



FINAL PROJECT REPORT EVALUATION FORM

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<u>Project Title:</u>	
1. In your view have the scientific objectives been achieved. If not, does this need to be addressed by SARF?	
2. Comment on the overall results of the project, including their significance for SARF.	
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Overall marking	1 - outstanding results 2 - results significantly above expectation 3 - satisfactory results 4 - results below expectation 5 - poor results
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SARF112: LOW-FREQUENCY ADDS AND PORPOISES (LEAP)

3

4 INFLUENCES OF LOWER-FREQUENCY 5 ACOUSTIC DETERRENT DEVICES (ADDS) 6 ON CETACEANS IN SCOTTISH COASTAL 7 WATERS 8



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- Acoustic Deterrent Devices (ADDs) are widely used in the Scottish finfish aquaculture sector as a non-lethal means to deter depredation of salmon by harbour and grey seals (*Phoca vitulina* and *Halichoerus grypus*) by emitting loud, aversive sounds into the surrounding marine environment. In so doing, large areas are inevitably exposed to ADD signals, with potentially deleterious effects on non-target species of conservation concern such as harbour porpoise (*Phocoena phocoena*) and other cetaceans. Impacts of particular concern include physical auditory injury (both temporary and permanent) and behavioural disturbance, potentially resulting in changes in behaviour and/or distribution with long-term deleterious effects.
- Increased awareness of these wider impacts of ADDs has led to the development of different mitigation approaches. One of these attempts to exploit differences in auditory sensitivity between seals and odontocete cetaceans, by lowering the ADD signal frequency from the commonly used range of 10-20kHz down to <2kHz, where porpoises' hearing sensitivity is considered to be reduced compared to seals.
- The present experiment aimed to compare the effectiveness of this approach by comparing the response of porpoises to two artificial signals: a high-frequency signal ('HF'; 8-18 kHz), and a low-Frequency signal ('LF'; 1-2 kHz). The chosen field site was Bloody Bay (Northern Sound of Mull), an area known to be frequented by porpoises. Harbour porpoise presence within the ensonified area during repeat exposures was evaluated using visual and acoustic methods.
- The Bloody Bay site was instrumented with an extensive array of passive acoustic monitoring (PAM) sensors moored at 22 locations out to 5 km from the signal source, which was itself deployed from the fish farm infrastructure. PAM data were mainly collected using C-PODs (porpoise click train detectors), as well as several broadband recorders. Whenever conditions permitted, visual observers were stationed on an elevated vantage point onshore to collect sightings of porpoises and other species as well as environmental data. An experimental video tracking procedure was implemented to record small-scale responsive movement of surfacing porpoises following commencement of signal transmission.
- Signal transmission varied randomly between HF and LF signals as well as a silent control. All transmissions (including the control) lasted for 2 hours, and were all followed by an enforced 2-hour silent 'recovery' period. The signal transmission system operated in one of two modes: 'Day' and 'Night' mode. In Day mode, the system was on permanent standby and could be remotely triggered when

85 porpoises or other cetaceans were sighted. Outside regular observing hours (e.g. at night) or during
86 periods of poor weather, the system could be set to Night mode, which involved transmission of a
87 regular sequence of signals (including silent control) on a 50% duty cycle (2 hours on, 2 hours off) until
88 actively interrupted. The system was controlled via text messages over the GSM mobile phone network.

- 89
- 90 • The experimental period during which signals were transmitted lasted a total of 33 days (08/09 -
91 11/10/2016). During this period, 138 transmissions took place, including 53 of the HF signal, 38 of the
92 LF signal, and 47 silent controls. All the equipment, with the exception of 2 C-PODs and one broadband
93 recorder, was recovered by 17/10/2016. One C-POD malfunctioned, bringing the total number of C-
94 POD datasets available for further analysis to 19.
 - 95
 - 96 • Visual observations of porpoises were infrequent (23 sighting events over 19 days), despite good
97 observing conditions. Most porpoises were sighted some distance from Bloody Bay within the central
98 and northern Sound of Mull, particularly near the entrance to Loch Sunart. As a result, the video
99 tracking procedure was often unable to adequately resolve surfacing animals to assess responses to
100 different ADD signals, although the validity of the method itself was confirmed. Groups of bottlenose
101 dolphins were observed on four occasions and one minke whale was sighted. In contrast to the scarcity
102 of cetacean sightings, harbour seals were regularly observed on a near-daily basis, often in close
103 proximity to the fish farm.
 - 104
 - 105 • The C-POD array provided a high-resolution dataset on presence of echolocating porpoises over the
106 course of the experiment. Datasets were analysed using GAM-GEE models to investigate the relative
107 importance of different covariates, including signal transmission, in determining porpoise acoustic
108 presence.
 - 109
 - 110 • Ambient noise levels at the site, as assessed by broadband hydrophones, did not appear to significantly
111 impact C-POD performance. Porpoise detections (defined as 'Porpoise-Positive Minutes' or PPMs)
112 varied considerably across the array. Broadly speaking, PPM detection rates were higher in the central
113 and northern Sound of Mull when compared to the Bloody Bay area, particularly compared to waters
114 immediately surrounding the fish farm where detection rates were low.
 - 115
 - 116 • When assessing the effect of different signal transmissions, porpoise detection rates at most moorings
117 were higher during silent control periods, suggesting that transmission of both HF and LF signals
118 reduced the probability of porpoise detections. This was surprising as little difference was expected
119 between exposure to LF signals and silent control periods. The results of this study therefore suggest
120 that low-frequency ADD signals may also affect detection probabilities of harbour porpoises.
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- Based on GAM-GEE modelling outcomes, ADD signal type was generally of lesser importance in determining porpoise detection probability. In all models across the array, observed highly heterogeneous porpoise detection rates were strongly linked to environmental variables, particularly the day-night cycle. Models indicated a strong link between darkness and porpoise presence in shallow inshore areas, as opposed to much more constant detection rates in deeper waters in the central Sound of Mull. This suggests regular movement of at least some porpoises towards inshore areas during night-time, potentially to take advantage of food resources, and provides independent confirmation of the apparent rarity of daytime visual observations of porpoises in the area. Ebb-flood and spring-neap tidal variables also appeared relevant, although patterns were more variable across the array.
 - Pre- and post-experiment deployment of a single C-POD at the fish farm barge provided long-term context for experimental outcomes. Pre-experimental detection rates in July-August 2016 were slightly higher when compared to experimental control periods, although declining in the week or so immediately prior to the beginning of the experiment. In contrast, post-experimental monitoring (initiated early November 2016, i.e. over two weeks after the end of the experiment) indicated a significant increase in porpoise detections at the fish farm barge. Both pre- and post-experimental monitoring indicated strong links to the day-night cycle, with the vast majority of detections occurring at night.
 - Although not the focus of this study, seals were not noticeably deterred from the vicinity of the fish farm by experimental ADD signal transmissions, with no obvious difference between HF or LF signals in terms of surface observations. Our observations therefore did not support the assumption that either ADD signal represented a meaningful deterrent to seals when attempting to prevent fish farm depredation. Further research is thus needed to identify components in ADD signals that initiate avoidance behaviour among target and non-target species, and the degree to which individual animals become habituated to ADD outputs over time.

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1 INTRODUCTION: ADDS IN SCOTLAND

152

153 Marine acoustic deterrents have long been used to prevent or minimize interactions between marine mammals
154 and human activity in industries such as fishing, offshore construction and aquaculture (Dawson et al. 2013;
155 Graham et al. 2009; Brandt et al. 2013a, 2013b). The present report will focus on *Acoustic Deterrent Devices*
156 (*ADDs*), designed to deter depredation of fish farms by marine mammals (typically pinnipeds) rather than
157 devices meant to alert marine mammals to the presence of fishing gear, often referred to as ‘pingers’ (Lien et
158 al. 1992; Kraus et al., 1997; Northridge et al., 2011; Dawson et al., 2013). *ADDs* may also be referred to as ‘seal
159 scammers’, ‘seal scarers’ or ‘Acoustic Harrassment Devices’ (*AHDs*) in the literature; the terms *ADD* and *AHD*
160 are not mutually exclusive and usage is not always consistent. For the purpose of the present report, all devices
161 discussed below are designed to mitigate marine mammal depredation and will be collectively referred to as
162 ‘*ADDs*’.

163

164 *ADDs* were first introduced to Scotland in the mid-1980s (Coram et al. 2014). Since then, their use in the Scottish
165 aquaculture sector has steadily increased, from <10% of 41 sites visited by Hawkins (1985), to 18% of 45 sites
166 visited in 1988 (Ross 1988) using *ADDs*. Following widespread uptake of *ADDs* in the 1990s, Quick et al. (2004)
167 reported *ADDs* in use among 52% of fish farms interviewed in 2001. This figure is in broad agreement with the
168 approximately 50% of fish farms reporting to be using *ADDs* more recently by Northridge et al. (2010) based on
169 questionnaire surveys. Use of *ADDs* in Scottish finfish aquaculture therefore appears to be widespread although
170 not universal, often with several devices deployed on individual farms. It is also worth noting that the use of
171 *ADDs* is increasingly being proposed as a potential tool to mitigate impacts beyond the aquaculture sector, e.g.
172 to reduce the risk of severe noise impacts during offshore construction (pile-driving) activities, or to reduce
173 collision risk among tidal turbines (Hermanssen et al. 2015; Gordon et al. 2007; Wilson & Carter 2013).

174

175 Considerable debate still surrounds the issue of long-term efficacy of *ADDs* in deterring seal depredation, and
176 the precise mechanisms of sound aversion underpinning their functionality remain poorly understood (e.g., Yurk
177 & Trites 2000; Jacobs & Terhune 2002; Quick et al. 2004; SMRU Ltd. 2007; Graham et al. 2009, 2011; Götz &
178 Janik 2010; Harris et al. 2014). Further complexity is introduced by differing animal responses to *ADDs* due to
179 species-specific and individual behaviour, motivation, habituation or reduced responsiveness due to hearing
180 damage (Götz & Janik 2013). Nevertheless, *ADDs* remain in widespread use as an anti-depredation method in
181 the Scottish finfish aquaculture sector, in the face of increasing restrictions on lethal seal control measures
182 introduced under the Marine (Scotland) Act 2010 (Scottish Government 2015).

183

184 Over the years, several different ADD types have been developed, many of which are available commercially.
185 While five different models of ADDs (Airmar™, Terecos™, Ace Aquatec™, Lofitech™ and Ferranti-Thomson™) are
186 known to have been used in Scottish finfish aquaculture, three of these (Airmar, Terecos and Ace Aquatec)
187 appear to account for the majority of ADDs in current use in the sector (Northridge et al. 2010, 2013; Coram et
188 al. 2014; Lepper et al. 2014). A review of commercially available ADD systems was carried out, with a summary
189 provided in Table 1 of acoustic signal characteristics of the most commonly used ADDs in the Scottish finfish
190 aquaculture sector. The different models differ in terms of their acoustic characteristics (e.g. signal type, duty
191 cycle, frequency range) as well as in terms of power supply and cost (e.g. Lepper et al. 2004; Coram et al. 2014;
192 Lepper et al. 2014). In general, however, most systems transmit single frequency tonal sinusoidal bursts, with
193 source levels at individual frequencies typically between 175 and 195 dB re 1 μ Pa-m (RMS; Table 1). Several
194 systems generate relatively high frequency single-frequency tonal bursts, for example the Airmar (dB plus II) at
195 10.3 kHz (Lepper et al. 2004) and the Lofitec at around 15 kHz (Fjälling et al. 2006). A variation is seen in the Ace
196 Aquatec family of system with the most recent US3 system generating a random sequenced series of pulses in
197 the frequency range 10-20 kHz (Ace Aquatec, 2016). In the case of the US3 system, each pulse consists of approx.
198 40 cycles of the fundamental frequency with a 50% duty cycle between pulses (Lepper et al. 2004). In
199 comparison, the Airmar dB plus II system generates a shorter 1.4 ms pulse, consisting of approx. 16 cycles of the
200 fundamental frequency with a 40 ms spacing (Lepper et al. 2004). A fourth system that has been used in Scottish
201 waters is the Terecos system, which generates a complex series of multi-frequency components with a high
202 degree of randomness in the sequence timing (Lepper et al., 2004).

203

204 Although most ADD models are designed to operate in the 5-30 kHz frequency range, they all generate both
205 fundamental and higher-frequency harmonics. In the Airmar, Lofitec and Ace Aquatec systems, harmonics only
206 involve a single frequency but are generated whenever the device is active. In contrast, the Terecos system is
207 designed to generate highly randomized patterns of broadband variant sounds in the 1.8 – 6.8 kHz frequency
208 range. However, signal structure and levels of ADD devices often remain poorly described and field
209 measurements do not always match information provided by manufacturers (Coram et al. 2014). Examples of
210 ADD waveforms and spectrograms are provided in Figure 1 to illustrate the signal output diversity inherent in
211 these devices.

212 Table 1. Acoustic signal characteristics of different ADD types currently used or proposed in Scottish finfish aquaculture. Adapted from Götz & Janik (2013). Values from particular references are indicated using *,
 213 ** and *** symbols.

Manufacturer	Type	Source level (dB re 1 μ Pa-m)	Peak frequencies and patterns	Temporal structure		Cetacean-friendly	Commercially available	References
				Duty cycle	Duration (s)			
Airmar (OTAQ, Mohn Aqua / Gaelforce Marine Technology)	Airmar dB Plus II	192.5 dB (RMS) * 198 dB (RMS)**	10.3 kHz with evenly spaced harmonics up to 103 kHz at SL >145 dB (RMS)*	50%	1.4ms segments at 40ms intervals; 2.25s/sequence*			*Lepper et al. 2004, 2014 ***Manufacturer manual
Ace Aquatec	US3 (Universal Scrammer)	193-194 dB (RMS) at 10 kHz*	Pulses centred at 28 different frequencies (10-65 kHz), 64 different patterns, chosen at random*	50%	3.3-14ms segments at 33.2-48.5ms intervals; 5s/sequence*			*Lepper et al. 2014 Northridge et al. 2013
Ace Aquatec	US3 (Low Frequency Variant)	195 dB (RMS) at peak frequencies*	1-2 kHz*	unknown	unknown	x	x	*Pers. comm. from manufacturer

Lofitech	Universal Scarer	193 dB (RMS) at 15.6 kHz*	14-15 kHz	12%**	500-550ms pulses in blocks of various lengths; 20-60s intervals***			*Shapiro et al. 2009 **Brandt et al. 2013a, 2013b *** Götz & Janik 2013
Terecos	DSMS-4	177-179 dB (RMS) at 4.9-6.6 kHz*	Complex randomized sequences of tonal blocks from 1.8-6.8 kHz with harmonics up to 27 kHz at SL >143 dB*	Highly randomized and user selectable*	Variable; 8ms segments; trains from 200ms to 8s**			*Lepper et al. 2004 **Reeves et al. 2001
Ferranti-Thomson	MK2 (Seal Scrammer) MK2 4X	194 dB (RMS) at 27 kHz* 200 dB (RMS) at 25 kHz**	Pulses centred at 5 different frequencies arranged in 5 randomly chosen sequences**	3% (maximal 5.5 sequences / hour)**	20ms pulses at 40ms interval; 20s/sequence**			*Yurk & Trites (2000) **Gordon & Northridge (2002)
Götz-Janik	Startle response deterrence	180 dB (RMS) at 1 kHz*	Pulse spanning 2-3 octave bands with 1 kHz peak and < 5ms rise time*	0.8%*	200ms pulse; 0.04 pulses/s at x pseudorandom at			*Götz & Janik (2015)

					intervals from 2-40s*			
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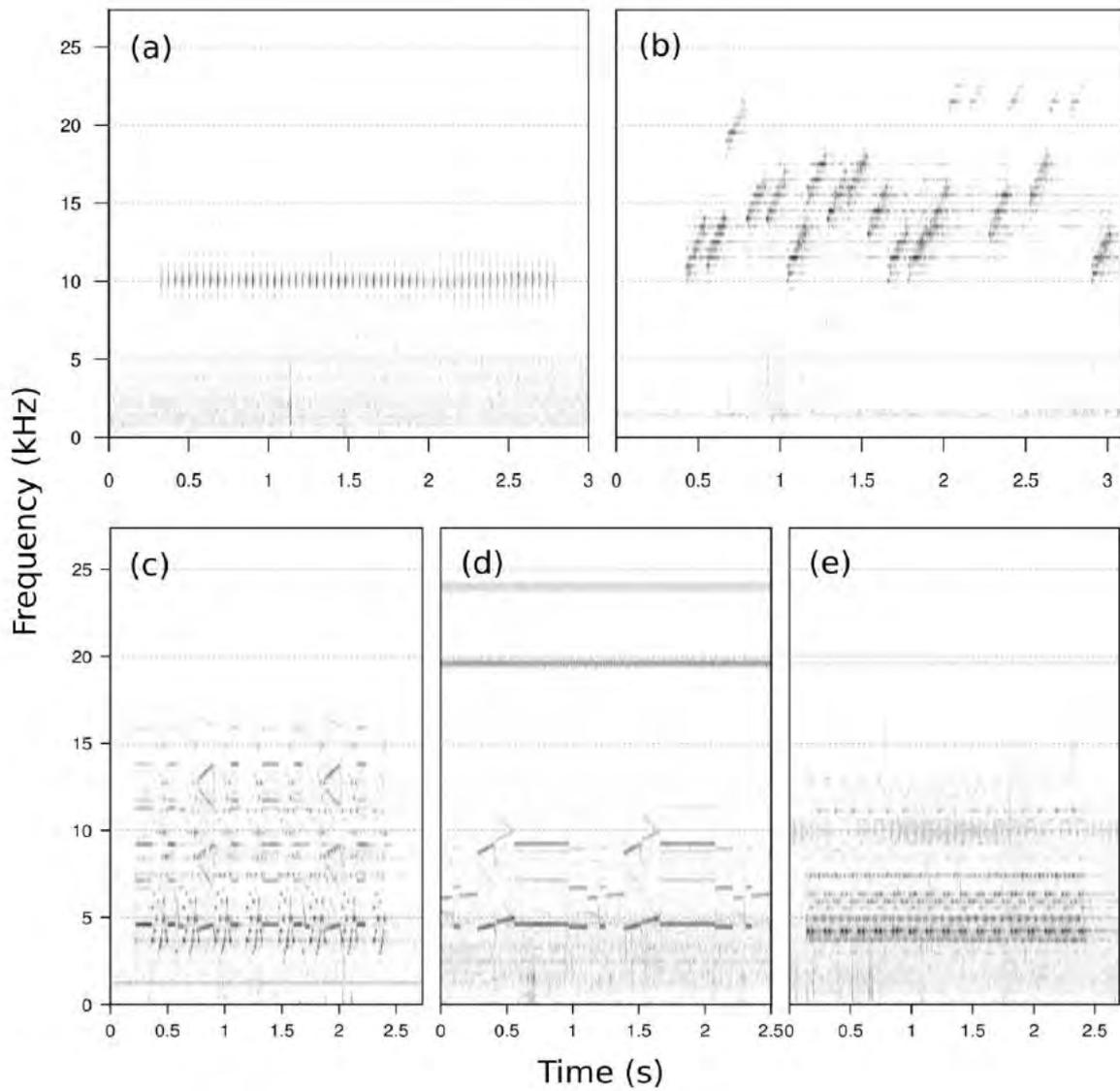


Figure 1. Examples of ADD spectrograms. Spectrogram parameters: FFT size = 1024 points, overlap = 50%, sample rate = 96 kHz; resulting in frequency and time resolution of 93.8 Hz and 10.67 ms, respectively. (a) Airmar™ (dB Plus II); (b) Ace Aquatec™ (US3); (c) Terecos™ (Type DSMS-4) Programme 4; (d) Terecos™ (Type DSMS-4) Programme 2; Terecos™ (Type DSMS-4) Programme 3.

216 2 IMPACTS OF ADDS ON CETACEANS

217 The majority of currently available ADDs are designed to operate through continuous or repeated emissions of
218 loud, aversive sounds that are mainly intended to deter pinnipeds from finfish aquaculture sites. In so doing,
219 large areas of the surrounding marine environment are inevitably exposed to ADD signals, with potentially
220 deleterious effects on non-target species such as cetaceans (Johnston & Woodley 1998; Jacobs & Terhune 2002;
221 Olesiuk et al. 2002; Brandt et al. 2013a, 2013b; Coram et al. 2014). Cetaceans rely on acoustics for foraging,
222 navigation and communication and are therefore considered to be particularly sensitive to anthropogenic noise
223 impacts such as those generated by ADDs (e.g. Nowacek et al. 2007). As with other sources of anthropogenic
224 noise, determining possible impacts of ADDs on cetaceans can be complex, with any impact dependent on
225 variables such as the acoustic sensitivity of the species of interest, signal frequency range and source level, the
226 number of devices in use at each fish farm, devices' duty cycles and local propagation characteristics. Potential
227 impacts to cetaceans from such elevated noise levels may include physical harm (hearing damage), physiological
228 stress responses to chronic noise exposure, behavioural responses (e.g. changes to behavioural patterns, up to
229 and including displacement from the ensonified area) and masking of biologically important sounds (e.g.
230 indicating the presence of prey, conspecifics or an approaching predator; Richardson et al. 1995; Nowacek et al.
231 2007).

232

233 Several recent studies have investigated the effects of ADDs on harbour porpoises (*Phocoena phocoena*) and
234 other cetacean species that also occur frequently along the west coast of Scotland, such as bottlenose dolphins
235 (*Tursiops truncatus*) and minke whales (*Balaenoptera acutorostrata*; e.g. Northridge et al. 2010; Coram et al.
236 2014; Lepper et al. 2014; Götz & Janik 2015). For the purpose of the present report, cetacean species of greatest
237 concern in inshore Scottish waters include harbour porpoise and bottlenose dolphin. Harbour porpoises are the
238 most frequently encountered cetacean species along the west coast of Scotland, and this area appears
239 significant at a European scale in terms of porpoise densities observed (e.g. Reid et al. 2003; Booth et al. 2013).
240 In contrast, only small numbers of bottlenose dolphins are resident along the west coast of Scotland (Cheney et
241 al. 2013). Other cetacean species known to be present in inshore Scottish waters (and thus exposed to
242 aquaculture-associated ADD noise) include killer whale (*Orcinus orca*), Risso's dolphin (*Grampus griseus*), short-
243 beaked common dolphin (*Delphinus delphis*), white-beaked dolphin (*Lagenorhynchus albirostris*) and minke
244 whale (*Balaenoptera acutorostrata*).

245

246 Both harbour porpoises and bottlenose dolphins are listed under Annex II of the EC Habitats Directive (EC 1992),
247 which requires strict protection measures to be applied to both individuals and populations, including the
248 establishment of Special Areas of Conservation (SACs) to protect habitats that are important for the survival of
249 the species. SACs are intended to contribute to a coherent European ecological network of protected sites, and

250 thereby ensure continued maintenance of Favourable Conservation Status (FCS) of the species involved. The
251 recently designated 'Inner Hebrides and the Minches' candidate Special Area of Conservation (cSAC) for harbour
252 porpoises encompasses a large part of the Scottish west coast, which also includes numerous finfish aquaculture
253 sites (Scottish Natural Heritage 2016). Given harbour porpoises' potential sensitivity to ADD noise, current levels
254 of ADD usage within and adjacent to the 'Inner Hebrides and the Minches' cSAC therefore potentially have a
255 negative impact on FCS for this species.

256

257 2.1 PHYSIOLOGICAL EFFECTS

258 Exposure to any sound above a certain threshold level can incur temporary or permanent hearing damage,
259 typically referred to as either a Temporary or Permanent Threshold Shift in hearing sensitivity at relevant
260 frequencies (TTS or PTS, respectively; Richardson et al. 1995; Southall et al. 2007). TTS and PTS thresholds are
261 species-specific and depend on the sound pressure level of the signal as well as exposure time. Lepper et al.
262 (2014) developed a generalised sensitivity model to predict ranges at which predetermined TTS-onset thresholds
263 (based on Southall et al. 2007) might be exceeded by existing ADD types based on maximum sound pressure
264 levels and cumulative sound exposure levels (SEL), also taking into account impacts of environmental factors
265 such as sediment type, water depth and seabed slope. Assuming no responsive movement, model outcomes
266 indicated that injurious exposure levels could be reached within several hours if animals remained within several
267 hundred metres of the sound source. Even considering the assumptions made in this model, the authors
268 concluded that “the risk that ADDs will cause hearing damage in marine mammals appears to be a real one that
269 cannot be discounted” (Lepper et al. 2014, p.72).

270 Götz & Janik (2013) used a model to estimate distances around an ADD sound source within which TTS and PTS
271 might occur for different species-groups, using multiple device types under different sound exposure scenarios.
272 These estimates show that ADDs with higher source levels or higher duty cycles (due to the deployment of
273 several devices in an array) require shorter exposure times in order to cause hearing damage. For example a 4-
274 transducer Airmar array will reach a TTS inducing sound exposure level (SEL) of 203 dB re $1\mu\text{Pa}^2\text{s}$ within 3 minutes
275 and would affect porpoises that stay within ~ 90 m of the array. Under the same 3-minute exposure conditions,
276 a harbour porpoise could potentially suffer PTS if remaining within 9 m of the transducer (Lucke et al. 2009; Götz
277 & Janik 2013). These examples indicate that, based on current understanding of marine mammal hearing
278 capabilities and underwater sound propagation characteristics, it is impossible to ensure that temporary or even
279 permanent hearing damage in marine mammals through ADD noise exposure can always be avoided.

280

281 Long-term exposure to chronic noise pollution can have significant deleterious effects on the health of both
282 humans and animals through a number of physiological pathways involving combinations of neural and
283 endocrine systems (summarised by Wright et al. 2007a, 2007b). Such responses may be difficult to detect in

284 free-living cetaceans, and most of our current knowledge is derived from studies using small numbers of captive
285 animals (e.g. Thomas et al. 1990; Miksis et al. 2001; Romano et al. 2004). However, stress hormone levels have
286 been measured in whales' blows, suggesting anthropogenic noise may have substantial impacts on health of
287 wild populations (Rolland et al. 2012). The effects of aquaculture-associated ADDs on cetaceans in this regard
288 remain poorly understood but merit further study in the light of currently available data on effects of other
289 anthropogenic noise sources (Wright et al. 2007b).

290

291 2.2 BEHAVIOURAL RESPONSES AND HABITAT DISPLACEMENT

292 Beyond physical injury, another important potential impact of underwater noise concerns its ability to induce
293 changes in animals' behavioural patterns and/or deter animals from ensonified areas, either temporarily or
294 permanently (Nowacek et al. 2007; Götz & Janik 2013). Several behavioural response studies have attempted to
295 either investigate behavioural effects of ADDs on cetaceans around fish farms or evaluate their potential to deter
296 animals from construction sites (e.g. Johnston 2002; Götz & Janik 2013; Lepper et al. 2014; Hermannsen et al.
297 2015). Airmar and Lofitech devices were the ADD types most often tested in these contexts. Olesiuk et al. (2002)
298 reported a significant decline in observations of harbour porpoises in British Columbia, Canada, out to the
299 maximum viewing distance of 3.5 km when an Airmar ADD (type unspecified) was activated. Johnston (2002)
300 tested a comparable ADD (Airmar dB II Plus) in the Bay of Fundy (Canada) and observed similar evasive responses
301 by harbour porpoises at distances of at least 1 km. Strong aversive responses were also reported by Brandt et
302 al. (2013a, 2013b) and Mikkelsen et al. (2017) using a Lofitech ADD; significant reductions in porpoise detections
303 out to 7.5 km were observed (Brandt et al. 2013b). Summarizing and evaluating results from several studies,
304 Hermannsen et al. (2015) reported minimum absolute deterrence distances for harbour porpoises of about 200
305 m and 350 m for Airmar and Lofitech devices, respectively. These distances typically correspond to signal
306 received levels of 130-150 dB re $1\mu\text{Pa}_{\text{rms}}$ depending on frequency range and device source level tested
307 (Hermannsen et al. 2015). However, absolute deterrence effects can extend over much larger ranges. For
308 example, Brandt et al. (2013a) reported avoidance responses by all observed porpoises within a range of 1.9 km
309 from an active Lofitech device, corresponding to estimated received levels ≥ 120 dB re $1\mu\text{Pa}_{\text{rms}}$. The closest
310 observed approach in this study was at about 800 m (132 dB re $1\mu\text{Pa}_{\text{rms}}$). In a separate study using passive
311 acoustic monitoring, Brandt et al. (2013b) found a significant deterrence effect of a Lofitech device up to 7.5 km
312 (113 dB re $1\mu\text{Pa}_{\text{rms}}$). Kastelein et al. (2015) tested the effect of Ace Aquatec and Lofitech ADDs on a captive
313 harbour porpoise and found strong deterrence effects at 139 dB re $1\mu\text{Pa}_{\text{rms}}$ for the former and 151 dB re $1\mu\text{Pa}_{\text{rms}}$
314 for the latter. These results correspond to absolute deterrence distances of 380-590 m and 40-150 m for Ace
315 Aquatec and Lofitech devices, respectively and a deterrence distance for most animals of 2-4 km (Hermannsen
316 et al. 2015).

317

318 Few studies have evaluated behavioural effects of ADDs on other cetacean species, but one study in the
319 Broughton Archipelago (British Columbia, Canada) found evidence of prolonged (6 years) habitat displacement
320 of killer whales, which the authors attributed to the introduction of ADDs in the study area (Morton & Symonds
321 2002). Sightings of Pacific white-sided dolphins (*Lagenorhynchus obliquidens*) also declined after ADDs were
322 introduced to the area (Morton 2000). In contrast, a study on ADD impacts on bottlenose dolphins in Sardinia
323 (Italy) did not find an effect of ADD activity on dolphin presence, group size or distance from the fish farm (Lopez
324 & Marino 2011). In the latter case, enhanced motivation of dolphins to stay in the area due to enhanced food
325 availability may have played a role. Götz & Janik (2015) noted that controlled exposure experiments involving
326 their startle-reflex ADD (Table 1; see Section 1.3) did not appear to affect minke whales observed at distances
327 >1000m, but could not rule out potential impacts at closer distances. Controlled exposure experiments with a
328 Lofitech ADD unit indicated significant changes to minke whale behaviour at distances of 500-1000 m when the
329 ADD was active, including increases to net swim speed and directness of movement (McGarry et al. 2017). This
330 suggests that some ADD types, at least, may also impact cetacean species traditionally considered more sensitive
331 to relatively low frequencies (Southall et al. 2007).

332

333 Masking occurs when a sound is influenced by another sound of similar frequency, thereby interfering with
334 reception and/or interpretation of the original sound of interest (Fletcher 1940). Broadband ADD signals (e.g.
335 Ace Aquatec and Terecos), in particular, overlap with communication and echolocation signals of several marine
336 mammal species, thereby raising the potential for communication masking in the vicinity of these devices (Götz
337 & Janik 2013). Masking of marine mammal vocalizations by anthropogenic noise has primarily been considered
338 in the context of shipping noise, which can result in a significant reduction of the space within which cetacean
339 communication can occur (Clark et al. 2009; Jensen et al. 2009). This problem has not been directly investigated
340 in the context of ADDs impacting species of concern in Scottish aquaculture and studies of the actual sound field
341 around fish farms with active ADDs are needed to study this problem more thoroughly. Masking potential of
342 some typical ADD sounds with centre frequencies around 10 kHz might be of less importance for harbour
343 porpoises, as there is evidence that porpoises are able to accurately detect tonal sounds between 8 and 16 kHz
344 in broadband noise (Kastelein et al. 2009, Booth 2010).

345

346 2.5 'CETACEAN-FRIENDLY' ADD SYSTEMS

347 Current concerns about potential impacts of ADD signals on non-target species such as harbour porpoise have
348 encouraged the development of novel ADD systems seeking to minimize such impacts while still acting as
349 effective pinniped deterrents. Use of such systems has been suggested as a possible means to achieve reductions
350 in acoustic impacts while continuing to use ADDs in otherwise sensitive areas, for example on aquaculture sites

351 within the 'Inner Hebrides and the Minches' candidate Special Area of Conservation (cSAC), designated to
352 protect harbour porpoises (Scottish Natural Heritage 2016; Marine Scotland 2016).

353

354 Several different approaches have been considered to reduce overall ADD acoustic output. For example, Ace
355 Aquatec have developed a 'Silent Scrammer'™ which only transmits sound when triggered through motion
356 sensors indicating the presence of a seal near the cages, thus reducing the total amount of sound produced over
357 time. Such systems can also be integrated with other non-acoustic components, such as electrified cage fences,
358 to further enhance deterrent effects without increasing acoustic output (Ace Aquatec Universal Scrammer 3™
359 [US3]; Ace Aquatec 2016).

360 Another potential means to reduce acoustic impacts of ADDs on porpoises and other species involves taking into
361 account the difference in low-frequency hearing capability between harbour porpoises and seals. Harbour
362 porpoise hearing has been shown to be relatively insensitive at frequencies <2.5 kHz even under low ambient
363 noise levels, whereas harbour seals' hearing remains more sensitive to sounds down to frequencies <1kHz under
364 similar conditions (Kastelein et al. 2002, 2010). This inter-species difference in sensitivity to frequencies <2.5 kHz
365 has led to the development of lower-frequency ADD systems aiming to increase target specificity. Ace Aquatec
366 has developed a low frequency version of the US3 system that generates randomized tonal burst in the 1-2 kHz
367 range, seeking to emit a signal that would deter pinnipeds whilst reducing or eliminating impacts on cetaceans
368 (Ace Aquatec, pers. comms, 2016; Table 1). The low-frequency Ace Aquatec US3 system is presently the only
369 commercially available ADD system adopting this approach. Details of system characteristics are, unfortunately,
370 scarce and no peer-reviewed descriptions are presently available of either 1) this device's long-term ability to
371 effectively deter seals or 2) potential responses of harbour porpoises and other non-target species to its acoustic
372 output across varying spatiotemporal scales.

373

374 Loud sounds with sharp rise times can elicit an autonomous startle reflex in mammals, including seals (Götz &
375 Janik 2011). Recent studies have demonstrated that grey seals (*Halichoerus grypus*) show sustained avoidance
376 behaviour after repeated exposure to startle reflex-inducing acoustic stimuli (Götz & Janik 2011). On the basis
377 of these findings, a novel ADD system intended to more effectively deter seals from fish farms, whilst avoiding
378 unintended effects on non-target species such as harbour porpoises, has been patented (Götz & Janik 2012).
379 The acoustic characteristics of this system are described in Table 1. At 1 kHz, peak frequencies for the deterrence
380 stimulus are well below traditional ADD systems and duty cycles can be low (0.8%, see Table 1; Götz & Janik
381 2015). Field trials showed the effectiveness of this system in deterring seals from fish farms while reducing the
382 risk to non-target species such as harbour porpoises (Götz & Janik 2011, 2015). Over a 2-month period,
383 significant reductions in observed seal numbers during sound exposure were observed without noticeable
384 habituation occurring, whereas no changes in porpoise relative abundance, distribution or behaviour were

385 observed (Götz & Janik 2015). However, received levels need to be loud (>145 dB re $1 \mu\text{Pa}_{\text{RMS}}$) and signal onset
386 sharp (<5 ms) to elicit a response; since both of these factors are affected by sound propagation through the
387 water column, the effectiveness of this method is likely limited to relatively short ranges around fish farms
388 (Coram et al. 2014; Götz & Janik 2015). This might be an advantage in the context of using ADDs continuously to
389 deter seals, as avoidance responses will be limited to the immediate area around the ADD. This would, however,
390 also mean that seals would have to be in close proximity to a fish farm for the deterrent to be effective; at such
391 close distances, individual seals' increased motivation to investigate a potential food source might reduce
392 deterrent efficacy. Another concern would be that lower frequencies generated by this device will propagate
393 over larger ranges and are likely to be more audible to other non-target species such as fish and baleen whales.
394 Potential effects of these ADD signals on such other species need to be investigated before large-scale
395 deployments of these devices can commence.

396

DRAFT - for peer review

397 3 EXPERIMENTAL METHODS

398 3.1 BACKGROUND AND PROJECT AIMS

399 The present study was commissioned by the Scottish Aquaculture Research Forum (SARF) to investigate the
400 potential impacts of ADDs that emit lower frequency sounds on non-target species such as harbour porpoises in
401 Scottish waters. Given that standard ADD devices are known to be capable of impacting harbour porpoises, their
402 continued usage could be affected by the recent designation of the 'Inner Hebrides and Minches' candidate SAC
403 for porpoises, which encompasses a substantial portion of the Scottish salmon aquaculture industry. ADDs that
404 emit sounds at lower frequencies have been proposed and marketed as a means to alleviate the noise impact
405 on these and other high-frequency sensitive cetacean species. These 'environmentally friendly' claims have yet
406 to receive independent quantitative evaluation, however.

407

408 Against this background, the present research project was initiated aiming to undertake a controlled exposure
409 experiment on an active fish farm on the west coast of Scotland. Simulated ADD sounds were played back to
410 porpoises upon visual detection by shore-based observers, or at regular intervals during night or poor weather.
411 Signals were specifically designed for this project to take advantage of the difference in auditory sensitivity
412 between seals and porpoises at frequencies <2.5 kHz. Responses of porpoises to ADD signal transmissions were
413 recorded through an array of passive acoustic detectors, as well as visually through onshore observers and an
414 experimental camera tracking array.

415

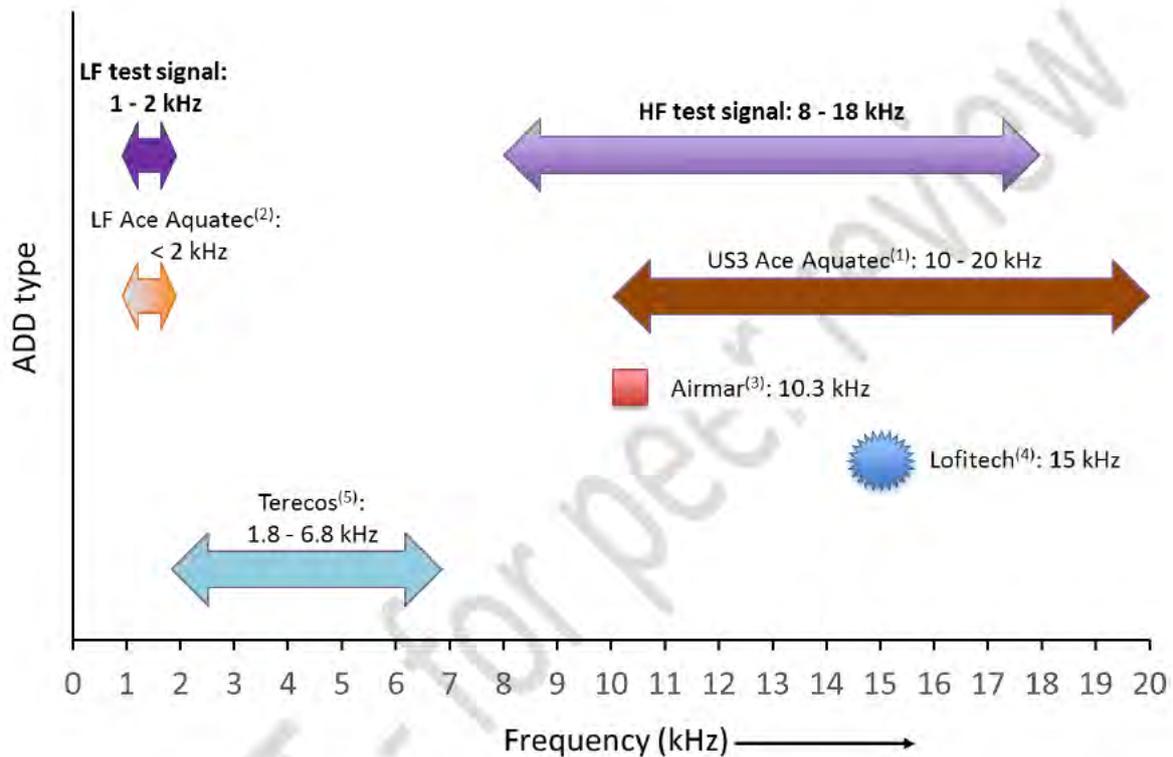
416 3.2 ACOUSTIC PLAYBACK SIGNAL DESIGN

417 Although several different ADD devices are presently available commercially, their signal output varies
418 substantially in terms of source level, frequency range, duty cycle, repeatability etc. (Table 1; Figure 1), and
419 uncertainty remains over which aspect(s) of the emitted signals might lead to a deterrence effect. No actual
420 ADDs of any particular brand were used in the present experiment in order to maintain impartiality towards all
421 suppliers, in line with SARF's original tendering specifications. Instead, a pair of artificial signals were designed
422 so as to encompass the approximate ranges of signals produced by several different ADD types presently in
423 commercial use in Scottish salmon aquaculture.

