From:	Sandra Gray
To:	[redacted]
Cc:	s.gray@sarf.org.uk
Subject:	RE: Evaluation of SARF112
Date:	04 April 2018 18:21:22
Attachments:	image001.jpg LEAP report _FINALDRAFT - March2018.PDF SARF Final Report Evaluation Form - Directors.doc

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Thanks [redacted]

Please now find attached the draft final report together with the evaluation form that requires completion.

Please use referee [redacted] when completing the form.

Look forward to hearing from you in due course.

Kind regards
Sandra
SARF

From: [redacted]
Sent: 04 April 2018 16:55
To: 'Sandra Gray' <s.gray@sarf.org.uk>
Subject: RE: Evaluation of SARF112

Of course Sandra.
[redacted]

From: Sandra Gray [mailto:s.gray@sarf.org.uk]
Sent: 04 April 2018 12:26
To: [redacted]
Cc: s.gray@sarf.org.uk
Subject: Evaluation of SARF112

Dear [redacted]

We are now in receipt of the draft final report for:

SARF112 - Influence of low frequency ADDs on cetaceans in Scottish coastal waters

Please could I ask whether you would be able to complete a SARF evaluation form for this. (You kindly assisted at the application appraisal stage in April 2016).

Many thanks,

Sandra Gray
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SARF112: LOW-FREQUENCY ADDS AND PORPOISES (LEAP)

INFLUENCES OF LOWER-FREQUENCY ACOUSTIC DETERRENT DEVICES (ADDS) ON CETACEANS IN SCOTTISH COASTAL WATERS

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EXECUTIVE SUMMARY

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

- The experimental period during which signals were transmitted lasted a total of 33 days (08/09 - 11/10/2016). During this period, 138 transmissions took place, including 53 of the HF signal, 38 of the LF signal, and 47 silent controls. All the equipment, with the exception of 2 C-PODs and one broadband recorder, was recovered by 17/10/2016. One C-POD malfunctioned, bringing the total number of C-POD datasets available for further analysis to 19.

- Visual observations of porpoises were infrequent (23 sighting events over 19 days), despite good observing conditions. Most porpoises were sighted some distance from Bloody Bay within the central and northern Sound of Mull, particularly near the entrance to Loch Sunart. As a result, the video tracking procedure was often unable to adequately resolve surfacing animals to assess responses to different ADD signals, although the validity of the method itself was confirmed. Groups of bottlenose dolphins were observed on four occasions and one minke whale was sighted. In contrast to the scarcity of cetacean sightings, harbour seals were regularly observed on a near-daily basis, often in close proximity to the fish farm.

- The C-POD array provided a high-resolution dataset on presence of echolocating porpoises over the course of the experiment. Datasets were analysed using GAM-GEE models to investigate the relative importance of different covariates, including signal transmission, in determining porpoise acoustic presence.

- Ambient noise levels at the site, as assessed by broadband hydrophones, did not appear to significantly impact C-POD performance. Porpoise detections (defined as 'Porpoise-Positive Minutes' or PPMs) varied considerably across the array. Broadly speaking, PPM detection rates were higher in the central and northern Sound of Mull when compared to the Bloody Bay area, particularly compared to waters immediately surrounding the fish farm where detection rates were low.

- When assessing the effect of different signal transmissions, porpoise detection rates at most moorings were higher during silent control periods, suggesting that transmission of both HF and LF signals reduced the probability of porpoise detections. This was surprising as little difference was expected between exposure to LF signals and silent control periods. The results of this study therefore suggest that low-frequency ADD signals may also affect detection probabilities of harbour porpoises.

- 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.

1 INTRODUCTION: ADDS IN SCOTLAND

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

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

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

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

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

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 *, ** and * symbols.**

Manufacturer	Type	Source level (dB re 1 µPa-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 pseudorandom at	x		*Götz & Janik (2015)

					intervals from 2-40s*			

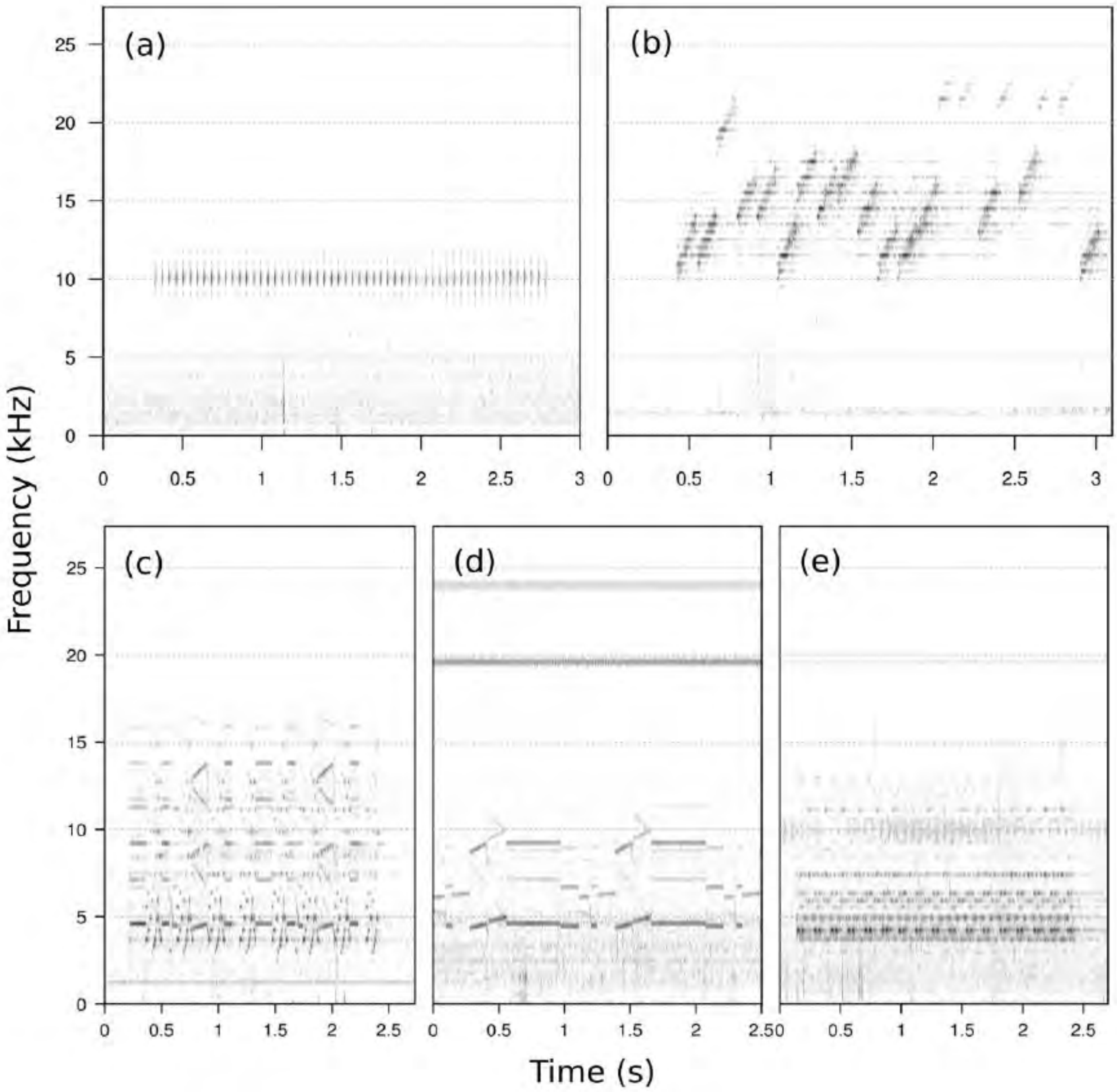


Figure 1. Examples of ADD spectrograms. Spectrogram parameters: FFT size = 1024 points, overlap = 50%, sample rate = 96 kHz; resulting in frequency and time resolution of 93.8 Hz and 10.67 ms, respectively. (a) Airmar™ (dB Plus II); (b) Ace Aquatec™ (US3); (c) Terecos™ (Type DSMS-4) Programme 4; (d)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

2 IMPACTS OF ADDS ON CETACEANS

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

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

Both harbour porpoises and bottlenose dolphins are listed under Annex II of the EC Habitats Directive (EC 1992), which requires strict protection measures to be applied to both individuals and populations, including the establishment of Special Areas of Conservation (SACs) to protect habitats that are important for the survival of the species. SACs are intended to contribute to a coherent European ecological network of protected sites, and thereby ensure continued maintenance of Favourable Conservation Status (FCS) of the species involved. The recently designated 'Inner Hebrides and the Minches' candidate Special Area of Conservation (cSAC) for harbour porpoises encompasses a large part of the Scottish west coast, which also includes numerous finfish aquaculture sites (Scottish Natural Heritage 2016). Given harbour porpoises' potential sensitivity to ADD noise, current levels of ADD usage within and adjacent to the 'Inner Hebrides and the Minches' cSAC therefore potentially have a negative impact on FCS for this species.

2.1 PHYSIOLOGICAL EFFECTS

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

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

Long-term exposure to chronic noise pollution can have significant deleterious effects on the health of both humans and animals through a number of physiological pathways involving combinations of neural and endocrine systems (summarised by Wright et al. 2007a, 2007b). Such responses may be difficult to detect in free-living cetaceans, and most of our current knowledge is derived from studies using small numbers of captive animals (e.g. Thomas et al. 1990; Miksis et al. 2001; Romano et al. 2004). However, stress hormone levels have been measured in whales' blows, suggesting anthropogenic noise may have substantial impacts on health of wild populations (Rolland et al. 2012). The effects of aquaculture-associated ADDs on cetaceans in this regard remain poorly understood but merit further study in the light of currently available data on effects of other anthropogenic noise sources (Wright et al. 2007b).

2.2 BEHAVIOURAL RESPONSES AND HABITAT DISPLACEMENT

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

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

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

2.5 'CETACEAN-FRIENDLY' ADD SYSTEMS

Current concerns about potential impacts of ADD signals on non-target species such as harbour porpoise have encouraged the development of novel ADD systems seeking to minimize such impacts while still acting as effective pinniped deterrents. Use of such systems has been suggested as a possible means to achieve reductions in acoustic impacts while continuing to use ADDs in otherwise sensitive areas, for example on aquaculture sites within the 'Inner Hebrides and the Minches' candidate Special Area of Conservation (cSAC), designated to protect harbour porpoises (Scottish Natural Heritage 2016; Marine Scotland 2016).

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

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

Loud sounds with sharp rise times can elicit an autonomous startle reflex in mammals, including seals (Götz & Janik 2011). Recent studies have demonstrated that grey seals (*Halichoerus grypus*) show sustained avoidance behaviour after repeated exposure to startle reflex-inducing acoustic stimuli (Götz & Janik 2011). On the basis of these findings, a novel ADD system intended to more effectively deter seals from fish farms, whilst avoiding unintended effects on non-target species such as harbour porpoises, has been patented (Götz & Janik 2012). The acoustic characteristics of this system are described in Table 1. At 1 kHz, peak frequencies for the deterrence stimulus are well below traditional ADD systems and duty cycles can be low (0.8%, see Table 1; Götz & Janik 2015). Field trials showed the effectiveness of this system in deterring seals from fish farms while reducing the risk to non-target species such as harbour porpoises (Götz & Janik 2011, 2015). Over a 2-month period, significant reductions in observed seal numbers during sound exposure were observed without noticeable habituation occurring, whereas no changes in porpoise relative abundance, distribution or behaviour were observed (Götz & Janik 2015). However, received levels need to be loud (>145 dB re 1 μPa_{RMS}) and signal onset sharp (<5 ms) to elicit a response; since both of these factors are affected by sound propagation through the water column, the effectiveness of this method is likely limited to relatively short ranges around fish farms (Coram et al. 2014; Götz & Janik 2015). This might be an advantage in the context of using ADDs continuously to deter seals, as avoidance responses will be limited to the immediate area around the ADD. This would, however, also mean that seals would have to be in close proximity to a fish farm for the deterrent to be effective; at such close distances, individual seals' increased motivation to investigate a potential food source might reduce deterrent efficacy. Another concern would be that lower frequencies generated by this device will propagate over larger ranges and are likely to be more audible to other non-target species such as fish and baleen whales. Potential effects of these ADD signals on such other species need to be investigated before large-scale deployments of these devices can commence.

3 EXPERIMENTAL METHODS

3.1 BACKGROUND AND PROJECT AIMS

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

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

3.2 ACOUSTIC PLAYBACK SIGNAL DESIGN

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

In the experimental design the potential difference between porpoises' and seals' behavioral responses to either high- / low-frequency ADD signals was applied. A high frequency (HF) test signal was designed using single frequency tonal bursts, similar to the Airmar, Lofitec and Ace Aquatec brands that represent the majority of ADDs in current use in Scottish salmon aquaculture. The random frequency sequencing and the pulse width and duty cycle of the Ace Aquatec were also adopted. The overall frequency range of transmission was extended from 8-18 kHz to capture the full frequency spectrum of all three systems (Figure 2). Specifically, the HF signal consisted of pulsed continuous wave sinusoidal tonal bursts at one of 21 randomly switching fundamental frequencies between 8 – 18 kHz at frequency intervals of 500 Hz. Each pulse contained 40 cycles of fundamental frequency with a rectangular pulse amplitude envelope, and the on – off duty cycle was 50%. Figure 3 illustrates the variation in pulse amplitude due to transducer response as well as pulse duration.

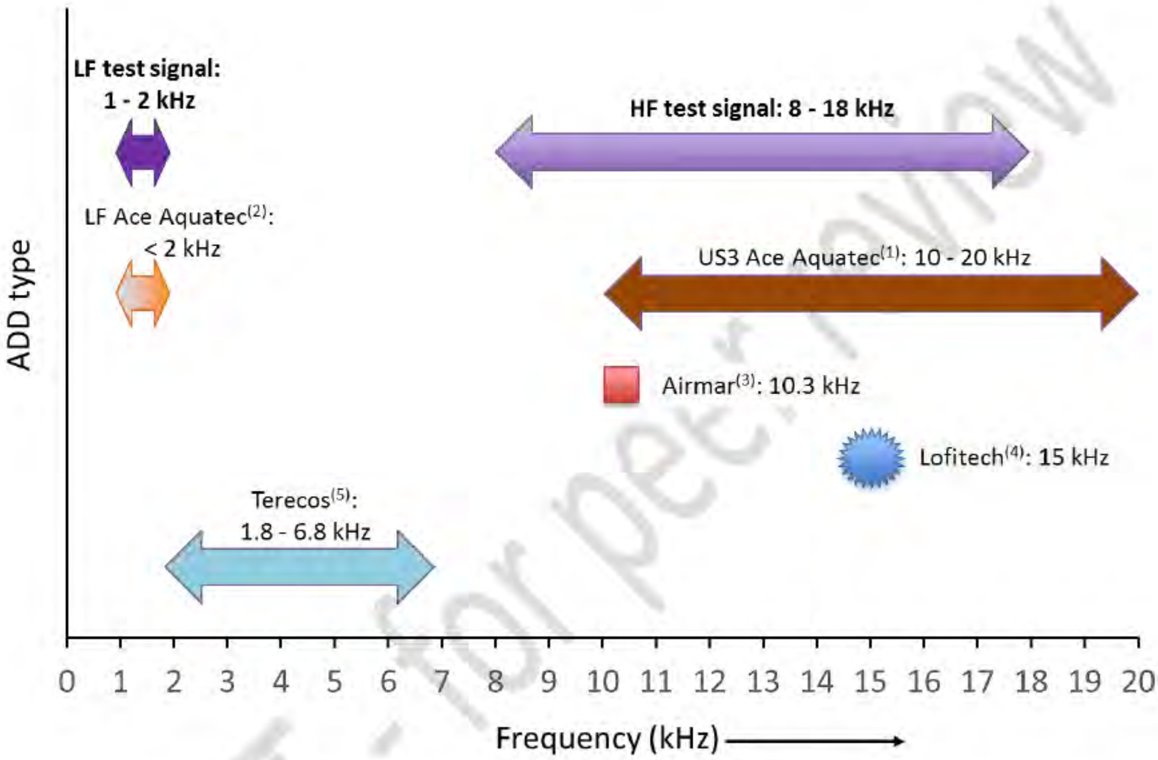


Figure 2. Output frequency ranges of the two test signals (LF and HF), compared to outputs from various existing ADD types (see Table 1 for details). Data on existing ADD outputs derived from 1) Ace Aquatec U3S manual (https://www.aceaquatec.com/us3specification); 2) Ace Aquatec pers. comm. (PL); 3)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

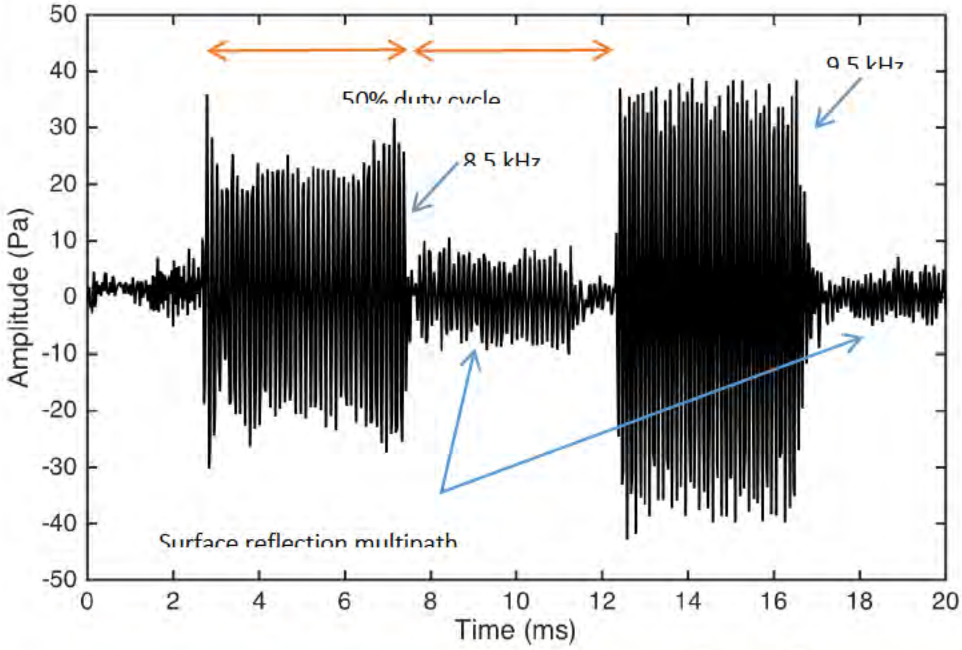


Figure 3. Time domain plot of two consecutive samples from the HF sequence – first pulse at 8.5 kHz and second at 9.5 kHz.

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

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

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 µPa-m	165 – 170.4 dB re 1 µPa-m

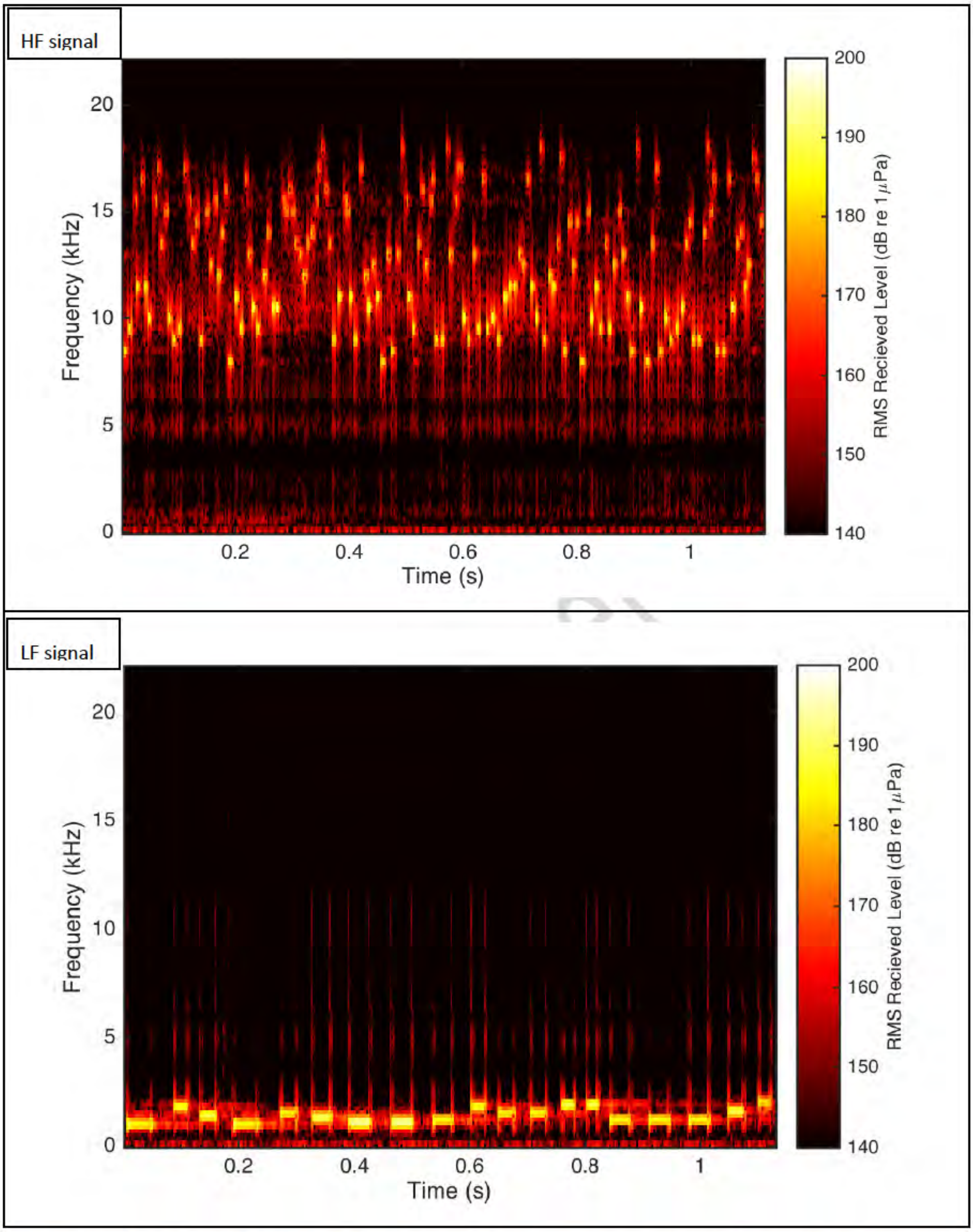


Figure 4. Spectral plot of a sample of the HF and LF signals received at a range of 8.5 m using a Reson 4014 balanced hydrophone. Analysis window was 256 FFT with 50 % overlap using a Hanning window. A 50 kHz low pass filter was applied. Original data were downsampled to a sample rate of 44.1 kHz.

3.3 SIGNAL TRANSMISSION

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

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

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

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

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

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

	Frequency (Hz)	Pulse duration (ms)	RMS Source Level (dB re 1 μPa-m)	Frequency (Hz)	Pulse duration (ms)	RMS Source Level (dB re 1 μPa-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			

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

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

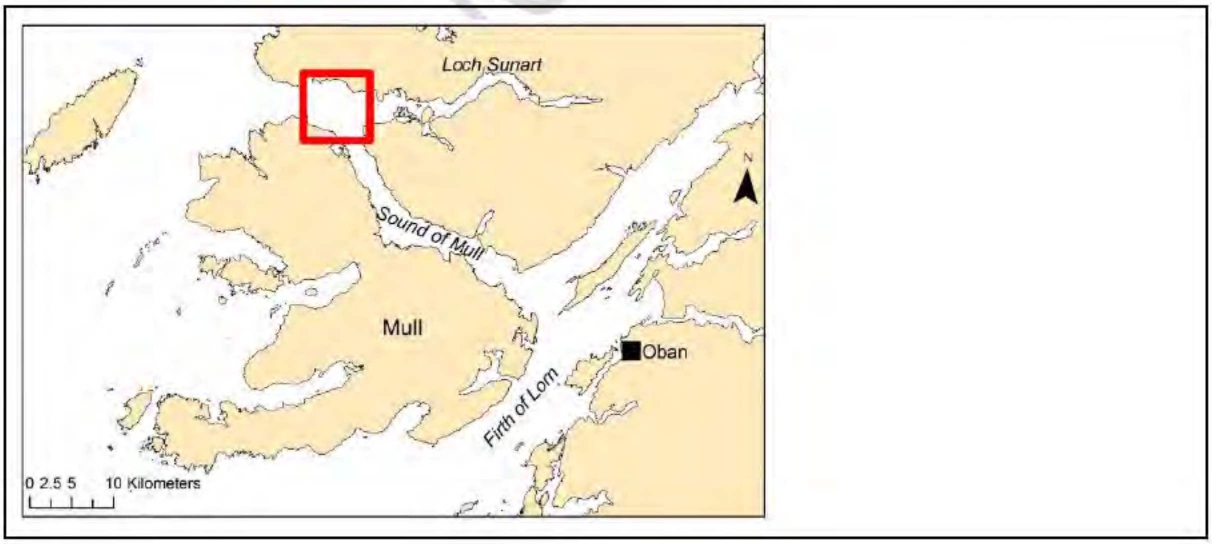
After several days of operation, it became apparent that the system drew more power when transmitting in Night mode than could be reliably replenished by the solar panels during the subsequent daytime, thus putting strain on the system's battery power supply. To preserve power throughout the experimental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

3.4 FIELDWORK LOCATION

The experiment took place in the Sound of Mull, on the west coast of Scotland, with observation efforts concentrated in Bloody Bay on the north shore of the Isle of Mull (56°38.626 N, 6°05.705 W; Figure 6). This location was chosen because it contained a salmon aquaculture site (owned by Scottish Sea Farms™/SSF) which operated under licensing restrictions preventing it from using ADDs (Scottish Natural Heritage, pers.comm. 2016). This meant that the experiment could be undertaken without interference from on-site operational ADDs, although effects of more distant ADDs on other fish farms could not be eliminated. Furthermore, Bloody Bay had previously been identified as a site where harbour porpoises were observed regularly (Carlström 2005; Carlström et al. 2009; Götz & Janik 2016). The feeder barge of the Bloody Bay salmon farm was used as a platform from which the underwater loudspeaker and associated hardware could be deployed, as well as passive acoustic detectors. Water depths in the immediate area around the fish farm were approximately 35-40 m (based on GEBCO™ bathymetry data).

3.5 PASSIVE ACOUSTIC DETECTOR ARRAY

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



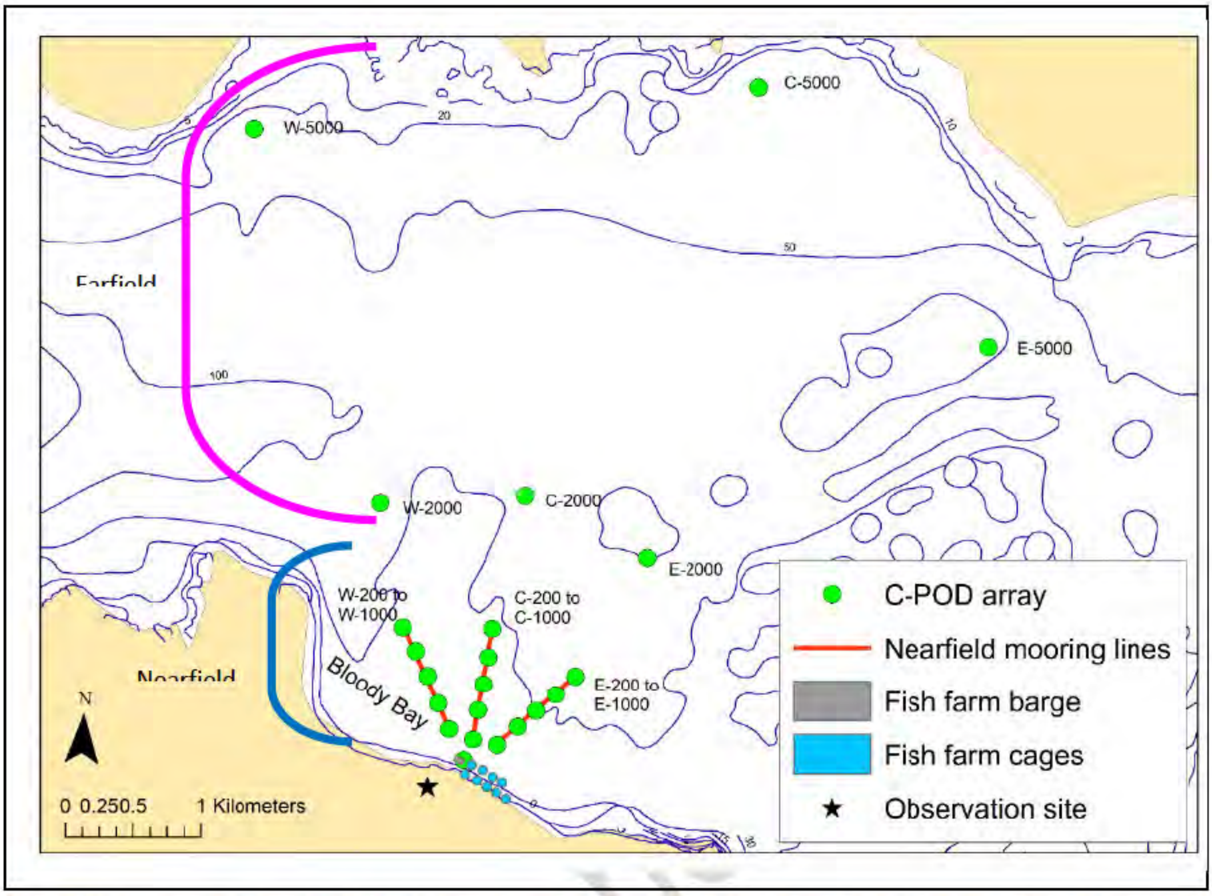


Figure 6. A) Overview of the Sound of Mull and adjacent areas. The Bloody Bay fieldwork site is indicated by the red box. B) Overview of LEAP passive acoustic mooring array in Bloody Bay and the northwestern Sound of Mull. Nearfield and Farfield components of the array are indicated. Note that the field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

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

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

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

- C-PODs are self-contained ultrasound monitors that select tonal clicks and record the time of occurrence, centre frequency, intensity, duration, bandwidth and frequency trend of tonal clicks within the frequency range 20 kHz - 160 kHz to 5-µs resolution. This allows them to monitor clicks from all odontocetes except sperm whales. Raw sound data are not stored, however, and the unit's design precludes manual configuration of click identification parameters. Maximum deployment times vary depending on environmental conditions but typically range over several months (Chelonia Ltd. 2011, 2013, 2014). This extended battery life makes them suitable for long-term monitoring experiments involving species such as harbour porpoise. A subset (n=8 units) of C-PODs' responses to artificial porpoise clicks had been tested previously as part of a different experiment, deploying an omnidirectional harbour porpoise click train synthesiser (PALv1; F^3 Maritime Technology 2012) at known distance. The PALv1 unit produced click trains with a centre frequency of 133 ± 0.5 kHz and source levels of 154 ± 2 dB (peak-to-peak; F^3 Maritime Technology 2012). Some variability in terms of C-PODs detecting PALv1 click trains was noted at the time; environmental factors (notably changes in C-POD orientation relative to the PALv1 sound source) were considered to be an important cause of this variability. No further calibration of C-PODs used in this experiment was performed.

  Occasionally, under high ambient noise conditions, C-PODs temporarily stop logging when reaching a pre-set buffer limit of 4,096 clicks per minute, until the start of the next minute (Booth 2016). The proportion of each minute thus lost can be used as a crude proxy of ambient noise levels across the array. C-PODs also contained an onboard tilt sensor, recording their deflection from vertical (0° = vertical; 90° = horizontal).

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

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

3.6 VISUAL OBSERVATIONS AND CAMERA ARRAY

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

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

3.7 DATA MANAGEMENT

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

4 RESULTS

4.1 SIGNAL TRANSMISSION EXPERIMENTS

The signal transmission system described under Section 3.3 was installed onto the fish farm barge and activated on 6/09/2016, following a delay of approximately 5 weeks due to an unexpectedly long licensing process. Despite this delay, the project succeeded in completing a successful fieldwork campaign combining simulated ADD transmissions with simultaneous acoustic and visual observations of porpoises. Following some tests, the actual experiment ran from 08/09/2016 until 11/10/2016 inclusive, or a total of 33 days. During this period, a total of 138 complete sound transmissions (including 53 HF signal transmissions, 38 LF signal transmissions, and 47 silent control "transmissions") were carried out. Transmissions were either triggered upon visual detection of animals or initiated on a random schedule (see Methods). Of all transmissions, 62 ran during daylight hours (i.e. started during daytime or immediately before sunrise), while 76 transmissions overlapped partially or wholly with hours of darkness (i.e. started during darkness or immediately before sunset). Visual observations occurred on 18 days between 9/09/2017 and 10/10/2017, and included both data from human observers and video camera tracking data. There was no significant difference in terms of when particular signals were transmitted in relation to daylight hours. All but three of the passive acoustic recorders were successfully recovered on 18/10/2016. The resulting dataset will be described in more detail below.

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

4.2 HARDWARE RECOVERY

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

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

4.3 PASSIVE ACOUSTIC MONITORING

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

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

C-POD datasets were truncated to exclude periods immediately after deployment and before recovery, such that the remaining datasets only contained entire days (1440 minutes per day). For this reason, the entire array (excluding the C-POD beneath the feeder barge) was defined to be active from 8/09/2016 at 00:00 GMT until 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. All other C-PODs remained operational until at least 16/10/2017 at 23:59 GMT, equivalent to 39 days.

Table 5. Summary of periods monitored by moored C-POD units across the array. *These units stopped <24 hrs prior to recovery. ** This 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

4.4 AMBIENT NOISE MONITORING

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

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

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

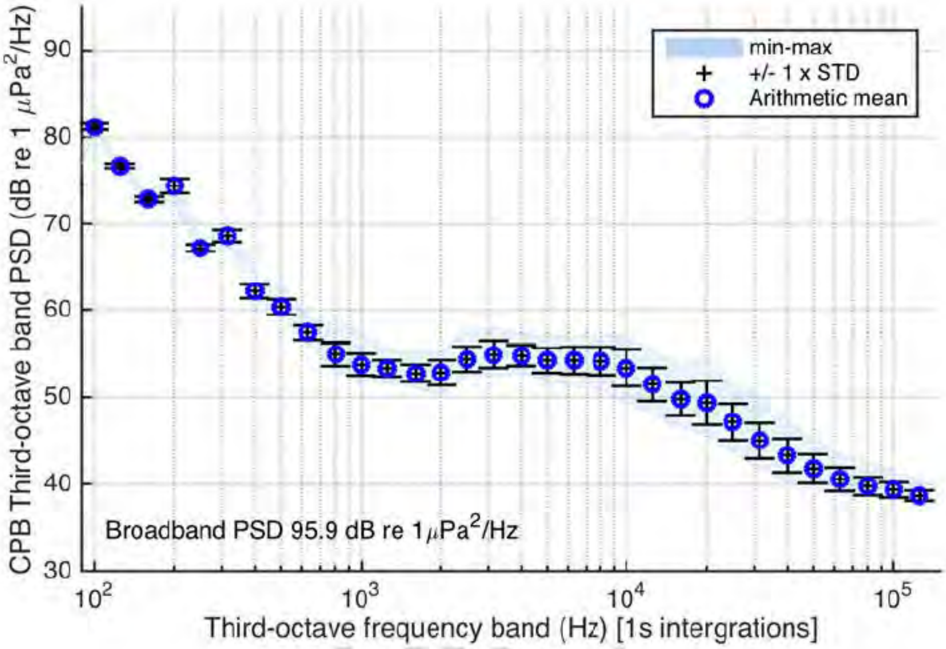


Figure 7. Power Spectral Density (PSD) in Third Octave Bands for a quiet period at 14:56 GMT on 11th October 2016. Total sample length 25 seconds, 1-second integration periods.

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

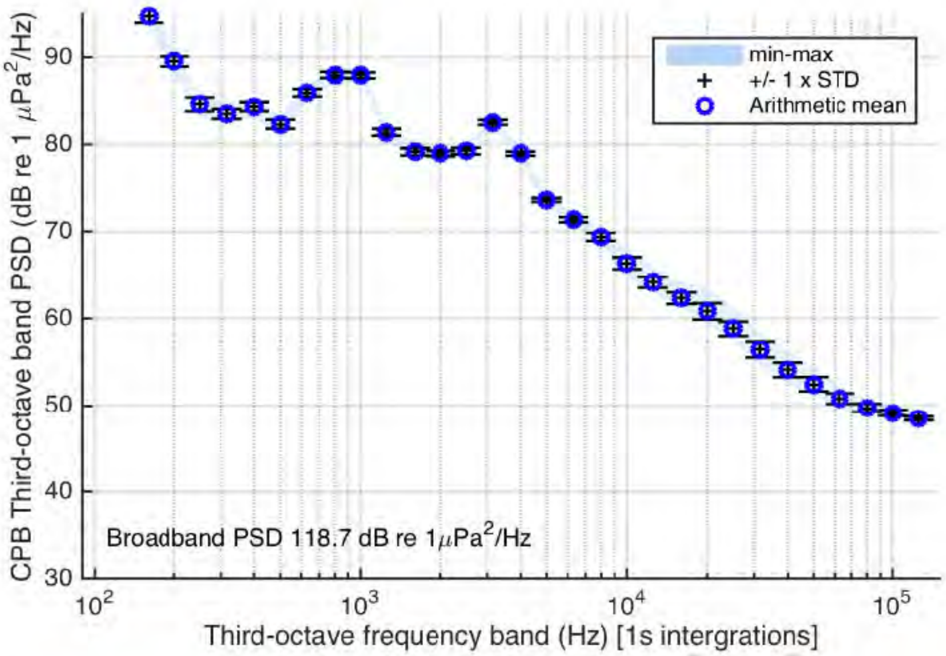


Figure 8. Power Spectral Density (PSD) in Third Octave Bands for low sea-state period at 15:01 GMT on 11th October 2016. Total sample length 25 seconds, 1-second integration periods. Likely contributions originated from specific barge or small boat operations.

By comparison, Figure 8 shows a 25-second period taken around 5 minutes later at 15:01 GMT. During this period, significantly elevated levels were observed at a range of frequencies. Most of this noise likely originated either from short-term barge based activities or nearby small boat operations with a broadband response of 118.7 dB re 1 μPa^2/Hz with levels approximately 30 dB higher in some frequency bands. For further comparison, Figure 9 shows a consecutive 25-second sample period taken a few moments later with a lower broadband response of 106.2 dB re 1 μPa^2/Hz. These data show that, although levels have dropped when compared to the previous sample, there was increased variation during the 25-second sample, most likely due to transitory noise from boat- or barge-based operations during this period.

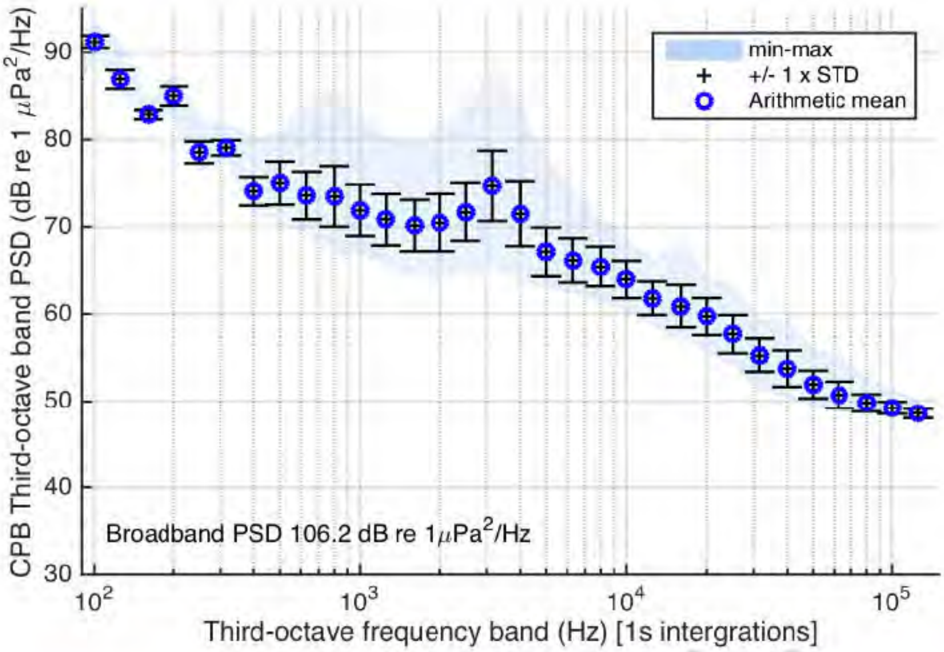


Figure 9. Power Spectral Density (PSD) in Third Octave Bands for low sea-state period. Consecutive 25s period from file started at 15:01 on 11th October 2016 compared to figure 9. Total sample length 25 seconds, 1-second integration periods. Transitory contributions from specific barge or small boat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

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

4.5 SIGNAL PROPAGATION MODELLING

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

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

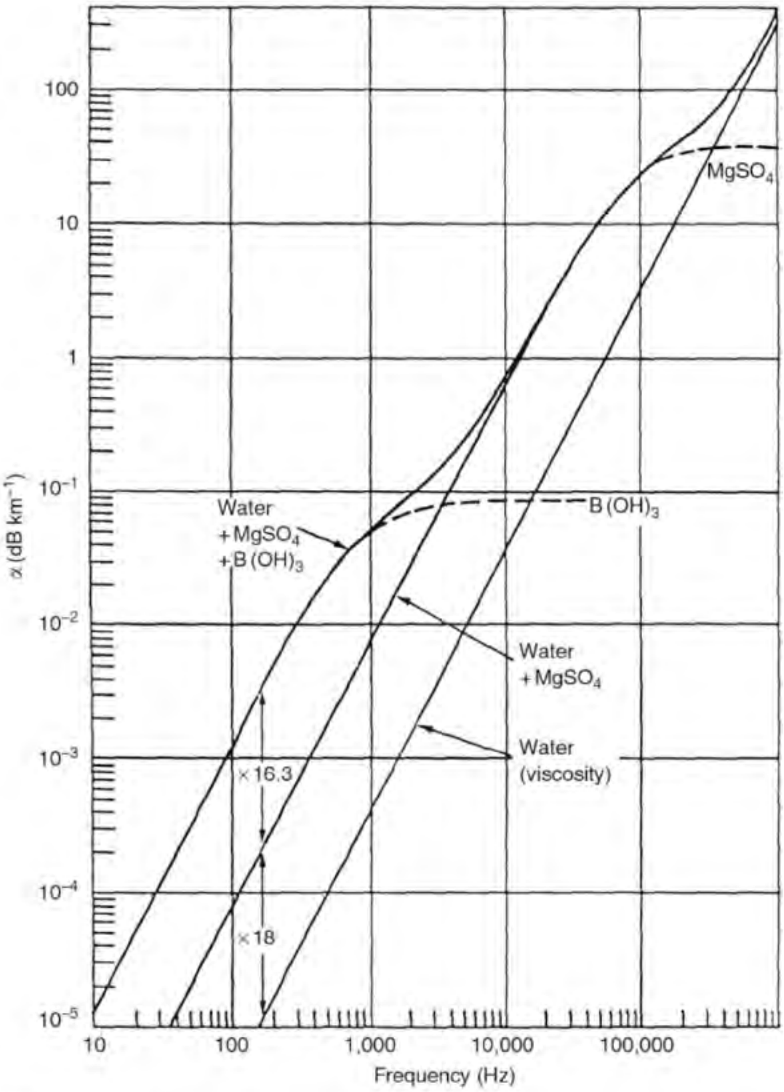


Figure 10. Underwater acoustic absorption versus frequency. Derived from Etter, 2003.

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

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

4.6 VISUAL OBSERVATIONS

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

4.6.1. MARINE MAMMAL SIGHTINGS

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

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

Table 6. Overview of observation events of different marine mammal species during the experiment. Individual observation events of porpoises and dolphins often involved >1 individual. *N.B.: Seal and otter sightings were not tracked and so numbers reflect the 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		

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

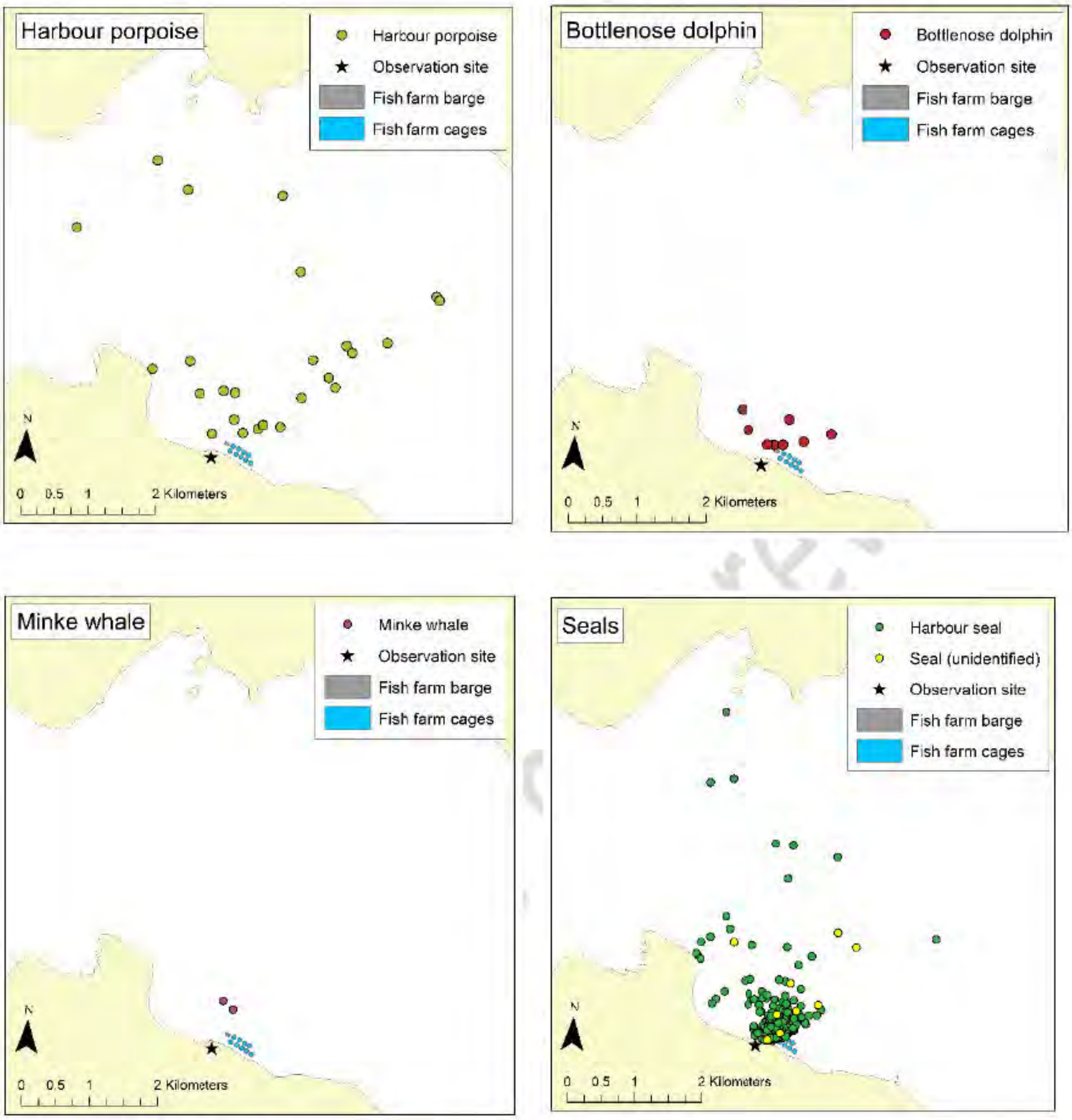


Figure 11. Approximate locations of sightings of different marine mammal species during the entire experimental period. Note that these positions are only approximations due to substantial variability in distance estimation among observers.

4.6.2 VISUAL TRACKING ANALYSIS

The visual tracking methodology (Section 3.6) was designed to provide insight into porpoises' initial responses to the experimental signals by tracking their surface movements at high resolution. Unfortunately, the small number of visual sightings of porpoises made this difficult (Table 6). In addition to being infrequent, most porpoise sightings occurred at considerable distance from the observation site (notably in the northern half of the Sound of Mull, towards the entrance to Loch Sunart several km away). At such distances, the cameras' resolution proved to be inadequate for reliably recording porpoises for tracking. For this reason, only a few sightings close to the fish farm were suitable for further analysis and the method was therefore unable to provide robust information on porpoises' responses to the experimental ADD signals. However, despite the small number of porpoises at the site in the autumn of 2016, we were able to demonstrate the general utility of the method, and would encourage further development of this tool. An example of a tracked group of porpoises is shown in Figure 12.

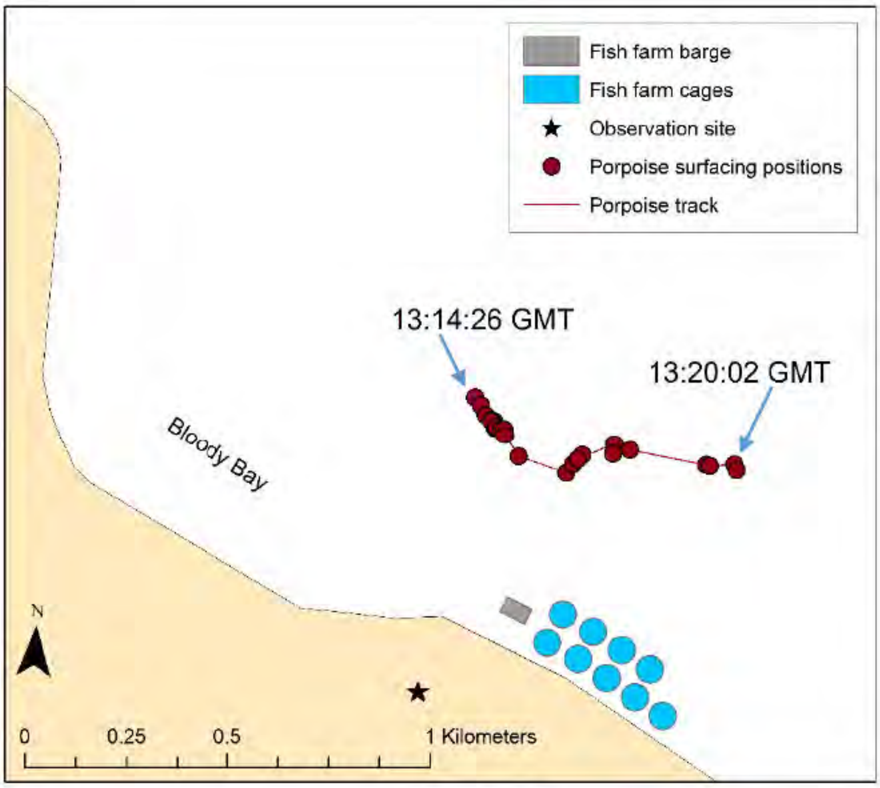


Figure 12. Example of tracked group of 3 porpoises observed on 14/09/2016, swimming from west to east.

4.6.3. SEAL OBSERVATIONS AROUND THE FISH FARM

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

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

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

In three cases <30 minutes, or <25%, of the entire 2-hour transmission period was observed (Table 7), and these cases were excluded from further analysis. Data from the remaining 14 cases were used to assess the relationship, if any, between signal type and standardised sighting rate of individual seal sighting events per minute, using a linear modelling approach through the *lm* tool in the R package *stats* v.3.4.3. Results indicated that there was no obvious relationship between the signal being transmitted and standardised seal sighting rates, irrespective of whether sightings of nearby seals (d.f. = 12; p = 0.5461), more distant seals (d.f. = 12; p = 0.2213), or all seals (d.f. =12; p = 0.4637) were used to populate the model.

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

4.7 C-POD DATA ANALYSIS

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

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

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 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 '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

4.7.1 EXPERIMENTAL RESULTS OF EXPOSURE EXPERIMENTS

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

Table 9. Summary of numbers of monitored minutes ($N_{MINUTES}$), number of PPMs (N_{PPM}), and average ratio of number of PPMs divided by total number of monitored minutes (F) during all experimental transmissions, detected by each C-POD between 08/09/2016 and 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
		$N_{MINUTES}$	N_{PPM}	F	$N_{MINUTES}$	N_{PPM}	F	$N_{MINUTES}$	N_{PPM}	F	N
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

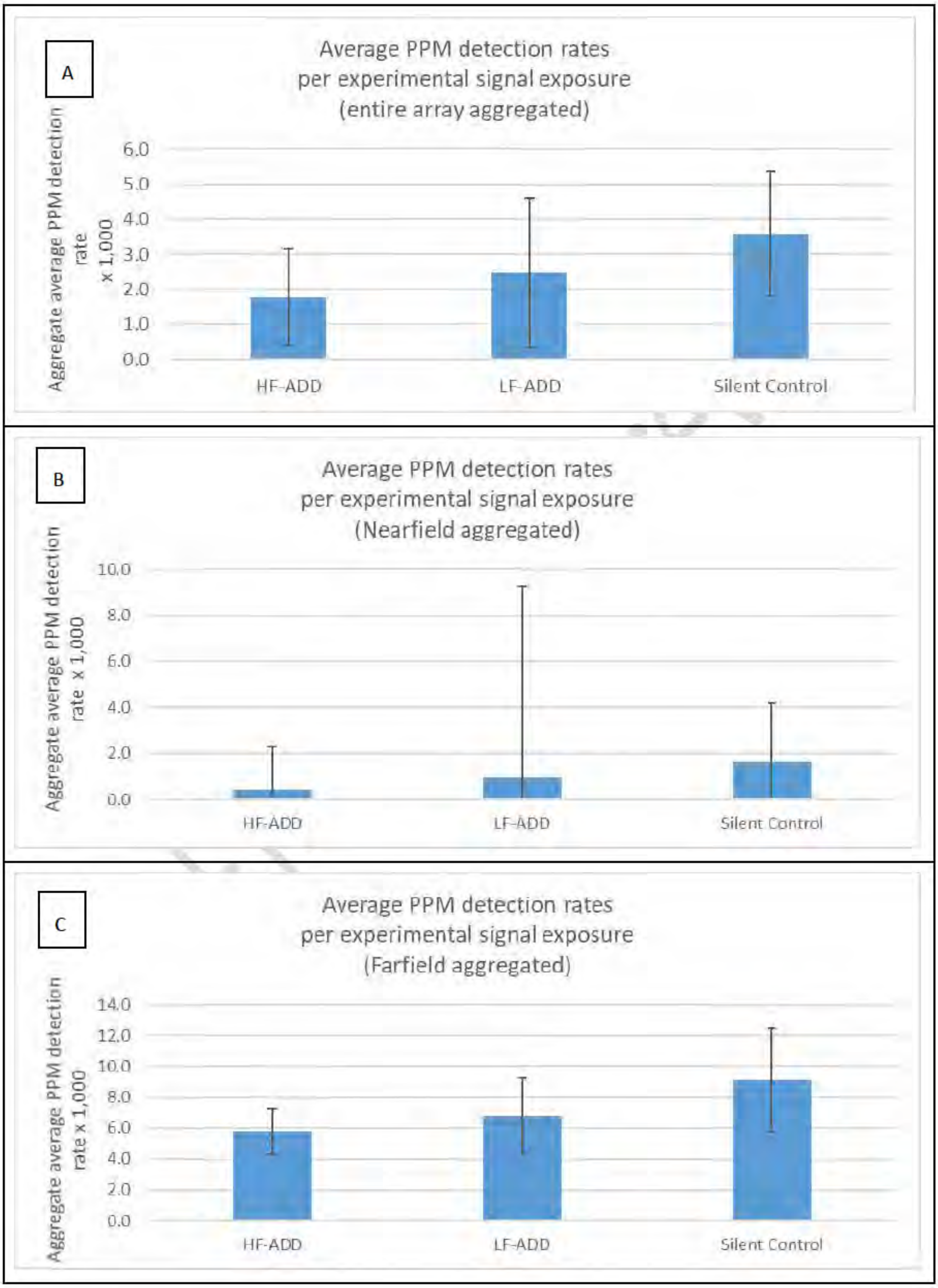

A
Average PPM detection rates
per experimental signal exposure
(entire array aggregated)
Aggregate average PPM detection rate x 1,000
6.0
5.0
4.0
3.0
2.0
1.0
0.0
HF-ADD
LF-ADD
Silent Control
B
Average PPM detection rates
per experimental signal exposure
(Nearfield aggregated)
Aggregate average PPM detection rate x 1,000
10.0
8.0
6.0
4.0
2.0
0.0
HF-ADD
LF-ADD
Silent Control
C
Average PPM detection rates
per experimental signal exposure
(Farfield aggregated)
Aggregate average PPM detection rate x 1,000
14.0
12.0
10.0
8.0
6.0
4.0
2.0
0.0
HF-ADD
LF-ADD
Silent Control

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

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

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

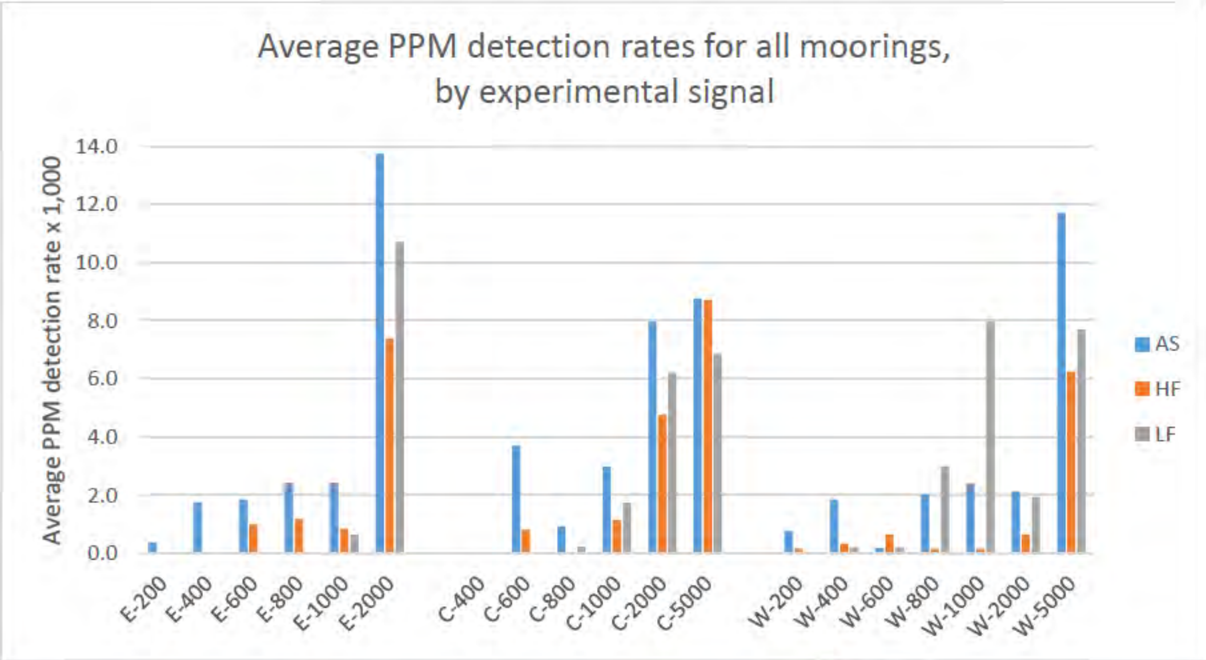


Figure 14. Average PPM detection rates (derived from Table 8, then multiplied by 1,000 for display purposes) across the experimental array under HF-signal, LF-signal, or Silent control (AS) control treatment.

4.7.2 CROSS-ARRAY VARIABILITY

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

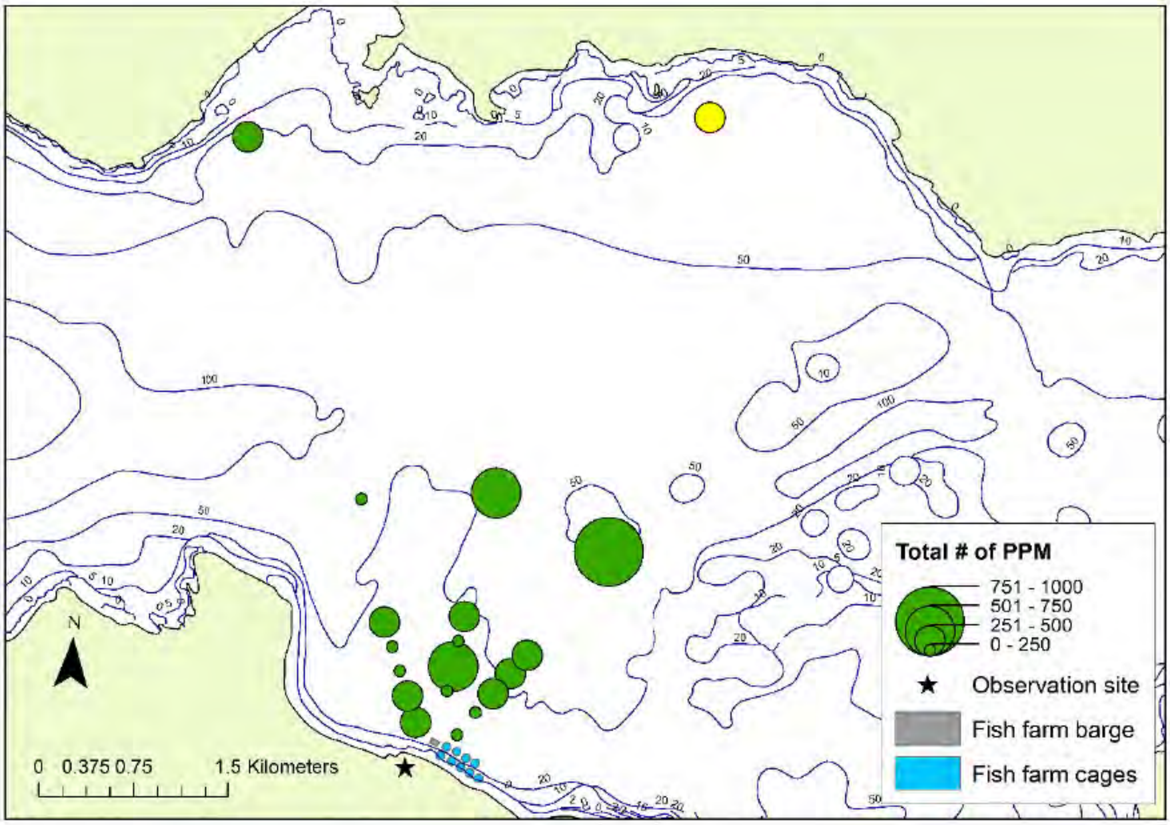


Figure 15. Summary of total numbers of PPMs reported during 8/09-16/10/2016. N.B.: the C-5000 C-POD (top right, yellow) was only operational up to 6/10/2016.

