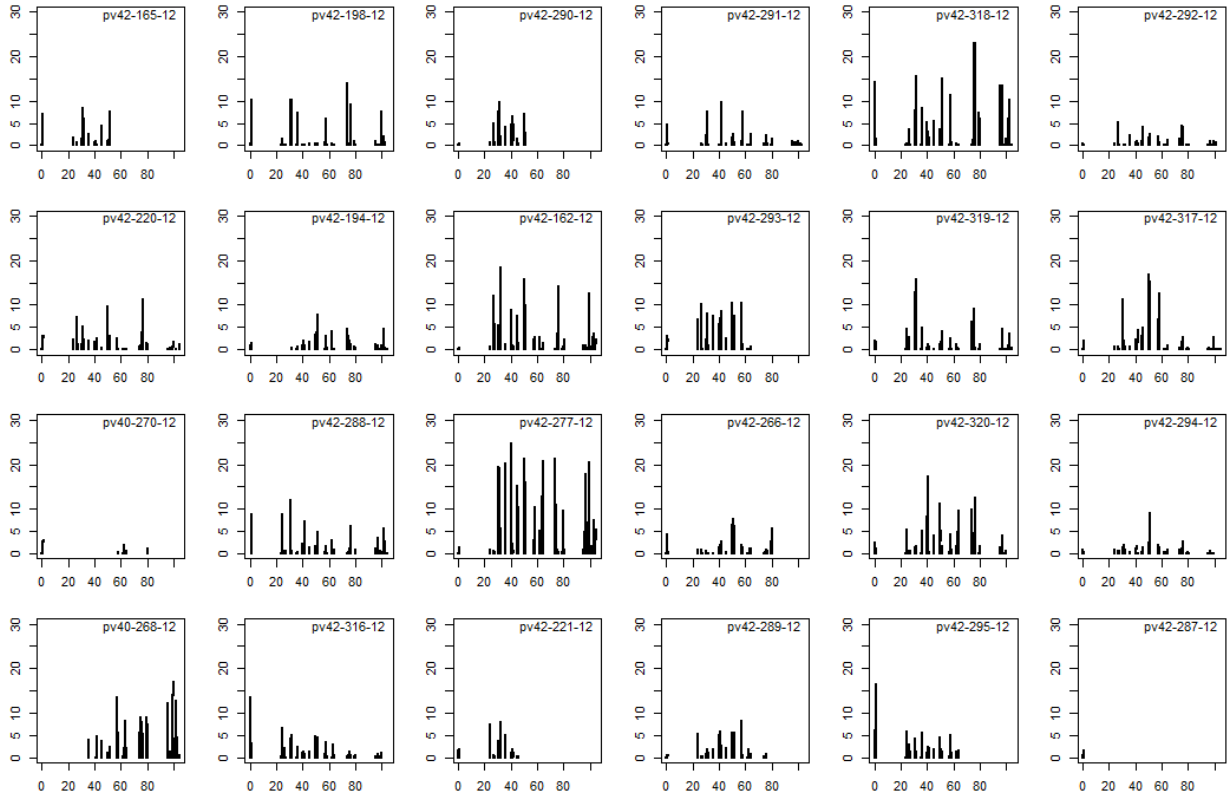
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575 Figure 4: Example of the movements and corresponding auditory damage predictions in a
 576 harbour seal during pile driving. The top panel shows the track of seal pv42-277-12 (grey line)
 577 during a 24hr period, its locations during pile driving (coloured by predicted received
 578 unweighted SELs), the wind turbine foundations (black stars), and the pile driving location (red
 579 point). The lower panels show the timeline of the pile driving with associated blow energy (kJ)
 580 of the piling strokes (black points). The left also shows the predicted growth and recovery of
 581 TTS (Kastak *et al.* 2005; Kastak *et al.* 2007) (blue line) and the right shows the predicted M-
 582 weighted cSEL (dB re 1 $\mu\text{Pa}^2\text{-s}$) (Southall *et al.* 2007) (red line).

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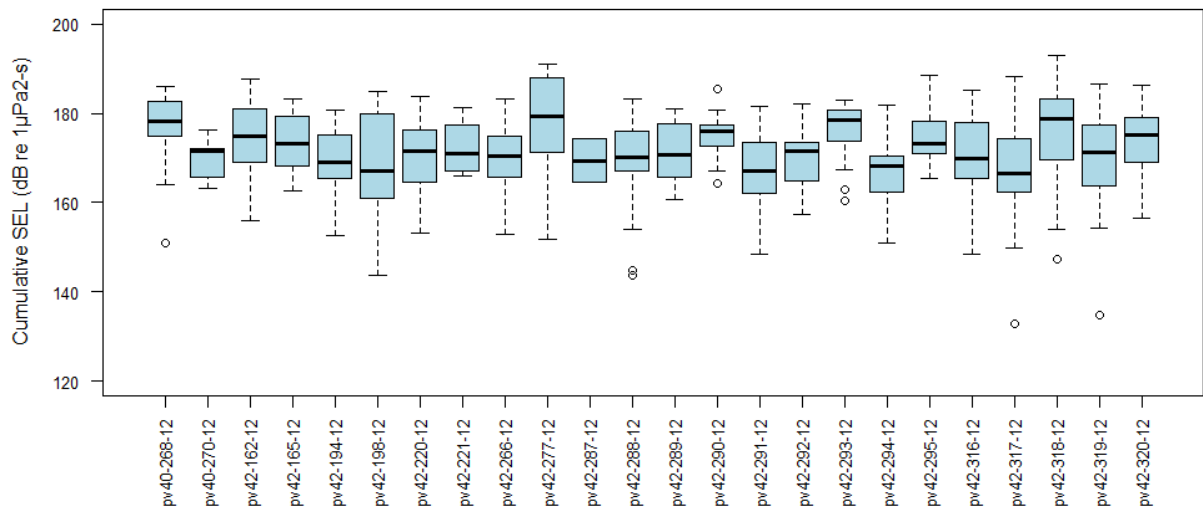
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587 Figure 5: Predicted TTS (dB) for each seal based on functions established for exposure to
 588 continuous, octave-band noise (Kastak *et al.* 2005; Kastak *et al.* 2007). Each panel shows time
 589 along the x-axis (days) and predicted TTS on the y-axis for each seal.

590



591

592 Figure 6: Summary of the M-weighted cSELs (M_{pw}) (dB re: 1 $\mu\text{Pa}^2\text{-s}$) for individual seals. The
 593 figure shows cSELs (M_{pw}) in 24hr periods with the median value (solid line), the 25th and 75th
 594 percentiles (grey boxes), the range without outliers (whiskers), and outliers (open circles).

595