424

425 In the experimental design the potential difference between porpoises' and seals' behavioral responses to either
426 high- / low-frequency ADD signals was applied. A high frequency (HF) test signal was designed using single
427 frequency tonal bursts, similar to the Airmar, Lofitec and Ace Aquatec brands that represent the majority of
428 ADDs in current use in Scottish salmon aquaculture. The random frequency sequencing and the pulse width and

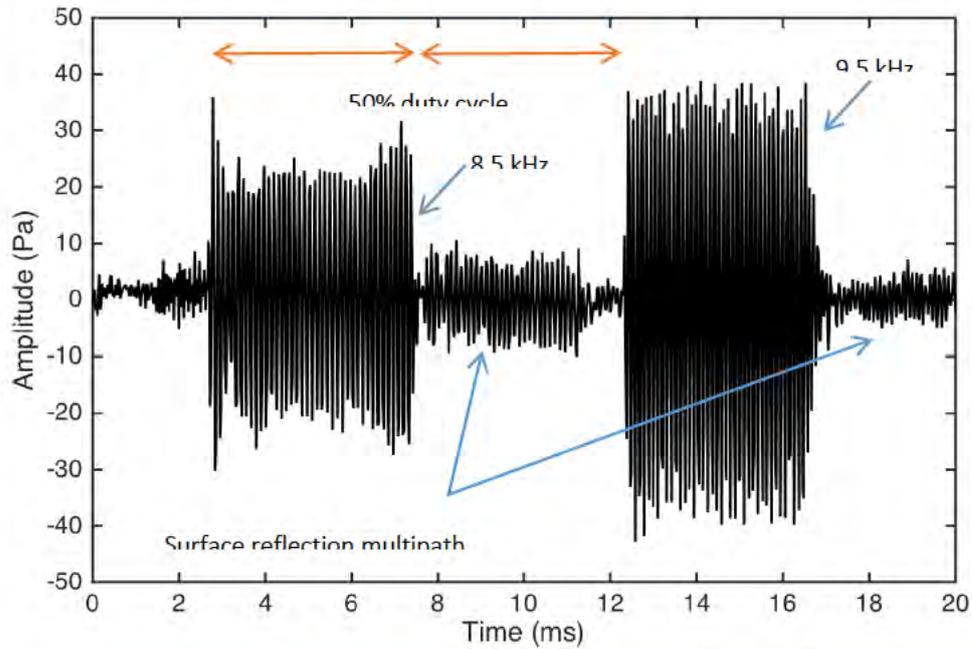
429 duty cycle of the Ace Aquatec were also adopted. The overall frequency range of transmission was extended
 430 from 8-18 kHz to capture the full frequency spectrum of all three systems (Figure 2). Specifically, the HF signal
 431 consisted of pulsed continuous wave sinusoidal tonal bursts at one of 21 randomly switching fundamental
 432 frequencies between 8 – 18 kHz at frequency intervals of 500 Hz. Each pulse contained 40 cycles of fundamental
 433 frequency with a rectangular pulse amplitude envelope, and the on – off duty cycle was 50%. Figure 3 illustrates
 434 the variation in pulse amplitude due to transducer response as well as pulse duration.



435

436 **Figure 2.** Output frequency ranges of the two test signals (LF and HF), compared to outputs from various existing ADD types (see Table 1
 437 for details). Data on existing ADD outputs derived from 1) Ace Aquatec U3S manual (<https://www.aceaquatec.com/us3specification>); 2)
 438 Ace Aquatec pers. comm. (PL); 3) Lepper et al. 2004, 2014; 4) Fjälling et al. 2006; 5) Lepper et al. 2014.

439



440

441 **Figure 3. Time domain plot of two consecutive samples from the HF sequence – first pulse at 8.5 kHz and second at 9.5 kHz.**

442

443 A similar low-frequency (LF) test signal was made up of pulsed continuous wave sinusoidal tonal bursts at one
 444 of 11 randomly switching fundamental frequencies between 1 – 2 kHz and frequency intervals at 100 Hz. Each
 445 pulse was made up of 40 cycles of fundamental frequency with a rectangular pulse amplitude envelope, and the
 446 on – off duty cycle was 50%. This signal was designed to produce outputs comparable to those from the Ace
 447 Aquatec US3 Low-Frequency variant ADD design, again based on frequency range and repeatability (Figure 2).

448

449 Evaluating the broadband multi-frequency nature of the Terecos system (described in Lepper et al. 2014) was
 450 felt to be beyond evaluation scope in the available experimental paradigm for the proposed trials and so was
 451 not included in the current experiment. Figure 2 illustrates the comparison between the experimental HF and
 452 LF signals, and existing ADD systems, in terms of fundamental frequency spectral distribution. Differences in HF
 453 and LF signal characteristics are further illustrated in Figure 4. Relevant parameters of both signals are
 454 summarized in Table 2.

455

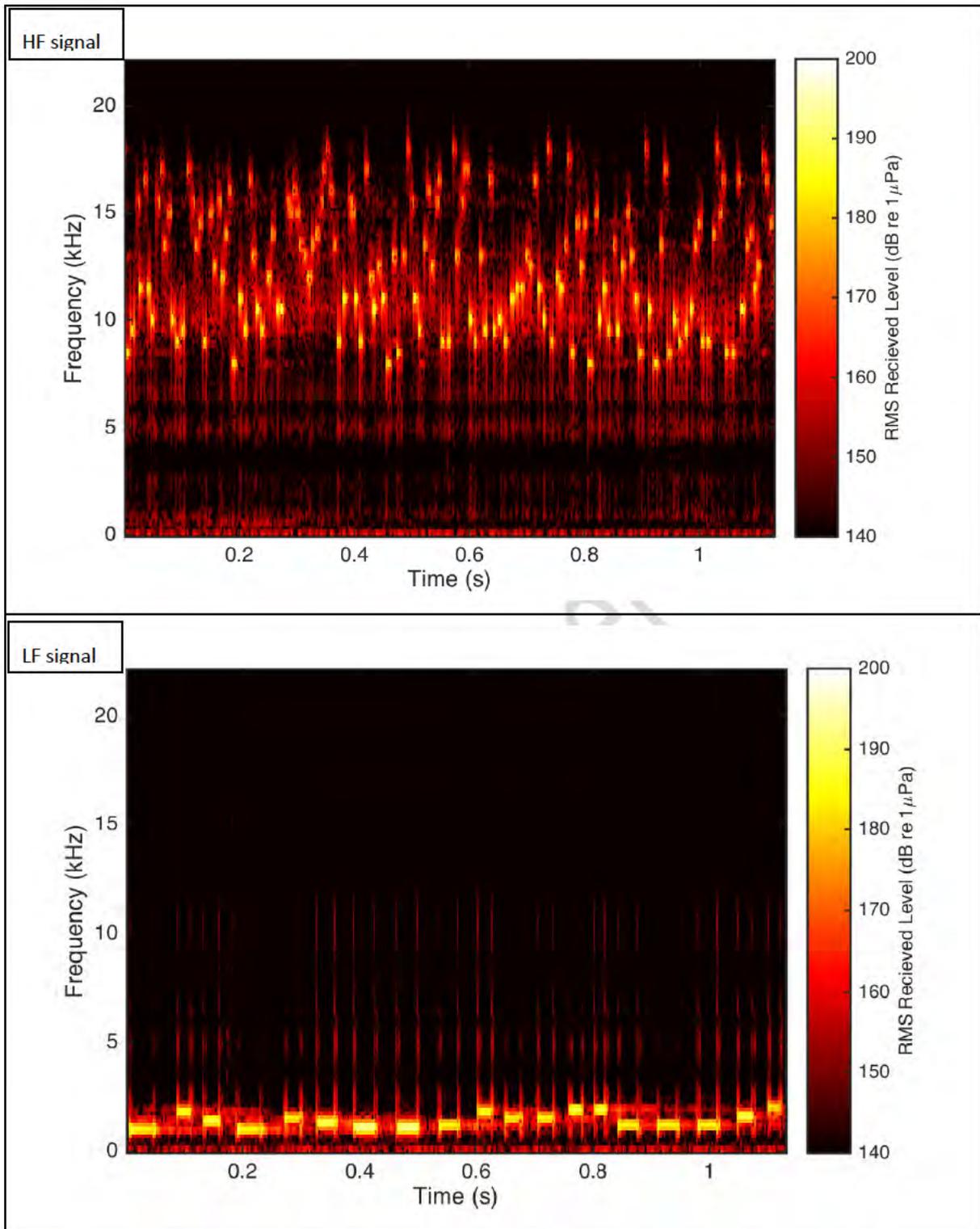
456

457 **Table 2. Summary of HF and LF artificial ADD signals used in the present experiment.**

Parameter	High-frequency (HF)	Low-frequency (LF)
Signal structure	pulsed continuous wave sinusoidal tonal bursts	
Frequency sequencing	Random as per Ace Aquatec™	
Number of fundamental frequencies	21	11
Fundamental frequency range	8 – 18 kHz	1 – 2 kHz
Frequency interval	500 Hz	100 Hz
# of cycles per pulse	40	40
Pulse duration	2.2 – 5.0 ms	20.0 – 40.0 ms
Duty cycle	50%	50%
RMS Source level	154.1 – 170.1 dB re 1 μ Pa-m	165 – 170.4 dB re 1 μ Pa-m

458

459



460 Figure 4. Spectral plot of a sample of the HF and LF signals received at a range of 8.5 m using a Reson 4014 balanced hydrophone. Analysis
 461 window was 256 FFT with 50 % overlap using a Hanning window. A 50 kHz low pass filter was applied. Original data were downsampled
 462 to a sample rate of 44.1 kHz.

463

464 3.3 SIGNAL TRANSMISSION

465 The HF and LF test signals were generated using a bespoke signal generation system. A National Instruments™
466 myRIO FPGA platform, programmed within the Laboratory Virtual Instrument Engineering Workbench
467 (LabVIEW) environment, was used to generate all the signal types and sequencing and session data. This was
468 linked via a Serial Peripheral Interface (SPI) bus to a Linkit™ GSM modem, allowing communication and control
469 both remotely and by the shore team of the signal source via mobile phone SMM messaging. Data such as mode
470 and battery life could also be accessed remotely via the GSM network. Generated signals were then fed to a
471 dedicated power amplifier and ultimately to a Lubell™ underwater loudspeaker system deployed 10.5 m below
472 the fish farm barge. A second complete signal synthesis system (including myRIO and Linkit elements) was
473 included in the overall system in case of primary system failure, with each of the GSM modems using SIM cards
474 from two separate mobile phone networks for additional redundancy.

475

476 The whole system was deployed from the fish farm barge in weatherproof housings, and was powered by three
477 large 12 V lead acid leisure batteries maintained with two ~200 W solar panels (Figure 5). The system was
478 designed to operate continuously without intervention of trials team for the project duration; periodic battery
479 swaps (every 3-4 days) were, however, carried out by the fish-farm crew to ensure continuous operation. Visual
480 confirmation of system activation was made via a beacon light visible from the shore in case of failure of SMM
481 messages.

482



483 Figure 5. A) Solar panels providing additional power to the signal transmission system aboard the fish farm barge; B) The signal
484 transmission control unit.

485

486 Calibration of the signal source from the Lubell speaker at each tonal frequency was undertaken in-situ. Test
487 trials recorded both signal types using a balanced RESON™ 4014 hydrophone with sensitivity of around -180 dB
488 re 1V/ μ Pa using a dedicated 20 dB balanced preamplifier. Measurements were made with preamplifiers / filters
489 in the frequency range 100 Hz – 200 kHz and <50 kHz. Data acquisition was carried out using a 16-bit National

490 Instruments 6521 DAQ system at a sample rate of 1.25 MSs⁻¹ with a voltage range of +/- 5V using bespoke data
 491 acquisition software. Both the DAQ and laptop (SurfacePro) were battery-powered. The RESON 4014
 492 hydrophone was deployed from the front of the barge 8.5 m directly in front of the sound source at the same
 493 depth of 10.5 m. In post-experimental analysis, the free-field direct path of the signal was identified, allowing
 494 RMS levels to be calculated on this basis (Table 3). Free-field source levels were then calculated using spherical
 495 spreading.

496

497 **Table 3. Summary of calculated RMS source levels for LF and HF signals at their relevant fundamental frequencies (N = 11 for LF signal,**
 498 **and 21 for HF signal).**

	Frequency (Hz)	Pulse duration (ms)	RMS Source Level (dB re 1 μ Pa-m)	Frequency (Hz)	Pulse duration (ms)	RMS Source Level (dB re 1 μ Pa-m)
LF signal	1000	40.00	170.4	1600	25.00	165.1
	1100	36.36	170.4	1700	23.53	165.0
	1200	33.33	167.9	1800	22.22	165.1
	1300	30.77	165.9	1900	21.05	165.1
	1400	28.57	165.5	2000	20.00	165.4
	1500	26.67	165.2			
HF signal	8000	5.00	162.4	13500	2.96	160.6
	8500	4.71	162.9	14000	2.86	159.9
	9000	4.44	163.9	14500	2.76	159.2
	9500	4.21	167.1	15000	2.67	154.1
	10000	4.00	170.0	15500	2.58	157.8
	10500	3.81	171.1	16000	2.50	156.8
	11000	3.64	169.9	16500	2.42	157.7
	11500	3.48	166.6	17000	2.35	156.1
	12000	3.33	164.6	17500	2.29	155.2
	12500	3.20	162.8	18000	2.22	154.3
	13000	3.08	160.9			

499

500 Transmissions were randomised between either the HF signal, the LF signal or silence (hereafter termed 'Silent
501 control'), without any obvious outward indication to the fieldwork team of which signal was being transmitted.
502 Each signal transmission lasted for 2 hours and was followed by a 2-hour recovery period during which no new
503 transmission could be triggered, to allow any displaced porpoises and other species to return to the ensonified
504 area. Once this recovery period has passed, the system automatically reset itself and could start transmitting
505 again.

506

507 The signal transmission system operated in one of two modes, hereafter termed 'Day' and 'Night' mode. In Day
508 mode, the system was on permanent standby and could be remotely triggered when porpoises or other
509 cetaceans were sighted by the fieldwork team engaged in visual porpoise surveys (see below for details). Outside
510 regular observing hours (at night or during periods of poor weather), the system could be switched to Night
511 mode, which involved transmission of a regular sequence of signals on a 50% duty cycle (2 hours on, 2 hours off)
512 until actively interrupted by the fieldwork team. Switching from Night to Day mode was only possible once the
513 final Night Mode transmission cycle and subsequent 2-hour recovery period had been completed. Switching
514 between the two modes was achieved through commands sent by text message.

515

516 After several days of operation, it became apparent that the system drew more power when transmitting in
517 Night mode than could be reliably replenished by the solar panels during the subsequent daytime, thus putting
518 strain on the system's battery power supply. To preserve power throughout the experimental period, the system
519 was deliberately kept in Day mode overnight on nine nights (as a result of which no transmissions of any kind
520 occurred during this time). This power shortage was eventually resolved through periodic recharging of batteries
521 by the fish farm barge's generator. Conversely, on five days where poor weather conditions precluded any visual
522 observation, the system was deliberately left in Night mode to ensure that at least some transmissions occurred
523 during this period.

524

525 3.4 FIELDWORK LOCATION

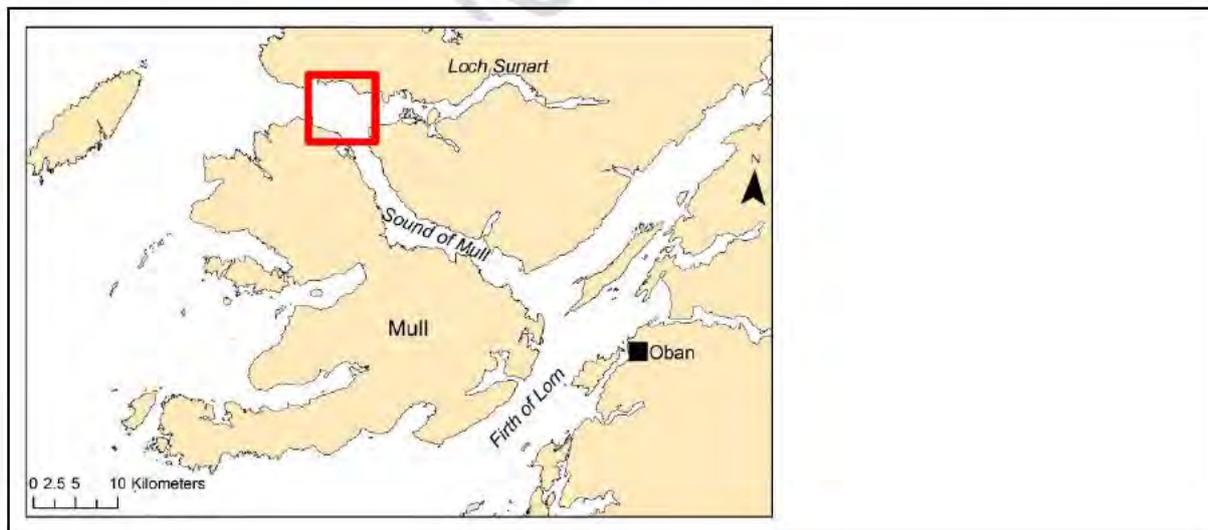
526 The experiment took place in the Sound of Mull, on the west coast of Scotland, with observation efforts
527 concentrated in Bloody Bay on the north shore of the Isle of Mull (56°38.626 N, 6°05.705 W; Figure 6). This
528 location was chosen because it contained a salmon aquaculture site (owned by Scottish Sea Farms™/SSF) which
529 operated under licensing restrictions preventing it from using ADDs (Scottish Natural Heritage, pers.comm.
530 2016). This meant that the experiment could be undertaken without interference from on-site operational ADDs,
531 although effects of more distant ADDs on other fish farms could not be eliminated. Furthermore, Bloody Bay

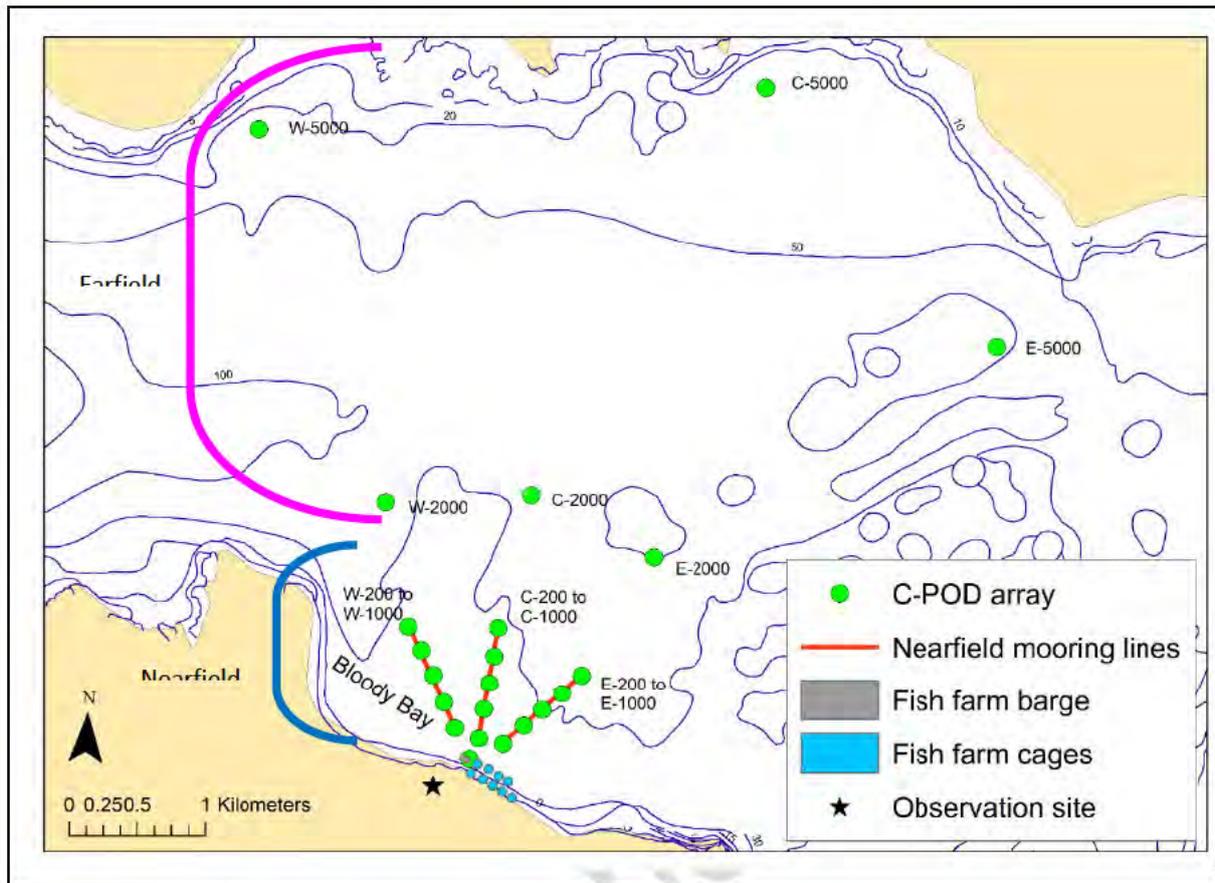
532 had previously been identified as a site where harbour porpoises were observed regularly (Carlström 2005;
533 Carlström et al. 2009; Götz & Janik 2016). The feeder barge of the Bloody Bay salmon farm was used as a platform
534 from which the underwater loudspeaker and associated hardware could be deployed, as well as passive acoustic
535 detectors. Water depths in the immediate area around the fish farm were approximately 35-40 m (based on
536 GEBCO™ bathymetry data).

537

538 3.5 PASSIVE ACOUSTIC DETECTOR ARRAY

539 An array of passive acoustic monitoring equipment was deployed around the SSF feeder barge, aimed at
540 recording harbour porpoise echolocation clicks as well as broad-spectrum ambient noise. The array extended
541 away from the signal source across the Sound of Mull, and contained 22 listening stations (Figure 6). All stations
542 out to 1,000 m from the signal source were defined as ‘Nearfield’ stations, whilst the more distant stations at
543 2,000 m and 5,000 m were referred to as ‘Farfield’ stations. The Nearfield component of the array consisted of
544 a single station beneath the fish farm barge adjacent to the underwater loudspeaker and three 800-m long
545 moorings radiating outwards from the barge, each containing five listening stations at 200-m intervals (i.e. at
546 approximately 200, 400, 600, 800 and 1000 m from the signal source; Table 4). These three replicate Nearfield
547 moorings provided redundancy for comprehensive passive acoustic monitoring of small-scale habitat use by
548 porpoises around the fish farm, at scales comparable to visual observations. The Farfield listening stations were
549 simple, solitary moorings intended to describe porpoise activity (and potential responses to signals) in more
550 distant, exposed parts of the Sound of Mull. Diagrams of mooring design are included in Appendix 1.





551 Figure 6. A) Overview of the Sound of Mull and adjacent areas. The Bloody Bay fieldwork site is indicated by the red box. B) Overview of
 552 LEAP passive acoustic mooring array in Bloody Bay and the northwestern Sound of Mull. Nearfield and Farfield components of the array
 553 are indicated. Note that the field of view from the observation site encompassed all three Nearfield mooring lines, but not the
 554 easternmost portion of the fish farm.

555 Experimental work was licensed under Marine Scotland license #06801/16/0 and SNH license #81281. Moorings
 556 were deployed and recovered using SAMS research vessels *Calanus* and *Seol Mara* with the exception of mooring
 557 C-5000, which was deployed through collaboration with a local marine renewable energy developer (AlbaTern
 558 Wave Energy). A temporary safety zone was implemented around the moorings by HM Coast Guard requesting
 559 a wide berth from all mariners during the experiment, mainly to prevent damage or loss of moorings through
 560 interactions with fishing gear.

561

562 Table 4. Summary of mooring array components.

Array section	Site name	Latitude	Longitude	Water depth (m rel. to CD)	Approximate distance to signal source (m)	Acoustic equipment at mooring

NEARFIELD	SSF Feeder Barge*	56 38.626	06 05.884	36	0	C-POD; RTSYS
NEARFIELD	E-200	56 38.691	06 05.600	35	270	C-POD
NEARFIELD	E-400	56 38.789	06 05.459	42	469	C-POD
NEARFIELD	E-600	56 38.838	06 05.334	51	647	C-POD
NEARFIELD	E-800	56 38.907	06 05.199	52	835	C-POD
NEARFIELD	E-1000	56 38.985	06 05.066	59	1032	C-POD; SoundTrap ¹
FARFIELD	E-2000	56 39.474	06 04.601	35	2020	C-POD
FARFIELD	E-5000	56 40.390	06 02.218	40	4941	C-POD
NEARFIELD	C-200	56 38.707	06 05.775	41	167	C-POD; SoundTrap ²
NEARFIELD	C-400	56 38.827	06 05.752	43	386	C-POD
NEARFIELD	C-600	56 38.931	06 05.725	47	583	C-POD
NEARFIELD	C-800	56 39.042	06 05.700	36	788	C-POD
NEARFIELD	C-1000	56 39.156	06 05.685	39	1000	C-POD
FARFIELD	C-2000	56 39.692	06 05.508	39	2011	C-POD
FARFIELD	C-5000	56°41.371	06 03.992	40	5435	C-POD; SoundTrap ²
NEARFIELD	W-200	56 38.743	06 05.952	49	252	C-POD

¹ High-frequency SoundTrap™

² Low-Frequency SoundTrap™

NEARFIELD	W-400	56 38.843	06 06.042	51	461	C-POD
NEARFIELD	W-600	56 38.951	06 06.129	47	680	C-POD
NEARFIELD	W-800	56 39.049	06 06.224	53	885	C-POD
NEARFIELD	W-1000	56 39.141	06 06.329	28	1085	C-POD
FARFIELD	W-2000	56 39.630	06 06.545	55	2005	C-POD
FARFIELD	W-5000	56 41.086	06 07.616	36	4920	C-POD

563

564 Each station contained a C-POD™ porpoise click detector, with some stations additionally being equipped with
565 a SoundTrap™ or RTSYS™ sound recorder (Table 3). Detector selection was determined through a combination
566 of unit battery capacity, price and availability among project partners:

- 567 • C-PODs are self-contained ultrasound monitors that select tonal clicks and record the time of
568 occurrence, centre frequency, intensity, duration, bandwidth and frequency trend of tonal clicks within
569 the frequency range 20 kHz - 160 kHz to 5- μ s resolution. This allows them to monitor clicks from all
570 odontocetes except sperm whales. Raw sound data are not stored, however, and the unit's design
571 precludes manual configuration of click identification parameters. Maximum deployment times vary
572 depending on environmental conditions but typically range over several months (Chelonia Ltd. 2011,
573 2013, 2014). This extended battery life makes them suitable for long-term monitoring experiments
574 involving species such as harbour porpoise. A subset (n=8 units) of C-PODs' responses to artificial
575 porpoise clicks had been tested previously as part of a different experiment, deploying an
576 omnidirectional harbour porpoise click train synthesiser (PALv1; F³ Maritime Technology 2012) at
577 known distance. The PALv1 unit produced click trains with a centre frequency of 133 ± 0.5 kHz and
578 source levels of 154 ± 2 dB (peak-to-peak; F³ Maritime Technology 2012). Some variability in terms of
579 C-PODs detecting PALv1 click trains was noted at the time; environmental factors (notably changes in
580 C-POD orientation relative to the PALv1 sound source) were considered to be an important cause of
581 this variability. No further calibration of C-PODs used in this experiment was performed.
582 Occasionally, under high ambient noise conditions, C-PODs temporarily stop logging when reaching a
583 pre-set buffer limit of 4,096 clicks per minute, until the start of the next minute (Booth 2016). The
584 proportion of each minute thus lost can be used as a crude proxy of ambient noise levels across the
585 array. C-PODs also contained an onboard tilt sensor, recording their deflection from vertical (0° =
586 vertical; 90° = horizontal).

- 587
- SoundTraps are compact self-contained broadband underwater sound recorders (Ocean Instruments 588 2017). Unlike C-PODs, they store raw sound data onboard for further study, but have a lesser battery 589 capacity resulting in the need for sampling according to a pre-programmed duty cycle to extend 590 recording duration. Two versions (SoundTrap 300 STD, with a working frequency range of 20 Hz-60 kHz, 591 and SoundTrap 300 HF, with a working frequency range of 20 Hz-150 kHz) were available for the present 592 experiment (N= 2 and 1 devices, respectively). The SoundTrap 300 units were included in the moorings 593 to provide validation of the transmitted ADD signal across the array. Units were programmed to sample 594 at a rate of 96 kHz (thereby measuring over a bandwidth of 49 kHz) on a 50% duty cycle.
 - The RTSYS EA-SDA14 multi-hydrophone recorder is a compact embedded acoustic recorder capable of 595 acquiring signals from up to four broadband hydrophones simultaneously (RTSYS 2016). A single unit 596 was deployed beneath the barge adjacent to the underwater loudspeaker to obtain information on 597 signal output for subsequent modelling of transmission loss across the array. It recorded on one channel 598 using a Reson TC4014, broadband omnidirectional hydrophone (sensitivity: -180 dB re 1 V/ μ Pa, flat 599 frequency response: 25 Hz-250kHz), for a period of 4 days during 16-19/09/2016.

601

602 C-POD data were analysed using the bespoke software CPOD.exe v.2.043 (Chelonia Ltd. 2014). This software 603 aims to detect and classify porpoise echolocation click trains based on frequency, duty cycle, train coherence 604 and quality. Only 'Moderate' and 'High' quality click trains, based on classification thresholds built into 605 CPOD.exe, were used for analysis. Processed CPOD data containing porpoise click train detections were 606 subsequently extracted and analysed in MS Excel™ 2016 and R 607 (R Core Team 2013). Soundtrap and RTSYS data were analysed using custom-written scripts in MatLab.

608

609 3.6 VISUAL OBSERVATIONS AND CAMERA ARRAY

610 Concurrent with the PAM monitoring, visual observations were carried out from a vantage point overlooking the 611 fish farm site (~14 m above Chart Datum; Figure 6). Access to the site was on foot or, more typically, via a boat 612 operated by SSF personnel, and was primarily limited by weather. Data were collected by a team of two to four 613 experienced observers throughout the survey period. Observations took place near-continuously from 614 approximately 08:30 to 15:00 GMT, or until conditions deteriorated. Visual observers scanned the site 615 continuously with the naked eye and binoculars for sightings of marine mammals for 50 minutes out of every 616 hour. Every 10 minutes, data were collected on environmental conditions (% cloud cover, visibility, glare, sea 617 state, tidal phase) and numbers of different kinds of vessels present in the area at the time. Approximate tidal 618 height data were collected on-site using a tidal gauge pole. Each hour, the observers switched tasks to limit 619 observer fatigue.

620

621 The visual observation team also collected photogrammetric data using an array of DSLR cameras to establish
622 the positions of surfacing harbour porpoises and other marine mammals, allowing their movements in response
623 to transmitted ADD sounds, if any, to be mapped post-survey. This method had been developed by researchers
624 at the IMARES research institute (Den Helder, the Netherlands; principle of method described by Hoekendijk et
625 al. 2015), and used locations of known reference points visible on the opposite shore to determine the position
626 of any surfacing marine mammals recorded by the cameras. Following guidance from IMARES staff, an array of
627 five DSLR cameras (Canon™ EOS 7D/600D using Sigma 70-200mm/70-300mm lenses) was mounted on a
628 stationary frame such that cameras' fields of view overlapped, resulting in a total field of view of approximately
629 30° from the onshore vantage point. A sixth 'mobile' DSLR camera was mounted on a tripod and aligned with a
630 pair of Swarovski™ 10 x 42 EL binoculars to scan the more distant parts of the survey area. At the start of each
631 visual survey, the height of the mobile camera above ground level was measured to the nearest cm to be able
632 to correct for small variations in vertical sighting angle. Additional parameters required for the analysis (e.g.
633 exact geographical location of camera array, tidal height, cloud cover etc.) were collected according to the
634 methods described by Hoekendijk et al. (2015). Tidal data were subsequently validated through comparison with
635 high-resolution data from the nearby Tobermory tidal gauge (part of the UK National Tidal Gauge Network,
636 owned and operated by the Environment Agency (EA)). All cameras were switched on whenever a porpoise or
637 other cetacean was observed, which was then tracked using the binoculars and mobile camera until it was lost
638 from view for more than 10 minutes or left the area. Cameras recorded video data in 10-minute blocks to
639 facilitate data storage and subsequent analysis.

640

641 3.7 DATA MANAGEMENT

642 Camera video data were downloaded and backed up onto Seagate™ 3TB external hard drives each day following
643 fieldwork. As the requirement to match events recorded on adjacent cameras was crucial, close attention had
644 to be paid to aligning the cameras' internal clocks. A slight but notable drift in the cameras' internal clocks had
645 been observed over periods of several hours or days, which was counteracted by resetting each camera
646 according to the clock on a handheld Garmin™ eTrex10 GPS unit each morning before commencing observations.
647 Following completion of the experiment, all data were backed up onto the SAMS archive server for safekeeping.

648

649 4 RESULTS

650 4.1 SIGNAL TRANSMISSION EXPERIMENTS

651 The signal transmission system described under Section 3.3 was installed onto the fish farm barge and activated
652 on 6/09/2016, following a delay of approximately 5 weeks due to an unexpectedly long licensing process. Despite
653 this delay, the project succeeded in completing a successful fieldwork campaign combining simulated ADD

654 transmissions with simultaneous acoustic and visual observations of porpoises. Following some tests, the actual
655 experiment ran from 08/09/2016 until 11/10/2016 inclusive, or a total of 33 days. During this period, a total of
656 138 complete sound transmissions (including 53 HF signal transmissions, 38 LF signal transmissions, and 47 silent
657 control “transmissions”) were carried out. Transmissions were either triggered upon visual detection of animals
658 or initiated on a random schedule (see Methods). Of all transmissions, 62 ran during daylight hours (i.e. started
659 during daytime or immediately before sunrise), while 76 transmissions overlapped partially or wholly with hours
660 of darkness (i.e. started during darkness or immediately before sunset). Visual observations occurred on 18 days
661 between 9/09/2016 and 10/10/2016, and included both data from human observers and video camera tracking
662 data. There was no significant difference in terms of when particular signals were transmitted in relation to
663 daylight hours. All but three of the passive acoustic recorders were successfully recovered on 18/10/2016. The
664 resulting dataset will be described in more detail below.

665

666 During the experiment, porpoises were seen less frequently in Bloody Bay than was expected given historical
667 observations (Carlström 2005; Carlström et al. 2009). The reasons for this were unclear but resulted in fewer
668 opportunities for daytime ADD sound transmission experiments than had originally been anticipated. The
669 system was manually triggered a total of nine times during visual observation periods as a direct result of
670 sightings of porpoises or dolphins. On 18 days where no porpoises were detected by visual observers during the
671 morning, the system was triggered at a random time during the day. This was done to account for the possibility
672 that the C-PODs, particularly the more distant Farfield ones, might be detecting porpoises that were not
673 reported by the visual observers, so that some relevant data might still be gathered.

674

675 4.2 HARDWARE RECOVERY

676 Anticipating a start date in early August 2016, a single C-POD was deployed in July 2016 below the fish farm
677 barge to gather pre-experiment baseline data on porpoise presence near the fish farm. This C-POD was present
678 from 15/07/2016 until recovery on 5/09/2016, immediately prior to the start of the experiment. Unforeseen
679 delays in the mooring license application process through Marine Scotland resulted in the experimental work
680 schedule being pushed back to September/October 2016. Deployment of all remaining moorings occurred from
681 5-7/09/2016 using SAMS R/V *Seol Mara*, with the exception of mooring C-5000, which had already been
682 deployed on 17/08/2016 through collaboration with AlbaTern Wave Energy. The entire array was therefore
683 functional by 07/09/2016; to facilitate analysis the effective start date and time used was 08/09/2016 at 00:00
684 GMT. Array recovery occurred on 18/10/2016 using SAMS R/V *Calanus*. The C-POD below the fish farm barge
685 was later replaced with another unit to provide longer-term information of post-experiment site usage by
686 porpoises. This second C-POD recorded data from 04/11/2016 until 3/02/2017.

687

688 On 13/09/2016, following a storm, the surface float of the central Nearfield mooring (position C-200)
689 disappeared. Because this was part of an 800 m long, complex mooring it was deemed unwise to lift and disrupt
690 the mooring further. It became apparent during the eventual retrieval of the full array of moorings on
691 18/10/2016 that the earlier loss of the C-200 surface float had also resulted in the loss of the vertical riser below
692 it, including the attached C-POD and SoundTrap detectors (Table 5). No monitoring data were therefore available
693 from this particular location. In addition, the acoustic release of the solitary E-5000 Farfield mooring failed to
694 respond to activation commands, preventing mooring recovery from this location as well. The reason for this
695 was unclear but could involve a technical fault in the acoustic release unit or displacement of the mooring
696 through interactions with commercial fishing gear. Subsequent efforts to contact this mooring's acoustic release
697 unit, by surveying out as far as 2 km from its original deployment location, were unfortunately unsuccessful. An
698 information campaign to alert the wider community to the fact of these losses and appeal for assistance in
699 relocating the missing equipment has to date not yielded any results, and these detectors should be considered
700 lost at present (Table 5).

701

702 4.3 PASSIVE ACOUSTIC MONITORING

703 Following recovery of the PAM equipment, all C-PODS but one were found to have performed well in terms of
704 data collection and storage. The exception was the C-POD deployed beneath the fish farm barge adjacent to the
705 Lubell loudspeaker, which appeared to have malfunctioned for unknown reasons shortly after having been
706 deployed. There were therefore no C-POD data available from this location covering the experimental period.
707 Fortunately, two of three adjacent C-PODs (E-200 and W-200) were successfully recovered and found to have
708 recorded the entire experimental period. C-PODs' detection radii are on the order of 200-300 m (Brandt et al.
709 2013; Nuuttila et al. 2013), suggesting that data from the E-200 and W-200 C-PODs (located ~200 m from the
710 sound source) could be used to indicate how porpoises might use the general area adjacent to the fish farm
711 barge itself. C-POD data from below the fish farm barge prior to and following the experiment (15/07 –
712 5/09/2016 and 04/11/2016 - 3/02/2017, respectively) indicated continued porpoise presence during these
713 periods (Appendix 2).

714

715 As the C-5000 C-POD had been deployed before the other moorings on 17/08/2016, the subsequent delay in
716 deploying the remainder of the array through the extended licensing application process resulted in the C-5000
717 C-POD's batteries being depleted by 7/10/2016, about 10 days before the recovery of the array. Other C-PODs
718 suffered only minor losses in terms of recording time due to battery depletion towards the end of the
719 experiment. The combined C-POD dataset available for analysis was therefore derived from 18 out of 21 C-PODs
720 (Table 5). Upon recovery, the HF-SoundTrap included in the E-1000 mooring was also found to have
721 malfunctioned at some point during the deployment for unknown reasons.

722

723 C-POD datasets were truncated to exclude periods immediately after deployment and before recovery, such
 724 that the remaining datasets only contained entire days (1440 minutes per day). For this reason, the entire array
 725 (excluding the C-POD beneath the feeder barge) was defined to be active from 8/09/2016 at 00:00 GMT until
 726 06/10/2016 at 23:59 GMT, for a total of 29 full days. The C-POD at C-5000 ceased to function the following day.
 727 All other C-PODs remained operational until at least 16/10/2017 at 23:59 GMT, equivalent to 39 days.