4.7.3 ENVIRONMENTAL DRIVERS OF VARIABILITY

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

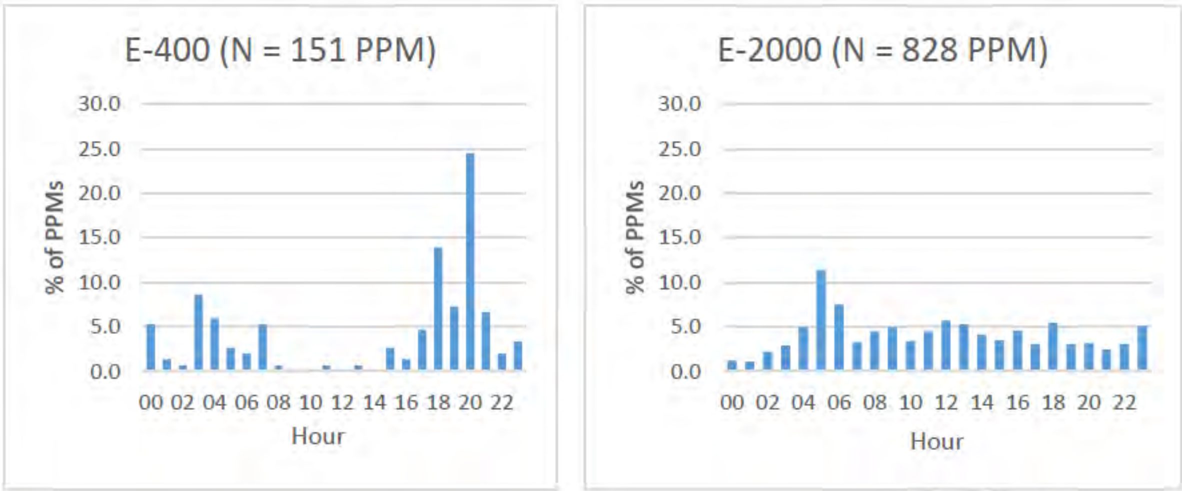


Figure 15. Examples of diurnal patterns of PPM detections from Nearfield (E-400) and Farfield (E-2000) C-PODs (data from 8/09-16/10/2016, aggregated).

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

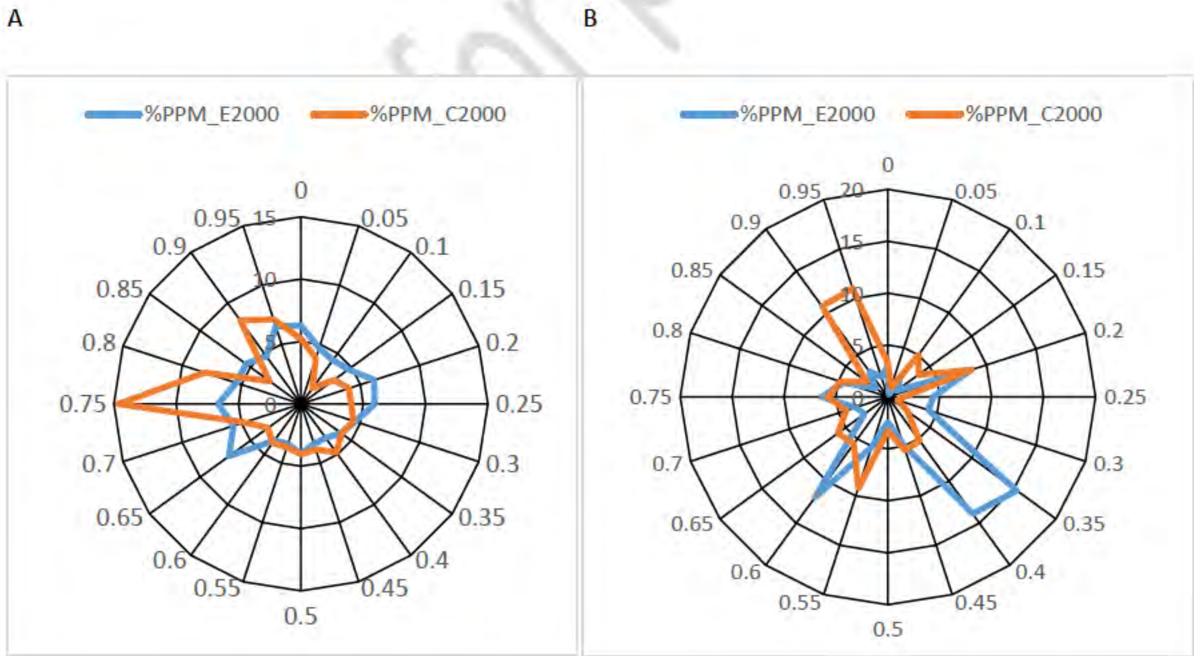


Figure 16. Examples of apparent variability in PPM detection rates at ebb-flood and spring-neap tidal scales. A) Normalised (% of total) PPM detections at locations E-2000 and C-2000 over the ebb-flood tidal cycle (0 = 1 = ebb at Tobermory tidal gauge); B) Normalised (% of total) PPM detections at locations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

4.7.4 PRE- AND POST-EXPERIMENTAL CONTEXT

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

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

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

4.8 ADVANCED MODELLING

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

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

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

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

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

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

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

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

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

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

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

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

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

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

5 DISCUSSION

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

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

Based on the limited number of exposure experiments that were visually observed (Section 4.6), seals were not noticeably deterred from the vicinity of the fish farm by either HF or LF signal transmissions. This was not the main focus of the present study and results should therefore be interpreted with caution. Seal detections at the surface were more frequent when either signal was being played than during silent control periods, suggesting they might seek to reduce noise exposure by lifting the head out of the water (Fjälling et al. 2006; Kvadsheim et al. 2010). Alternatively, seals could have been responding to a 'dinner bell' effect, having learnt to associate the sound of ADDs with the presence of food (be it captive salmon or wild fish attracted to the cages). It is worth noting that these observations occurred around a fish farm that traditionally has not used active ADDs, where such signals might therefore have been perceived as more novel and worthy of inspection by curious seals. Conversations with SSF staff indicated that seals were regularly observed near the Bloody Bay fish farm, implying that the artificial ADD signals were not suddenly attracting seals to an otherwise seal-free site. Our observations did not support the assumption that ADD signals actually deter seals from fish farms, which has itself been the subject of debate for many years (e.g. Jacobs & Terhune, 2002; Quick et al., 2004; Graham et al., 2009; Götz & Janik, 2013; Coram et al. 2014; SCOS, 2016).

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

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

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

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

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

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

6 ACKNOWLEDGEMENTS

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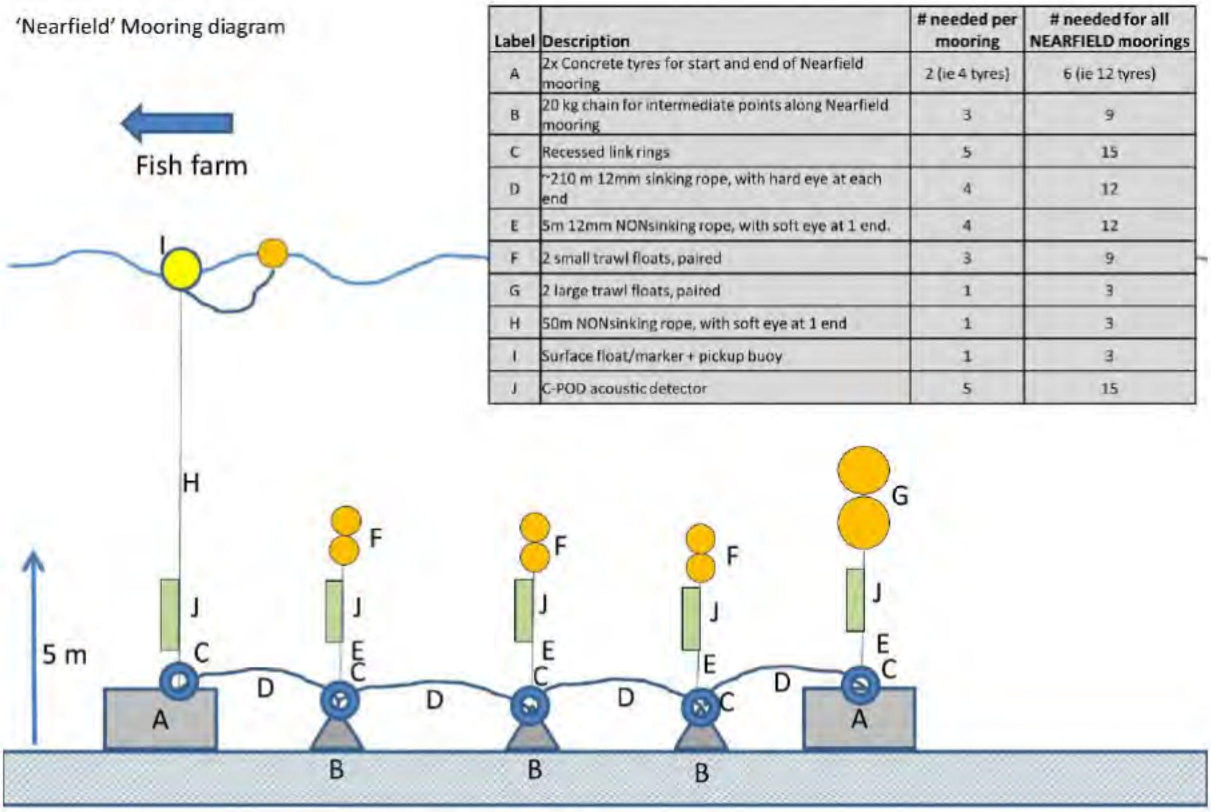
APPENDIX 1 - MOORING DESIGN

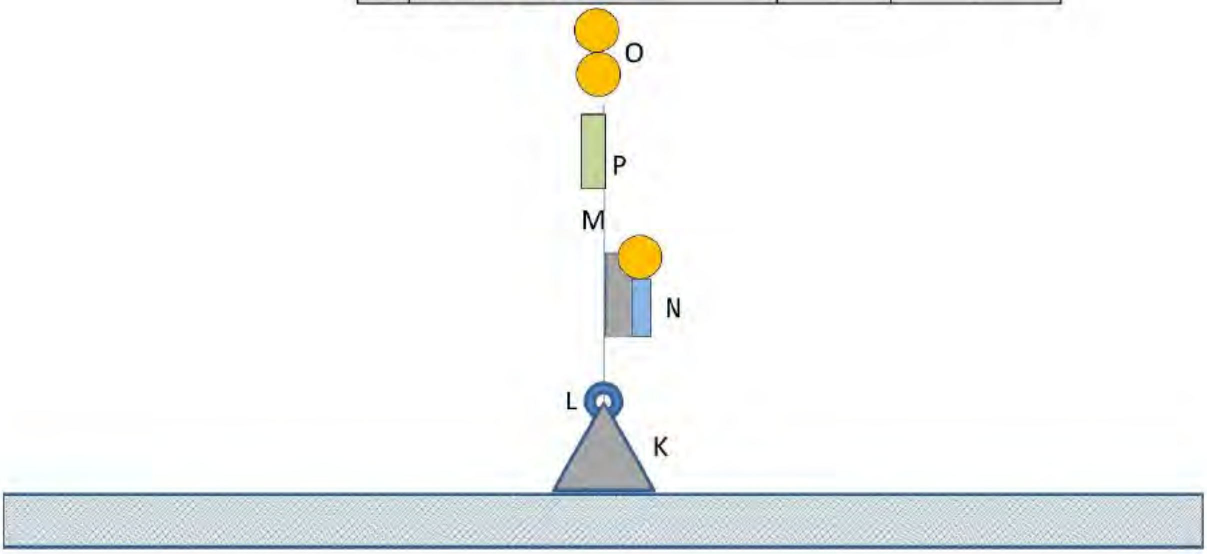
Overview of mooring structures used in Nearfield and Farfield moorings, respectively.



Label	Description	# needed per mooring	# needed for all NEARFIELD moorings
A	2x Concrete tyres for start and end of Nearfield mooring	2 (ie 4 tyres)	6 (ie 12 tyres)
B	20 kg chain for intermediate points along Nearfield mooring	3	9
C	Recessed link rings	5	15
D	~210 m 12mm sinking rope, with hard eye at each end	4	12
E	5m 12mm NONsinking rope, with soft eye at 1 end.	4	12
F	2 small trawl floats, paired	3	9
G	2 large trawl floats, paired	1	3
H	50m NONsinking rope, with soft eye at 1 end	1	3
I	Surface float/marker + pickup buoy	1	3
J	C-POD acoustic detector	5	15

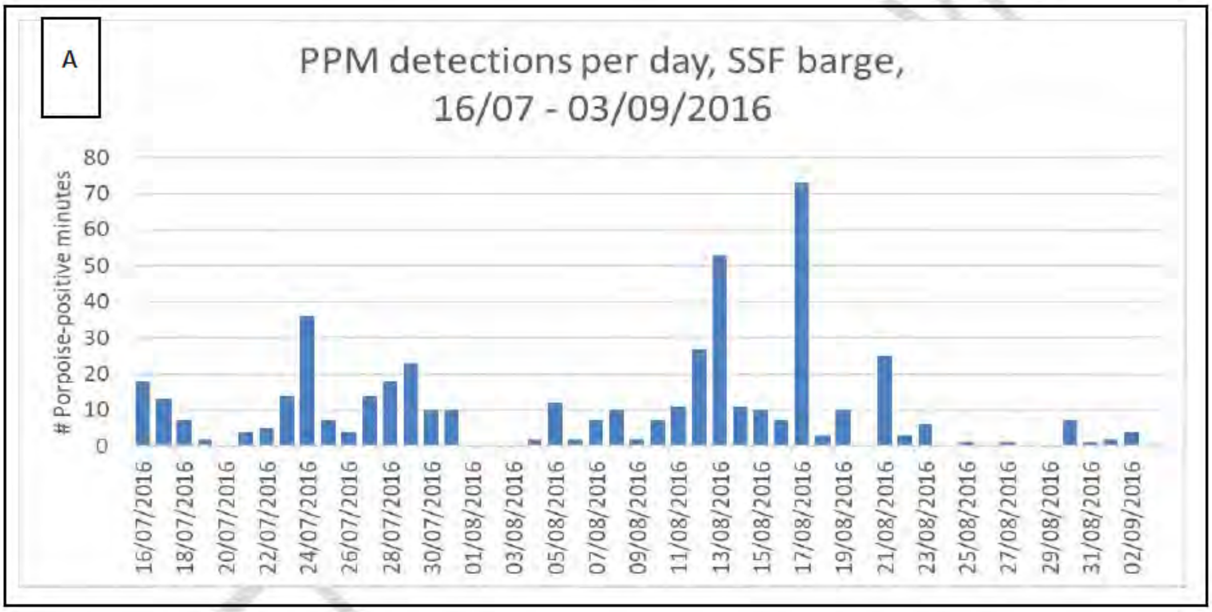
'Farfield' mooring diagram

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



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.



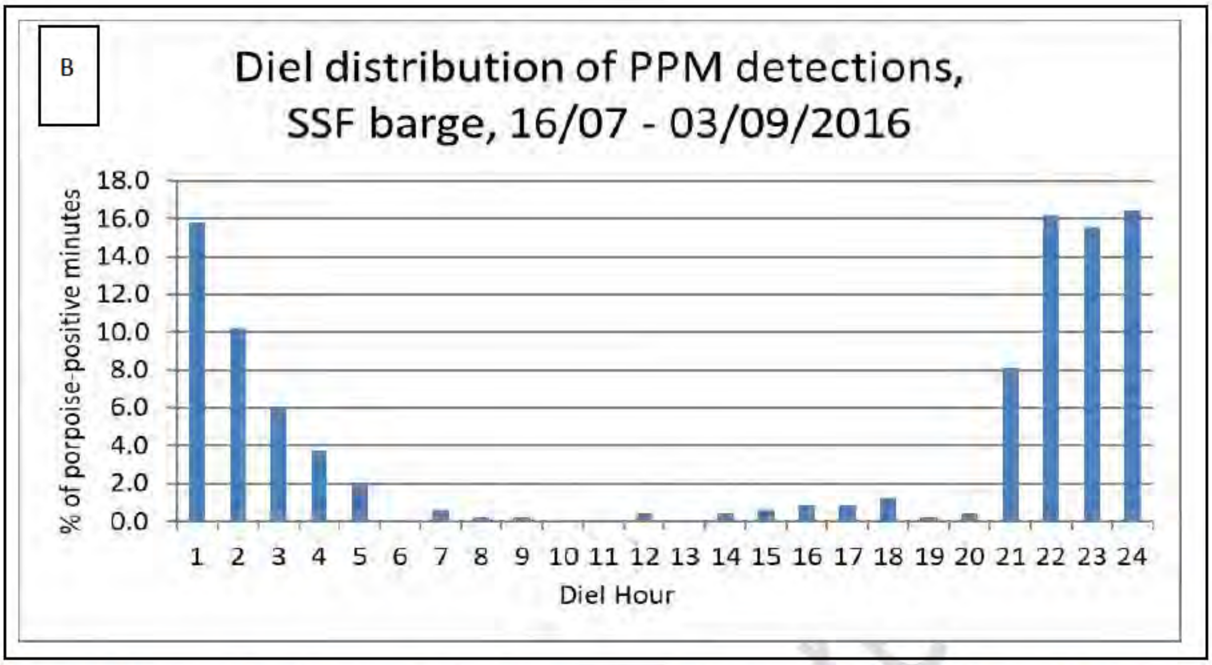


Figure A3.1. A) Overview of overall PPM numbers during pre-experimental deployment at the Bloody Bay fish farm, 16/07 – 3/09/2016 (partial start & end days excluded). B) Overview of distribution of PPMs by hour across a 24-hour day (data aggregated over 16/07 – 3/09/2016 (partial start & end days excluded).

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

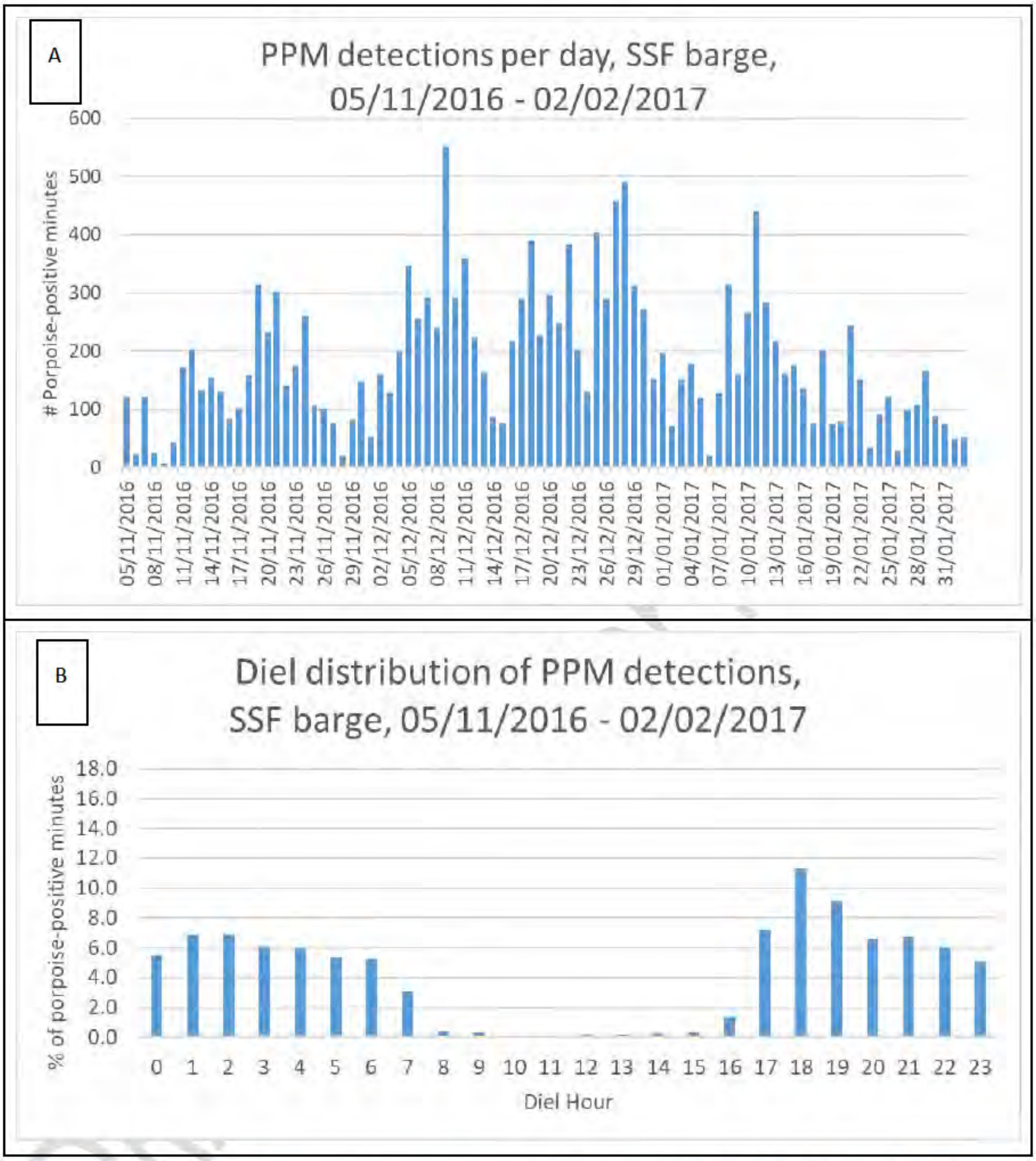


Figure A3.2. A) Overview of overall PPM numbers during pre-experimental deployment at the Bloody Bay fish farm, 05/11/2016 – 02/02/2017 (partial start & end days excluded). B) Overview of distribution of PPMs by hour across a 24-hour day (data aggregated over 05/11/2016 – 02/02/2017 (partial start &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

APPENDIX 3 - OVERVIEW OF # PPM/DAY ACROSS ARRAY

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 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

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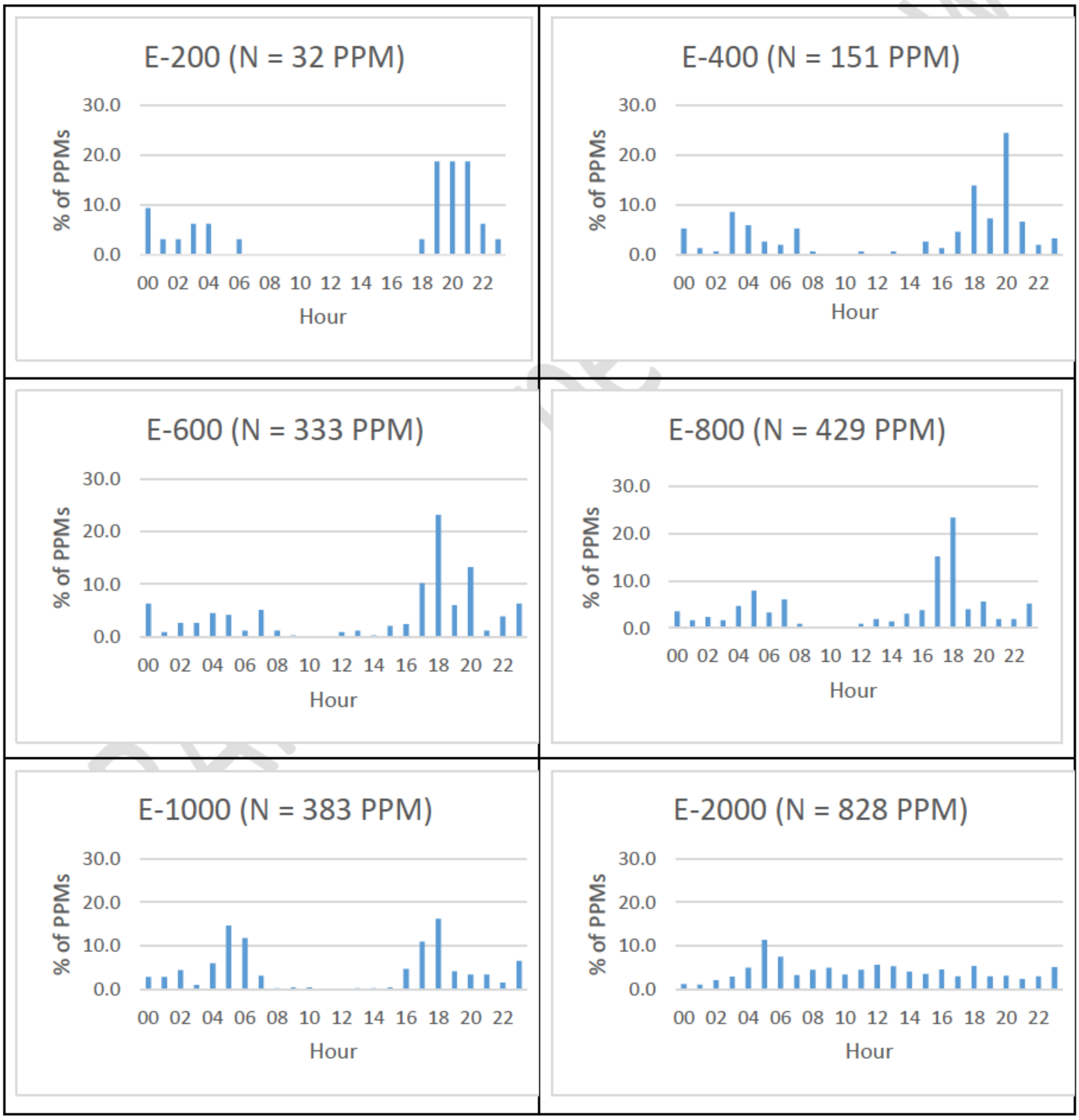
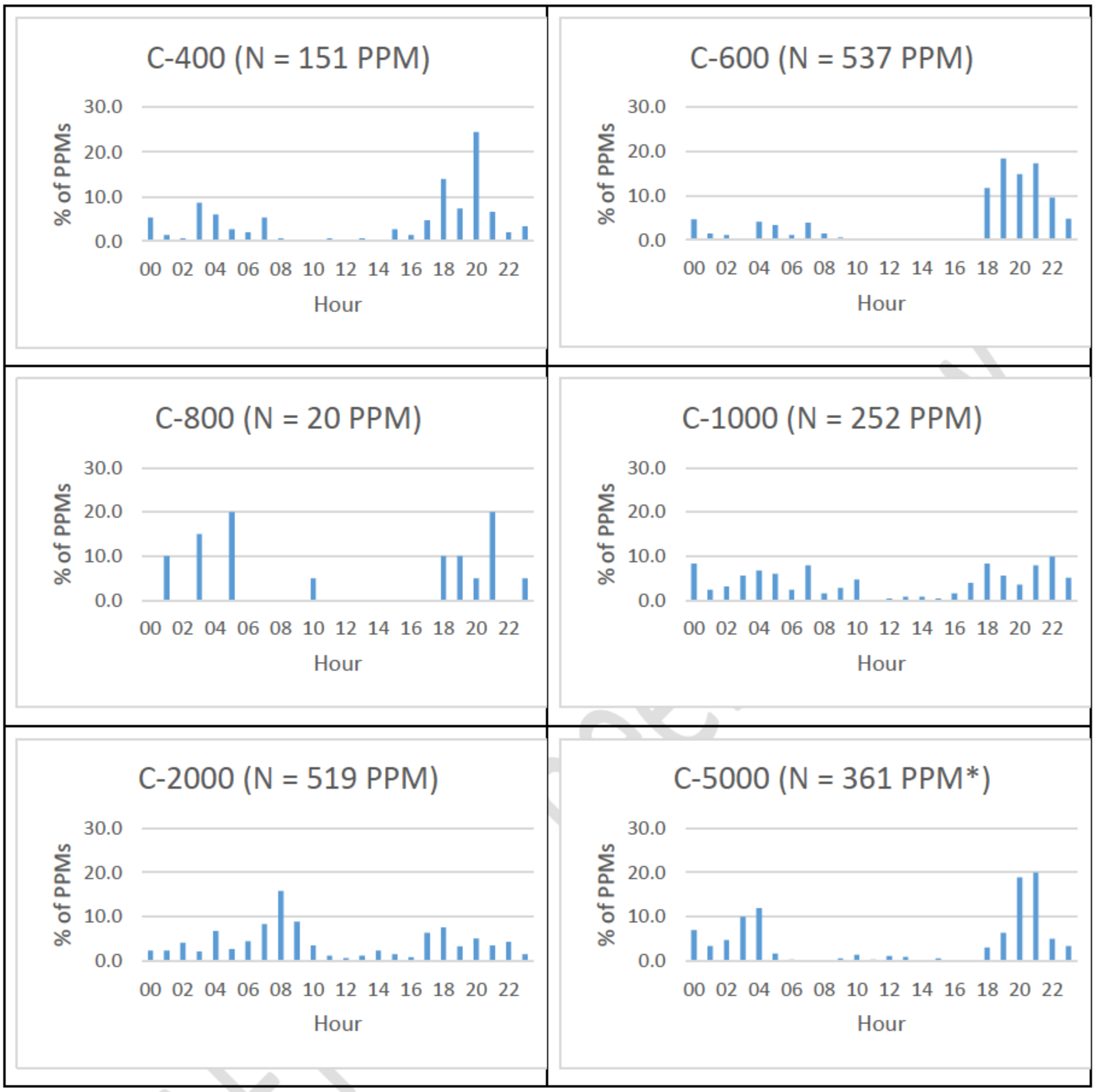
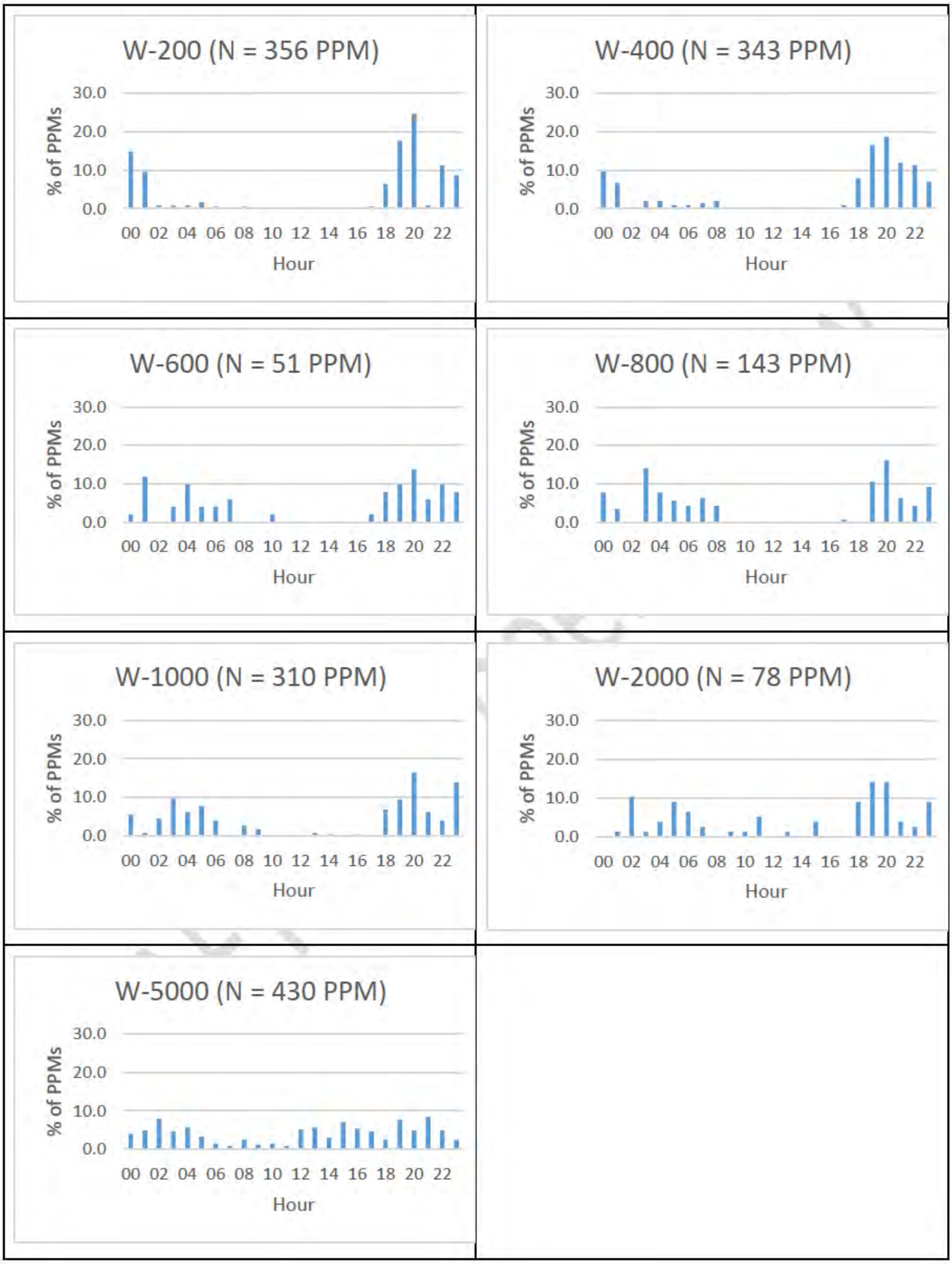
APPENDIX 4 – DIEL VARIABILITY IN PPM DETECTIONS

The following graphs illustrate, for each mooring, the diel patterns among PPM detections observed throughout the experimental period. Total numbers of PPMs are indicated for each mooring. Moorings are aggregated according to their presence along the Eastern, Central and Western mooring lines. Detection rates were generally highest at night, particularly during evenings, except for Farfield moorings such as E-2000 and W-5000.




C-400 (N = 151 PPM)
C-600 (N = 537 PPM)
C-800 (N = 20 PPM)
C-1000 (N = 252 PPM)
C-2000 (N = 519 PPM)
C-5000 (N = 361 PPM*)
% of PPMs
30.0
20.0
10.0
0.0
00 02 04 06 08 10 12 14 16 18 20 22
Hour


W-200 (N = 356 PPM)
W-400 (N = 343 PPM)
W-600 (N = 51 PPM)
W-800 (N = 143 PPM)
W-1000 (N = 310 PPM)
W-2000 (N = 78 PPM)
W-5000 (N = 430 PPM)
% of PPMs
30.0
20.0
10.0
0.0
00 02 04 06 08 10 12 14 16 18 20 22
Hour

APPENDIX 5 - GAM DESCRIPTORS AND OUTPUTS

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

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

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

Table A8.1. List of available covariates considered for models. * Indicates covariates that were only considered for compound models.

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		

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

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

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

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

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

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

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

Full array model

Model:	Entire array
Model structure:	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)
Confusion matrix:	(see below)
AUC value:	0.8436431

Confusion matrix:

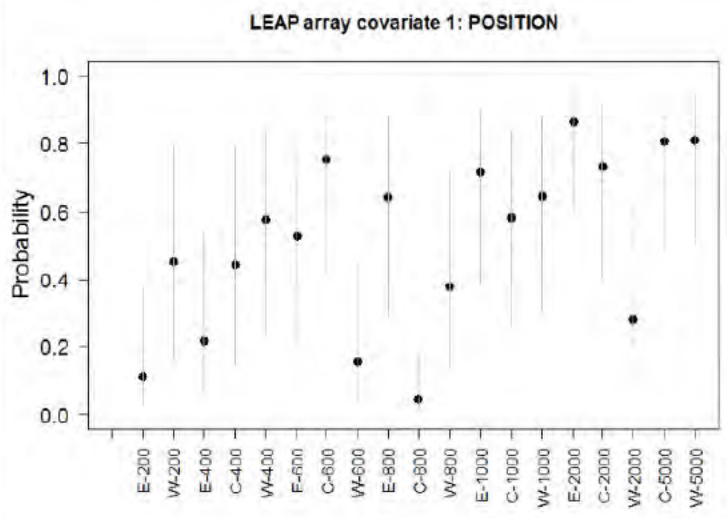
		Expected	
		Porpoise	No porpoise
Observed	Porpoise	81.3%	27.3%
	No porpoise	18.7%	72.7%

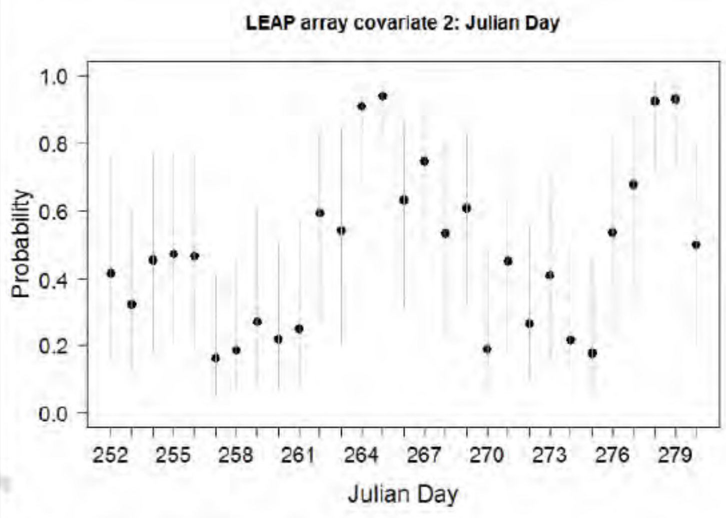
Results of Wald's tests for all significant covariates for the final model:

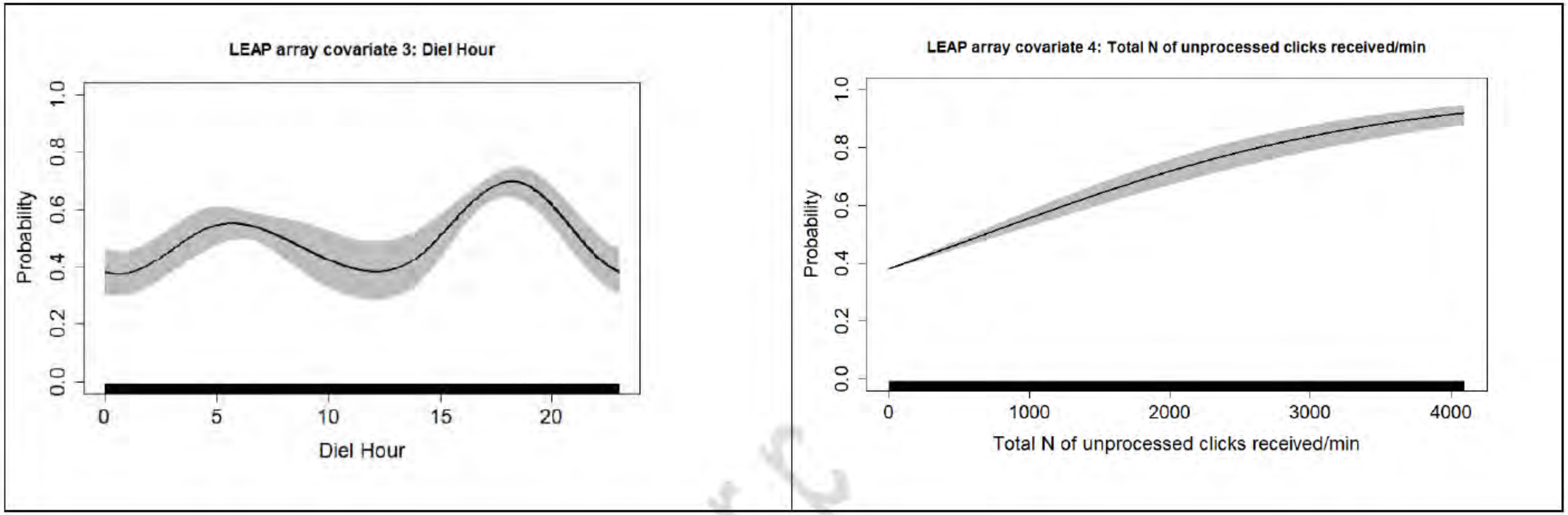
Covariates (in descending order of significance)	Form	Degrees of Freedom	χ^2 score	P-value
POSITION	factor	18	423.14	$<2.2\cdot10^{-16}$
JULDAY	factor	28	273.52	$<2.2\cdot10^{-16}$
HOUR	Cyclic B-spline	4	138.73	$<2.2\cdot10^{-16}$
Nall_m	linear	1	169.23	$<2.2\cdot10^{-16}$
Signal_Type	factor	3	37.69	$3.291\cdot10^{-8}$
HiLoTide	Cyclic B-spline	4	27.66	$1.462\cdot10^{-5}$

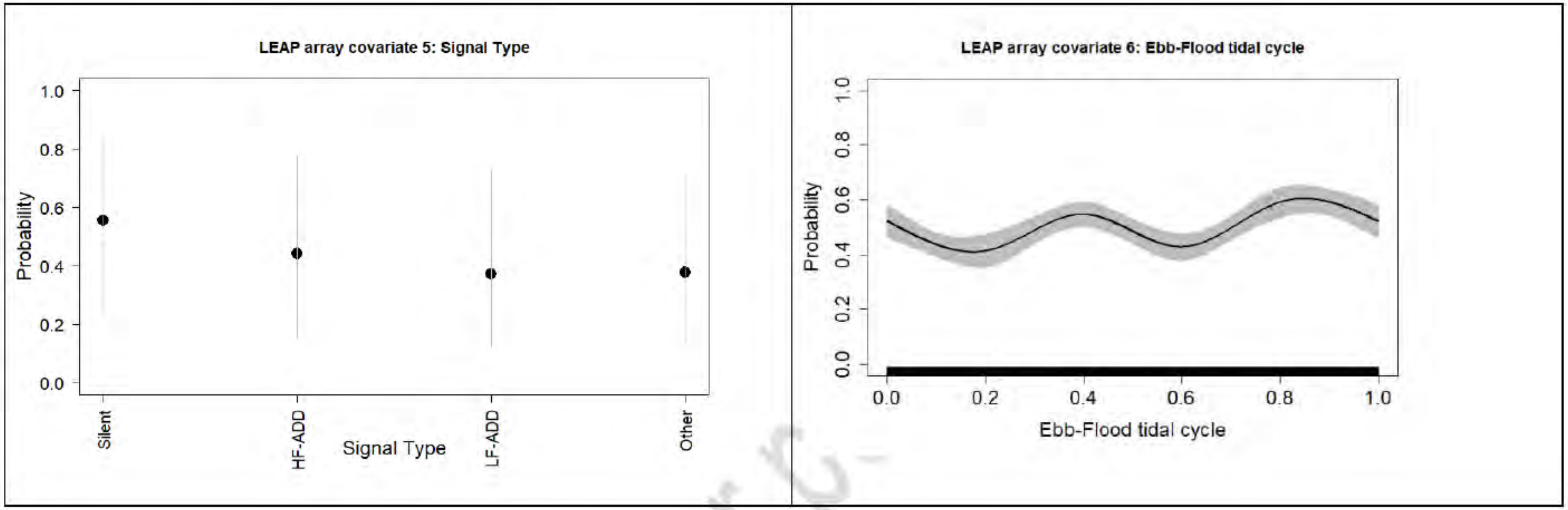
DAYTIMENum	factor	3	15.00	0.001819

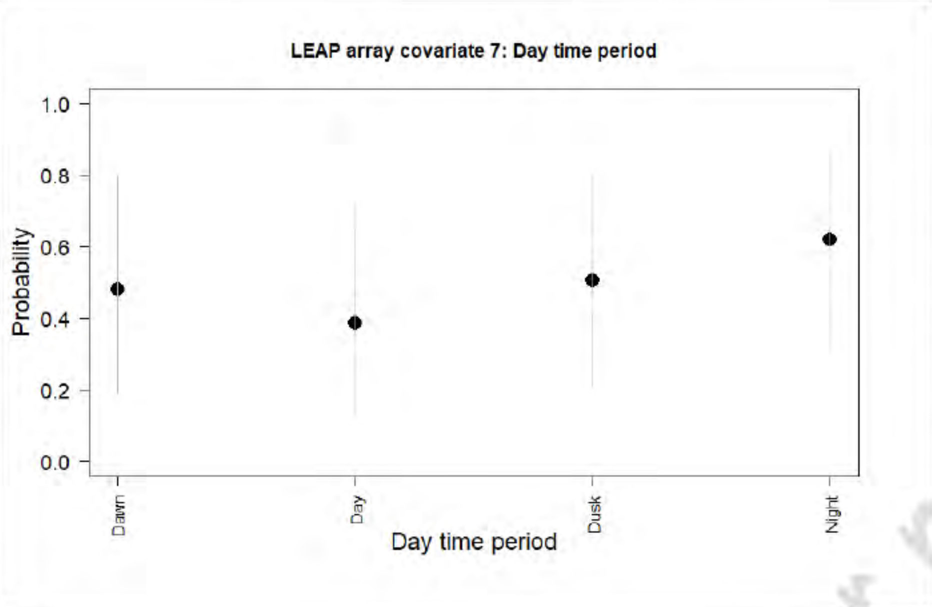
SpringNeap	Cyclic B-spline	4	11.35	0.022868

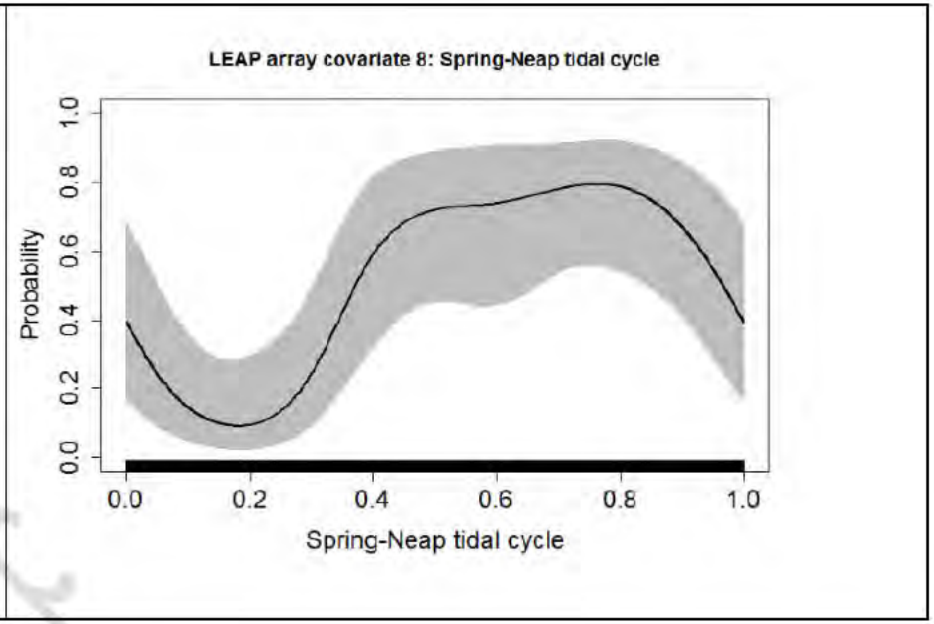

LEAP array covariate 1: POSITION
Probability
1.0
0.8
0.6
0.4
0.2
0.0
E-200
W-200
E-400
C-400
W-400
E-600
C-600
W-600
E-800
C-800
W-800
E-1000
C-1000
W-1000
E-2000
C-2000
W-2000
C-5000
W-5000


LEAP array covariate 2: Julian Day
Probability
1.0
0.8
0.6
0.4
0.2
0.0
252
255
258
261
264
267
270
273
276
279
Julian Day


LEAP array covariate 3: Diel Hour
Probability
0.0
0.2
0.4
0.6
0.8
1.0
0
5
10
15
20
Diel Hour
LEAP array covariate 4: Total N of unprocessed clicks received/min
Probability
0.0
0.2
0.4
0.6
0.8
1.0
0
1000
2000
3000
4000
Total N of unprocessed clicks received/min


LEAP array covariate 5: Signal Type
Probability
1.0
0.8
0.6
0.4
0.2
0.0
Silent
HF-ADD
LF-ADD
Other
Signal Type
LEAP array covariate 6: Ebb-Flood tidal cycle
Probability
0.0
0.2
0.4
0.6
0.8
1.0
Ebb-Flood tidal cycle


LEAP array covariate 7: Day time period
Probability
1.0
0.8
0.6
0.4
0.2
0.0
Dawn
Day
Dusk
Night
Day time period


LEAP array covariate 8: Spring-Neap tidal cycle
Probability
0.0
0.2
0.4
0.6
0.8
1.0
Spring-Neap tidal cycle

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Nearfield model

Model:	Nearfield moorings (E-200-E1000, C-400-1000, & W-200-1000)
Model structure:	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)
Confusion matrix:	(see below)

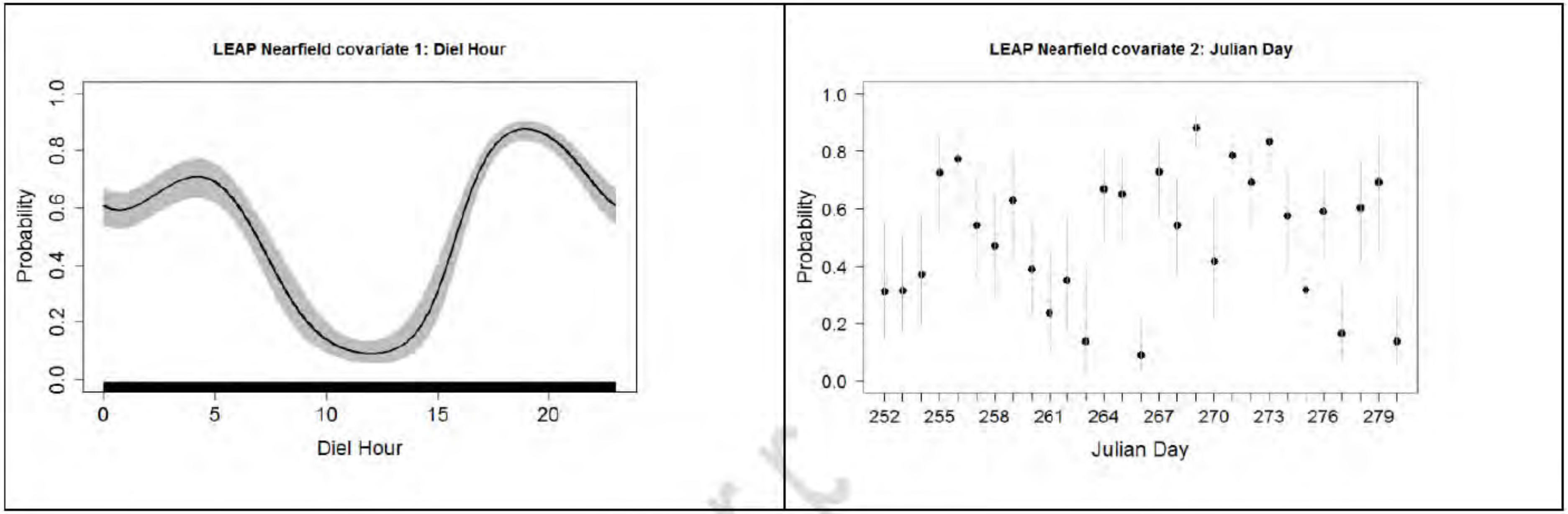
		Expected	
		Porpoise	No porpoise
Observed	Porpoise	80.6%	19.2%
	No porpoise	19.4%	80.8%

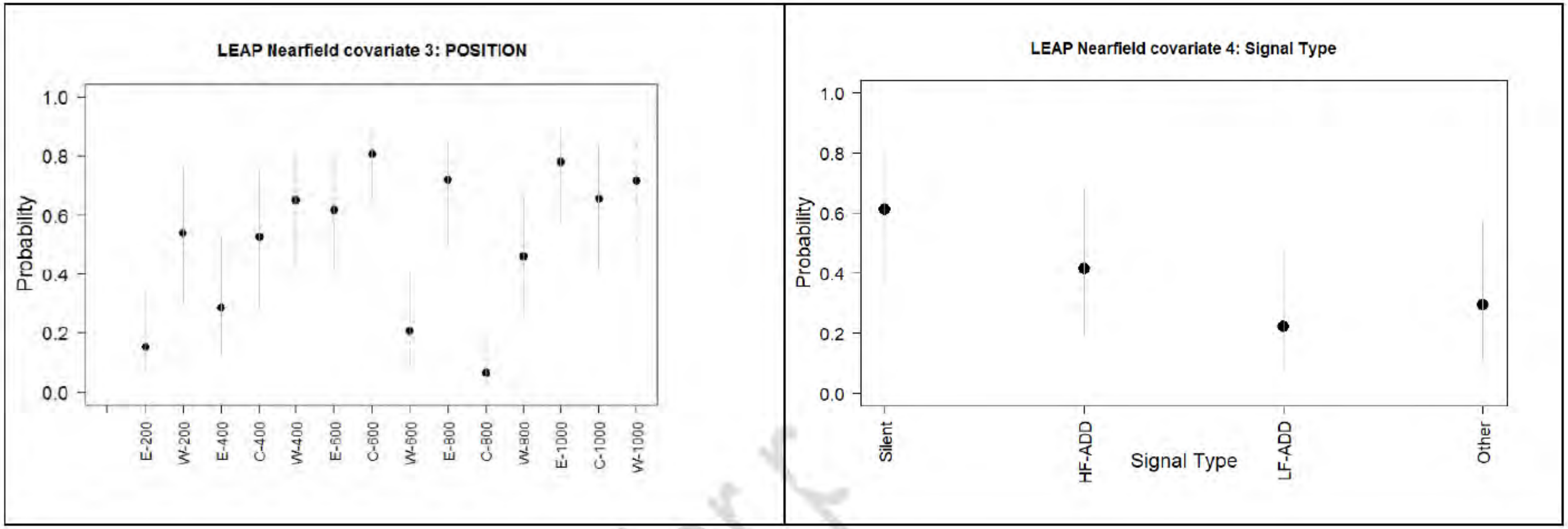
AUC value:	0.8893874

Results of Wald's tests for all significant covariates for the final model:

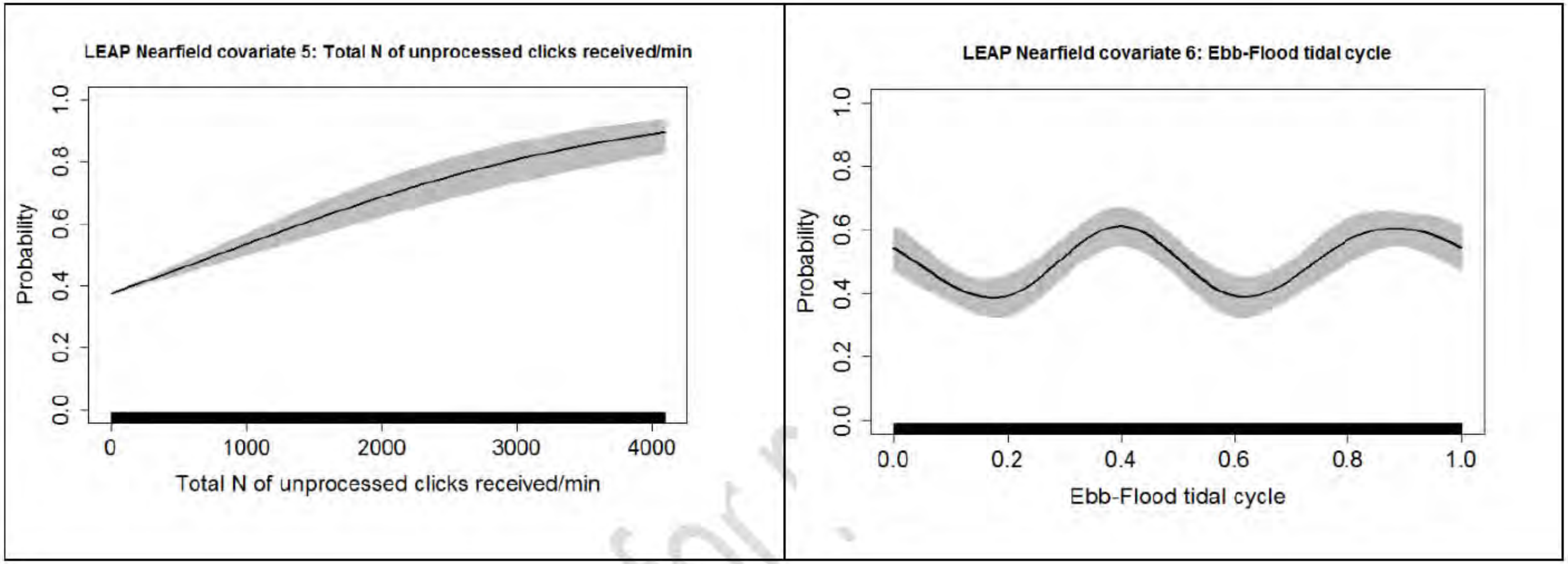
Covariates (in descending order of significance)	Form	Degrees of Freedom	χ^2 score	P-value
HOUR	Cyclic B-spline	4	165.23	$<2.2\cdot10^{-16}$
JULDAY	factor	28	367.38	$<2.2\cdot10^{-16}$
POSITION	factor	13	195.50	$<2.2\cdot10^{-16}$
Signal_Type	factor	3	61.93	$2.272\cdot10^{-13}$
Nall_m	linear	1	73.34	$<2.2\cdot10^{-16}$

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


LEAP Nearfield covariate 1: Diel Hour
Probability
0.0
0.2
0.4
0.6
0.8
1.0
0
5
10
15
20
Diel Hour
LEAP Nearfield covariate 2: Julian Day
Probability
0.0
0.2
0.4
0.6
0.8
1.0
252
255
258
261
264
267
270
273
276
279
Julian Day



LEAP Nearfield covariate 3: POSITION
Probability
1.0
0.8
0.6
0.4
0.2
0.0
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
LEAP Nearfield covariate 4: Signal Type
Silent
HF-ADD
LF-ADD
Other
Signal Type


LEAP Nearfield covariate 5: Total N of unprocessed clicks received/min
Probability
0.0
0.2
0.4
0.6
0.8
1.0
0
1000
2000
3000
4000
Total N of unprocessed clicks received/min
LEAP Nearfield covariate 6: Ebb-Flood tidal cycle
Probability
0.0
0.2
0.4
0.6
0.8
1.0
0.0
0.2
0.4
0.6
0.8
1.0
Ebb-Flood tidal cycle

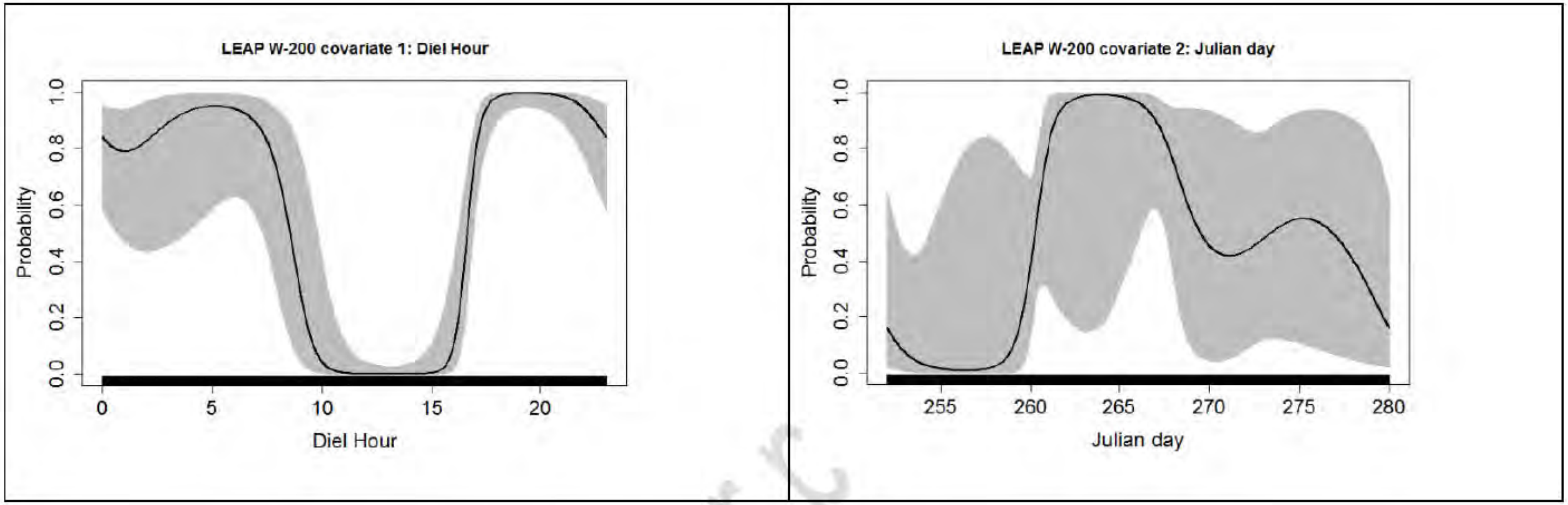
Model:	W-200
Model structure:	POD5<-geeglm(PPM ~ AvgHrBasisMat + bs(JULDAY , knots=mean(JULDAY)) + Nall_m, family = binomial, corstr="independence", id=Panel, data=W200)
Confusion matrix:	