728

729 **Table 5. Summary of periods monitored by moored C-POD units across the array. *These units stopped <24 hrs prior to recovery. ** This**
 730 **unit was deployed several weeks earlier than the other devices and failed 11 days before recovery.**

Array section	Site name	Date/Time in (GMT)	Date/Time out (GMT)	Effective monitoring duration (d, h, min)
NEARFIELD	SSF Feeder Barge	05/09/2016 13:27	Unit malfunctioned; no data recovered	
NEARFIELD	E-200	06/09/2016 09:42	18/10/2016 14:21	42 d 04 h 39 min
NEARFIELD	E-400	06/09/2016 09:45	17/10/2016 14:54	41 d 05 h 09 min*
NEARFIELD	E-600	06/09/2016 09:48	18/10/2016 14:32	42 d 04 h 44 min
NEARFIELD	E-800	06/09/2016 09:49	18/10/2016 14:33	42 d 04 h 44 min
NEARFIELD	E-1000	06/09/2016 09:51	18/10/2016 11:37	42 d 01 h 46 min*
FARFIELD	E-2000	07/09/2016 09:59	18/10/2016 12:09	41 d 02 h 10 min
FARFIELD	E-5000	07/09/2016 10:14	Mooring lost; no data recovered	
NEARFIELD	C-200	06/09/2016 09:08	Mooring lost; no data recovered	
NEARFIELD	C-400	06/09/2016 09:12	18/10/2016 16:31	42 d 07 h 19 min
NEARFIELD	C-600	06/09/2016 09:14	18/10/2016 16:24	42 d 07 h 10 min
NEARFIELD	C-800	06/09/2016 09:16	18/10/2016 16:18	42 d 07 h 02 min
NEARFIELD	C-1000	06/09/2016 09:20	18/10/2016 16:16	42 d 01 h 46 min

FARFIELD	C-2000	07/09/2016 09:36	18/10/2016 11:57	41 d 02 h 21 min
FARFIELD	C-5000	17/08/2016 10:42	07/10/2016 03:38	50 d 16 h 56 min**
NEARFIELD	W-200	05/09/2016 14:14	18/10/2016 15:21	43 d 01 h 07 min
NEARFIELD	W-400	05/09/2016 14:18	18/10/2016 15:25	43 d 01 h 07 min
NEARFIELD	W-600	05/09/2016 14:23	18/10/2016 15:32	43 d 01 h 09 min
NEARFIELD	W-800	05/09/2016 14:26	18/10/2016 15:38	43 d 01 h 12 min
NEARFIELD	W-1000	05/09/2016 14:28	18/10/2016 15:44	43 d 01 h 16 min
FARFIELD	W-2000	07/09/2016 09:24	18/10/2016 11:49	41 d 02 h 25 min
FARFIELD	W-5000	07/09/2016 09:02	18/10/2016 13:14	41 d 04 h 12 min

731

732 4.4 AMBIENT NOISE MONITORING

733 The acoustic environment was periodically sampled during the experimental period both across the array
734 and at the fish farm barge site itself using SoundTraps and RTSYS units, as well as broadband hydrophone
735 systems during the retrieval phase. In the case of the RTSYS units data was collected continuously from 22:02
736 on the 16th September to 18:04 on the 9th September with a 56 second recording made every 3 minutes.
737 Soundtrap deployments were made from 5th September through to the 10th September. Both systems captured
738 both active transmission and 'system silent' ambient noise conditions. Data from a later deployment of the
739 RTSYS system was unfortunately un-retrievable due to hard disk failure.

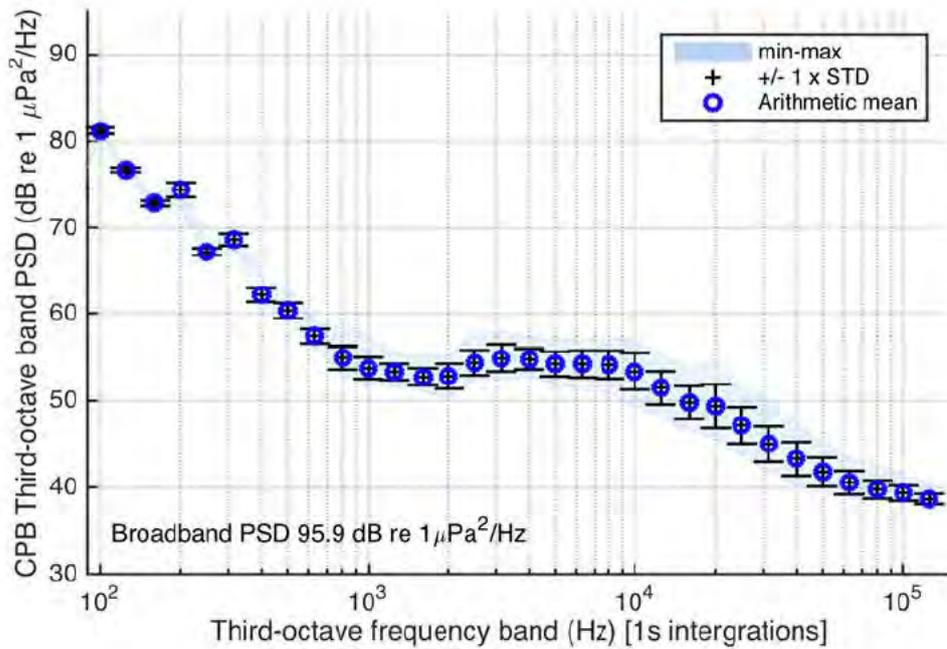
740

741 Typical examples of ambient noise conditions captured during the array removal period are presented here to
742 illustrate a snapshot of noise conditions across the experimental period at times when acoustic systems were
743 'silent'. Data are in Third Octave Bands in the range 100 Hz- 200 kHz in line with spectral analyses carried out for
744 the periods with transmissions. Each relatively short-term sample was based on 25 seconds of data. This was
745 subdivided into one-second integration blocks to allow assessment of variation and generation of mean values
746 across each of the 25-second samples. Data were recorded using a RESON 4014 wideband hydrophone
747 connected to a RTSYS EA-SDA14 recorder suspended from the barge. Recorded data were band-pass filtered
748 between 100 Hz – 200 kHz and recorded at a sample rate of 1.25 MSs⁻¹.

749

750 Figure 7 shows one of the quietest periods with no transmission at the barge in good sea-state conditions with
751 a light breeze and no rain, taken on 11th October 2016 at 14:56 GMT.

752

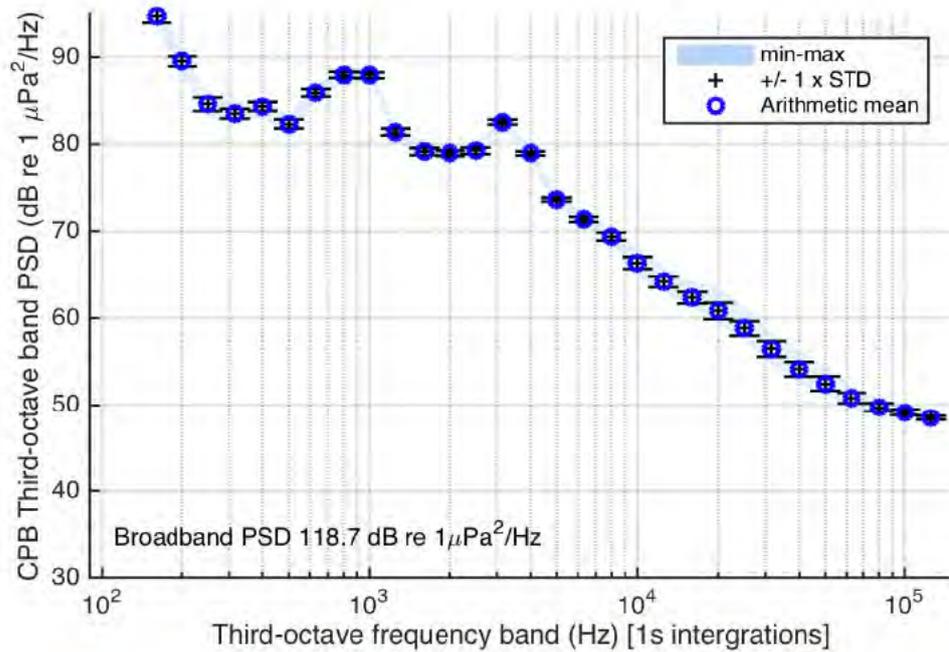


753

754 Figure 7. Power Spectral Density (PSD) in Third Octave Bands for a quiet period at 14:56 GMT on 11th October 2016. Total sample length
755 25 seconds, 1-second integration periods.

756

757 These levels are in line with similar sea-state noise levels at other sites with a broadband PSD of 95.9 dB re 1
758 μPa²/Hz. The data also indicate relatively low variability during this period with only slightly increased standard
759 deviations and maximum and minimum values for frequencies >10 kHz.

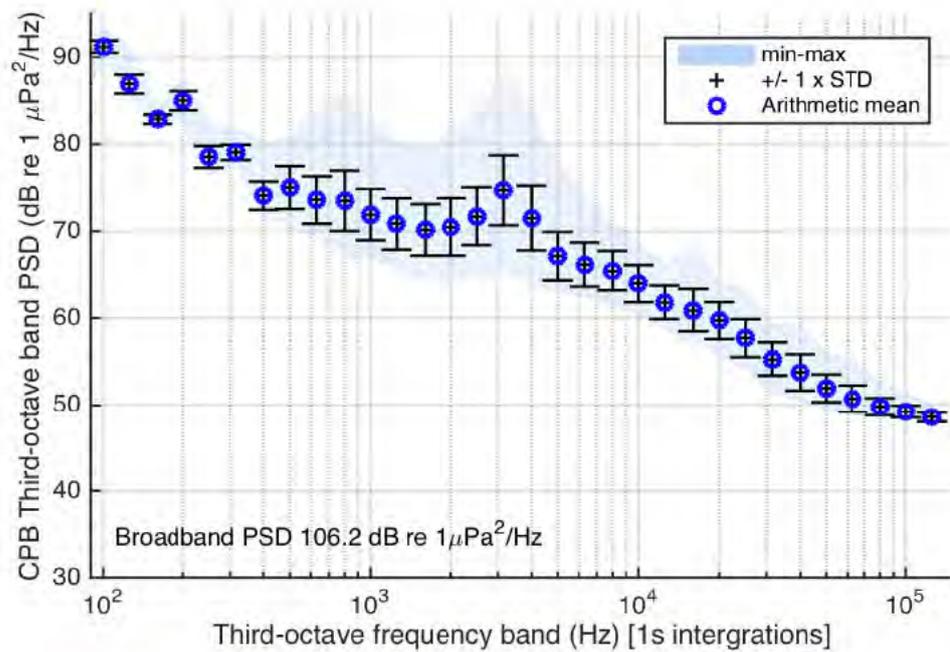


760

761 **Figure 8. Power Spectral Density (PSD) in Third Octave Bands for low sea-state period at 15:01 GMT on 11th October 2016. Total sample**
 762 **length 25 seconds, 1-second integration periods. Likely contributions originated from specific barge or small boat operations.**

763 By comparison, Figure 8 shows a 25-second period taken around 5 minutes later at 15:01 GMT. During this
 764 period, significantly elevated levels were observed at a range of frequencies. Most of this noise likely originated
 765 either from short-term barge based activities or nearby small boat operations with a broadband response of
 766 118.7 dB re 1 μPa²/Hz with levels approximately 30 dB higher in some frequency bands. For further comparison,
 767 Figure 9 shows a consecutive 25-second sample period taken a few moments later with a lower broadband
 768 response of 106.2 dB re 1 μPa²/Hz. These data show that, although levels have dropped when compared to the
 769 previous sample, there was increased variation during the 25-second sample, most likely due to transitory noise
 770 from boat- or barge-based operations during this period.

771



772

773 **Figure 9. Power Spectral Density (PSD) in Third Octave Bands for low sea-state period. Consecutive 25s period from file started at 15:01**
 774 **on 11th October 2016 compared to figure 9. Total sample length 25 seconds, 1-second integration periods. Transitory contributions from**
 775 **specific barge or small boat operations.**

776 These examples suggest that general noise levels at the barge and in the Sound of Mull could vary at short notice
 777 (occasional >40 dB variation) due to changing weather conditions (wind, sea-state, rain etc.) and contributions
 778 from nearby boat and barge operations. These operations were relatively infrequent and general background
 779 noise levels were in line with a relatively narrow waterway with a relatively low numbers of passing vessels.
 780 Further work is required to assess long-term variability in ambient noise levels at this site.

781

782 **4.5 SIGNAL PROPAGATION MODELLING**

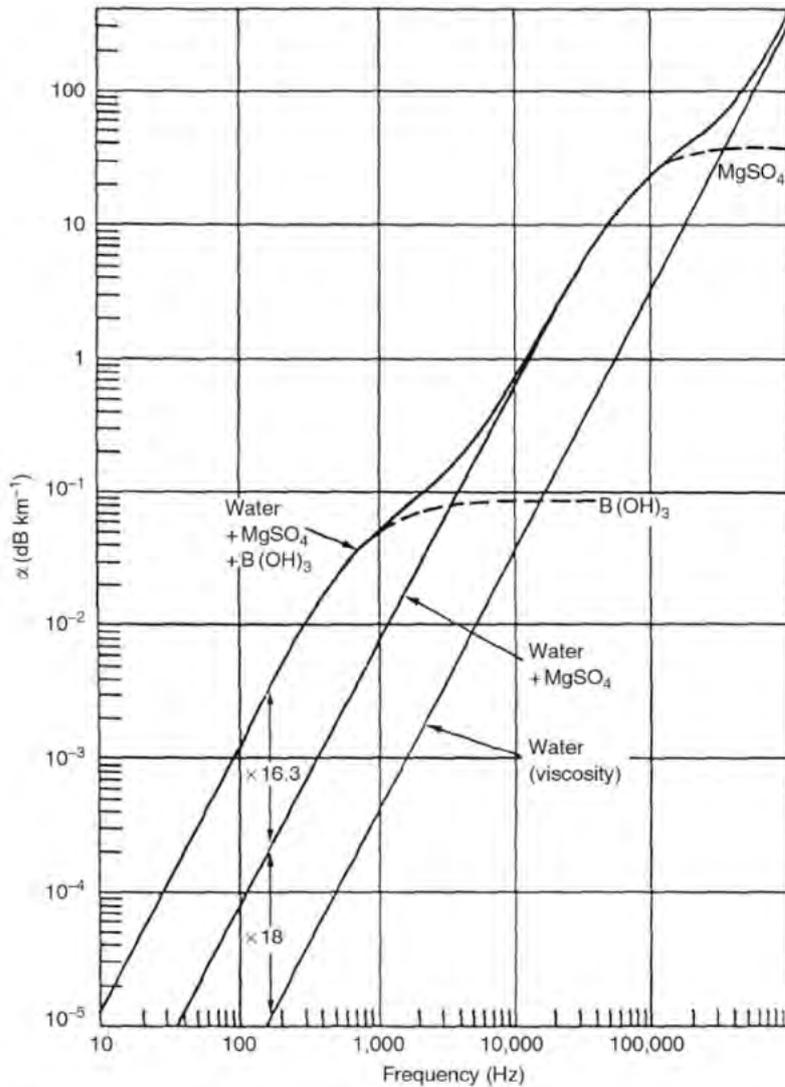
783 Signal propagation across the channel is likely to be complicated by nearshore and relatively shallow- water
 784 propagation conditions as well as variations in bathymetry. These conditions are likely to cause variation in
 785 propagation conditions across a range of frequencies due to differences in modal shapes and absorption effects.
 786 The latter, in particular, may play a role at larger distances and higher frequencies.

787

788 Comparison of classic absorption data taken from various researchers shown in Figure 10 (based on Etter, 2003)
 789 shows that absorption rates of around 0.05 dB/km could be expected at 1 kHz, compared to 0.8 dB/km at 10
 790 kHz and approximately 2 dB/km at 20 kHz. At the Farfield sites, therefore, one might expect to observe more
 791 significant loss per km for the HF signal due to absorption. Even at a distance of several km the variation in losses

792 of the key frequency components would range from 0.2 dB in the 1-2 kHz range of the LF signal to approx. 1-2
 793 dB at 10 kHz in the HF signal. This effect would increase towards the Farfield moorings with increasingly
 794 significant losses of higher frequencies at greater distance.

795



796

797

798 *Figure 10. Underwater acoustic absorption versus frequency. Derived from Etter, 2003.*

799

800 Analysis of Farfield SoundTrap data from position C-5000 of both HF and LF signal types indicated that both
 801 signals were nonetheless easily detectable above background noise levels. This suggested that the entire array
 802 was ensounded by the experimental signals, allowing direct comparison of porpoise detection rates between C-

803 PODs. Received levels would still be expected to be lower among the Farfield moorings, and hence behavioural
804 response could be expected to be less pronounced; this aspect was not analysed in the present experiment due
805 to an absence of RL data from each individual mooring.

806

807 4.6 VISUAL OBSERVATIONS

808 Visual observations were collected on 18 days between 9/09/2017 and 10/10/2017 (or 56% of the total number
809 of days during which the experiment took place). Visual observations only took place under relatively good
810 weather conditions that allowed clear views across the Sound of Mull. Due to the northward-facing aspect of
811 the observation site, observations were not impeded by glare of sunlight reflected off the sea surface. Average
812 daily Beaufort sea state during visual observation periods varied between approximately 0.5 and 2.5; however,
813 sea state varied considerably over the course of a day due to local weather conditions. Bloody Bay was often
814 more sheltered from prevailing winds than the central Sound of Mull, resulting in heterogeneous observation
815 conditions across the Sound. These conditions were recorded by the field team where appropriate. Observed
816 vessel traffic was dominated by Caledonian MacBrayne ferries traversing the site, including both the local
817 Tobermory/Kilchoan ferry (crossing the Sound of Mull several times daily) and the larger ferries on routes
818 between Oban and Coll, Tiree and the Outer Hebrides. Other commonly observed vessel types included fishing
819 vessels (mainly small inshore vessels targeting lobster and crab), tour boats and yachts. Trawling activity was
820 noted to be mainly limited to nights and stormy conditions that prevented trawlers from accessing the main
821 fishing grounds to the west of Mull.

822

823 4.6.1. MARINE MAMMAL SIGHTINGS

824 Harbour porpoises were observed on 23 occasions spread out over 9 days (Table 6). Observations varied in
825 duration from a single surfacing to repeated sightings during the course of 30 minutes or more. Porpoises were
826 observed singly or in groups of up to four animals. Most porpoises were sighted outside Bloody Bay, i.e. >1 km
827 away from the observation site within the central and northern Sound of Mull, and particularly towards the
828 entrance to Loch Sunart (Figure 6); porpoises were sighted within 1km from the fish farm on three occasions.
829 Bottlenose dolphins were observed on four separate occasions (Table 6). As with porpoises, dolphin sightings
830 varied in duration from a single brief surfacing event to extended observations for up to 30 minutes. Dolphins
831 travelled singly or in groups of up to five individuals, and were generally observed closer to the observation site.
832 Their active surface behaviour facilitated detection by the observers. Finally, a single minke whale was observed
833 on 28/09/2016 in Bloody Bay (Table 5).

834

835 Seals were regularly observed on all but one day of the experimental period, with multiple observations
 836 throughout each day (Table 6). Because the focus of the experiment was on porpoises, no signal transmissions
 837 were initiated when a seal was sighted. Visual observers recorded occurrence, number and species of seals
 838 present and estimated location and surface behaviour, but no efforts were made to track individual seals or
 839 record the duration of their surface intervals. Seals were most often observed near the fish farm but were also
 840 seen throughout Bloody Bay and the wider Sound of Mull; no surface feeding behaviour was observed. All seals
 841 observed under sufficiently calm conditions to permit species identification were harbour seals (Table 6). Seals
 842 were typically noted to be stationary or slowly swimming at the surface. Observations typically involved single
 843 or two seals at a time. Visual observations confirmed reports from the SSF staff that small numbers of seals
 844 might be present at any given moment. A single otter (*Lutra lutra*) was also observed in the water along the
 845 shoreline below the observation site on three days (Table 6).

846

847 **Table 6. Overview of observation events of different marine mammal species during the experiment. Individual observation events of**
 848 **porpoises and dolphins often involved >1 individual. *N.B.: Seal and otter sightings were not tracked and so numbers reflect the**
 849 **cumulative number of observations throughout the day, potentially involving multiple observations of the same individuals.**

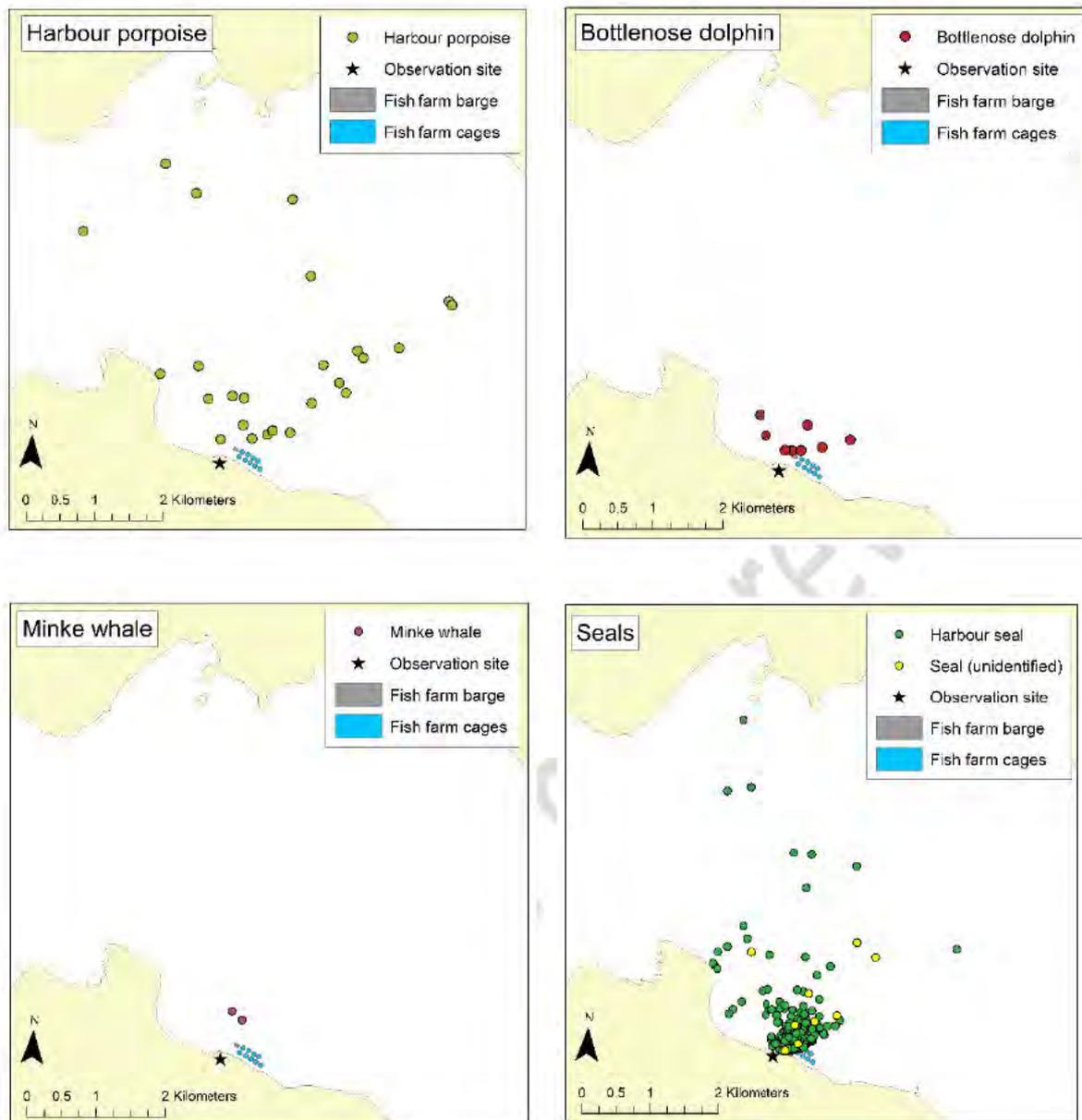
Date	Harbour porpoise	Bottlenose dolphin	Minke whale	Harbour seal*	Unknown seal*	Otter
10/09/2016				4	2	
11/09/2016				1		
13/09/2016		1				
14/09/2016	5			15	5	
15/09/2016	2			7		
16/09/2016				1		
17/09/2016	1			18	3	
19/09/2016	2	1		56	1	
20/09/2016		1		7		

22/09/2016				9		1
26/09/2016	1			9		1
28/09/2016			1	13		
30/09/2016	5	1		65		
01/10/2016	3			85		
02/10/2016				34		
08/10/2016				18		2
09/10/2016	1			11		
10/10/2016	3			31		

850

851 Bearings of sightings for all species were initially estimated visually relative to the community of Kilchoan, on
852 the far shore of the Sound of Mull, which deviated approximately 10° from true North. This deviation in bearings
853 was subsequently corrected at the data processing stage. Distances of sightings to the observers, however, could
854 only be estimated by comparison against stationary objects at known distances, e.g. the surface floats of the
855 Nearfield C-POD array. It was nevertheless apparent that porpoises were typically sighted in the central and
856 northern Sound of Mull, while seal sightings were strongly concentrated around the fish farm (Figure 11). Other
857 species were sighted insufficiently frequently to assess any heterogeneity in distribution.

858

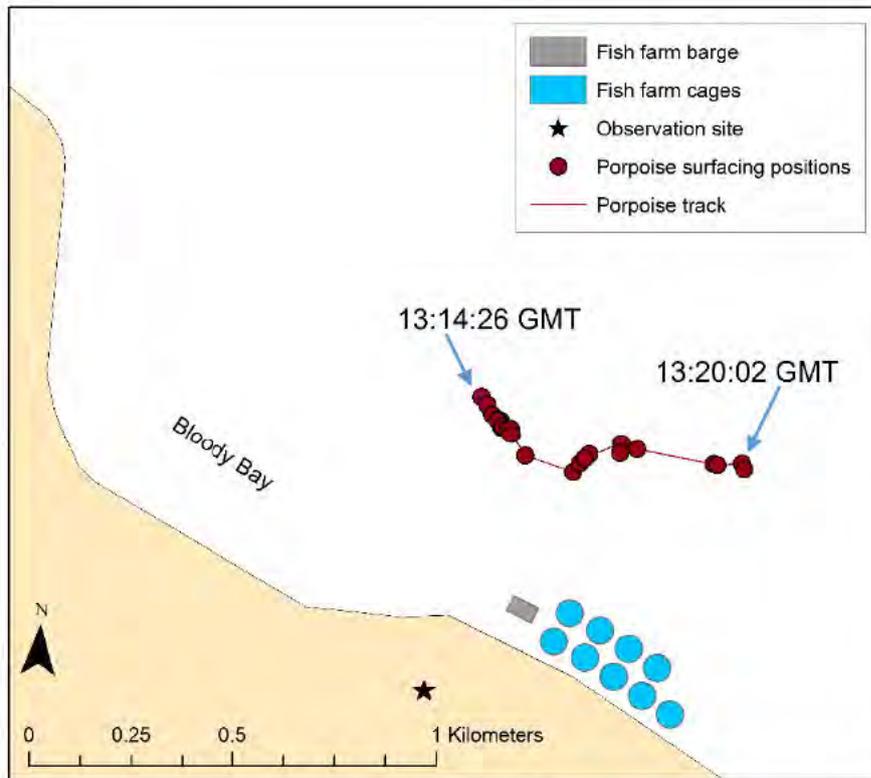


859 **Figure 11. Approximate locations of sightings of different marine mammal species during the entire experimental period. Note that these**
 860 **positions are only approximations due to substantial variability in distance estimation among observers.**

861 **4.6.2 VISUAL TRACKING ANALYSIS**

862 The visual tracking methodology (Section 3.6) was designed to provide insight into porpoises' initial responses
 863 to the experimental signals by tracking their surface movements at high resolution. Unfortunately, the small
 864 number of visual sightings of porpoises made this difficult (Table 6). In addition to being infrequent, most
 865 porpoise sightings occurred at considerable distance from the observation site (notably in the northern half of
 866 the Sound of Mull, towards the entrance to Loch Sunart several km away). At such distances, the cameras'
 867 resolution proved to be inadequate for reliably recording porpoises for tracking. For this reason, only a few
 868 sightings close to the fish farm were suitable for further analysis and the method was therefore unable to provide

869 robust information on porpoises' responses to the experimental ADD signals. However, despite the small
870 number of porpoises at the site in the autumn of 2016, we were able to demonstrate the general utility of the
871 method, and would encourage further development of this tool. An example of a tracked group of porpoises is
872 shown in Figure 12.



873

874 **Figure 12.** Example of tracked group of 3 porpoises observed on 14/09/2016, swimming from west to east.

875

876 4.6.3. SEAL OBSERVATIONS AROUND THE FISH FARM

877 Although not the main focus of this study, visual observations on seals surfacing around the fish farm allowed
878 for some initial analysis of effects of the experimental ADD signals on them as well. Seals were observed during
879 17 experiments (Table 7).

880

881 **Table 7.** Summary of seal sighting events during experimental transmissions of HF (n = 5) and LF signals (n = 7), as well as silent controls
882 (n = 5). Seal sightings have been divided into nearby and distant groups, based on approximate distances from the fish farm barge

883 estimated from visual sighting data. Experiments marked with * were observed for <30 minutes and were excluded from subsequent
 884 analysis.

Signal type	Experiment nr.	# Minutes observed (out of 120)	Number of nearby seal sightings (<500m from barge)	Sightings (Near)	Number of distant seal sightings (>500m from barge)	Sightings ratio (Distant)	Total number of seal sightings
Silent control	14	42	1	0.02	0	0	1
	35	38	3	0.08	0	0	3
	40	75	0	0.00	0	0	0
	56	21*	0	0.00	0	0	0
	101	75	9	0.12	0	0	9
HF-signal	24	91	0	0.00	0	0.00	0
	84	95	4	0.04	0	0.00	4
	91	66	7	0.11	4	0.06	11
	96	97	37	0.38	17	0.18	54
	136	2*	0	0.00	0	0.00	0
LF-signal	13	17*	0	0.00	0	0.00	0
	29	91	5	0.05	4	0.04	9
	34	98	0	0.00	1	0.01	1
	45	98	4	0.04	6	0.06	10
	55	97	10	0.10	8	0.08	18
	90	93	17	0.18	8	0.09	25
	131	100	4	0.04	1	0.01	5

885

886 In three cases <30 minutes, or <25%, of the entire 2-hour transmission period was observed (Table 7), and these
 887 cases were excluded from further analysis. Data from the remaining 14 cases were used to assess the
 888 relationship, if any, between signal type and standardised sighting rate of individual seal sighting events per
 889 minute, using a linear modelling approach through the *lm* tool in the R package *stats* v.3.4.3. Results indicated
 890 that there was no obvious relationship between the signal being transmitted and standardised seal sighting

891 rates, irrespective of whether sightings of nearby seals (d.f. = 12; $p = 0.5461$), more distant seals (d.f. = 12; $p =$
892 0.2213), or all seals (d.f. = 12; $p = 0.4637$) were used to populate the model.

893

894 Standardised seal sighting rates were lowest during silent controls, and highest during transmission of the HF
895 signals (Table 7). These results are preliminary and should be interpreted cautiously; potential explanations
896 could include 1) seals spending more time with their heads above the water to avoid noise exposure, thereby
897 being observed more easily, and/or 2) seals being encouraged to seek out the vicinity of the fish farm based on
898 the presence of an ADD signal (a 'dinner bell effect'; Carretta & Barlow 2011; Coram et al. 2014). These ancillary
899 observations therefore did not support the notion that either ADD signal used here was acting as an effective
900 deterrent of seals from the immediate area around the fish farm.

901

902 4.7 C-POD DATA ANALYSIS

903 C-PODs experienced temporary buffer saturation (cf. Booth 2016) and related loss of detection capacity during
904 <5% of the entire deployment period, typically as isolated minutes. This suggested that noise did not unduly
905 affect the functionality of the C-POD array. The effect was most pronounced among C-PODs near the fish farm
906 barge and appeared largely associated with well-defined events associated with fish farm operations (notably
907 during the restocking process which occurred between 22-24/09/2016 and involved vessel activity well above
908 normal levels). To ensure that these events would not confound the results, minutes from which more than 6
909 seconds (i.e. $\geq 10\%$) were lost (ranging from 65 to 2083 minutes, or 0.2% - 4.9% of total experimental period, per
910 C-POD) were excluded from further analysis. Due to the removal of such 'noisy' minutes, not all C-PODs' record
911 of each experimental session equated to 120 minutes of monitored time. In 73 cases involving 11 experimental
912 transmissions (2.8% of all 2606 CPOD-transmission combinations), individual C-PODs were found to have
913 recorded <100 full minutes; these data were removed from further analysis to maintain approximately equal
914 coverage across the array.

915

916 All C-POD data were initially analysed at a temporal resolution of whole minutes, with each minute classified as
917 1 (a "Porpoise-Positive Minute", or PPM) or 0 on the basis of presence/absence of porpoise click trains, as
918 defined by the classifiers within the bespoke software CPOD.exe (Section 3.5; Table 8). Only click trains classified
919 as "Moderate" or "High" quality were used in subsequent analyses (Carlström, 2005). Twenty unprocessed click
920 trains from each C-POD (or all potential detections for C-PODs where $N < 50$) were checked visually to assess false
921 positive rates on the basis of parameters such as frequency distribution, SPL and train duration, following
922 Chelonia Ltd. (2013). False positive rates fell between 0-5% in all samples, suggesting that the risk of false
923 positives affecting interpretation of the datasets was low.

924

925 **Table 8. Overview of porpoise detections across the C-POD array during 8/09-16/10/2016. * The C-5000 C-POD ceased to function on**
 926 **7/10/2016; the figures listed for this unit therefore were derived over a shorter period than the other units. Note that this table includes**
 927 **'off-effort' periods in between transmissions.**

Array section	Site name	# PPM	Average daily PPM detection rate (#PPM/day)
NEARFIELD	E-200	32	0.82
NEARFIELD	E-400	151	3.87
NEARFIELD	E-600	333	8.54
NEARFIELD	E-800	429	11.00
NEARFIELD	E-1000	383	9.82
FARFIELD	E-2000	828	21.23
NEARFIELD	C-400	151	3.87
NEARFIELD	C-600	537	13.77
NEARFIELD	C-800	20	0.51
NEARFIELD	C-1000	252	6.46
FARFIELD	C-2000	519	13.31
FARFIELD	C-5000	361*	12.38*
NEARFIELD	W-200	356	9.13
NEARFIELD	W-400	343	8.79
NEARFIELD	W-600	51	1.31
NEARFIELD	W-800	143	3.67

NEARFIELD	W-1000	310	7.95
FARFIELD	W-2000	78	2.00
FARFIELD	W-5000	430	11.03

928

929 **4.7.1 EXPERIMENTAL RESULTS OF EXPOSURE EXPERIMENTS**

930 Due to the randomised nature of transmission selection, the total number of HF and LF exposures and silent
931 control trials was not equal (summarised in Section 4.1). PPM detection rates during the experimental period
932 (08/09-11/10/2016) were standardised for each C-POD by dividing the number of PPMs by the total number of
933 monitored minutes over each experimental transmission. For each signal type, all PPM detection rates were
934 averaged across the array to produce an aggregate average. The maximum number of PPM observed during any
935 experimental transmission was 19, representing approximately 15% of the total 2-hour experimental period.
936 PPM detection results, aggregated by signal type, are summarised for each mooring in Table 9. At almost all
937 moorings, the greatest number of PPMs was observed during silent control periods.

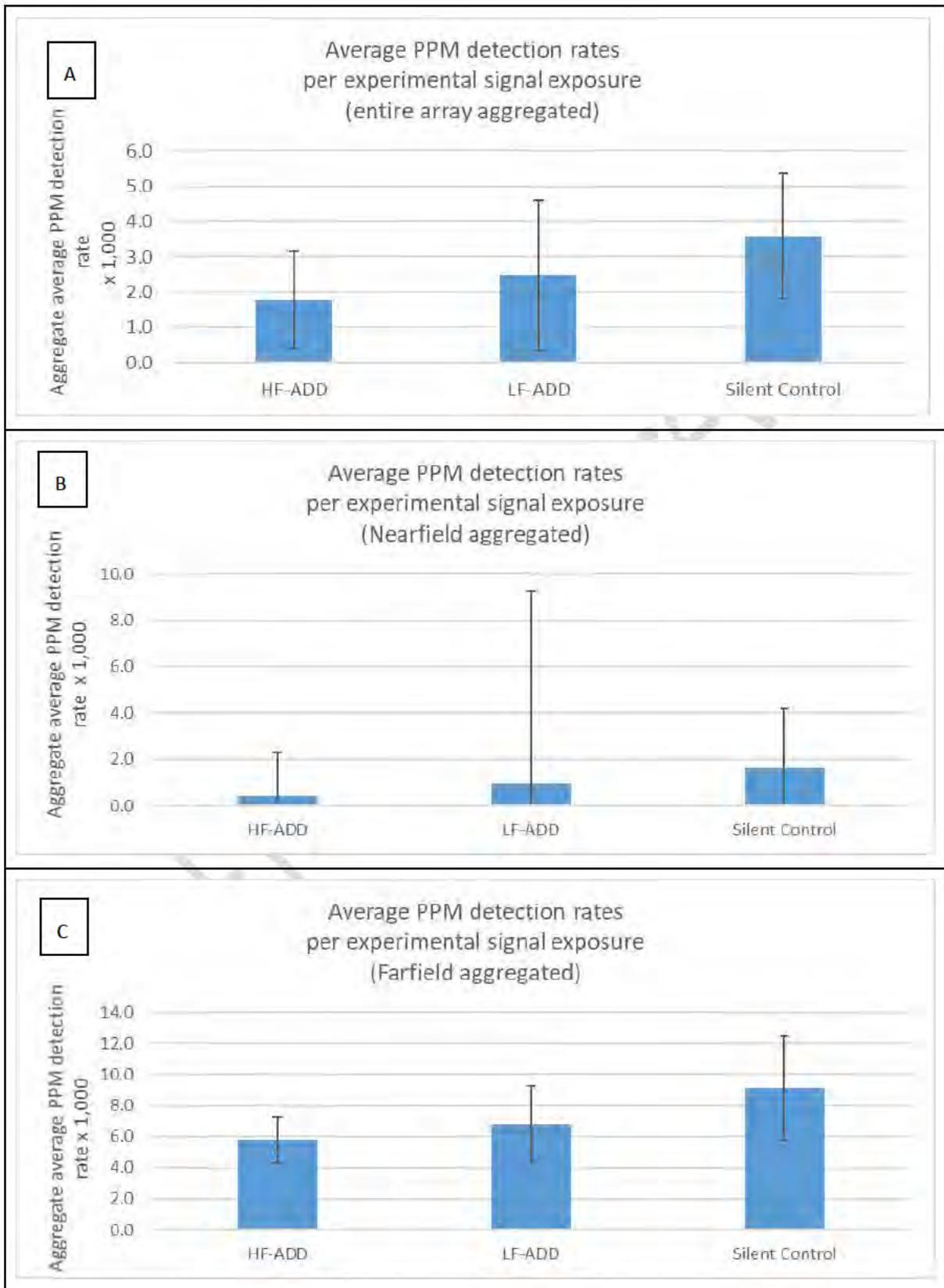
938

939 **Table 9. Summary of numbers of monitored minutes ($N_{MINUTES}$), number of PPMs (N_{PPM}), and average ratio of number of PPMs divided by**
940 **total number of monitored minutes (F) during all experimental transmissions, detected by each C-POD between 08/09/2016 and**
941 **11/10/2016 inclusive. *N.B.: The C-5000 C-POD only collected data until 06/10/2016, inclusive.**

Array Element	Mooring	HF signal			LF signal			Silent Control signal			TOTAL N
		$N_{MINUTES}$	N_{PPM}	F	$N_{MINUTES}$	N_{PPM}	F	$N_{MINUTES}$	N_{PPM}	F	
Nearfield	E-200	5749	0	0	4678	0	0	5138	2	0.00039	2
	W-200	5738	1	0.00018	4667	0	0	5127	4	0.00078	5
	E-400	5639	0	0	4608	0	0	5064	9	0.00176	9
	C-400	6082	0	0	4665	0	0	5359	0	0	0
	W-400	6090	2	0.00033	4670	1	0.00021	5369	10	0.00185	13
	E-600	5938	6	0.00100	4624	0	0	5339	10	0.00185	16
	C-600	6102	5	0.00082	4658	0	0	5377	20	0.00371	25
	W-600	6083	4	0.00065	4660	1	0.00021	5251	1	0.00019	6
	E-800	5909	7	0.00118	4602	0	0	5306	13	0.00243	20
	C-800	5861	0	0	4566	1	0.00024	5259	5	0.00094	6

	W-800	6092	1	0.00016	4644	14	0.00299	5367	11	0.00204	26
	E-1000	5935	5	0.00085	4624	3	0.00064	5342	13	0.00244	21
	C-1000	6063	7	0.00114	4630	8	0.00175	5347	16	0.00298	31
	W-1000	6087	1	0.00016	4641	37	0.00796	5376	13	0.00241	51
Farfield	E-2000	5965	44	0.00739	4659	50	0.01071	5381	74	0.01374	168
	C-2000	6112	29	0.00476	4655	29	0.00620	5399	43	0.00796	101
	W-2000	6152	4	0.00065	4622	9	0.00194	5570	12	0.00214	25
	C-5000*	5373	47	0.00870	4075	28	0.00598	4671	41	0.00876	116
	W-5000	6218	39	0.00625	4676	36	0.00770	5634	66	0.01171	141
TOTAL		113188	202	0.00178	87624	217	0.00247	100676	363	0.00358	782

942

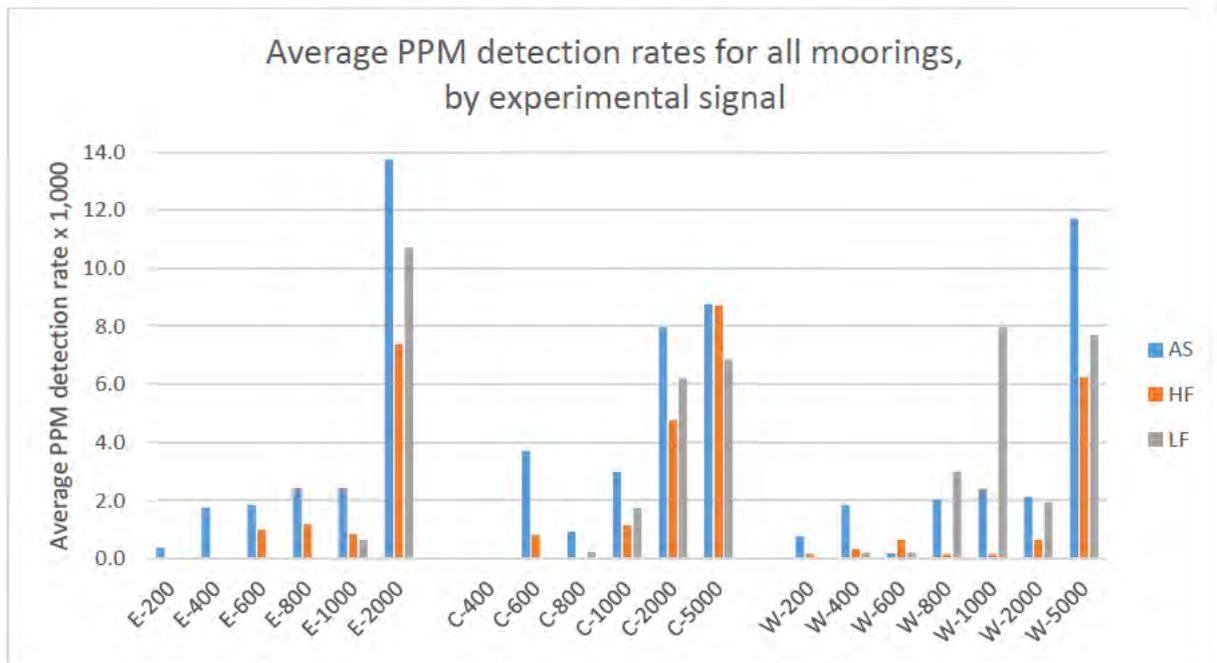


944 **Figure 13. Aggregated average PM detection rates (\pm SE) for (A) all C-PODs combined, (B) the Nearfield and (C) Farfield datasets, for the**
945 **three different experimental transmissions (HF-ADD, LF-ADD, and 'Silent control'). Values were derived from Table 8 and multiplied by**
946 **1,000 for display purposes.**

947 Aggregate average PPM detection rates were highest in Silent Control exposures and lowest during transmission
948 of HF-ADD signals (Figure 13). Based on aggregated results, LF-ADD signal transmissions also resulted in reduced
949 PPM detection rates, contrary to original expectations of detection rates under these conditions broadly
950 resembling those observed under Silent Control exposures.