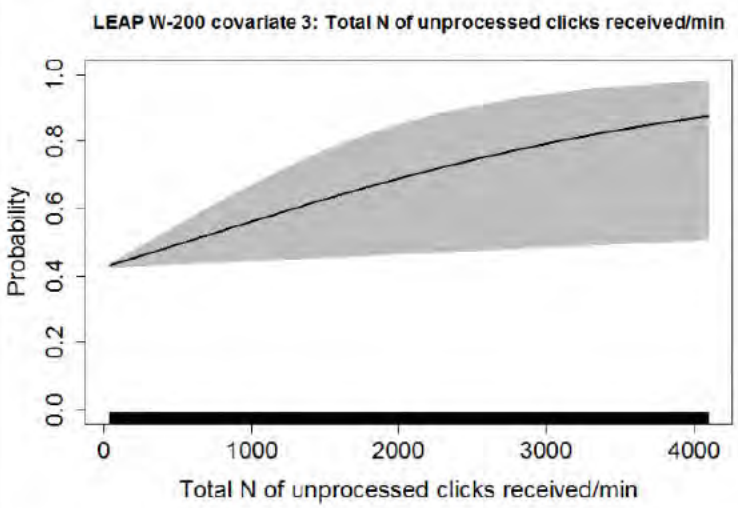
		Expected	
		Porpoise	No porpoise
Observed	Porpoise	77.5%	6.8%
	No porpoise	22.5%	93.2%

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


LEAP W-200 covariate 1: Diel Hour
Probability
0.0
0.2
0.4
0.6
0.8
1.0
0
5
10
15
20
Diel Hour
LEAP W-200 covariate 2: Julian day
Probability
0.0
0.2
0.4
0.6
0.8
1.0
255
260
265
270
275
280
Julian day


LEAP W-200 covariate 3: Total N of unprocessed clicks received/min
Probability
0.0
0.2
0.4
0.6
0.8
1.0
0
1000
2000
3000
4000
Total N of unprocessed clicks received/min

1795

Model:	E-400
Model structure:	POD5<-geeglm(PPM ~ AvgHrBasisMat + SprNpBasisMat + Nall_m, family = binomial, corstr="independence", id=Panel, data=E400)

Confusion matrix:

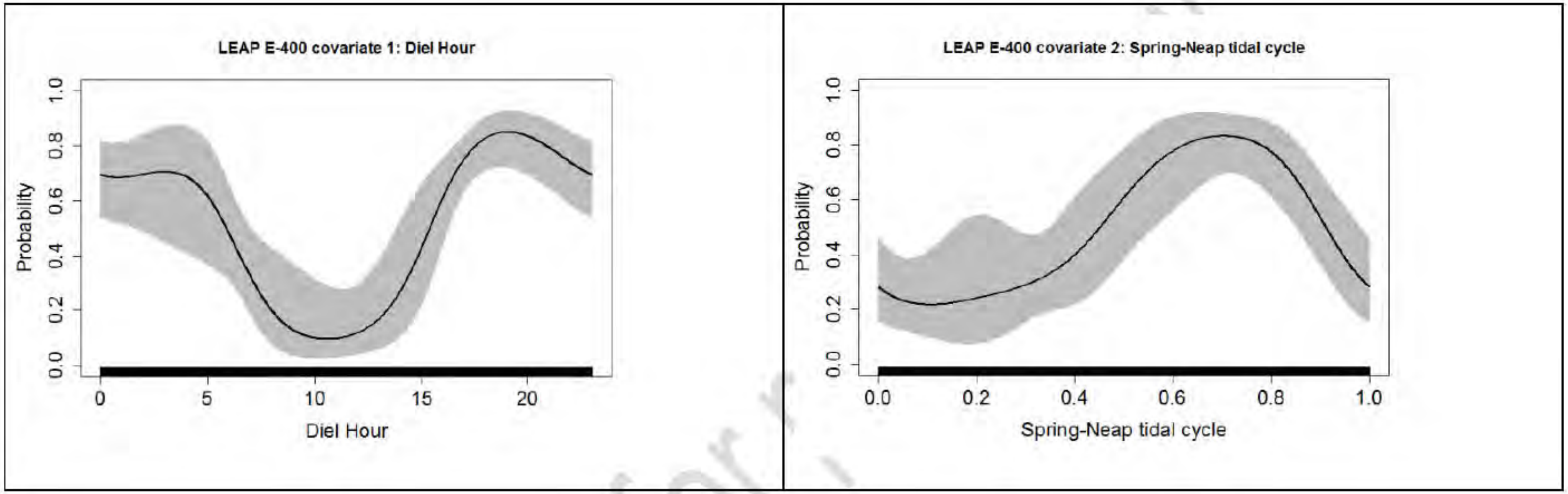
		Expected	
		Porpoise	No porpoise
Observed	Porpoise	74.7%	22.4%
	No porpoise	25.3%	77.6%

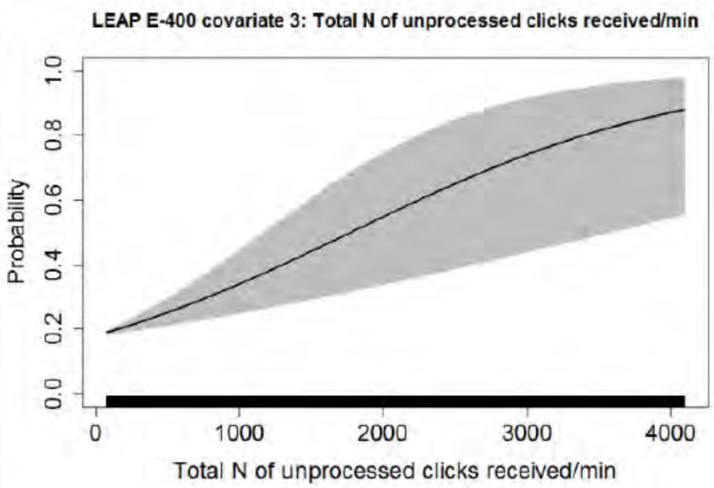
AUC value:	0.8263694

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	$3.749\cdot10^{-5}$
SpringNeap	Cyclic B-spline	4	17.091	0.0018557
Nall_m	linear	1	14.680	0.0001274

1797


LEAP E-400 covariate 1: Diel Hour
Probability
0.0
0.2
0.4
0.6
0.8
1.0
0
5
10
15
20
Diel Hour
LEAP E-400 covariate 2: Spring-Neap tidal cycle
Probability
0.0
0.2
0.4
0.6
0.8
1.0
Spring-Neap tidal cycle


LEAP E-400 covariate 3: Total N of unprocessed clicks received/min
Probability
0.0
0.2
0.4
0.6
0.8
1.0
0
1000
2000
3000
4000
Total N of unprocessed clicks received/min

1798

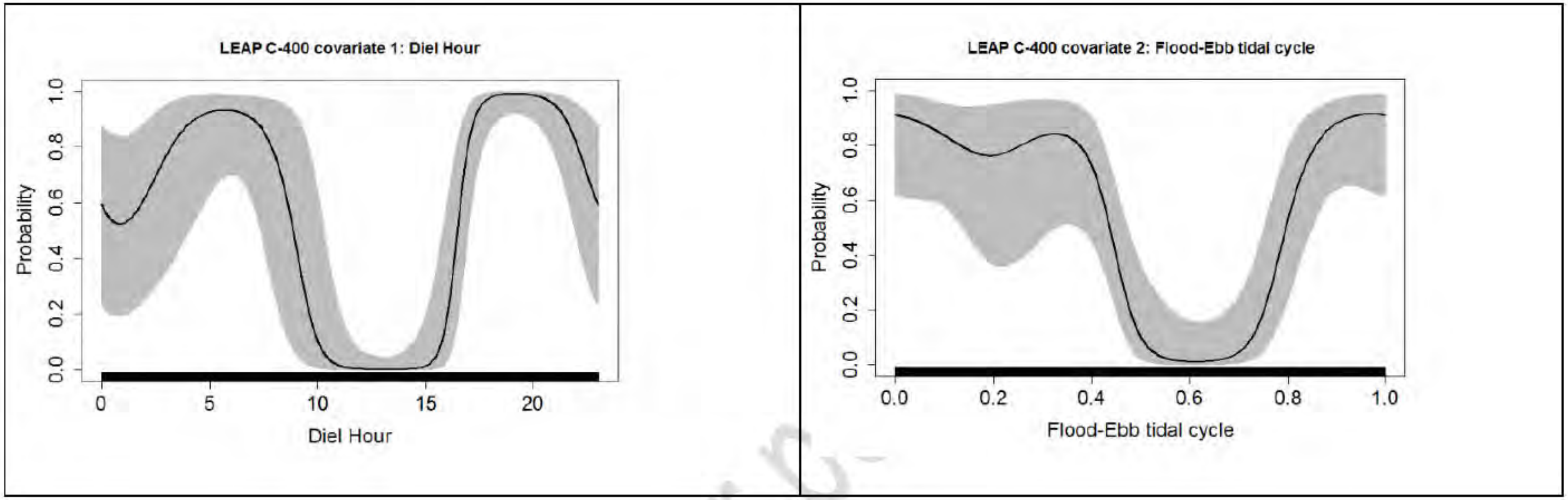
Model:	C-400
Model structure:	POD5<-geeglm(PPM ~ AvgHrBasisMat + TideBasisMat + bs(JULDAY , knots=mean(JULDAY)) + Nall_m, family = binomial, corstr="independence", id=Panel, data=C400)
Confusion matrix:	

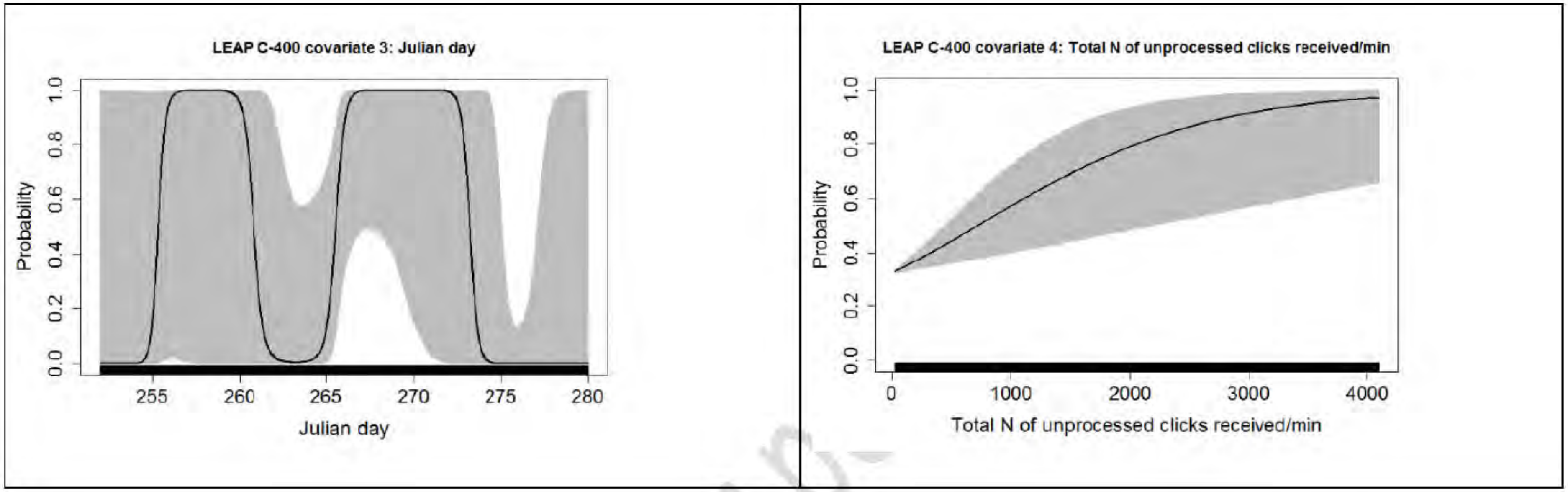
		Expected	
		Porpoise	No porpoise
Observed	Porpoise	89.3%	10.8%
	No porpoise	10.7%	89.2%

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


LEAP C-400 covariate 1: Diel Hour
Probability
0.0
0.2
0.4
0.6
0.8
1.0
0
5
10
15
20
Diel Hour
LEAP C-400 covariate 2: Flood-Ebb tidal cycle
Probability
0.0
0.2
0.4
0.6
0.8
1.0
Flood-Ebb tidal cycle


LEAP C-400 covariate 3: Julian day
Probability
0.0
0.2
0.4
0.6
0.8
1.0
255
260
265
270
275
280
Julian day
LEAP C-400 covariate 4: Total N of unprocessed clicks received/min
Probability
0.0
0.2
0.4
0.6
0.8
1.0
0
1000
2000
3000
4000
Total N of unprocessed clicks received/min

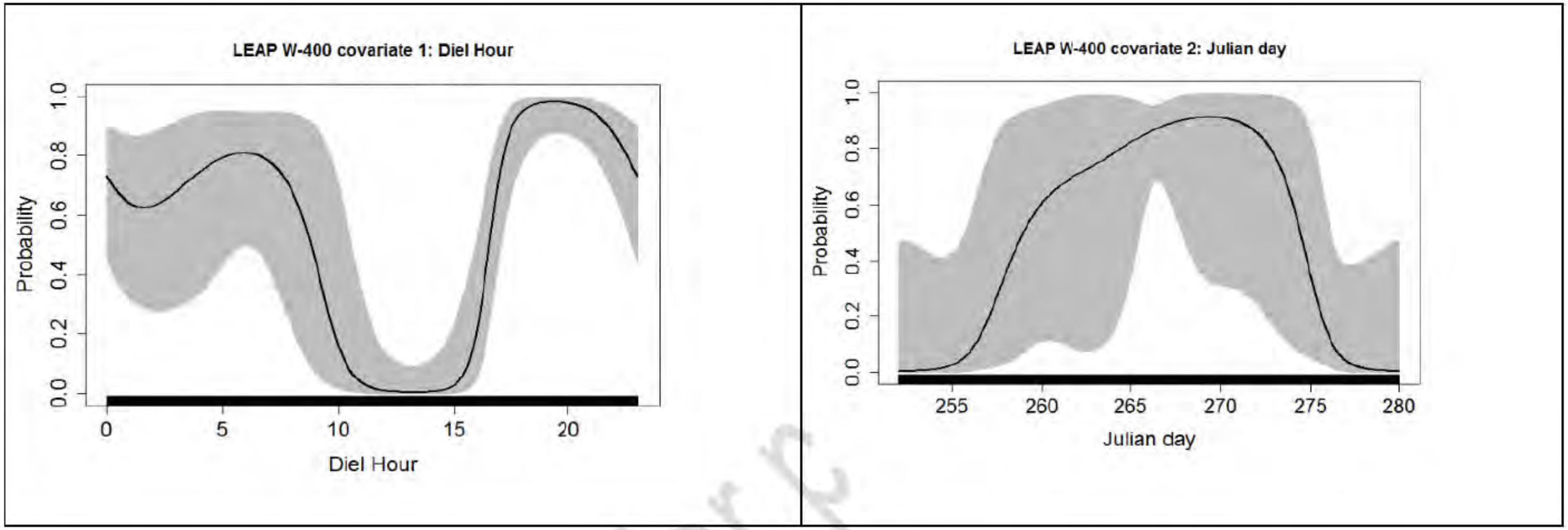
Model:	W-400
Model structure:	POD5<-geeglm(PPM ~ AvgHrBasisMat + bs(JULDAY , knots=mean(JULDAY)) + as.factor(Signal_Type) + Nall_m + TideBasisMat, family = binomial, corstr="independence", id=Panel, data=W400)
Confusion matrix:	(see matrix below)

		Expected	
		Porpoise	No porpoise
Observed	Porpoise	88.4%	21.9%
	No porpoise	11.6%	78.1%

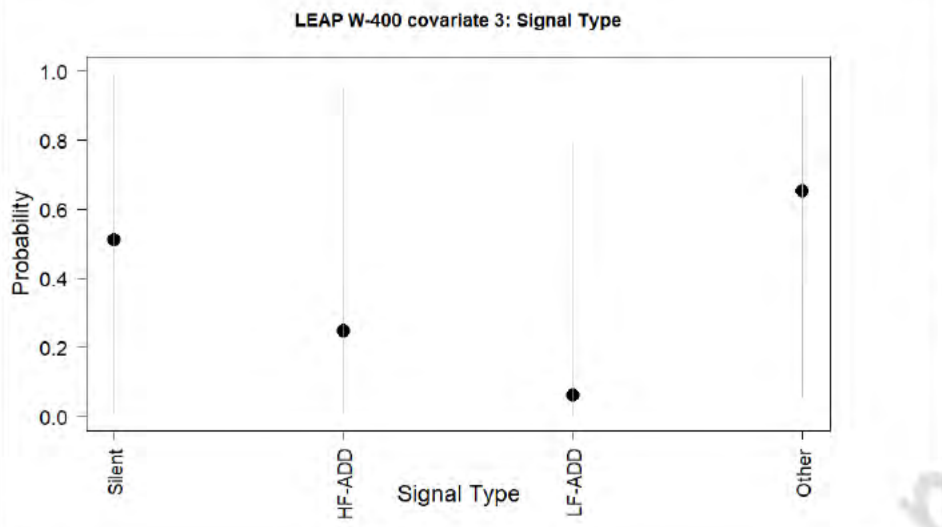
AUC value:	0.9068351

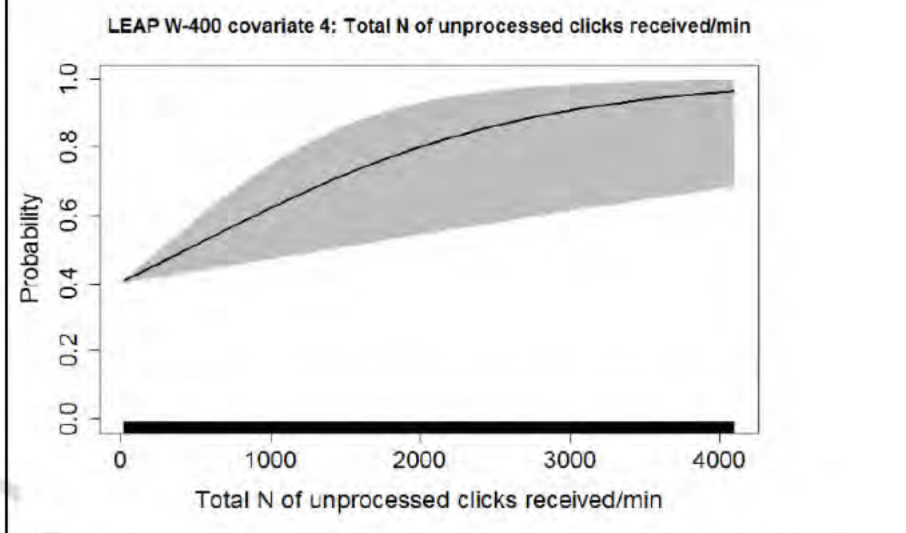
Results of Wald's tests for all significant covariates for the final model:

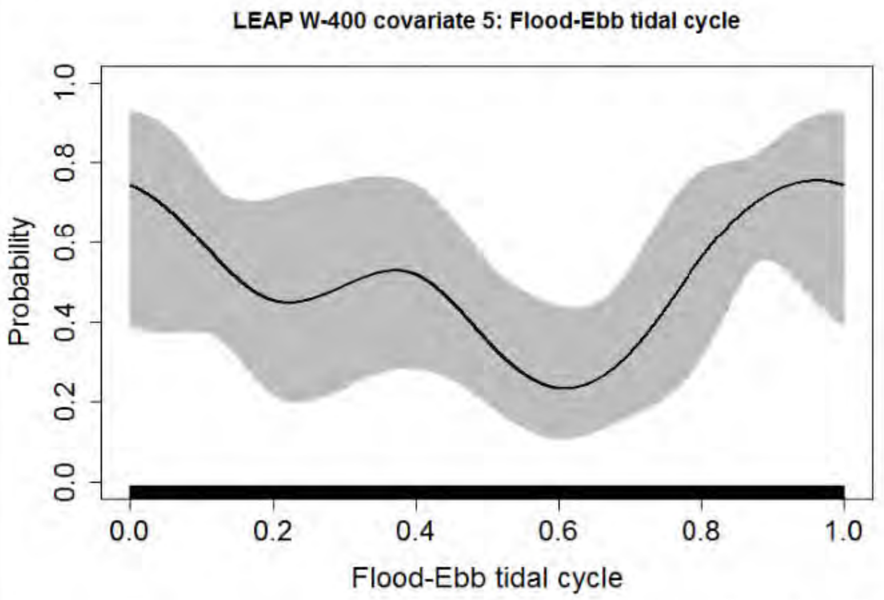
Covariates (in descending order of significance)	Form	Degrees of Freedom	χ^2 score	P-value
HOUR	Cyclic B-spline	4	21.8619	0.0002135
JULDAY	Cubic B-spline	4	17.9475	0.0012636
Signal_Type	Factor	3	13.8378	0.0031345
Nall_m	Linear	1	7.2002	0.0072895
HiLoTide	Cyclic B-spline	4	11.4568	0.0218828



LEAP W-400 covariate 1: Diel Hour
Probability
0.0
0.2
0.4
0.6
0.8
1.0
0
5
10
15
20
Diel Hour
LEAP W-400 covariate 2: Julian day
Probability
0.0
0.2
0.4
0.6
0.8
1.0
255
260
265
270
275
280
Julian day


LEAP W-400 covariate 3: Signal Type
Probability
1.0
0.8
0.6
0.4
0.2
0.0
Silent
HF-ADD
LF-ADD
Other
Signal Type


LEAP W-400 covariate 4: Total N of unprocessed clicks received/min
Probability
1.0
0.8
0.6
0.4
0.2
0.0
0
1000
2000
3000
4000
Total N of unprocessed clicks received/min


LEAP W-400 covariate 5: Flood-Ebb tidal cycle
Probability
0.0
0.2
0.4
0.6
0.8
1.0
Flood-Ebb tidal cycle

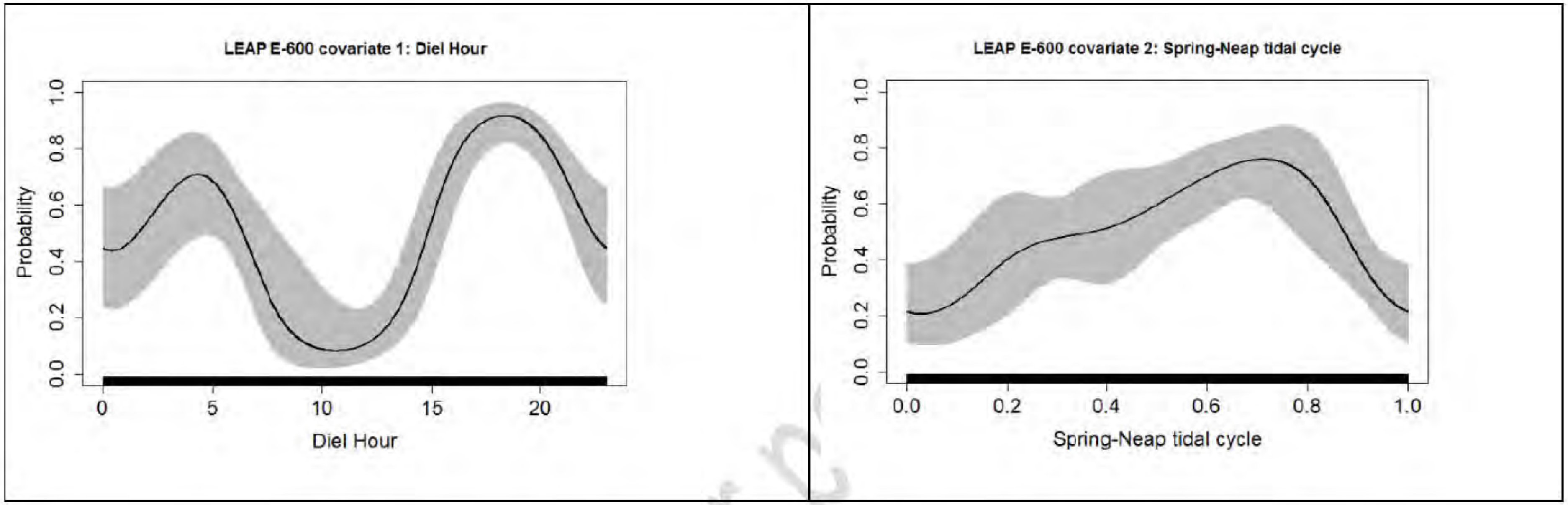
Model:	E-600
Model structure:	POD5<-geeglm(PPM ~ AvgHrBasisMat + bs(JULDAY , knots=mean(JULDAY)) + SprNpBasisMat + TideBasisMat, family = binomial, corstr="independence", id=Panel, data=E600)
Confusion matrix:	

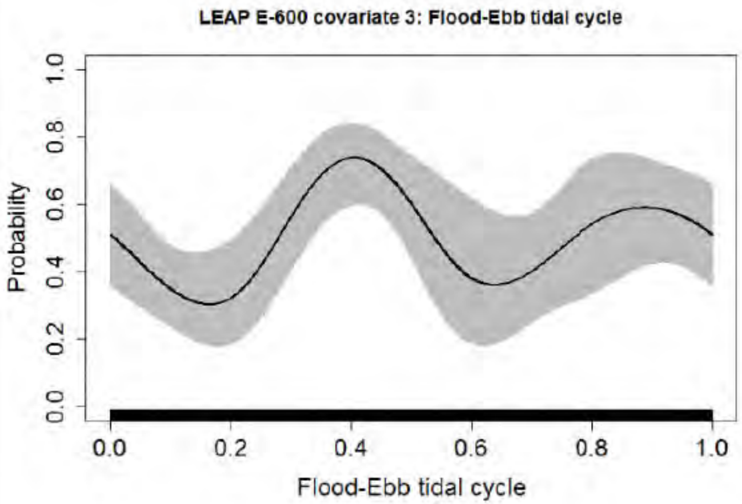
		Expected	
		Porpoise	No porpoise
Observed	Porpoise	75.5%	23.6%
	No porpoise	24.5%	76.4%

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


LEAP E-600 covariate 1: Diel Hour
Probability
0.0
0.2
0.4
0.6
0.8
1.0
0
5
10
15
20
Diel Hour
LEAP E-600 covariate 2: Spring-Neap tidal cycle
Probability
0.0
0.2
0.4
0.6
0.8
1.0
0.0
0.2
0.4
0.6
0.8
1.0
Spring-Neap tidal cycle



LEAP E-600 covariate 3: Flood-Ebb tidal cycle
Probability
0.0
0.2
0.4
0.6
0.8
1.0
Flood-Ebb tidal cycle

1804

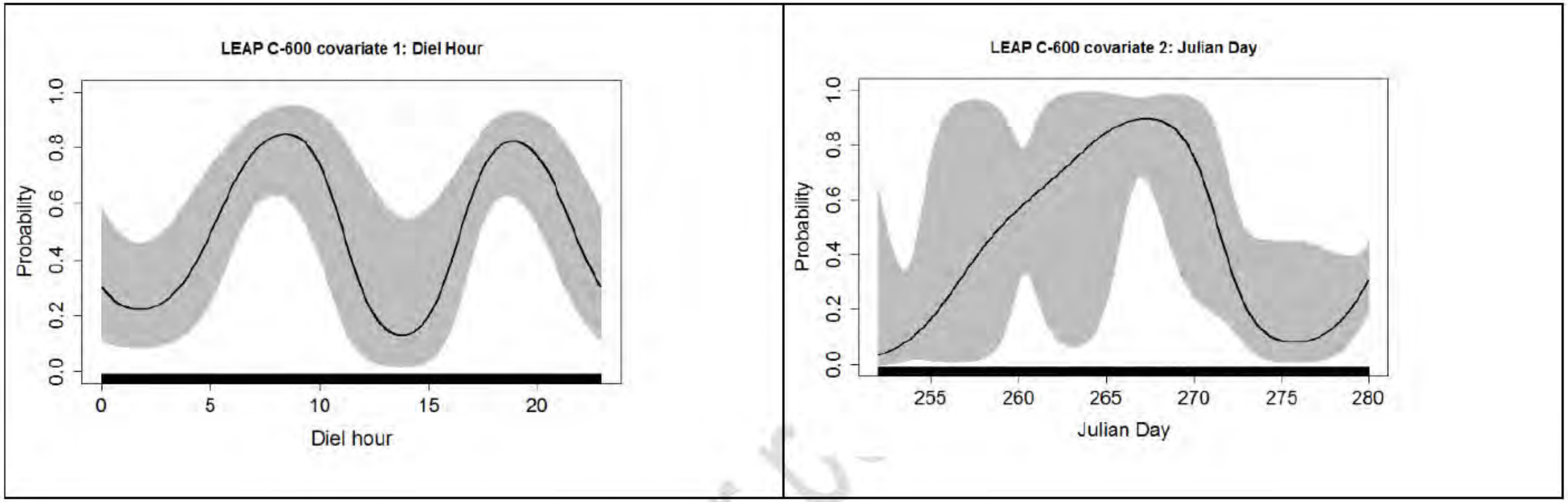
Model:	C-600
Model structure:	POD7<-geeglm(PPM ~ AvgHrBasisMat + bs(JULDAY , knots=mean(JULDAY)) + Nall_m + as.factor(DAYTIMENum), family = binomial, corstr="independence", id=Panel, data=C600)
Confusion matrix:	

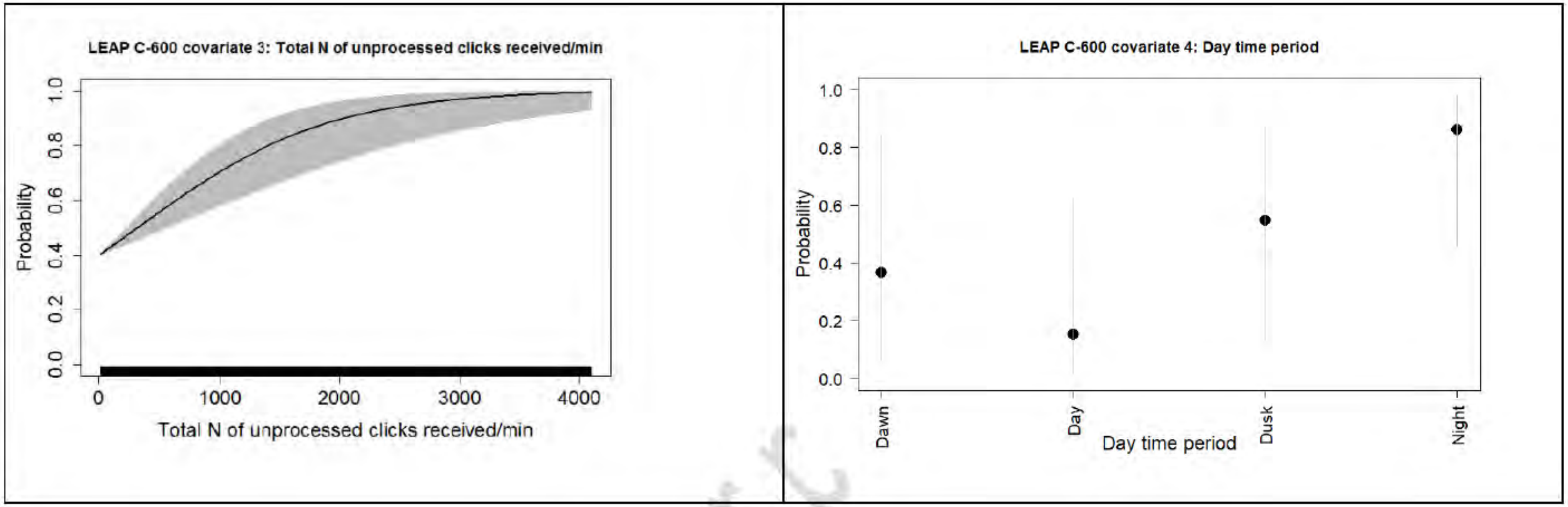
		Expected	
		Porpoise	No porpoise
Observed	Porpoise	77.0%	15.6%
	No porpoise	23.0%	84.4%

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


LEAP C-600 covariate 1: Diel Hour
Probability
Diel hour
LEAP C-600 covariate 2: Julian Day
Probability
Julian Day


LEAP C-600 covariate 3: Total N of unprocessed clicks received/min
Probability
0.0
0.2
0.4
0.6
0.8
1.0
0
1000
2000
3000
4000
Total N of unprocessed clicks received/min
LEAP C-600 covariate 4: Day time period
Probability
0.0
0.2
0.4
0.6
0.8
1.0
Dawn
Day
Dusk
Night
Day time period

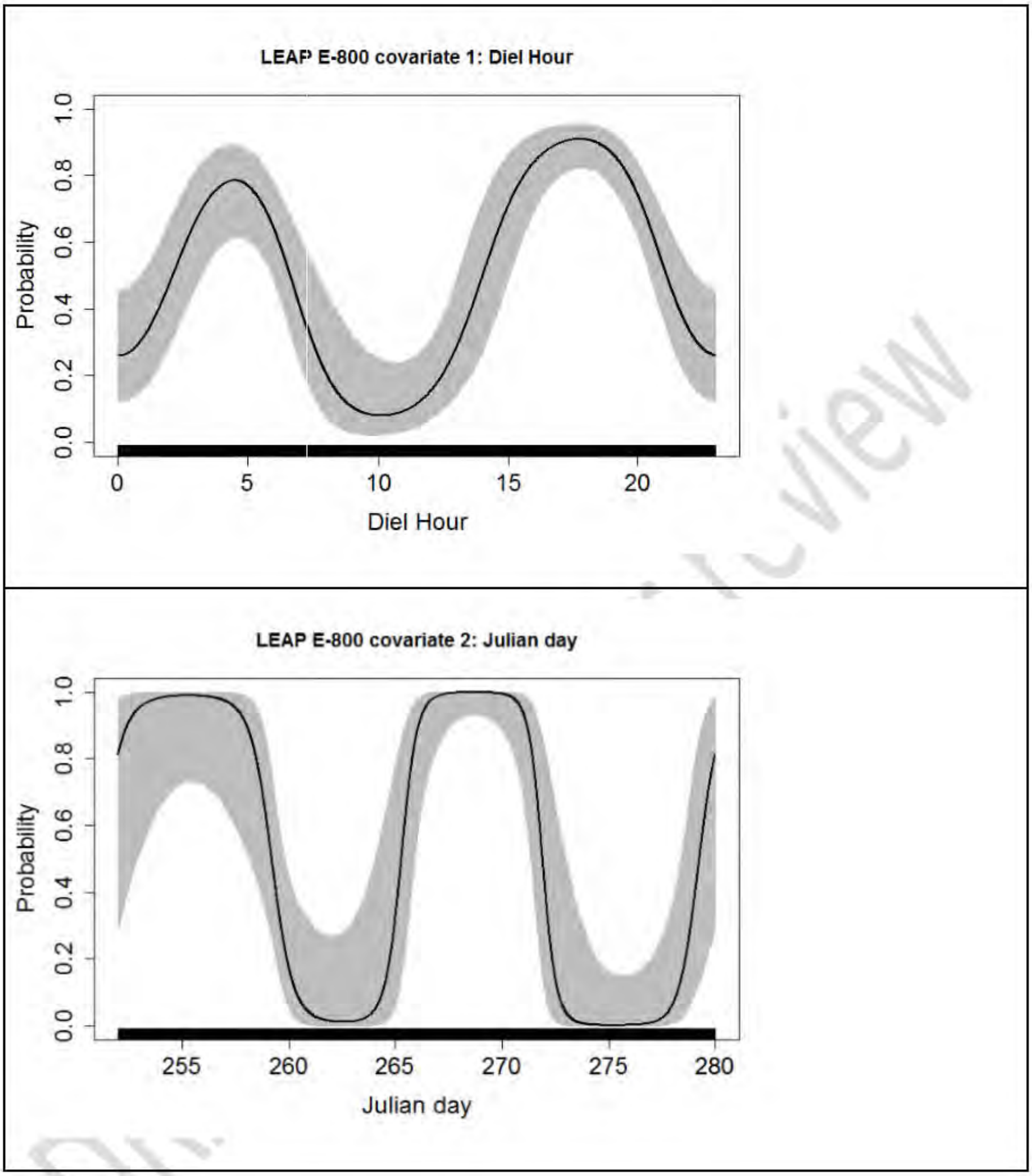
Model:	E-800
Model structure:	POD7<-geeglm(PPM ~ AvgHrBasisMat + bs(JULDAY , knots=mean(JULDAY)), family = binomial, corstr="independence", id=Panel, data=E800)
Confusion matrix:	

		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



LEAP E-800 covariate 1: Diel Hour
Probability
0.0
0.2
0.4
0.6
0.8
1.0
0
5
10
15
20
Diel Hour
LEAP E-800 covariate 2: Julian day
Probability
0.0
0.2
0.4
0.6
0.8
1.0
255
260
265
270
275
280
Julian day

Model:	W-800
Model structure:	POD5<-geeglm(PPM ~ AvgHrBasisMat + Nall_m + as.factor(Signal_Type) , family = binomial, corstr="independence", id=Panel, data=W800)

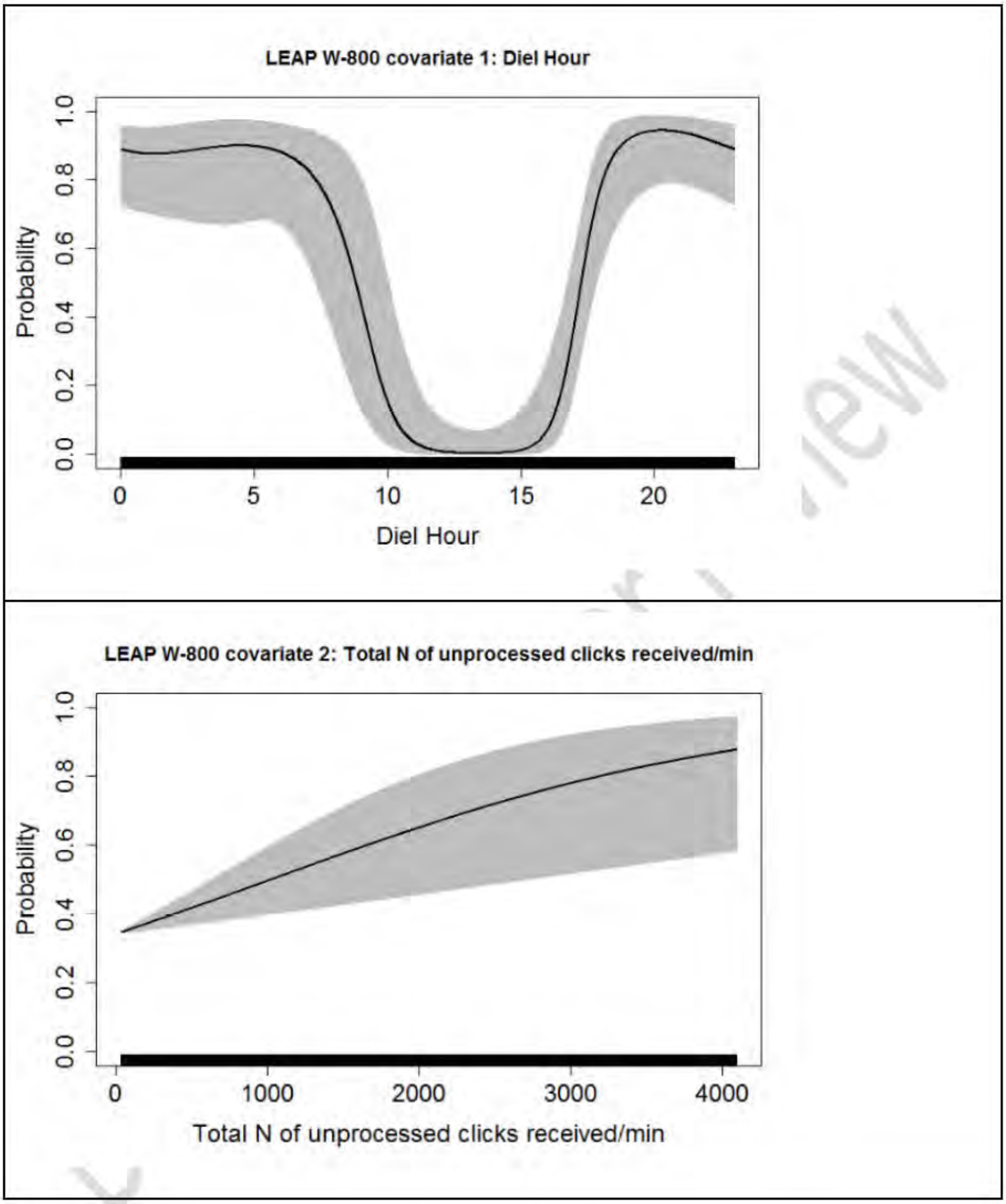
Confusion matrix:

		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



LEAP W-800 covariate 1: Diel Hour
Probability
0.0
0.2
0.4
0.6
0.8
1.0
0
5
10
15
20
Diel Hour
LEAP W-800 covariate 2: Total N of unprocessed clicks received/min
Probability
0.0
0.2
0.4
0.6
0.8
1.0
0
1000
2000
3000
4000
Total N of unprocessed clicks received/min

Model:	E-1000
Model structure:	POD4<-geeglm(PPM ~ AvgHrBasisMat + as.factor(Signal_Type)+ TideBasisMat + SprNpBasisMat, family = binomial, corstr="independence", id=Panel, data=E1000)
Confusion matrix:	

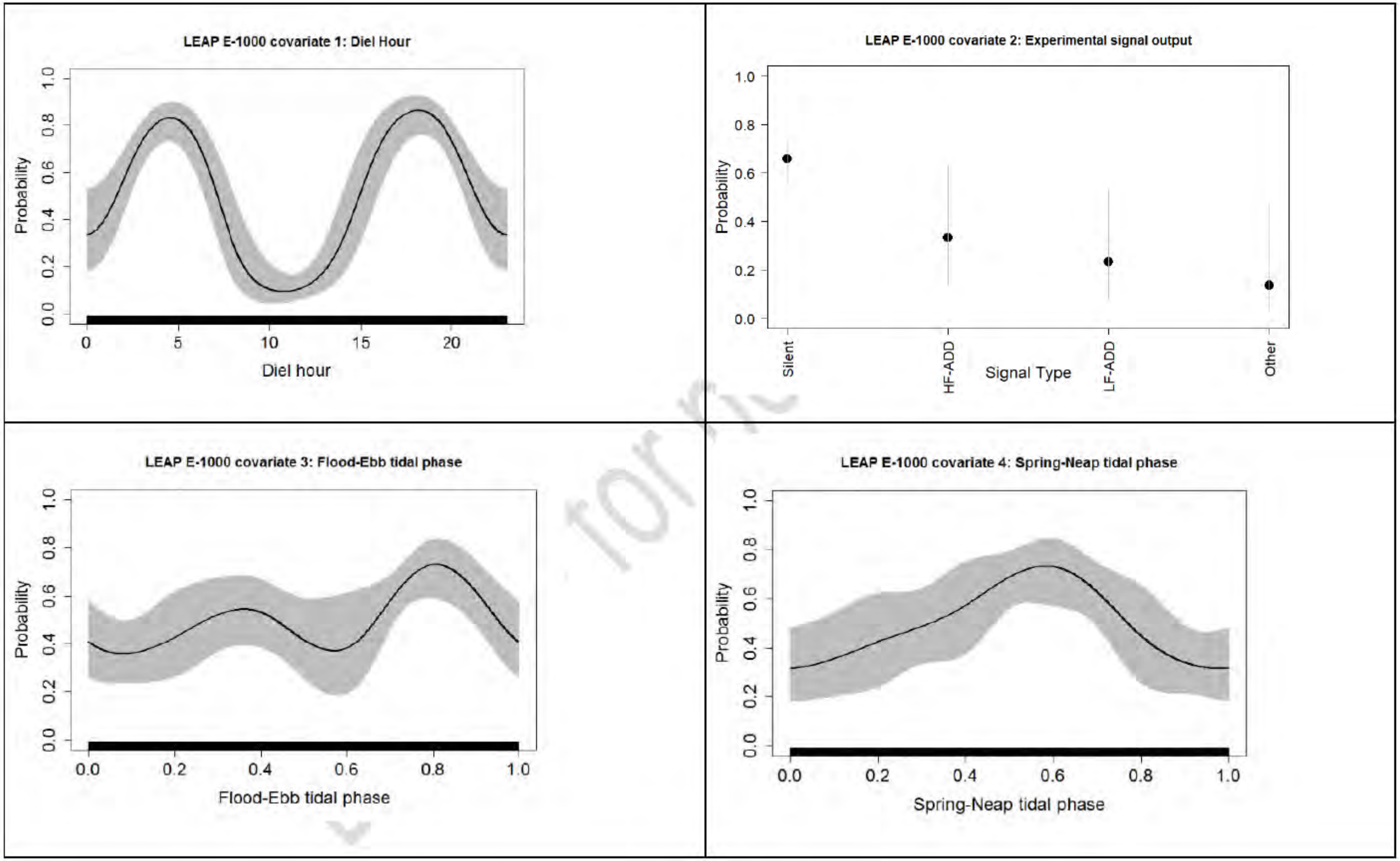
		Expected	
		Porpoise	No porpoise
Observed	Porpoise	83.7%	26.7%
	No porpoise	16.3%	73.3%

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

1813



LEAP E-1000 covariate 1: Diel Hour
Probability
Diel hour
LEAP E-1000 covariate 2: Experimental signal output
Probability
Silent
HF-ADD
LF-ADD
Other
Signal Type
LEAP E-1000 covariate 3: Flood-Ebb tidal phase
Probability
Flood-Ebb tidal phase
LEAP E-1000 covariate 4: Spring-Neap tidal phase
Probability
Spring-Neap tidal phase

1814

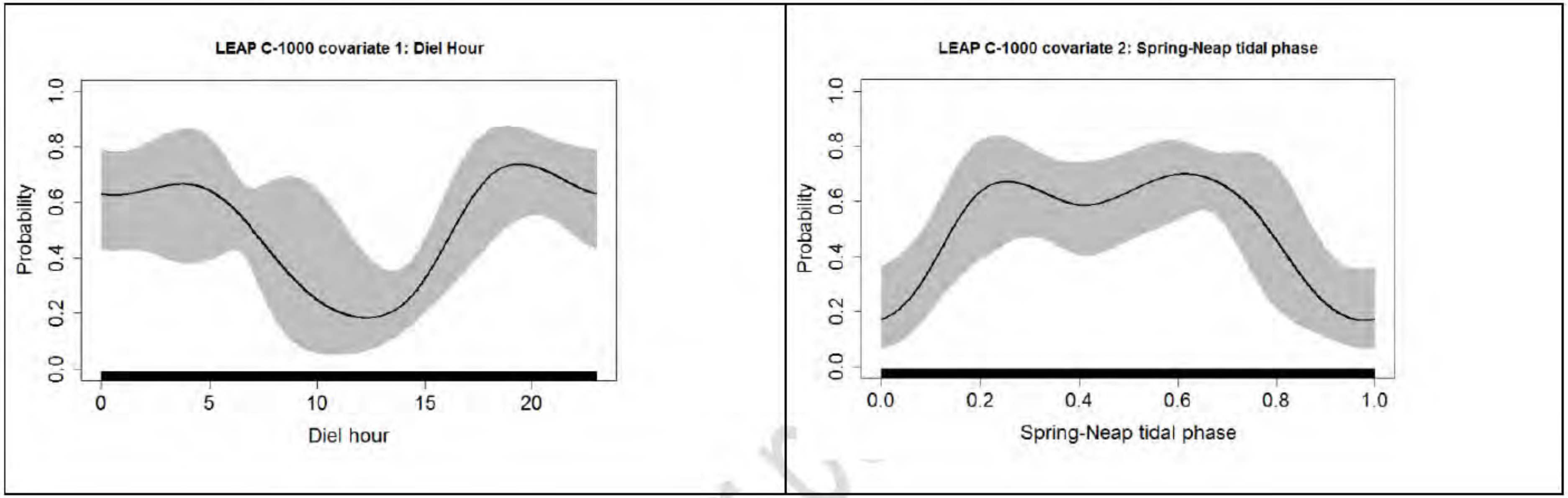
Model:	C-1000
Model structure:	POD5<-geeglm(PPM ~ AvgHrBasisMat + SprNpBasisMat + TideBasisMat, family = binomial, corstr="independence", id=Panel, data=C1000)
Confusion matrix:	(see below)
AUC value:	0.7798787

Confusion matrix:

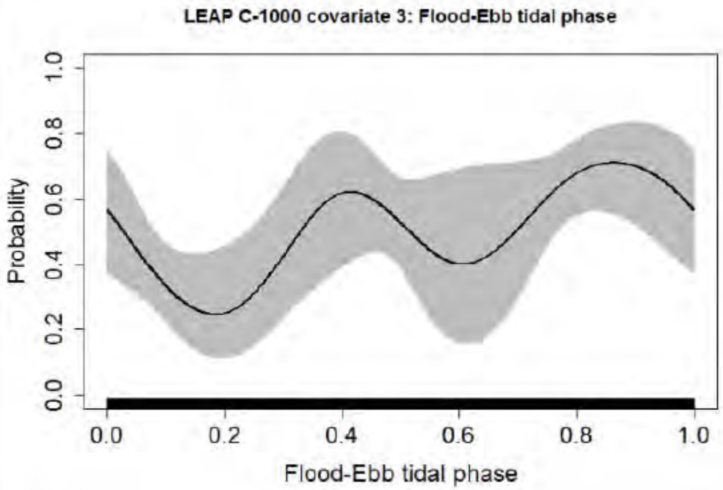
		Expected	
		Porpoise	No porpoise
Observed	Porpoise	73.0%	27.9%
	No porpoise	27.0%	72.1%

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



LEAP C-1000 covariate 1: Diel Hour
Probability
0.0
0.2
0.4
0.6
0.8
1.0
0
5
10
15
20
Diel hour
LEAP C-1000 covariate 2: Spring-Neap tidal phase
Probability
0.0
0.2
0.4
0.6
0.8
1.0
0.0
0.2
0.4
0.6
0.8
1.0
Spring-Neap tidal phase


LEAP C-1000 covariate 3: Flood-Ebb tidal phase
Probability
0.0
0.2
0.4
0.6
0.8
1.0
Flood-Ebb tidal phase

1816

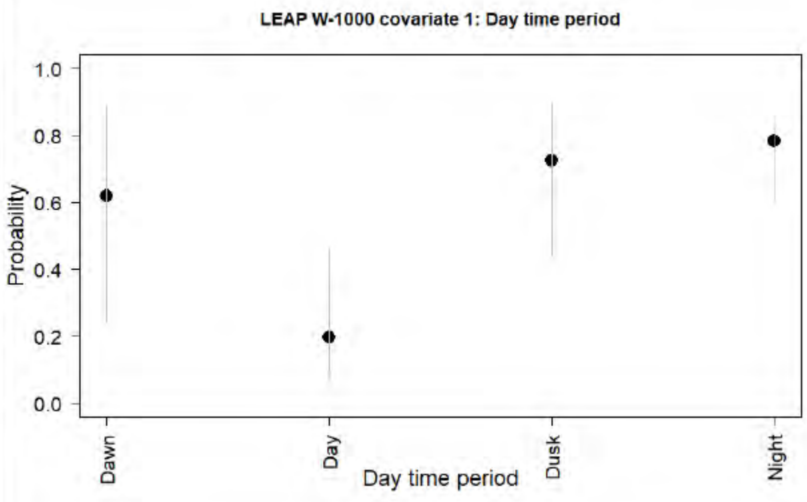
Model:	W-1000
Model structure:	POD5<-geeglm(PPM ~ as.factor(DAYTIMENum) + as.factor(Signal_Type) + Nall_m, family = binomial, corstr="independence", id=Panel, data=W1000)
Confusion matrix:	

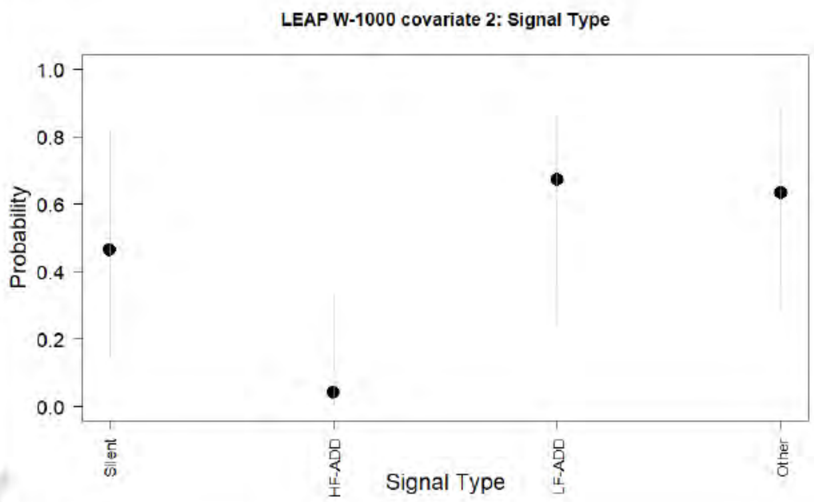
		Expected	
		Porpoise	No porpoise
Observed	Porpoise	87.8%	37.7%
	No porpoise	12.2%	62.3%

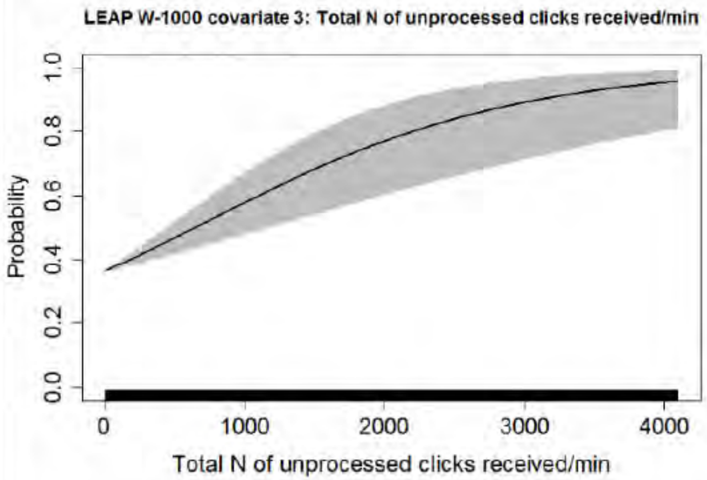
AUC value:	0.8144675

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	$6.547 \cdot 10^{-6}$


LEAP W-1000 covariate 1: Day time period
Probability
1.0
0.8
0.6
0.4
0.2
0.0
Dawn
Day
Dusk
Night
Day time period


LEAP W-1000 covariate 2: Signal Type
Probability
1.0
0.8
0.6
0.4
0.2
0.0
Silent
HF-ADD
LF-ADD
Other
Signal Type


LEAP W-1000 covariate 3: Total N of unprocessed clicks received/min
Probability
0.0
0.2
0.4
0.6
0.8
1.0
0
1000
2000
3000
4000
Total N of unprocessed clicks received/min

Model:	E-2000
Model structure:	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)

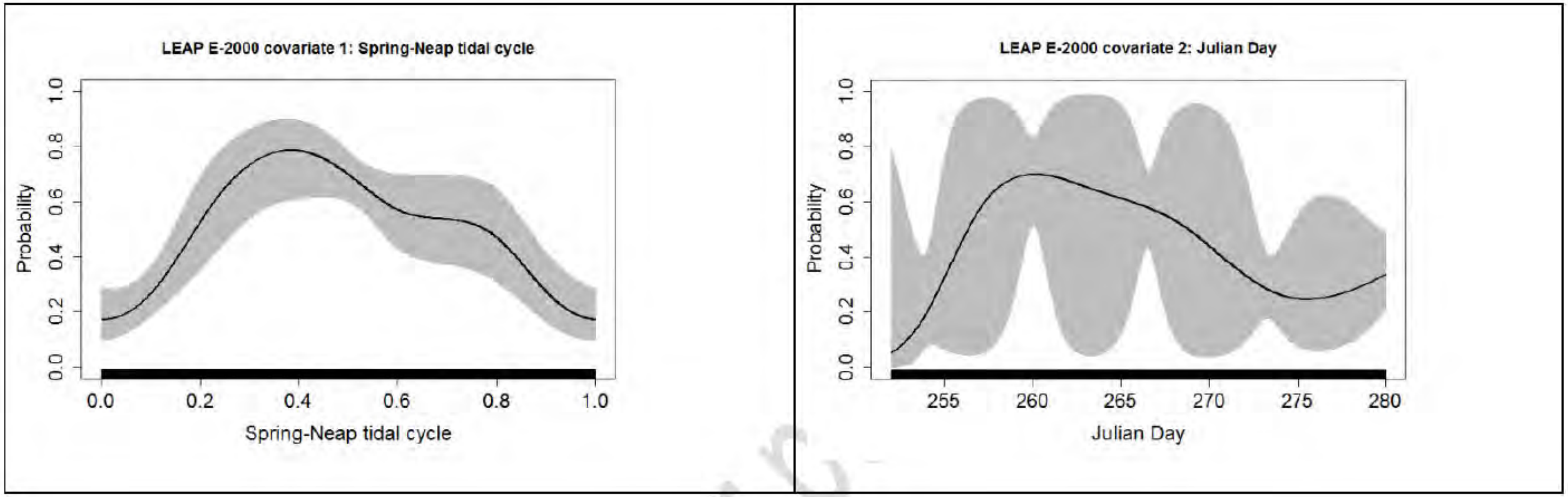
Confusion matrix:

		Expected	
		Porpoise	No porpoise
Observed	Porpoise	75.5%	32.1%
	No porpoise	24.5%	67.9%

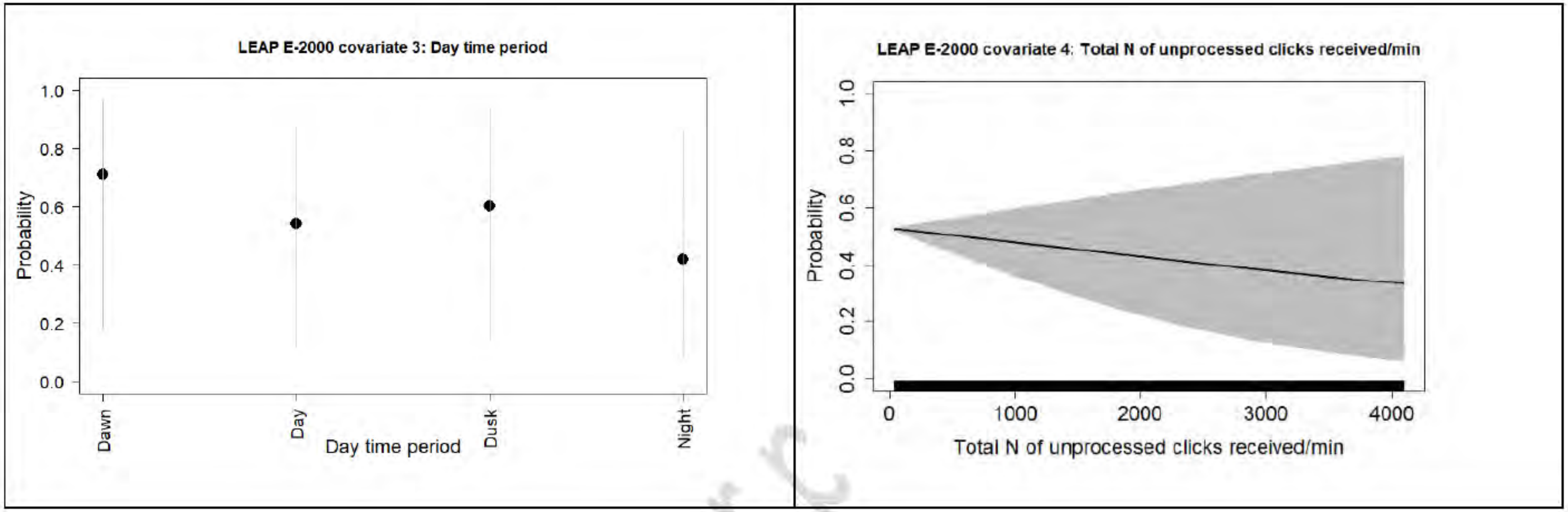
AUC value:	0.7766977

Results of Wald's tests for all significant covariates for the final model:

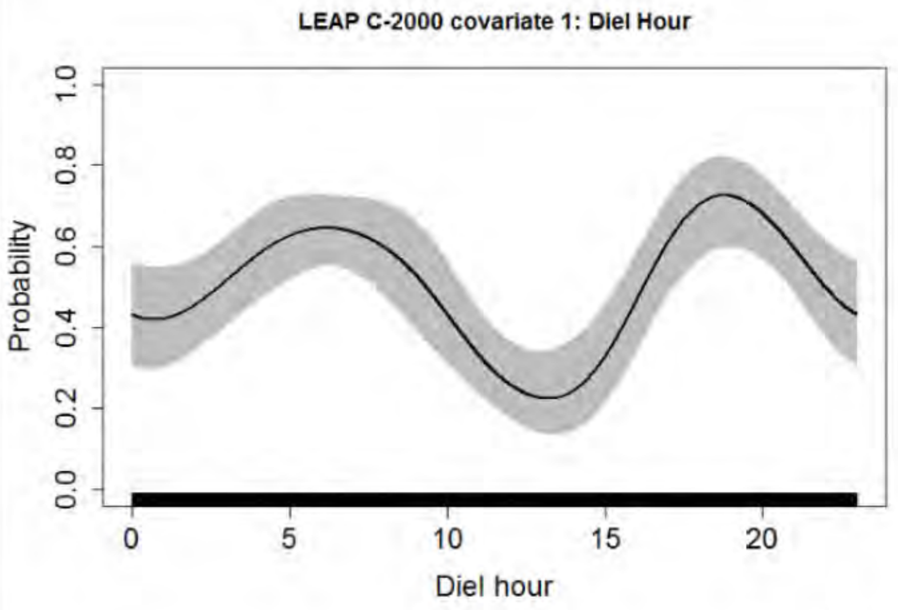
Covariates (in descending order of significance)	Form	Degrees of Freedom	χ^2 score	P-value
SpringNeap	Cyclic B-spline	4	37.671	$1.310 \cdot 10^{-7}$
JULDAY	Cubic B-spline	4	18.033	0.001216
DAYTIMENum	Factor	3	14.029	0.002866
Nall_m	Cubic B-spline	4	32.284	$1.674 \cdot 10^{-6}$