951 Once moorings were assessed individually, however, considerable variability among standardised PPM
952 detection rates became apparent (Table 9; Figure 14). PPM detection rates at Nearfield moorings closest to the
953 barge were substantially lower during both HF and LF signal transmissions than during the silent control. This
954 pattern was noted at moorings E-200 to E-1000, C-400 to C-1000, and W-200 to W-600. At the distant edge of
955 the Nearfield array (e.g. W-800 and W-1000), as well as the Farfield moorings, differences between one or both
956 experimental treatment(s) and the silent controls were reduced (Table 9; Figure 14). While standardised
957 detection rates were still highest overall during silent controls at each mooring (except W-1000 where detection
958 rates under the LF signal exposure were relatively high, and almost non-existent under the HF signal exposure),
959 only in one case (C-5000, along the opposite shore across the Sound of Mull) were HF-exposed detection rates
960 notably higher than LF-exposed detection rates. There was an order of magnitude difference in terms of absolute
961 numbers of PPMs detected at different C-PODs, even among adjacent ones (cf. results from C-600, C-800 and C-
962 1000; Table 9). The reasons for these differences are presently unclear, but their occurrence suggests that the
963 effects on porpoise detection of the signals themselves may be modulated by environmental parameters driving
964 spatiotemporal heterogeneity across the array. Possible explanations for this heterogeneity include stochastic
965 differences in individual porpoises' distribution, habitat use and/or echolocation rates (Linnenschmidt et al.
966 2013). In summary, and acknowledging limited sample sizes, it appears that, close to the sound source (i.e.
967 within 600m – 1 km), there was little difference between HF and LF signals in terms of their apparent effect on
968 porpoise detection rates, which in both cases declined relative to silent control periods. Further away, among
969 Farfield moorings where detection rates were generally higher, the effects of different signals were mixed; in
970 most cases differences in detection rates were limited and there was no obvious consistent pattern across the
971 array (Figure 14). These results qualify the high-level aggregate average PPM detection rates across the array
972 (Table 9; Figure 13) and suggest that heterogeneous observations at specific moorings (e.g. W-1000) may have
973 a substantial effect on the overall result.

974



975

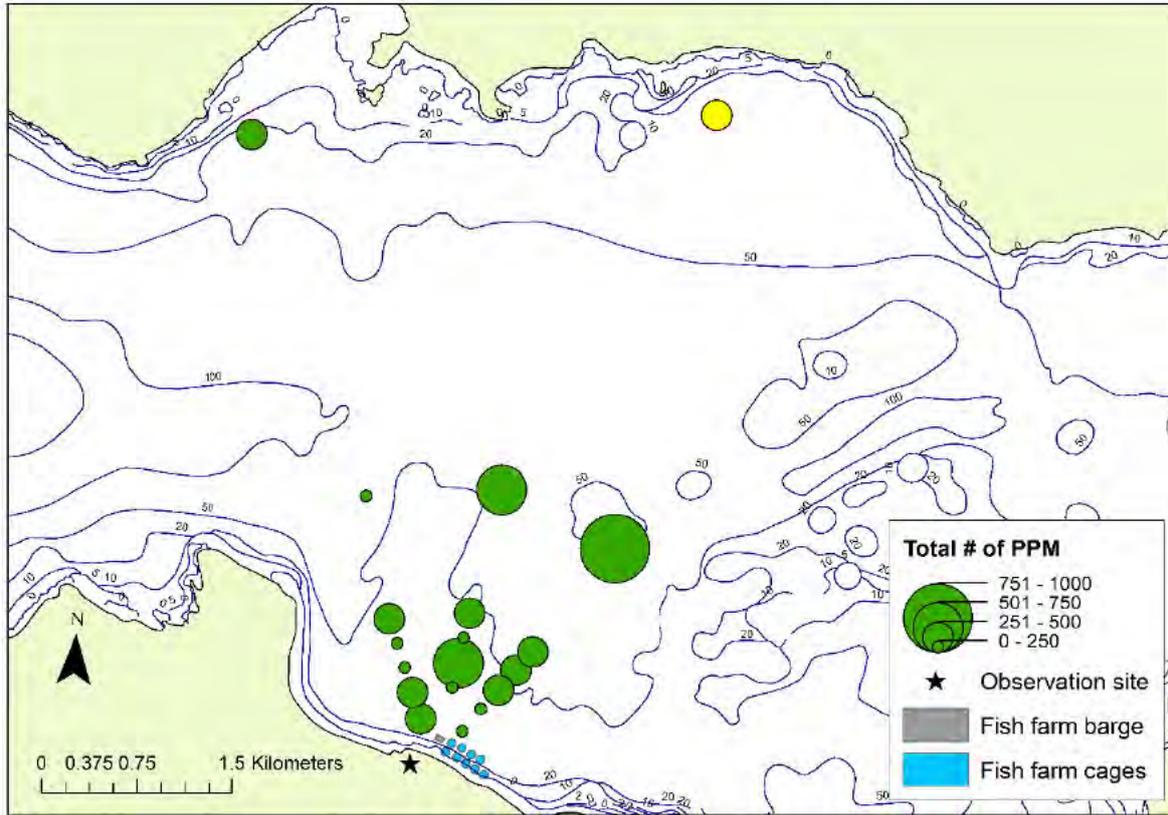
976 **Figure 14. Average PPM detection rates (derived from Table 8, then multiplied by 1,000 for display purposes) across the experimental**
 977 **array under HF-signal, LF-signal, or Silent control (AS) control treatment.**

978

979 **4.7.2 CROSS-ARRAY VARIABILITY**

980 PPM detection rates varied considerably across the array (Figure 15). Broadly speaking, PPM detection rates
 981 were higher in the central and northern Sound of Mull when compared to the Nearfield array within Bloody Bay.
 982 Porpoises were detected at one or more C-PODs on every day of the experiment, confirming that porpoises used
 983 the area regularly during this time. Substantial daily variations in PPM detection rates (0->100 PPM/day) were
 984 observed across the array (Appendix 3). Generally speaking, PPM detection rates were consistently high at
 985 Farfield array sites (notably E-2000, C-2000 and W-5000). At other sites, notably within the Nearfield array, daily
 986 PPM detection rates were more variable or consistently low (e.g. E-200, C-800, W-600). Peaks in PPM detection
 987 rates across the entire array were observed on three days in particular (11/09/2016, 25/09/2016 and
 988 15/10/2016; Appendix 3).

989



990

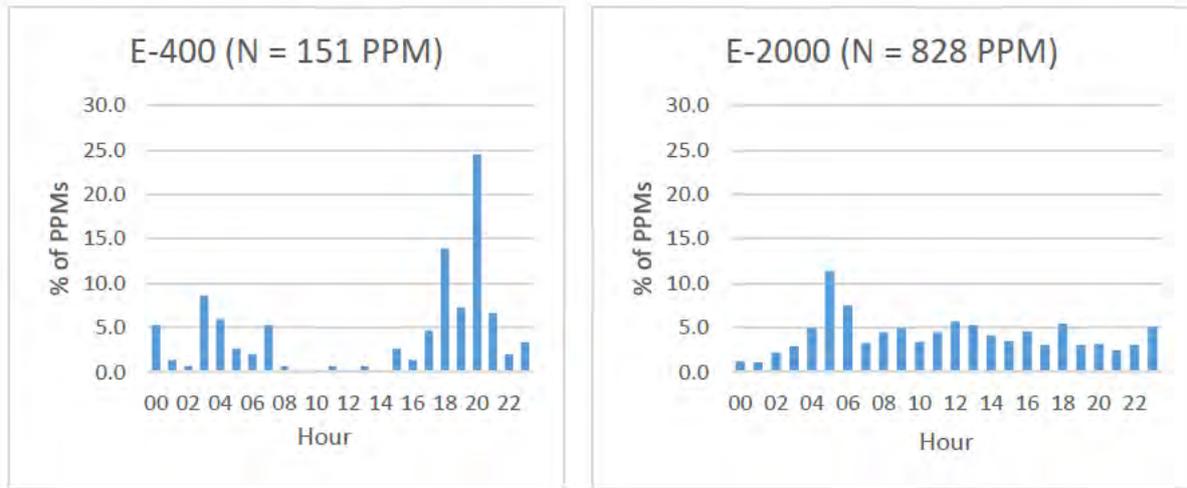
991 **Figure 15. Summary of total numbers of PPMs reported during 8/09-16/10/2016. N.B.: the C-5000 C-POD (top right, yellow) was only**
 992 **operational up to 6/10/2016.**

993

994 **4.7.3 ENVIRONMENTAL DRIVERS OF VARIABILITY**

995 Considerable diel variability in PPM detection rates was observed at most C-PODs with peaks in detection rates
 996 around dawn and dusk contrasting with no or very few detections during daylight hours. This pattern was
 997 particularly notable in C-PODs close to shore (e.g. E-400; Figure 15; Appendix 4, but also the C-5000 C-POD near
 998 the opposite shore), and reinforced the impression, based on visual observations, that porpoises did not
 999 regularly use the inshore waters of Bloody Bay during daylight hours. In contrast, porpoise click trains were
 1000 detected throughout the day on most days at mooring E-2000, in line with visual observations of porpoises in
 1001 that general area (Figure 15). These results suggested small-scale spatiotemporal heterogeneity in the use of
 1002 the Sound of Mull by harbour porpoises, indicating increased detection rates in inshore areas after dark. A lack
 1003 of daytime click detections in the Nearfield array was confirmed by a concurrent absence of visual sightings.

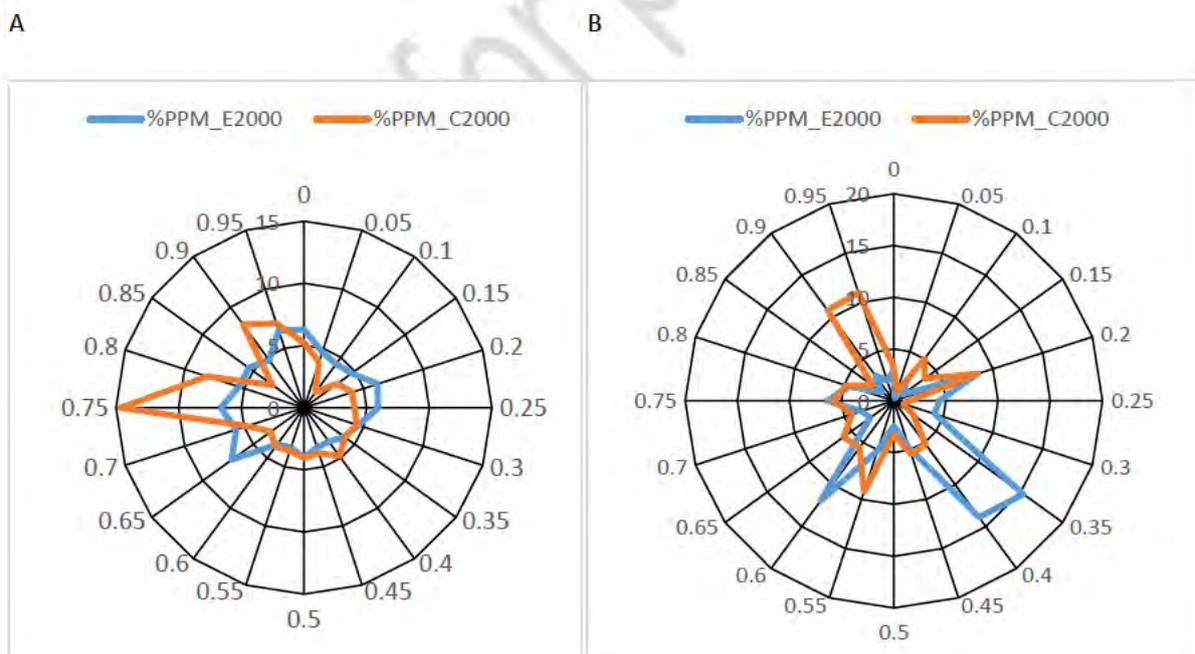
1004



1005 **Figure 15.** Examples of diurnal patterns of PPM detections from Nearfield (E-400) and Farfield (E-2000) C-PODs (data from 8/09-
 1006 16/10/2016, aggregated).

1007 Additional variability in PPM detection rates across the array was noted over ebb-flood and spring-neap tidal
 1008 cycles (Figure 16) but no consistent patterns were observed, again suggesting substantial heterogeneity in
 1009 habitat usage.

1010



1011 **Figure 16.** Examples of apparent variability in PPM detection rates at ebb-flood and spring-neap tidal scales. A) Normalised (% of total)
 1012 PPM detections at locations E-2000 and C-2000 over the ebb-flood tidal cycle (0 = 1 = ebb at Tobermory tidal gauge); B) Normalised (% of
 1013 total) PPM detections at locations E-2000 and C-2000 over the spring-neap tidal cycle (0 = 1 = spring ebb tide at Tobermory tidal gauge).
 1014 All data from 8/09-16/10/2016, aggregated.

1015

1016 4.7.4 PRE- AND POST-EXPERIMENTAL CONTEXT

1017 C-POD data collected from the fish farm barge prior to the experiment indicated substantially higher average
1018 detection rates (0.00670 PPMs/total # of minutes monitored; SE = 0.00135) when compared to data collected
1019 by adjacent C-PODs E-200 and W-200 during the experimental period (specifically the silent control; Table 9).
1020 The pre-experiment baseline data indicated substantial daily variability in terms of total numbers of PPMs
1021 detected, with a decline in daily detection rates during the two weeks prior to starting transmissions (Appendix
1022 2, Figure A2.1A). A strong diel pattern was once again apparent, with >80% of PPMs detected in the 7-hour
1023 period between 21:00 – 04:00, and almost zero detections during daylight hours (Appendix 2, Figure A2.1B).

1024

1025 In contrast, detection rates were significantly higher during the post-experimental winter deployment (Appendix
1026 2). Despite ongoing daily variability, very high average detection rates (0.13080 PPMs/total # of minutes
1027 monitored; SE = 0.00881) were observed consistently throughout the deployment period (Appendix 2, Figure
1028 A2.2A). The diel pattern persisted with almost no detections during daytime, although the distribution of
1029 detections during night-time was more spread out during the longer nights (>90% of PPMs detected in the 14-
1030 hour period between 17:00 – 06:00, Appendix 2, Figure A2.2B).

1031

1032 These results suggest that porpoises continued to use the area immediately surrounding the fish farm barge
1033 before and after the experiment. There were substantial differences in daily porpoise detection rates during the
1034 seven-month period covered by the various C-POD deployments. Detection rates were significantly higher in
1035 winter when compared to both pre-deployment summer data and experimental data collected in
1036 September/October; it is unclear what might have caused these substantial differences. The same C-POD was
1037 used during both pre- and post-experimental monitoring, and deployments proceeded in a comparable fashion
1038 in terms of attachment and recovery, suggesting that the results do not represent an experimental artefact. If
1039 these data do indicate substantial seasonal variability in site usage by porpoises, the apparent absence of
1040 detections during the experimental period may be less influenced by the signal transmissions and more by long-
1041 term seasonal variability in distribution. Interestingly, the diel pattern of detections remained present from
1042 summer to winter, albeit more spread out across a longer period of darkness in winter. This could either suggest
1043 an increase in echolocating porpoises near the detector or a greater reliance on echolocation during seasonally
1044 low light levels.

1045

1046 4.8 ADVANCED MODELLING

1047 Following on from the initial analyses described in Section 4.7, porpoise presence, as inferred through PPM
1048 detections, was analysed in more detail using logistic generalised additive models (GAMs) and generalised
1049 estimation equations (GEEs; Liang & Zeger 1986). This analysis was undertaken to investigate the relative
1050 importance of different covariates (including environmental covariates as well as signal states) on porpoise
1051 detections. Modelling approaches followed here were based on methods described in greater detail by Pirotta
1052 et al. (2011). C-POD data were modelled at three different scales:

- 1053 1) at each individual mooring (where appropriate; only moorings with >50 PPMs were subjected to
1054 modelling),
- 1055 2) across the combined Nearfield moorings, and
- 1056 3) across the entire array.

1057 Models were based on a binomial Generalised Additive Modelling (GAM) framework with an independent
1058 correlation structure and a logit-link function to determine explanatory relevance of environmental covariates,
1059 and were designed and run using the open-source programming language R (v.3.4.2; R Core Team, 2013). In
1060 these models, the response variable (PPM) was defined as a binary record (1 = presence, 0 = absence).
1061 Generalised Estimation Equations (GEEs; Liang & Zeger 1986) were used to address temporal autocorrelation,
1062 again following Pirotta et al. (2011). The independent correlation structure was used because of uncertainty
1063 about the actual underlying structure within the datasets, and also because GEEs are considered to be robust
1064 against misspecification of the correlation structure (Liang & Zeger 1986; Pan 2001). The logit link function was
1065 chosen because it allowed the probability of porpoise detections to be modelled as a linear function of
1066 covariates, thereby satisfying a core assumption of GEEs (Zuur et al. 2009a; Garson 2013). Temporal
1067 autocorrelation was investigated using the *acf* autocorrelation function within the *stats* package in R (threshold
1068 = 0.05; Venables and Ripley 2002) to define blocks of data within which uniform autocorrelation was expected
1069 (Liang & Zeger 1986; Garson 2013). Block sizes varied from 5 to 145 minutes between moorings across the array.

1070

1071 For comparative purposes, only data from September 8 up to October 6 2016, inclusive, were used for this
1072 modelling effort, as this facilitated aggregation of data from all moorings (including the abbreviated C-5000
1073 deployment) within larger-scale models. As a result, PPM counts were generally lower than in previous analyses
1074 (Table 10).

1075

1076 **Table 10. Overview of PPM detections during period used for modelling effort, 8/09 – 6/10/2016.**

Array section	Site name	#PPM	Daily PPM detection rate (#PPM/day)
---------------	-----------	------	-------------------------------------

NEARFIELD	E-200	15	0.51
NEARFIELD	E-400	97	3.33
NEARFIELD	E-600	204	7.00
NEARFIELD	E-800	263	9.02
NEARFIELD	E-1000	283	9.71
FARFIELD	E-2000	748	25.66
NEARFIELD	C-400	97	3.33
NEARFIELD	C-600	309	10.60
NEARFIELD	C-800	15	0.51
NEARFIELD	C-1000	159	5.45
FARFIELD	C-2000	319	10.94
FARFIELD	C-5000	361	12.38
NEARFIELD	W-200	111	3.81
NEARFIELD	W-400	155	5.32
NEARFIELD	W-600	30	1.03
NEARFIELD	W-800	110	3.77
NEARFIELD	W-1000	238	8.16
FARFIELD	W-2000	53	1.82
FARFIELD	W-5000	352	12.07

1078 Further details of the GAM-GEE modelling approach, a list of covariates used, and individual model results are
1079 provided in Appendix 5. All covariates included in final models listed in Appendix 5 were retained based on their
1080 ability to explain statistically significant amounts of residual variability within the PPM observational dataset.
1081 Model quality (expressed as fractions of correctly predicted observations and AUC scores; see Appendix 5 for
1082 details) varied, with some models being substantially better at correctly predicting both presence and absence
1083 of PPMs than others. Comparatively poor model quality in some cases was likely driven by relatively small sample
1084 sizes (numbers of PPMs).

1085

1086 The GAM-GEE modelling approach used here has allowed the relative significance of different covariates to be
1087 determined, and thus provide insight into the relative importance of the experimental signal transmissions
1088 versus a range of environmental variables in determining presence of echolocating porpoises. It is, however,
1089 important to interpret the results with caution. In particular, each successive covariate included in the models
1090 referenced below and in Appendix 4 describes progressively less and less residual variability under the influence
1091 of all other previously assessed covariates. The PPM-covariate relationships observed should therefore not be
1092 taken out of that multi-covariate context and considered independently.

1093 The various single-mooring models illustrated the importance of different combinations of covariates among
1094 moorings, emphasizing the apparent heterogeneity observed in PPM detection rates across the array. Overall,
1095 both the single-mooring and array model results aligned well with earlier observations described in Section 4.7,
1096 in terms of which covariates turned out to be important. Most significantly, the presence of an experimental
1097 signal (Signal_Type) never was the primary covariate in any of the models, indicating that the presence of either
1098 LF or HF signal was not the most important factor in determining presence of echolocating porpoises.

1099

1100 The single-mooring models can be summarised as follows (details of covariates to be found in Appendix 5):

- 1101 • Diel hour (HOUR) and Julian Day (JULDAY) were consistently among the most important covariates for
1102 nearly all models, confirming the apparent significance of diel and seasonal cycles in driving small-scale
1103 porpoise distribution.
- 1104 • The spring-neap tidal cycle (SpringNeap) also appeared important in many cases, particularly for
1105 moorings further offshore, with ebb-flood tidal cycle (HiLoTide) generally less important.
- 1106 • Signal_Type (HF vs. LF signals vs. silent control vs. 'other' non-experimental time) was of secondary
1107 significance (2nd or 3rd covariate) for a small number of single-mooring models (W-400, E-1000 and W-
1108 1000; Appendix 5). Responses were variable, with the greatest likelihood of porpoise detection often
1109 associated with periods of silence (either the silent controls or the intermediate non-experimental
1110 periods).

- 1111 • Number of unprocessed clicks detected per minute (Nall_m) was a frequently occurring covariate
1112 although its relative importance varied across the array, ranking higher among more distant moorings
1113 (e.g. W-2000 and W-5000; Appendix 5).
- 1114 • Time of Day (DAYTIMENum), a factorial covariate introduced to capture intermediate temporal
1115 patterns linked with daylight levels, turned out to be dismissed from most models due to strong
1116 collinearity with Diel Hour. In the four single-mooring models where it was retained (C-600, W-1000, E-
1117 2000 and C-5000; Appendix 5), all models but one (E-2000) indicated that most residual variability was
1118 explained by periods of darkness, particularly Night and Dawn.

1119

1120 For the Nearfield-only and whole-array models, the following patterns were observed, which were broadly
1121 similar to observations made for single-mooring model outcomes (Appendix 5):

- 1122 • Diel hour (HOUR), Julian day (JULDAY) and mooring location (POSITION) were among the top three
1123 covariates in terms of significance for both compound models, although not in the same order
1124 (POSITION ranking top for the full array model, compared to HOUR among the Nearfield-only model).
- 1125 • Signal_Type (HF vs. LF signals vs. silent control vs. 'other' non-experimental time) and Number of
1126 unprocessed clicks detected per minute (Nall_m) alternated ranks among both models but were less
1127 important than HOUR, JULDAY or POSITION. In both compound models, the residual probability of PPM
1128 detection was highest during silent control periods ('AS') than during either HF or LF signals.
- 1129 • Ebb-flood tidal cycle (HiLoTide) was the least important covariate for the Nearfield-only model. It was
1130 also a low-ranking covariate in the whole-array model, but was followed by Time of Day (DAYTIMENum)
1131 and spring-neap tidal cycle (SpringNeap).

1132

1133 Modelling results were influenced by relatively low porpoise detection rates across inshore moorings. Moreover,
1134 the available covariates are likely to act as proxies for more ephemeral factors such as prey abundance and
1135 distribution, which cannot be measured easily but are far more ecologically relevant to porpoises. Nonetheless,
1136 the present modelling results confirm that porpoise distribution across the array during the experiment was
1137 largely driven by environmental variability rather than the experimental signal, and that there was typically little
1138 difference between responses generated by either the HF or the LF ADD signal.

1139 5 DISCUSSION

1140 The present experiment did not provide conclusive evidence to support the hypothesis that LF-ADD signals result
1141 in significantly higher harbour porpoise detection rates than 'standard' HF-ADD signals. Instead, porpoise
1142 detection rates were, as a rule, greatest during silent control periods and reduced during both HF- and LF-signal
1143 transmissions (Table 9; Figure 13, 14; Appendix 5), suggesting that porpoises might be responding to both signal
1144 types. ADD signals did not often feature as significant covariates in individual GAM-GEE models (Appendix 5);
1145 instead, other factors, notably the day-night cycle, were typically more important in determining harbour
1146 porpoise presence. Porpoises appeared to seek out inshore waters after nightfall, with a particular peak around
1147 dusk and dawn, whereas open waters in the central Sound of Mull were occupied more consistently. Because
1148 so few porpoises were observed at the Bloody Bay fish farm site during daylight hours, no clear trends in
1149 porpoises' immediate surface responses to signal transmission starts could be observed. The surface tracking
1150 approach using the SLR camera array was, however, confirmed to work as intended and can provide high-
1151 resolution observations if animals can be followed at ranges <1km from the observation site.

1152

1153 The experiment made use of bespoke HF and LF signals, designed to incorporate features of various different
1154 ADD types. Also, source levels of both HF and LF signals were lower due to experimental equipment limitations
1155 (up to approximately 170 dB re 1 μ Pa-m RMS, Table 2) than those of commercially available ADDs, which may
1156 exceed 190 dB re 1 μ Pa-m (RMS; Table 1). However, SoundTrap data confirmed that both signals were detectable
1157 at the C-5000 mooring, and that the entire area could thus be considered ensonified during all transmission
1158 experiments. Porpoises' apparent responses to exposure to either HF or LF signals, in terms of reduced acoustic
1159 detection rates compared to silent control periods, could be explained in several ways, including animals' ability
1160 to detect and respond to higher-frequency harmonics rather than the peak frequency of both signals. However,
1161 as Figure 4 illustrates for the tested experimental signals, potential higher-frequency harmonics are at
1162 significantly lower levels than the designed fundamental frequencies. Any such responses could potentially be
1163 reinforced by more general 'neophobic' tendencies to avoid novel stimuli often observed in porpoises (e.g.
1164 Dawson et al., 1998).

1165

1166 Based on the limited number of exposure experiments that were visually observed (Section 4.6), seals were not
1167 noticeably deterred from the vicinity of the fish farm by either HF or LF signal transmissions. This was not the
1168 main focus of the present study and results should therefore be interpreted with caution. Seal detections at the
1169 surface were more frequent when either signal was being played than during silent control periods, suggesting
1170 they might seek to reduce noise exposure by lifting the head out of the water (Fjälling et al. 2006; Kvadsheim et
1171 al. 2010). Alternatively, seals could have been responding to a 'dinner bell' effect, having learnt to associate the
1172 sound of ADDs with the presence of food (be it captive salmon or wild fish attracted to the cages). It is worth

1173 noting that these observations occurred around a fish farm that traditionally has not used active ADDs, where
1174 such signals might therefore have been perceived as more novel and worthy of inspection by curious seals.
1175 Conversations with SSF staff indicated that seals were regularly observed near the Bloody Bay fish farm, implying
1176 that the artificial ADD signals were not suddenly attracting seals to an otherwise seal-free site. Our observations
1177 did not support the assumption that ADD signals actually deter seals from fish farms, which has itself been the
1178 subject of debate for many years (e.g. Jacobs & Terhune, 2002; Quick et al., 2004; Graham et al., 2009; Götz &
1179 Janik, 2013; Coram et al. 2014; SCOS, 2016).

1180

1181 The divergent responses of seals and porpoises to both HF and LF signals was contrary to what might have been
1182 expected if deterrence was assumed to be solely or largely driven by both groups' hearing capabilities at lower
1183 frequencies (e.g. Kastelein et al. 2002, 2010). Similar responses to an artificial ADD signal (resembling the output
1184 of a 12-kHz Lofitech unit) were observed by Mikkelsen et al. (2017), suggesting that other factors may be more
1185 important in determining time spent by different species in the vicinity of fish farms equipped with ADDs. This
1186 feeds into the ongoing discussion of precisely which component(s) of an ADD signal are important in initiating
1187 avoidance behaviour (Coram et al. 2014). Direct comparisons with responses to existing ADD types are hindered
1188 by continued lack of publicly available testing data. Testing other LF-ADDs under rigorous experimental
1189 circumstances, as previously proposed (e.g. Northridge et al. 2013; Coram et al. 2014), would allow
1190 determination to what extent differences in signal characteristics might influence deterrence efficacy among
1191 seals and other species (as has been done by Götz & Janik 2015, 2016).

1192

1193 The observed porpoise detection rates during HF and LF signal transmissions may have been influenced by the
1194 fact that harbour porpoises along the west coast of Scotland were almost certainly not naïve in terms of previous
1195 ADD exposure. ADDs of one type or another have been present in many parts of western Scotland for many
1196 years (e.g. Northridge et al. 2010; Coram et al. 2014), and the majority of porpoises alive today in western
1197 Scottish waters are likely to have encountered them many times previously. Although the Bloody Bay fish farm
1198 itself is prevented by license from deploying ADDs, porpoises moving along the Sound of Mull would be exposed
1199 to numerous ADDs from other farms. Comparatively muted responses to an, admittedly novel, set of ADD signals
1200 from the Bloody Bay farm might therefore not be entirely unexpected. The present experiment was set up to
1201 accurately mimic conditions around a real, operational fish farm, in the full knowledge of the potential for a
1202 degree of habituation towards ADD signals having occurred among western Scottish porpoises. Future tests in
1203 areas without ADD-equipped fish farms, elsewhere within Scotland or further afield, would thus be informative
1204 to determine differences in responses of (presumed) naïve porpoises to the two signal types (following e.g.
1205 Mikkelsen et al. 2017).

1206

1207 Heterogeneity among porpoise detection rates across the array was considerable, with detection rates being
1208 both higher and more consistent in deeper waters in the central Sound of Mull. Inshore moorings in the Nearfield
1209 array reported lower numbers of detections, often with a strong bias towards periods after sunset/before
1210 sunrise. These patterns indicate heterogeneous use of habitats by harbour porpoises across the Sound of Mull.
1211 This cyclical dawn/dusk pattern among harbour porpoise detections has been identified previously (e.g.,
1212 Schaffeld et al. 2016; Benjamins et al. 2017; Nuuttila et al. 2017; Williamson et al. 2017), including at the Bloody
1213 Bay field site (Carlström 2005). The present study did not investigate which possible environmental drivers might
1214 be underpinning the observed patterns in the Sound of Mull, but they are likely to include diurnal/nocturnal
1215 activity patterns of prey items in nearshore areas.

1216

1217 Porpoises were detected on C-PODs at or near the fish farm barge both prior to, during and after the experiment
1218 (Appendix 2). These observations suggest that porpoises were not deterred by the fish farm infrastructure per
1219 se. Official wildlife sighting reports and anecdotal observations collected by SSF staff suggested that porpoises
1220 could be observed within a few hundred metres of the Bloody Bay fish farm, although this was not reflected in
1221 our visual observations during the experiment. Such observations are supported by reports from elsewhere (e.g.
1222 Haarr et al. 2009) suggesting that fish farm infrastructure without ADDs does not lead to long-term habitat
1223 exclusion of porpoises. Little is known about how porpoises might make use of marine infrastructure such as
1224 fish farms; potential reasons for actively approaching farms might include seeking shelter from storm conditions
1225 (suggested by Haarr et al. 2009), or potentially feeding. Fish farms can attract a variety of wild fish species (e.g.
1226 Dempster et al. 2009, 2010), themselves attracted by excess food, fouling organisms on the cage structures etc.,
1227 and such concentrations of wild fish might attract porpoises (or, indeed, seals; Coram et al. 2014; Callier et al.
1228 2017). Individual porpoises' decisions to seek out the vicinity of fish farms will likely be influenced by animals'
1229 body condition, reproductive status, presence of predators, etc. Individuals who are sick, injured, nursing a calf,
1230 or otherwise nutritionally impaired may be more likely to seek out fish aggregations near fish farms, if present.
1231 Such attraction could inadvertently lead to increased exposure of these individuals to high levels of ADD noise
1232 with potential negative consequences (Lepper et al. 2014). Further work is needed to clarify the ecological role
1233 of fish farms in terms of their ability to attract harbour porpoise (and other top predators) through mediation of
1234 wild fish aggregations (Callier et al. 2017).

1235 Seasonal variation in porpoise detection rates, as evidenced by pre- and post-experimental data (Appendix 2),
1236 was substantial although its underlying causes remain unclear. The decline in daily porpoise detection rates at
1237 least 10 days prior to the commencement of the experiment suggests that, although the presence of artificial
1238 ADD signals might have had a negative impact on porpoise activity around the fish farm, this decline was not
1239 initiated by the experimental transmissions. The subsequent increase in daily detection rates during winter
1240 months was surprising and reinforces the importance of long-term monitoring to capture seasonal/interannual

1241 variability. These results indicate that porpoises did not exhibit long-term avoidance of the site following the
1242 completion of the experiment.

1243

1244 In summary, the highest PPM detection rates occurred during silent control periods. Comparatively low PPM
1245 detection rates corresponding to LF-ADD signal transmission suggested that this type of signal was detectable
1246 by porpoises, contrary to original expectations. Substantial heterogeneity in detection rates across the array
1247 suggested that environmental drivers, rather than ADD signal type, were highly important in determining
1248 spatiotemporal detection patterns. Sample sizes in the Nearfield array immediately adjacent to the fish farm
1249 barge were limited for unknown reasons, but thought to be unrelated to the experiment itself.

1250

1251

DRAFT - for peer review

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1277

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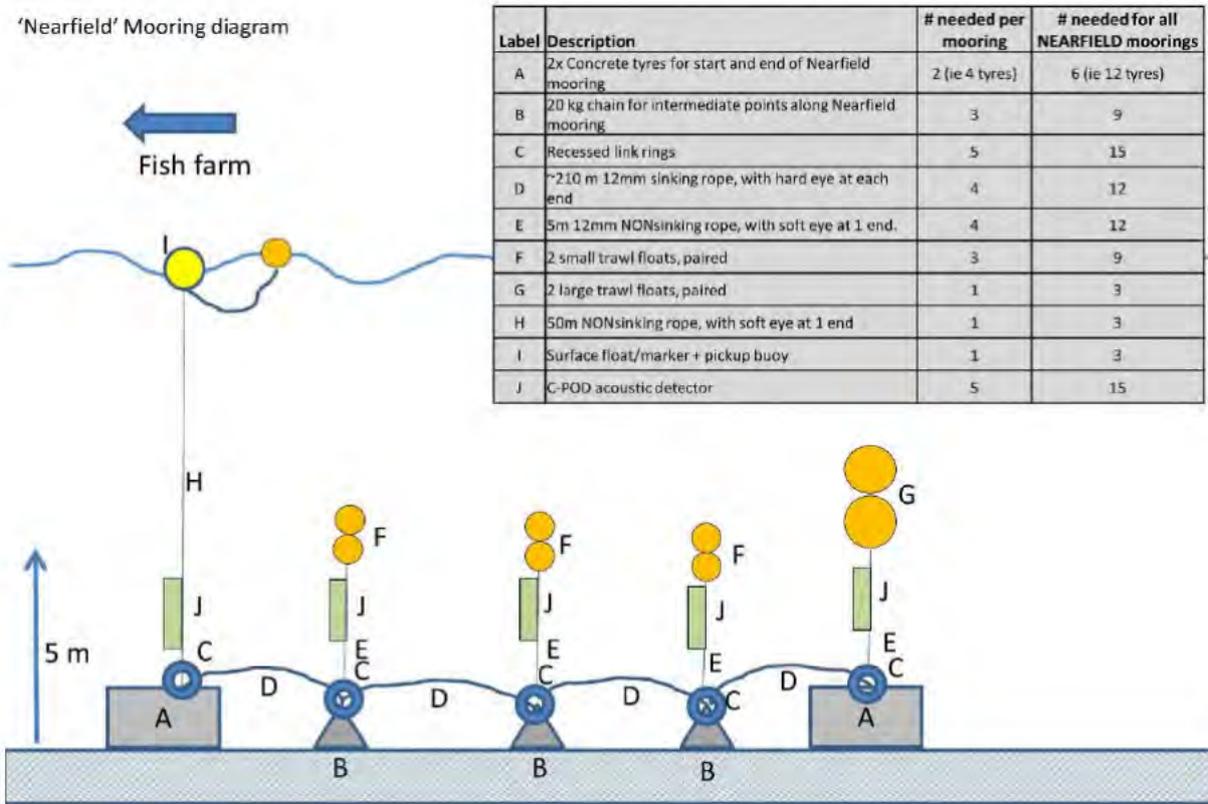
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APPENDIX 1 - MOORING DESIGN

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Overview of mooring structures used in Nearfield and Farfield moorings, respectively.

'Nearfield' Mooring diagram



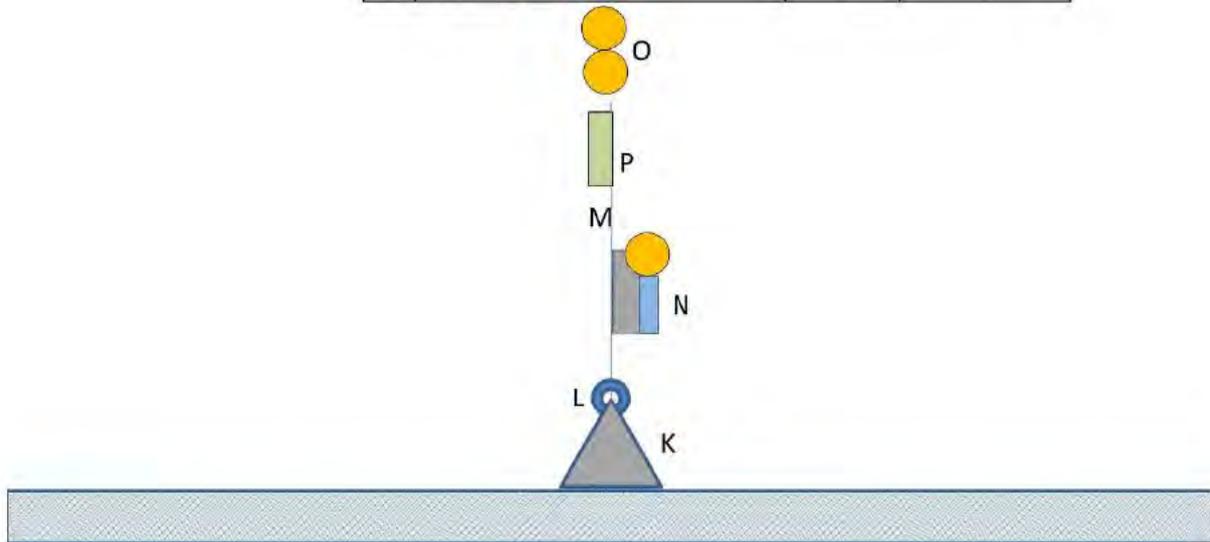
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DRAFT - FOR

'Farfield'
mooring diagram

Label	Description	# needed per mooring	# needed for all FARFIELD moorings
K	20 kg chain for Farfield mooring	1	6
L	Recessed link rings	1	6
M	5m 12mm NONsinking rope, with soft eye at 1 end	1	5 (not needed for single Fiobuoy mooring)
N	Sonardyne/Fiobuoy LRT system	1	6 (5 Sonardyne, 1 Fiobuoy)
O	2 small trawl floats, paired	1	5
P	C-POD acoustic detector	1	6

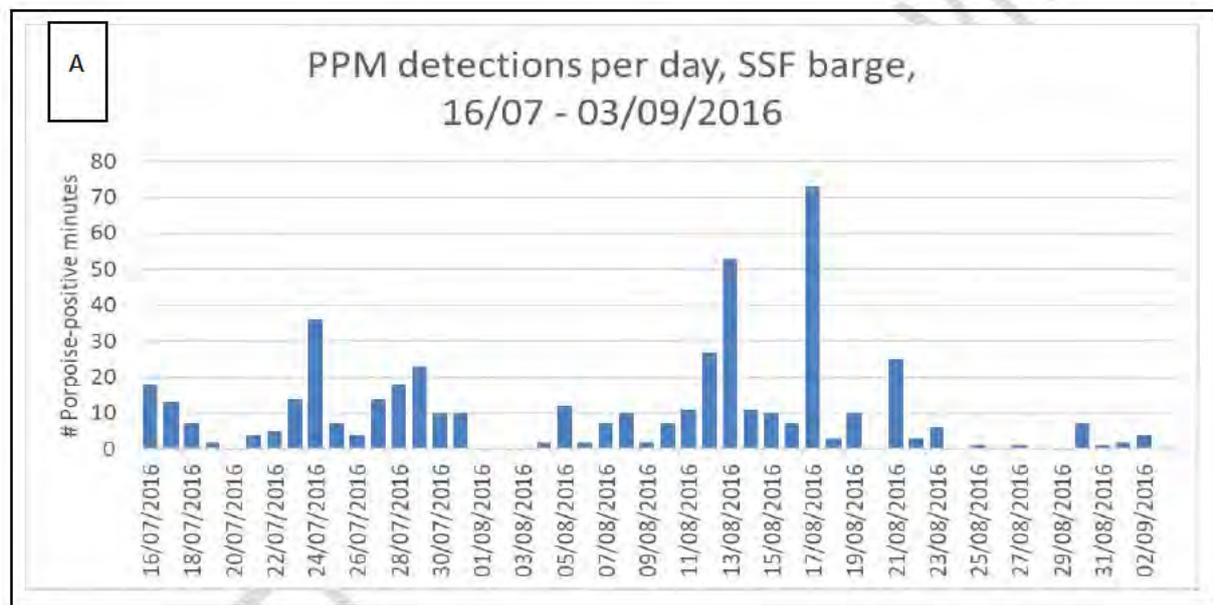


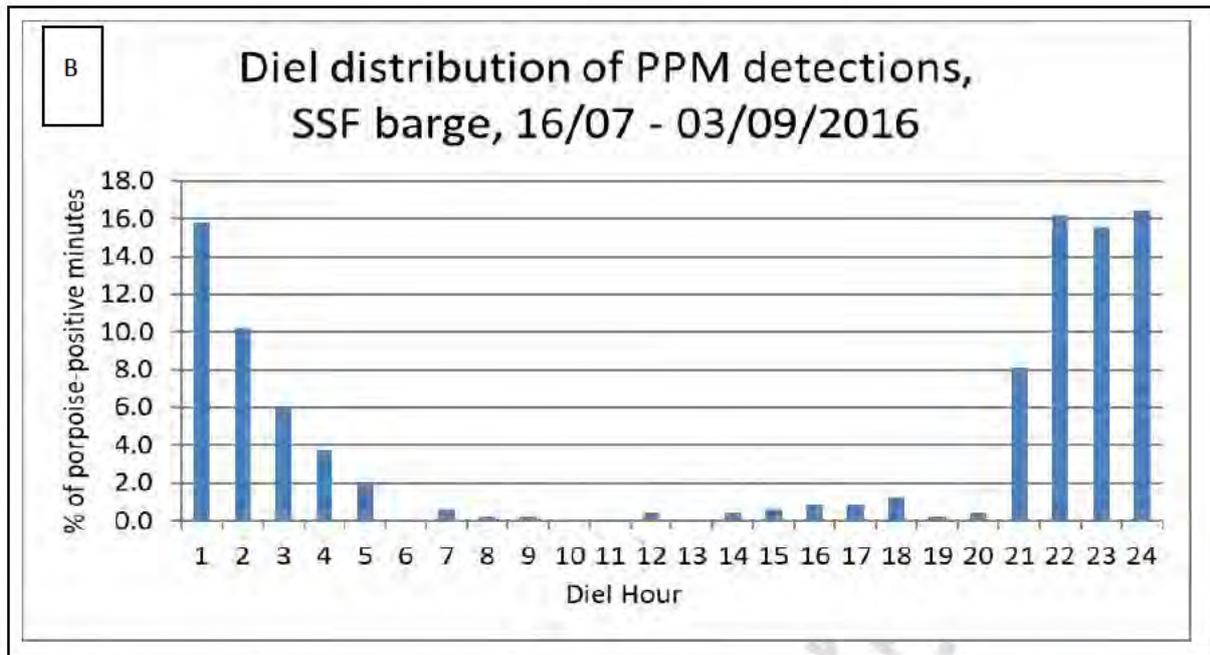
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APPENDIX 2 – PRE- AND POST-EXPERIMENTAL DATA FROM C-POD BENEATH FISH FARM BARGE

Prior to commencing the experiment, the Bloody Bay fish farm barge was monitored using a single C-POD to obtain baseline data on porpoise presence in the immediate vicinity of the fish farm. This exercise was subsequently repeated following removal of all other experimental infrastructure, to determine whether porpoise presence changed over time. Data on total daily PPM detection numbers and overall diel PPM distribution are presented in Figure A3.1.

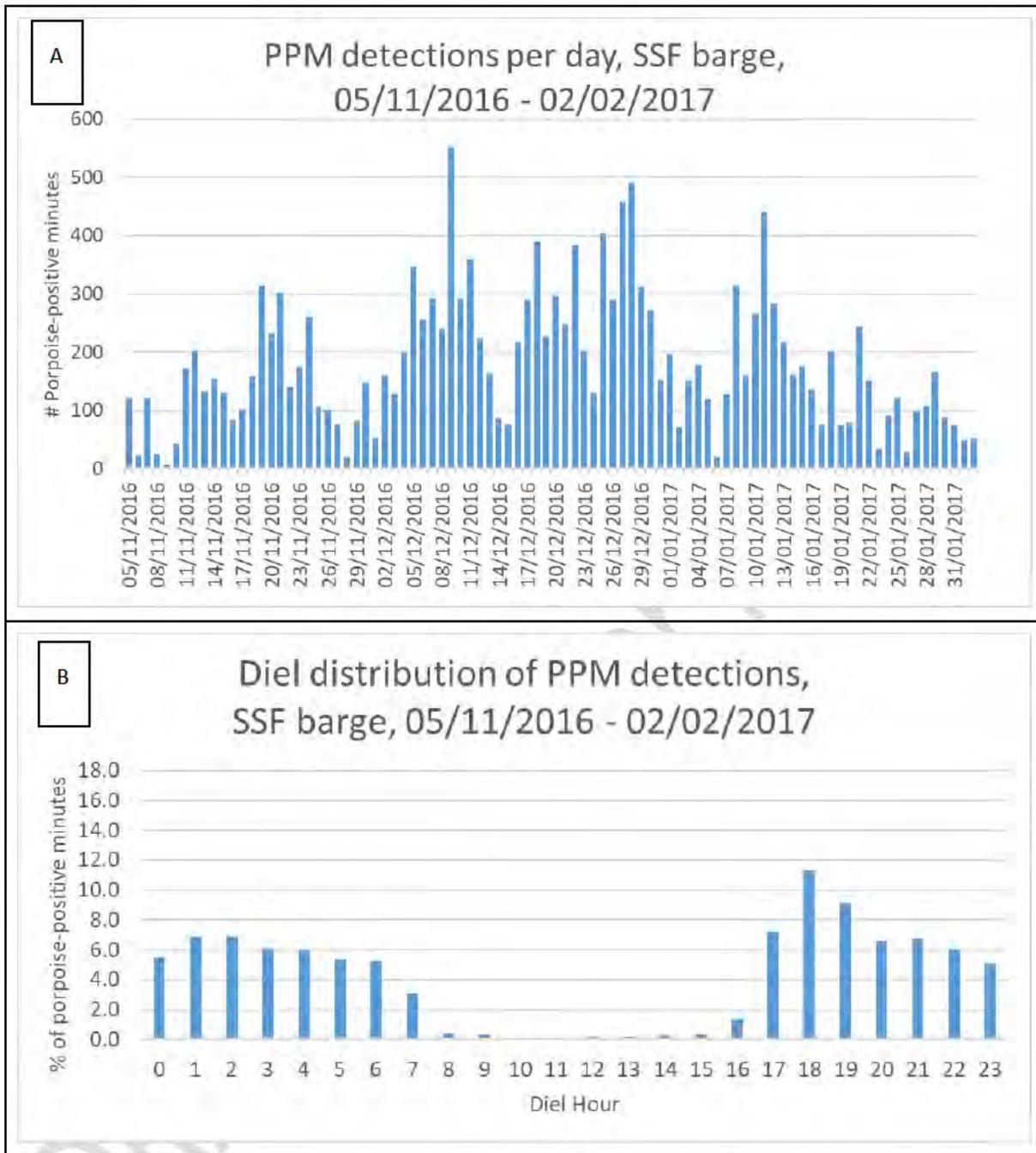




1677 Figure A3.1. A) Overview of overall PPM numbers during pre-experimental deployment at the Bloody Bay fish farm, 16/07 – 3/09/2016
 1678 (partial start & end days excluded). B) Overview of distribution of PPMs by hour across a 24-hour day (data aggregated over 16/07 –
 1679 3/09/2016 (partial start & end days excluded).

1680 Following recovery of the experimental infrastructure, the same C-POD used for pre-experimental baseline
 1681 monitoring was redeployed for further monitoring of the fish farm site. The C-POD was deployed from 4/11/2016
 1682 until being recovered in late February 2017; the battery turned out to have failed on 03/02/2017, providing
 1683 approximately 3 months' worth of data. Data on total daily PPM detection numbers and overall diel PPM
 1684 distribution during this time are presented in Figure A3.2.

1685



1686 Figure A3.2. A) Overview of overall PPM numbers during pre-experimental deployment at the Bloody Bay fish farm, 05/11/2016 –
 1687 02/02/2017 (partial start & end days excluded). B) Overview of distribution of PPMs by hour across a 24-hour day (data aggregated
 1688 over 05/11/2016 – 02/02/2017 (partial start & end days excluded).

1689

1690

1691 APPENDIX 3 - OVERVIEW OF # PPM/DAY ACROSS ARRAY

1692 Summary of daily PPM detections per mooring, at increasing distance from the sound source below the fish farm barge (from E-200 & W-200 out to C-5000 & W-5000). Cells
 1693 are colour-coded with low values in green and high values in red.

DATE	E-200	W-200	E-400	C-400	W-400	E-600	C-600	W-600	E-800	C-800	W-800	E-1000	C-1000	W-1000	E-2000	C-2000	W-2000	C-5000	W-5000
08/09/2016	0	0	3	3	0	2	0	0	1	0	0	6	6	0	28	0	1	9	18
09/09/2016	0	0	1	1	0	0	0	2	1	0	2	6	2	2	25	5	0	19	18
10/09/2016	0	0	1	1	0	7	1	0	10	0	0	4	5	0	5	10	0	119	55
11/09/2016	0	0	0	0	0	18	3	0	35	0	0	44	4	0	29	35	2	23	23
12/09/2016	0	6	5	5	7	11	9	0	18	2	10	35	19	9	41	19	1	28	19
13/09/2016	0	0	4	4	0	2	0	0	3	0	13	19	1	13	8	8	0	0	2
14/09/2016	0	1	2	2	1	1	8	0	2	0	4	0	2	15	16	1	0	1	37
15/09/2016	0	0	1	1	0	4	26	0	9	0	0	9	7	0	30	9	1	0	20
16/09/2016	1	0	3	3	0	4	0	0	3	3	0	1	2	7	16	8	0	1	20
17/09/2016	0	0	0	0	0	0	2	0	0	0	3	0	0	5	7	5	7	4	7
18/09/2016	0	0	0	0	5	0	10	1	2	0	1	3	0	0	15	3	10	3	32

19/09/2016	0	0	0	0	0	0	0	0	0	0	1	0	1	5	2	2	0	12	4
20/09/2016	0	3	2	2	7	13	12	5	5	2	8	3	4	25	12	9	0	9	1
21/09/2016	1	6	0	0	1	9	3	1	8	1	8	8	8	19	52	18	3	10	15
22/09/2016	0	0	0	0	0	0	0	0	0	0	0	3	0	3	36	0	1	12	7
23/09/2016	0	13	5	5	18	8	46	2	2	1	6	27	8	10	104	8	4	10	4
24/09/2016	0	0	1	1	1	0	10	4	4	0	8	5	2	8	111	21	1	16	5
25/09/2016	2	41	18	18	55	29	79	3	40	3	19	28	27	28	42	12	1	0	12
26/09/2016	0	0	2	2	0	0	1	0	5	0	0	17	5	1	12	9	0	9	12
27/09/2016	0	6	15	15	9	27	34	1	22	1	0	16	8	15	74	21	1	2	4
28/09/2016	4	10	4	4	17	1	17	3	8	0	1	7	3	3	12	16	1	6	8
29/09/2016	1	10	12	12	11	48	9	0	60	1	9	18	15	21	15	19	6	5	3
30/09/2016	0	1	8	8	4	6	3	0	3	0	6	2	1	9	8	4	6	5	4
01/10/2016	3	0	2	2	0	1	0	0	3	0	1	3	0	4	4	2	3	1	3
02/10/2016	0	3	3	3	9	4	25	4	14	0	0	7	0	3	4	1	0	4	0

03/10/2016	0	0	0	0	2	0	0	1	1	0	0	1	1	0	0	4	1	20	14
04/10/2016	2	2	2	2	2	6	5	2	3	1	3	10	6	11	11	30	0	22	4
05/10/2016	1	9	2	2	6	3	5	0	0	0	6	0	22	22	19	32	2	7	1
06/10/2016	0	0	1	1	0	0	1	1	1	0	1	1	0	0	10	8	0	4	0
07/10/2016	0	0	1	1	0	0	5	1	1	0	1	10	1	5	3	9	3		1
08/10/2016	0	0	2	2	0	0	1	0	0	0	0	0	2	3	0	1	0		0
09/10/2016	0	6	0	0	1	1	0	0	5	0	1	1	0	1	5	12	2		3
10/10/2016	2	5	8	8	21	2	26	5	1	4	1	1	7	3	1	8	0		23
11/10/2016	2	9	2	2	5	6	14	0	8	0	0	4	9	2	3	17	2		12
12/10/2016	1	14	0	0	14	11	14	0	14	0	4	13	3	8	6	8	9		13
13/10/2016	1	0	4	4	0	23	22	1	27	0	9	14	12	16	21	9	6		7
14/10/2016	1	9	0	0	30	5	55	4	2	0	4	2	5	7	4	17	1		6
15/10/2016	5	80	26	26	50	61	59	5	80	1	0	38	24	23	25	56	1		5
16/10/2016	5	122	11	11	67	20	32	5	28	0	13	17	30	4	12	63	2		8

1695

APPENDIX 4 – DIEL VARIABILITY IN PPM DETECTIONS

1696

The following graphs illustrate, for each mooring, the diel patterns among PPM detections observed

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throughout the experimental period. Total numbers of PPMs are indicated for each mooring. Moorings are

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aggregated according to their presence along the Eastern, Central and Western mooring lines. Detection rates

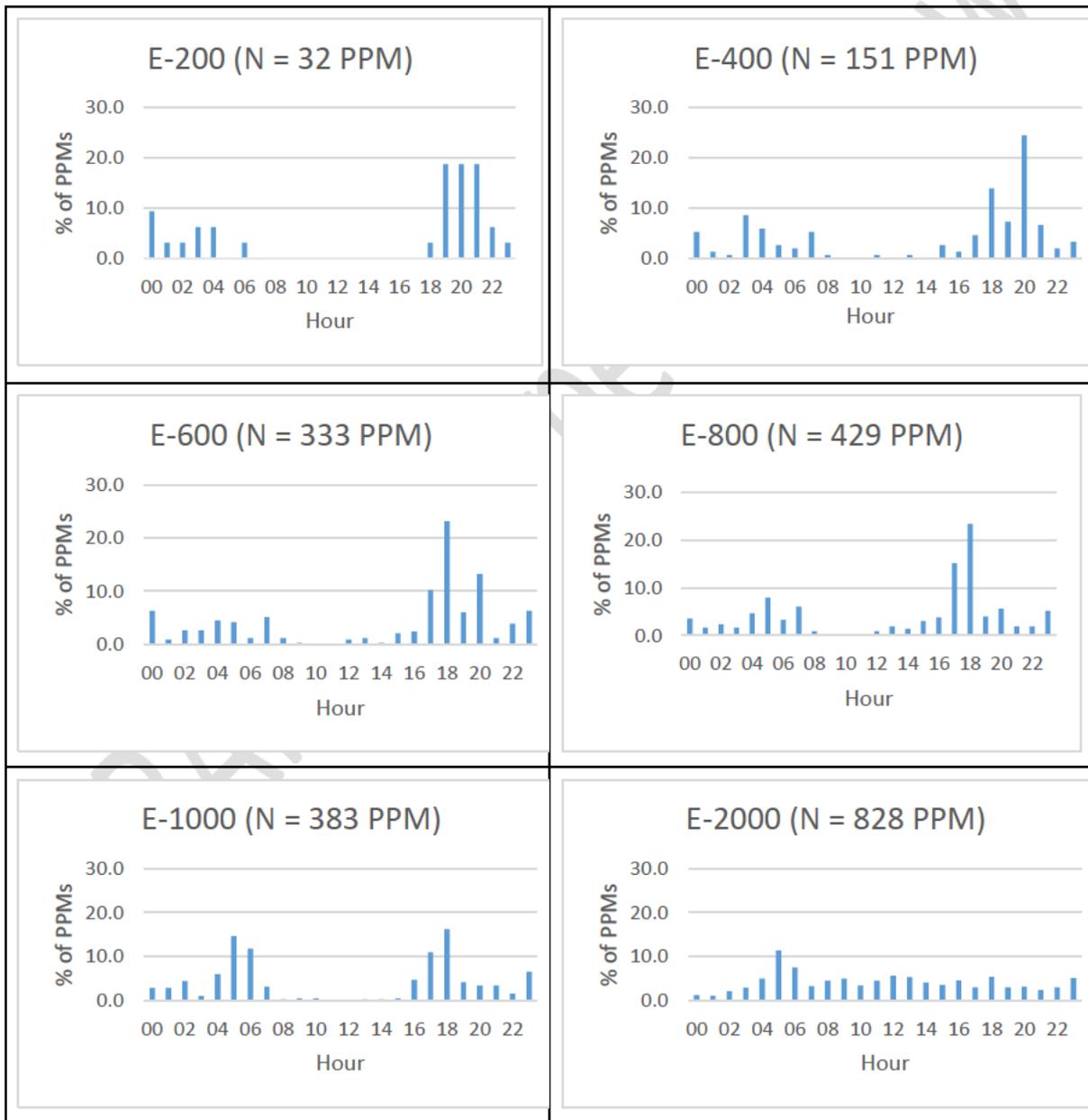
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were generally highest at night, particularly during evenings, except for Farfield moorings such as E-2000 and

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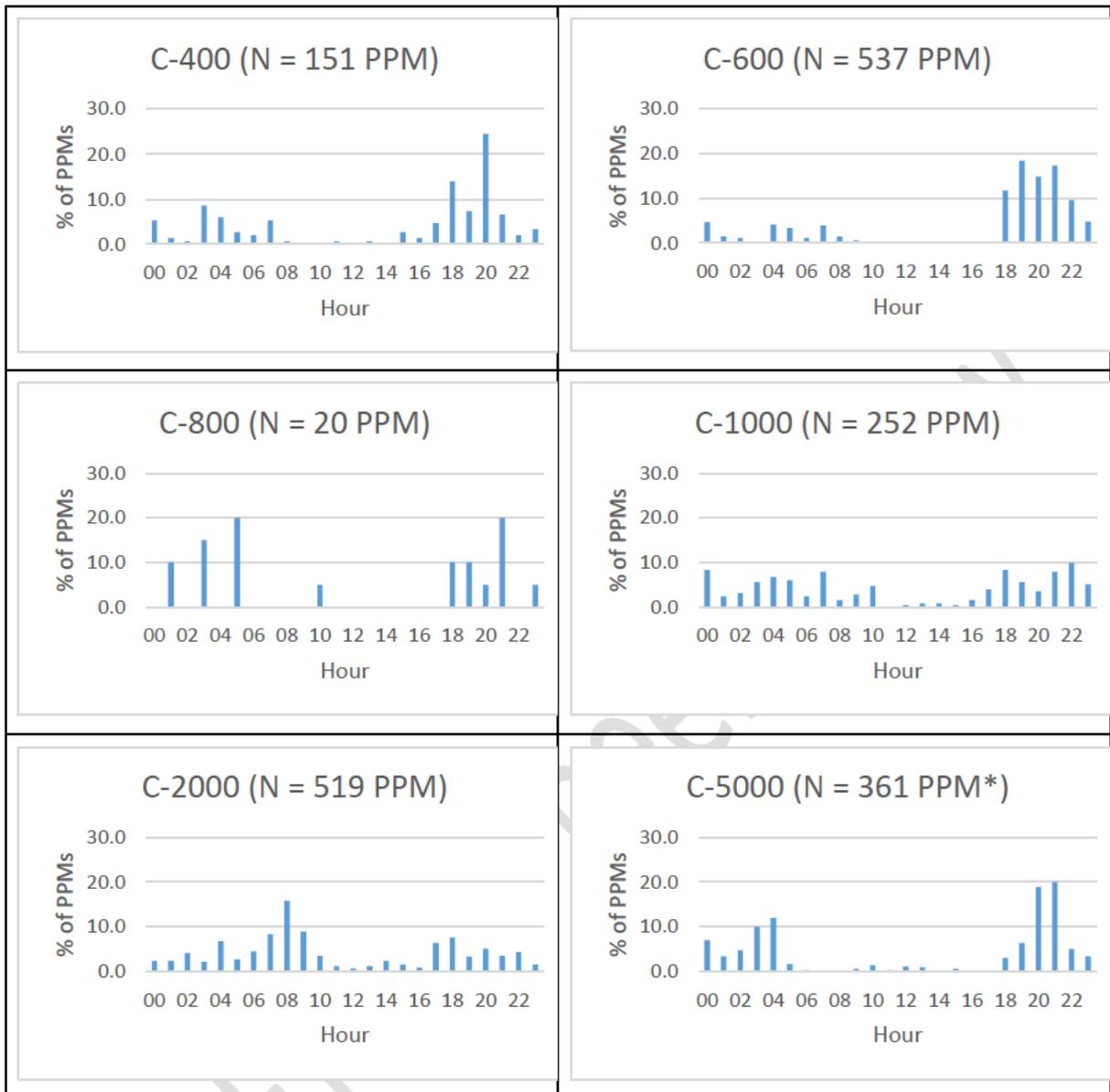
W-5000.

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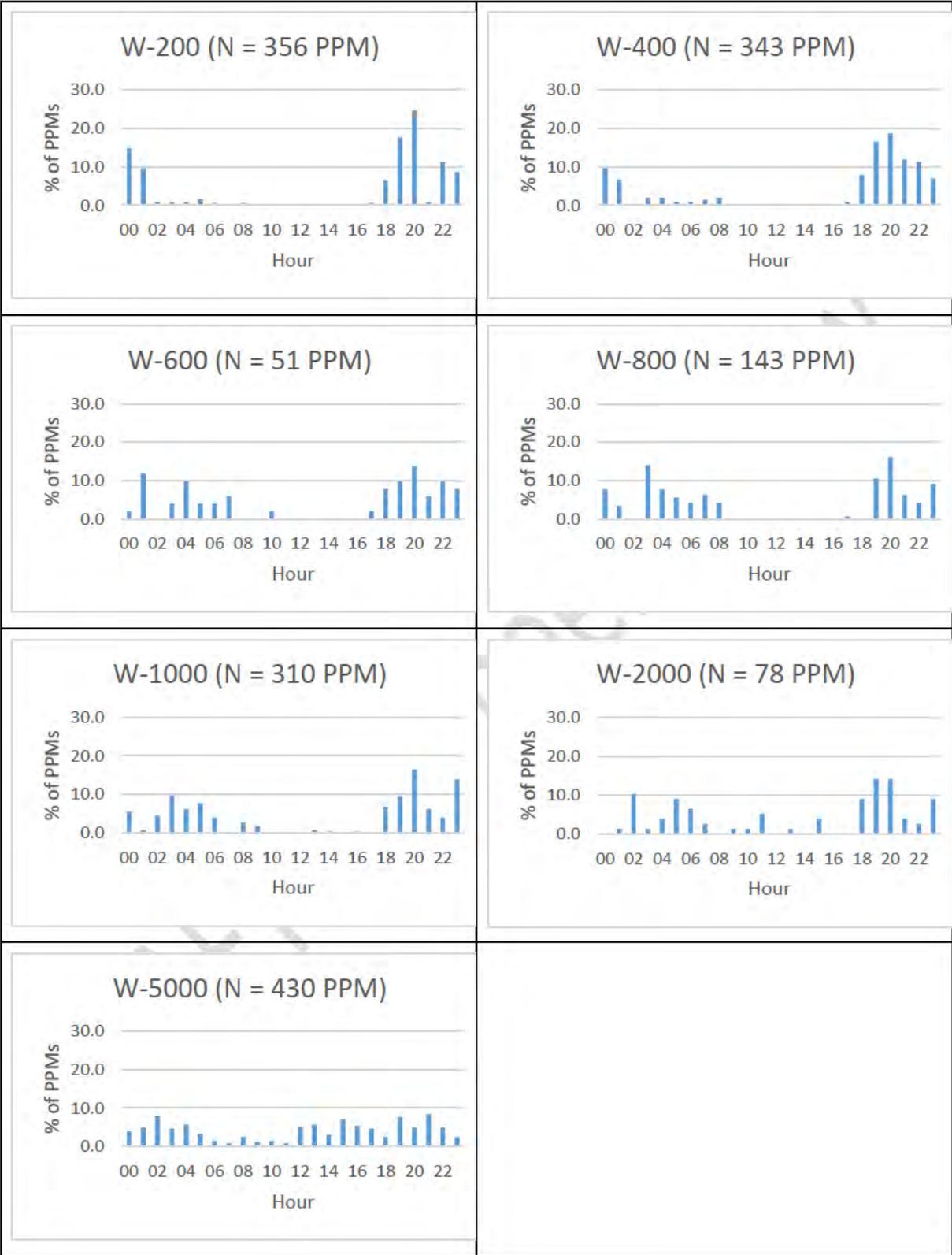
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APPENDIX 5 - GAM DESCRIPTORS AND OUTPUTS

1710 This Section contains model outputs for 1) the entire LEAP array, 2) for the Nearfield component only, and 3) for
1711 all individual C-PODs where at least 50 PPMs were detected during the experimental period. Porpoise presence
1712 was modelled using binomial-based GAM-GEEs with an independent correlation structure and a logit link
1713 function to describe the relationship between covariates and porpoise click train detection presence (the
1714 response variable, described in a binary presence/absence format). This approach closely follows the one initially
1715 described by Pirotta et al. (2011) and the following text is adapted from an in-depth description of this method
1716 by Benjamins et al. (2016, 2017).

1717 Models are only intended to describe available records and should not be extrapolated to other datasets. The
1718 independent correlation structure was used because of uncertainty in the actual underlying structure within the
1719 datasets, and because GEEs were considered robust against correlation structure misspecification (Liang & Zeger
1720 1986; Pan 2001). The logit link function was chosen because it allowed the probability of porpoise detections to
1721 be modelled as a linear function of covariates, one of the core assumptions of GEEs (Zuur et al. 2009a; Garson
1722 2013).

1723 Data exploration protocols described by Zuur et al. (2010) and Zuur (2012) were used to identify outliers, data
1724 variability, relationships between covariates and response variable, and collinearity between covariates.
1725 Modelling was initiated using a basic GLM as a means to assess collinearity of covariates, following Zuur (2012).
1726 Collinear and non-significant covariates were removed during subsequent analyses. Collinearity among
1727 covariates was investigated using the $GVIF^{(1/(2 \cdot Df))}$ output of the R function *vif* (part of the *car* package; Fox
1728 & Weisberg 2011), to account for combinations of linear, cyclic and factorial covariates. A list of available
1729 covariates is included in Table A8.1. The POSITION covariate was found to be collinear with numerous descriptive
1730 covariates (e.g. bathymetry, sediment type, distance from shore) and was therefore retained as a means to
1731 capture the residual variability derived from all these other covariates, which were subsequently removed.
1732 HiLoTide and SpringNeap covariates were defined on the basis of data obtained from the Tobermory tidal gauge
1733 (part of the UK National Tidal Gauge Network).

1734

Covariate	Unit	Scale	Description	use in model	# of models used
POSITION	Name of positions	N/A	19 location identifiers, incorporating local variation pertinent to each mooring location (depth, sediment type, distance from shore, etc.)	Factor	2*
JULDAY	Number	252 - 280	Julian day number	Linear or cubic B-spline	9
HOUR	Hour	0 - 23	Number of hour per day	Cyclic B-spline	14
Temp	°C	1.6 - 19 degrees	POD temp logger (not calibrated)	Linear or cubic B-spline	Not used
Angle	Degree (°)	0 - 180°	Avg. deflection from vertical, where 0° = CPOD pointing straight up	Linear or cubic B-spline	Not used
Nall_m	Number	0 - 4096	Number of raw clicks received each minute	Linear or cubic B-spline	12
D_Source_m	Number	252 - 5435	Estimated distance (in m) from sound source	Linear or cubic B-spline	Not used
D_Shore_m	Number	362 - 2107	Estimated shortest distance (in m) from any shore	Linear or cubic B-spline	Not used

Angle_shore	Degree (°)	-56.161179 - 176.885639	Angle to closest shore (check ARCGIS to determine scale)	Cyclic B-spline	Not used
Est_depth_m	Number	28 - 59	Estimated depth (m, rel. to CD) at site	Linear or cubic B-spline	Not used
Sed_type	Number	1-3	Approx sediment type (1 = mud, 2 = sandy mud, 3 = sand)	Factor	Not used
HiLoTide	Fraction	0 - 1	Cyclic variable denoting ebb-flood tide (0 = 1 = Low Tide as measured at Tobermory tidal gauge)	Cyclic B-spline	9
SpringNeap	Fraction	0 - 1	Cyclic variable denoting spring-neap tide (0 = 1 = Spring Low as measured at Tobermory tidal gauge)	Cyclic B-spline	8
DAYTIMENum	Number	1 - 4	Numeric descriptor of period of day (relevant for daylight levels; 1 = Dawn, 2 = Day, 3 = Dusk, 4 = Night)	Factor	4
Exper_ON	Binary	0 - 1	Binary variable indicating whether each minute was part of an experiment or time in between	Factor	Not used
Signal_Type	Number	0 - 3	Numeric descriptor of experimental status; 0 -	Factor	5

			intermediate time (no sound); 1 – silent control (no sound); 2 = HF ADD; 3 = LF ADD		
--	--	--	---	--	--

1736

1737 GAMs offer the ability to incorporate nonlinear responses to variables and therefore provide a more flexible and
 1738 powerful tool than Generalised Linear Models (GLMs) to clarify the interactions between marine mammals and
 1739 their environment (e.g. Hastie et al. 2005). GAMs assume independence between model residuals, which is likely
 1740 to be violated where conditions at time t may closely resemble those at $t-1$ and $t+1$ (such as might be expected
 1741 in the present case). This temporal autocorrelation could cause the uncertainty surrounding model estimates to
 1742 be underestimated. To address this problem, autocorrelation in the data was investigated using the R
 1743 autocorrelation function *acf* (Venables and Ripley 2002). These results were used to define blocks of data within
 1744 which autocorrelation was present, using Generalised Estimation Equations (GEEs; Liang & Zeger 1986). Using
 1745 this approach, uniform autocorrelation was expected within the blocks but not between them (Garson 2013).
 1746 This is appropriate when studying population-level effects (in contrast to animal-specific response patterns, e.g.
 1747 GAMMs; Fieberg et al. 2009, 2010) and particularly suitable for binomial distributions. GEEs are considered to
 1748 be relatively robust even if block sizes are misspecified (Hardin & Hilbe 2003). Block sizes were specified for each
 1749 model in Table A8.2.

1750 **Table A8.2. Overview of block sizes used for individual and compound models to address temporal autocorrelation.**

Array section	Site name	Block size (minutes)
NEARFIELD	E-200	5
NEARFIELD	E-400	30
NEARFIELD	E-600	118
NEARFIELD	E-800	137
NEARFIELD	E-1000	117
FARFIELD	E-2000	145
NEARFIELD	C-400	72

NEARFIELD	C-600	100
NEARFIELD	C-800	5
NEARFIELD	C-1000	40
FARFIELD	C-2000	45
FARFIELD	C-5000	121
NEARFIELD	W-200	45
NEARFIELD	W-400	71
NEARFIELD	W-600	6
NEARFIELD	W-800	17
NEARFIELD	W-1000	64
FARFIELD	W-2000	10
FARFIELD	W-5000	55

1751

1752 Covariates were considered as either 1) linear terms, 2) factors, or 3) 1-dimensional smooth terms with 4 degrees
 1753 of freedom. The latter were modelled as either cubic B- splines with one internal knot positioned at the average
 1754 value of each variable, or as cyclic penalized cubic regression splines (specifically those covariates identified as
 1755 'cyclic' in Table A8.1).

1756 The Quasi-likelihood under Independence model Criterion (QICu; Pan 2001), a modification of Akaike's
 1757 Information Criterion (Akaike 1974) appropriate for GEE models, was used to identify which covariates should
 1758 be retained in the final model, using the R library *yags* (Carey 2004). Covariates were removed one at a time in
 1759 a backwards stepwise model selection process, and models with the lowest QICu values were taken forward up
 1760 to the point where removal of further covariates no longer resulted in lower QICu values. At this point, the final
 1761 GAM model was fitted using the R function *geeglm* (contained within R package *geepack*; Halekoh et al. 2006)
 1762 to assess the statistical significance of the remaining covariates within the correlation structure specified within
 1763 the GEE. The Wald's Test (Hardin & Hilbe 2003) was used to determine each covariate's significance; non-
 1764 significant covariates were removed from the model using backwards stepwise model selection.

1765 Model quality was expressed through a combination of confusion matrices and Area under the Curve (*auc*)
1766 calculations. Each model summary below contains a Confusion Matrix, which describes how well the binary
1767 model predictions matched observed values (e.g. how often an observed detection was predicted by the model),
1768 thereby summarising the goodness of fit of the model (Fielding & Bell 1997; Pirotta et al. 2011). Green cells in
1769 each Confusion Matrix represent correctly predicted fractions, whereas grey cells indicate incorrectly predicted
1770 fractions. Higher values in Green cells indicate a better working model. The *auc* value describes the area
1771 contained beneath the Receiver Operating Characteristic (ROC) curve associated with each model, which
1772 illustrates the relationship between true and false positive rates (Boyce et al. 2002). *AUC* values range from 0-1,
1773 with higher *auc* values indicating a correspondingly better-performing model.

1774 Following identification of the final model, plots were generated describing the probabilistic relationship
1775 between each contributing explanatory covariate and the model response variable (PPM presence/absence).
1776 Confidence intervals around these plots were based on the standard errors of the GAM-GEE model.