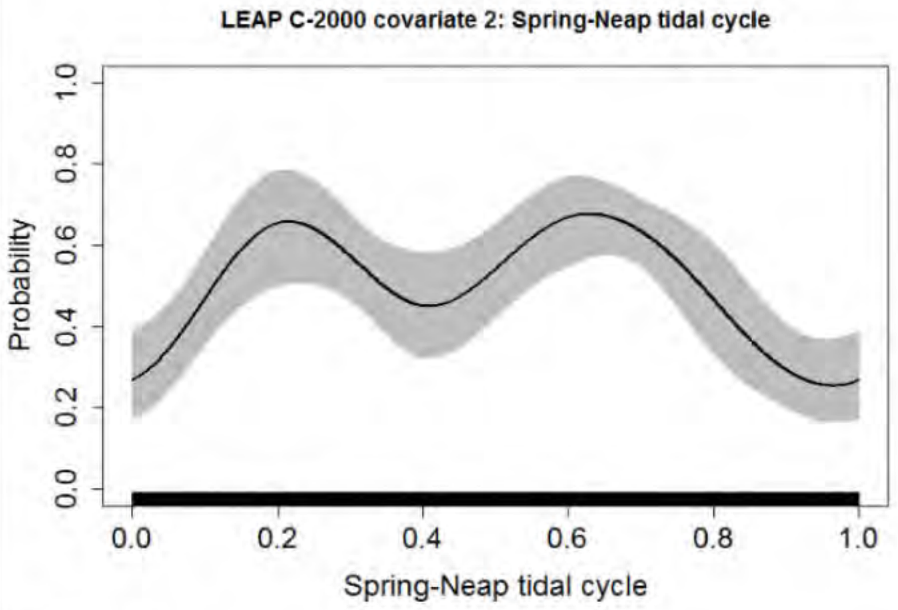


LEAP E-2000 covariate 1: Spring-Neap tidal cycle
Probability
0.0
0.2
0.4
0.6
0.8
1.0
Spring-Neap tidal cycle
LEAP E-2000 covariate 2: Julian Day
Probability
0.0
0.2
0.4
0.6
0.8
1.0
255
260
265
270
275
280
Julian Day


LEAP E-2000 covariate 3: Day time period
Probability
1.0
0.8
0.6
0.4
0.2
0.0
Dawn
Day
Dusk
Night
Day time period
LEAP E-2000 covariate 4: Total N of unprocessed clicks received/min
Probability
0.0
0.2
0.4
0.6
0.8
1.0
0
1000
2000
3000
4000
Total N of unprocessed clicks received/min

<table>
<tr><td>Model:</td><td colspan="4">C-2000</td></tr>
<tr><td>Model structure:</td><td colspan="4">POD5<-geeglm(PPM ~ bs(Nall_m , knots=mean(Nall_m)) + as.factor(DAYTIMENum) + AvgHrBasisMat + SprNpBasisMat, family = binomial, corstr="independence", id=Panel, data=C2000)</td></tr>
<tr><td>Confusion matrix:</td><td colspan="4">
<table>
<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>74.9%</td><td>32.2%</td></tr>
<tr><td></td><td>No porpoise</td><td>25.1%</td><td>67.8%</td></tr>
</table>
</td></tr>
<tr><td>AUC value:</td><td colspan="4">0.7749851</td></tr>
<tr><td colspan="5">Results of Wald's tests for all significant covariates for the final model:</td></tr>
<tr><td>Covariates (in descending order of significance)</td><td>Form</td><td>Degrees of Freedom</td><td>χ^2 score</td><td>P-value</td></tr>
<tr><td>HOUR</td><td>Cyclic B-spline</td><td>4</td><td>22.842</td><td>0.0001362</td></tr>
<tr><td>SpringNeap</td><td>Cyclic B-spline</td><td>4</td><td>19.751</td><td>0.0005593</td></tr>
</table>


LEAP C-2000 covariate 1: Diel Hour
Probability
0.0
0.2
0.4
0.6
0.8
1.0
0
5
10
15
20
Diel hour


LEAP C-2000 covariate 2: Spring-Neap tidal cycle
Probability
0.0
0.2
0.4
0.6
0.8
1.0
0.0
0.2
0.4
0.6
0.8
1.0
Spring-Neap tidal cycle

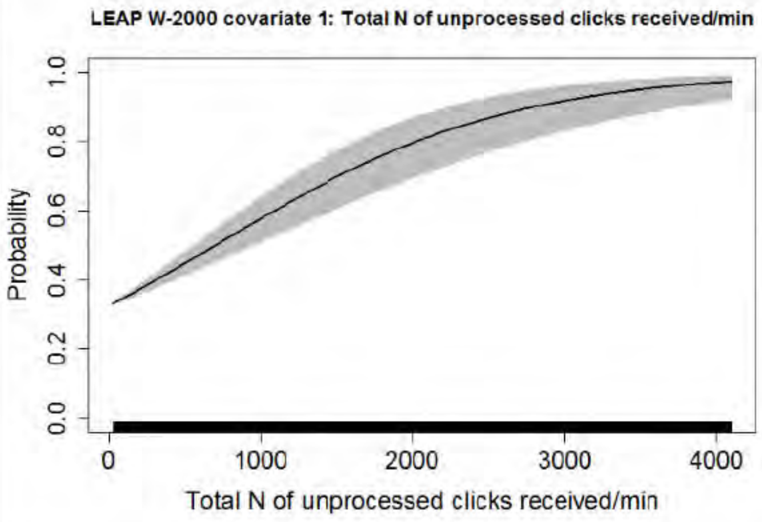
Model:	W-2000
Model structure:	POD5<-geeglm(PPM ~ Nall_m + TideBasisMat + SprNpBasisMat, family = binomial, corstr="independence", id=Panel, data=W2000)
Confusion matrix:	

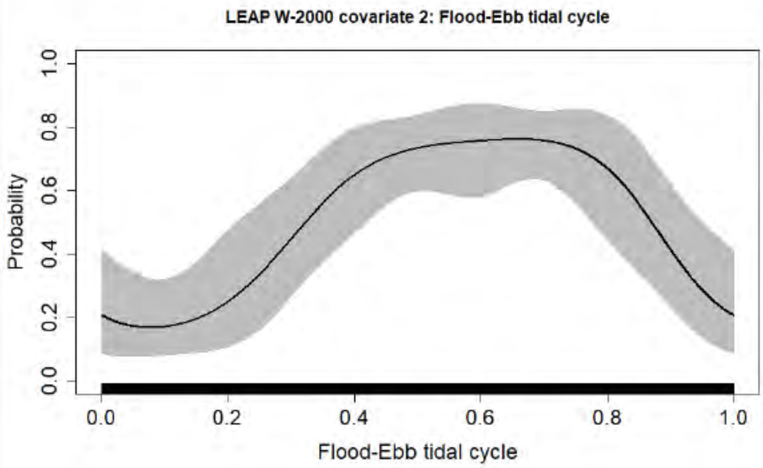
		Expected	
		Porpoise	No porpoise
Observed	Porpoise	88.5%	46.9%
	No porpoise	11.5%	53.1%

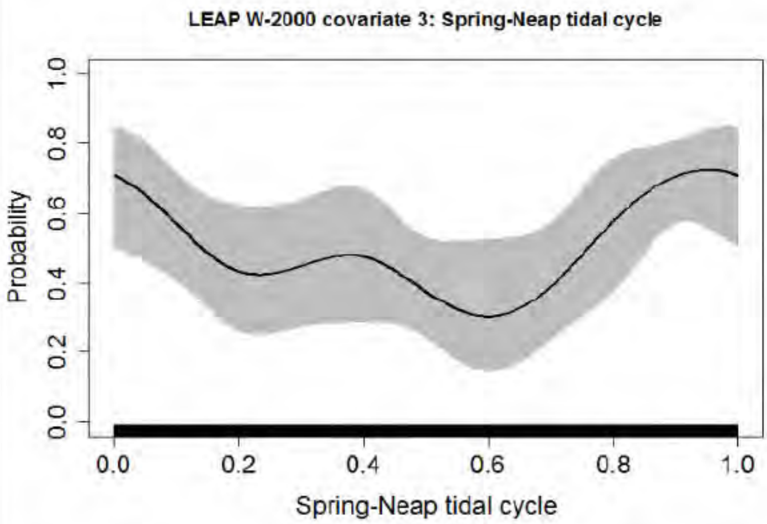
AUC value:	0.7838515

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	$<2.2\cdot10^{-16}$
HiLoTide	Cyclic B-spline	4	22.245	0.0001791
SpringNeap	Cyclic B-spline	4	10.022	0.0400520


LEAP W-2000 covariate 1: Total N of unprocessed clicks received/min
Probability
0.0
0.2
0.4
0.6
0.8
1.0
0
1000
2000
3000
4000
Total N of unprocessed clicks received/min


LEAP W-2000 covariate 2: Flood-Ebb tidal cycle
Probability
0.0
0.2
0.4
0.6
0.8
1.0
0.0
0.2
0.4
0.6
0.8
1.0
Flood-Ebb tidal cycle


LEAP W-2000 covariate 3: Spring-Neap tidal cycle
Probability
0.0
0.2
0.4
0.6
0.8
1.0
0.0
0.2
0.4
0.6
0.8
1.0
Spring-Neap tidal cycle

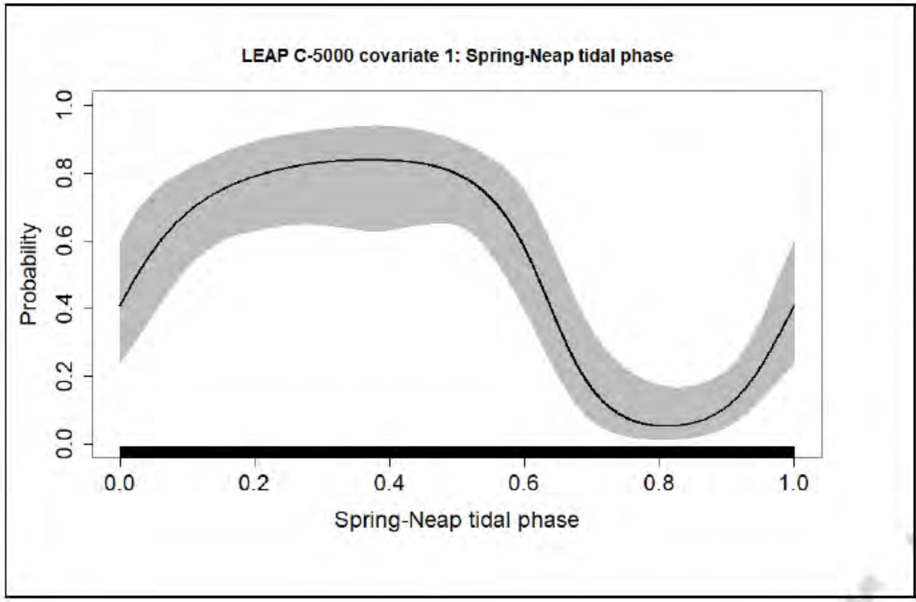
Model:	C-5000
Model structure:	POD5<-geeglm(PPM ~ SprNpBasisMat + bs(JULDAY , knots=mean(JULDAY)) + Nall_m + as.factor(DAYTIMENum) + AvgHrBasisMat, family = binomial, corstr="independence", id=Panel, data=C5000)
Confusion matrix:	
AUC value:	0.8861703

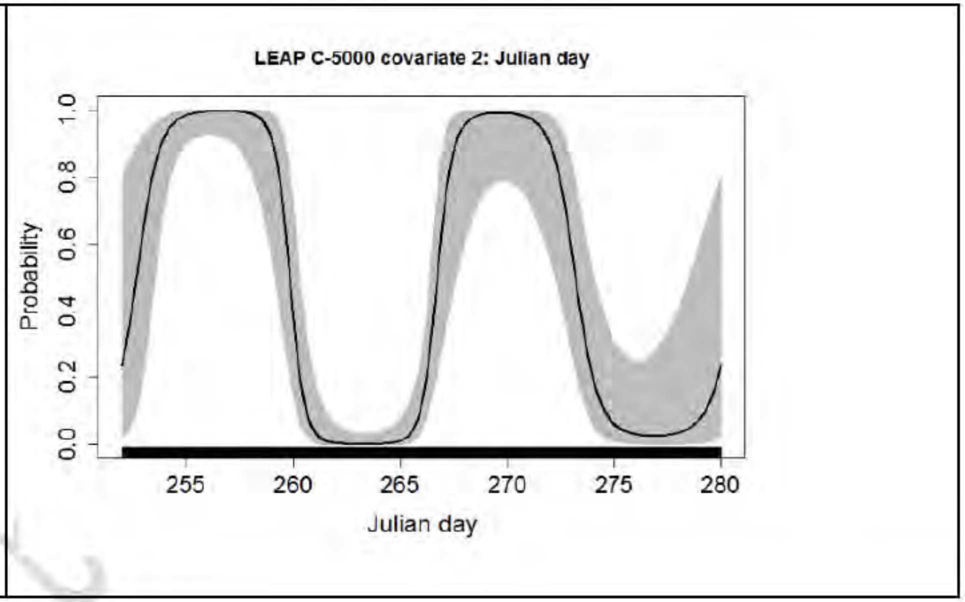
Confusion matrix:

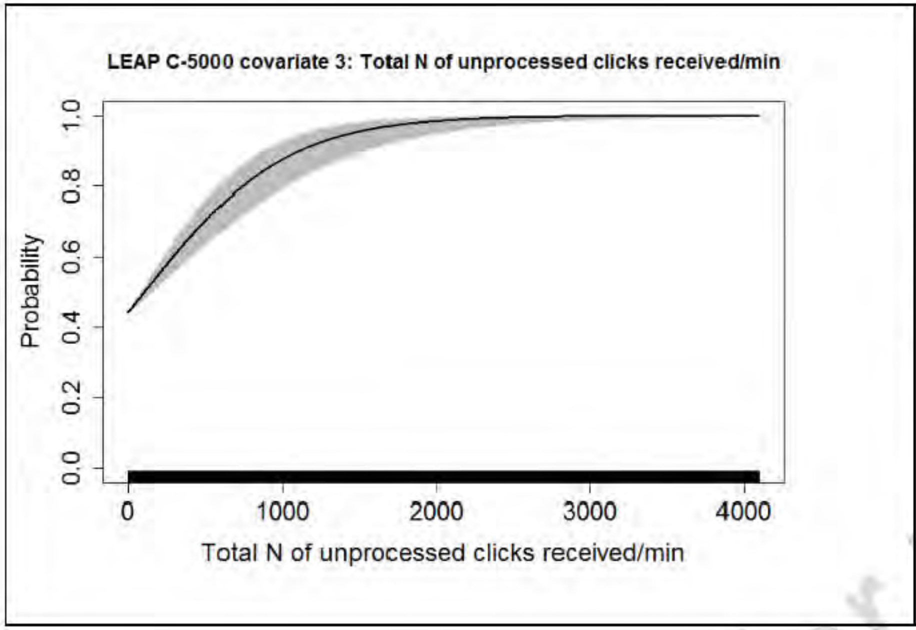
		Expected	
		Porpoise	No porpoise
Observed	Porpoise	80.1%	15.5%
	No porpoise	19.9%	84.5%

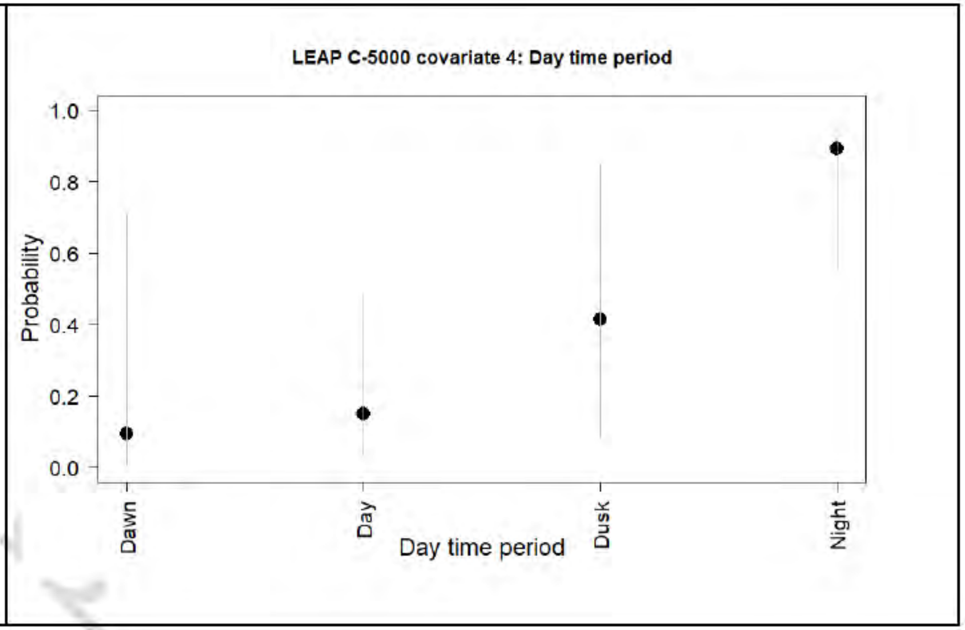
Results of Wald's tests for all significant covariates for the final model:

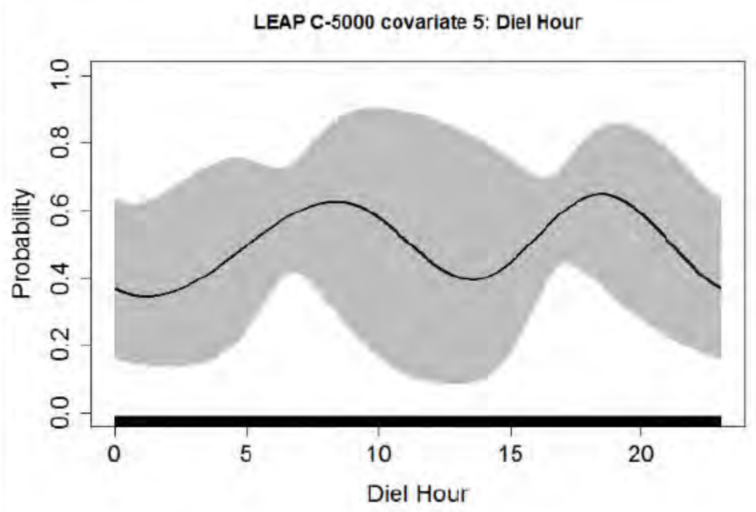
Covariates (in descending order of significance)	Form	Degrees of Freedom	χ^2 score	P-value
SpringNeap	Cyclic B-spline	4	14.806	0.005121
JULDAY	Cubic B-spline	4	15.829	0.003036
Nall_m	Linear	1	49.829	$1.678 \cdot 10^{-12}$
DAYTIMENum	Factor	3	40.503	$8.335 \cdot 10^{-9}$
HOUR	Cyclic B-spline	4	12.875	$3.291 \cdot 10^{-8}$


LEAP C-5000 covariate 1: Spring-Neap tidal phase
Probability
0.0
0.2
0.4
0.6
0.8
1.0
Spring-Neap tidal phase


LEAP C-5000 covariate 2: Julian day
Probability
0.0
0.2
0.4
0.6
0.8
1.0
255
260
265
270
275
280
Julian day


LEAP C-5000 covariate 3: Total N of unprocessed clicks received/min
Probability
0.0
0.2
0.4
0.6
0.8
1.0
0
1000
2000
3000
4000
Total N of unprocessed clicks received/min


LEAP C-5000 covariate 4: Day time period
Probability
0.0
0.2
0.4
0.6
0.8
1.0
Dawn
Day
Dusk
Night
Day time period


LEAP C-5000 covariate 5: Diel Hour
Probability
0.0
0.2
0.4
0.6
0.8
1.0
0
5
10
15
20
Diel Hour

1827

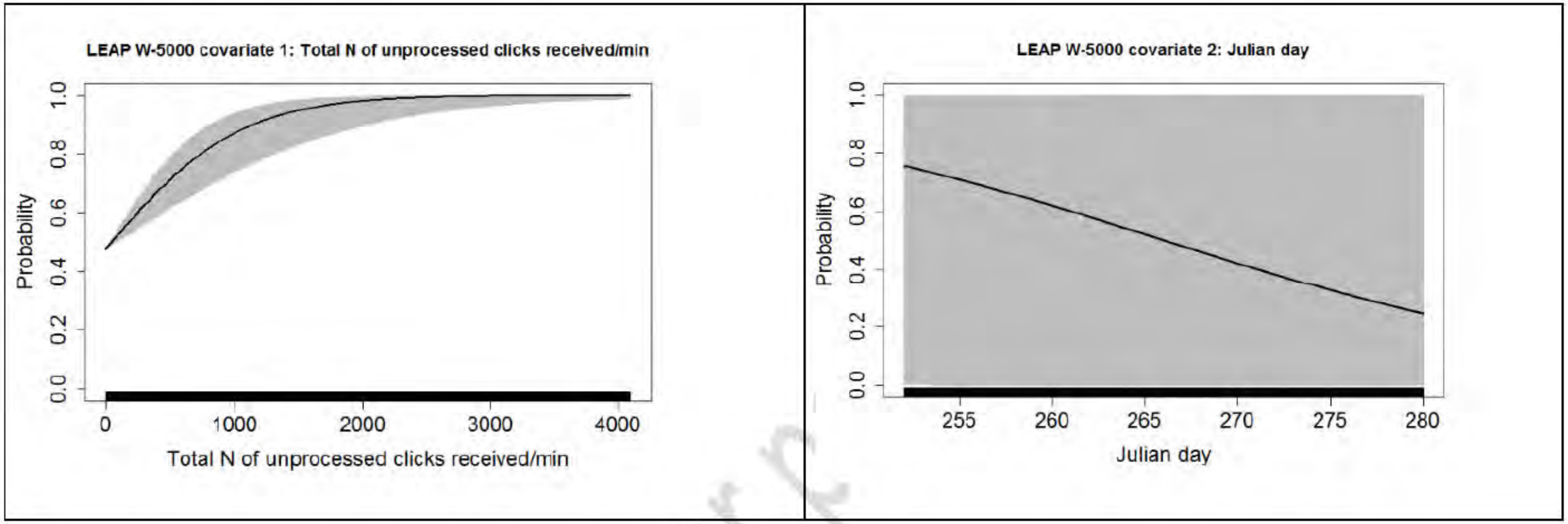
Model:	W-5000
Model structure:	POD5<-geeglm(PPM ~ Nall_m + JULDAY + AvgHrBasisMat + TideBasisMat, family = binomial, corstr="independence", id=Panel, data=W5000)
Confusion matrix:	

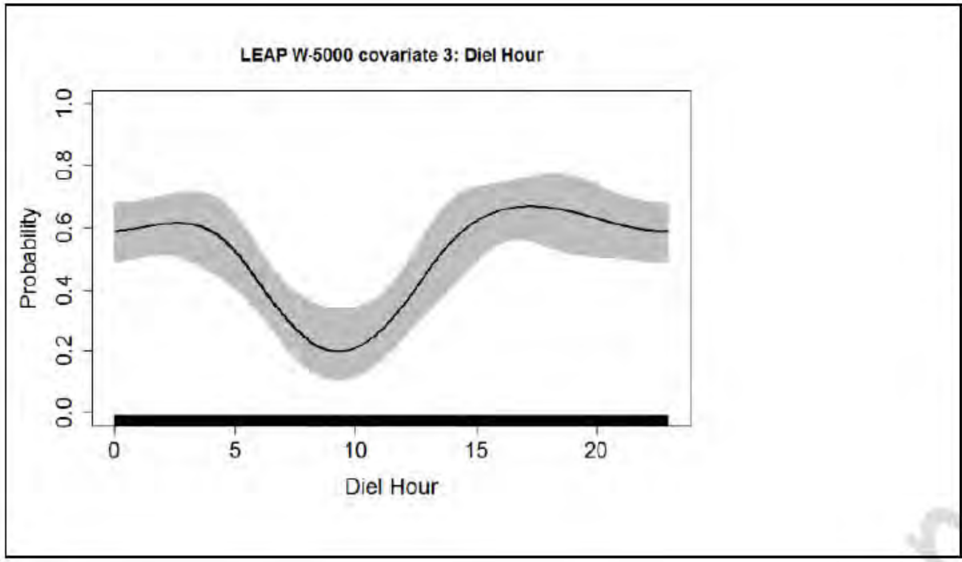
		Expected	
		Porpoise	No porpoise
Observed	Porpoise	58.8%	13.2%
	No porpoise	41.2%	86.6%

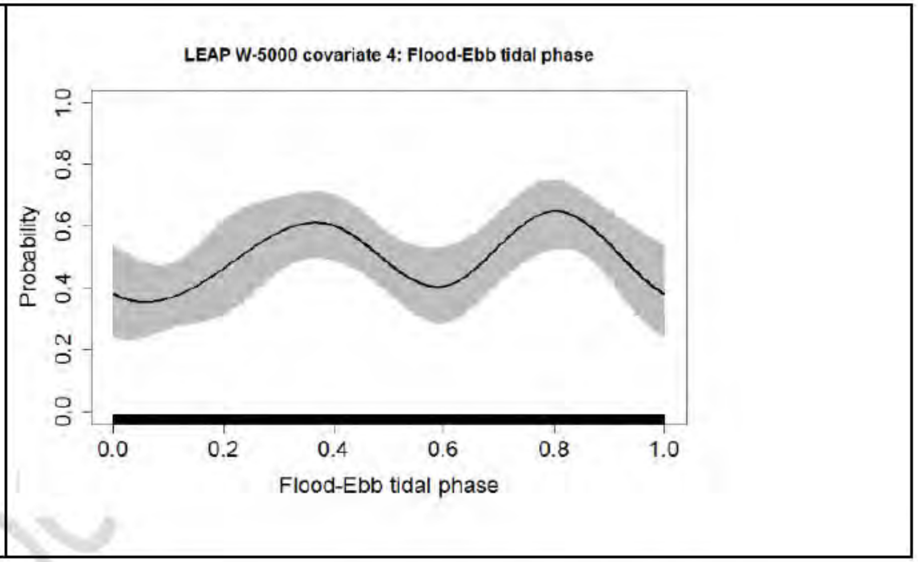
AUC value:	0.7942572

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


LEAP W-5000 covariate 1: Total N of unprocessed clicks received/min
Probability
0.0
0.2
0.4
0.6
0.8
1.0
0
1000
2000
3000
4000
Total N of unprocessed clicks received/min
LEAP W-5000 covariate 2: Julian day
Probability
0.0
0.2
0.4
0.6
0.8
1.0
255
260
265
270
275
280
Julian day


LEAP W-5000 covariate 3: Diel Hour
Probability
0.0
0.2
0.4
0.6
0.8
1.0
0
5
10
15
20
Diel Hour


LEAP W-5000 covariate 4: Flood-Ebb tidal phase
Probability
0.0
0.2
0.4
0.6
0.8
1.0
Flood-Ebb tidal phase

1829

Scottish Aquaculture Research Forum

FINAL PROJECT REPORT EVALUATION FORM

Project Number:	Completion Date:
Project Title:	
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.	
3. Is there a need for further work? If so, explain.	
Overall marking	1 - outstanding results 2 - results significantly above expectation 3 - satisfactory results 4 - results below expectation 5 - poor results
REFEREE ID:	Date

____

SARF112: LOW-FREQUENCY ADDS AND PORPOISES (LEAP)

INFLUENCES OF LOWER-FREQUENCY ACOUSTIC DETERRENT DEVICES (ADDS) ON CETACEANS IN SCOTTISH COASTAL WATERS

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SAMS   Loughborough University

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EXECUTIVE SUMMARY

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

- The experimental period during which signals were transmitted lasted a total of 33 days (08/09 - 11/10/2016). During this period, 138 transmissions took place, including 53 of the HF signal, 38 of the LF signal, and 47 silent controls. All the equipment, with the exception of 2 C-PODs and one broadband recorder, was recovered by 17/10/2016. One C-POD malfunctioned, bringing the total number of C-POD datasets available for further analysis to 19.

- Visual observations of porpoises were infrequent (23 sighting events over 19 days), despite good observing conditions. Most porpoises were sighted some distance from Bloody Bay within the central and northern Sound of Mull, particularly near the entrance to Loch Sunart. As a result, the video tracking procedure was often unable to adequately resolve surfacing animals to assess responses to different ADD signals, although the validity of the method itself was confirmed. Groups of bottlenose dolphins were observed on four occasions and one minke whale was sighted. In contrast to the scarcity of cetacean sightings, harbour seals were regularly observed on a near-daily basis, often in close proximity to the fish farm.

- The C-POD array provided a high-resolution dataset on presence of echolocating porpoises over the course of the experiment. Datasets were analysed using GAM-GEE models to investigate the relative importance of different covariates, including signal transmission, in determining porpoise acoustic presence.

- Ambient noise levels at the site, as assessed by broadband hydrophones, did not appear to significantly impact C-POD performance. Porpoise detections (defined as ‘Porpoise-Positive Minutes’ or PPMs) varied considerably across the array. Broadly speaking, PPM detection rates were higher in the central and northern Sound of Mull when compared to the Bloody Bay area, particularly compared to waters immediately surrounding the fish farm where detection rates were low.

- When assessing the effect of different signal transmissions, porpoise detection rates at most moorings were higher during silent control periods, suggesting that transmission of both HF and LF signals reduced the probability of porpoise detections. This was surprising as little difference was expected between exposure to LF signals and silent control periods. The results of this study therefore suggest that low-frequency ADD signals may also affect detection probabilities of harbour porpoises.

- 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.

1 INTRODUCTION: ADDS IN SCOTLAND

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

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

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

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

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

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 *, ** and * symbols.**

Manufacturer	Type	Source level (dB re 1 µPa-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 randomize d 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 pseudorandom at	x		*Götz & Janik (2015)

					intervals from 2-40s*			

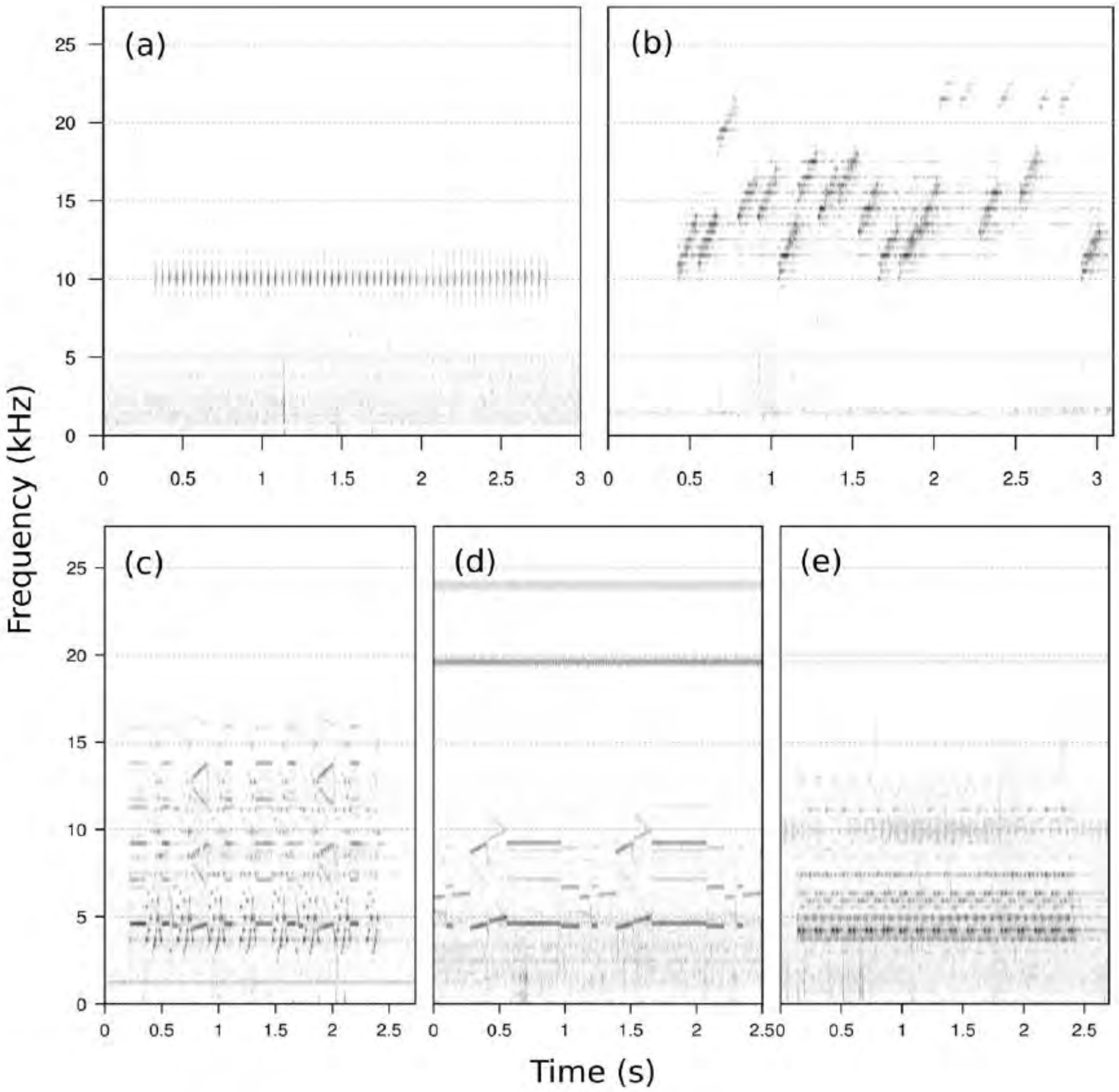


Figure 1. Examples of ADD spectrograms. Spectrogram parameters: FFT size = 1024 points, overlap = 50%, sample rate = 96 kHz; resulting in frequency and time resolution of 93.8 Hz and 10.67 ms, respectively. (a) Airmar™ (dB Plus II); (b) Ace Aquatec™ (US3); (c) Terecos™ (Type DSMS-4) Programme 4; (d)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

2 IMPACTS OF ADDS ON CETACEANS

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

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

Both harbour porpoises and bottlenose dolphins are listed under Annex II of the EC Habitats Directive (EC 1992), which requires strict protection measures to be applied to both individuals and populations, including the establishment of Special Areas of Conservation (SACs) to protect habitats that are important for the survival of the species. SACs are intended to contribute to a coherent European ecological network of protected sites, and thereby ensure continued maintenance of Favourable Conservation Status (FCS) of the species involved. The recently designated 'Inner Hebrides and the Minches' candidate Special Area of Conservation (cSAC) for harbour porpoises encompasses a large part of the Scottish west coast, which also includes numerous finfish aquaculture sites (Scottish Natural Heritage 2016). Given harbour porpoises' potential sensitivity to ADD noise, current levels of ADD usage within and adjacent to the 'Inner Hebrides and the Minches' cSAC therefore potentially have a negative impact on FCS for this species.

2.1 PHYSIOLOGICAL EFFECTS

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

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

Long-term exposure to chronic noise pollution can have significant deleterious effects on the health of both humans and animals through a number of physiological pathways involving combinations of neural and endocrine systems (summarised by Wright et al. 2007a, 2007b). Such responses may be difficult to detect in free-living cetaceans, and most of our current knowledge is derived from studies using small numbers of captive animals (e.g. Thomas et al. 1990; Miksis et al. 2001; Romano et al. 2004). However, stress hormone levels have been measured in whales' blows, suggesting anthropogenic noise may have substantial impacts on health of wild populations (Rolland et al. 2012). The effects of aquaculture-associated ADDs on cetaceans in this regard remain poorly understood but merit further study in the light of currently available data on effects of other anthropogenic noise sources (Wright et al. 2007b).

2.2 BEHAVIOURAL RESPONSES AND HABITAT DISPLACEMENT

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

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

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

2.5 'CETACEAN-FRIENDLY' ADD SYSTEMS

Current concerns about potential impacts of ADD signals on non-target species such as harbour porpoise have encouraged the development of novel ADD systems seeking to minimize such impacts while still acting as effective pinniped deterrents. Use of such systems has been suggested as a possible means to achieve reductions in acoustic impacts while continuing to use ADDs in otherwise sensitive areas, for example on aquaculture sites within the 'Inner Hebrides and the Minches' candidate Special Area of Conservation (cSAC), designated to protect harbour porpoises (Scottish Natural Heritage 2016; Marine Scotland 2016).

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

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

Loud sounds with sharp rise times can elicit an autonomous startle reflex in mammals, including seals (Götz & Janik 2011). Recent studies have demonstrated that grey seals (*Halichoerus grypus*) show sustained avoidance behaviour after repeated exposure to startle reflex-inducing acoustic stimuli (Götz & Janik 2011). On the basis of these findings, a novel ADD system intended to more effectively deter seals from fish farms, whilst avoiding unintended effects on non-target species such as harbour porpoises, has been patented (Götz & Janik 2012). The acoustic characteristics of this system are described in Table 1. At 1 kHz, peak frequencies for the deterrence stimulus are well below traditional ADD systems and duty cycles can be low (0.8%, see Table 1; Götz & Janik 2015). Field trials showed the effectiveness of this system in deterring seals from fish farms while reducing the risk to non-target species such as harbour porpoises (Götz & Janik 2011, 2015). Over a 2-month period, significant reductions in observed seal numbers during sound exposure were observed without noticeable habituation occurring, whereas no changes in porpoise relative abundance, distribution or behaviour were observed (Götz & Janik 2015). However, received levels need to be loud (>145 dB re 1 μPa_{RMS}) and signal onset sharp (<5 ms) to elicit a response; since both of these factors are affected by sound propagation through the water column, the effectiveness of this method is likely limited to relatively short ranges around fish farms (Coram et al. 2014; Götz & Janik 2015). This might be an advantage in the context of using ADDs continuously to deter seals, as avoidance responses will be limited to the immediate area around the ADD. This would, however, also mean that seals would have to be in close proximity to a fish farm for the deterrent to be effective; at such close distances, individual seals' increased motivation to investigate a potential food source might reduce deterrent efficacy. Another concern would be that lower frequencies generated by this device will propagate over larger ranges and are likely to be more audible to other non-target species such as fish and baleen whales. Potential effects of these ADD signals on such other species need to be investigated before large-scale deployments of these devices can commence.

3 EXPERIMENTAL METHODS

3.1 BACKGROUND AND PROJECT AIMS

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

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

3.2 ACOUSTIC PLAYBACK SIGNAL DESIGN

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

In the experimental design the potential difference between porpoises' and seals' behavioral responses to either high- / low-frequency ADD signals was applied. A high frequency (HF) test signal was designed using single frequency tonal bursts, similar to the Airmar, Lofitec and Ace Aquatec brands that represent the majority of ADDs in current use in Scottish salmon aquaculture. The random frequency sequencing and the pulse width and duty cycle of the Ace Aquatec were also adopted. The overall frequency range of transmission was extended from 8-18 kHz to capture the full frequency spectrum of all three systems (Figure 2). Specifically, the HF signal consisted of pulsed continuous wave sinusoidal tonal bursts at one of 21 randomly switching fundamental frequencies between 8 – 18 kHz at frequency intervals of 500 Hz. Each pulse contained 40 cycles of fundamental frequency with a rectangular pulse amplitude envelope, and the on – off duty cycle was 50%. Figure 3 illustrates the variation in pulse amplitude due to transducer response as well as pulse duration.

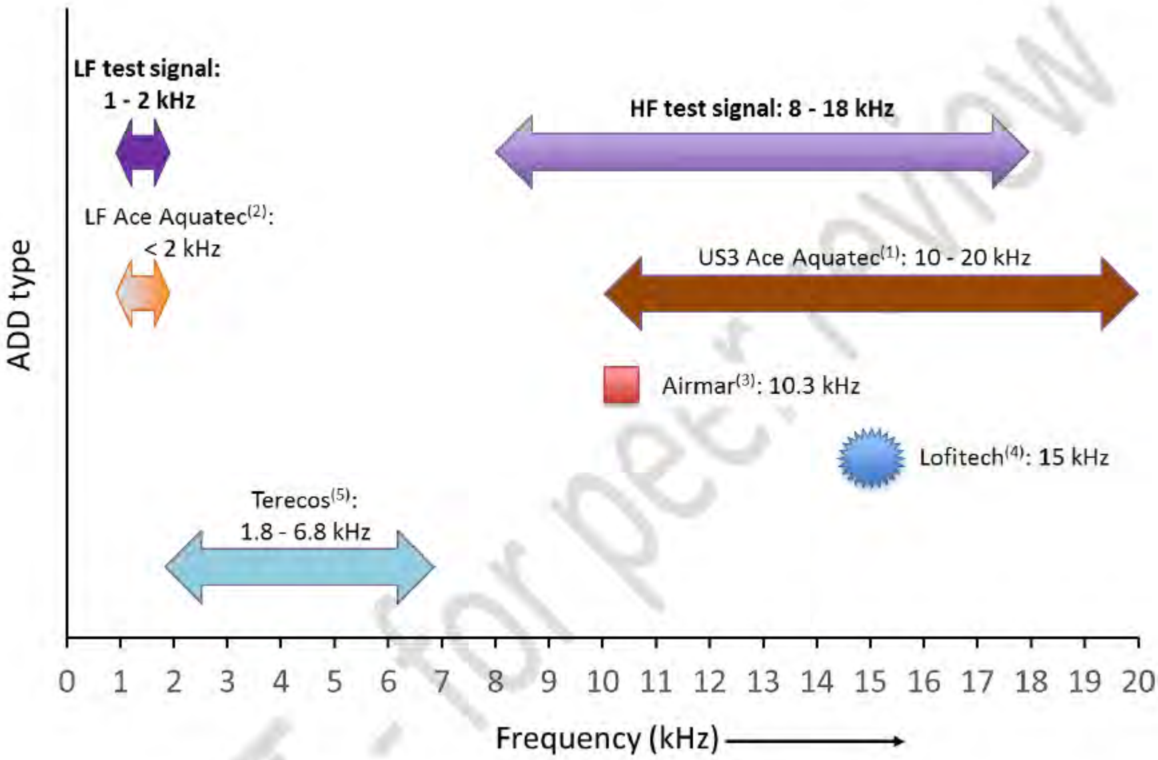


Figure 2. Output frequency ranges of the two test signals (LF and HF), compared to outputs from various existing ADD types (see Table 1 for details). Data on existing ADD outputs derived from 1) Ace Aquatec U3S manual (https://www.aceaquatec.com/us3specification); 2) Ace Aquatec pers. comm. (PL); 3)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

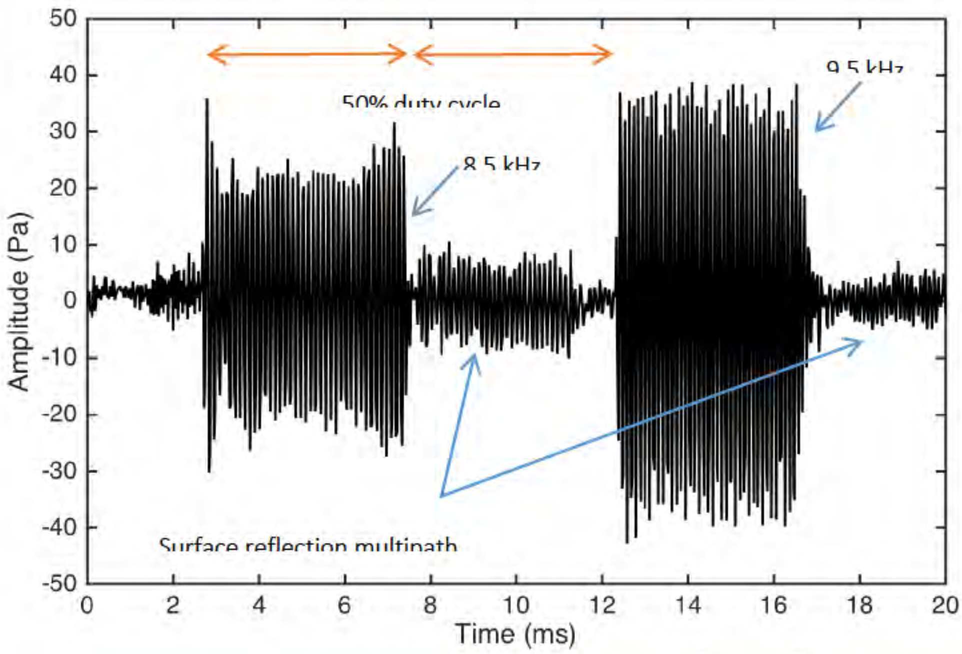


Figure 3. Time domain plot of two consecutive samples from the HF sequence – first pulse at 8.5 kHz and second at 9.5 kHz.

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

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

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 µPa-m	165 – 170.4 dB re 1 µPa-m

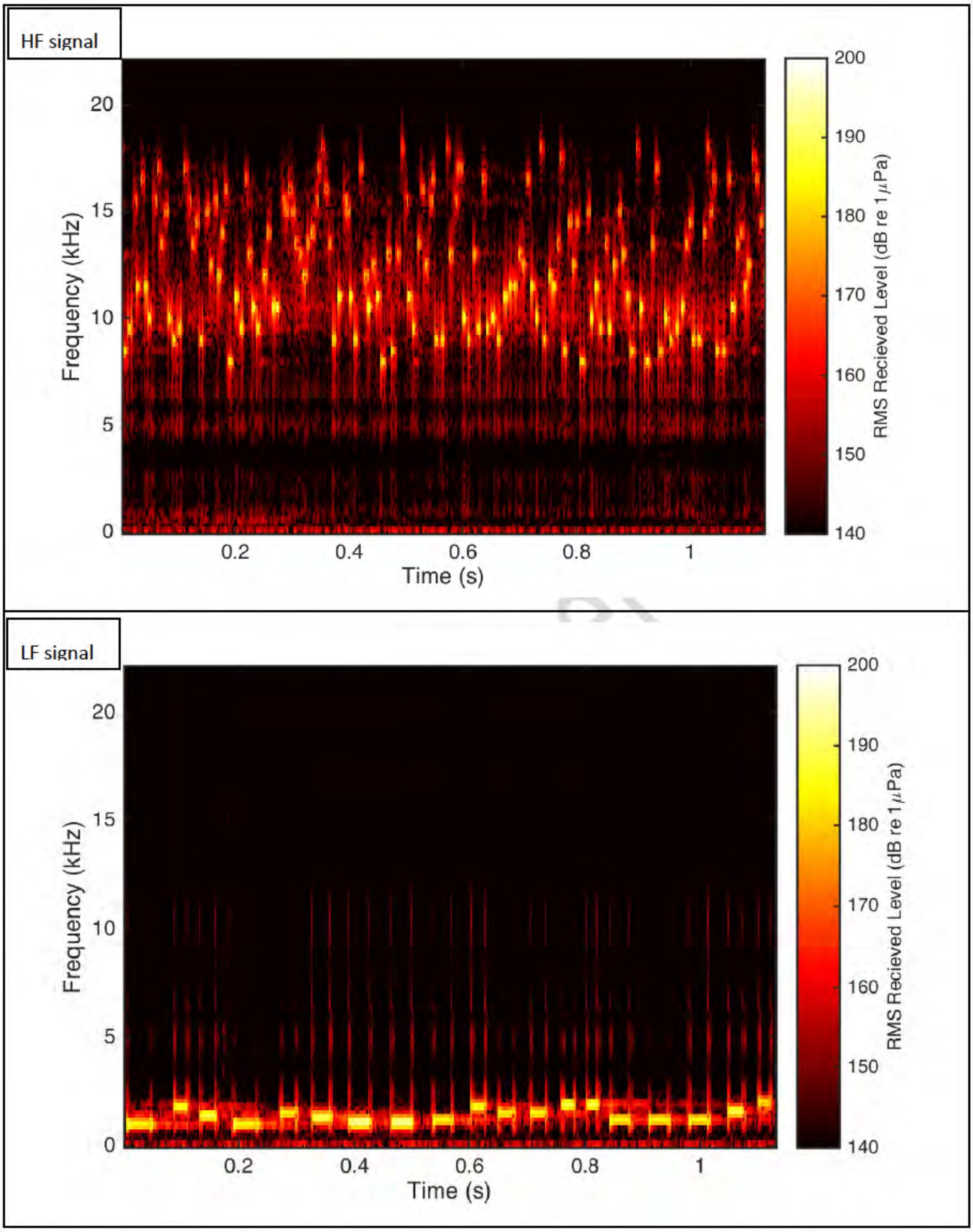


Figure 4. Spectral plot of a sample of the HF and LF signals received at a range of 8.5 m using a Reson 4014 balanced hydrophone. Analysis window was 256 FFT with 50 % overlap using a Hanning window. A 50 kHz low pass filter was applied. Original data were downsampled to a sample rate of 44.1 kHz.

3.3 SIGNAL TRANSMISSION

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

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

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

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

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

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

	Frequency (Hz)	Pulse duration (ms)	RMS Source Level (dB re 1 µPa-m)	Frequency (Hz)	Pulse duration (ms)	RMS Source Level (dB re 1 µPa-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			

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

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

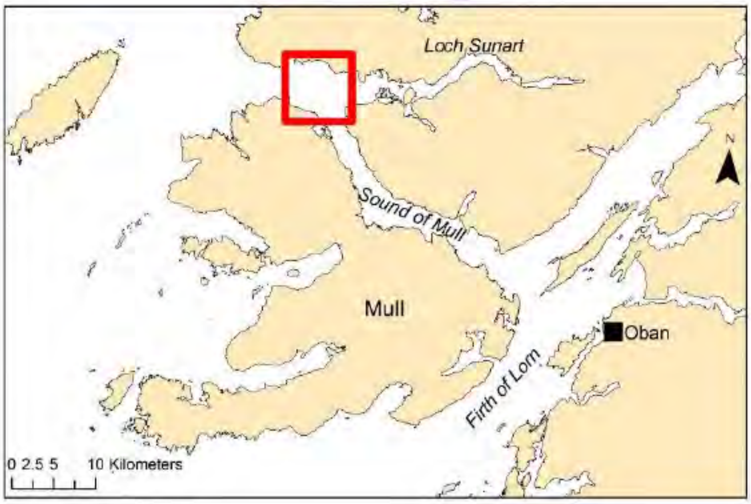
After several days of operation, it became apparent that the system drew more power when transmitting in Night mode than could be reliably replenished by the solar panels during the subsequent daytime, thus putting strain on the system's battery power supply. To preserve power throughout the experimental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

3.4 FIELDWORK LOCATION

The experiment took place in the Sound of Mull, on the west coast of Scotland, with observation efforts concentrated in Bloody Bay on the north shore of the Isle of Mull (56°38.626 N, 6°05.705 W; Figure 6). This location was chosen because it contained a salmon aquaculture site (owned by Scottish Sea Farms™/SSF) which operated under licensing restrictions preventing it from using ADDs (Scottish Natural Heritage, pers.comm. 2016). This meant that the experiment could be undertaken without interference from on-site operational ADDs, although effects of more distant ADDs on other fish farms could not be eliminated. Furthermore, Bloody Bay had previously been identified as a site where harbour porpoises were observed regularly (Carlström 2005; Carlström et al. 2009; Götz & Janik 2016). The feeder barge of the Bloody Bay salmon farm was used as a platform from which the underwater loudspeaker and associated hardware could be deployed, as well as passive acoustic detectors. Water depths in the immediate area around the fish farm were approximately 35-40 m (based on GEBCO™ bathymetry data).

3.5 PASSIVE ACOUSTIC DETECTOR ARRAY

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



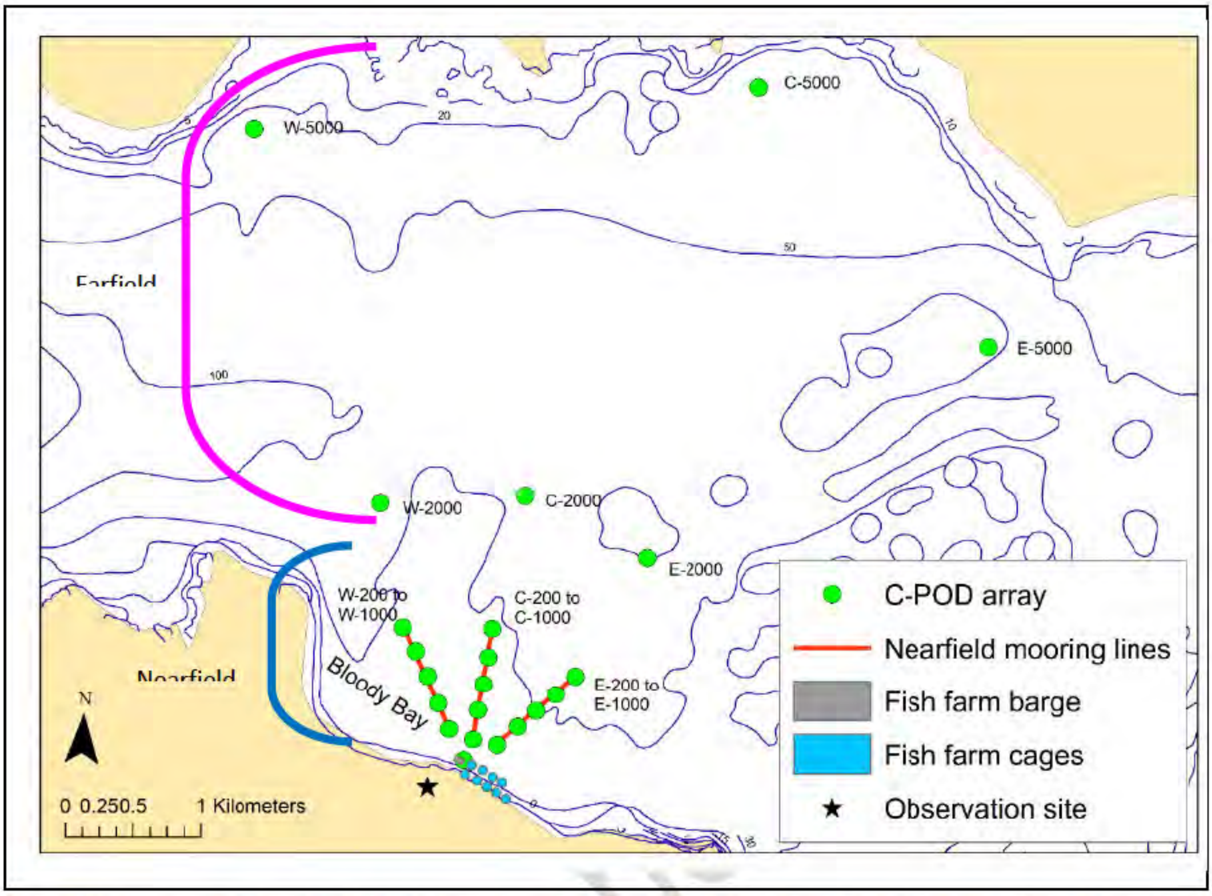


Figure 6. A) Overview of the Sound of Mull and adjacent areas. The Bloody Bay fieldwork site is indicated by the red box. B) Overview of LEAP passive acoustic mooring array in Bloody Bay and the northwestern Sound of Mull. Nearfield and Farfield components of the array are indicated. Note that the field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

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

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

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

- C-PODs are self-contained ultrasound monitors that select tonal clicks and record the time of occurrence, centre frequency, intensity, duration, bandwidth and frequency trend of tonal clicks within the frequency range 20 kHz - 160 kHz to 5-µs resolution. This allows them to monitor clicks from all odontocetes except sperm whales. Raw sound data are not stored, however, and the unit's design precludes manual configuration of click identification parameters. Maximum deployment times vary depending on environmental conditions but typically range over several months (Chelonia Ltd. 2011, 2013, 2014). This extended battery life makes them suitable for long-term monitoring experiments involving species such as harbour porpoise. A subset (n=8 units) of C-PODs' responses to artificial porpoise clicks had been tested previously as part of a different experiment, deploying an omnidirectional harbour porpoise click train synthesiser (PALv1; F³ Maritime Technology 2012) at known distance. The PALv1 unit produced click trains with a centre frequency of 133 ± 0.5 kHz and source levels of 154 ± 2 dB (peak-to-peak; F³ Maritime Technology 2012). Some variability in terms of C-PODs detecting PALv1 click trains was noted at the time; environmental factors (notably changes in C-POD orientation relative to the PALv1 sound source) were considered to be an important cause of this variability. No further calibration of C-PODs used in this experiment was performed.

  Occasionally, under high ambient noise conditions, C-PODs temporarily stop logging when reaching a pre-set buffer limit of 4,096 clicks per minute, until the start of the next minute (Booth 2016). The proportion of each minute thus lost can be used as a crude proxy of ambient noise levels across the array. C-PODs also contained an onboard tilt sensor, recording their deflection from vertical (0° = vertical; 90° = horizontal).

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

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

3.6 VISUAL OBSERVATIONS AND CAMERA ARRAY

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

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

3.7 DATA MANAGEMENT

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

4 RESULTS

4.1 SIGNAL TRANSMISSION EXPERIMENTS

The signal transmission system described under Section 3.3 was installed onto the fish farm barge and activated on 6/09/2016, following a delay of approximately 5 weeks due to an unexpectedly long licensing process. Despite this delay, the project succeeded in completing a successful fieldwork campaign combining simulated ADD transmissions with simultaneous acoustic and visual observations of porpoises. Following some tests, the actual experiment ran from 08/09/2016 until 11/10/2016 inclusive, or a total of 33 days. During this period, a total of 138 complete sound transmissions (including 53 HF signal transmissions, 38 LF signal transmissions, and 47 silent control "transmissions") were carried out. Transmissions were either triggered upon visual detection of animals or initiated on a random schedule (see Methods). Of all transmissions, 62 ran during daylight hours (i.e. started during daytime or immediately before sunrise), while 76 transmissions overlapped partially or wholly with hours of darkness (i.e. started during darkness or immediately before sunset). Visual observations occurred on 18 days between 9/09/2017 and 10/10/2017, and included both data from human observers and video camera tracking data. There was no significant difference in terms of when particular signals were transmitted in relation to daylight hours. All but three of the passive acoustic recorders were successfully recovered on 18/10/2016. The resulting dataset will be described in more detail below.

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

4.2 HARDWARE RECOVERY

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

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

4.3 PASSIVE ACOUSTIC MONITORING

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

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

C-POD datasets were truncated to exclude periods immediately after deployment and before recovery, such that the remaining datasets only contained entire days (1440 minutes per day). For this reason, the entire array (excluding the C-POD beneath the feeder barge) was defined to be active from 8/09/2016 at 00:00 GMT until 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. All other C-PODs remained operational until at least 16/10/2017 at 23:59 GMT, equivalent to 39 days.

Table 5. Summary of periods monitored by moored C-POD units across the array. *These units stopped <24 hrs prior to recovery. ** This 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

4.4 AMBIENT NOISE MONITORING

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

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

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

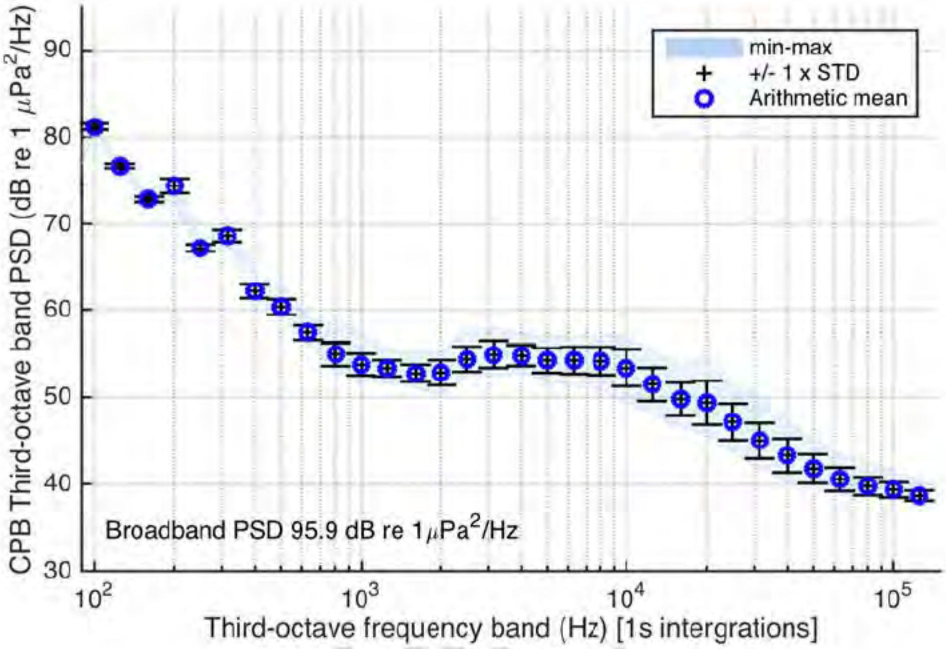


Figure 7. Power Spectral Density (PSD) in Third Octave Bands for a quiet period at 14:56 GMT on 11th October 2016. Total sample length 25 seconds, 1-second integration periods.

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

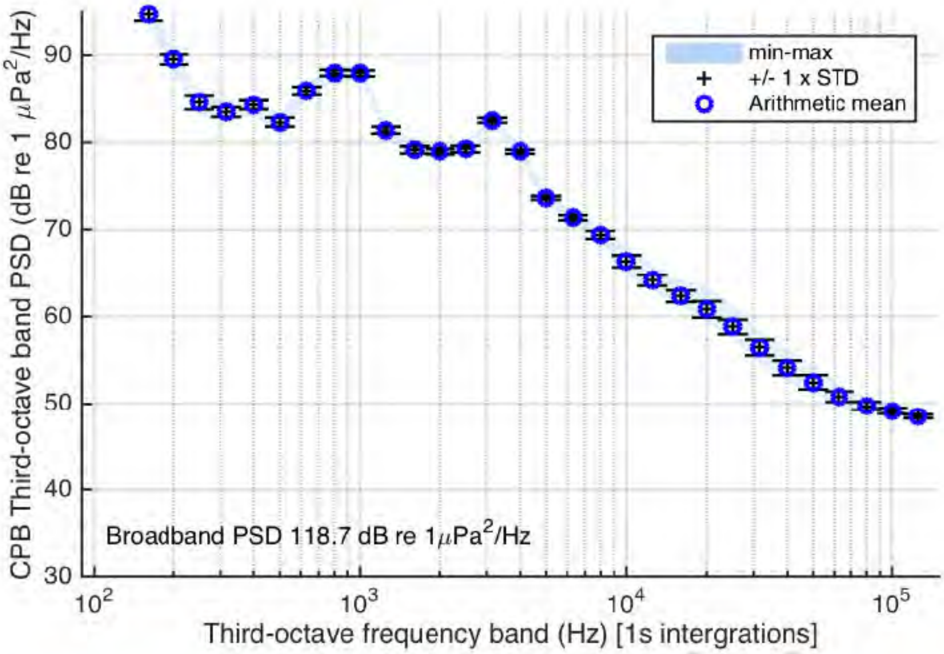


Figure 8. Power Spectral Density (PSD) in Third Octave Bands for low sea-state period at 15:01 GMT on 11th October 2016. Total sample length 25 seconds, 1-second integration periods. Likely contributions originated from specific barge or small boat operations.

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

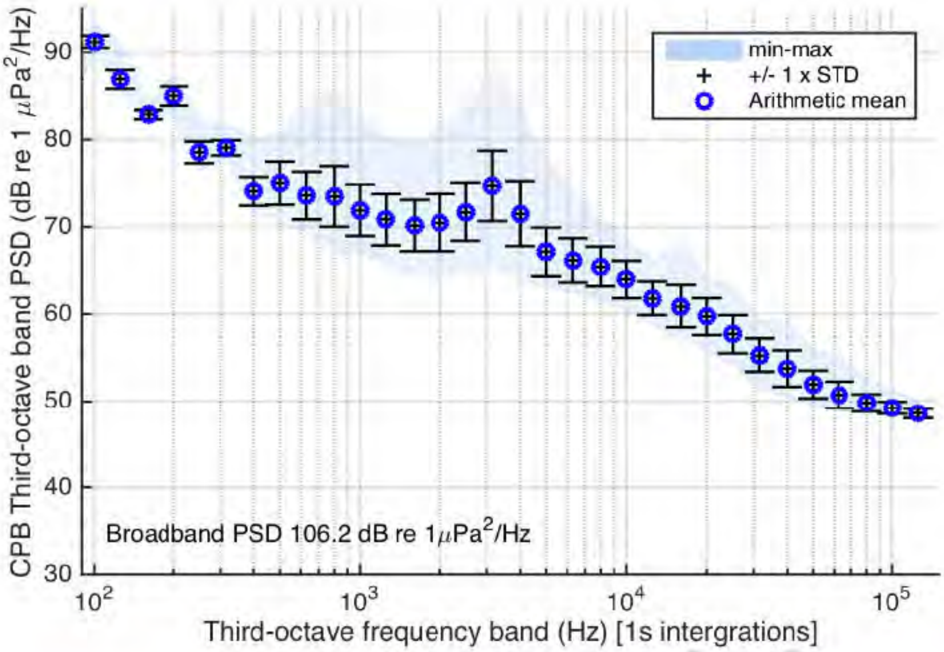


Figure 9. Power Spectral Density (PSD) in Third Octave Bands for low sea-state period. Consecutive 25s period from file started at 15:01 on 11th October 2016 compared to figure 9. Total sample length 25 seconds, 1-second integration periods. Transitory contributions from specific barge or small boat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

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

4.5 SIGNAL PROPAGATION MODELLING

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

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

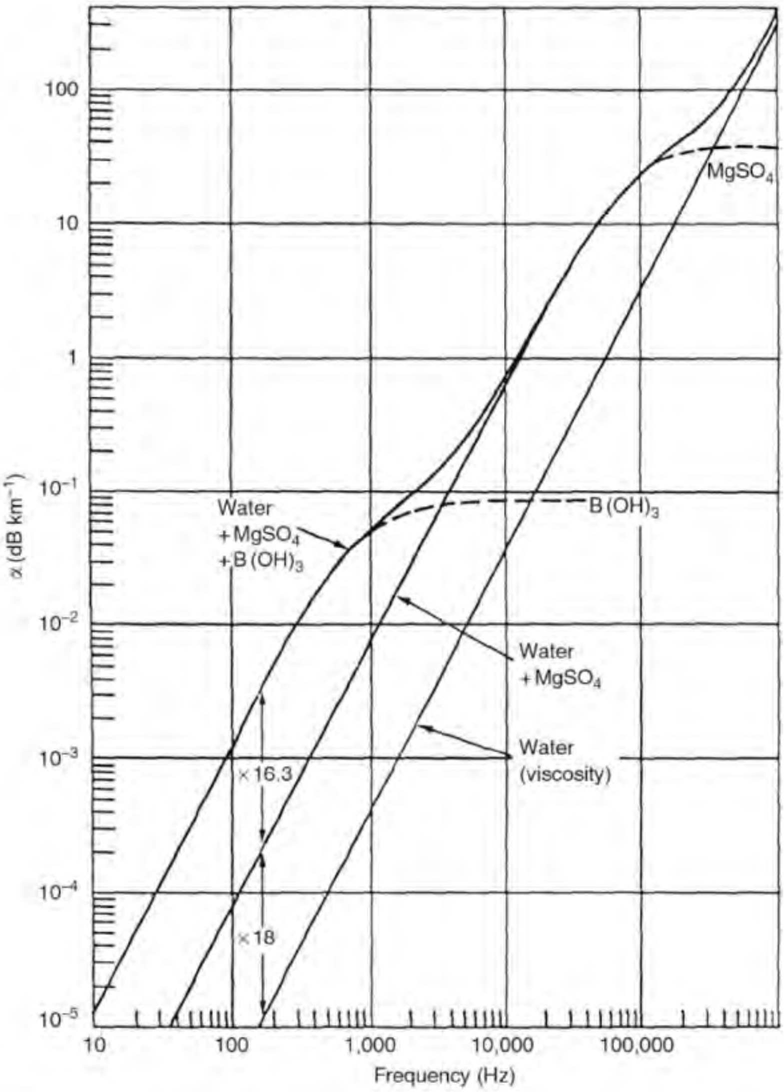


Figure 10. Underwater acoustic absorption versus frequency. Derived from Etter, 2003.

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

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

4.6 VISUAL OBSERVATIONS

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

4.6.1. MARINE MAMMAL SIGHTINGS

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

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

Table 6. Overview of observation events of different marine mammal species during the experiment. Individual observation events of porpoises and dolphins often involved >1 individual. *N.B.: Seal and otter sightings were not tracked and so numbers reflect the 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		

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

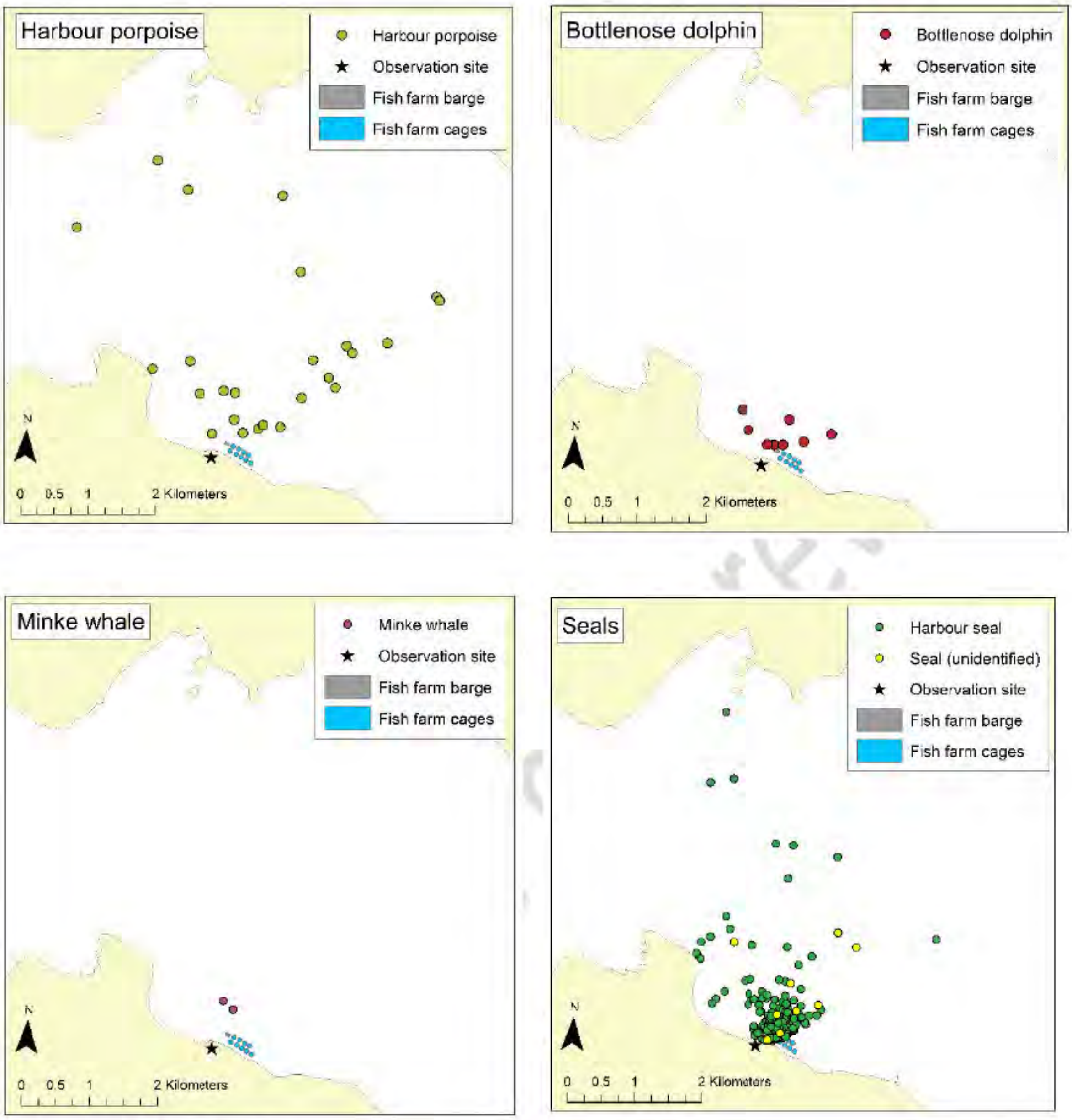


Figure 11. Approximate locations of sightings of different marine mammal species during the entire experimental period. Note that these positions are only approximations due to substantial variability in distance estimation among observers.

4.6.2 VISUAL TRACKING ANALYSIS

The visual tracking methodology (Section 3.6) was designed to provide insight into porpoises' initial responses to the experimental signals by tracking their surface movements at high resolution. Unfortunately, the small number of visual sightings of porpoises made this difficult (Table 6). In addition to being infrequent, most porpoise sightings occurred at considerable distance from the observation site (notably in the northern half of the Sound of Mull, towards the entrance to Loch Sunart several km away). At such distances, the cameras' resolution proved to be inadequate for reliably recording porpoises for tracking. For this reason, only a few sightings close to the fish farm were suitable for further analysis and the method was therefore unable to provide robust information on porpoises' responses to the experimental ADD signals. However, despite the small number of porpoises at the site in the autumn of 2016, we were able to demonstrate the general utility of the method, and would encourage further development of this tool. An example of a tracked group of porpoises is shown in Figure 12.

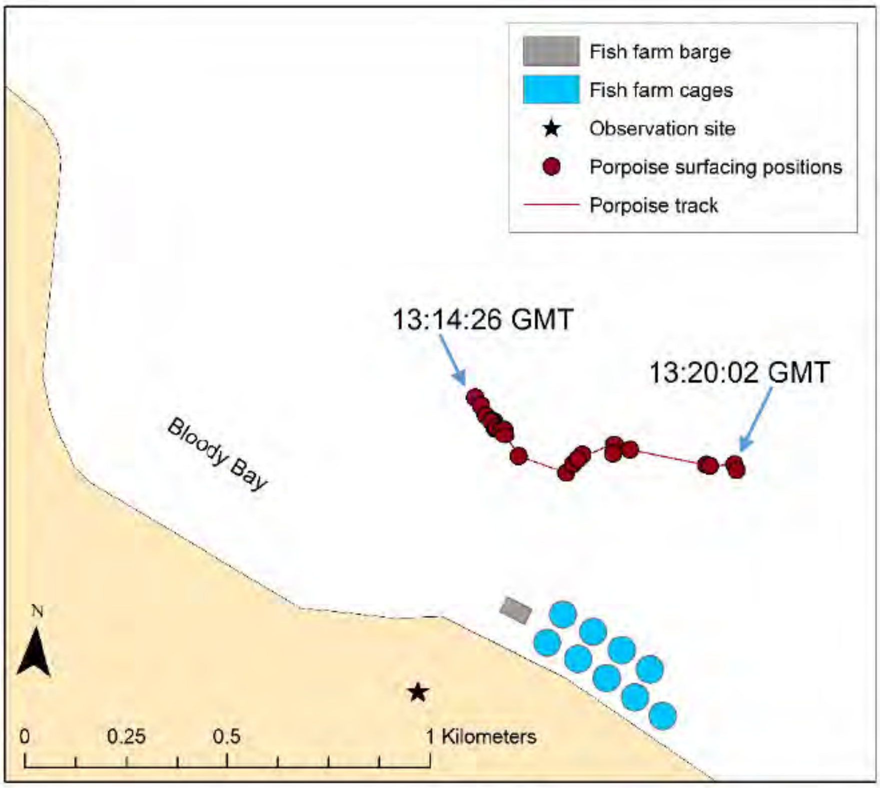


Figure 12. Example of tracked group of 3 porpoises observed on 14/09/2016, swimming from west to east.

4.6.3. SEAL OBSERVATIONS AROUND THE FISH FARM

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

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

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

In three cases <30 minutes, or <25%, of the entire 2-hour transmission period was observed (Table 7), and these cases were excluded from further analysis. Data from the remaining 14 cases were used to assess the relationship, if any, between signal type and standardised sighting rate of individual seal sighting events per minute, using a linear modelling approach through the *lm* tool in the R package *stats* v.3.4.3. Results indicated that there was no obvious relationship between the signal being transmitted and standardised seal sighting rates, irrespective of whether sightings of nearby seals (d.f. = 12; p = 0.5461), more distant seals (d.f. = 12; p = 0.2213), or all seals (d.f. =12; p = 0.4637) were used to populate the model.

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

4.7 C-POD DATA ANALYSIS

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

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

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 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 '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

4.7.1 EXPERIMENTAL RESULTS OF EXPOSURE EXPERIMENTS

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

Table 9. Summary of numbers of monitored minutes ($N_{MINUTES}$), number of PPMs (N_{PPM}), and average ratio of number of PPMs divided by total number of monitored minutes (F) during all experimental transmissions, detected by each C-POD between 08/09/2016 and 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
		$N_{MINUTES}$	N_{PPM}	F	$N_{MINUTES}$	N_{PPM}	F	$N_{MINUTES}$	N_{PPM}	F	N
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

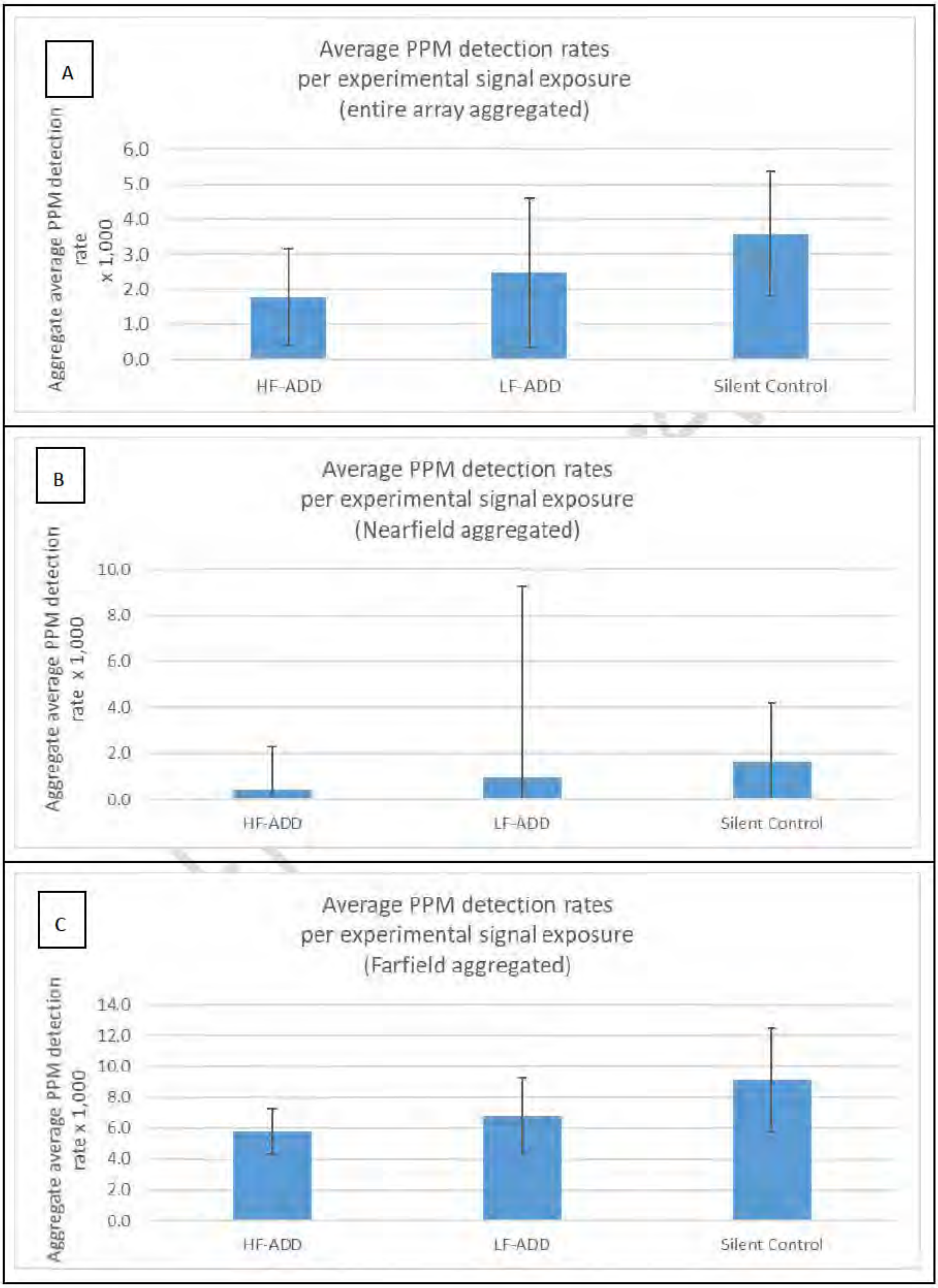

A
Average PPM detection rates
per experimental signal exposure
(entire array aggregated)
Aggregate average PPM detection rate x 1,000
6.0
5.0
4.0
3.0
2.0
1.0
0.0
HF-ADD
LF-ADD
Silent Control
B
Average PPM detection rates
per experimental signal exposure
(Nearfield aggregated)
Aggregate average PPM detection rate x 1,000
10.0
8.0
6.0
4.0
2.0
0.0
HF-ADD
LF-ADD
Silent Control
C
Average PPM detection rates
per experimental signal exposure
(Farfield aggregated)
Aggregate average PPM detection rate x 1,000
14.0
12.0
10.0
8.0
6.0
4.0
2.0
0.0
HF-ADD
LF-ADD
Silent Control

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

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

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

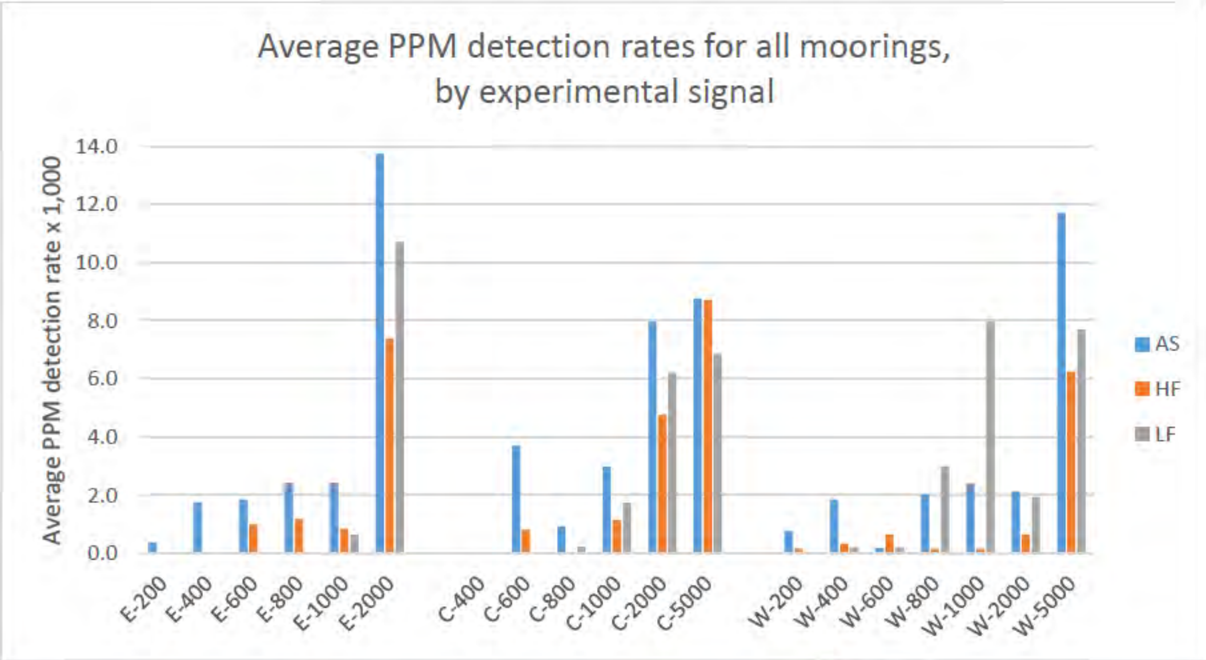


Figure 14. Average PPM detection rates (derived from Table 8, then multiplied by 1,000 for display purposes) across the experimental array under HF-signal, LF-signal, or Silent control (AS) control treatment.

4.7.2 CROSS-ARRAY VARIABILITY

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

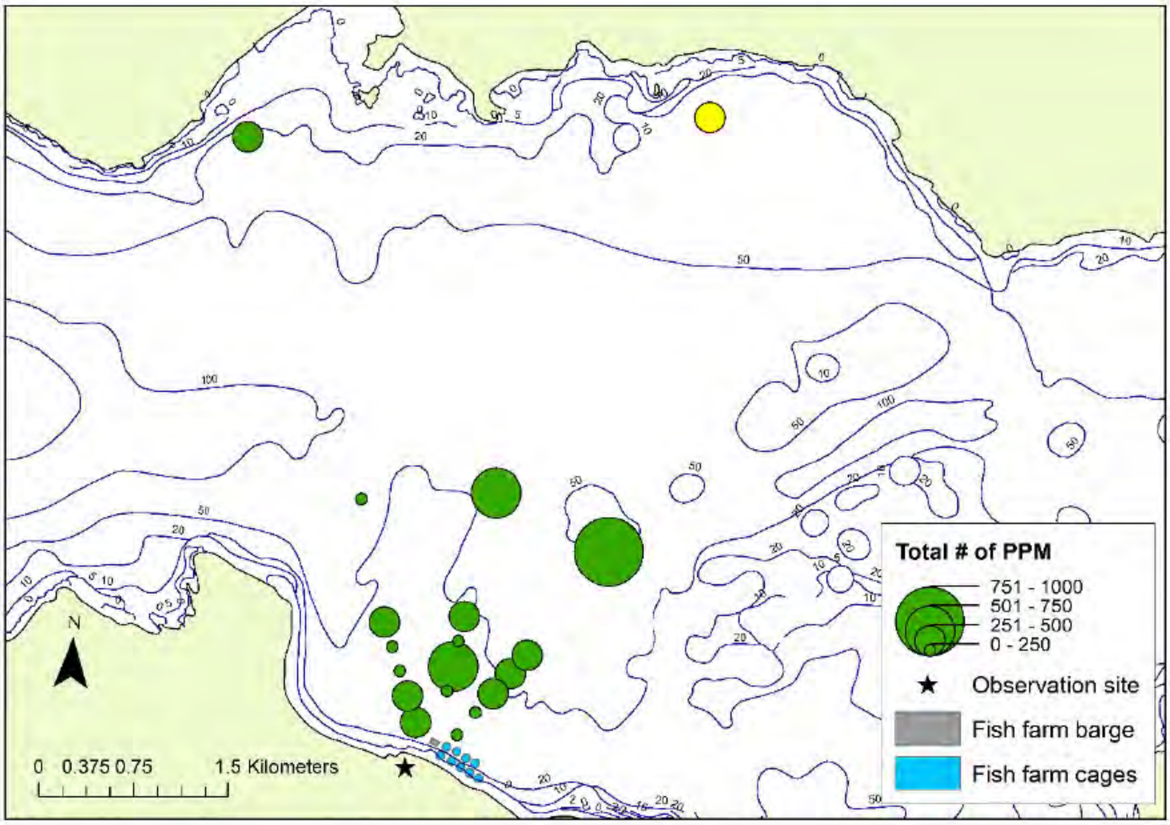


Figure 15. Summary of total numbers of PPMs reported during 8/09-16/10/2016. N.B.: the C-5000 C-POD (top right, yellow) was only operational up to 6/10/2016.

4.7.3 ENVIRONMENTAL DRIVERS OF VARIABILITY

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

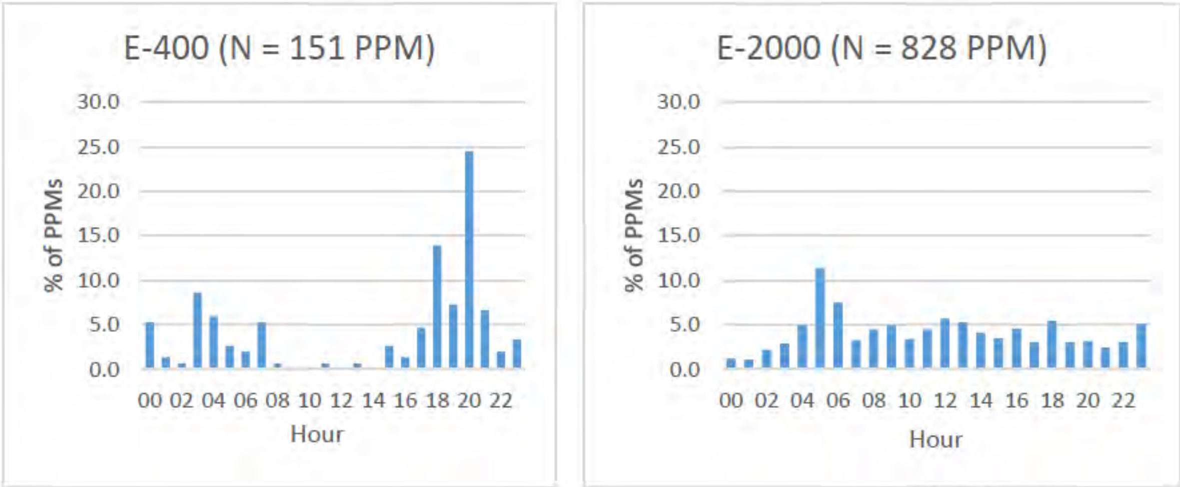


Figure 15. Examples of diurnal patterns of PPM detections from Nearfield (E-400) and Farfield (E-2000) C-PODs (data from 8/09-16/10/2016, aggregated).

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

A B

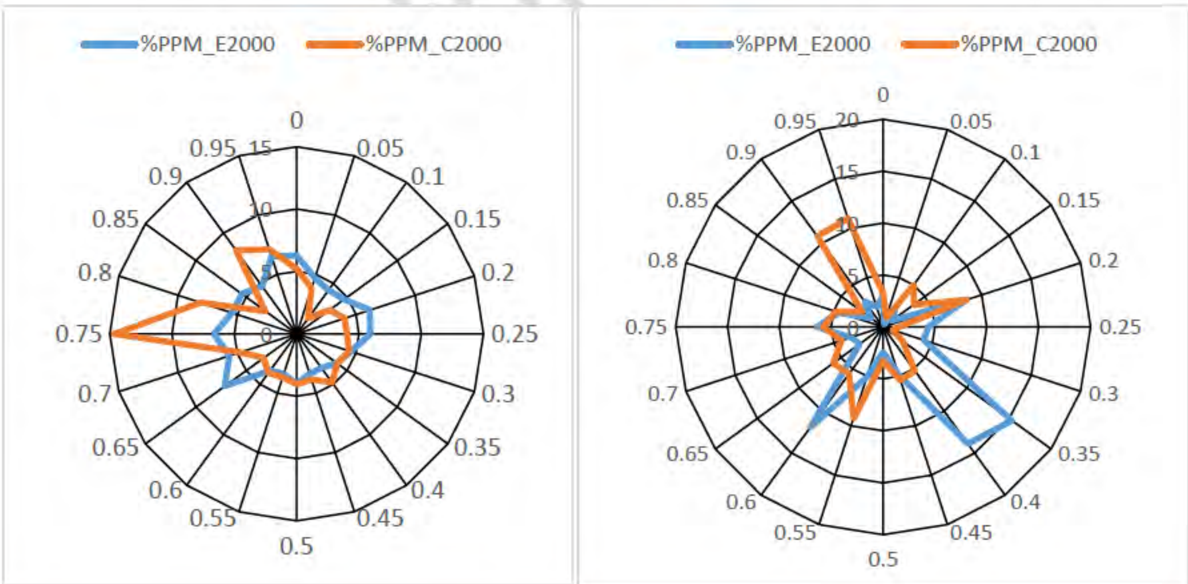


Figure 16. Examples of apparent variability in PPM detection rates at ebb-flood and spring-neap tidal scales. A) Normalised (% of total) PPM detections at locations E-2000 and C-2000 over the ebb-flood tidal cycle (0 = 1 = ebb at Tobermory tidal gauge); B) Normalised (% of total) PPM detections at locations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

4.7.4 PRE- AND POST-EXPERIMENTAL CONTEXT

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

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

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

4.8 ADVANCED MODELLING

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

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

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

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

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

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

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

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

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

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

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

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

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

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

5 DISCUSSION

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

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

Based on the limited number of exposure experiments that were visually observed (Section 4.6), seals were not noticeably deterred from the vicinity of the fish farm by either HF or LF signal transmissions. This was not the main focus of the present study and results should therefore be interpreted with caution. Seal detections at the surface were more frequent when either signal was being played than during silent control periods, suggesting they might seek to reduce noise exposure by lifting the head out of the water (Fjälling et al. 2006; Kvadsheim et al. 2010). Alternatively, seals could have been responding to a 'dinner bell' effect, having learnt to associate the sound of ADDs with the presence of food (be it captive salmon or wild fish attracted to the cages). It is worth noting that these observations occurred around a fish farm that traditionally has not used active ADDs, where such signals might therefore have been perceived as more novel and worthy of inspection by curious seals. Conversations with SSF staff indicated that seals were regularly observed near the Bloody Bay fish farm, implying that the artificial ADD signals were not suddenly attracting seals to an otherwise seal-free site. Our observations did not support the assumption that ADD signals actually deter seals from fish farms, which has itself been the subject of debate for many years (e.g. Jacobs & Terhune, 2002; Quick et al., 2004; Graham et al., 2009; Götz & Janik, 2013; Coram et al. 2014; SCOS, 2016).

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

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

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

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

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

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

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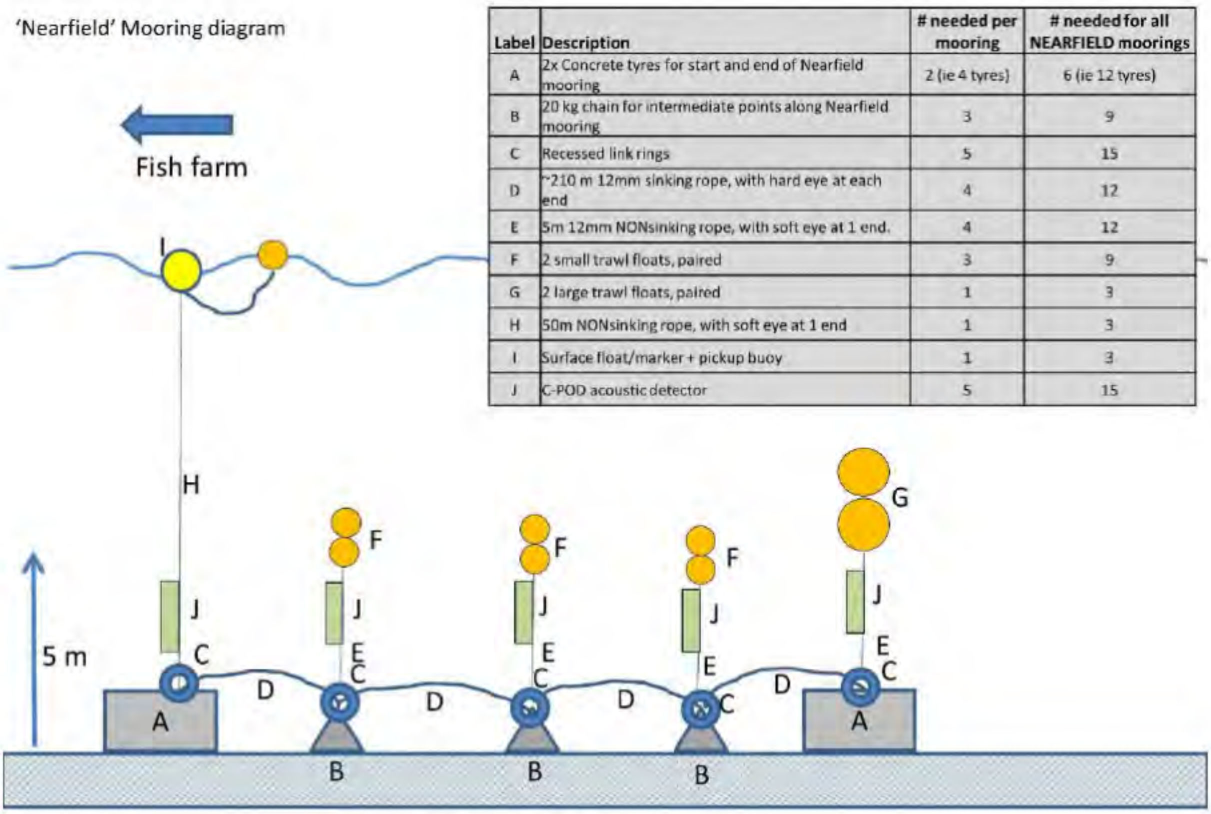
APPENDIX 1 - MOORING DESIGN

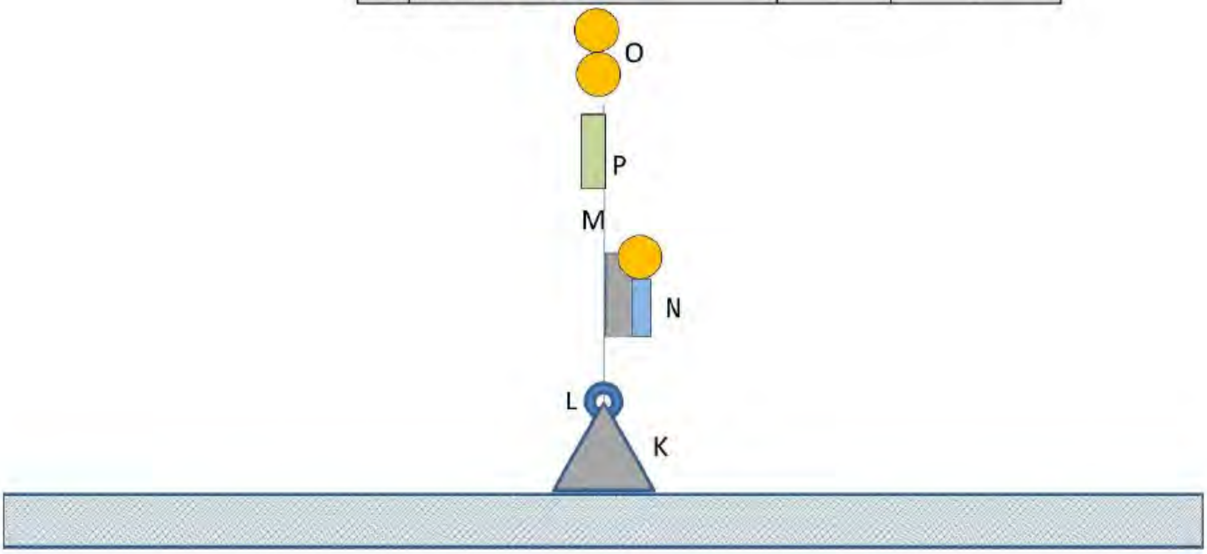
Overview of mooring structures used in Nearfield and Farfield moorings, respectively.



Label	Description	# needed per mooring	# needed for all NEARFIELD moorings
A	2x Concrete tyres for start and end of Nearfield mooring	2 (ie 4 tyres)	6 (ie 12 tyres)
B	20 kg chain for intermediate points along Nearfield mooring	3	9
C	Recessed link rings	5	15
D	~210 m 12mm sinking rope, with hard eye at each end	4	12
E	5m 12mm NONsinking rope, with soft eye at 1 end.	4	12
F	2 small trawl floats, paired	3	9
G	2 large trawl floats, paired	1	3
H	50m NONsinking rope, with soft eye at 1 end	1	3
I	Surface float/marker + pickup buoy	1	3
J	C-POD acoustic detector	5	15

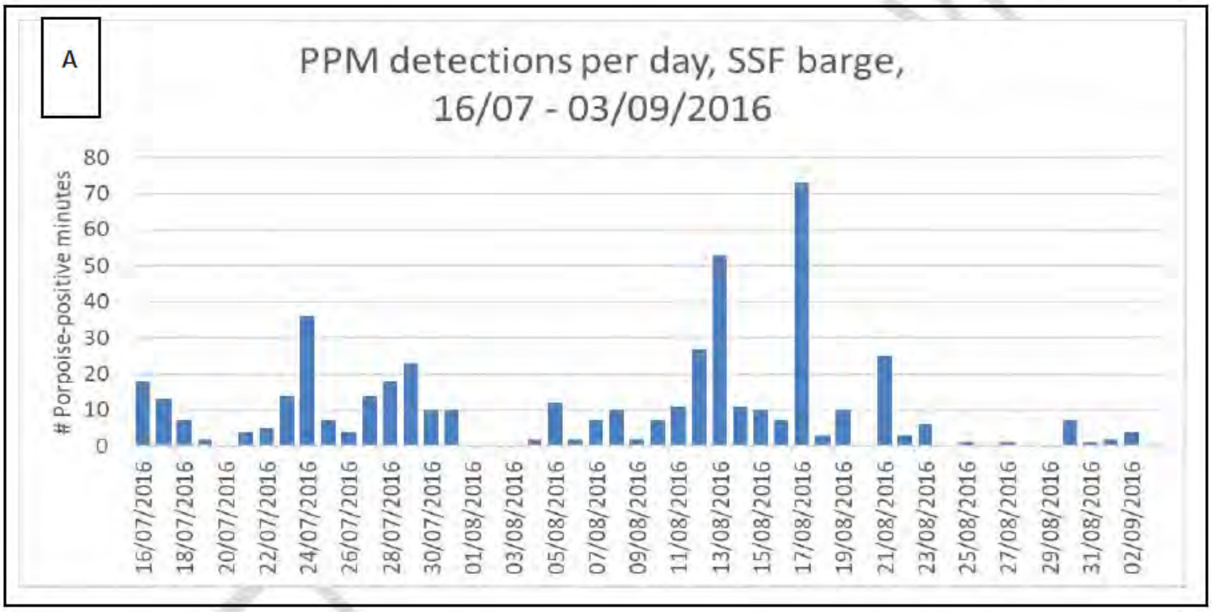
'Farfield' mooring diagram

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 FloBuoy 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



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.



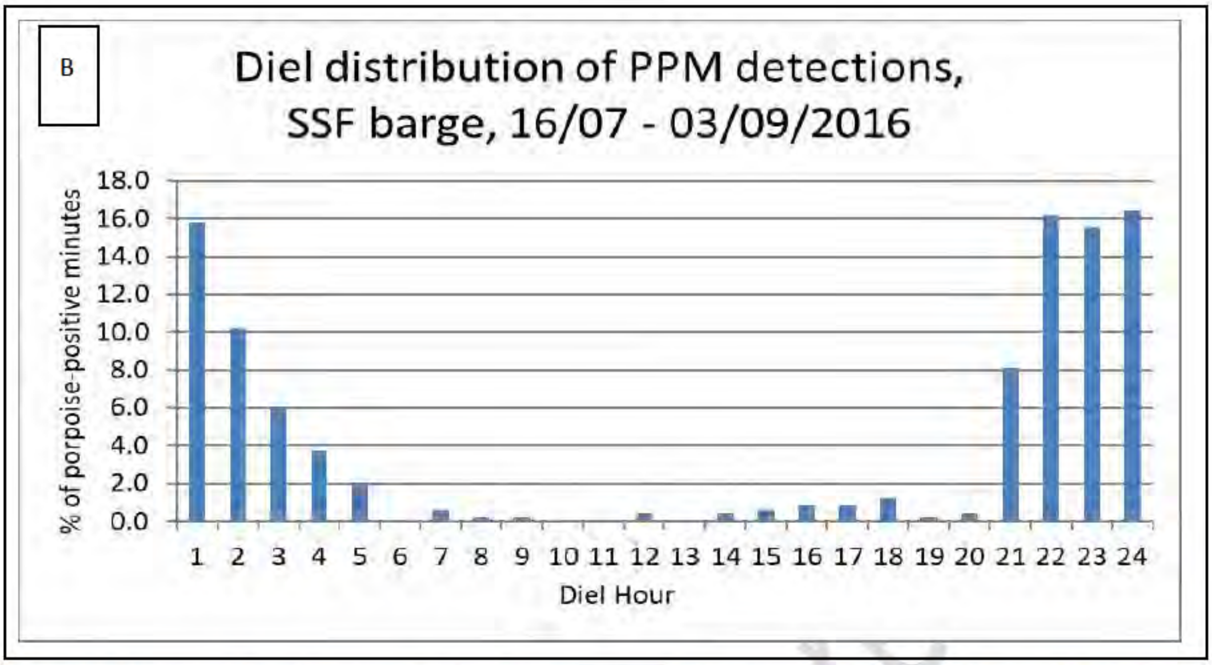


Figure A3.1. A) Overview of overall PPM numbers during pre-experimental deployment at the Bloody Bay fish farm, 16/07 – 3/09/2016 (partial start & end days excluded). B) Overview of distribution of PPMs by hour across a 24-hour day (data aggregated over 16/07 – 3/09/2016 (partial start & end days excluded).

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

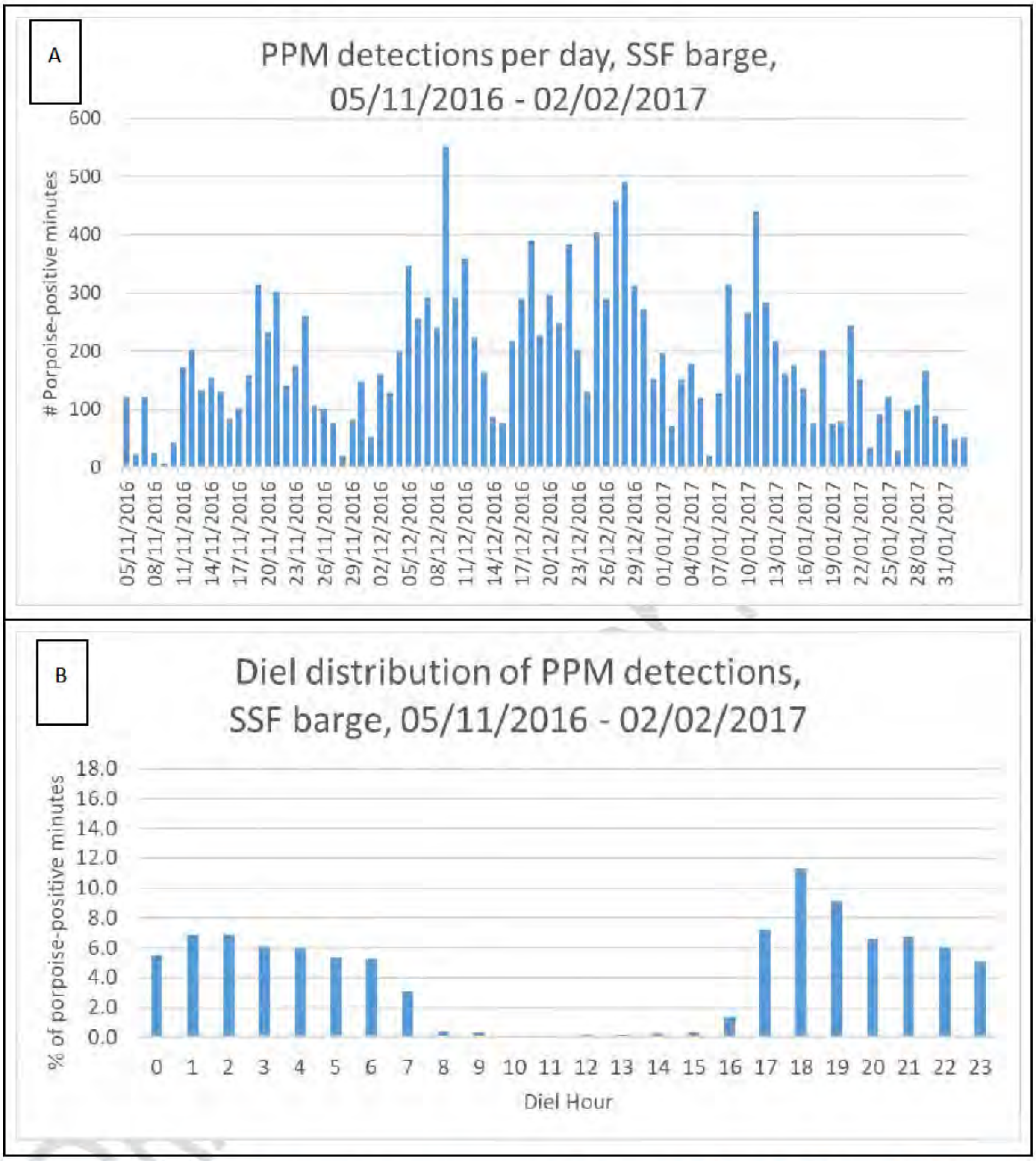


Figure A3.2. A) Overview of overall PPM numbers during pre-experimental deployment at the Bloody Bay fish farm, 05/11/2016 – 02/02/2017 (partial start & end days excluded). B) Overview of distribution of PPMs by hour across a 24-hour day (data aggregated over 05/11/2016 – 02/02/2017 (partial start &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

APPENDIX 3 - OVERVIEW OF # PPM/DAY ACROSS ARRAY

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 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

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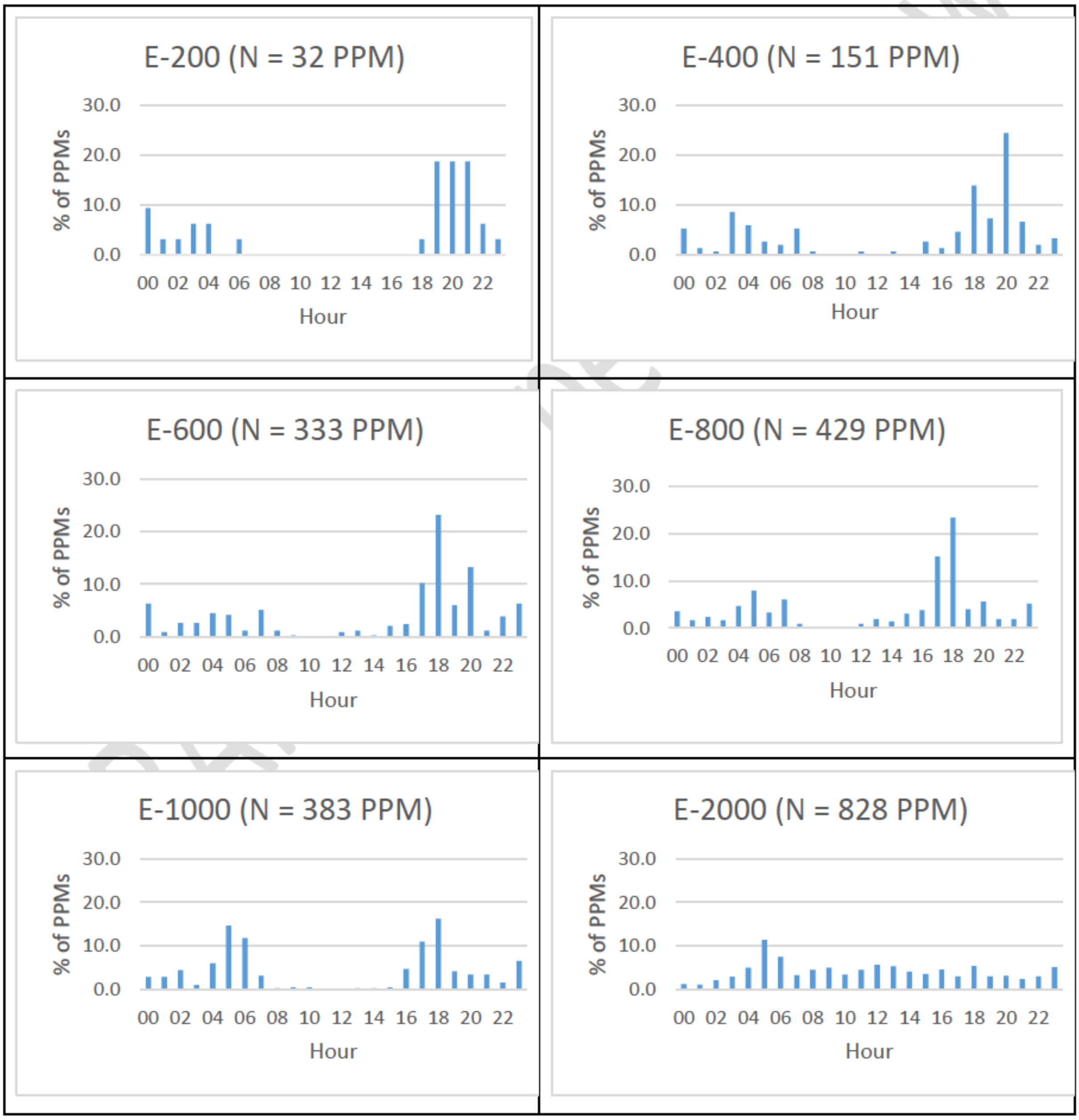
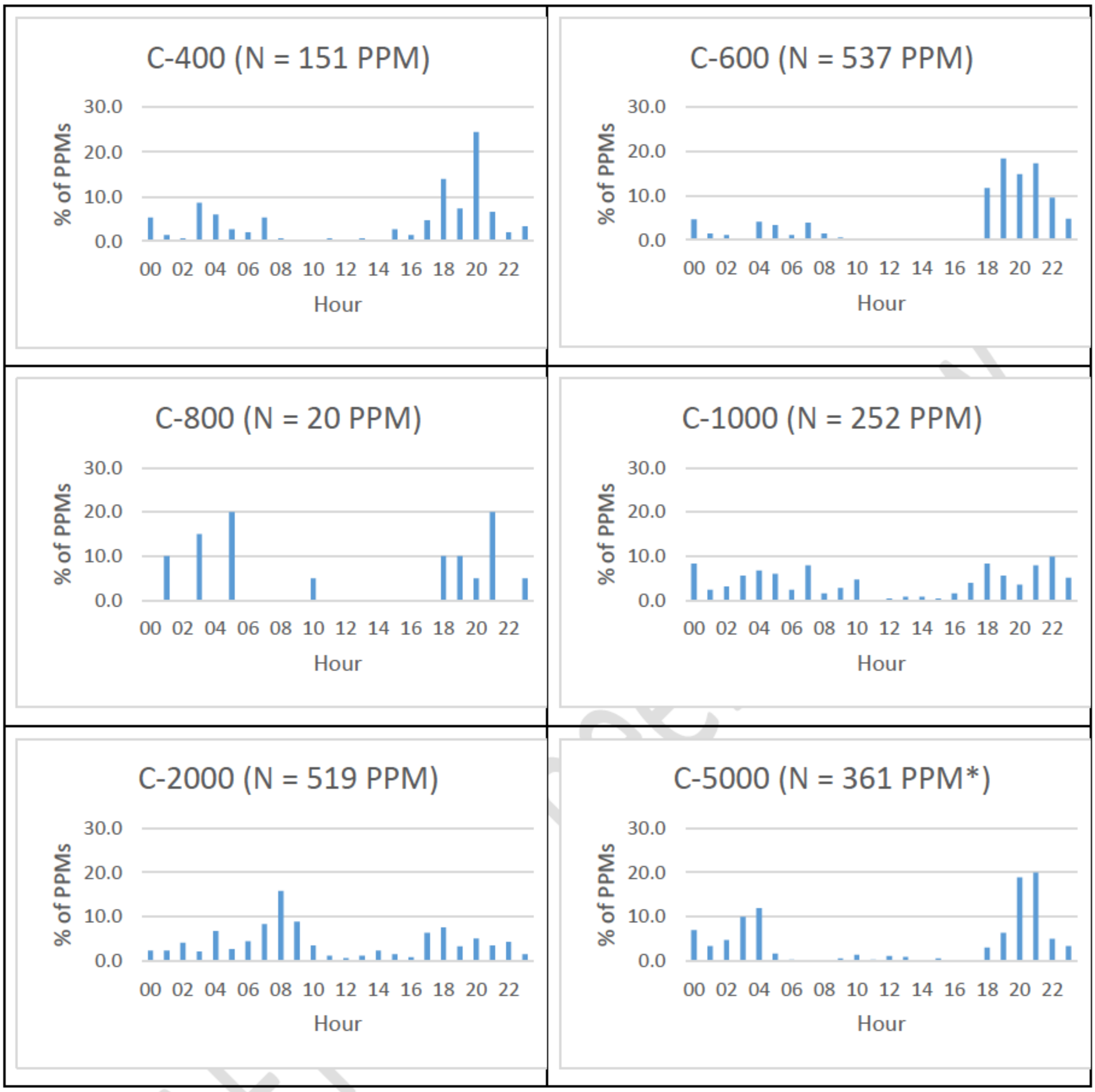
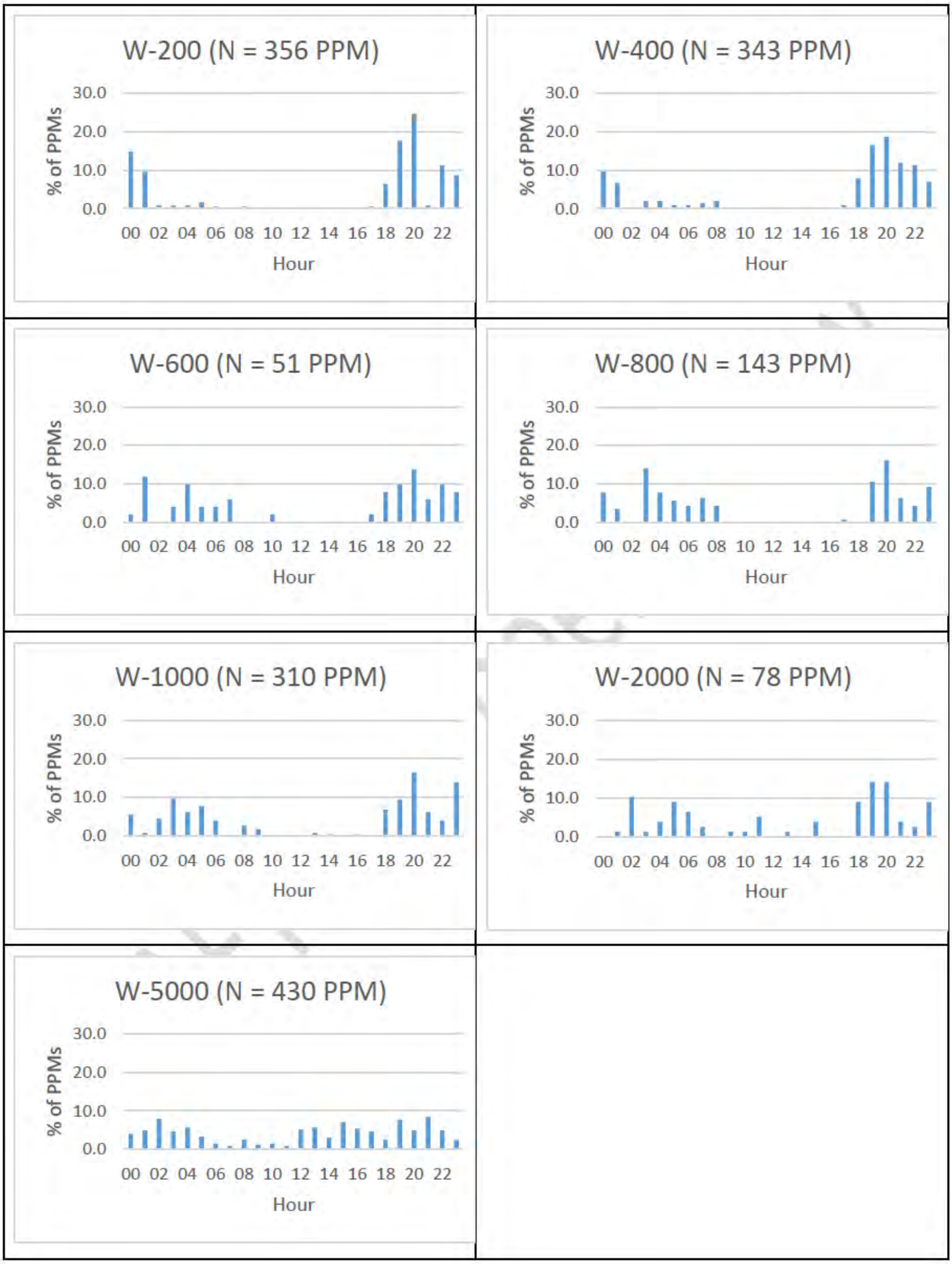
APPENDIX 4 – DIEL VARIABILITY IN PPM DETECTIONS

The following graphs illustrate, for each mooring, the diel patterns among PPM detections observed throughout the experimental period. Total numbers of PPMs are indicated for each mooring. Moorings are aggregated according to their presence along the Eastern, Central and Western mooring lines. Detection rates were generally highest at night, particularly during evenings, except for Farfield moorings such as E-2000 and W-5000.




C-400 (N = 151 PPM)
C-600 (N = 537 PPM)
C-800 (N = 20 PPM)
C-1000 (N = 252 PPM)
C-2000 (N = 519 PPM)
C-5000 (N = 361 PPM*)
% of PPMs
0.0
10.0
20.0
30.0
00 02 04 06 08 10 12 14 16 18 20 22
Hour


W-200 (N = 356 PPM)
W-400 (N = 343 PPM)
W-600 (N = 51 PPM)
W-800 (N = 143 PPM)
W-1000 (N = 310 PPM)
W-2000 (N = 78 PPM)
W-5000 (N = 430 PPM)
% of PPMs
30.0
20.0
10.0
0.0
00 02 04 06 08 10 12 14 16 18 20 22
Hour

APPENDIX 5 - GAM DESCRIPTORS AND OUTPUTS

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

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

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

Table A8.1. List of available covariates considered for models. * Indicates covariates that were only considered for compound models.