1777 Covariates were plotted independently to visualise the probabilistic relationship between each covariate and
1778 the binary response variable (porpoise detection) for each model. Covariates were plotted in declining order of
1779 significance in terms of their explanatory power. It is important to reiterate that while GAMs allowed the relative
1780 significance of different covariates to be determined, the results should be interpreted with care. Importantly,
1781 **less significant covariates' relationships to the response variable were dependent upon the inclusion of more**
1782 **significant covariates in the model, and should therefore be interpreted as explaining residual amounts of**
1783 **variation in the presence of more significant covariates, rather than seen in isolation.**

1784

1785

Model:	Entire array			
Model structure:	<pre> POD2<-geeglm(PPM ~ as.factor(POSITION) + as.factor(JULDAY) + AvgHrBasisMat + Nall_m + as.factor(Signal_Type) + TideBasisMat + as.factor(DAYTIMENum) + SprNpBasisMat, family = binomial, corstr="independence", id=Panel, data=Array) </pre>			
Confusion matrix:			Expected	
			Porpoise	No porpoise
	Observed	Porpoise	81.3%	27.3%
		No porpoise	18.7%	72.7%
AUC value:	0.8436431			
Results of Wald's tests for all significant covariates for the final model:				
Covariates (in descending order of significance)	Form	Degrees of Freedom	χ^2 score	P-value
POSITION	factor	18	423.14	$<2.2 \cdot 10^{-16}$
JULDAY	factor	28	273.52	$<2.2 \cdot 10^{-16}$
HOUR	Cyclic B-spline	4	138.73	$<2.2 \cdot 10^{-16}$
Nall_m	linear	1	169.23	$<2.2 \cdot 10^{-16}$
Signal_Type	factor	3	37.69	$3.291 \cdot 10^{-8}$
HiLoTide	Cyclic B-spline	4	27.66	$1.462 \cdot 10^{-5}$

DAYTIMENum	factor	3	15.00	0.001819
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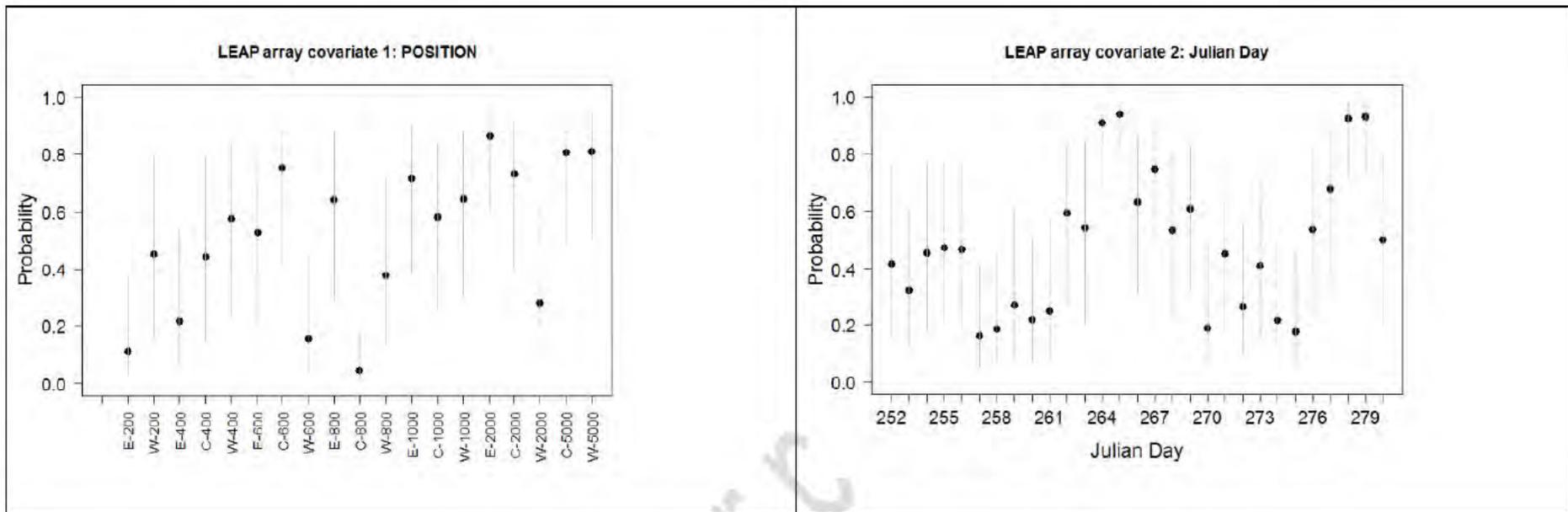
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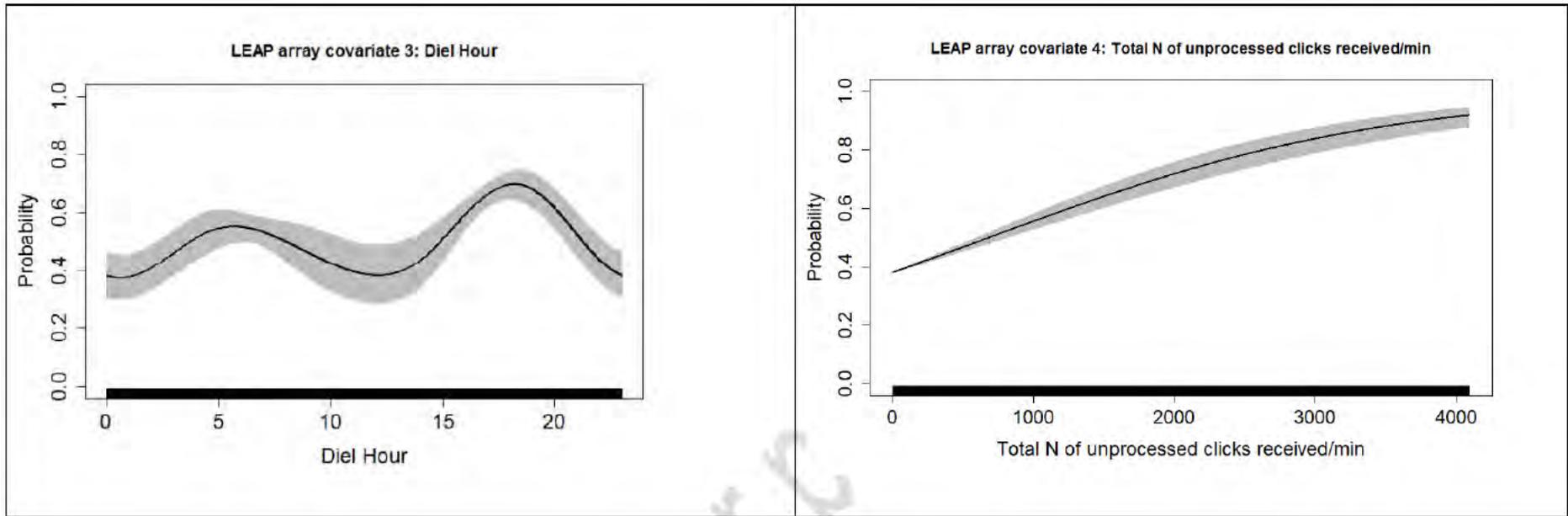
SpringNeap	Cyclic B-spline	4	11.35	0.022868
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1788

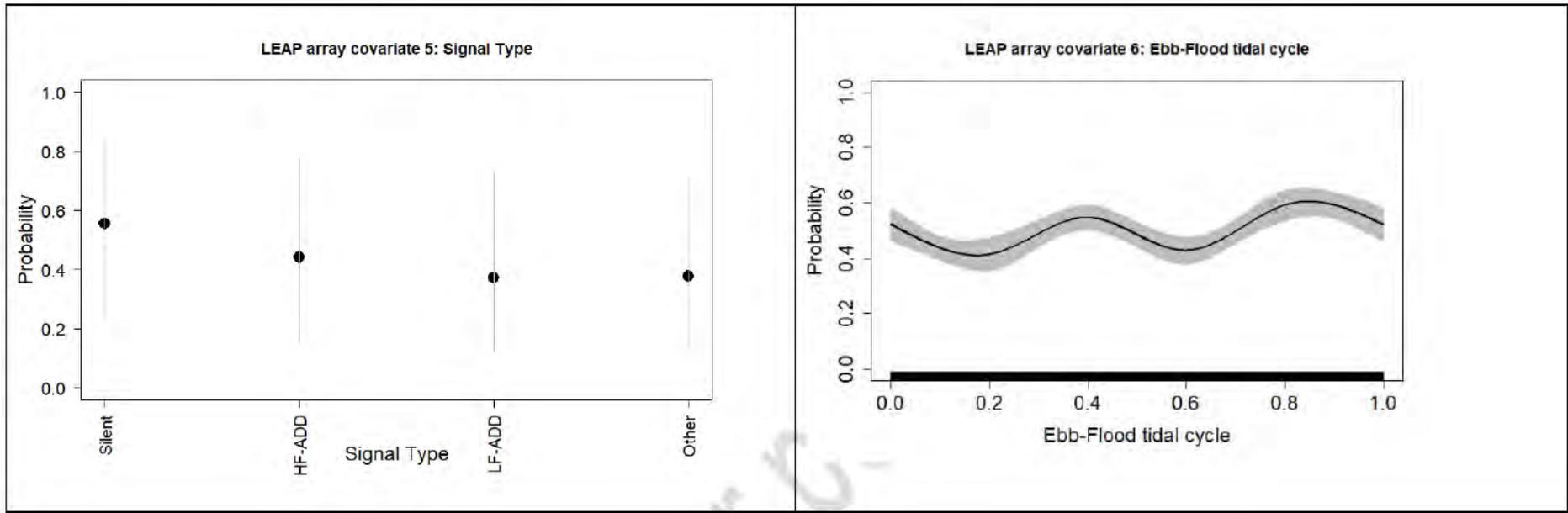
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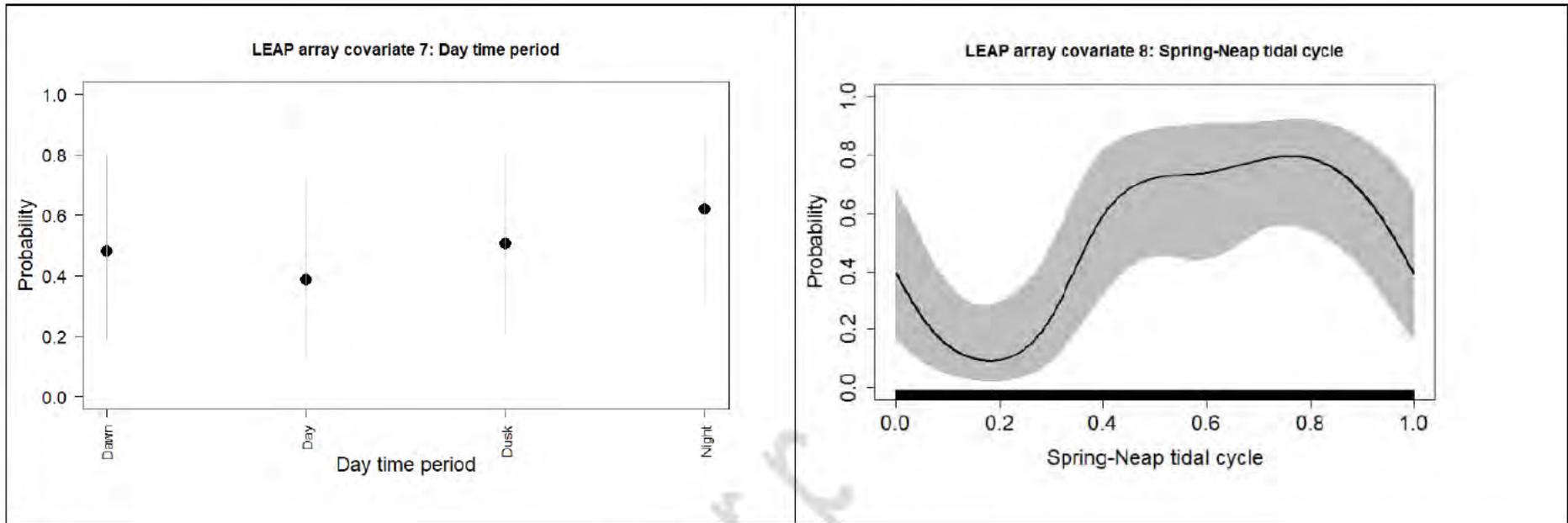


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1789

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1790 Nearfield model

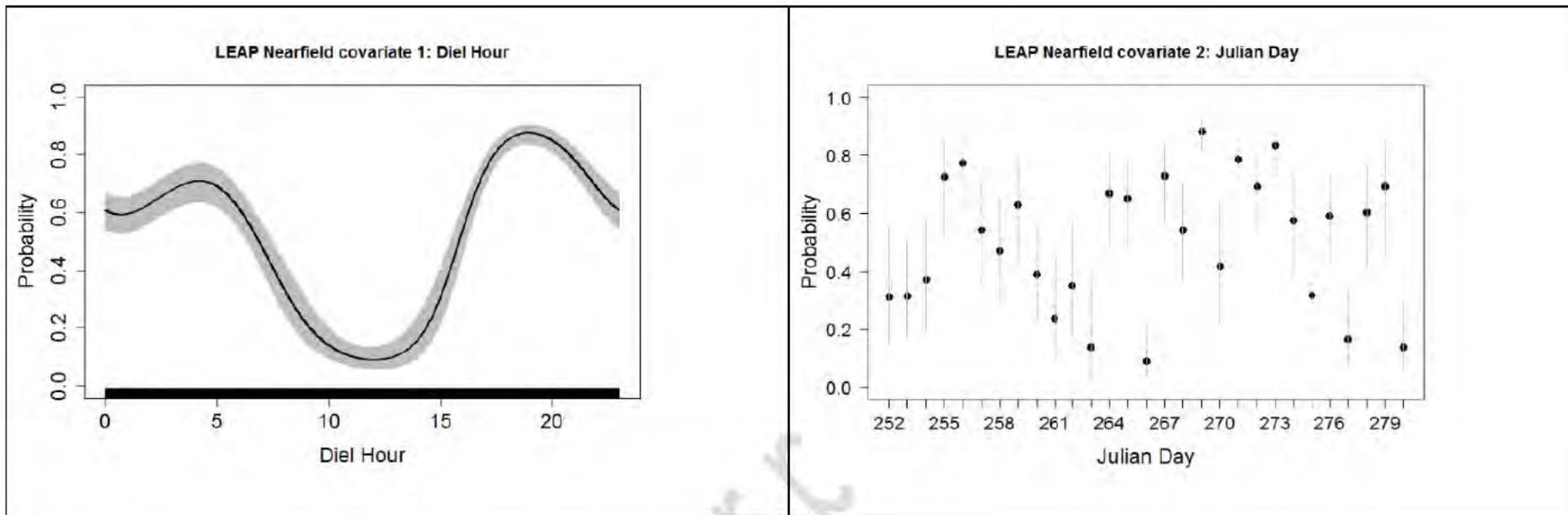
1791

Model:	Nearfield moorings (E-200-E1000, C-400-1000, & W-200-1000)																			
Model structure:	<code>POD3<-geeglm(PPM ~ AvgHrBasisMat + as.factor(JULDAY) + as.factor(POSITION) + as.factor(Signal_Type) + Nall_m + TideBasisMat, family = binomial, corstr="independence", id=Panel, data=Nearfield)</code>																			
Confusion matrix:	<table border="1"> <tr> <td></td> <td></td> <td>Expected</td> <td></td> </tr> <tr> <td></td> <td></td> <td>Porpoise</td> <td>No porpoise</td> </tr> <tr> <td>Observed</td> <td>Porpoise</td> <td>80.6%</td> <td>19.2%</td> </tr> <tr> <td></td> <td>No porpoise</td> <td>19.4%</td> <td>80.8%</td> </tr> </table>						Expected				Porpoise	No porpoise	Observed	Porpoise	80.6%	19.2%		No porpoise	19.4%	80.8%
		Expected																		
		Porpoise	No porpoise																	
Observed	Porpoise	80.6%	19.2%																	
	No porpoise	19.4%	80.8%																	
AUC value:	0.8893874																			
Results of Wald's tests for all significant covariates for the final model:																				
Covariates (in descending order of significance)	Form	Degrees of Freedom	χ^2 score	P-value																
HOUR	Cyclic B-spline	4	165.23	$<2.2 \cdot 10^{-16}$																
JULDAY	factor	28	367.38	$<2.2 \cdot 10^{-16}$																
POSITION	factor	13	195.50	$<2.2 \cdot 10^{-16}$																
Signal_Type	factor	3	61.93	$2.272 \cdot 10^{-13}$																
Nall_m	linear	1	73.34	$<2.2 \cdot 10^{-16}$																

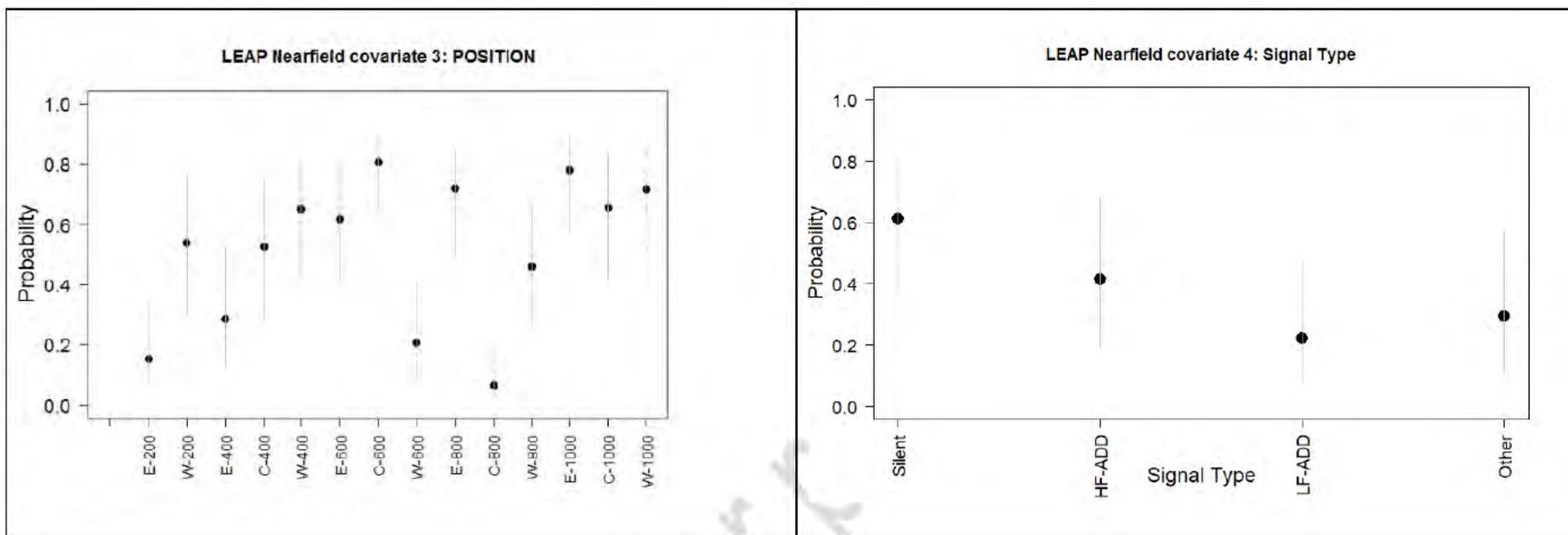
HiLoTide	Cyclic B-spline	4	33.07	$1.158 \cdot 10^{-6}$
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1792

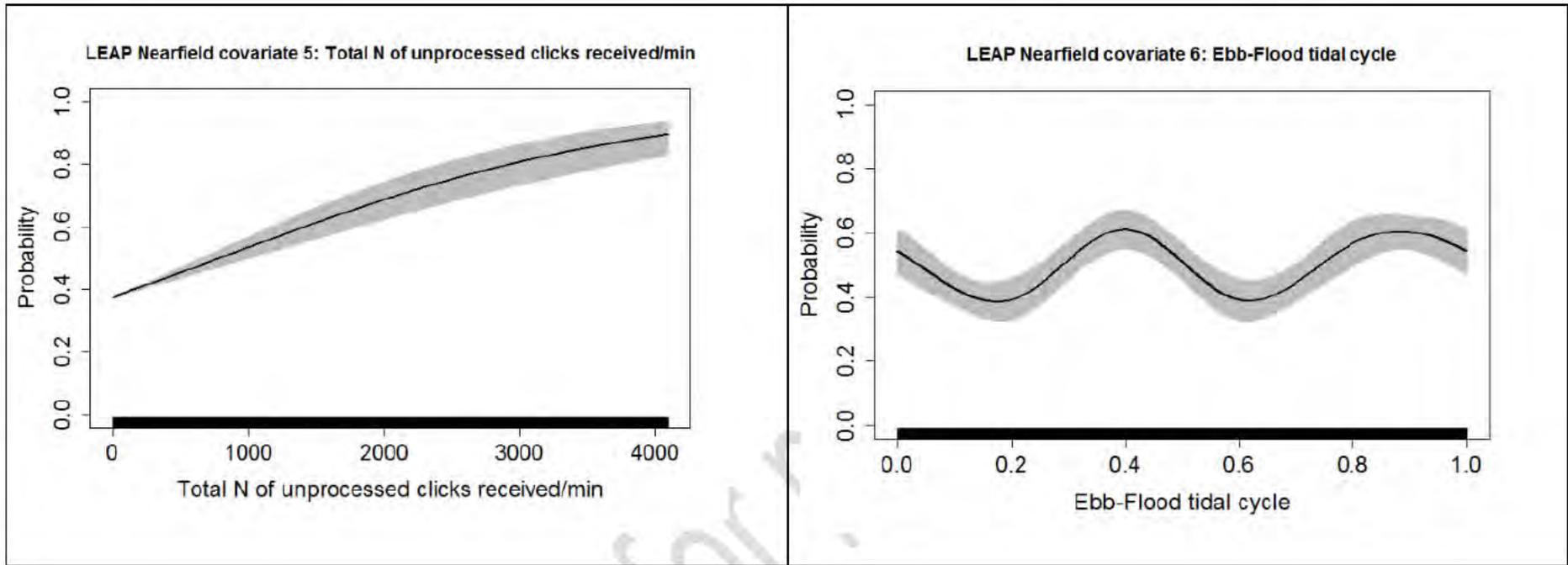
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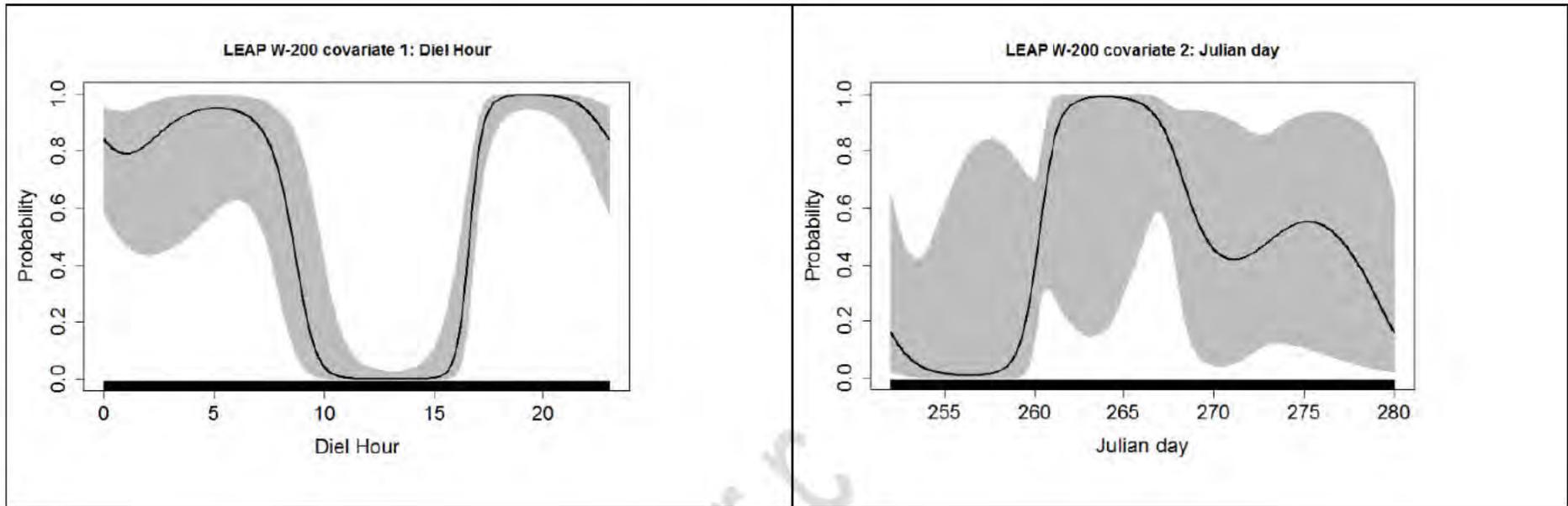


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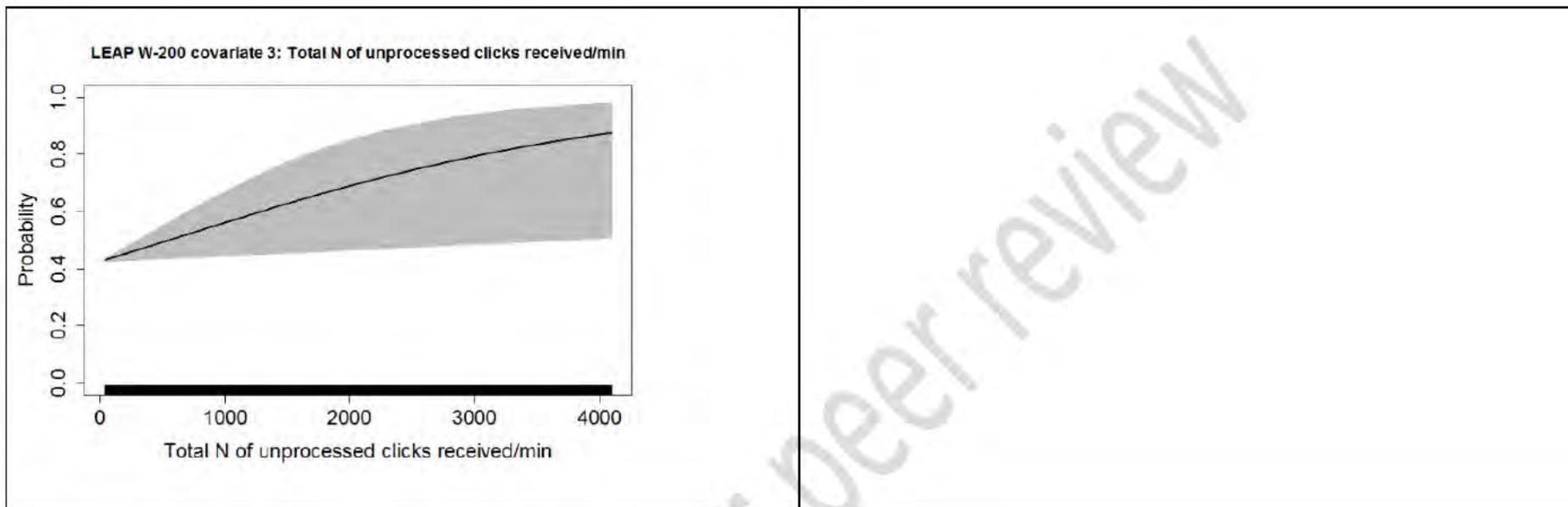
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Model:	W-200																			
Model structure:	<code>POD5<-geeglm(PPM ~ AvgHrBasisMat + bs(JULDAY , knots=mean(JULDAY)) + Nall_m, family = binomial, corstr="independence", id=Panel, data=W200)</code>																			
Confusion matrix:	<table border="1"> <tr> <td></td> <td></td> <td>Expected</td> <td></td> </tr> <tr> <td></td> <td></td> <td>Porpoise</td> <td>No porpoise</td> </tr> <tr> <td>Observed</td> <td>Porpoise</td> <td>77.5%</td> <td>6.8%</td> </tr> <tr> <td></td> <td>No porpoise</td> <td>22.5%</td> <td>93.2%</td> </tr> </table>						Expected				Porpoise	No porpoise	Observed	Porpoise	77.5%	6.8%		No porpoise	22.5%	93.2%
		Expected																		
		Porpoise	No porpoise																	
Observed	Porpoise	77.5%	6.8%																	
	No porpoise	22.5%	93.2%																	
AUC value:	0.905853																			
Results of Wald's tests for all significant covariates for the final model:																				
Covariates (in descending order of significance):	Form	Degrees of Freedom	χ^2 score	P-value																
HOUR	Cyclic B-spline	4	24.6722	$5.855 \cdot 10^{-5}$																
JULDAY	Cubic B-spline	4	9.9928	0.04055																
Nall_m	linear	1	5.3750	0.02043																

1794



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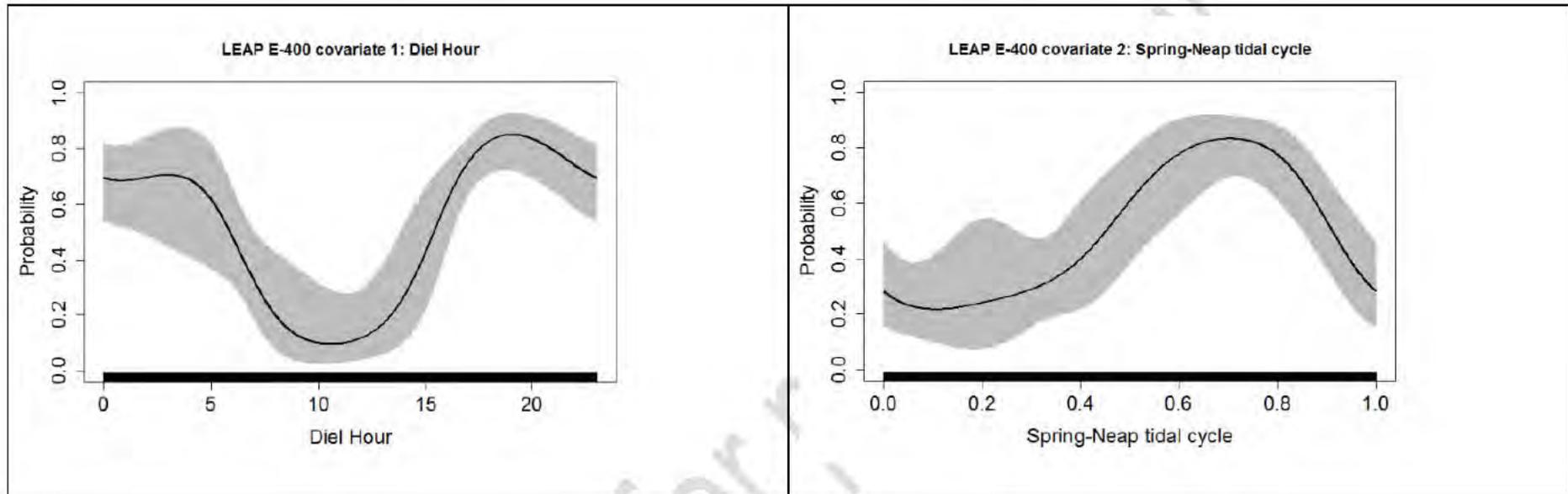


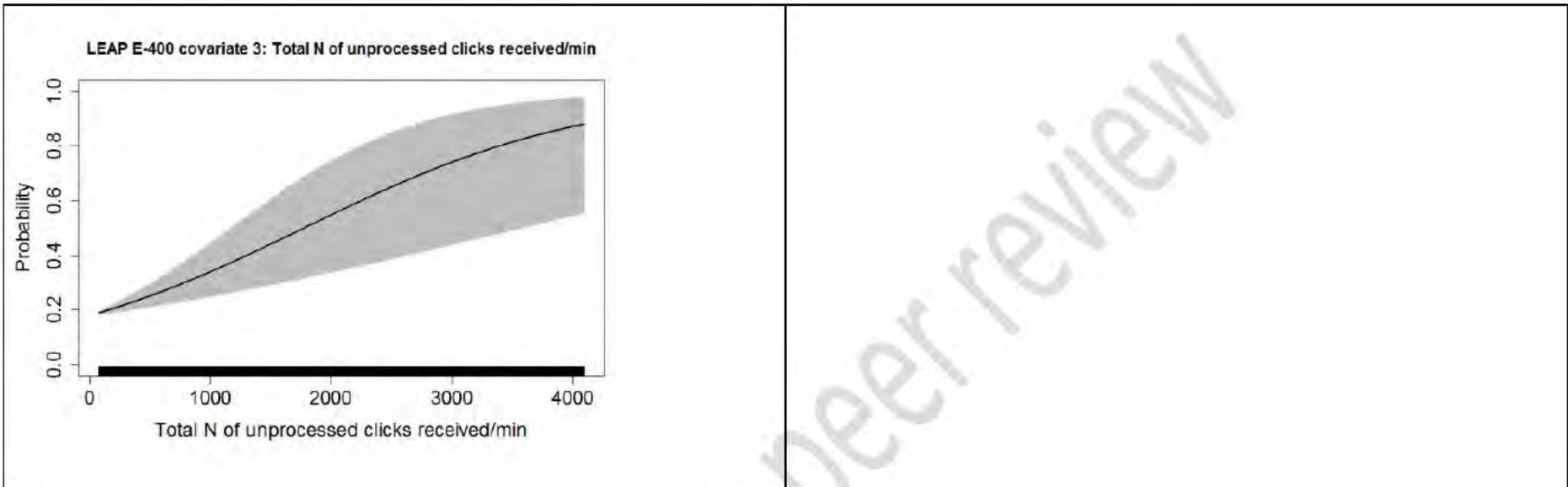
1795

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Model:	E-400																			
Model structure:	<pre> POD5<-geeglm(PPM ~ AvgHrBasisMat + SprNpBasisMat + Nall_m, family = binomial, corstr="independence", id=Panel, data=E400) </pre>																			
Confusion matrix:	<table border="1"> <tr> <td></td> <td></td> <td>Expected</td> <td></td> </tr> <tr> <td></td> <td></td> <td>Porpoise</td> <td>No porpoise</td> </tr> <tr> <td>Observed</td> <td>Porpoise</td> <td>74.7%</td> <td>22.4%</td> </tr> <tr> <td></td> <td>No porpoise</td> <td>25.3%</td> <td>77.6%</td> </tr> </table>						Expected				Porpoise	No porpoise	Observed	Porpoise	74.7%	22.4%		No porpoise	25.3%	77.6%
		Expected																		
		Porpoise	No porpoise																	
Observed	Porpoise	74.7%	22.4%																	
	No porpoise	25.3%	77.6%																	
AUC value:	0.8263694																			
Results of Wald's tests for all significant covariates for the final model:																				
Covariates (in descending order of significance)	Form	Degrees of Freedom	χ^2 score	P-value																
HOUR	Cyclic B-spline	4	25.635	$3.749 \cdot 10^{-5}$																
SpringNeap	Cyclic B-spline	4	17.091	0.0018557																
Nall_m	linear	1	14.680	0.0001274																

1796



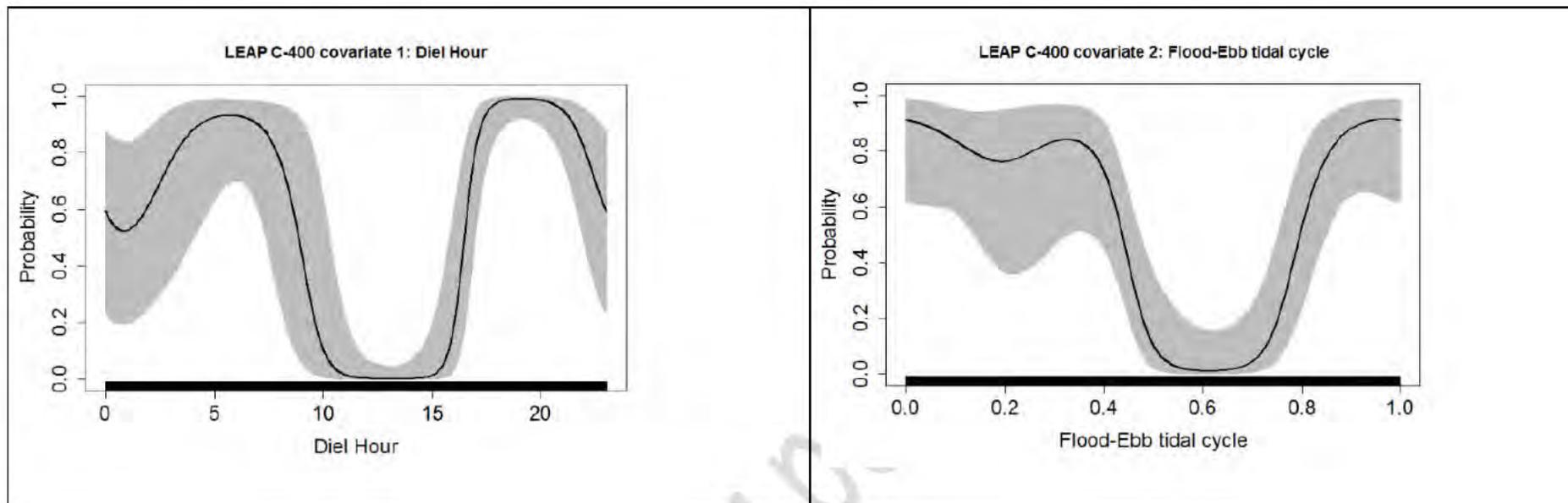


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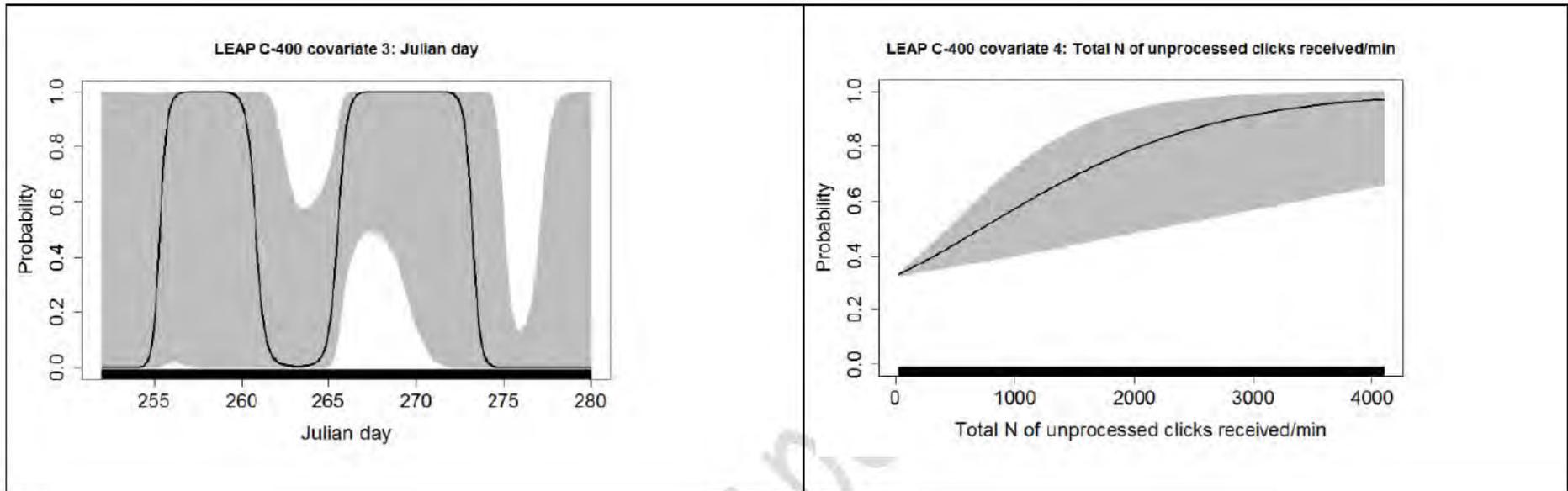
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Model:	C-400																			
Model structure:	<pre> POD5<-geeglm(PPM ~ AvgHrBasisMat + TideBasisMat + bs(JULDAY , knots=mean(JULDAY)) + Nall_m, family = binomial, corstr="independence", id=Panel, data=C400) </pre>																			
Confusion matrix:	<table border="1"> <tr> <td></td> <td></td> <td>Expected</td> <td></td> </tr> <tr> <td></td> <td></td> <td>Porpoise</td> <td>No porpoise</td> </tr> <tr> <td>Observed</td> <td>Porpoise</td> <td>89.3%</td> <td>10.8%</td> </tr> <tr> <td></td> <td>No porpoise</td> <td>10.7%</td> <td>89.2%</td> </tr> </table>						Expected				Porpoise	No porpoise	Observed	Porpoise	89.3%	10.8%		No porpoise	10.7%	89.2%
		Expected																		
		Porpoise	No porpoise																	
Observed	Porpoise	89.3%	10.8%																	
	No porpoise	10.7%	89.2%																	
AUC value:	0.943135																			
Results of Wald's tests for all significant covariates for the final model:																				
Covariates (in descending order of significance)	Form	Degrees of Freedom	χ^2 score	P-value																
HOUR	Cyclic B-spline	4	14.0194	0.007233																
HiLotide	Cyclic B-spline	4	13.7363	0.008186																
JULDAY	Cubic B-spline	4	15.3708	0.003991																
Nall_m	linear	1	8.5291	0.003495																