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		

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

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

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

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

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

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

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

Full array model

Model:	Entire array
Model structure:	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)
Confusion matrix:	(see below)
AUC value:	0.8436431

Confusion matrix:

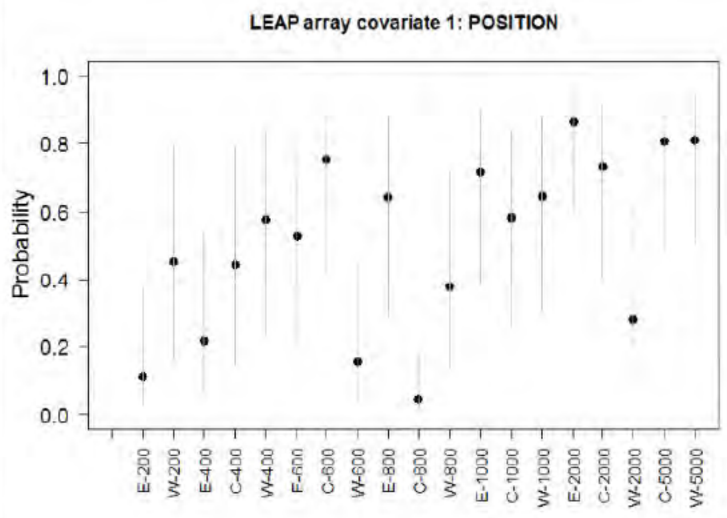
		Expected	
		Porpoise	No porpoise
Observed	Porpoise	81.3%	27.3%
	No porpoise	18.7%	72.7%

Results of Wald's tests for all significant covariates for the final model:

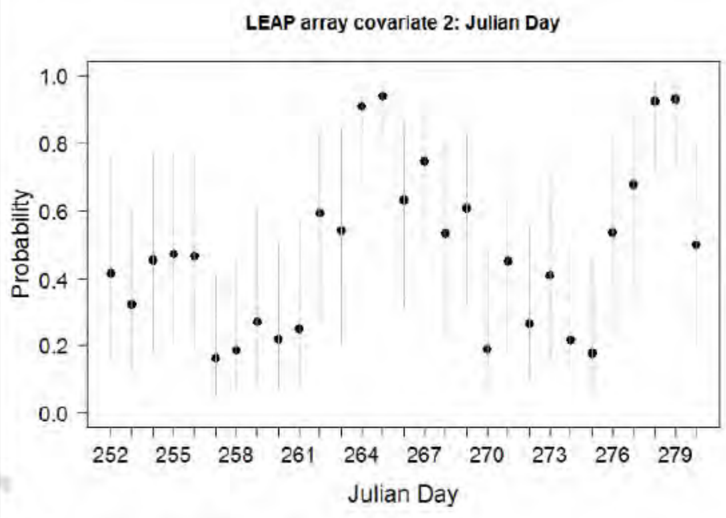
Covariates (in descending order of significance)	Form	Degrees of Freedom	χ^2 score	P-value
POSITION	factor	18	423.14	$<2.2 \cdot 10^{-16}$
JULDAY	factor	28	273.52	$<2.2 \cdot 10^{-16}$
HOUR	Cyclic B-spline	4	138.73	$<2.2 \cdot 10^{-16}$
Nall_m	linear	1	169.23	$<2.2 \cdot 10^{-16}$
Signal_Type	factor	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

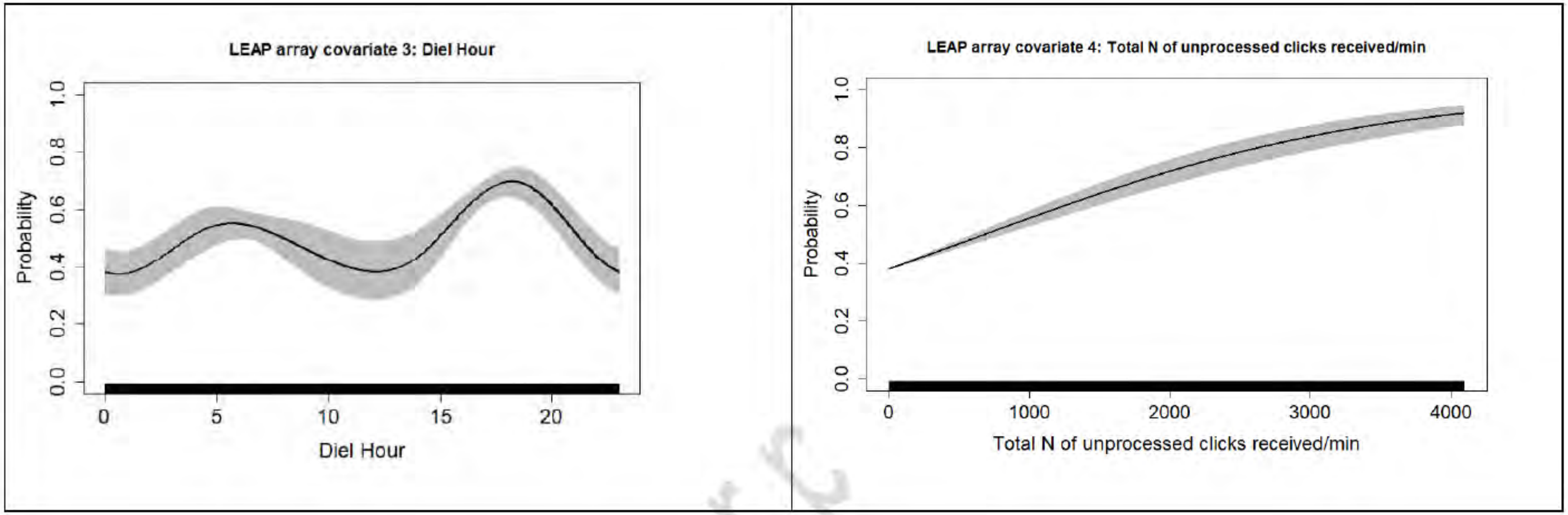
SpringNeap	Cyclic B-spline	4	11.35	0.022868

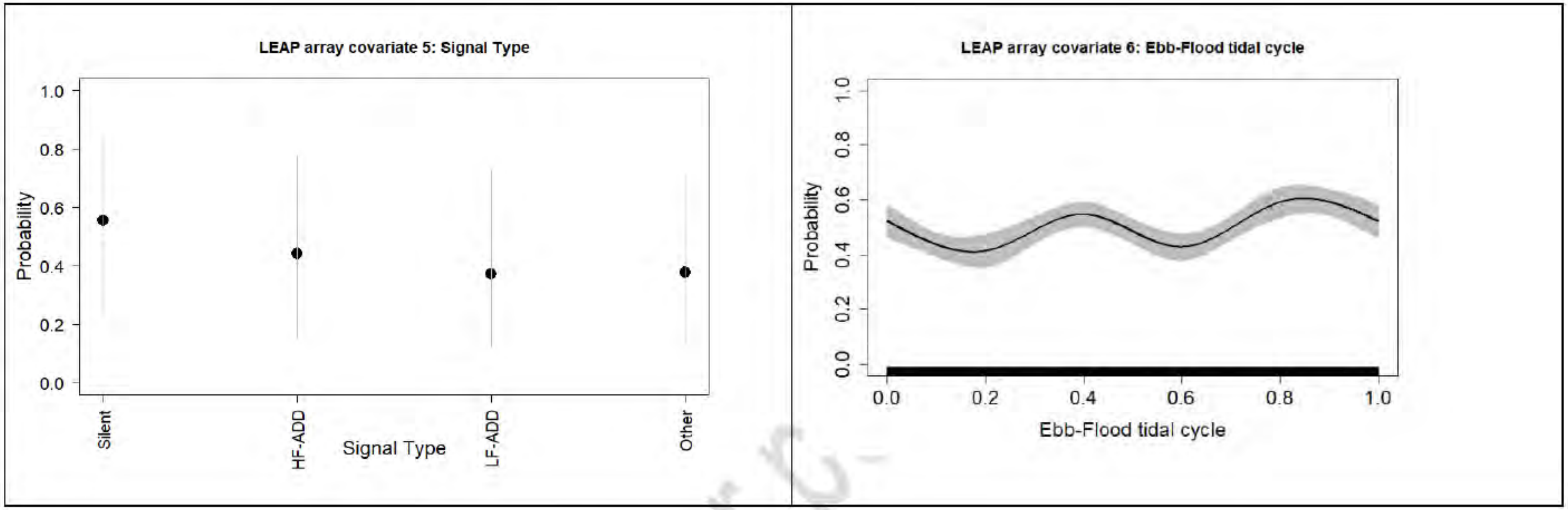


LEAP array covariate 1: POSITION
Probability
1.0
0.8
0.6
0.4
0.2
0.0
E-200
W-200
E-400
C-400
W-400
E-600
C-600
W-600
E-800
C-800
W-800
E-1000
C-1000
W-1000
E-2000
C-2000
W-2000
C-5000
W-5000

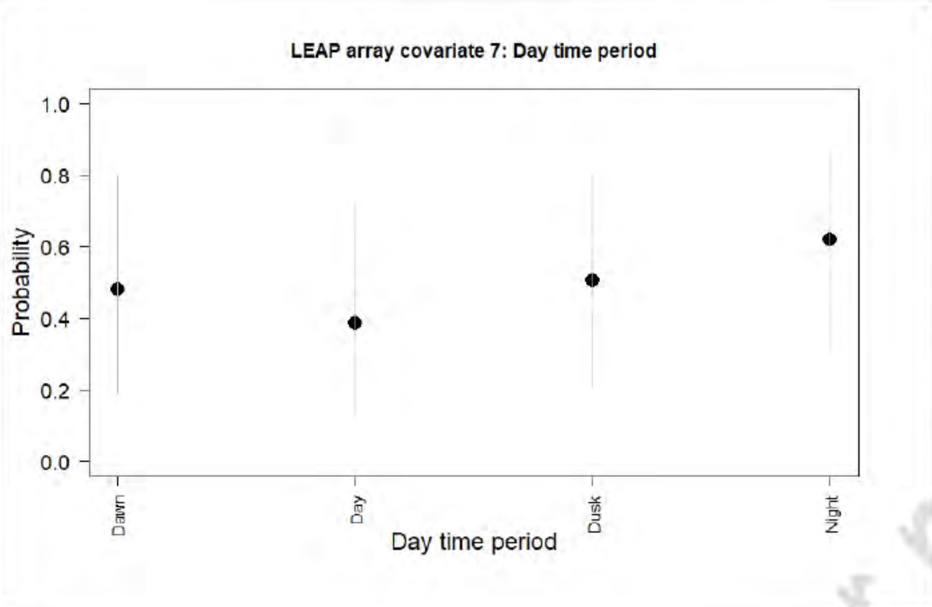


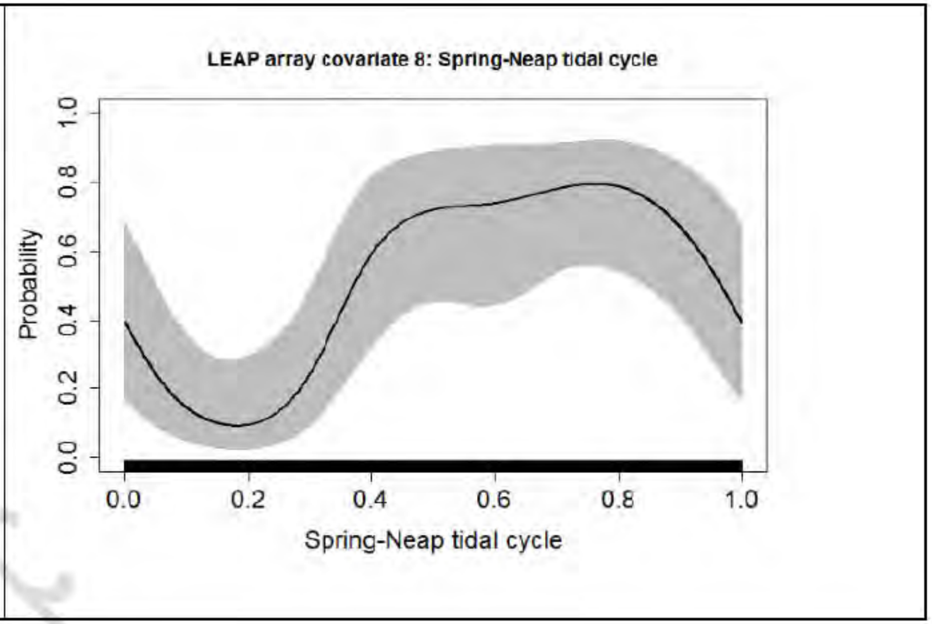
LEAP array covariate 2: Julian Day
Probability
1.0
0.8
0.6
0.4
0.2
0.0
252
255
258
261
264
267
270
273
276
279
Julian Day


LEAP array covariate 3: Diel Hour
Probability
0.0
0.2
0.4
0.6
0.8
1.0
0
5
10
15
20
Diel Hour
LEAP array covariate 4: Total N of unprocessed clicks received/min
Probability
0.0
0.2
0.4
0.6
0.8
1.0
0
1000
2000
3000
4000
Total N of unprocessed clicks received/min



LEAP array covariate 5: Signal Type
Probability
1.0
0.8
0.6
0.4
0.2
0.0
Silent
HF-ADD
LF-ADD
Other
Signal Type
LEAP array covariate 6: Ebb-Flood tidal cycle
Probability
0.0
0.2
0.4
0.6
0.8
1.0
Ebb-Flood tidal cycle


LEAP array covariate 7: Day time period
Probability
1.0
0.8
0.6
0.4
0.2
0.0
Dawn
Day
Dusk
Night
Day time period


LEAP array covariate 8: Spring-Neap tidal cycle
Probability
1.0
0.8
0.6
0.4
0.2
0.0
0.0
0.2
0.4
0.6
0.8
1.0
Spring-Neap tidal cycle

1789

Nearfield model

Model:	Nearfield moorings (E-200-E1000, C-400-1000, & W-200-1000)
Model structure:	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)
Confusion matrix:	

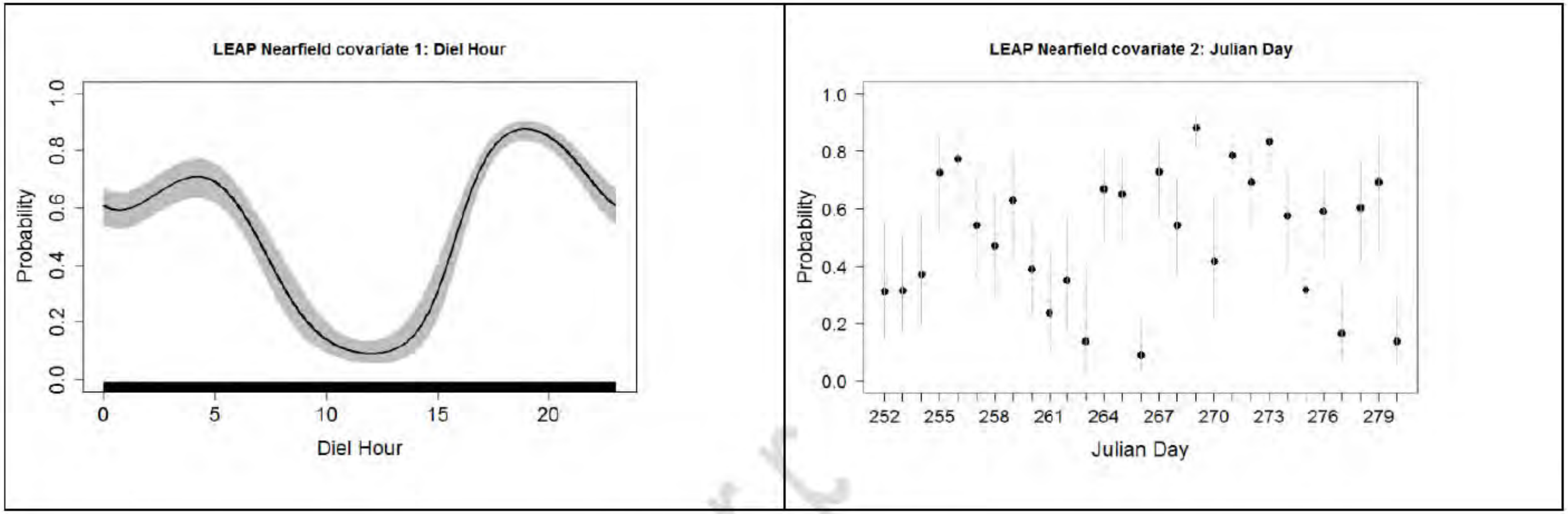
		Expected	
		Porpoise	No porpoise
Observed	Porpoise	80.6%	19.2%
	No porpoise	19.4%	80.8%

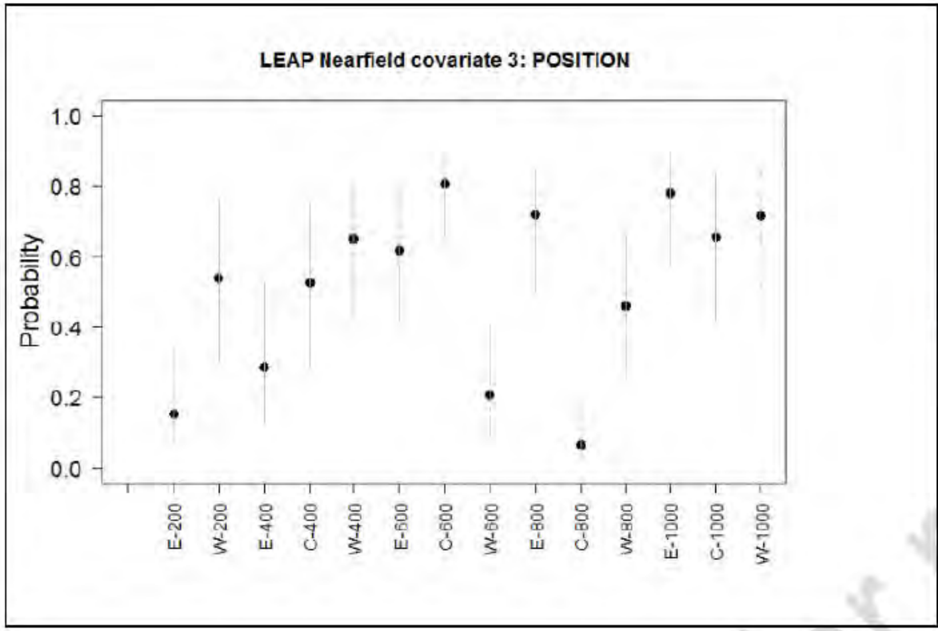
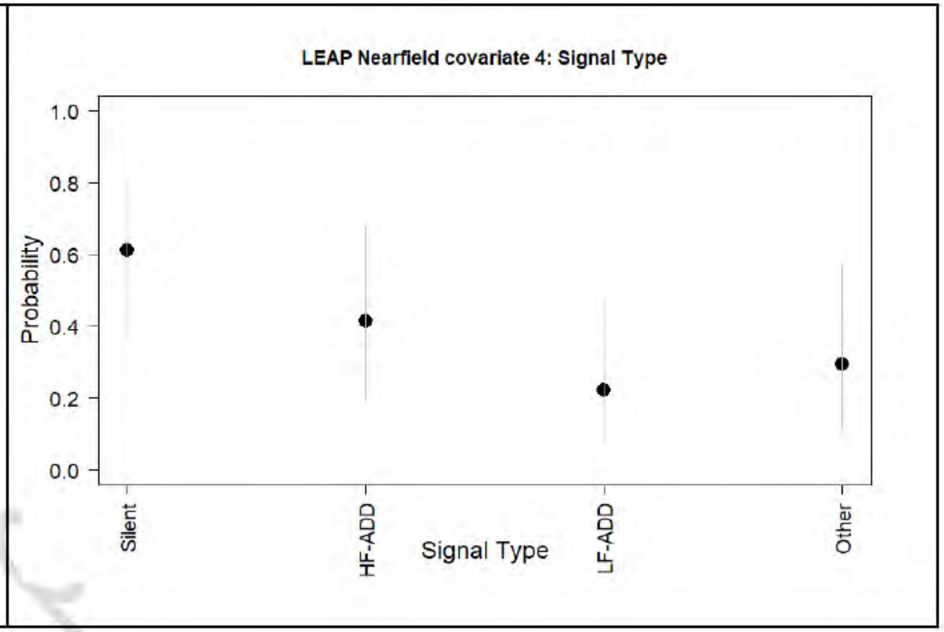
AUC value:	0.8893874

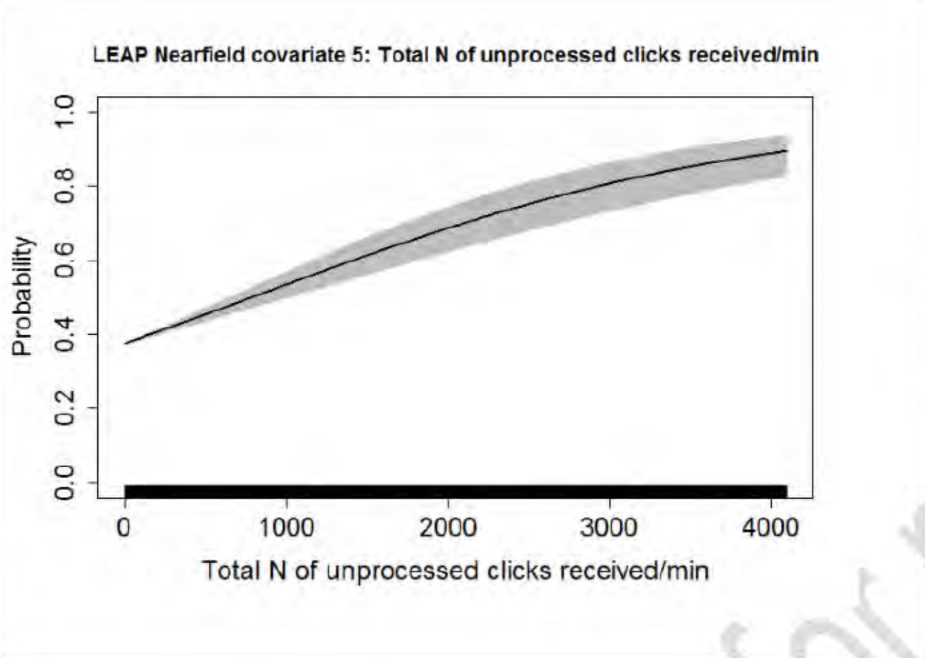
Results of Wald's tests for all significant covariates for the final model:

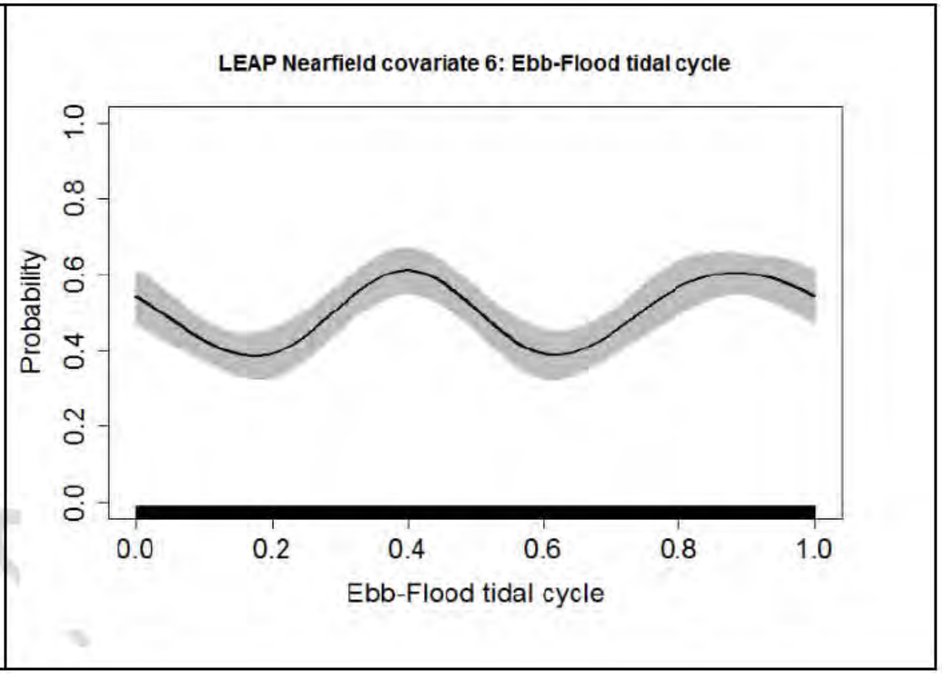
Covariates (in descending order of significance)	Form	Degrees of Freedom	χ^2 score	P-value
HOUR	Cyclic B-spline	4	165.23	$<2.2\cdot10^{-16}$
JULDAY	factor	28	367.38	$<2.2\cdot10^{-16}$
POSITION	factor	13	195.50	$<2.2\cdot10^{-16}$
Signal_Type	factor	3	61.93	$2.272\cdot10^{-13}$
Nall_m	linear	1	73.34	$<2.2\cdot10^{-16}$

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


LEAP Nearfield covariate 1: Diel Hour
Probability
0.0
0.2
0.4
0.6
0.8
1.0
0
5
10
15
20
Diel Hour
LEAP Nearfield covariate 2: Julian Day
Probability
0.0
0.2
0.4
0.6
0.8
1.0
252
255
258
261
264
267
270
273
276
279
Julian Day


LEAP Nearfield covariate 3: POSITION
Probability
1.0
0.8
0.6
0.4
0.2
0.0
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

LEAP Nearfield covariate 4: Signal Type
Probability
1.0
0.8
0.6
0.4
0.2
0.0
Silent
HF-ADD
LF-ADD
Other
Signal Type

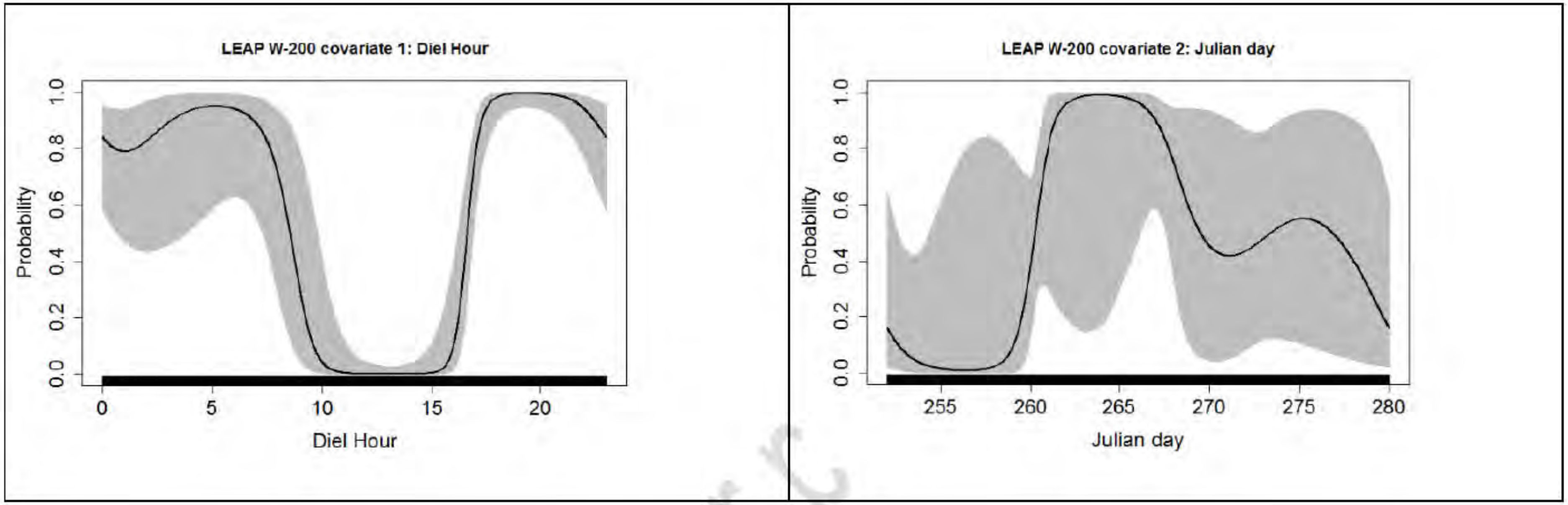

LEAP Nearfield covariate 5: Total N of unprocessed clicks received/min
Probability
0.0
0.2
0.4
0.6
0.8
1.0
0
1000
2000
3000
4000
Total N of unprocessed clicks received/min

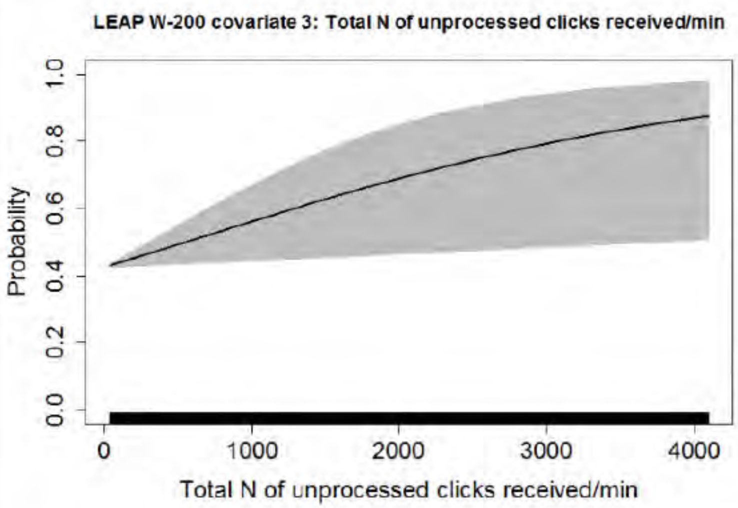

LEAP Nearfield covariate 6: Ebb-Flood tidal cycle
Probability
0.0
0.2
0.4
0.6
0.8
1.0
0.0
0.2
0.4
0.6
0.8
1.0
Ebb-Flood tidal cycle

Model:	W-200
Model structure:	POD5<-geeglm(PPM ~ AvgHrBasisMat + bs(JULDAY , knots=mean(JULDAY)) + Nall_m, family = binomial, corstr="independence", id=Panel, data=W200)
Confusion matrix:	

		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

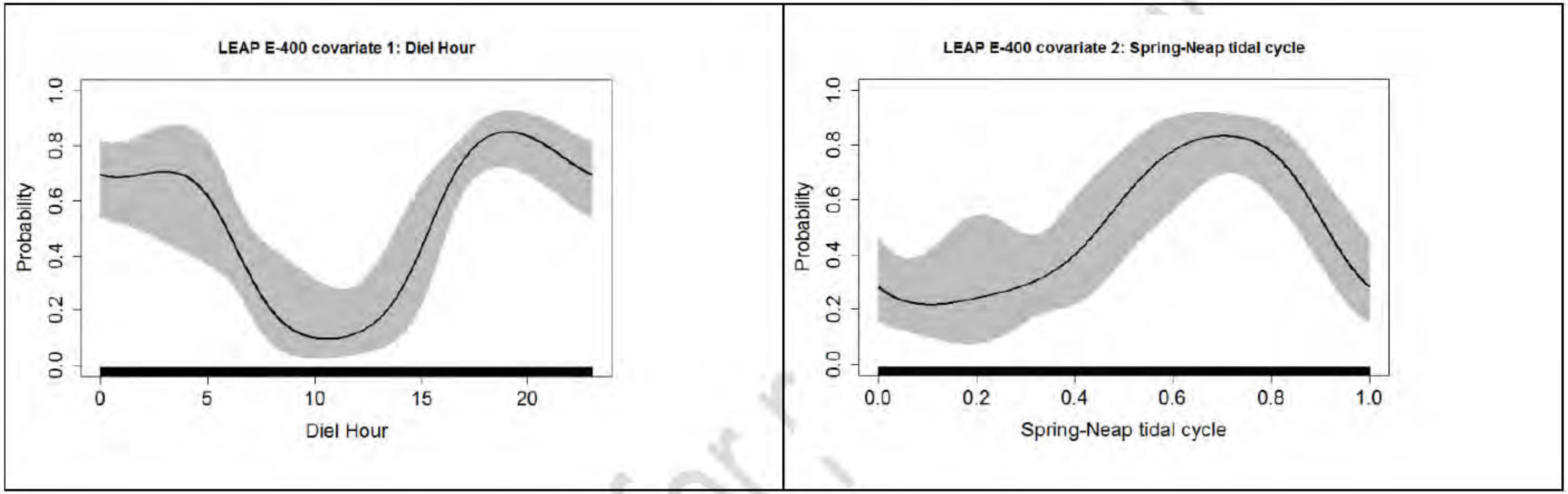

LEAP W-200 covariate 1: Diel Hour
Probability
0.0
0.2
0.4
0.6
0.8
1.0
0
5
10
15
20
Diel Hour
LEAP W-200 covariate 2: Julian day
Probability
0.0
0.2
0.4
0.6
0.8
1.0
255
260
265
270
275
280
Julian day

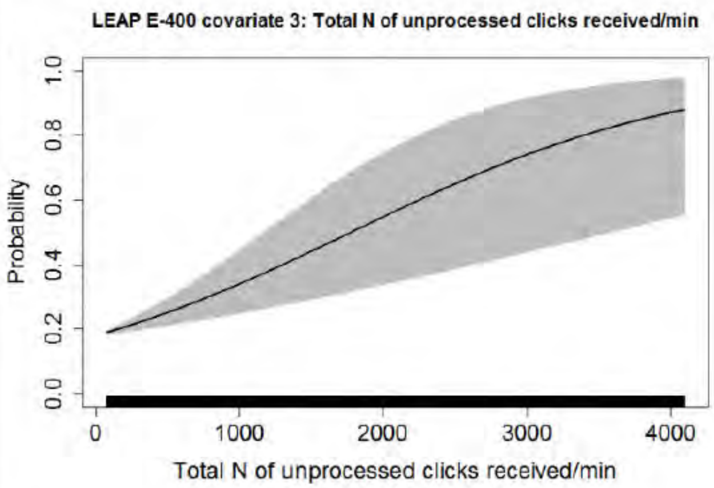

LEAP W-200 covariate 3: Total N of unprocessed clicks received/min
Probability
0.0
0.2
0.4
0.6
0.8
1.0
0
1000
2000
3000
4000
Total N of unprocessed clicks received/min

Model:	E-400
Model structure:	POD5<-geeglm(PPM ~ AvgHrBasisMat + SprNpBasisMat + Nall_m, family = binomial, corstr="independence", id=Panel, data=E400)
Confusion matrix:	

		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	$3.749\cdot10^{-5}$
SpringNeap	Cyclic B-spline	4	17.091	0.0018557
Nall_m	linear	1	14.680	0.0001274


LEAP E-400 covariate 1: Diel Hour
Probability
0.0
0.2
0.4
0.6
0.8
1.0
0
5
10
15
20
Diel Hour
LEAP E-400 covariate 2: Spring-Neap tidal cycle
Probability
0.0
0.2
0.4
0.6
0.8
1.0
Spring-Neap tidal cycle


LEAP E-400 covariate 3: Total N of unprocessed clicks received/min
Probability
0.0
0.2
0.4
0.6
0.8
1.0
0
1000
2000
3000
4000
Total N of unprocessed clicks received/min

1798

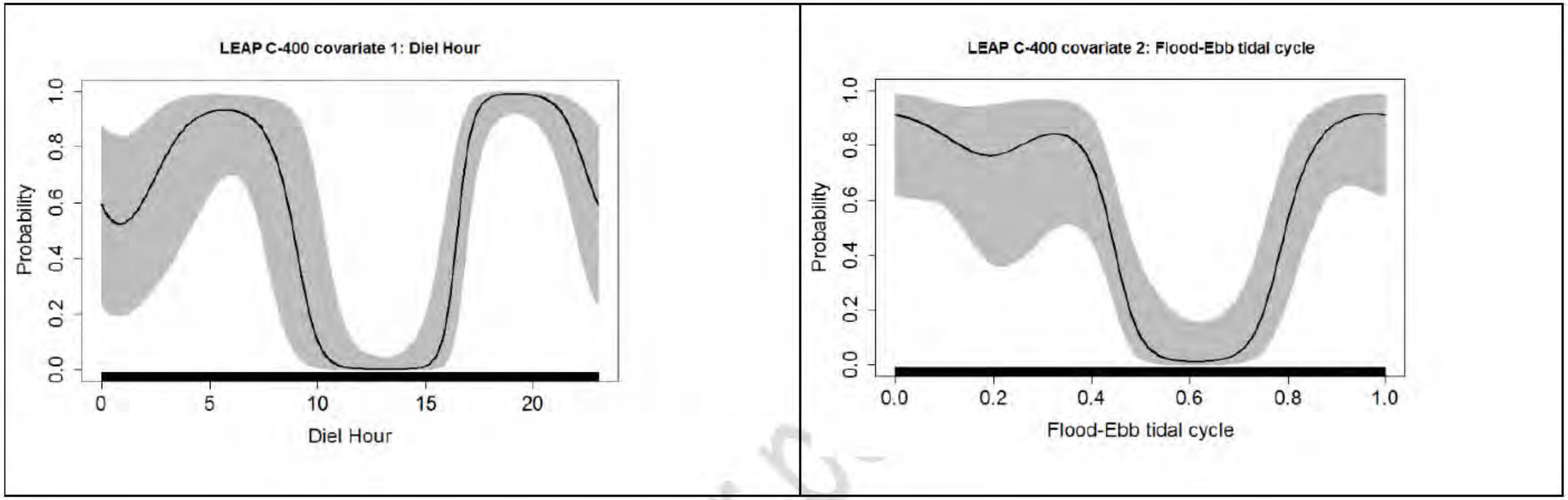
Model:	C-400
Model structure:	POD5<-geeglm(PPM ~ AvgHrBasisMat + TideBasisMat + bs(JULDAY , knots=mean(JULDAY)) + Nall_m, family = binomial, corstr="independence", id=Panel, data=C400)
Confusion matrix:	(see below)

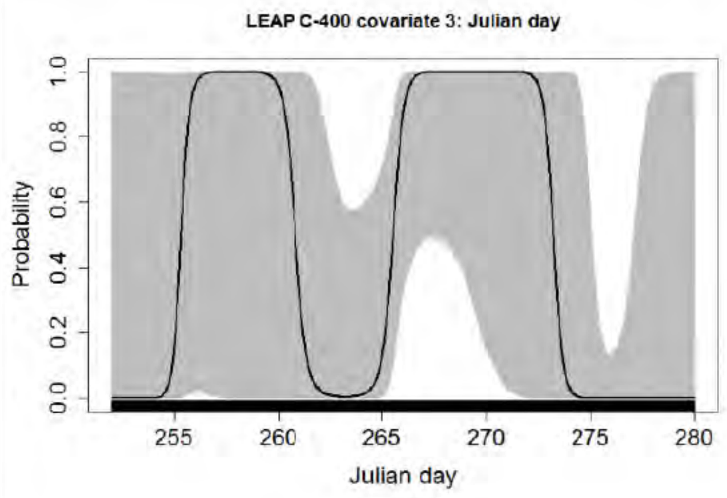
		Expected	
		Porpoise	No porpoise
Observed	Porpoise	89.3%	10.8%
	No porpoise	10.7%	89.2%

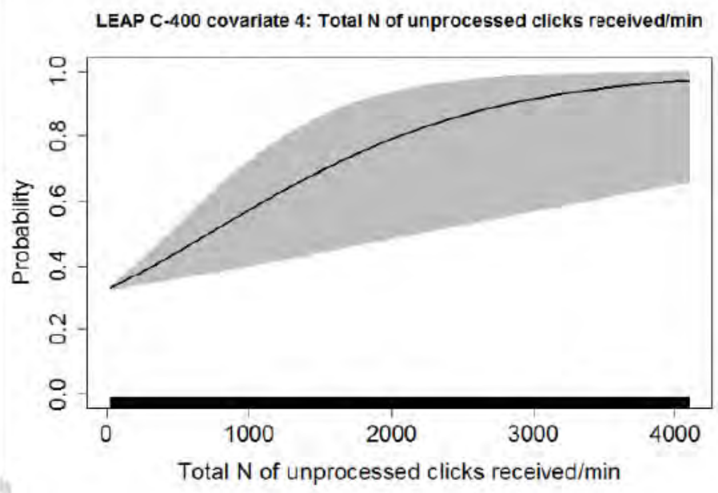
AUC value:	0.943135

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


LEAP C-400 covariate 1: Diel Hour
Probability
Diel Hour
LEAP C-400 covariate 2: Flood-Ebb tidal cycle
Probability
Flood-Ebb tidal cycle


LEAP C-400 covariate 3: Julian day
Probability
0.0
0.2
0.4
0.6
0.8
1.0
255
260
265
270
275
280
Julian day


LEAP C-400 covariate 4: Total N of unprocessed clicks received/min
Probability
0.0
0.2
0.4
0.6
0.8
1.0
0
1000
2000
3000
4000
Total N of unprocessed clicks received/min

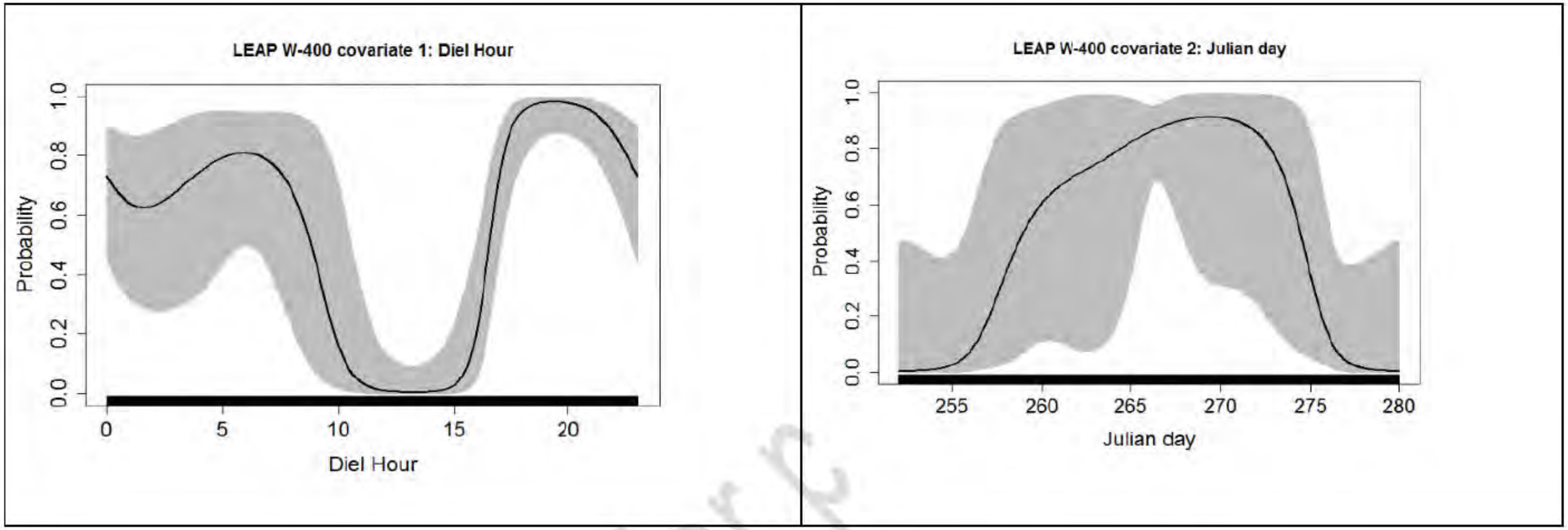
Model:	W-400
Model structure:	POD5<-geeglm(PPM ~ AvgHrBasisMat + bs(JULDAY , knots=mean(JULDAY)) + as.factor(Signal_Type) + Nall_m + TideBasisMat, family = binomial, corstr="independence", id=Panel, data=W400)
Confusion matrix:	

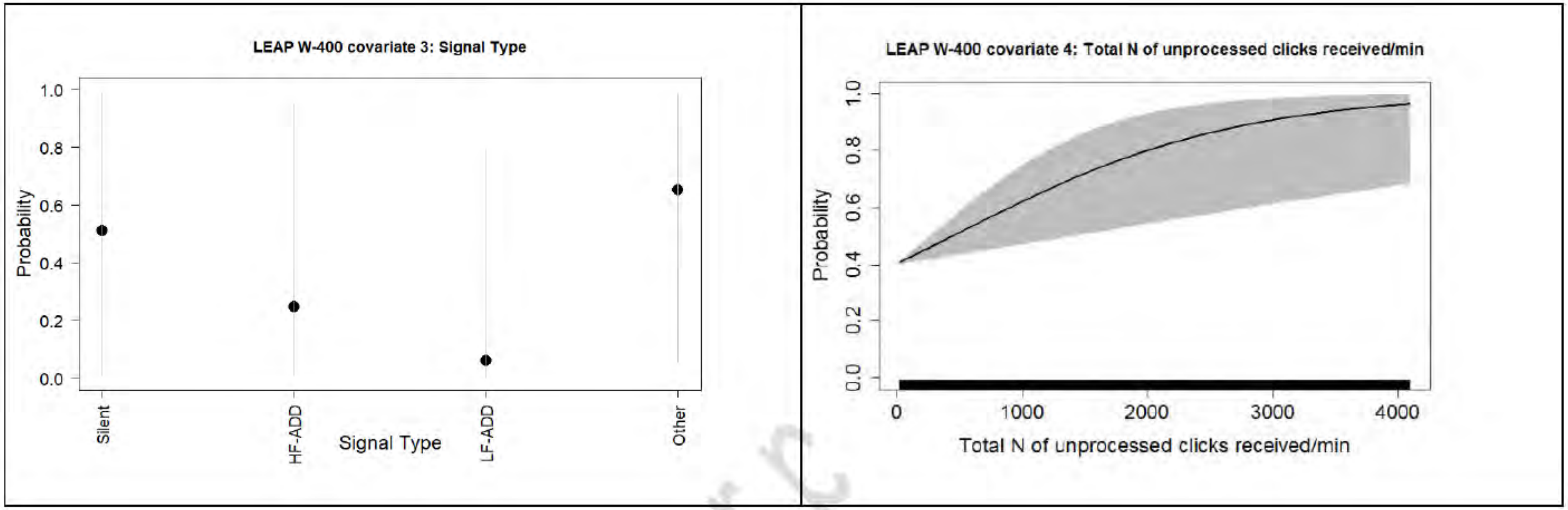
		Expected	
		Porpoise	No porpoise
Observed	Porpoise	88.4%	21.9%
	No porpoise	11.6%	78.1%

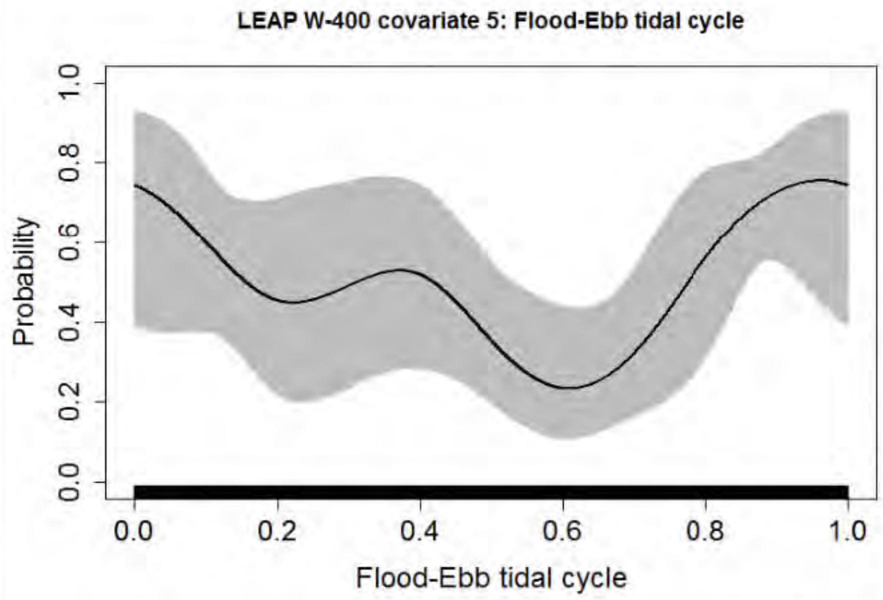
AUC value:	0.9068351

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


LEAP W-400 covariate 1: Diel Hour
Probability
Diel Hour
0.0
0.2
0.4
0.6
0.8
1.0
0
5
10
15
20
LEAP W-400 covariate 2: Julian day
Probability
Julian day
255
260
265
270
275
280


LEAP W-400 covariate 3: Signal Type
Probability
1.0
0.8
0.6
0.4
0.2
0.0
Silent
HF-ADD
LF-ADD
Other
Signal Type
LEAP W-400 covariate 4: Total N of unprocessed clicks received/min
Probability
0
1000
2000
3000
4000
Total N of unprocessed clicks received/min


LEAP W-400 covariate 5: Flood-Ebb tidal cycle
Probability
0.0
0.2
0.4
0.6
0.8
1.0
0.0
0.2
0.4
0.6
0.8
1.0
Flood-Ebb tidal cycle

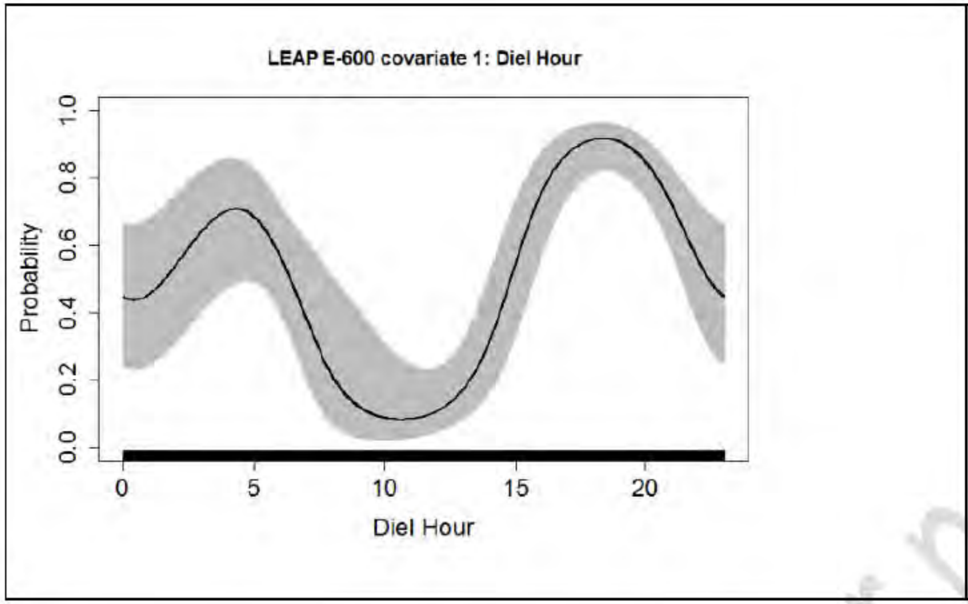
Model:	E-600
Model structure:	POD5<-geeglm(PPM ~ AvgHrBasisMat + bs(JULDAY , knots=mean(JULDAY)) + SprNpBasisMat + TideBasisMat, family = binomial, corstr="independence", id=Panel, data=E600)
Confusion matrix:	

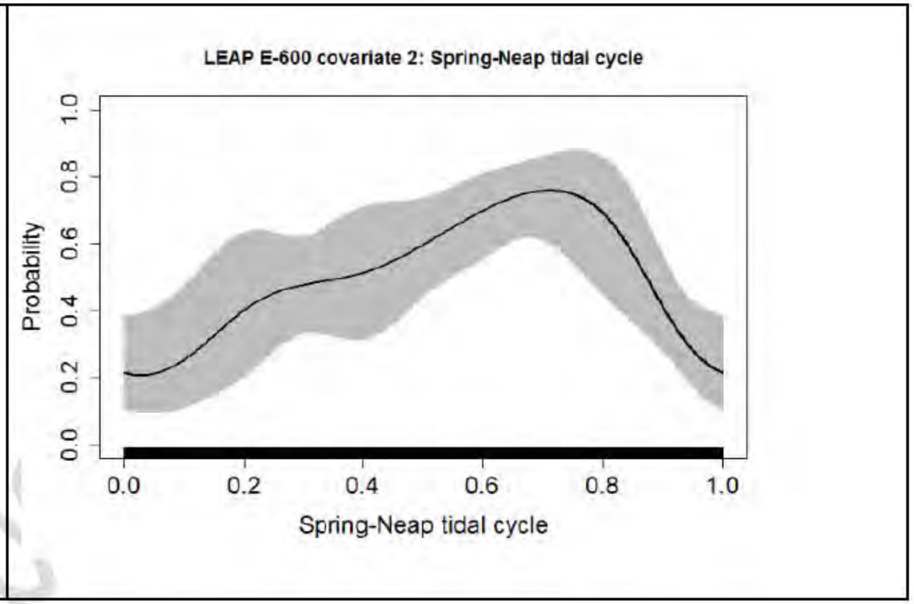
		Expected	
		Porpoise	No porpoise
Observed	Porpoise	75.5%	23.6%
	No porpoise	24.5%	76.4%

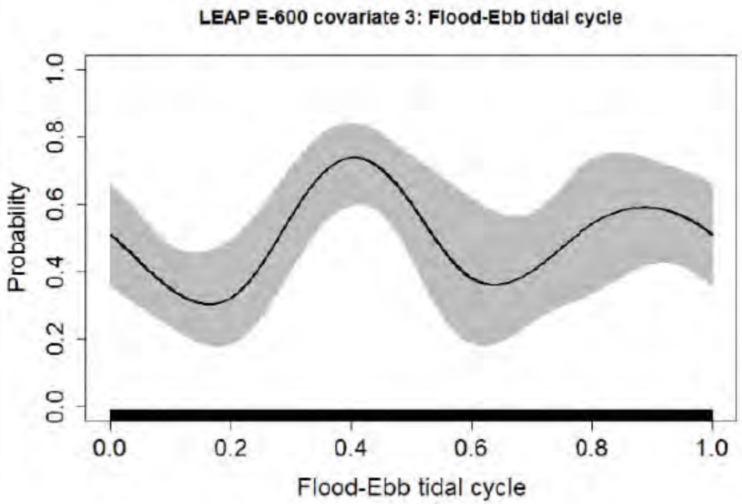
AUC value:	0.8365278

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


LEAP E-600 covariate 1: Diel Hour
Probability
0.0
0.2
0.4
0.6
0.8
1.0
0
5
10
15
20
Diel Hour


LEAP E-600 covariate 2: Spring-Neap tidal cycle
Probability
0.0
0.2
0.4
0.6
0.8
1.0
0.0
0.2
0.4
0.6
0.8
1.0
Spring-Neap tidal cycle



LEAP E-600 covariate 3: Flood-Ebb tidal cycle
Probability
0.0
0.2
0.4
0.6
0.8
1.0
Flood-Ebb tidal cycle

1804

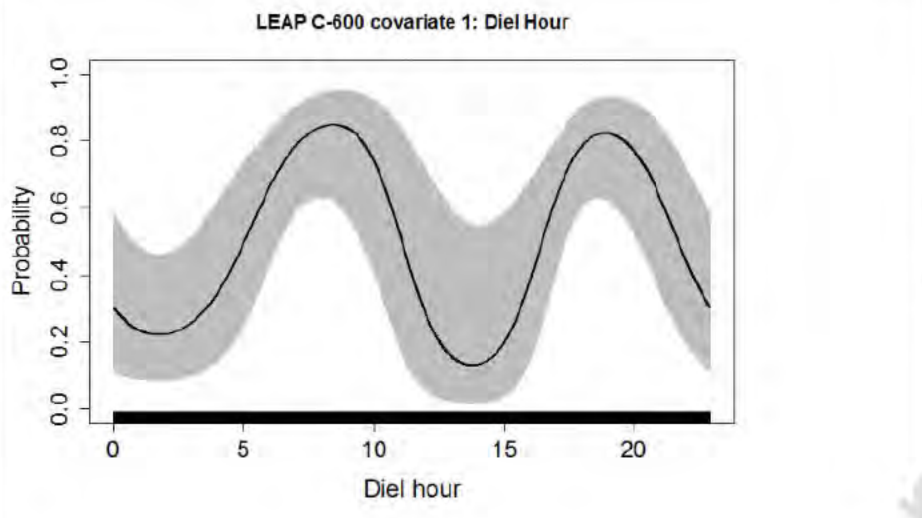
Model:	C-600
Model structure:	POD7<-geeglm(PPM ~ AvgHrBasisMat + bs(JULDAY , knots=mean(JULDAY)) + Nall_m + as.factor(DAYTIMENum), family = binomial, corstr="independence", id=Panel, data=C600)
Confusion matrix:	

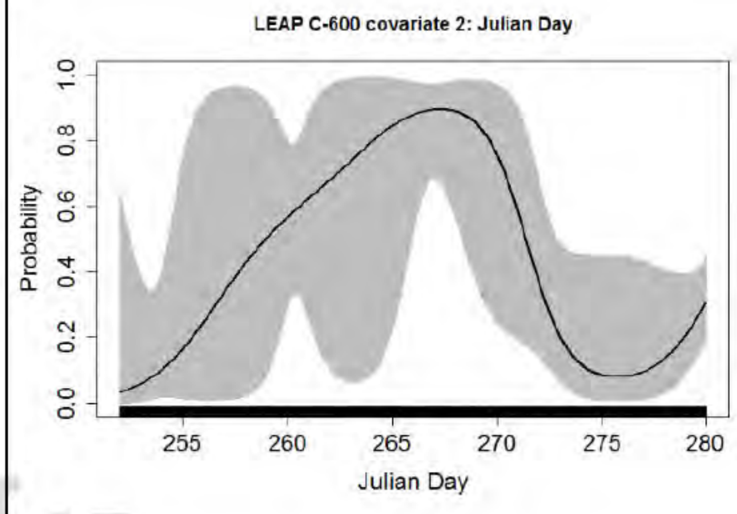
		Expected	
		Porpoise	No porpoise
Observed	Porpoise	77.0%	15.6%
	No porpoise	23.0%	84.4%

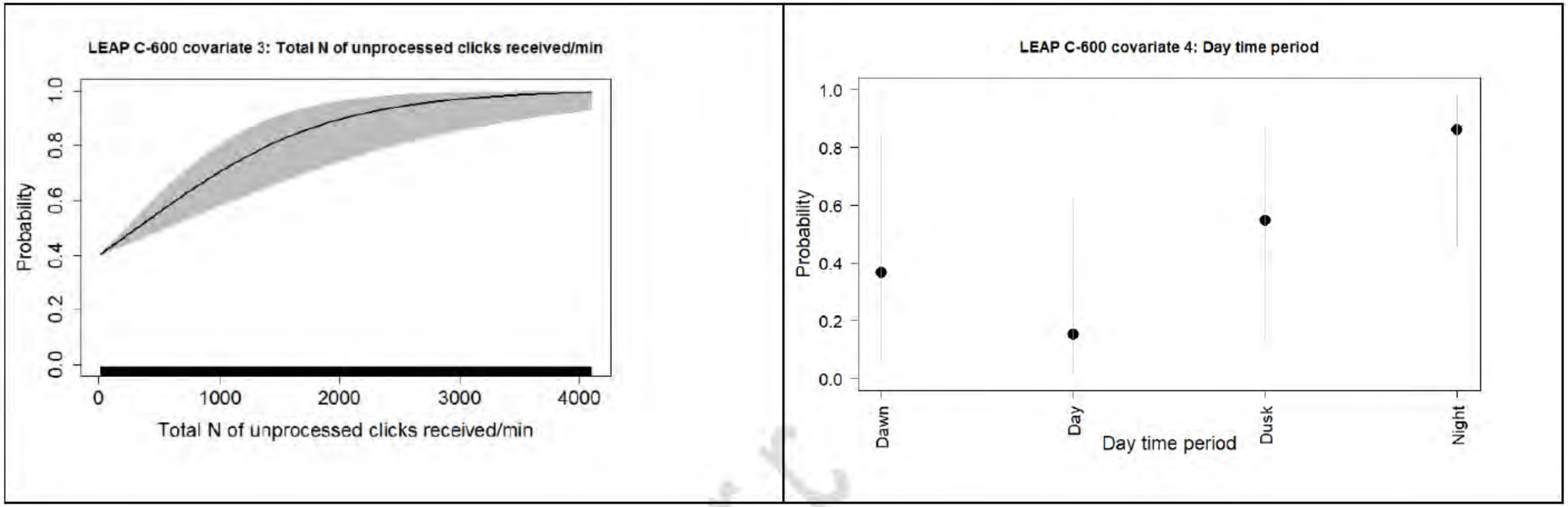
AUC value:	0.8862971

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


LEAP C-600 covariate 1: Diel Hour
Probability
1.0
0.8
0.6
0.4
0.2
0.0
0
5
10
15
20
Diel hour


LEAP C-600 covariate 2: Julian Day
Probability
1.0
0.8
0.6
0.4
0.2
0.0
255
260
265
270
275
280
Julian Day


LEAP C-600 covariate 3: Total N of unprocessed clicks received/min
Probability
0.0
0.2
0.4
0.6
0.8
1.0
0
1000
2000
3000
4000
Total N of unprocessed clicks received/min
LEAP C-600 covariate 4: Day time period
Probability
0.0
0.2
0.4
0.6
0.8
1.0
Dawn
Day
Dusk
Night
Day time period

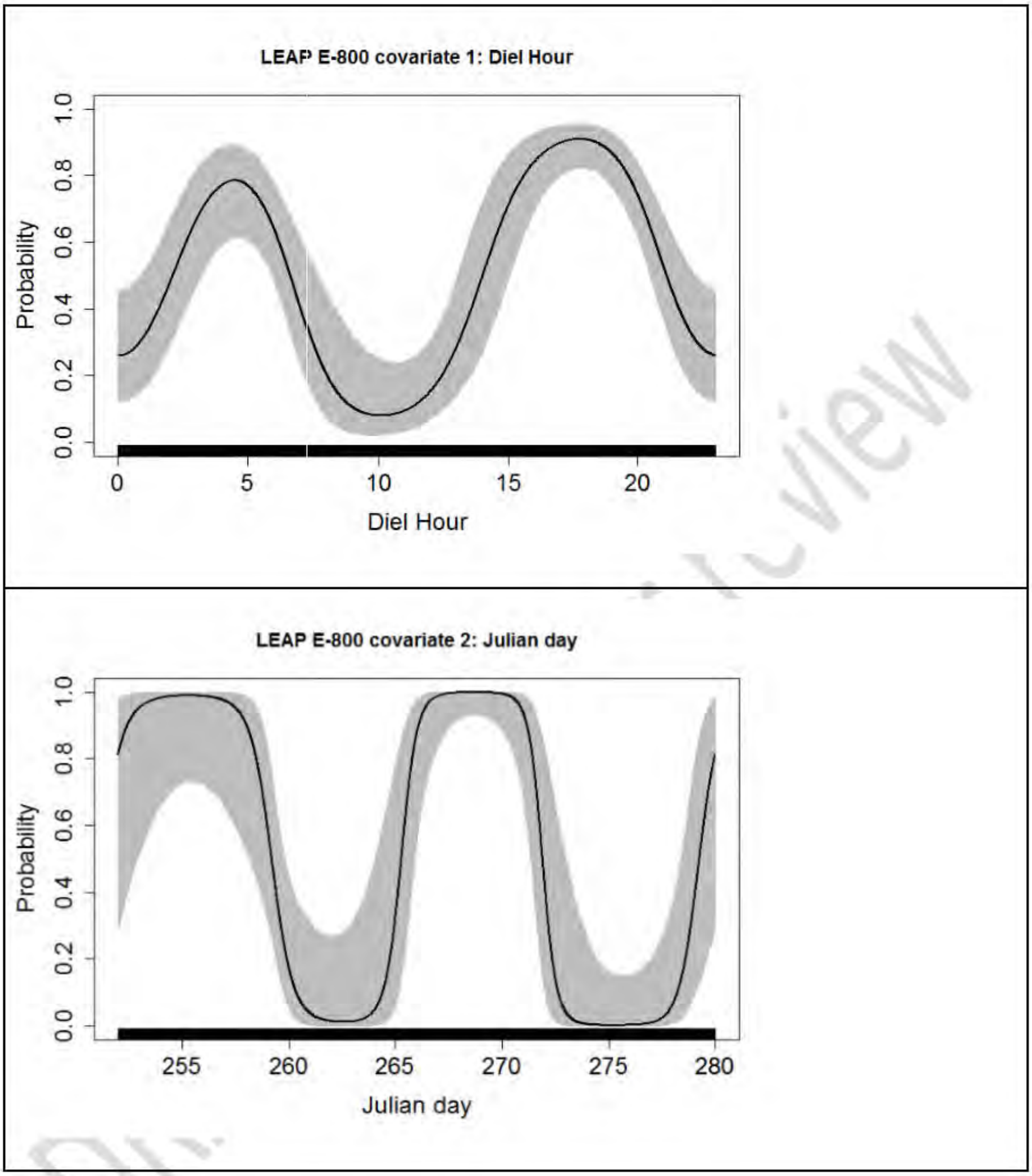
Model:	E-800
Model structure:	POD7<-geeglm(PPM ~ AvgHrBasisMat + bs(JULDAY , knots=mean(JULDAY)), family = binomial, corstr="independence", id=Panel, data=E800)
Confusion matrix:	