1799



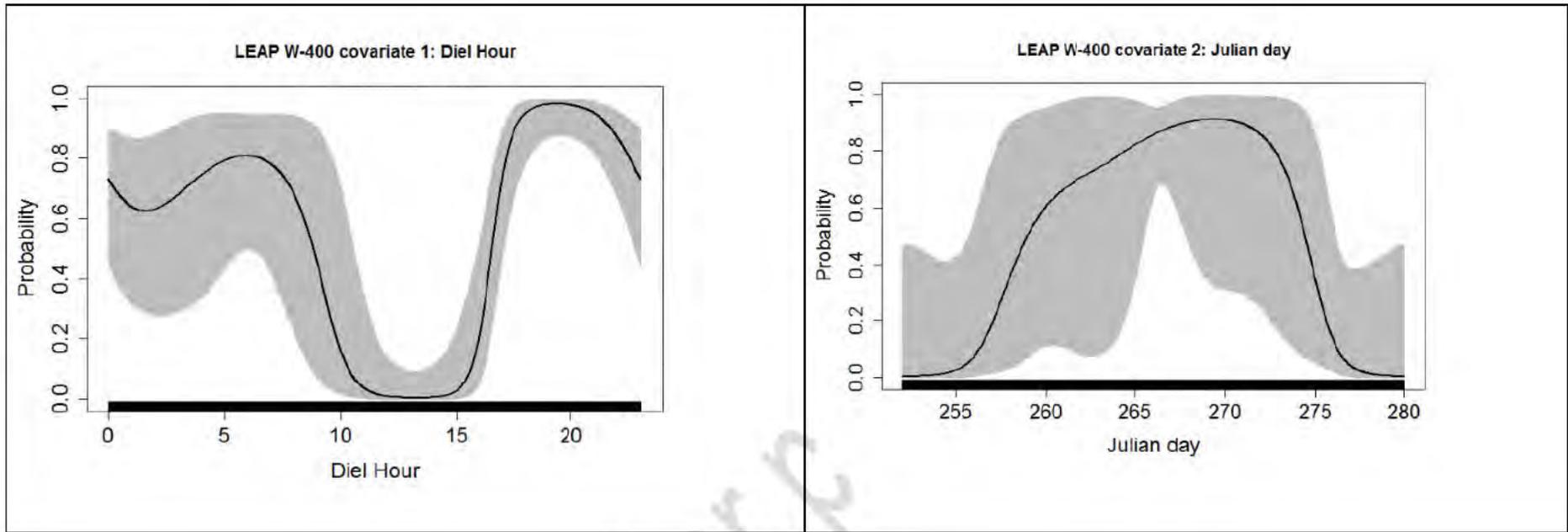
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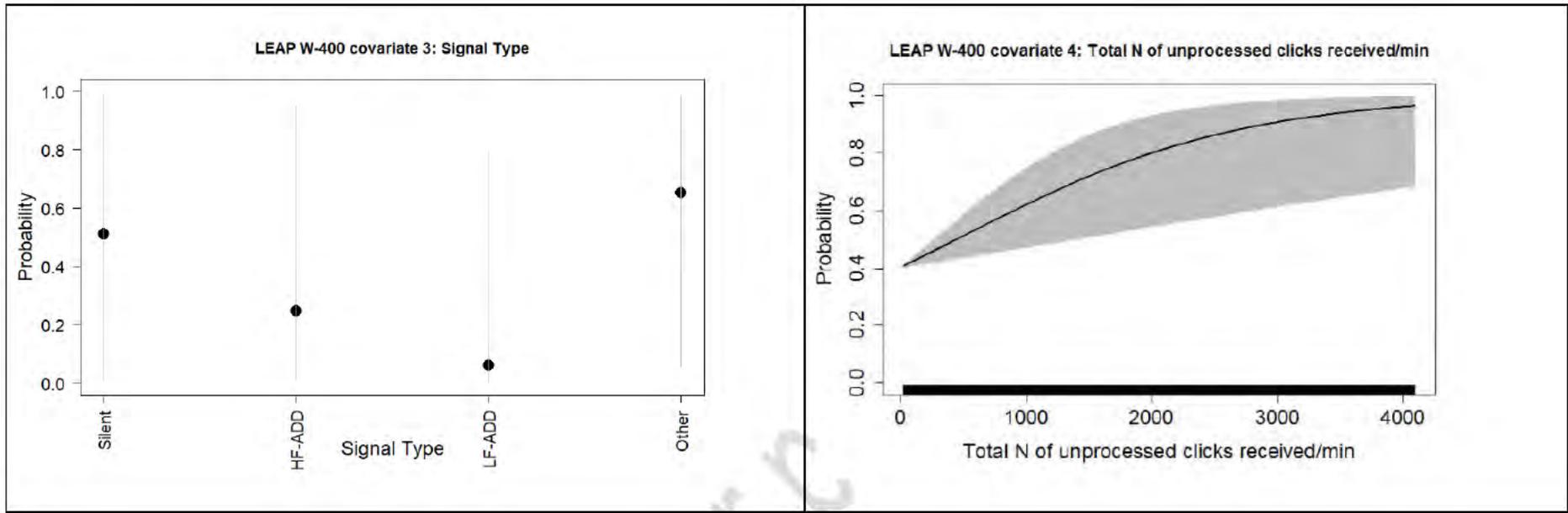
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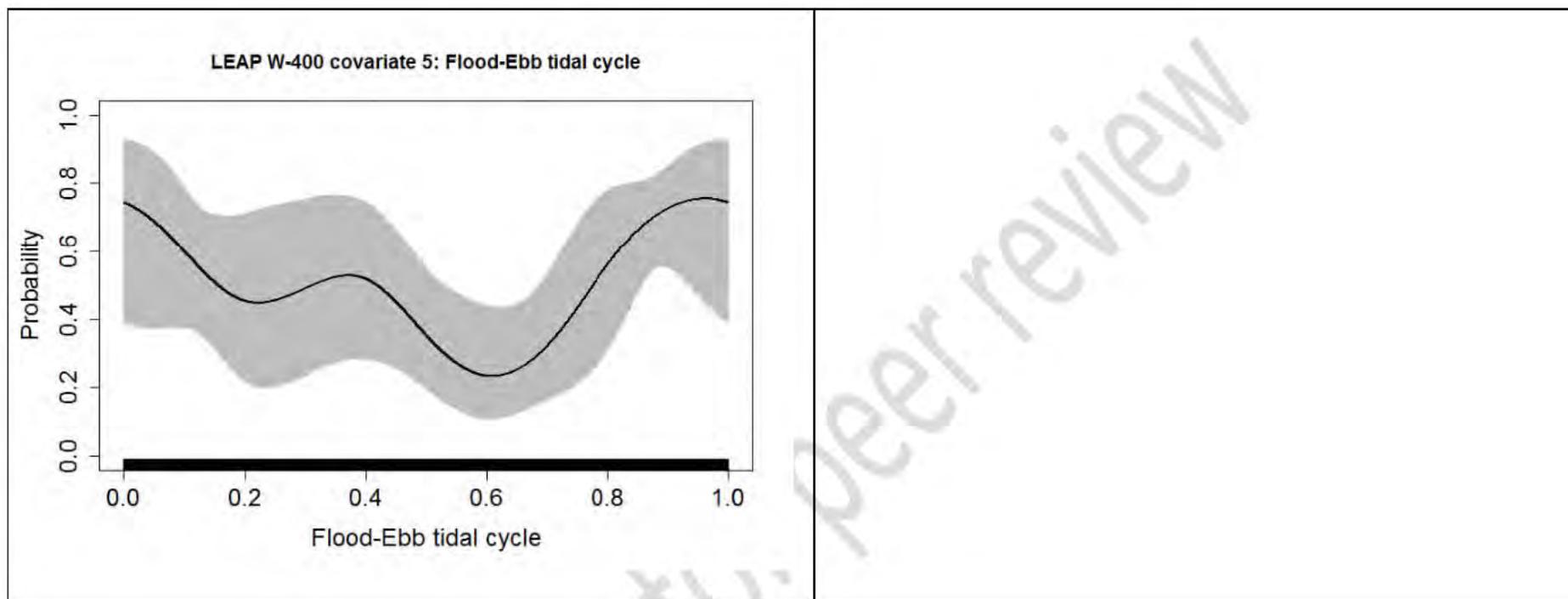
Model:	W-400																		
Model structure:	<code>POD5<-geeglm(PPM ~ AvgHrBasisMat + bs(JULDAY , knots=mean(JULDAY)) + as.factor(Signal_Type) + Nall_m + TideBasisMat, family = binomial, corstr="independence", id=Panel, data=W400)</code>																		
Confusion matrix:	<table border="1"> <thead> <tr> <th colspan="2"></th> <th colspan="2">Expected</th> </tr> <tr> <th colspan="2"></th> <th>Porpoise</th> <th>No porpoise</th> </tr> </thead> <tbody> <tr> <th rowspan="2">Observed</th> <th>Porpoise</th> <td>88.4%</td> <td>21.9%</td> </tr> <tr> <th>No porpoise</th> <td>11.6%</td> <td>78.1%</td> </tr> </tbody> </table>						Expected				Porpoise	No porpoise	Observed	Porpoise	88.4%	21.9%	No porpoise	11.6%	78.1%
		Expected																	
		Porpoise	No porpoise																
Observed	Porpoise	88.4%	21.9%																
	No porpoise	11.6%	78.1%																
AUC value:	0.9068351																		
Results of Wald's tests for all significant covariates for the final model:																			
Covariates (in descending order of significance)	Form	Degrees of Freedom	χ^2 score	P-value															
HOUR	Cyclic B-spline	4	21.8619	0.0002135															
JULDAY	Cubic B-spline	4	17.9475	0.0012636															
Signal_Type	Factor	3	13.8378	0.0031345															
Nall_m	Linear	1	7.2002	0.0072895															
HiLoTide	Cyclic B-spline	4	11.4568	0.0218828															



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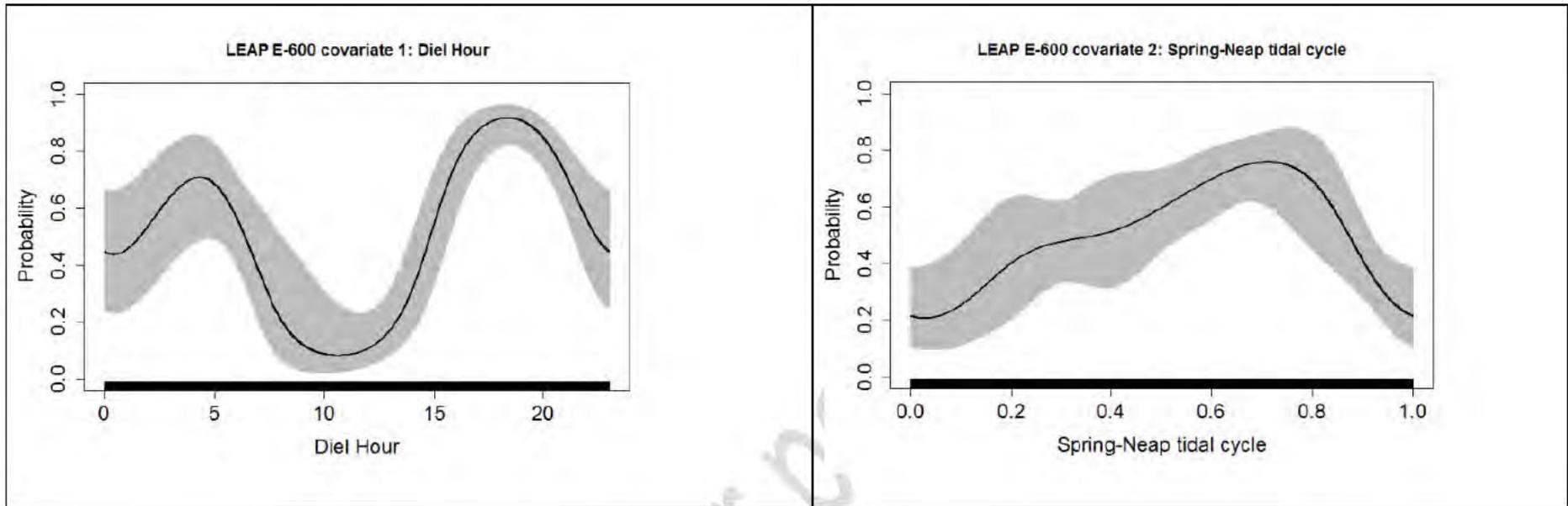


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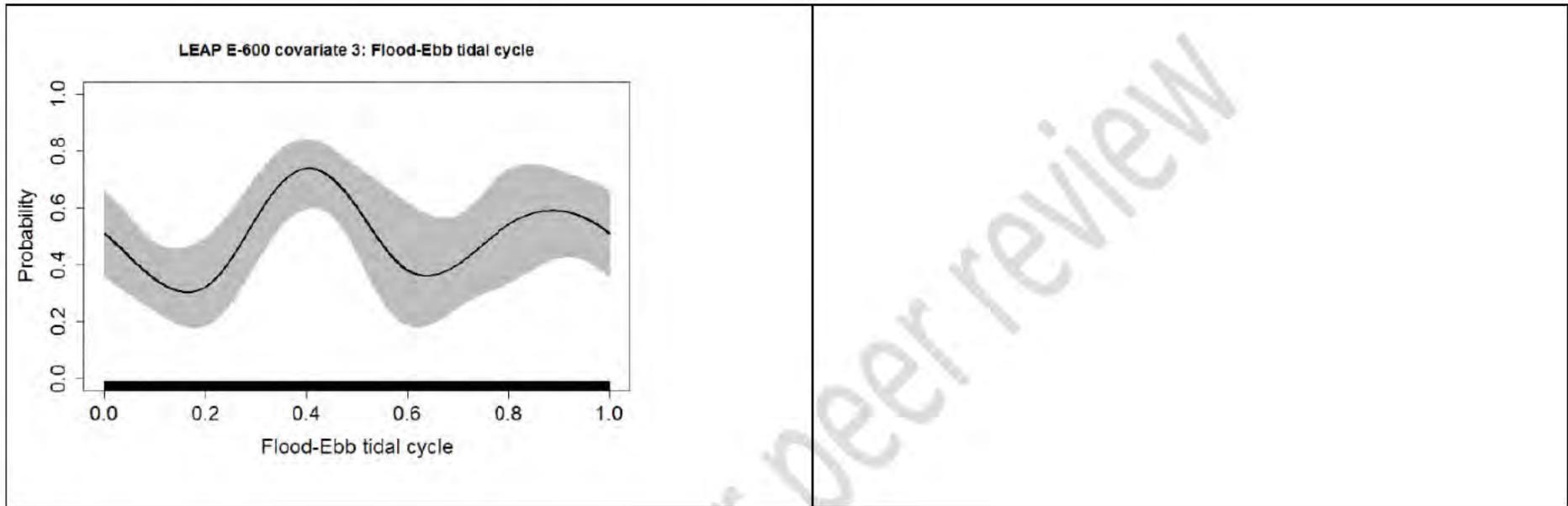


1802

Model:	E-600																						
Model structure:	<code>POD5<-geeglm(PPM ~ AvgHrBasisMat + bs(JULDAY , knots=mean(JULDAY)) + SprNpBasisMat + TideBasisMat, family = binomial, corstr="independence", id=Panel, data=E600)</code>																						
Confusion matrix:	<table border="1"> <thead> <tr> <th colspan="2"></th> <th colspan="2">Expected</th> </tr> <tr> <th colspan="2"></th> <th>Porpoise</th> <th>No porpoise</th> </tr> </thead> <tbody> <tr> <th rowspan="2">Observed</th> <th>Porpoise</th> <td>75.5%</td> <td>23.6%</td> </tr> <tr> <th>No porpoise</th> <td>24.5%</td> <td>76.4%</td> </tr> <tr> <th colspan="2"></th> <td></td> <td></td> </tr> </tbody> </table>						Expected				Porpoise	No porpoise	Observed	Porpoise	75.5%	23.6%	No porpoise	24.5%	76.4%				
		Expected																					
		Porpoise	No porpoise																				
Observed	Porpoise	75.5%	23.6%																				
	No porpoise	24.5%	76.4%																				
AUC value:	0.8365278																						
Results of Wald's tests for all significant covariates for the final model:																							
Covariates (in descending order of significance)	Form	Degrees of Freedom	χ^2 score	P-value																			
HOUR	Cyclic B-spline	4	34.277	$6.538 \cdot 10^{-7}$																			
SpringNeap	Cyclic B-spline	4	14.105	0.006967																			
HiLoTide	Cyclic B-spline	4	13.362	0.009636																			



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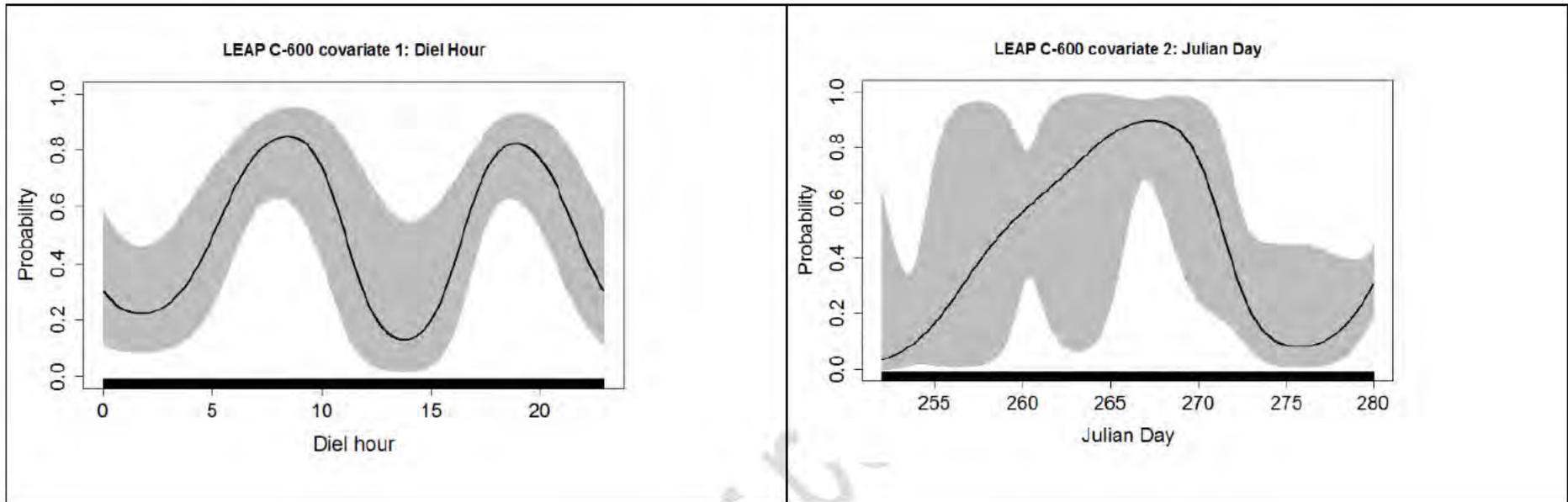


1804

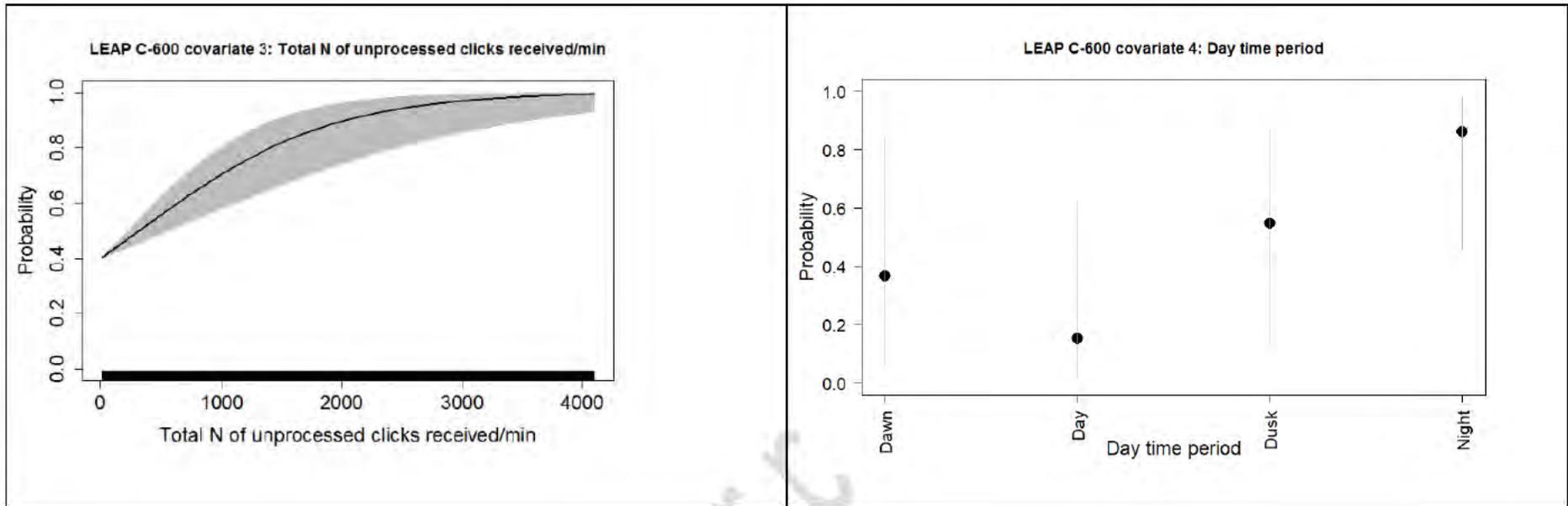
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Model:	C-600																			
Model structure:	<code>POD7<-geeglm(PPM ~ AvgHrBasisMat + bs(JULDAY , knots=mean(JULDAY)) + Nall_m + as.factor(DAYTIMENum), family = binomial, corstr="independence", id=Panel, data=C600)</code>																			
Confusion matrix:	<table border="1"> <tr> <td></td> <td></td> <td>Expected</td> <td></td> </tr> <tr> <td></td> <td></td> <td>Porpoise</td> <td>No porpoise</td> </tr> <tr> <td>Observed</td> <td>Porpoise</td> <td>77.0%</td> <td>15.6%</td> </tr> <tr> <td></td> <td>No porpoise</td> <td>23.0%</td> <td>84.4%</td> </tr> </table>						Expected				Porpoise	No porpoise	Observed	Porpoise	77.0%	15.6%		No porpoise	23.0%	84.4%
		Expected																		
		Porpoise	No porpoise																	
Observed	Porpoise	77.0%	15.6%																	
	No porpoise	23.0%	84.4%																	
AUC value:	0.8862971																			
Results of Wald's tests for all significant covariates for the final model:																				
Covariates (in descending order of significance)	Form	Degrees of Freedom	χ^2 score	P-value																
HOUR	Cyclic B-spline	4	33.592	$9.034 \cdot 10^{-7}$																
JULDAY	Cubic B-spline	4	32.976	$1.208 \cdot 10^{-6}$																
Nall_m	Linear	1	23.235	$1.434 \cdot 10^{-6}$																
DAYTIMENum	Factor	3	20.308	0.0001465																

1805



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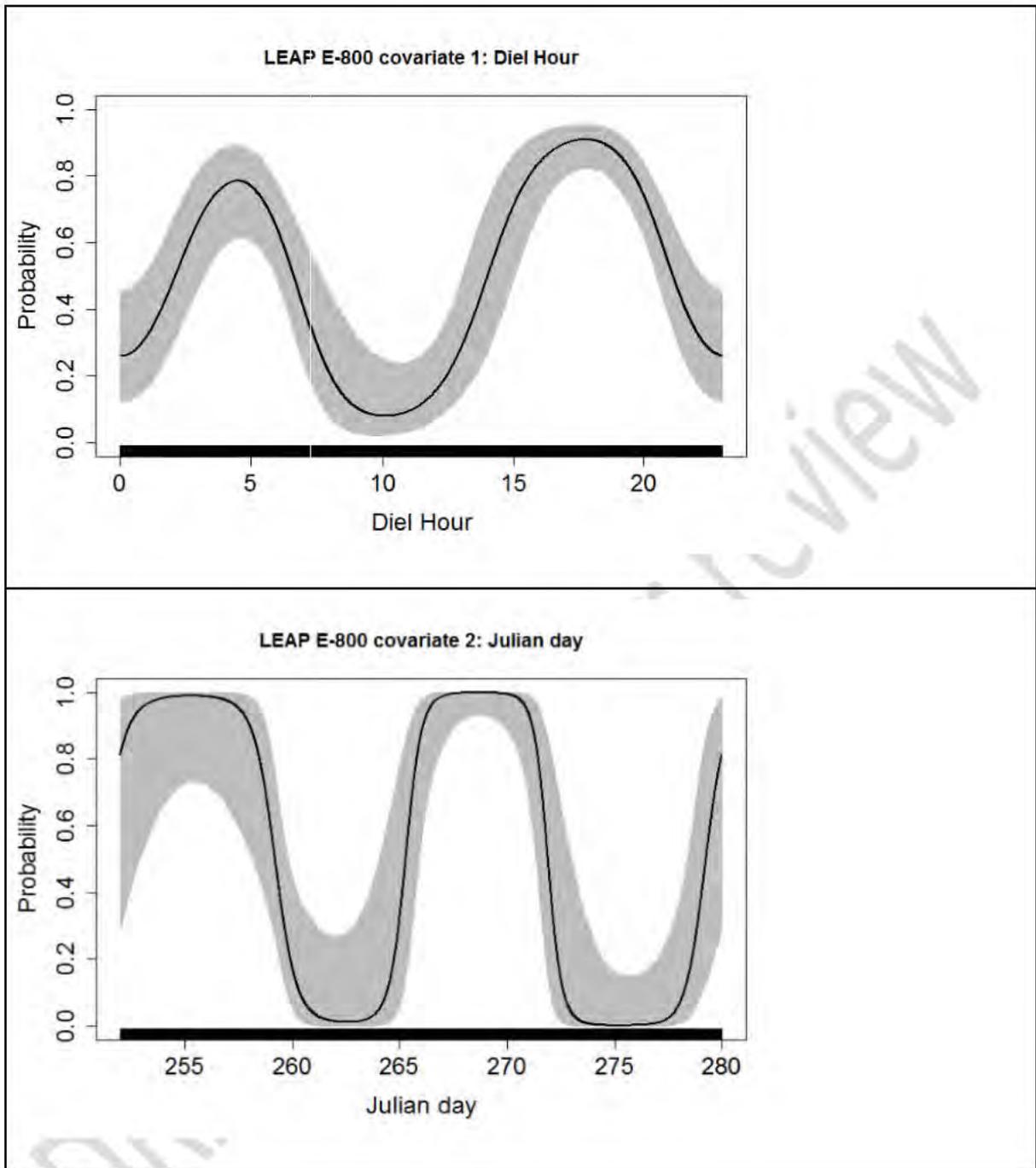


1806

DRAFT - for review

Model:	E-800																			
Model structure:	<pre> POD7<-geeglm(PPM ~ AvgHrBasisMat + bs(JULDAY , knots=mean(JULDAY)), family = binomial, corstr="independence", id=Panel, data=E800) </pre>																			
Confusion matrix:	<table border="1"> <tr> <td></td> <td></td> <td>Expected</td> <td></td> </tr> <tr> <td></td> <td></td> <td>Porpoise</td> <td>No porpoise</td> </tr> <tr> <td>Observed</td> <td>Porpoise</td> <td>80.2%</td> <td>25.6%</td> </tr> <tr> <td></td> <td>No porpoise</td> <td>19.8%</td> <td>74.4%</td> </tr> </table>						Expected				Porpoise	No porpoise	Observed	Porpoise	80.2%	25.6%		No porpoise	19.8%	74.4%
		Expected																		
		Porpoise	No porpoise																	
Observed	Porpoise	80.2%	25.6%																	
	No porpoise	19.8%	74.4%																	
AUC value:	0.841899																			
Results of Wald's tests for all significant covariates for the final model:																				
Covariates (in descending order of significance)	Form	Degrees of Freedom	χ^2 score	P-value																
HOUR	Cyclic B-spline	4	31.865	$2.039 \cdot 10^{-6}$																
JULDAY	Cubic B-spline	4	11.591	0.02067																

1807

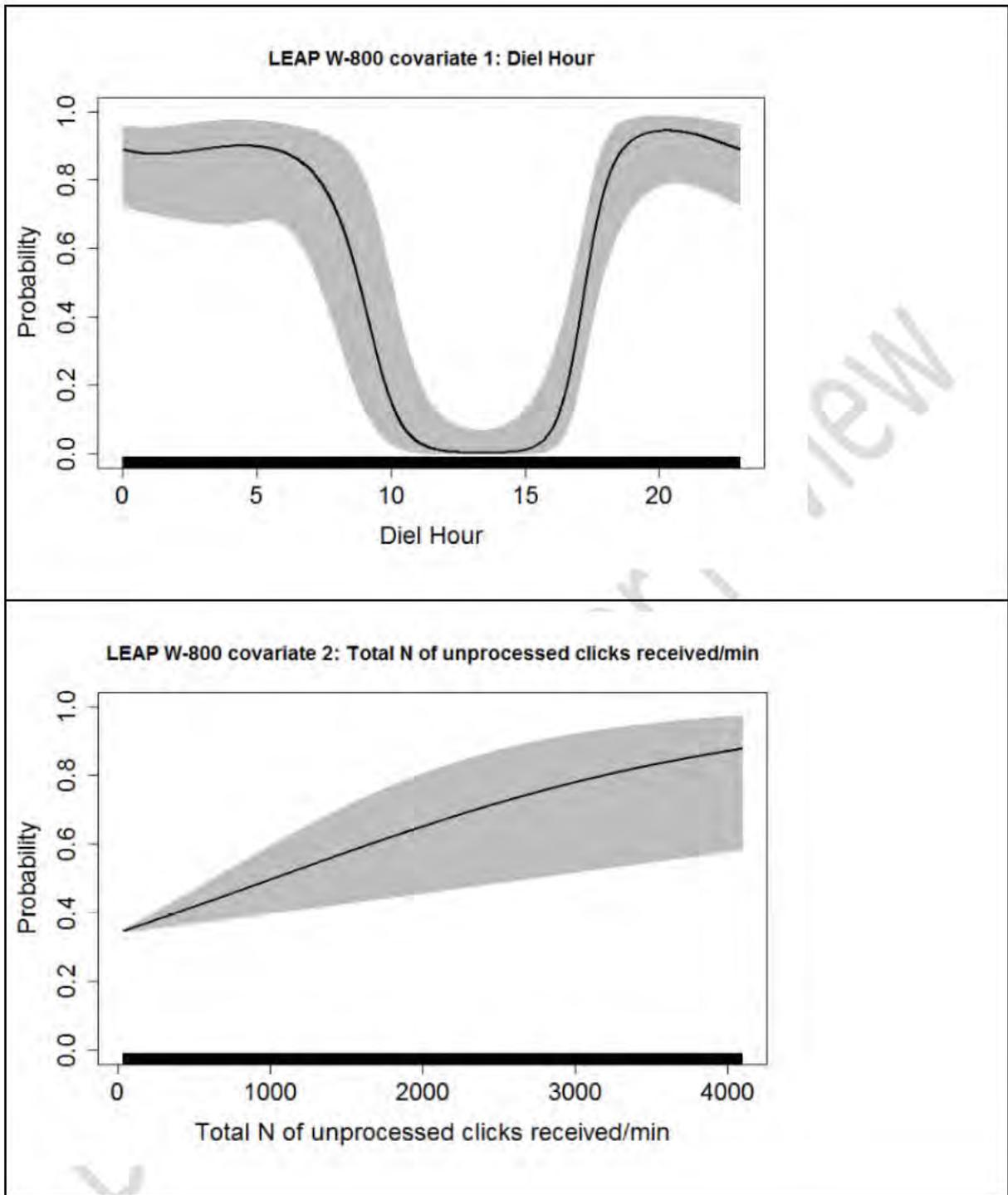


1808

1809

Model:	W-800																			
Model structure:	POD5<-geeglm(PPM ~ AvgHrBasisMat + Nall_m + as.factor(Signal_Type) , family = binomial, corstr="independence", id=Panel, data=W800)																			
Confusion matrix:	<table border="1"> <tr> <td></td> <td></td> <td>Expected</td> <td></td> </tr> <tr> <td></td> <td></td> <td>Porpoise</td> <td>No porpoise</td> </tr> <tr> <td>Observed</td> <td>Porpoise</td> <td>90.9%</td> <td>47.4%</td> </tr> <tr> <td></td> <td>No porpoise</td> <td>9.1%</td> <td>52.6%</td> </tr> </table>						Expected				Porpoise	No porpoise	Observed	Porpoise	90.9%	47.4%		No porpoise	9.1%	52.6%
		Expected																		
		Porpoise	No porpoise																	
Observed	Porpoise	90.9%	47.4%																	
	No porpoise	9.1%	52.6%																	
AUC value:	0.7830794																			
Results of Wald's tests for all significant covariates for the final model:																				
Covariates (in descending order of significance)	Form	Degrees of Freedom	χ^2 score	P-value																
HOUR	Cyclic B-spline	4	16.0326	0.002976																
Nall_m	linear	1	9.9207	0.001634																

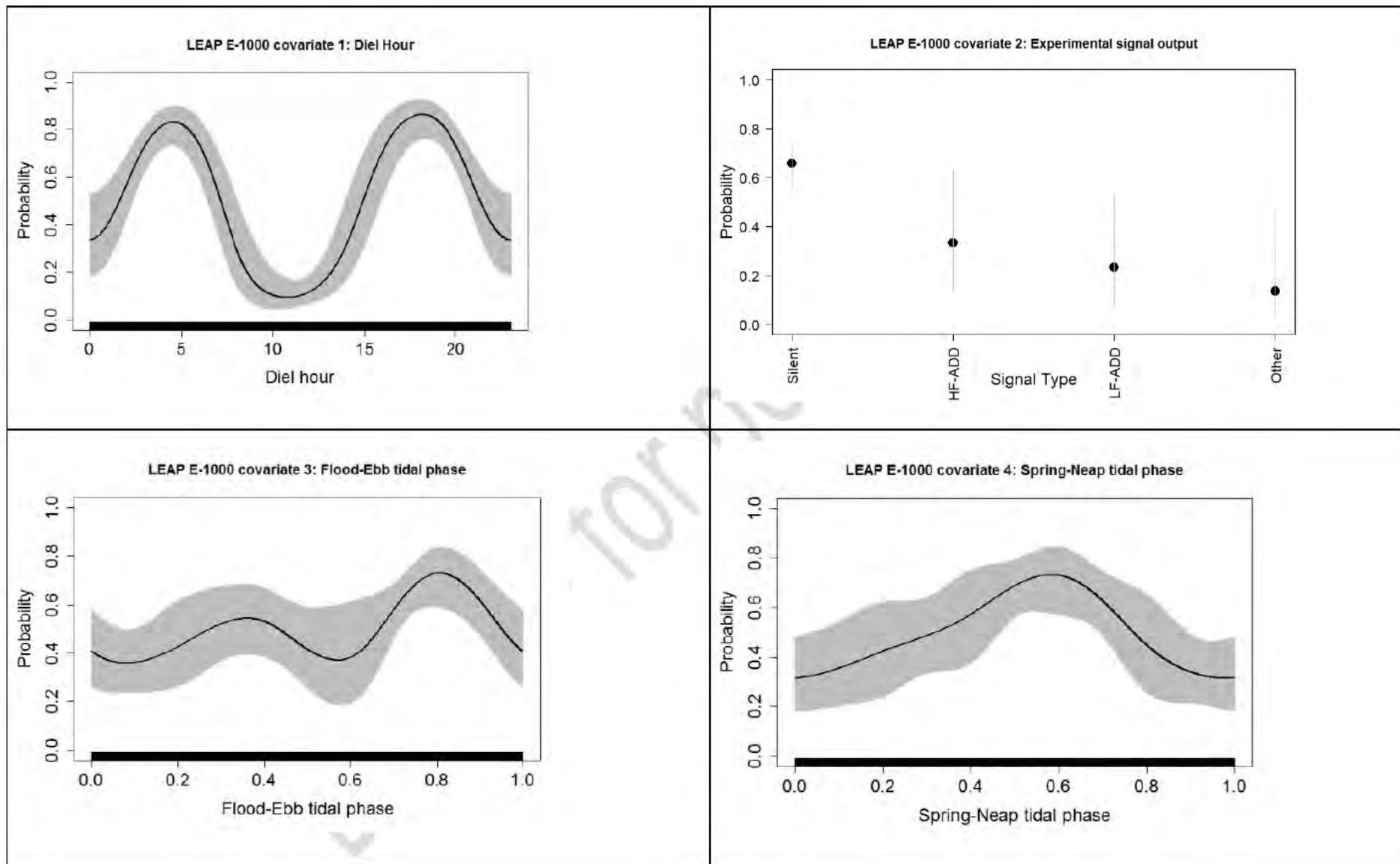
1810



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1812

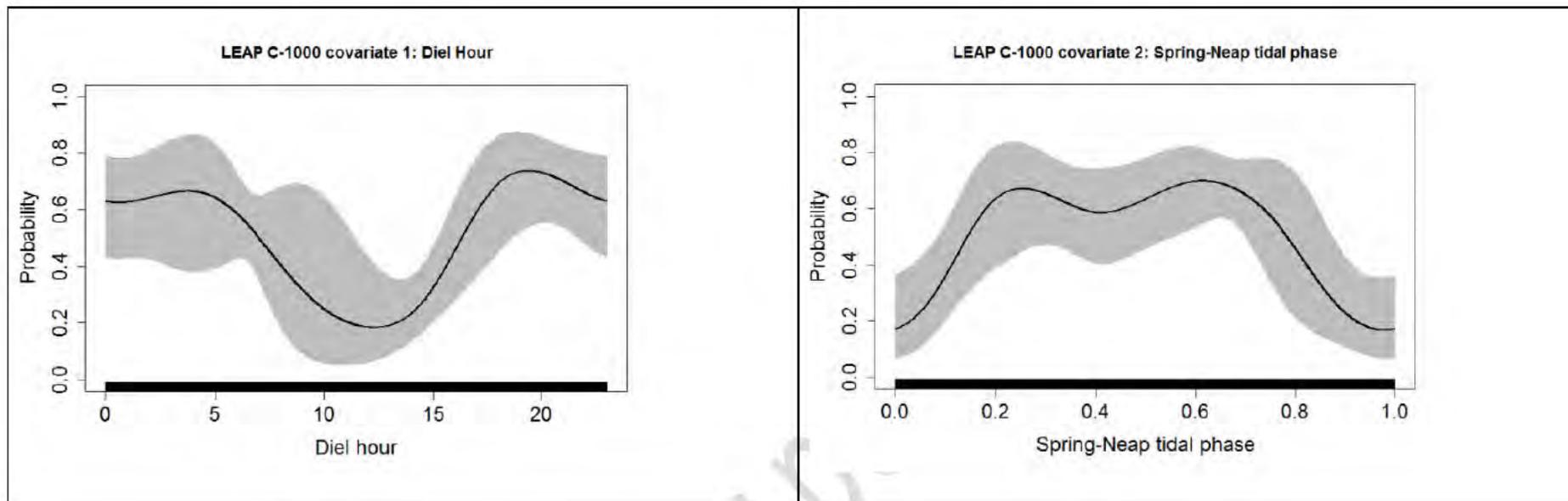
Model:	E-1000																		
Model structure:	<pre> POD4<-geeglm(PPM ~ AvgHrBasisMat + as.factor(Signal_Type)+ TideBasisMat + SprNpBasisMat, family = binomial, corstr="independence", id=Panel, data=E1000) </pre>																		
Confusion matrix:	<table border="1"> <thead> <tr> <th colspan="2"></th> <th colspan="2">Expected</th> </tr> <tr> <th colspan="2"></th> <th>Porpoise</th> <th>No porpoise</th> </tr> </thead> <tbody> <tr> <th rowspan="2">Observed</th> <th>Porpoise</th> <td>83.7%</td> <td>26.7%</td> </tr> <tr> <th>No porpoise</th> <td>16.3%</td> <td>73.3%</td> </tr> </tbody> </table>						Expected				Porpoise	No porpoise	Observed	Porpoise	83.7%	26.7%	No porpoise	16.3%	73.3%
		Expected																	
		Porpoise	No porpoise																
Observed	Porpoise	83.7%	26.7%																
	No porpoise	16.3%	73.3%																
AUC value:	0.8554172																		
Results of Wald's tests for all significant covariates for the final model:																			
Covariates (in descending order of significance)	Form	Degrees of Freedom	χ^2 score	P-value															
HOUR	Cyclic B-spline	4	76.904	$7.772 \cdot 10^{-16}$															
Signal_Type	Factor	1	25.397	$1.276 \cdot 10^{-5}$															
HiLoTide	Cyclic B-spline	4	16.484	0.002434															
SpringNeap	Cyclic B-spline	4	14.722	0.005313															



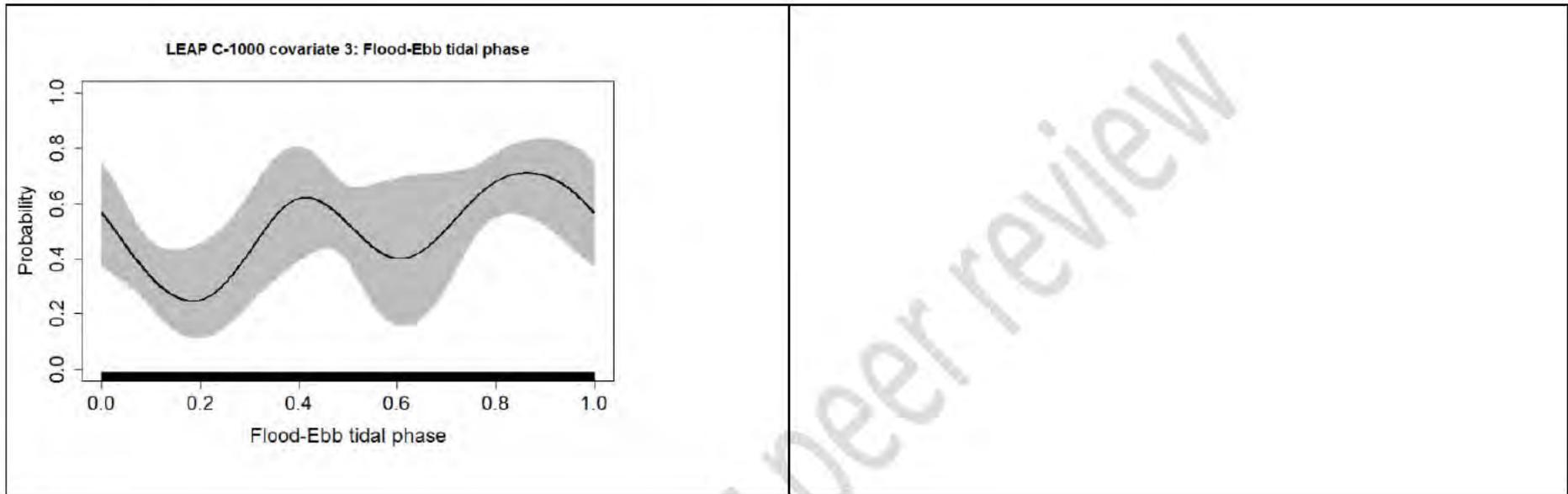
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Model:	C-1000																			
Model structure:	POD5<-geeglm(PPM ~ AvgHrBasisMat + SprNpBasisMat + TideBasisMat, family = binomial, corstr="independence", id=Panel, data=C1000)																			
Confusion matrix:	<table border="1"> <tr> <td></td> <td></td> <td>Expected</td> <td></td> </tr> <tr> <td></td> <td></td> <td>Porpoise</td> <td>No porpoise</td> </tr> <tr> <td>Observed</td> <td>Porpoise</td> <td>73.0%</td> <td>27.9%</td> </tr> <tr> <td></td> <td>No porpoise</td> <td>27.0%</td> <td>72.1%</td> </tr> </table>						Expected				Porpoise	No porpoise	Observed	Porpoise	73.0%	27.9%		No porpoise	27.0%	72.1%
		Expected																		
		Porpoise	No porpoise																	
Observed	Porpoise	73.0%	27.9%																	
	No porpoise	27.0%	72.1%																	
AUC value:	0.7798787																			
Results of Wald's tests for all significant covariates for the final model:																				
Covariates (in descending order of significance)	Form	Degrees of Freedom	χ^2 score	P-value																
HOUR	Cyclic B-spline	4	19.7491	0.0005597																
SpringNeap	Cyclic B-spline	4	18.3390	0.0010594																
HiLoTide	Cyclic B-spline	4	9.9507	0.0412661																