		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


LEAP E-800 covariate 1: Diel Hour
Probability
0.0
0.2
0.4
0.6
0.8
1.0
0
5
10
15
20
Diel Hour
LEAP E-800 covariate 2: Julian day
Probability
0.0
0.2
0.4
0.6
0.8
1.0
255
260
265
270
275
280
Julian day

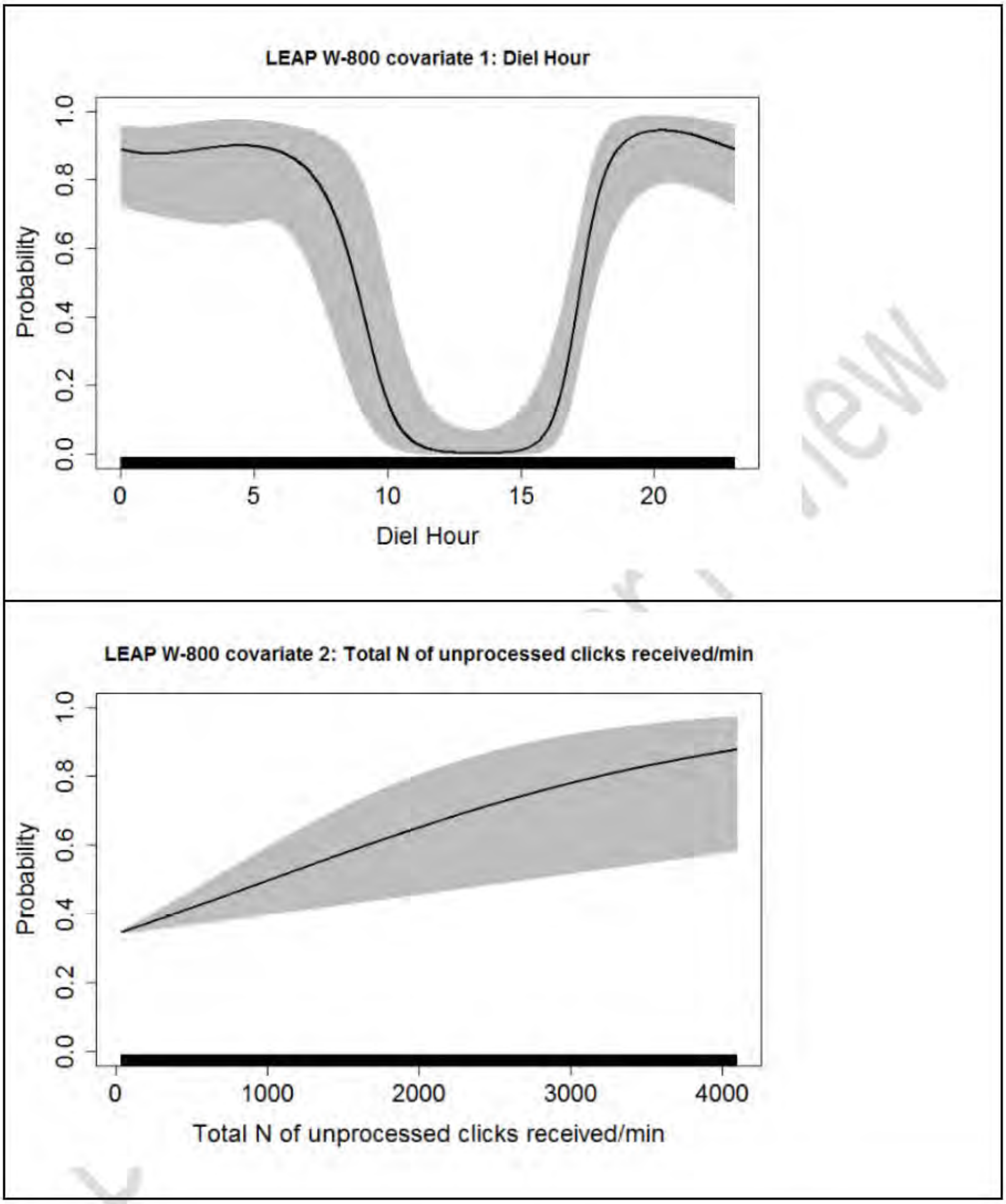
Model:	W-800
Model structure:	POD5<-geeglm(PPM ~ AvgHrBasisMat + Nall_m + as.factor(Signal_Type) , family = binomial, corstr="independence", id=Panel, data=W800)
Confusion matrix:	

		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


LEAP W-800 covariate 1: Diel Hour
Probability
0.0
0.2
0.4
0.6
0.8
1.0
0
5
10
15
20
Diel Hour
LEAP W-800 covariate 2: Total N of unprocessed clicks received/min
Probability
0.0
0.2
0.4
0.6
0.8
1.0
0
1000
2000
3000
4000
Total N of unprocessed clicks received/min

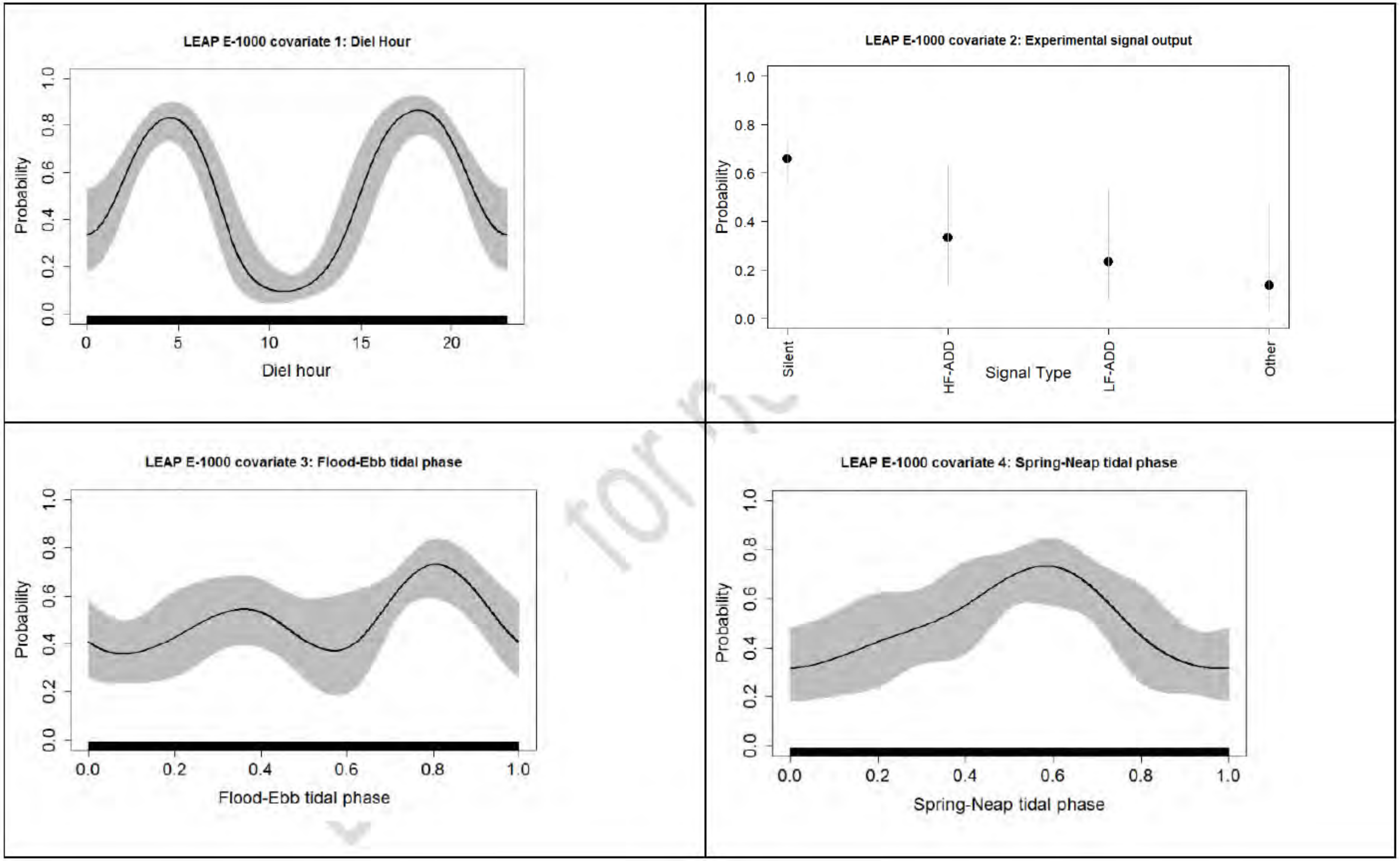
Model:	E-1000
Model structure:	POD4<-geeglm(PPM ~ AvgHrBasisMat + as.factor(Signal_Type)+ TideBasisMat + SprNpBasisMat, family = binomial, corstr="independence", id=Panel, data=E1000)
Confusion matrix:	

		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


LEAP E-1000 covariate 1: Diel Hour
Probability
Diel hour
LEAP E-1000 covariate 2: Experimental signal output
Probability
Silent
HF-ADD
LF-ADD
Other
Signal Type
LEAP E-1000 covariate 3: Flood-Ebb tidal phase
Probability
Flood-Ebb tidal phase
LEAP E-1000 covariate 4: Spring-Neap tidal phase
Probability
Spring-Neap tidal phase

1814

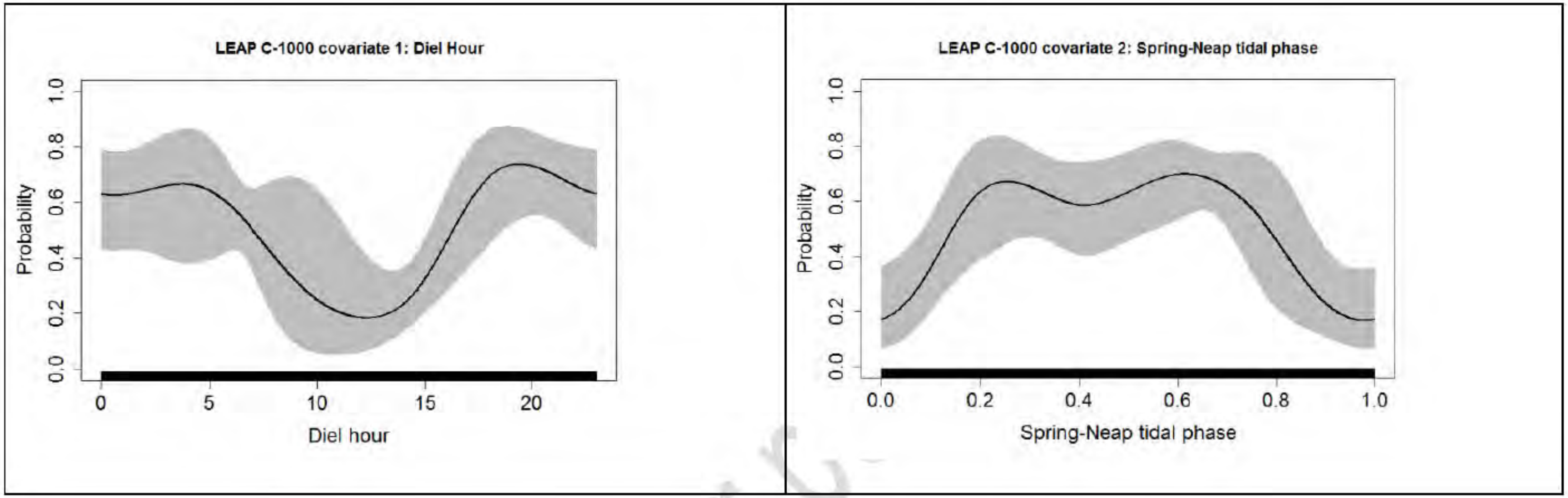
Model:	C-1000
Model structure:	POD5<-geeglm(PPM ~ AvgHrBasisMat + SprNpBasisMat + TideBasisMat, family = binomial, corstr="independence", id=Panel, data=C1000)
Confusion matrix:	

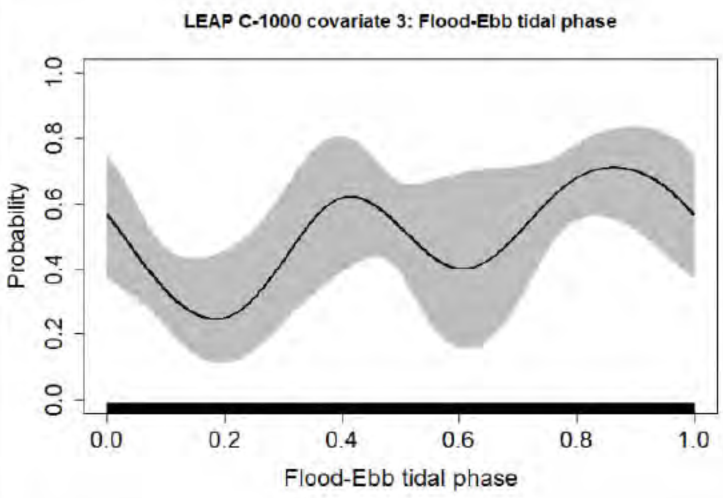
		Expected	
		Porpoise	No porpoise
Observed	Porpoise	73.0%	27.9%
	No porpoise	27.0%	72.1%

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


LEAP C-1000 covariate 1: Diel Hour
Probability
0.0
0.2
0.4
0.6
0.8
1.0
0
5
10
15
20
Diel hour
LEAP C-1000 covariate 2: Spring-Neap tidal phase
Probability
0.0
0.2
0.4
0.6
0.8
1.0
0.0
0.2
0.4
0.6
0.8
1.0
Spring-Neap tidal phase


LEAP C-1000 covariate 3: Flood-Ebb tidal phase
Probability
0.0
0.2
0.4
0.6
0.8
1.0
Flood-Ebb tidal phase

1816

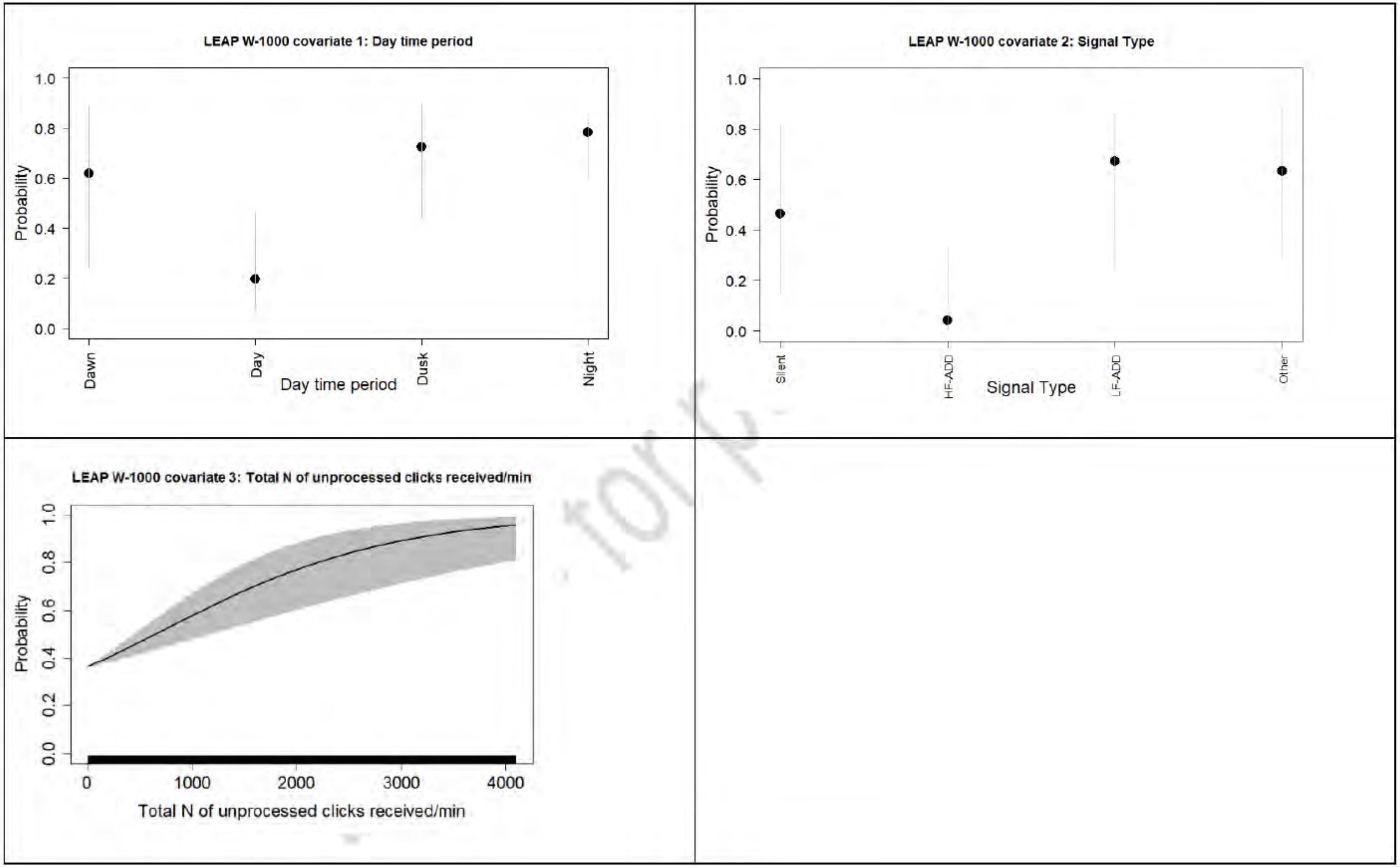
Model:	W-1000
Model structure:	POD5<-geeglm(PPM ~ as.factor(DAYTIMENum) + as.factor(Signal_Type) + Nall_m, family = binomial, corstr="independence", id=Panel, data=W1000)
Confusion matrix:	

		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:

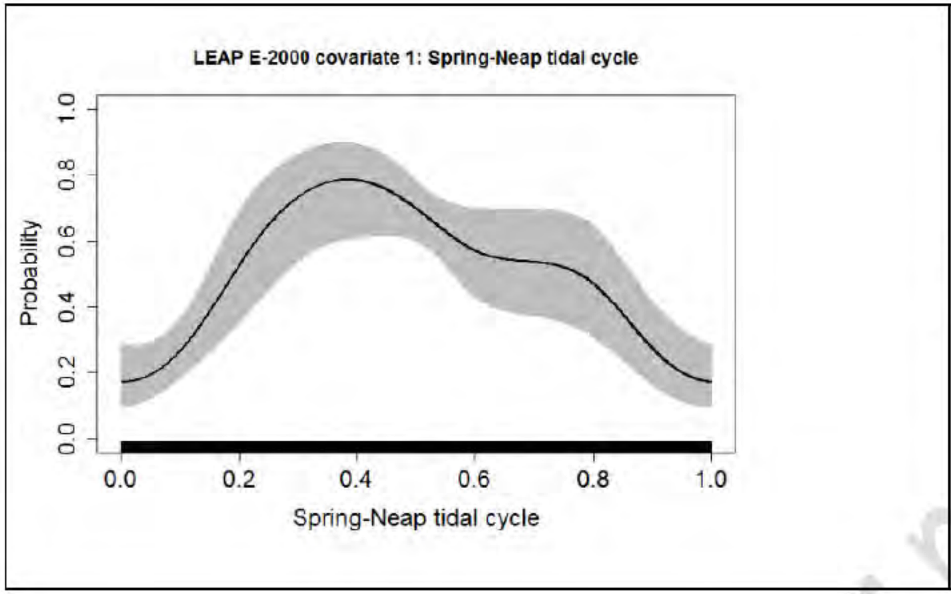
Covariates (in descending order of significance)	Form	Degrees of Freedom	χ^2 score	P-value
DAYTIMENum	Factor	3	27.750	$4.099 \cdot 10^{-6}$
Signal_Type	Factor	3	15.159	0.001685
Nall_m	Linear	1	20.321	$6.547 \cdot 10^{-6}$


LEAP W-1000 covariate 1: Day time period
Probability
1.0
0.8
0.6
0.4
0.2
0.0
Dawn
Day
Dusk
Night
Day time period
LEAP W-1000 covariate 2: Signal Type
Probability
Silent
HF-ADD
LF-ADD
Other
Signal Type
LEAP W-1000 covariate 3: Total N of unprocessed clicks received/min
0
1000
2000
3000
4000
Total N of unprocessed clicks received/min

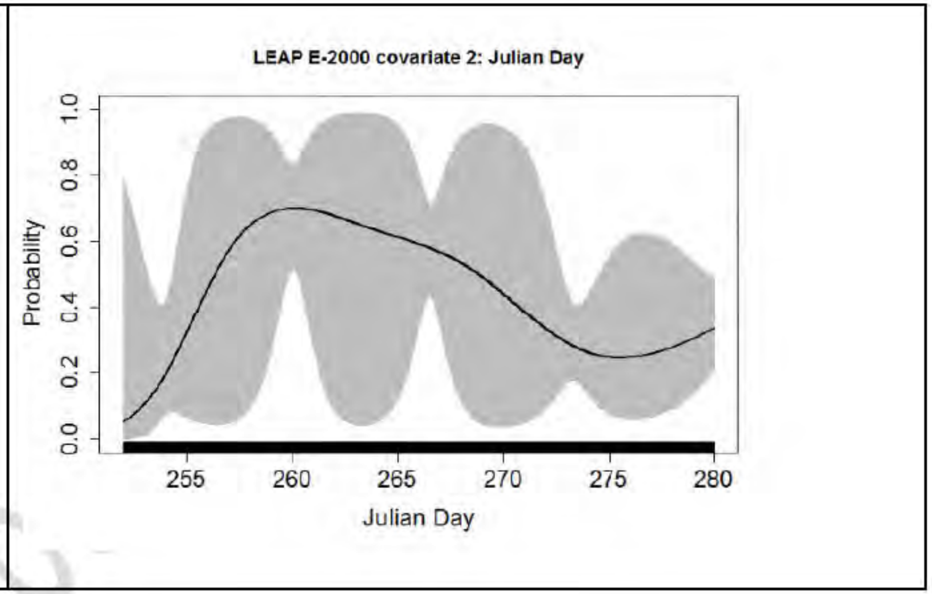
Model:	E-2000			
Model structure:	POD5<-geeglm(PPM ~ SprNpBasisMat + bs(JULDAY , knots=mean(JULDAY)) + as.factor(DAYTIMENum) + bs(Nall_m , knots=mean(Nall_m)), family = binomial, corstr="independence", id=Panel, data=E2000)			
Confusion matrix:	(see matrix below)			
AUC value:	0.7766977			
Results of 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	$1.674 \cdot 10^{-6}$

Confusion matrix:

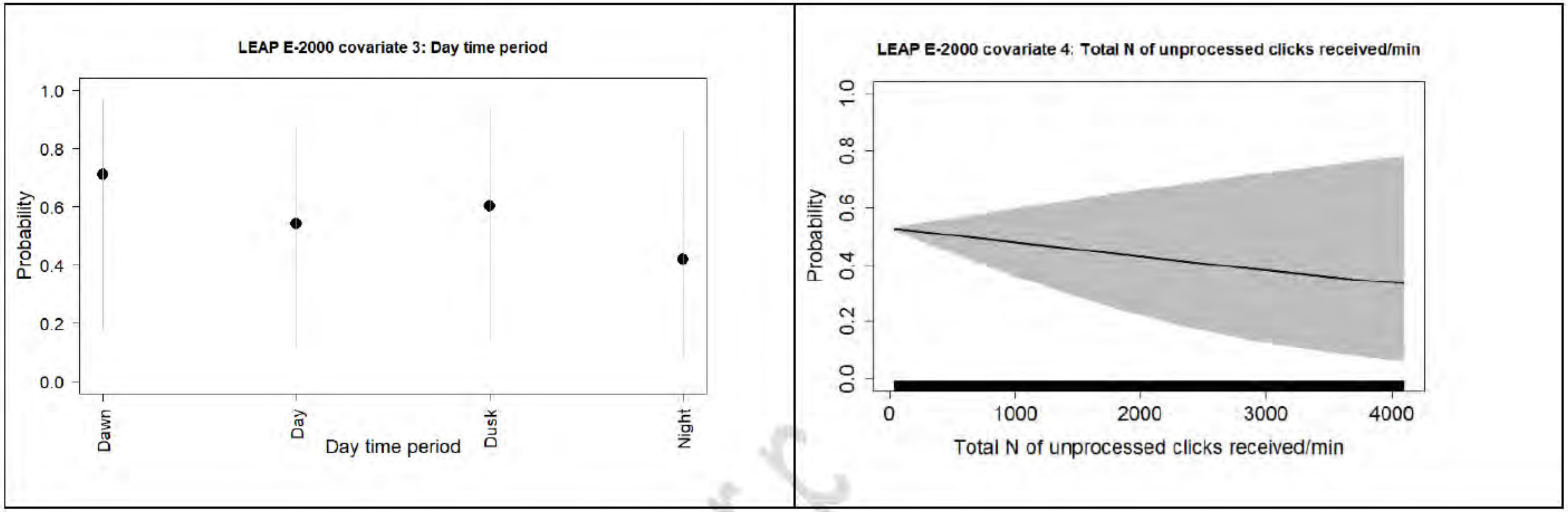
		Expected	
		Porpoise	No porpoise
Observed	Porpoise	75.5%	32.1%
	No porpoise	24.5%	67.9%



LEAP E-2000 covariate 1: Spring-Neap tidal cycle
Probability
0.0
0.2
0.4
0.6
0.8
1.0
Spring-Neap tidal cycle



LEAP E-2000 covariate 2: Julian Day
Probability
0.0
0.2
0.4
0.6
0.8
1.0
255
260
265
270
275
280
Julian Day


LEAP E-2000 covariate 3: Day time period
Probability
1.0
0.8
0.6
0.4
0.2
0.0
Dawn
Day
Dusk
Night
Day time period
LEAP E-2000 covariate 4: Total N of unprocessed clicks received/min
Probability
0
1000
2000
3000
4000
Total N of unprocessed clicks received/min

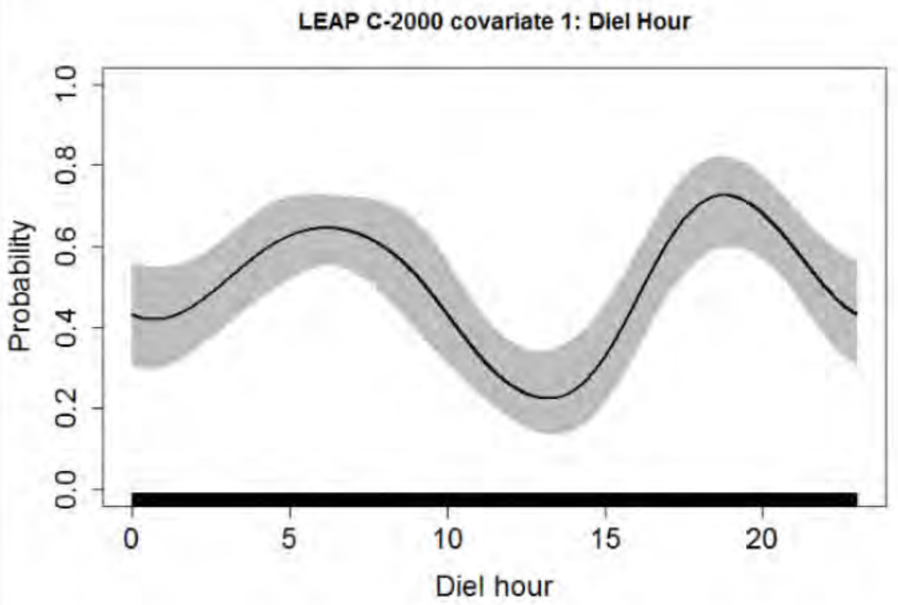
Model:	C-2000
Model structure:	POD5<-geeglm(PPM ~ bs(Nall_m , knots=mean(Nall_m)) + as.factor(DAYTIMENum) + AvgHrBasisMat + SprNpBasisMat, family = binomial, corstr="independence", id=Panel, data=C2000)
Confusion matrix:	

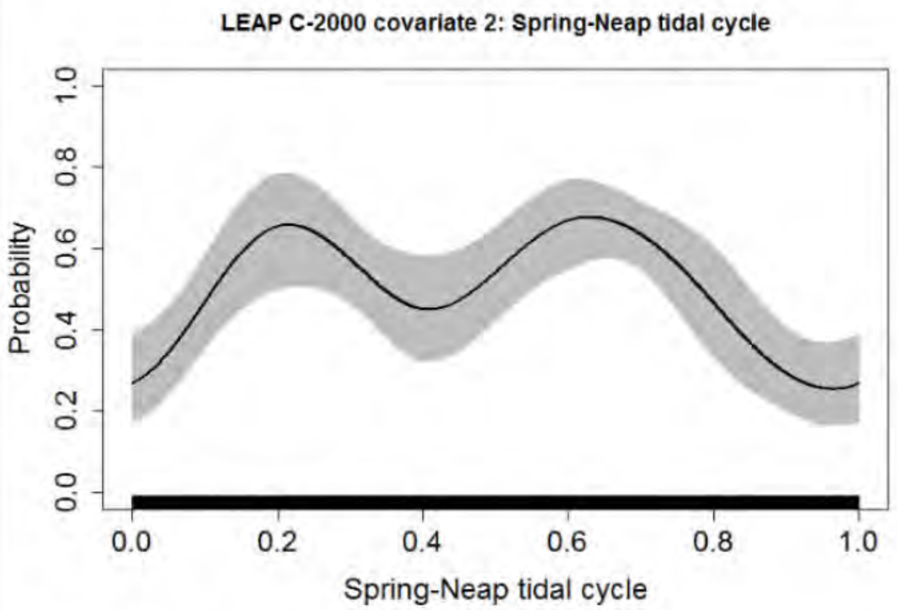
		Expected	
		Porpoise	No porpoise
Observed	Porpoise	74.9%	32.2%
	No porpoise	25.1%	67.8%

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


LEAP C-2000 covariate 1: Diel Hour
Probability
0.0
0.2
0.4
0.6
0.8
1.0
0
5
10
15
20
Diel hour


LEAP C-2000 covariate 2: Spring-Neap tidal cycle
Probability
0.0
0.2
0.4
0.6
0.8
1.0
0.0
0.2
0.4
0.6
0.8
1.0
Spring-Neap tidal cycle

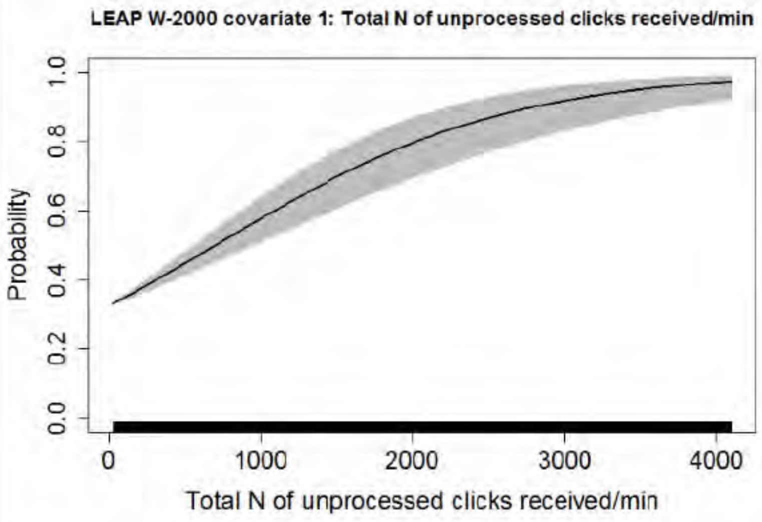
Model:	W-2000
Model structure:	POD5<-geeglm(PPM ~ Nall_m + TideBasisMat + SprNpBasisMat, family = binomial, corstr="independence", id=Panel, data=W2000)
Confusion matrix:	

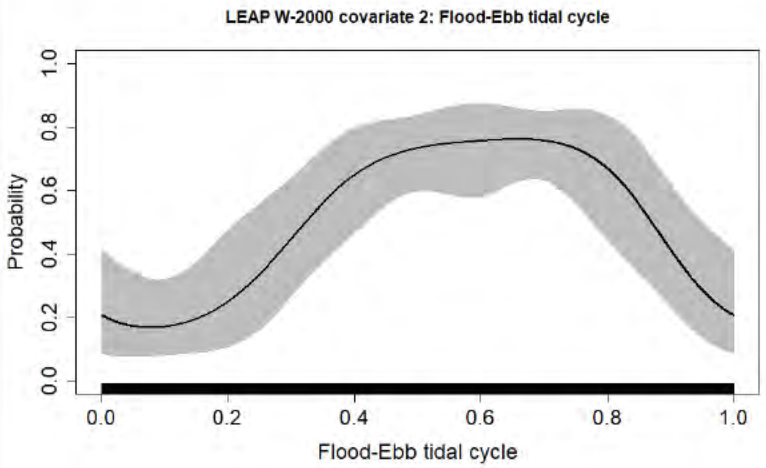
		Expected	
		Porpoise	No porpoise
Observed	Porpoise	88.5%	46.9%
	No porpoise	11.5%	53.1%

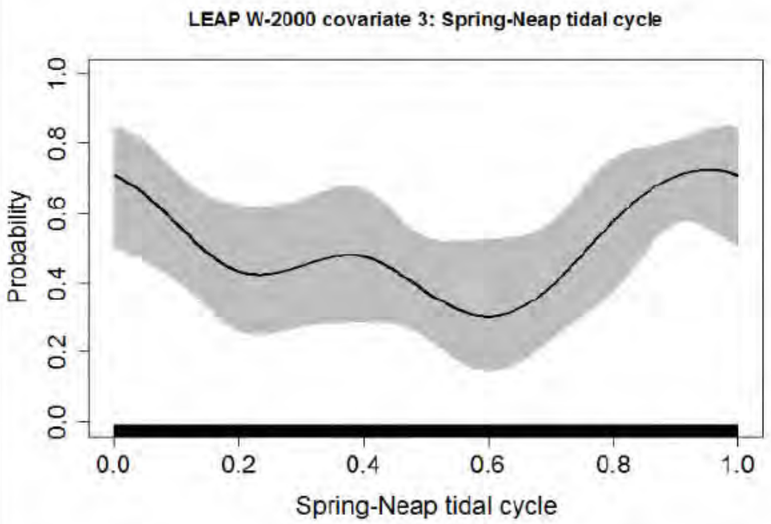
AUC value:	0.7838515

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	$<2.2\cdot10^{-16}$
HiLoTide	Cyclic B-spline	4	22.245	0.0001791
SpringNeap	Cyclic B-spline	4	10.022	0.0400520


LEAP W-2000 covariate 1: Total N of unprocessed clicks received/min
Probability
0.0
0.2
0.4
0.6
0.8
1.0
0
1000
2000
3000
4000
Total N of unprocessed clicks received/min


LEAP W-2000 covariate 2: Flood-Ebb tidal cycle
Probability
0.0
0.2
0.4
0.6
0.8
1.0
Flood-Ebb tidal cycle


LEAP W-2000 covariate 3: Spring-Neap tidal cycle
Probability
0.0
0.2
0.4
0.6
0.8
1.0
Spring-Neap tidal cycle

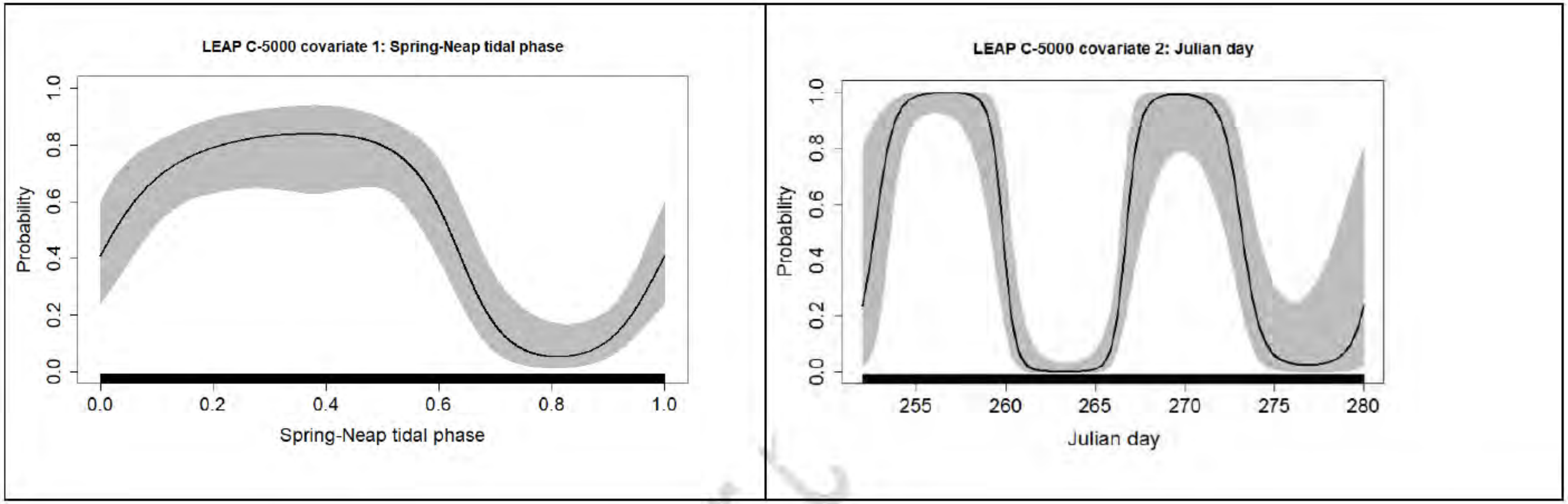
Model:	C-5000
Model structure:	POD5<-geeglm(PPM ~ SprNpBasisMat + bs(JULDAY , knots=mean(JULDAY)) + Nall_m + as.factor(DAYTIMENum) + AvgHrBasisMat, family = binomial, corstr="independence", id=Panel, data=C5000)
Confusion matrix:	(see below)

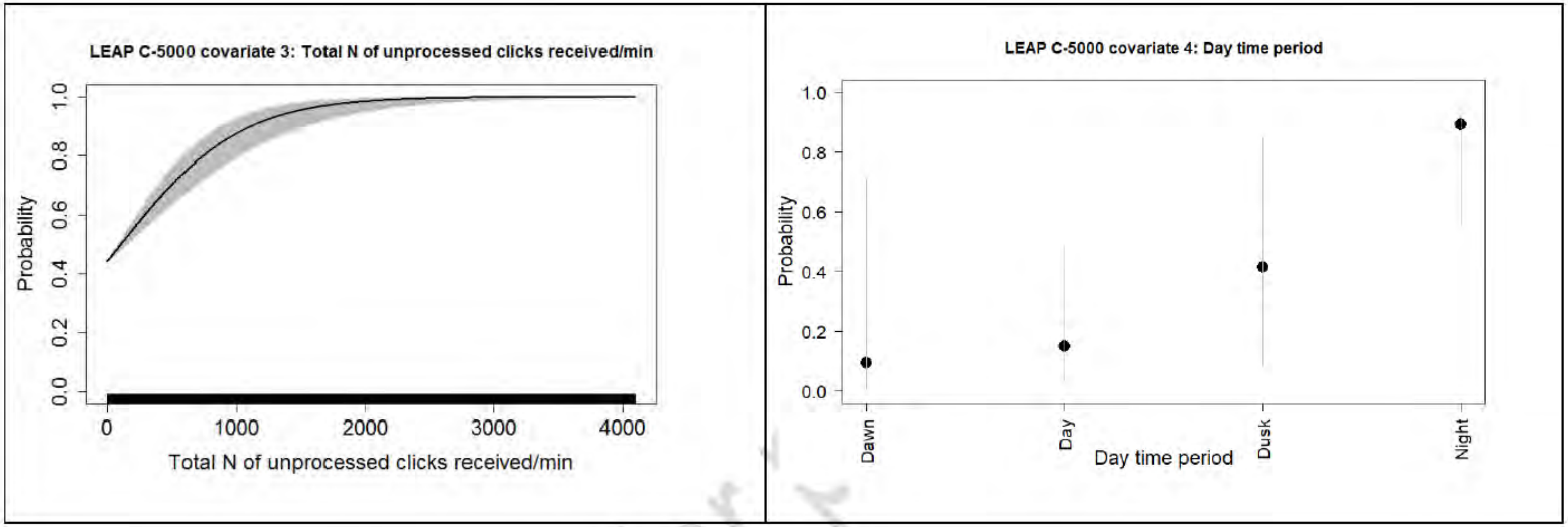
		Expected	
		Porpoise	No porpoise
Observed	Porpoise	80.1%	15.5%
	No porpoise	19.9%	84.5%

AUC value:	0.8861703

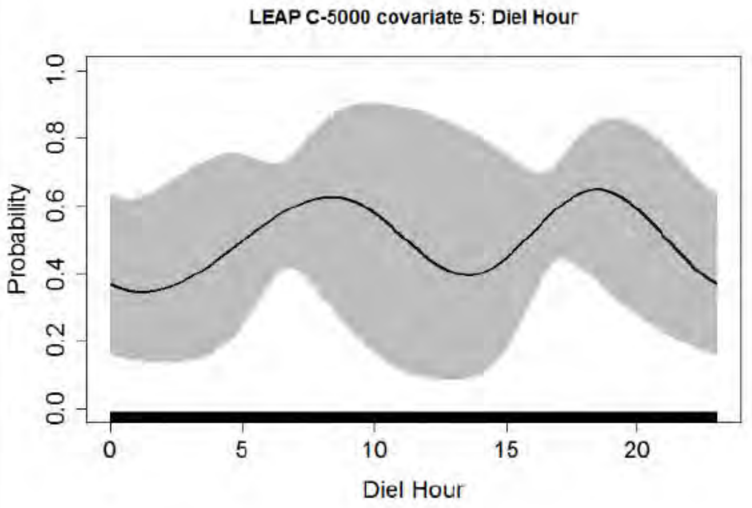
Results of Wald's tests for all significant covariates for the final model:

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	$3.291 \cdot 10^{-8}$


LEAP C-5000 covariate 1: Spring-Neap tidal phase
Probability
0.0
0.2
0.4
0.6
0.8
1.0
Spring-Neap tidal phase
LEAP C-5000 covariate 2: Julian day
Probability
255
260
265
270
275
280
Julian day



LEAP C-5000 covariate 3: Total N of unprocessed clicks received/min
Probability
0.0
0.2
0.4
0.6
0.8
1.0
0
1000
2000
3000
4000
Total N of unprocessed clicks received/min
LEAP C-5000 covariate 4: Day time period
Probability
0.0
0.2
0.4
0.6
0.8
1.0
Dawn
Day
Dusk
Night
Day time period

LEAP C-5000 covariate 5: Diel Hour Probability 0.0 0.2 0.4 0.6 0.8 1.0 0 5 10 15 20 Diel Hour	

1827

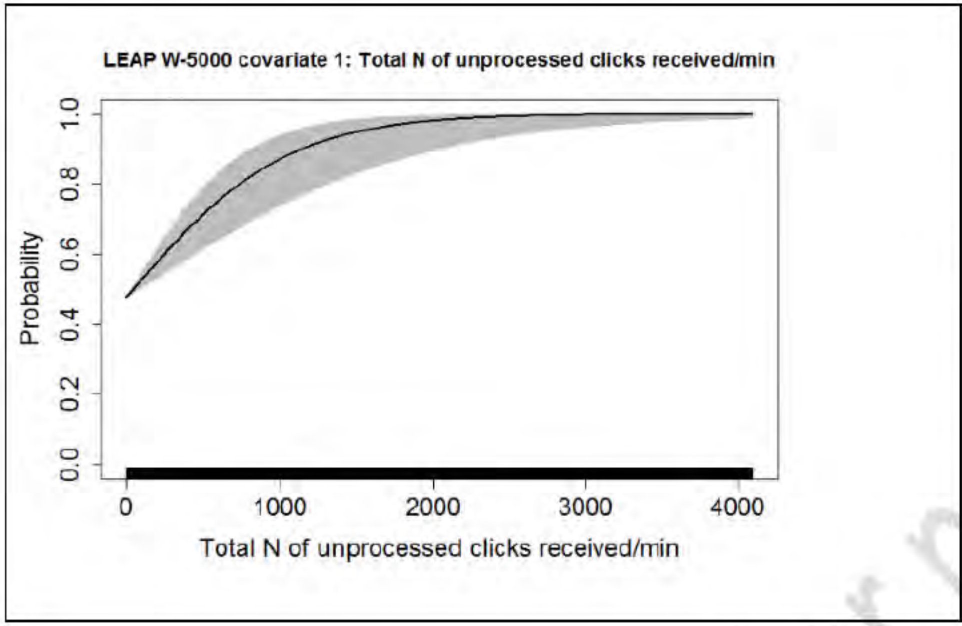
Model:	W-5000
Model structure:	POD5<-geeglm(PPM ~ Nall_m + JULDAY + AvgHrBasisMat + TideBasisMat, family = binomial, corstr="independence", id=Panel, data=W5000)
Confusion matrix:	

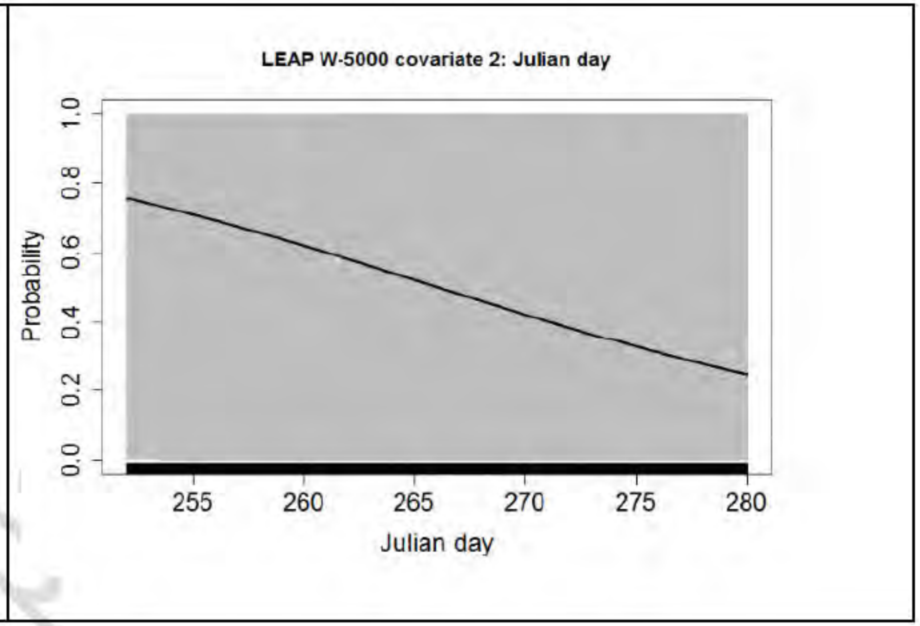
		Expected	
		Porpoise	No porpoise
Observed	Porpoise	58.8%	13.2%
	No porpoise	41.2%	86.6%

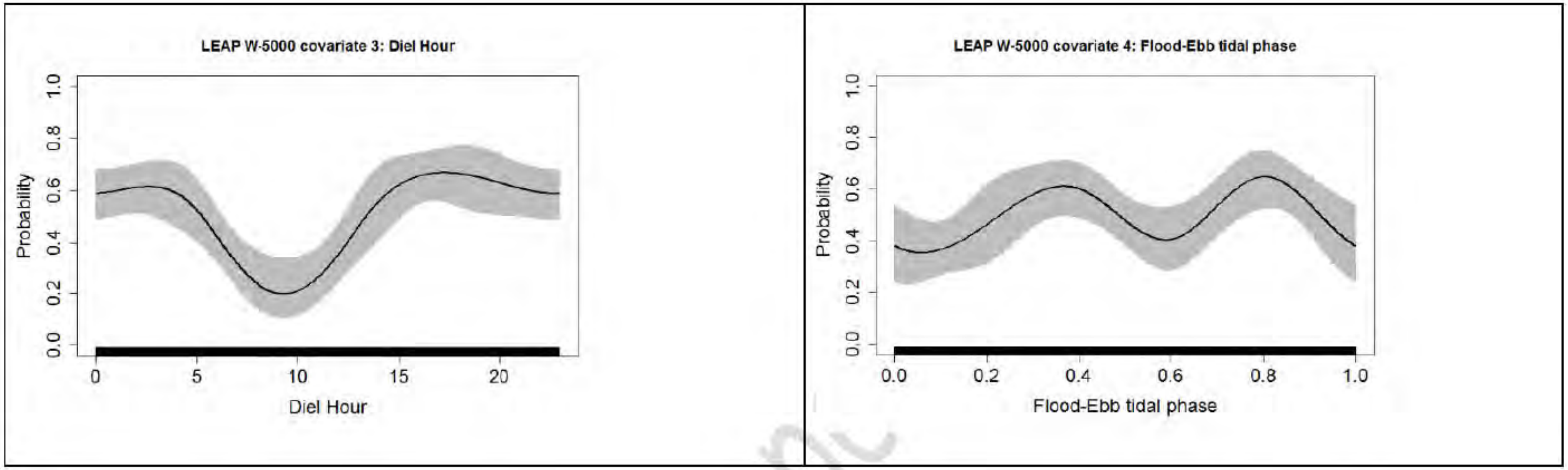
AUC value:	0.7942572

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


LEAP W-5000 covariate 1: Total N of unprocessed clicks received/min
Probability
0.0
0.2
0.4
0.6
0.8
1.0
0
1000
2000
3000
4000
Total N of unprocessed clicks received/min


LEAP W-5000 covariate 2: Julian day
Probability
0.0
0.2
0.4
0.6
0.8
1.0
255
260
265
270
275
280
Julian day


LEAP W-5000 covariate 3: Diel Hour
Probability
0.0
0.2
0.4
0.6
0.8
1.0
0
5
10
15
20
Diel Hour
LEAP W-5000 covariate 4: Flood-Ebb tidal phase
Probability
0.0
0.2
0.4
0.6
0.8
1.0
0.0
0.2
0.4
0.6
0.8
1.0
Flood-Ebb tidal phase

From: Sandra Gray
To: Alastair Mitchell ; Alex Adrian; Craig Burton; David Sandison ; "Doug McLeod"; Douglas Sinclair; George Lees; Iain Berrill; Iain Sutherland; Nick Lake; Piers Hart ; rob.raynard@scotland.gsi.gov.uk
Cc: "Richard Slaski"
Subject: SARF112 - final report
Date: 05 June 2018 17:59:44

Dear All,

SARF112 - Influence of low frequency ADDs on cetaceans in Scottish coastal waters

Please find attached the final report for the above project. This has been updated in light of comments made by the referees.

Please also find attached the 3 referees reports.

Please could you provide any comments that you may have by **Friday 22nd June.** After this date the report will be uploaded on to the website, a copy lodged with the British Library & final payment made to the contractor.

Kind regards,

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FINAL PROJECT REPORT EVALUATION FORM

Project Number: SAR112	Completion Date: April (?) 2018

Project Title: INFLUENCES OF LOWER-FREQUENCY ACOUSTIC DETERRENT DEVICES (ADDS) ON CETACEANS IN SCOTTISH COASTAL WATERS

1. In your view have the scientific objectives been achieved. If not, does this need to be addressed by SARF?

Objectives 1 to 3 were achieved via a well planned and executed research programme. Regarding Objective 4, it has proven difficult to discern the effects of “low” versus “high” frequency sounds on harbour porpoises during field experiments, thereby curtailing the primary goal of the project.

1. Collate data on key acoustic characteristics of ADD devices
   - Note, limited information available from manufacturers on specs of commercial devices
2. Theoretically determine the sensitivity of harbour porpoises and bottlenose dolphins to ‘lower frequency’ ADD signals
   - Achieved via literature review
3. Implement a robust field-based study on an active fish farm, comparing porpoise responses to simulated lower and “standard” ADD sounds
   - Note, acoustic monitoring was partly compromised by failure (incl. battery exhaustion) and loss of some devices in the field. This was taken into account during data analysis and interpretation.
   - Note a potential confounding factor in reduced power output of the bespoke sound signals, when compared to commercial ADDs
   - The sub-objective of discerning effects of low frequency ADD on porpoise behaviour using video measurements was not met owing to few and distant sightings. This did not compromise the overall project.
4. Review and analyse results from ADD outputs and empirical field results, with respect to impact of lower frequency ADDs on cetaceans
   - Note the confounding effects of other variables, well described in the report.
   - Note the absence of recommendations on use of ADDs in context of marine aquaculture and developing regulatory frameworks in Scottish waters. ***The discussion should be revised to address this.***

2. Comment on the overall results of the project, including their significance for SARF.

The LEAP project has yielded interesting findings on spatial, diurnal and seasonal behaviour differences among harbour porpoises in the Sound of Mull, as measured by acoustic monitoring.

However, the primary goal of comparing the effects of low frequency versus high frequency ADDs on cetaceans in the vicinity of fish farms has proven elusive. The authors have discussed potential reasons for this and have suggested further work aimed at reducing confounding factors.

An attempt has been made to include seals in the analysis of effects of low frequency ADDs and to compare the behavioural responses of seals versus porpoises. Noting that effects on seals were not part of the SARF call for proposals, that significant assumptions have been drawn from limited data, along with the various stakeholder sensitivities around the use and efficacy of ADDs, this reviewer urges caution on whether & how to refer to seal effects in the final report

Related to the previous comment, the authors should discuss to what extent recommendations can be made on the use of low frequency ADDs, based on the current findings. This was an important aspect of the original SARF Call (to guide regulation of ADDs, etc), which has not been addressed in the draft report.

3. Is there a need for further work? If so, explain.

It is not clear that investing further funds to evaluate low frequency ADDs in the field would produce clearer results than in the current project, owing to the complexities involved.

Overall marking	1 - outstanding results **2 - results significantly above expectation** 3 - satisfactory results 4 - results below expectation 5 - poor results

REFEREE ID: REF01 Date 13 May 2018

Please indicate whether you wish to receive payment (Yes/No) Y

Additional Comments**:**

FINAL PROJECT REPORT EVALUATION FORM

Project Number: SARF112	**Completion Date**:

Project Title: Influence of low frequency ADD's on cetaceans in Scottish coastal waters.

1. In your view have the scientific objectives been achieved. If not, does this need to be addressed by SARF?

The contractor has delivered what was asked. The methods used for the experiments appear to have been very rigorous and professional. To that extent I believe that the scientific objectives have been achieved.

2. Comment on the overall results of the project, including their significance for SARF.

The results were rather inconclusive insofar as the contention that low frequency (LF), as opposed to high frequency (HF), ADD's would have a much less measurable impact on cetaceans behaviour. In short it was expected that the LF ADD's would not deter cetaceans as much as the HF ADD's. This was not the outcome – the harbour porpoises observed appear to be impacted by both LF and HF ADD's.

Although not the result that was expected the result is very significant for SARF in that the impact of LF and HF ADD's on cetacean behaviour is more complex than had been thought.

An additional result was that seal behaviour did not appear to be being impacted by ADD's in the way that is expected. This impact of ADD's on seal behaviour was not one of the objectives of this project, but these additional observations are valuable nevertheless.

3. Is there a need for further work? If so, explain.

It is clear that the impact of ADD's on marine mammals is neither simple nor yet fully understood. Given the public perception of the impacts of fish farming on the seal and cetacean populations, the stringent conditions in this respect contained within the ASC certifications and the recent ban on importing Scottish salmon into the USA if there is an associated mortality of marine mammals this is a live issue to say the least.

To that extent ADD's are one of the few tools available to fish farmers to protect their stock from seal predation, more work should be undertaken in this area

Overall marking	1 - outstanding results 2 - results significantly above expectation **3 - satisfactory results** 4 - results below expectation 5 - poor results
REFEREE ID: **ID: REF02.** Date 6 April. 2018 Please indicate whether you wish to receive payment (**Yes**/No)	

Additional Comments**:**

FINAL PROJECT REPORT EVALUATION FORM

Project Number: 112	Completion Date: March 2018

Project Title: Low-frequency ADDS and Porpoises (LEAP); Influences of lower-frequency acoustic deterrents (ADDS) on cetaceans in Scottish coastal waters

1. In your view have the scientific objectives been achieved. If not, does this need to be addressed by SARF?

Yes; this is a thorough report that is consistent with the project scope. One proposed component of the field work (visual tracking of porpoises) proved not to be viable due to low porpoise numbers in the near-field area which could, readily, be tracked. But this was a subsidiary element of the work and does not detract significantly from the robustness of the rest of the study.

2. Comment on the overall results of the project, including their significance for SARF

The findings from this study were hindered by a relatively low occurrence of harbour porpoise in the area than was expected. Monitoring conducted prior to the trial showed that the detections were already reducing before the trial commenced.

Notwithstanding the relatively low sample size, this study finds that there was a reduction of porpoise detections in the near-field when either the LF or HF signal was emitted, in comparison to the silent periods. There was not a discernible pattern in the far-field data. The data shows a reduction in detections, it does not show a complete deterrence effect. Having said that, this shows that there is a localised deterrence effect from acoustic signals even with porpoise that are likely to be familiar with ADDs. The reduction in detections appears, generally, less during LF signal transmission than during HF signal transmission, but not substantially so. Though the study used replicated sound signals, rather than actual ADDs, this suggests caution about advocating ‘low frequency ADDs’ as a means of minimising or avoiding effects on cetaceans.

This study used a signal that is lower in volume than most commercially available ADDs; it is possible that the localised deterrence may be over a greater distance when the volume is increased.

This study also considers the environmental variables and finds that the decrease in detections is driven primarily by environmental variability rather than the experimental signal (in particular the day-night cycle). This study notes the heterogeneity of habitat use by porpoise, and that diel and seasonal cycles may be more important here than an acoustic deterrent signal.

Although seals were not the focus for this study, their presence was noted in enough detail to consider their response to the acoustic trial. Here, seals were not noticeably deterred by either signal. This clearly has some bearing on the relevance of using ADDs to deter seals from fish-farms in the first place (again noting the caveat that the study employed replicated sound signals not commercial ADDs).

3. Is there a need for further work? If so, explain.

This study adds to the debate on effects of ADDs on small cetaceans, however there are still uncertainties and therefore it does not conclusively elucidate the effect of ADDs. The overall abundance of harbour porpoise in

the study area was lower than had been expected during project planning (possibly reflecting seasonal variations) and this precluded use of the 'visual tracking' approach as well as reducing overall sample size for the CPOD work. Re-running the monitoring earlier in the season, at this location (or applying it another suitable location), would be highly beneficial in terms of validating the results, especially given the unexpected findings, and elucidating near field behaviour of porpoises in response to signal transmission. Moreover, it would provide the opportunity to check more thoroughly the apparent absence of effects of signal transmission on seals, which would be of considerable significance in relation to the applicability of ADD use as seal deterrents. This study used a synthetic signal, as was recommended; however, it is not known what component of an acoustic signal causes an animal to alter its behaviour. It is difficult to look at this when there is a lack of publically available information on the commercial ADDs.

Overall marking	1 - outstanding results 2 - results significantly above expectation 3 - satisfactory results 4 - results below expectation 5 - poor results
REFEREE ID: REF03	Date 10 May 2018

Additional comments

- **Overall marking**. As noted above, porpoise numbers in the study area proved far lower than expected during project planning, reducing the volume of CPOD data for analysis and precluding the use of the visual tracking approach. As a result it is difficult to rate the results as 'significantly above expectation' and hence the overall marking of 3. That said the authors have done an excellent job of analysing the data that were secured, considering the relevant issues and controlling factors that may have influenced these, and presenting a clearly written, illustrated and presented report, with few edits and typos evident.
- **HF / LF Response**. While the results illustrate a clear reduction in porpoise detection (relative to silent control periods) when either high or low frequency signals were being transmitted, the graphics (Figure 13 especially) suggest this reduction was less apparent during LF signal transmission than that of HF signals. Indeed, without a silent control, one could argue from these data that LF signals had a demonstrably lower impact on porpoise detections than did the HF signals. Little is made of this in the report (specifically Results / Discussion / Summary sections), the difference in response seeming to be underplayed. I believe a few sentences need to be added in to these sections either drawing out this difference or explaining why it is not statistically relevant while the difference relative to the control is.
- **Recommendations.** The project proposal from SAMS indicated that recommendations would be made on the basis of this study (for SARF / the industry as I recall?). None appear to be presented.

Minor Text / Formatting Comments

- Executive Summary. Para 3. Correct text justification.
- Table 1. Format to fit page.
- Figure 1. Should this have been in colour?

- Figure 3. Amend text embedded in figure (partly obscured).
- Figures and Tables generally. Keep captions / titles with associated graphics (some of these appear on separate pages).
- Reference list. Keep font size / style consistent: a few (eg Southall et al 2007) are in different style.
- Line 303 pg 14. I found this paragraph perhaps not as clear as it could be. This details what has been found in the literature relating to absolute disturbance. One sentence suggests that for Airmar and Lofitech the absolute deterrence distance is around 200-350m. Then it is noted that Brandt found absolute deterrence at 1.9km, but that the closest approach was 800m, so it's not clear if all animals were displaced at this range.
  We understand from this section therefore that the absolute deterrence range is in the order of a few hundred meters, but that there could be a reduction in porpoise density out to 7.5km. But for most HP there is a reduction in density somewhere between 2-4km. Is it worth looking at the text in this section to make it clearer, by highlighting that there is variability in the literature?
- It is great to see that SSF have been so helpful in this study.
- Figure 13 – it is not clear how the values have been derived from table 8. We cannot replicate the numbers by multiplying by 1000
- Figure 13 – shows the average detections together with the standard error. There appears to be overlap in the rates between categories, was there an assessment as to whether there was a statistically significant difference between categories?

SARF112: Low-Frequency ADDs and Porpoises (LEAP)

Influences of lower-frequency Acoustic Deterrent Devices (ADDs) on cetaceans in Scottish coastal waters

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EXECUTIVE SUMMARY

- Acoustic Deterrent Devices (ADDs) are widely used in the Scottish finfish aquaculture sector as a non-lethal means to deter depredation of Atlantic salmon (*Salmo salar*) 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, western Scotland), an area known to be frequented by porpoises, which contained a fish farm operated by Scottish Sea Farms (SSF). 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 deployed from the fish farm infrastructure. PAM data were collected using C-PODs (porpoise click train detectors), as well as several broadband recorders. Whenever conditions permitted, visual observers collected sightings of porpoises and other species as well as environmental data from an elevated onshore vantage point. An experimental video tracking procedure was implemented to record small-scale responsive movement of surfacing porpoises upon onset of signal transmission.