1815



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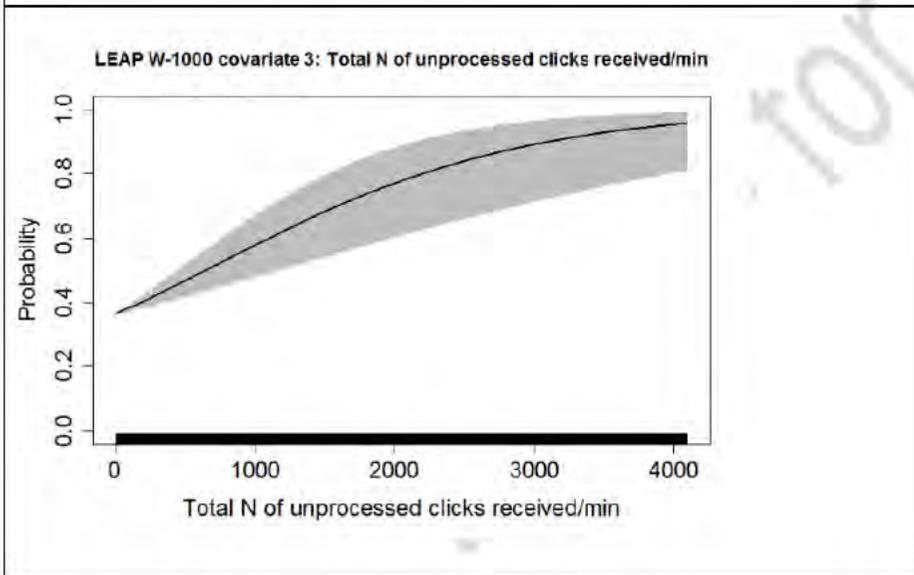
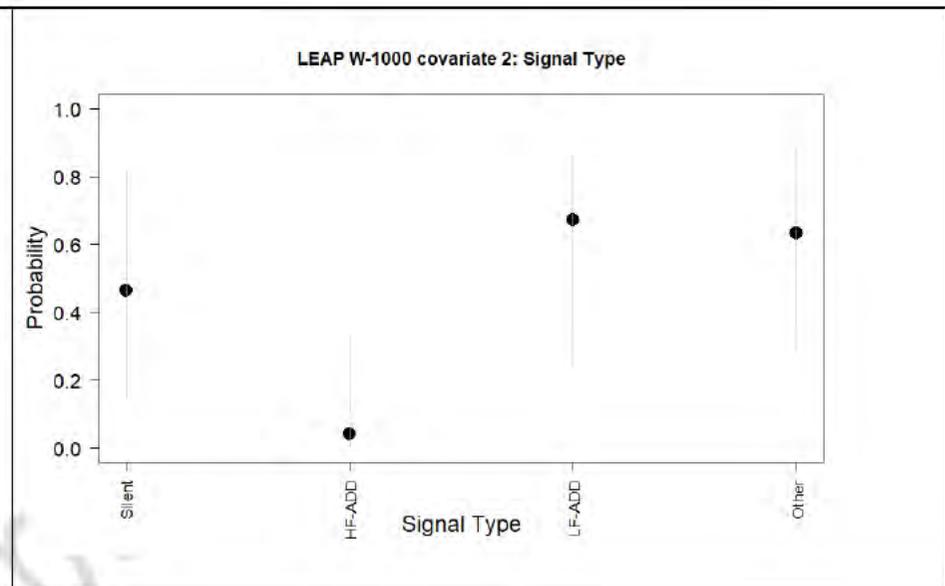
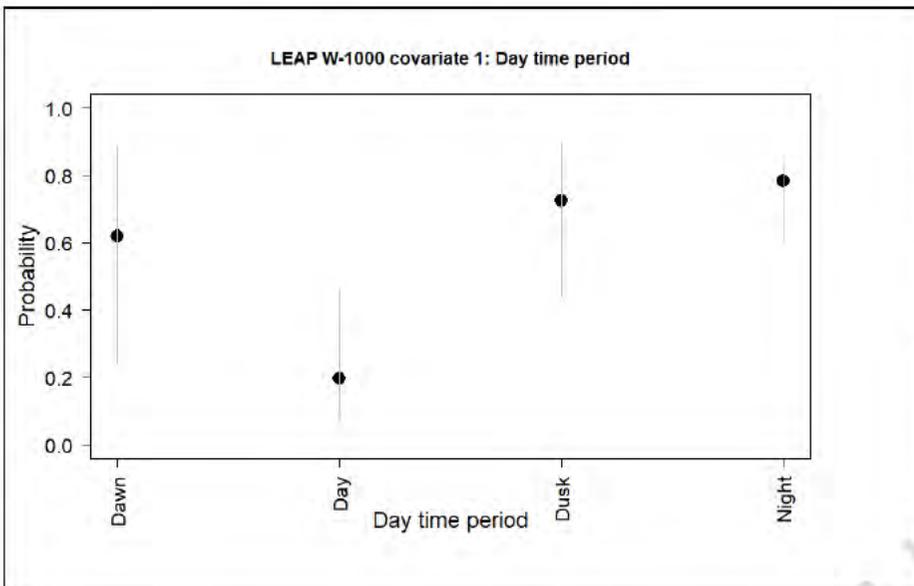


1816

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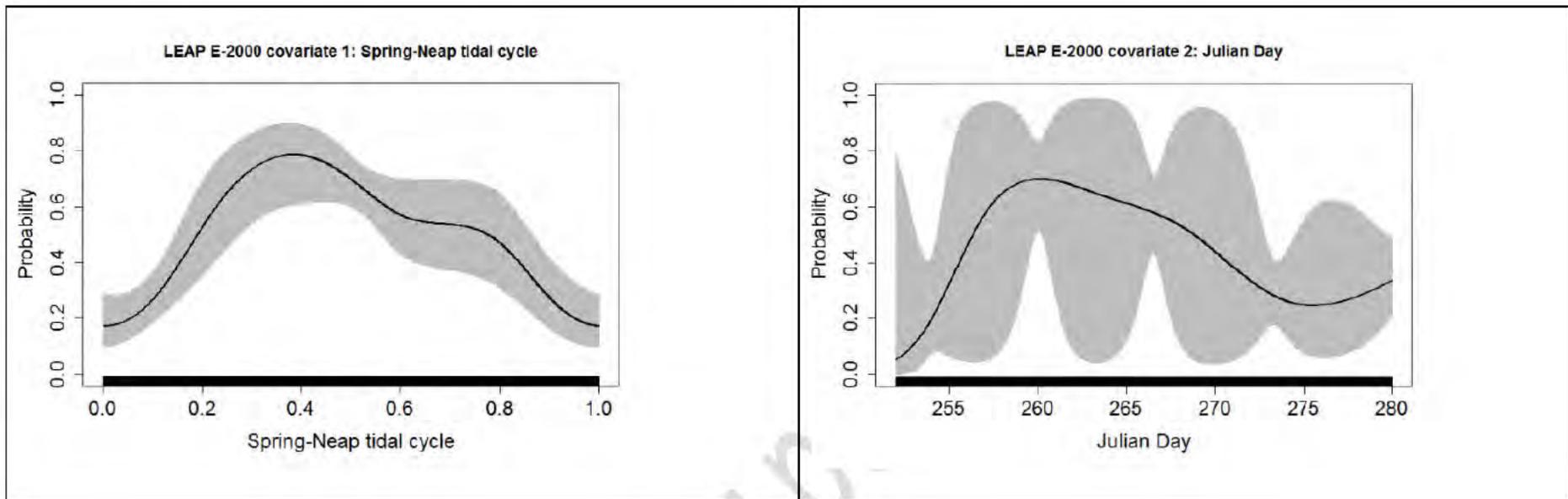
Model:	W-1000																			
Model structure:	<pre> POD5<-geeglm(PPM ~ as.factor(DAYTIMENum) + as.factor(Signal_Type) + Nall_m, family = binomial, corstr="independence", id=Panel, data=W1000) </pre>																			
Confusion matrix:	<table border="1"> <tr> <td></td> <td></td> <td>Expected</td> <td></td> </tr> <tr> <td></td> <td></td> <td>Porpoise</td> <td>No porpoise</td> </tr> <tr> <td>Observed</td> <td>Porpoise</td> <td>87.8%</td> <td>37.7%</td> </tr> <tr> <td></td> <td>No porpoise</td> <td>12.2%</td> <td>62.3%</td> </tr> </table>						Expected				Porpoise	No porpoise	Observed	Porpoise	87.8%	37.7%		No porpoise	12.2%	62.3%
		Expected																		
		Porpoise	No porpoise																	
Observed	Porpoise	87.8%	37.7%																	
	No porpoise	12.2%	62.3%																	
AUC value:	0.8144675																			
Results of Wald's tests for all significant covariates for the final model:																				
Covariates (in descending order of significance)	Form	Degrees of Freedom	χ^2 score	P-value																
DAYTIMENum	Factor	3	27.750	$4.099 \cdot 10^{-6}$																
Signal_Type	Factor	3	15.159	0.001685																
Nall_m	Linear	1	20.321	$6.547 \cdot 10^{-6}$																

1817

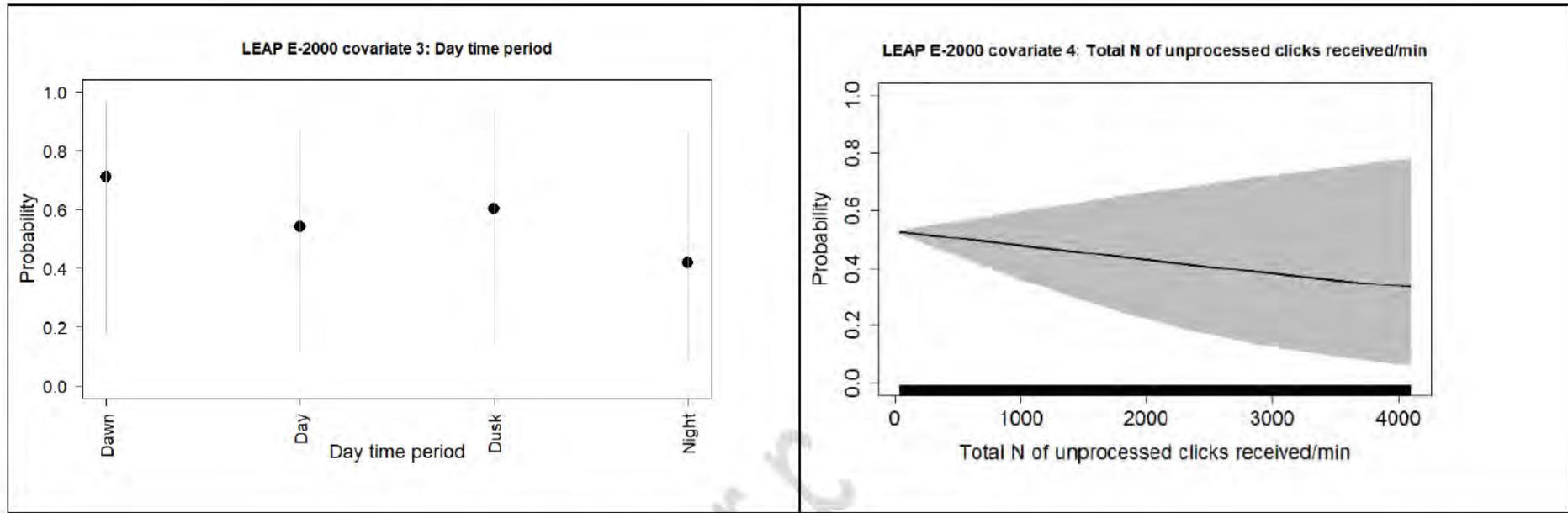


Model:	E-2000																			
Model structure:	<code>POD5<-geeglm(PPM ~ SprNpBasisMat + bs(JULDAY , knots=mean(JULDAY)) + as.factor(DAYTIMENum) + bs(Nall_m , knots=mean(Nall_m)), family = binomial, corstr="independence", id=Panel, data=E2000)</code>																			
Confusion matrix:	<table border="1"> <tr> <td></td> <td></td> <td>Expected</td> <td></td> </tr> <tr> <td></td> <td></td> <td>Porpoise</td> <td>No porpoise</td> </tr> <tr> <td>Observed</td> <td>Porpoise</td> <td>75.5%</td> <td>32.1%</td> </tr> <tr> <td></td> <td>No porpoise</td> <td>24.5%</td> <td>67.9%</td> </tr> </table>						Expected				Porpoise	No porpoise	Observed	Porpoise	75.5%	32.1%		No porpoise	24.5%	67.9%
		Expected																		
		Porpoise	No porpoise																	
Observed	Porpoise	75.5%	32.1%																	
	No porpoise	24.5%	67.9%																	
AUC value:	0.7766977																			
Results of Wald's tests for all significant covariates for the final model:																				
Covariates (in descending order of significance)	Form	Degrees of Freedom	χ^2 score	P-value																
SpringNeap	Cyclic B-spline	4	37.671	$1.310 \cdot 10^{-7}$																
JULDAY	Cubic B-spline	4	18.033	0.001216																
DAYTIMENum	Factor	3	14.029	0.002866																
Nall_m	Cubic B-spline	4	32.284	$1.674 \cdot 10^{-6}$																

1819



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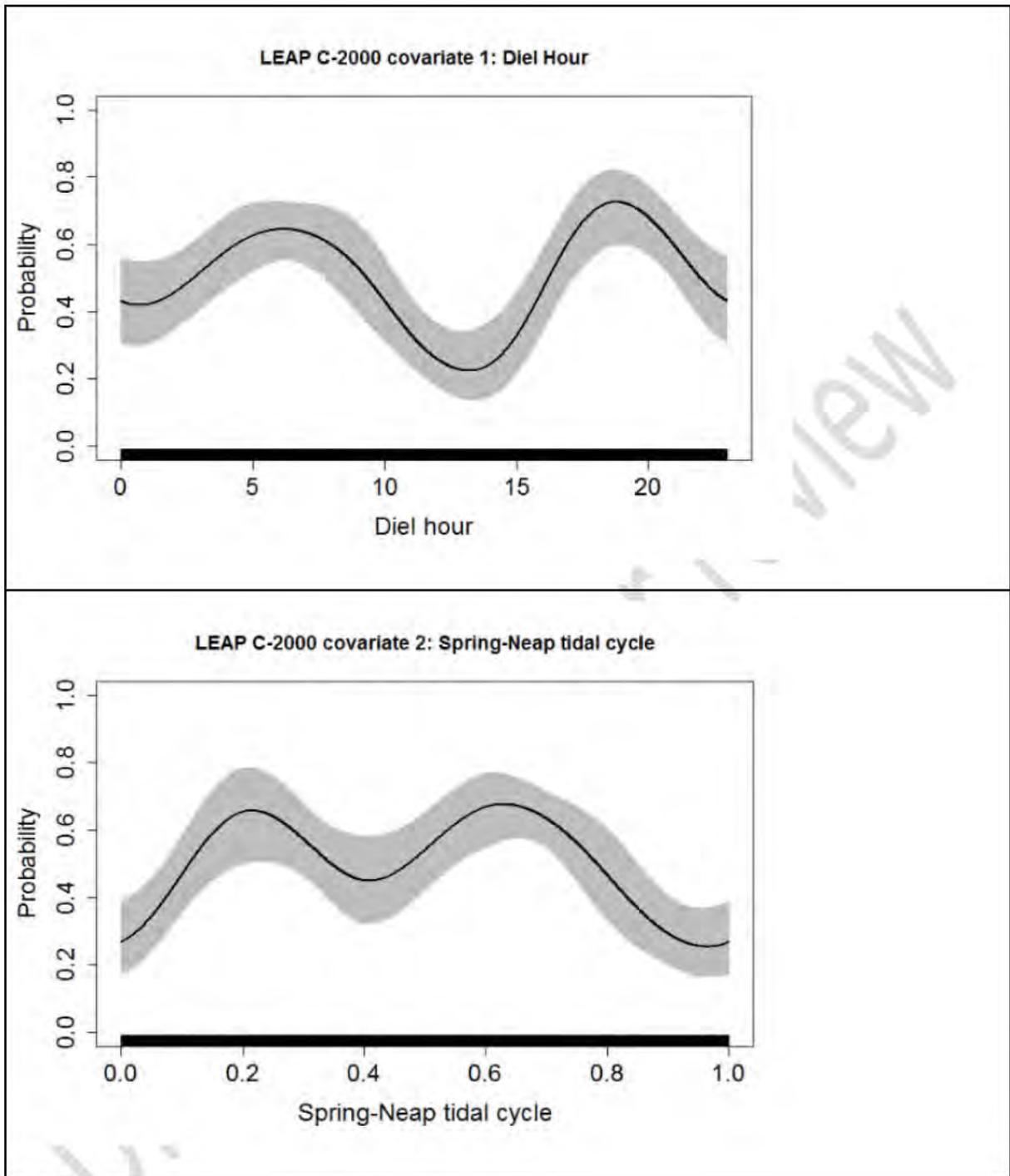


1820

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Model:	C-2000																		
Model structure:	<code>POD5<-geeglm(PPM ~ bs(Nall_m , knots=mean(Nall_m)) + as.factor(DAYTIMENum) + AvgHrBasisMat + SprNpBasisMat, family = binomial, corstr="independence", id=Panel, data=C2000)</code>																		
Confusion matrix:	<table border="1"> <thead> <tr> <th colspan="2"></th> <th colspan="2">Expected</th> </tr> <tr> <th colspan="2"></th> <th>Porpoise</th> <th>No porpoise</th> </tr> </thead> <tbody> <tr> <th rowspan="2">Observed</th> <th>Porpoise</th> <td>74.9%</td> <td>32.2%</td> </tr> <tr> <th>No porpoise</th> <td>25.1%</td> <td>67.8%</td> </tr> </tbody> </table>						Expected				Porpoise	No porpoise	Observed	Porpoise	74.9%	32.2%	No porpoise	25.1%	67.8%
		Expected																	
		Porpoise	No porpoise																
Observed	Porpoise	74.9%	32.2%																
	No porpoise	25.1%	67.8%																
AUC value:	0.7749851																		
Results of Wald's tests for all significant covariates for the final model:																			
Covariates (in descending order of significance)	Form	Degrees of Freedom	χ^2 score	P-value															
HOUR	Cyclic B-spline	4	22.842	0.0001362															
SpringNeap	Cyclic B-spline	4	19.751	0.0005593															

1821

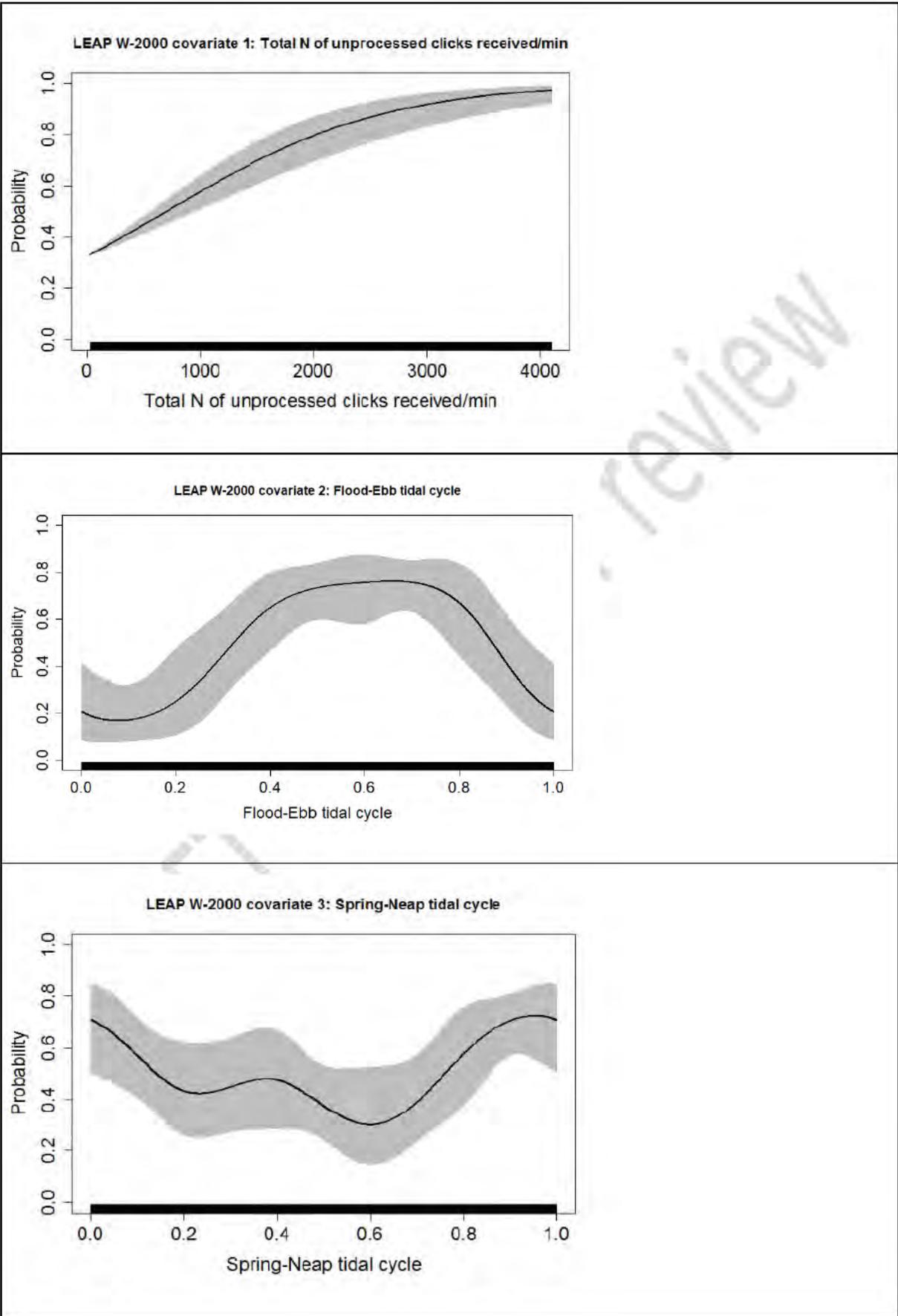


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1823

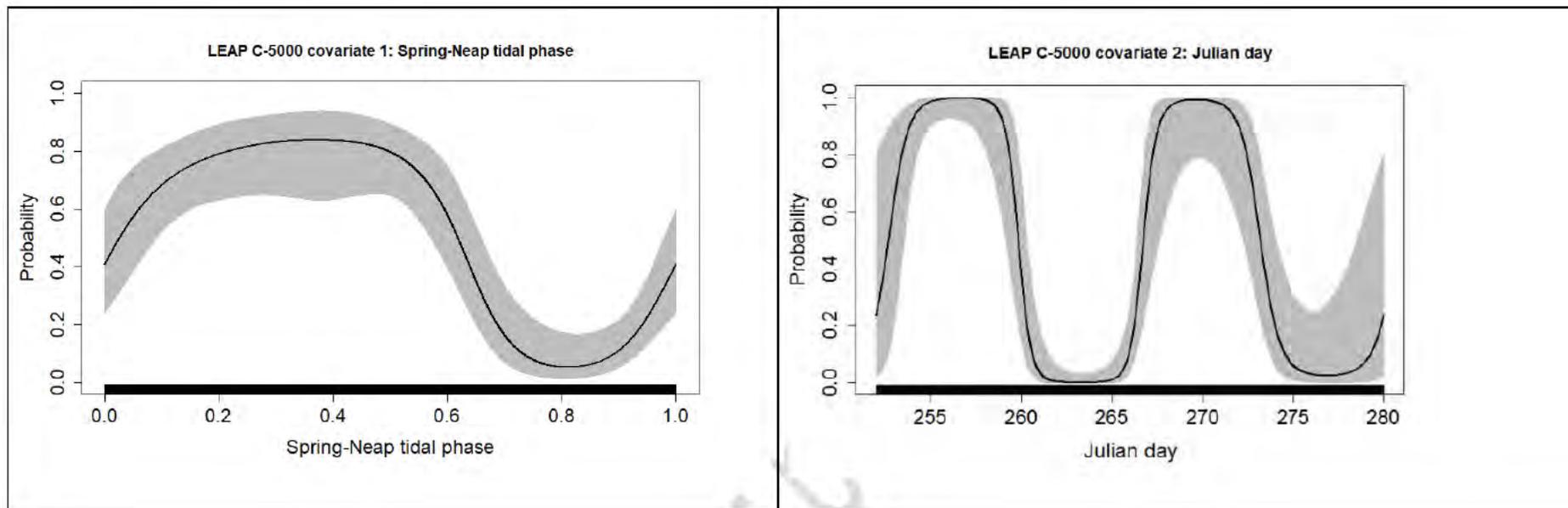
Model:	W-2000																			
Model structure:	POD5<-geeglm(PPM ~ Nall_m + TideBasisMat + SprNpBasisMat, family = binomial, corstr="independence", id=Panel, data=W2000)																			
Confusion matrix:	<table border="1"> <tr> <td></td> <td></td> <td>Expected</td> <td></td> </tr> <tr> <td></td> <td></td> <td>Porpoise</td> <td>No porpoise</td> </tr> <tr> <td>Observed</td> <td>Porpoise</td> <td>88.5%</td> <td>46.9%</td> </tr> <tr> <td></td> <td>No porpoise</td> <td>11.5%</td> <td>53.1%</td> </tr> </table>						Expected				Porpoise	No porpoise	Observed	Porpoise	88.5%	46.9%		No porpoise	11.5%	53.1%
		Expected																		
		Porpoise	No porpoise																	
Observed	Porpoise	88.5%	46.9%																	
	No porpoise	11.5%	53.1%																	
AUC value:	0.7838515																			
Results of Wald's tests for all significant covariates for the final model:																				
Covariates (in descending order of significance)	Form	Degrees of Freedom	χ^2 score	P-value																
Nall_m	Linear	1	83.446	<2.2·10 ⁻¹⁶																
HiLoTide	Cyclic B-spline	4	22.245	0.0001791																
SpringNeap	Cyclic B-spline	4	10.022	0.0400520																

1824

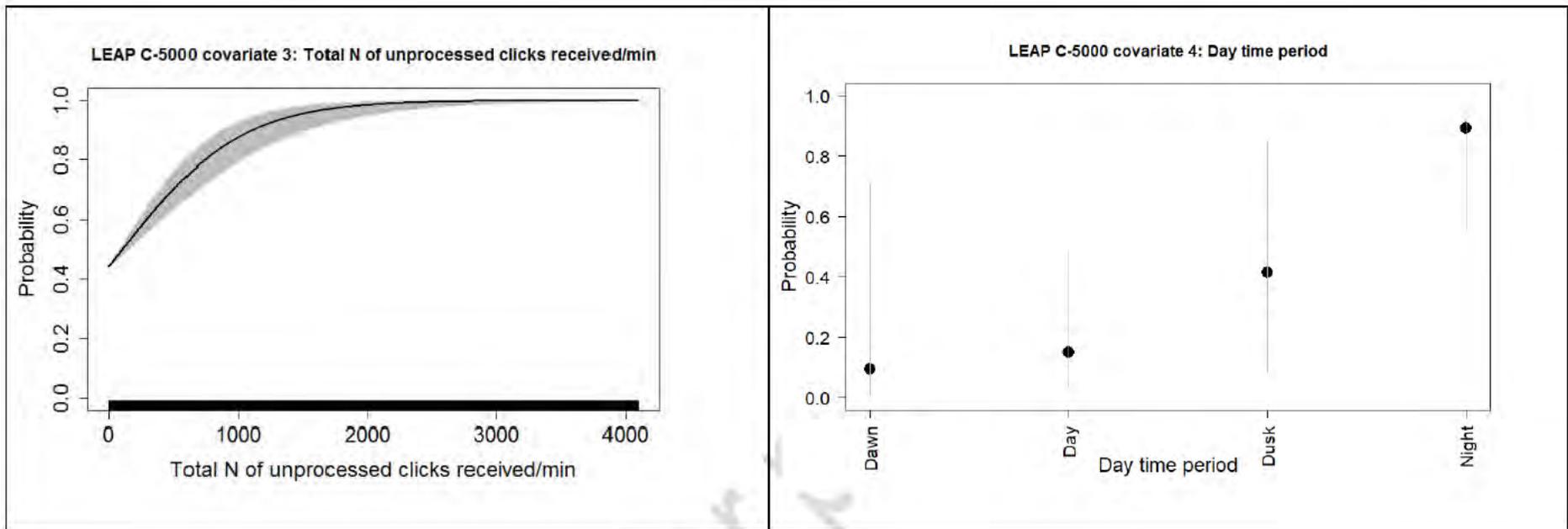


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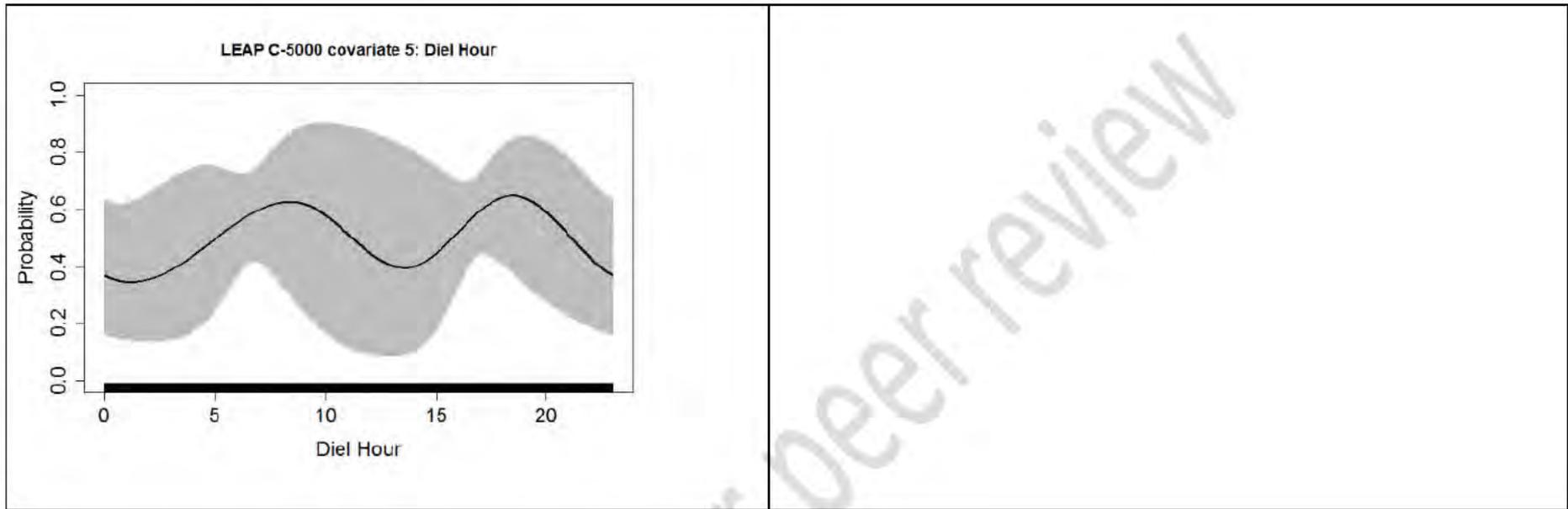
Model:	C-5000																			
Model structure:	<pre> POD5<-geeglm(PPM ~ SprNpBasisMat + bs(JULDAY , knots=mean(JULDAY)) + Nall_m + as.factor(DAYTIMENum) + AvgHrBasisMat, family = binomial, corstr="independence", id=Panel, data=C5000) </pre>																			
Confusion matrix:	<table border="1"> <tr> <td></td> <td></td> <td>Expected</td> <td></td> </tr> <tr> <td></td> <td></td> <td>Porpoise</td> <td>No porpoise</td> </tr> <tr> <td>Observed</td> <td>Porpoise</td> <td>80.1%</td> <td>15.5%</td> </tr> <tr> <td></td> <td>No porpoise</td> <td>19.9%</td> <td>84.5%</td> </tr> </table>						Expected				Porpoise	No porpoise	Observed	Porpoise	80.1%	15.5%		No porpoise	19.9%	84.5%
		Expected																		
		Porpoise	No porpoise																	
Observed	Porpoise	80.1%	15.5%																	
	No porpoise	19.9%	84.5%																	
AUC value:	0.8861703																			
Results of Wald's tests for all significant covariates for the final model:																				
Covariates (in descending order of significance)	Form	Degrees of Freedom	χ^2 score	P-value																
SpringNeap	Cyclic B-spline	4	14.806	0.005121																
JULDAY	Cubic B-spline	4	15.829	0.003036																
Nall_m	Linear	1	49.829	$1.678 \cdot 10^{-12}$																
DAYTIMENum	Factor	3	40.503	$8.335 \cdot 10^{-9}$																
HOUR	Cyclic B-spline	4	12.875	$3.291 \cdot 10^{-8}$																



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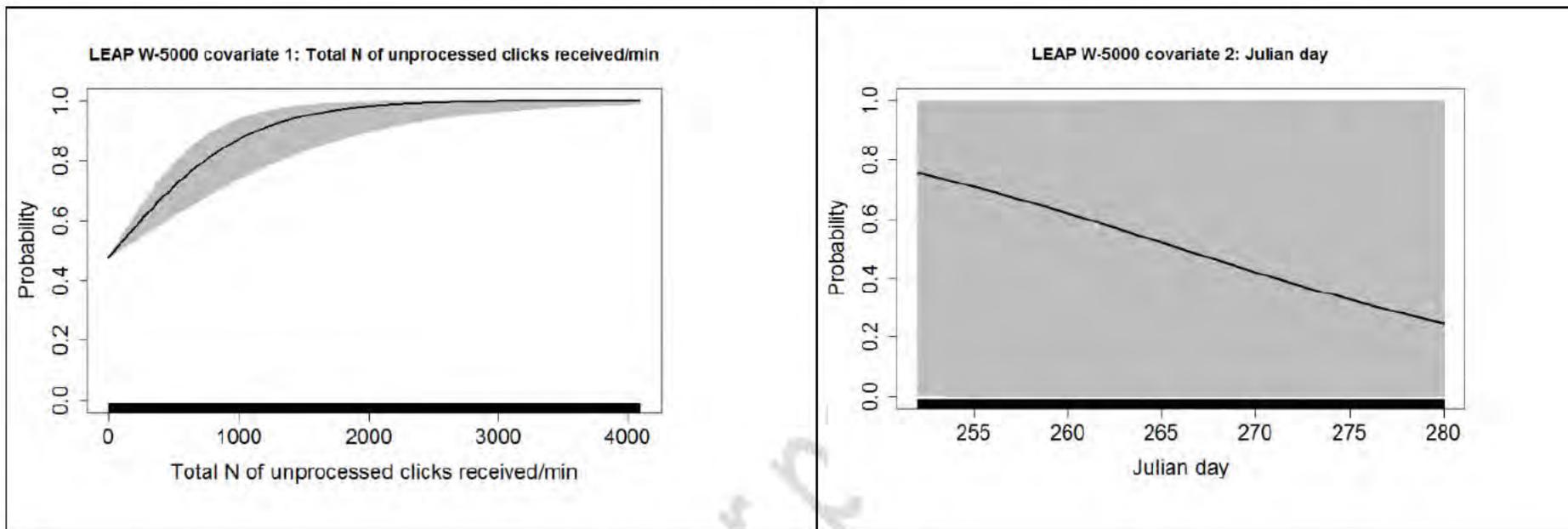


1827

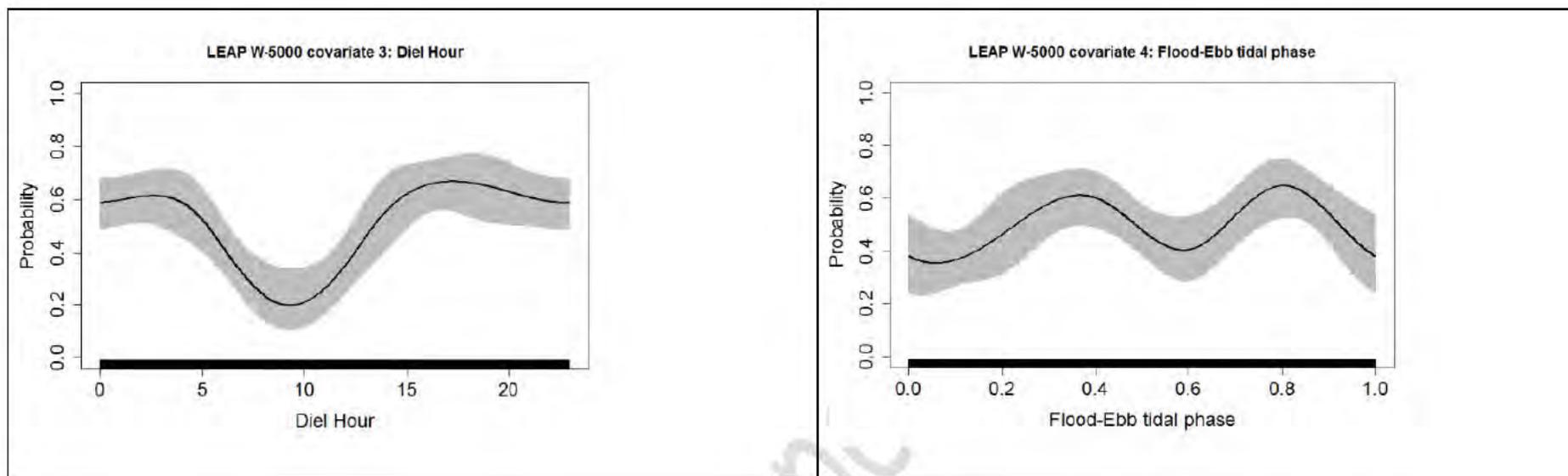
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Model:	W-5000																			
Model structure:	POD5<-geeglm(PPM ~ Nall_m + JULDAY + AvgHrBasisMat + TideBasisMat, family = binomial, corstr="independence", id=Panel, data=W5000)																			
Confusion matrix:	<table border="1"> <tr> <td></td> <td></td> <td>Expected</td> <td></td> </tr> <tr> <td></td> <td></td> <td>Porpoise</td> <td>No porpoise</td> </tr> <tr> <td>Observed</td> <td>Porpoise</td> <td>58.8%</td> <td>13.2%</td> </tr> <tr> <td></td> <td>No porpoise</td> <td>41.2%</td> <td>86.6%</td> </tr> </table>						Expected				Porpoise	No porpoise	Observed	Porpoise	58.8%	13.2%		No porpoise	41.2%	86.6%
		Expected																		
		Porpoise	No porpoise																	
Observed	Porpoise	58.8%	13.2%																	
	No porpoise	41.2%	86.6%																	
AUC value:	0.7942572																			
Results of Wald's tests for all significant covariates for the final model:																				
Covariates (in descending order of significance)	Form	Degrees of Freedom	χ^2 score	P-value																
Nall_m	Linear	1	26.5280	$2.597 \cdot 10^{-7}$																
JULDAY	Linear	1	30.7183	$2.983 \cdot 10^{-8}$																
HOUR	Cyclic B-spline	4	16.7938	0.00212																
HiLoTide	Cyclic B-spline	4	9.6231	0.04728																

1828



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1829

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