- Signal transmission varied randomly between the HF signal, the LF signal and a silent control. All transmissions, including the silent 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 porpoises or other cetaceans were sighted. Outside regular observing hours (e.g. at night) or during periods of poor weather, the system could be set to Night mode, which involved transmission of a regular sequence of signals (including silent control) on a 50% duty cycle (2 hours on, 2 hours off) until actively interrupted. The system was remotely controlled through text messages over the GSM mobile phone network.

- The experimental period during which signals were transmitted lasted a total of 33 days (08/09 - 11/10/2016). During this period, 138 transmissions occurred, including 53 of the HF signal, 38 of the LF signal, and 47 silent controls. All the equipment, with the exception of 2 C-PODs and one broadband recorder, was recovered by 17/10/2016. One C-POD malfunctioned, bringing the total number of C-POD datasets available for further analysis to 19.

- Visual observations of porpoises were infrequent (23 sighting events over 19 days), despite good observing conditions. Most porpoises were sighted well outside Bloody Bay within the central and northern Sound of Mull, particularly towards the entrance to Loch Sunart. As a result, the video tracking procedure was often unable to resolve surfacing animals to assess responses to different ADD signals, although the validity of the method itself was confirmed. Groups of bottlenose dolphins were observed on four occasions and one minke whale was sighted. In contrast to the scarcity of cetacean sightings, harbour seals were regularly observed on a near-daily basis, often in close proximity to the fish farm.

- The C-POD array provided a high-resolution dataset on presence of echolocating porpoises over the course of the experiment. Datasets were analysed using nonparametric statistical tests and GAM-GEE models to investigate the relative importance of different covariates, including signal transmission, in determining porpoise acoustic presence.

- Ambient noise levels at the site, as assessed by broadband hydrophones, did not appear to significantly impact C-POD performance. Porpoise detections (defined as 'Porpoise-Positive Minutes' or PPMs) varied considerably across the array. Broadly speaking, PPM detection rates were higher in the central and northern Sound of Mull when compared to the Bloody

Bay area, particularly compared to waters immediately surrounding the fish farm where detection rates were low.

- When assessing the effect of different signal transmissions, porpoise detection rates at most moorings were substantially lower during the signal transmissions than during silent control periods, suggesting that transmission of both HF and LF signals reduced the probability of porpoise detections. This was contrary to the expectation that LF signal transmissions would not impact porpoise behaviour and therefore generate similar detection rates to those observed during silent control periods. A statistically significant difference between porpoise detection rates during the different treatments was demonstrated for aggregated data from across the entire array as well as among the Nearfield moorings, although not among the Farfield moorings. No significant differences in porpoise detection rates could be demonstrated between LF and HF signals, whereas detection rates during silent control periods were significantly higher than both of them. The results of this study therefore suggest that low-frequency ADD signals can also affect harbour porpoise behaviour.

- 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, the observed 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 the night, 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 results. 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 for unknown reasons. 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. The experimental results therefore did not support the assumption that either ADD signal, as used in the present experiment, represented a meaningful deterrent to seals when attempting to prevent fish farm depredation.

- Based on the experimental results, the present study provides no strong evidence that widespread application of commercially available lower-frequency ADDs with signal characteristics similar to those tested would, by themselves, result in significantly reduced risk of acoustic impacts on harbour porpoises in Scottish waters, when compared to existing ADD signals.

- Given the results presented here, several recommendations can be made. These include, in decreasing order of priority:
    1. The effectiveness of alternative non-acoustic mitigation methods (e.g. appropriate fish husbandry, good net maintenance, improved net tensioning, and stronger net materials) should be investigated. These methods potentially harbour unrealised opportunities for successful mitigation of seal depredation but have not benefited from equivalent attention compared to ADDs. Preferably, and assuming that these methods are at least equally successful in mitigating depredation by seals, the use of one or more of these methods should be promoted over the use of ADDs.
    2. There is a need for improved understanding of ADD use and distribution in Scottish waters, to better document ADD-associated noise pollution in the context of other conservation activities such as the establishment of Marine Protected Areas. This improved understanding is also relevant in the light of other regulatory requirements to report noise pollution (e.g. under the EC Marine Strategy Framework Directive; EC 2008).
    3. If the continued use of ADDs is deemed to be unavoidable, there is a need to consider alternative ADD designs that both reduce overall noise output and are as species-specific as possible. The present study has shown reductions in porpoise detection

rates during both LF and HF signal transmissions, implying that merely shifting the signal frequency downwards was insufficient to prevent impacts on porpoises.

4. If the continued use of ADDs is deemed to be unavoidable, there is a need to establish definitively 1) whether such ADDs actually work in terms of long-term, effective deterrence of seals, 2) which signal characteristics and/or modes of operation contribute to different ADD models' effectiveness, and 3) which other variables (e.g. time of year, weather, presence of fish farm staff) influence seal depredation events and apparent ADD effectiveness. The key aim of these enquiries, and any further development of ADD design and/or deployment methods that might result from them, should be the long-term reduction of inadvertent noise pollution resulting from ADD use.

1 INTRODUCTION: ADDS IN SCOTLAND

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

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

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

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

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

*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 *, ** and *** symbols.*

Manufacturer	Type	Source level (dB re 1 µPa-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 pseudorandom at intervals from 2-40s*	x		*Götz & Janik (2015)

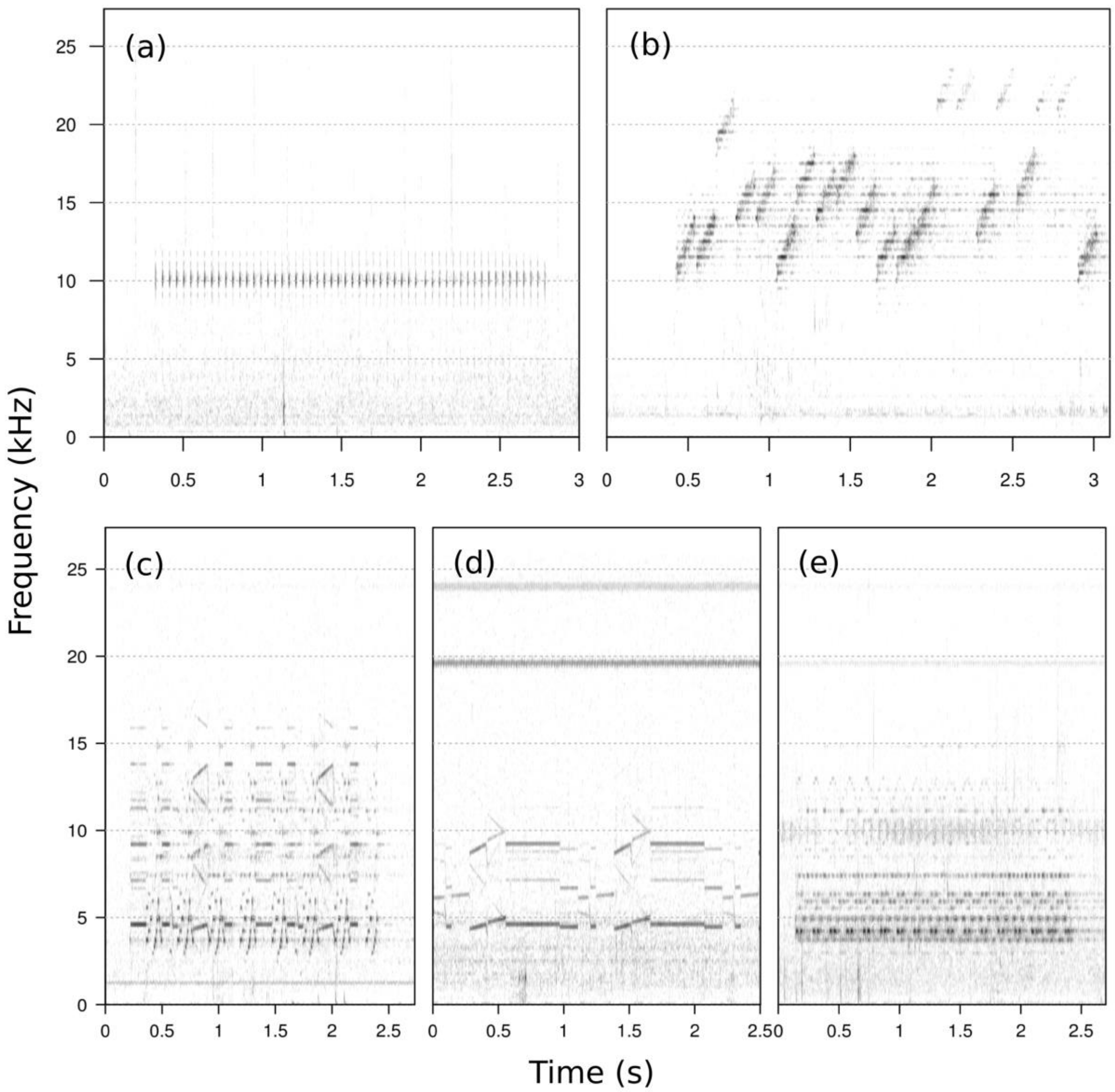

Figure 1. Examples of ADD spectrograms. Spectrogram parameters: FFT size = 1024 points, overlap = 50%, sample rate = 96 kHz; resulting in frequency and time resolution of 93.8 Hz and 10.67 ms, respectively. (a) Airmar™ (dB Plus II); (b) Ace Aquatec™ (US3); (c) Terecos™ (Type DSMS-4) Programme 4; (d)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

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2 IMPACTS OF ADDS ON CETACEANS

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

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

Both harbour porpoises and bottlenose dolphins are listed under Annex II of the EC Habitats Directive (EC 1992), which requires strict protection measures to be applied to both individuals and populations, including the establishment of Special Areas of Conservation (SACs) to protect habitats that are important for the survival of the species. SACs are intended to contribute to a coherent European ecological network of protected sites, and thereby ensure continued maintenance of Favourable Conservation Status (FCS) of the species involved. The recently designated 'Inner Hebrides and the Minches' candidate Special Area of Conservation (cSAC) for harbour porpoises encompasses a large part of the Scottish west coast, which also includes numerous finfish aquaculture sites (Scottish Natural Heritage 2016). Given harbour porpoises' potential sensitivity to ADD noise, current levels of ADD usage within and adjacent to the 'Inner Hebrides and the Minches' cSAC therefore potentially have a negative impact on FCS for this species.

2.1 PHYSIOLOGICAL EFFECTS

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

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

Long-term exposure to chronic noise pollution can have significant deleterious effects on the health of both humans and animals through a number of physiological pathways involving combinations of neural and endocrine systems (summarised by Wright et al. 2007a, 2007b). Such responses may be difficult to detect in free-living cetaceans, and most of our current knowledge is derived from studies using small numbers of captive animals (e.g. Thomas et al. 1990; Miksis et al. 2001; Romano et al. 2004). However, stress hormone levels have been measured in whales' blows, suggesting anthropogenic noise may have substantial impacts on health of wild populations (Rolland et al. 2012). The effects of aquaculture-associated ADDs on cetaceans in this regard remain poorly understood but merit further study in the light of currently available data on effects of other anthropogenic noise sources (Wright et al. 2007b).

2.2 BEHAVIOURAL RESPONSES AND HABITAT DISPLACEMENT

Beyond physical injury, another important potential impact of underwater noise concerns its ability to induce changes in animals' behavioural patterns and/or deter animals from ensonified areas, either temporarily or permanently (Nowacek et al. 2007; Götz & Janik 2013). Several behavioural response studies have attempted to either investigate behavioural effects of ADDs on cetaceans around fish farms or evaluate their potential to deter animals from construction sites (e.g. Olesiuk et al. 2002; Johnston 2002; Götz & Janik 2013; Lepper et al. 2014; Hermannsen et al. 2015). Airmar and Lofitech devices were the ADD types most often tested in these contexts.

Reported results suggested consistent deterrence of porpoises from the vicinity of the ADD sound source, but there was substantial variation in terms of the distances over which this deterrence was observed (Table 2). Summarizing and evaluating results from several studies, Hermannsen et al. (2015) estimated **minimum** absolute deterrence distances (within which all harbour porpoises could be expected to be deterred) of approx. 200 m and 350 m from source for Airmar and Lofitech devices, respectively. These distances typically correspond to signal received levels of 130-150 dB re $1\mu Pa_{rms}$ depending on frequency range and device source level tested (Hermannsen et al. 2015). However, absolute deterrence effects can extend over much larger ranges. For example, Brandt et al. (2013a) reported avoidance responses by all observed porpoises within a range of 1.9 km from an active Lofitech device, corresponding to estimated received levels ≥120 dB re 1μPa$_{rms}$ (Table 2). Kastelein et al. (2015) tested the effect of Ace Aquatec and Lofitech ADDs on a captive harbour porpoise and found strong deterrence effects at 139 dB re 1μPa$_{rms}$ for the former and 151 dB re 1μPa$_{rms}$ for the latter. These results correspond to absolute deterrence distances of 380-590 m and 40-150 m for Ace Aquatec and Lofitech devices, respectively and a deterrence distance for most animals of 2-4 km (Hermannsen et al. 2015). The maximum reaction distance observed (involving a Lofitech ADD) was at least 7.5 km (Brandt et al. 2013b), corresponding to estimated received levels ≥110 dB re 1μPa$_{rms}$ (Table 2). In summary, porpoises have been shown to be deterred from around ADDs at distances ranging from several hundred metres to several kilometres. It is worth noting that long-term use of ADDs may lead to habituation or reduced avoidance responses among porpoises, as indicated by results presented by Northridge et al. (2010).

Table 2. Summary of minimum deterrence and reaction distances of harbour porpoises to ADD sounds reported in the literature. Note that substantial differences exist between these studies in terms of ADD types used, main frequencies and source levels, which account for some of the variability between studies. Table modified from Hermannsen et al. (2015).

Study	Method	Type of ADD; frequency; source level	Deterrence distance for most animals	Absolute deterrence distance; estimated received level	Maximum deterrence distance; estimated received level
Olesiuk et al. 2002	Visual observations	Airmar; 10 kHz; 194 dB re 1µPa pp	Not estimated	200 m; 148 dB re 1µPa pp	3500 m (>90%); 106 dB re 1 µPa pp**
Johnston 2002	Visual surveys and theodolite tracking	Airmar dB II Plus; 10 kHz 181 dB re 1µPa pp	Not estimated	640 m (all); 128 dB re 1µPa pp	Not estimated
Northridge et al. 2010	T-PODs and hydrophone array	Airmar; 10 kHz	~ 900 m	0 m (worst case assumptions)	4000 m
Brandt et al. 2013a	Visual surveys and theodolite tracking	Lofitech; 13.5-15 kHz; 189 dB re 1µPa pp	1300 m*	<768 m	2400 m; 129 dB re 1µPa pp**
Brandt et al. 2013b	C-PODs and aerial surveys	Lofitech; 13.5-15 kHz; 189 dB re 1µPa pp	1900 m	350 m; 146 dB re 1µPa pp	7500 m; 113 dB re 1µPa
Kastelein et al. 2015	Visual study on captive porpoise	Ace Aquatec; 10-40 kHz; 193 dB re 1µPa rms	4 km; 117 dB re 1µPa (Ace Aquatec)***	Strong avoidance response: 380-590 m**** (Ace Aquatec)	Not estimated

		Lofitech; 13.5-15 kHz; 189 dB re 1μPa pp	2 km; 121 dB re 1μPa (Lofitech)	Strong avoidance response: 40-150 m**** (Lofitech)	

**See Hermannsen et al. (2015) for details.*

***Derived from Tougaard et al. (2015).*

****Extrapolated from sound levels causing evasive reactions; see Hermannsen et al. (2015) for details.*

*****Extrapolated based on assumption of a spherical transmission loss and an absorption of 1 dB/km; see Hermannsen et al. (2015) for details.*

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

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

2.5 'CETACEAN-FRIENDLY' ADD SYSTEMS

Current concerns about potential impacts of ADD signals on non-target species such as harbour porpoise have encouraged the development of novel ADD systems seeking to minimize such impacts while still acting as effective pinniped deterrents. Use of such systems has been suggested as a possible means to achieve reductions in acoustic impacts while continuing to use ADDs in otherwise sensitive areas, for example on aquaculture sites within the 'Inner Hebrides and the Minches' candidate Special Area of Conservation (cSAC), designated to protect harbour porpoises (Scottish Natural Heritage 2016; Marine Scotland 2016).

Several different approaches have been considered to reduce overall ADD acoustic output. For example, Ace Aquatec have developed a 'Silent Scrammer'™ which only transmits sound when triggered through motion sensors indicating the presence of a seal near the cages, thus reducing the total amount of sound produced over time. Such systems can also be integrated with other non-acoustic components, such as electrified cage fences, to further enhance deterrent effects without increasing acoustic output (Ace Aquatec Universal Scrammer 3™ [US3]; Ace Aquatec 2016). Another potential means to reduce acoustic impacts of ADDs on porpoises and other species involves taking into account the difference in low-frequency hearing capability between harbour porpoises and seals. Harbour porpoise hearing has been shown to be relatively insensitive at frequencies <2.5 kHz even under low ambient noise levels, whereas harbour seals' hearing remains more sensitive to sounds down to frequencies <1 kHz under similar conditions (Kastelein et al. 2002, 2010). This inter-species difference in sensitivity to frequencies <2.5 kHz has led to the development of lower-frequency ADD systems aiming to increase target specificity. Ace Aquatec has developed a low frequency version of the US3 system that generates randomized tonal burst in the 1-2 kHz range, seeking to emit a signal that would deter pinnipeds whilst reducing or eliminating impacts on cetaceans (Ace Aquatec, pers.

comms, 2016; Table 1). The low-frequency Ace Aquatec US3 system is presently the only commercially available ADD system adopting this approach. Details of system characteristics are, unfortunately, scarce and no peer-reviewed descriptions are presently available of either 1) this device's long-term ability to deter seals effectively or 2) any potential responses of harbour porpoises and other non-target species to its acoustic output across varying spatiotemporal scales.

Loud sounds with sharp rise times can elicit an autonomous startle reflex in mammals, including seals (Götz & Janik 2011). Recent studies have demonstrated that grey seals (*Halichoerus grypus*) show sustained avoidance behaviour after repeated exposure to startle reflex-inducing acoustic stimuli (Götz & Janik 2011). On the basis of these findings, a novel ADD system intended to more effectively deter seals from fish farms, whilst avoiding unintended effects on non-target species such as harbour porpoises, has been patented (Götz & Janik 2012). The acoustic characteristics of this system are described in Table 1. At 1 kHz, peak frequencies for the deterrence stimulus are well below traditional ADD systems and duty cycles can be low (0.8%, see Table 1; Götz & Janik 2015). Field trials showed the effectiveness of this system in deterring seals from fish farms while reducing the risk to non-target species such as harbour porpoises (Götz & Janik 2011, 2015). Over a 2-month period, significant reductions in observed seal numbers during sound exposure were observed without noticeable habituation occurring, whereas no changes in porpoise relative abundance, distribution or behaviour were observed (Götz & Janik 2015). However, received levels needed to be loud (>145 dB re 1 μPa_{RMS}) and signal onset sharp (<5 ms) to elicit a response; since both of these factors are affected by sound propagation through the water column, the effectiveness of this method is likely limited to relatively short ranges around fish farms (Coram et al. 2014; Götz & Janik 2015). This might be an advantage in the context of using ADDs continuously to deter seals, as avoidance responses will be limited to the immediate area around the ADD. This would, however, also mean that seals would have to be in close proximity to a fish farm for the deterrent to be effective; at such close distances, individual seals' increased motivation to investigate a potential food source might reduce deterrent efficacy. Another concern would be that lower frequencies generated by this device will propagate over larger ranges and are likely to be more audible to other non-target species such as fish and baleen whales. Potential effects of these ADD signals on such other species need to be investigated before large-scale deployments of these devices can commence.

3 EXPERIMENTAL METHODS

3.1 BACKGROUND AND PROJECT AIMS

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

Against this background, the present research project sought to undertake a controlled sound exposure experiment on an active fish farm on the west coast of Scotland to evaluate porpoises' responses (expressed as detection rates of porpoise echolocation calls). Simulated ADD sounds were played back to porpoises upon visual detection by shore-based observers, or at regular intervals during night or poor weather. Signals were specifically designed for this project to take advantage of the difference in auditory sensitivity between seals and porpoises at frequencies <2.5 kHz. Responses of porpoises to ADD signal transmissions were recorded through an array of passive acoustic detectors, as well as visually through onshore observers and an experimental camera tracking array.

3.2 ACOUSTIC PLAYBACK SIGNAL DESIGN

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

In the experimental design, the potential difference between porpoises' and seals' hearing sensitivities to either high- / low-frequency ADD signals was applied. A high frequency (HF) test signal was designed using single frequency tonal bursts, similar to the Airmar, Lofitec and Ace Aquatec brands that represent the majority of ADDs in current use in Scottish salmon aquaculture. The random frequency sequencing and the pulse width and duty cycle of the Ace Aquatec were also adopted. The overall frequency range of transmission was extended from 8-18 kHz to capture the full frequency spectrum of all three systems (Figure 2). Specifically, the HF signal consisted of pulsed continuous wave sinusoidal tonal bursts at one of 21 randomly switching fundamental frequencies between 8 – 18 kHz at frequency intervals of 500 Hz. Each pulse contained 40 cycles of fundamental frequency with a rectangular pulse amplitude envelope, and the on – off duty cycle was 50%. Figure 3 illustrates the variation in pulse amplitude due to transducer response as well as pulse duration.

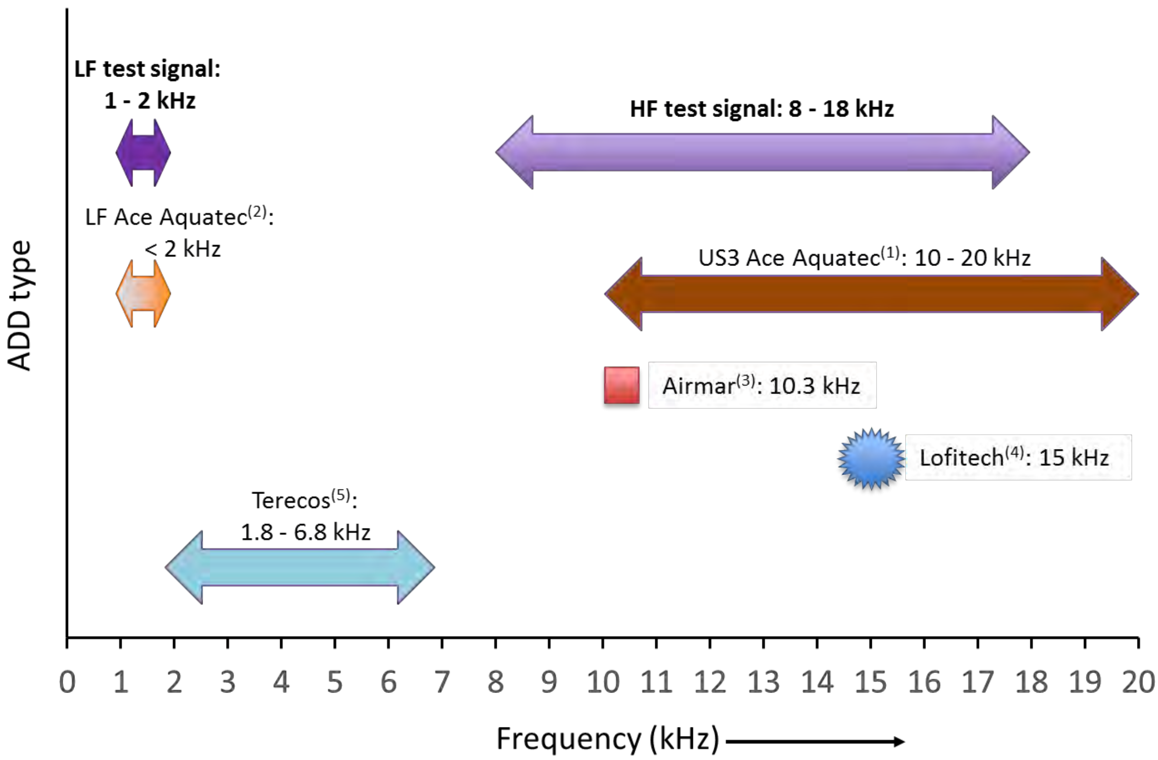

Figure 2. Output frequency ranges of the two test signals (LF and HF), compared to outputs from various existing ADD types (see Table 1 for details). Data on existing ADD outputs derived from 1) Ace Aquatec U3S manual (https://www.aceaquatec.com/us3specification); 2) Ace Aquatec pers. comm. (PL); 3)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

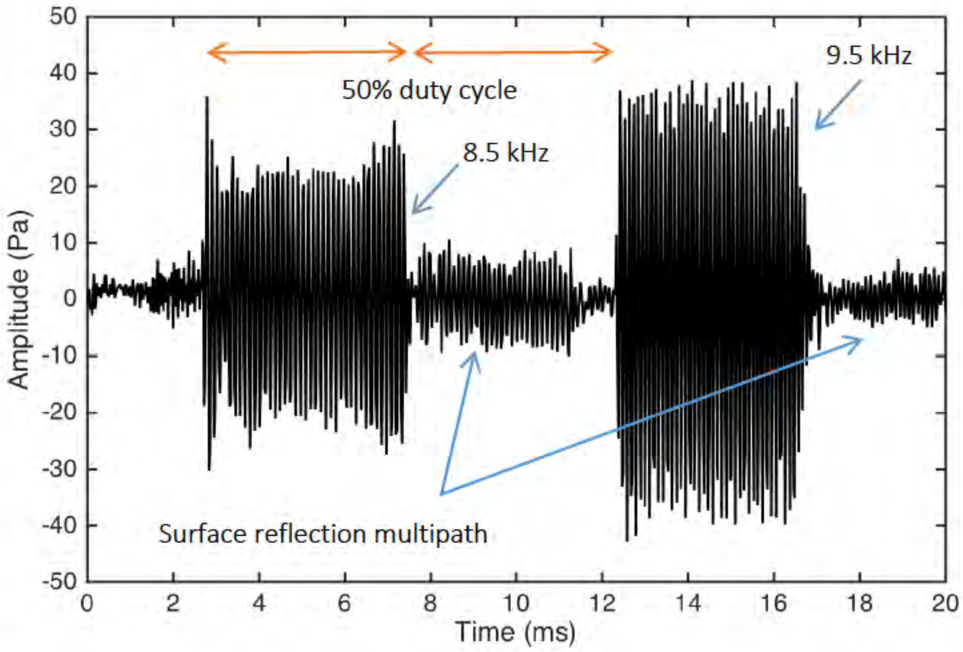

Figure 3. Time domain plot of two consecutive samples from the HF sequence – first pulse at 8.5 kHz and second at 9.5 kHz.

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

Evaluating the broadband multi-frequency nature of the Terecos system (described in Lepper et al. 2014) was felt to be beyond evaluation scope in the available experimental paradigm for the proposed trials and so was not included in the current experiment. Figure 2 illustrates the comparison between the experimental HF and LF signals, and existing ADD systems, in terms of fundamental frequency spectral distribution. Differences in HF and LF signal characteristics are further illustrated in Figure 4. Relevant parameters of both signals are summarized in Table 3.

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 µPa-m	165 – 170.4 dB re 1 µPa-m

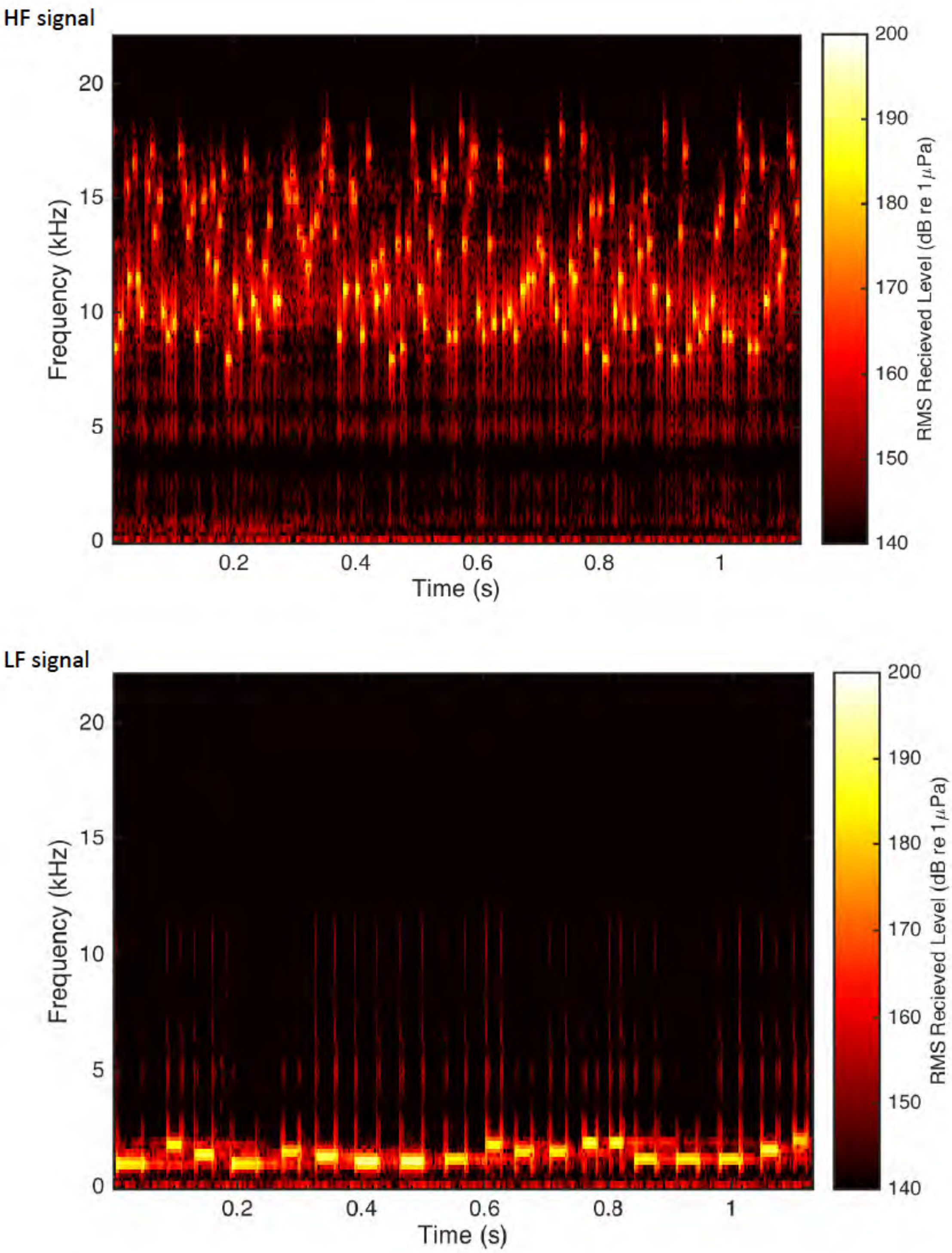

Figure 4. Spectral plot of a sample of the HF and LF signals received at a range of 8.5 m using a Reson 4014 balanced hydrophone. Analysis window was 256 FFT with 50 % overlap using a Hanning window. A 50 kHz low pass filter was applied. Original data were downsampled to a sample rate of 44.1 kHz.

3.3 SIGNAL TRANSMISSION

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

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

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

Calibration of the signal source from the Lubell speaker at each tonal frequency was undertaken in-situ. Test trials recorded both signal types using a balanced RESON™ 4014 hydrophone with sensitivity of around -180 dB re 1V/µPa using a dedicated 20 dB balanced preamplifier. Measurements were made with preamplifiers / filters in the frequency range 100 Hz – 200 kHz and <50 kHz. Data acquisition was carried out using a 16-bit National Instruments 6521 DAQ system at a sample rate of 1.25 MSs^{-1} with a voltage range of +/- 5V using bespoke data acquisition software. Both the DAQ and laptop (SurfacePro) were battery-powered. The RESON 4014 hydrophone was deployed from the front of the fish farm barge at 8.5 m directly in front of the sound source, at the same depth of 10.5 m. In post-experimental analysis, the free-field direct path of the signal was identified, allowing RMS levels to be calculated on this basis (Table 4). Free-field source levels were then calculated using spherical spreading.

Table 4. Summary of calculated RMS source levels for LF and HF signals at their relevant fundamental frequencies (N = 11 for LF signal, and 21 for HF signal).

	Frequency (Hz)	Pulse duration (ms)	RMS Source Level (dB re 1 µPa-m)	Frequency (Hz)	Pulse duration (ms)	RMS Source Level (dB re 1 µPa-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			

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

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

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

3.4 FIELDWORK LOCATION

The experiment took place in the Sound of Mull, on the west coast of Scotland, with observation efforts concentrated in Bloody Bay on the north shore of the Isle of Mull (56°38.626 N, 6°05.705 W; Figure 6). This location was chosen because it contained a salmon aquaculture site (owned by Scottish Sea Farms™/SSF) which operated under licensing restrictions preventing it from using ADDs (Scottish Natural Heritage, pers.comm. 2016). This meant that the experiment could be undertaken without interference from on-site operational ADDs, although effects of more distant ADDs deployed by other fish farms in the area could not be eliminated. Furthermore, Bloody Bay had previously been identified as a site where harbour porpoises were observed regularly (Carlström 2005; Carlström et al. 2009; Götz & Janik 2016). The Bloody Bay fish farm barge was used as a platform from which the underwater loudspeaker and associated hardware could be deployed, as well as passive acoustic detectors. Water depths in the immediate area around the fish farm were approximately 35-40 m (based on GEBCO™ bathymetry data).

3.5 PASSIVE ACOUSTIC DETECTOR ARRAY

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

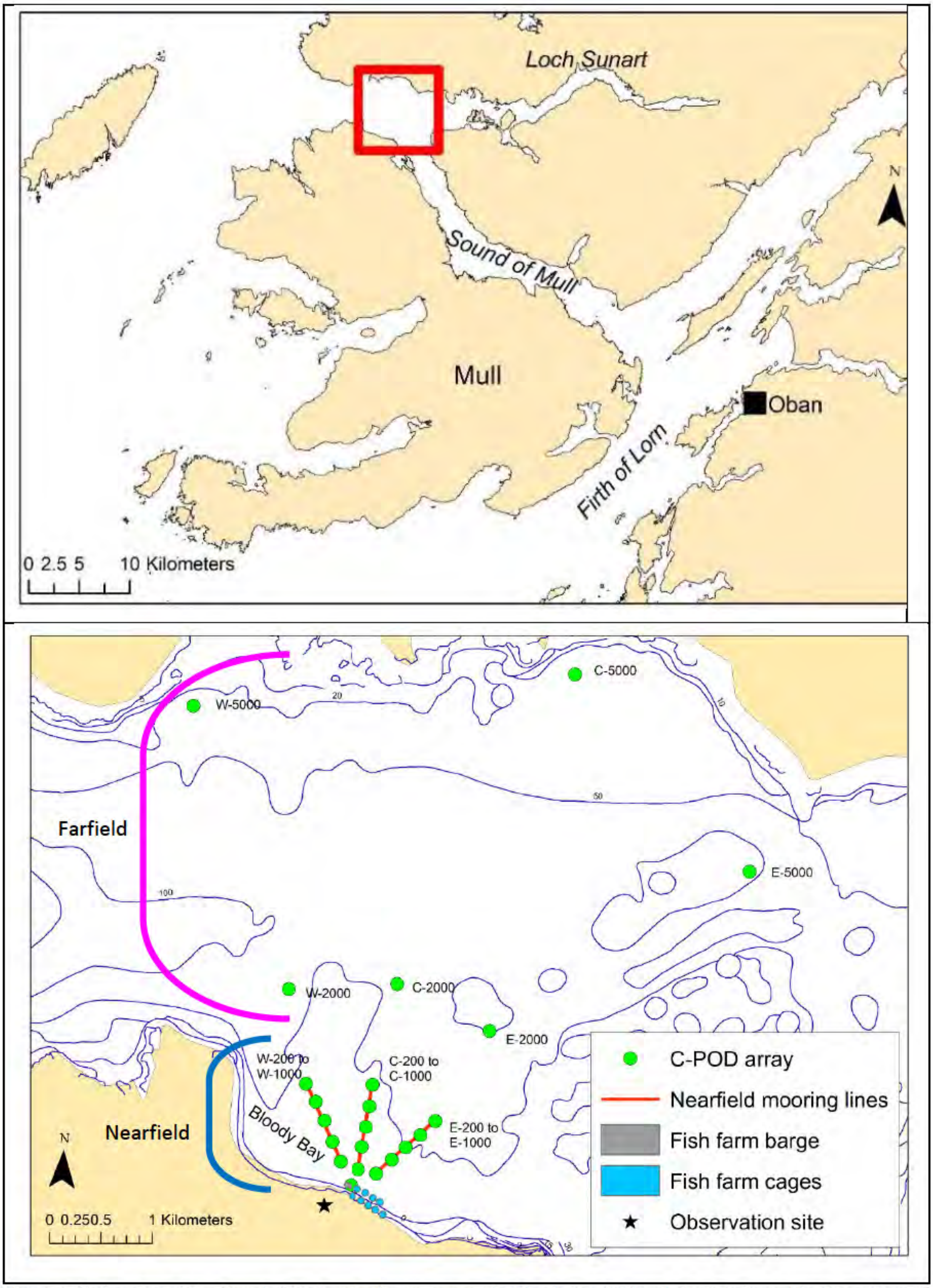

Figure 6. A) Overview of the Sound of Mull and adjacent areas. The Bloody Bay fieldwork site is indicated by the red box. B) Overview of LEAP passive acoustic mooring array in Bloody Bay and the northwestern Sound of Mull. Nearfield and Farfield components of the array are indicated. Note that the field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

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

Table 5. 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	Fish farm 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

[1] High-frequency SoundTrap™

[2] Low-Frequency SoundTrap™

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
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

Each station contained a C-POD™ porpoise click detector, with some stations additionally being equipped with a SoundTrap™ or RTSYS™ sound recorder (Table 4). Detector selection was determined through a combination of unit battery capacity, price and availability among project partners:

- C-PODs are self-contained ultrasound monitors that select tonal clicks and record the time of occurrence, centre frequency, intensity, duration, bandwidth and frequency trend of tonal clicks within the frequency range 20 kHz - 160 kHz to 5-µs resolution. This allows them to monitor clicks from all odontocetes except sperm whales. Raw sound data are not stored, however, and the unit's design precludes manual configuration of click identification parameters. Maximum deployment times vary depending on environmental conditions but typically range over several months (Chelonia Ltd. 2011, 2013, 2014). This extended battery life makes them suitable for long-term monitoring experiments involving species such as harbour porpoise. A subset (n=8 units) of C-PODs' responses to artificial porpoise clicks had been tested previously as part of a different experiment, deploying an omnidirectional harbour porpoise click train synthesiser (PALv1; F^3 Maritime Technology 2012) at known distance. The PALv1 unit produced click trains with a centre frequency of 133 ± 0.5 kHz and source levels of 154 ± 2 dB (peak-to-peak; F^3 Maritime Technology 2012). Some variability in terms of C-PODs detecting PALv1 click trains was noted at the time; environmental factors (notably changes in C-POD orientation relative to the PALv1 sound source) were considered to be an important cause of this variability. No further calibration of C-PODs used in this experiment was performed.

Occasionally, under high ambient noise conditions, C-PODs temporarily stop logging when reaching a pre-set buffer limit of 4,096 clicks per minute, until the start of the next minute (Booth 2016). The proportion of each minute thus lost can be used as a crude proxy of ambient noise levels across the array. C-PODs also contained an onboard tilt sensor, recording their deflection from vertical (0° = vertical; 90° = horizontal).

- SoundTraps are compact self-contained broadband underwater sound recorders (Ocean Instruments 2017). Unlike C-PODs, they store raw sound data onboard for further study, but have a lesser battery capacity resulting in the need for sampling according to a pre-programmed duty cycle to extend recording duration. Two versions (SoundTrap 300 STD, with a working frequency range of 20 Hz-60 kHz, and SoundTrap 300 HF, with a working frequency range of 20 Hz-150 kHz) were available for the present experiment (N= 2 and 1 devices, respectively). The SoundTrap 300 units were included in the moorings to provide validation of the transmitted ADD signal across the array. Units were programmed to sample 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 acquiring signals from up to four broadband hydrophones simultaneously (RTSYS 2016). A single unit was deployed beneath the fish farm barge adjacent to the underwater loudspeaker to obtain information on signal output for subsequent modelling of transmission loss across the array. It recorded on one channel using a Reson TC4014, broadband omnidirectional hydrophone (sensitivity: -180 dB re 1 V/µPa, flat frequency response: 25 Hz-250kHz), for a period of 4 days during 16-19/09/2016.

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

3.6 VISUAL OBSERVATIONS AND CAMERA ARRAY

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

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

3.7 DATA MANAGEMENT

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

4 RESULTS

4.1 SIGNAL TRANSMISSION EXPERIMENTS

The signal transmission system described under Section 3.3 was installed onto the fish farm barge and activated on 6/09/2016, following a delay of approximately 5 weeks due to an unexpectedly long licensing process. Despite this delay, the project succeeded in completing a successful fieldwork campaign combining simulated ADD transmissions with simultaneous acoustic and visual observations of porpoises. Following some tests, the actual experiment ran from 08/09/2016 until 11/10/2016 inclusive, or a total of 33 days. During this period, a total of 138 complete sound transmissions (including 53 HF signal transmissions, 38 LF signal transmissions, and 47 silent control "transmissions") were carried out. Transmissions were either triggered upon visual detection of animals or initiated on a random schedule (see Methods). Of all transmissions, 62 ran during daylight hours (i.e. started during daytime or immediately before sunrise), while 76 transmissions overlapped partially or wholly with hours of darkness (i.e. started during darkness or immediately before sunset). Visual observations occurred on 18 days between 9/09/2017 and 10/10/2017, and included both data from human observers and video camera tracking data. There was no significant difference in terms of when particular signals were transmitted in relation to daylight hours. All but three of the passive acoustic recorders were successfully recovered on 18/10/2016. The resulting dataset will be described in more detail below.

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

4.2 HARDWARE RECOVERY

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

On 13/09/2016, following a storm, the surface float of the central Nearfield mooring (position C-200) was noted to have disappeared. Because this was part of an 800 m long, complex mooring it was deemed unwise to lift and disrupt the mooring further. It became apparent during the retrieval of the full array on 18/10/2016 that the earlier loss of the C-200 surface float had also resulted in the loss of the vertical riser below it, including the attached C-POD and SoundTrap detectors (Table 6). No monitoring data were therefore available from this particular location. In addition, the acoustic release of the solitary E-5000 Farfield mooring failed to respond to activation commands, preventing mooring recovery from this location as well. The reason for this was unclear but could involve a technical fault in the acoustic release unit or displacement of the mooring through interactions with commercial fishing gear. Subsequent efforts to contact this mooring's acoustic release unit, by surveying out as far as 2 km from its original deployment location, were unfortunately unsuccessful. An information campaign to alert the wider community to the fact of these losses and appeal for assistance in relocating the missing equipment has to date not yielded any results, and these detectors should be considered lost at present (Table 6).

4.3 PASSIVE ACOUSTIC MONITORING

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

As the C-5000 C-POD had been deployed before the other moorings on 17/08/2016, the subsequent delay in deploying the remainder of the array through the extended licensing application process resulted in the C-5000 C-POD's batteries being depleted by 7/10/2016, about 10 days before the recovery of the array. Other C-PODs suffered only minor losses in terms of recording time due to battery depletion towards the end of the experiment. The combined C-POD dataset available for analysis was therefore derived from 18 out of 21 C-PODs (Table 6). Upon recovery, the HF-SoundTrap included in the E-1000 mooring was also found to have malfunctioned at some point during the deployment for unknown reasons.

C-POD datasets were truncated to exclude periods immediately after deployment and before recovery, such that the remaining datasets only contained entire days (1440 minutes per day). For this reason, the entire array (excluding the C-POD beneath the fish farm barge) was defined to be active from 8/09/2016 at 00:00 GMT until 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. All other C-PODs remained operational until at least 16/10/2017 at 23:59 GMT, equivalent to 39 full days.

*Table 6. Summary of periods monitored by moored C-POD units across the array. *These units stopped <24 hrs prior to recovery. ** This 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	Fish farm 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

4.4 AMBIENT NOISE MONITORING

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

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

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

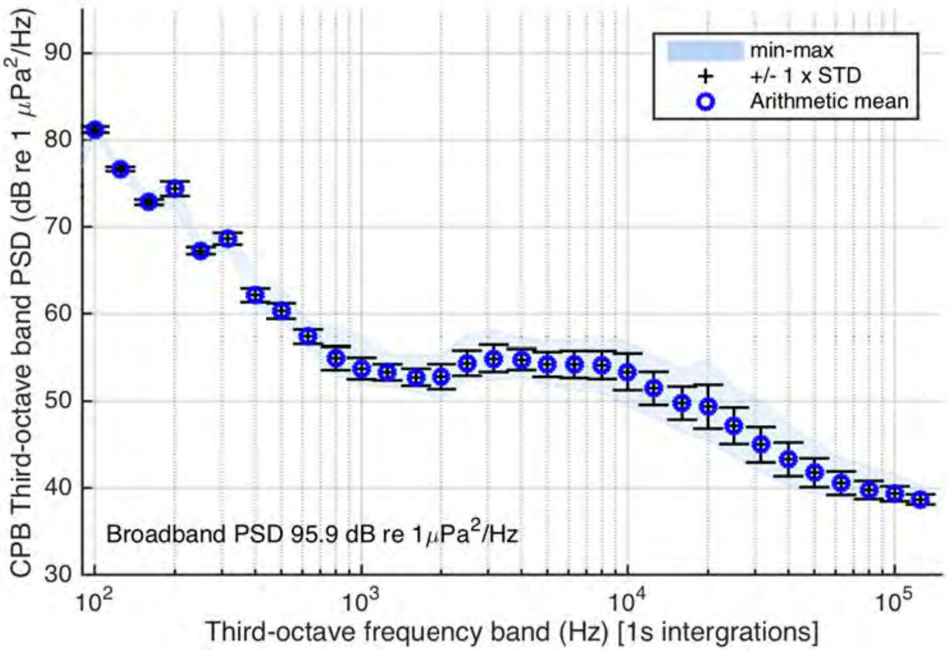

Figure 7. Power Spectral Density (PSD) in Third Octave Bands for a quiet period at 14:56 GMT on 11th October 2016. Total sample length 25 seconds, 1-second integration periods.

These levels are in line with similar sea-state noise levels at other sites with a broadband PSD of 95.9 dB re 1 μPa^2/Hz. The data also indicate relatively low variability during this period with only slightly increased standard deviations and maximum and minimum values for frequencies >10 kHz.

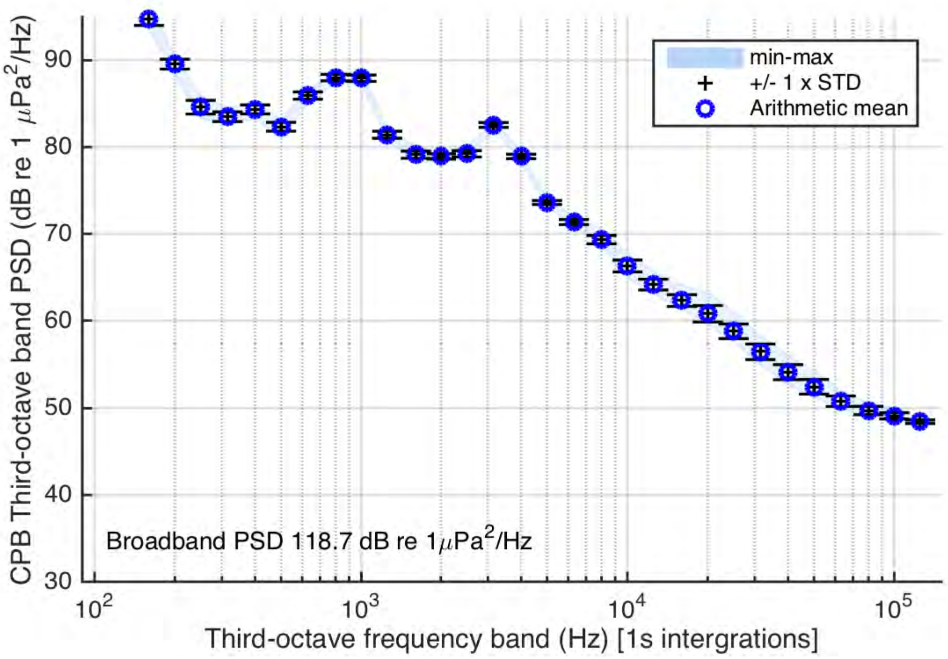

Figure 8. Power Spectral Density (PSD) in Third Octave Bands for low sea-state period at 15:01 GMT on 11th October 2016. Total sample length 25 seconds, 1-second integration periods. Likely contributions originated from specific barge or small boat operations.

By comparison, Figure 8 shows a 25-second period taken around 5 minutes later at 15:01 GMT. During this period, significantly elevated levels were observed at a range of frequencies. Most of this noise likely originated either from short-term barge-based activities or nearby small boat operations with a broadband response of 118.7 dB re 1 μPa^2/Hz with levels approximately 30 dB higher in some frequency bands. For further comparison, Figure 9 shows a consecutive 25-second sample period taken a few moments later with a lower broadband response of 106.2 dB re 1 μPa^2/Hz. These data show that, although levels dropped when compared to the previous sample, there was increased variation during the 25-second sample, most likely due to transitory noise from boat- or barge-based operations during this period.

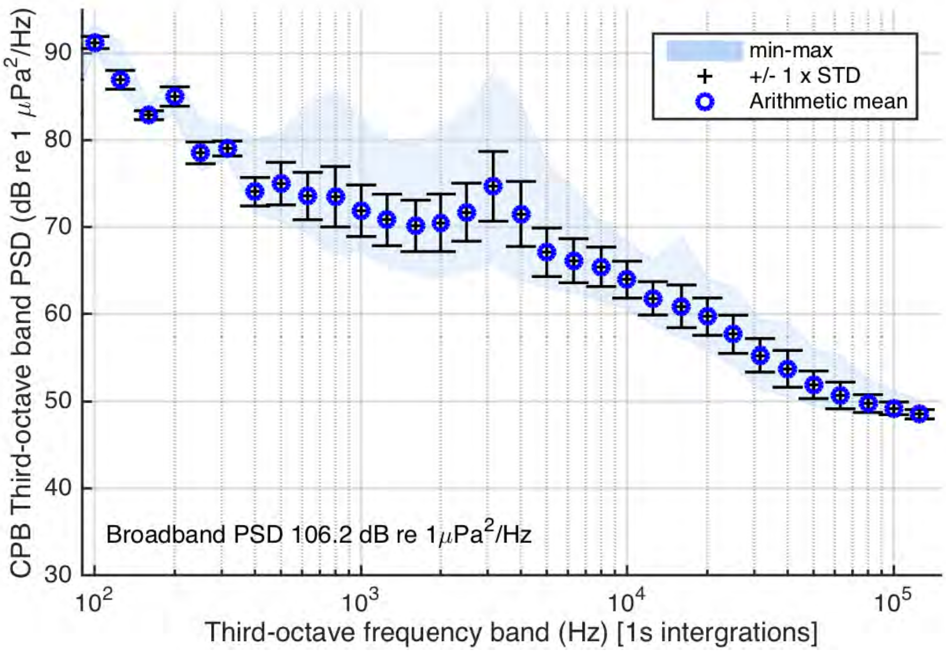

Figure 9. Power Spectral Density (PSD) in Third Octave Bands for low sea-state period. Consecutive 25s period from file started at 15:01 on 11th October 2016 compared to figure 9. Total sample length 25 seconds, 1-second integration periods. Transitory contributions from specific barge-based or small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

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

4.5 SIGNAL PROPAGATION MODELLING

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

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

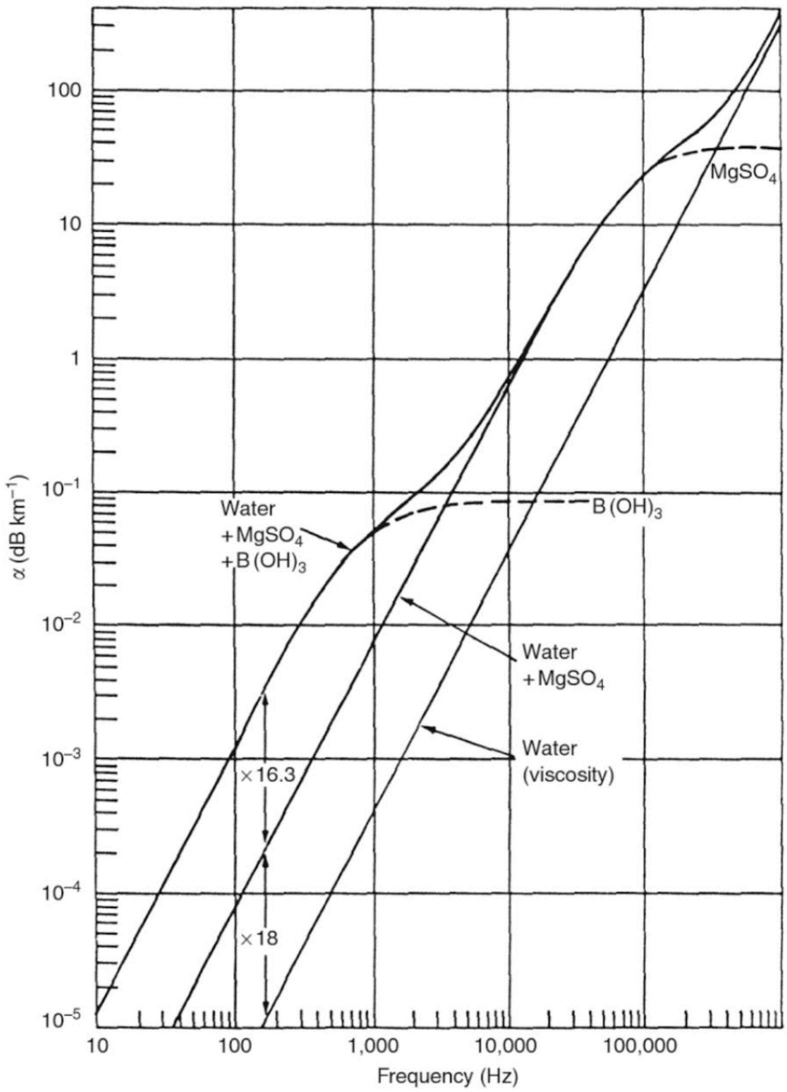

Figure 10. Underwater acoustic absorption versus frequency. Derived from Etter (2003).

Analysis of Farfield SoundTrap data from position C-5000 of both HF and LF signal types indicated that both signals were nonetheless easily detectable above background noise levels. This suggested that the entire array was ensonified by the experimental signals, allowing direct comparison of porpoise detection rates between C-PODs. Received levels would still be expected to be lower among the Farfield moorings, and hence behavioural response could be expected to be less pronounced; this aspect was not analysed in the present experiment due to an absence of RL data from each individual mooring.

4.6 VISUAL OBSERVATIONS

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

4.6.1. Marine mammal sightings

Harbour porpoises were observed on 23 occasions spread out over 9 days (Table 7). Observations varied in duration from a single surfacing to repeated sightings during the course of 30 minutes or more. Porpoises were observed singly or in groups of up to four animals. Most porpoises were sighted outside Bloody Bay, i.e. >1 km away from the observation site within the central and northern Sound of Mull, and particularly towards the entrance to Loch Sunart (Figure 6); porpoises were sighted within 1km from the fish farm on three occasions. Bottlenose dolphins were observed on four separate occasions (Table 7). As with porpoises, dolphin sightings varied in duration from a single brief surfacing event to extended observations for up to 30 minutes. Dolphins travelled singly or in groups of up to five individuals, and were generally observed closer to the observation site.. Their active surface behaviour facilitated detection by the observers. Finally, a single minke whale was observed on 28/09/2016 in Bloody Bay (Table 6).

Seals were regularly observed on all but one day of the experimental period, with multiple observations throughout each day (Table 7). Because the focus of the experiment was on porpoises, no signal transmissions were initiated when a seal was sighted. Visual observers recorded occurrence, number and species of seals present and estimated location and surface behaviour, but no efforts were made to track individual seals or record the duration of their surface intervals. Seals were most often observed near the fish farm but were also seen throughout Bloody Bay and the wider Sound of Mull; no surface feeding behaviour was observed. All seals observed under sufficiently calm conditions to permit species identification were harbour seals (Table 7). Seals were typically noted to be stationary or slowly swimming at the surface. Observations typically involved single or two seals at a time. Visual observations confirmed reports from the SSF staff that small numbers of seals might be present at any given moment. A single otter (*Lutra lutra*) was also observed in the water along the shoreline below the observation site on three days (Table 7).

*Table 7. Overview of observation events of different marine mammal species during the experiment. Individual observation events of porpoises and dolphins often involved >1 individual. *N.B.: Seal and otter sightings were not tracked and so numbers reflect the 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		

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

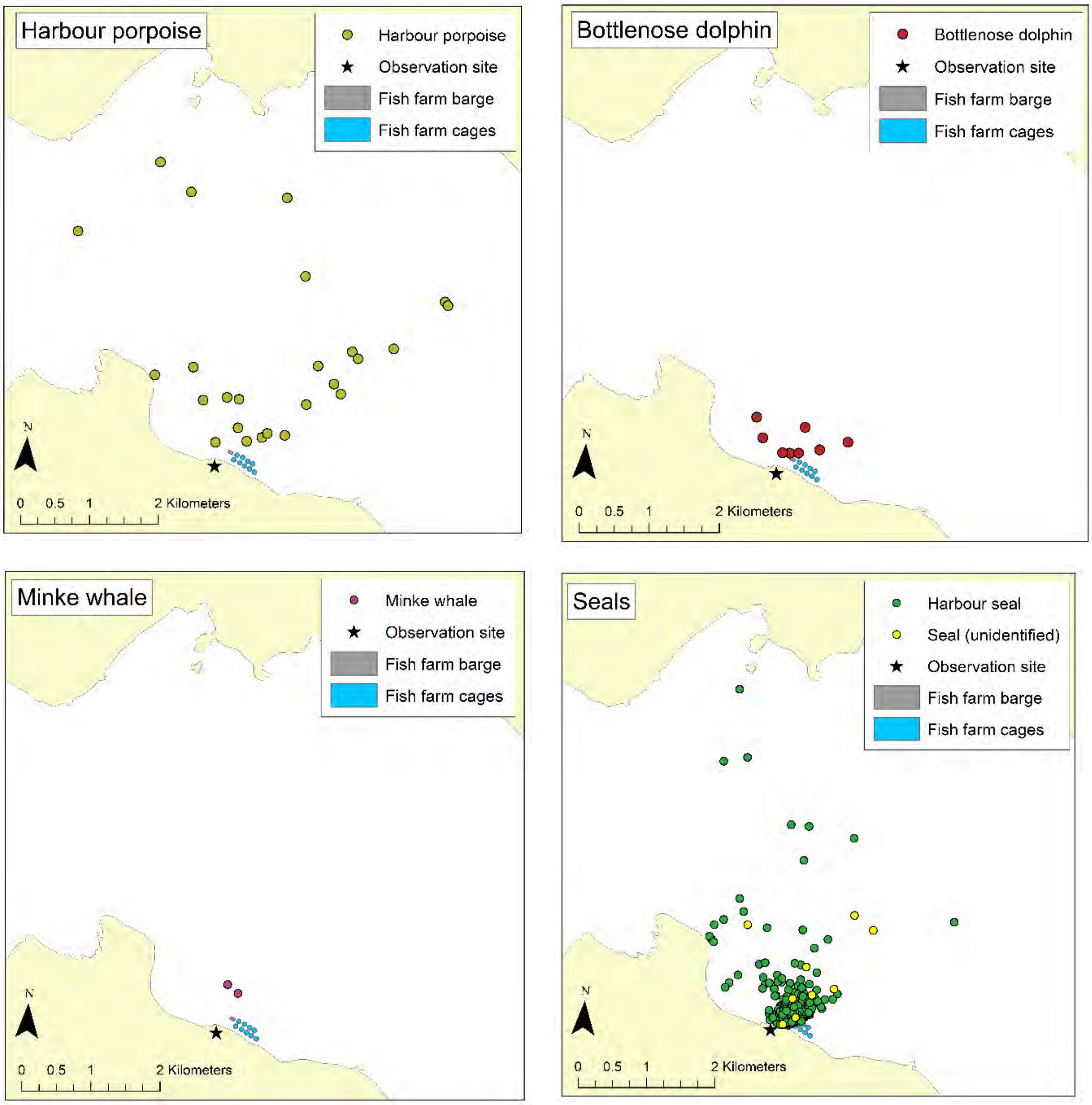

Figure 11. Approximate locations of sightings of different marine mammal species during the entire experimental period. Note that these positions are only approximations due to substantial variability in distance estimation among observers.

4.6.2 Visual tracking analysis

The visual tracking methodology (Section 3.6) was designed to provide insight into porpoises' initial responses to the experimental signals by tracking their surface movements at high resolution. Unfortunately, the small number of visual sightings of porpoises made this difficult (Table 7). In addition to being infrequent, most porpoise sightings occurred at considerable distance from the observation site (notably in the northern half of the Sound of Mull, towards the entrance to Loch Sunart several km away). At such distances, the cameras' resolution proved to be inadequate for reliably recording porpoises for tracking. For this reason, only a few sightings close to the fish farm were suitable for further analysis and the method was therefore unable to provide robust information on porpoises' responses to the experimental ADD signals. However, despite the small number of porpoises at the site in the autumn of 2016, we were able to demonstrate the general utility of the method, and would encourage further development of this tool. An example of a tracked group of porpoises is shown in Figure 12.

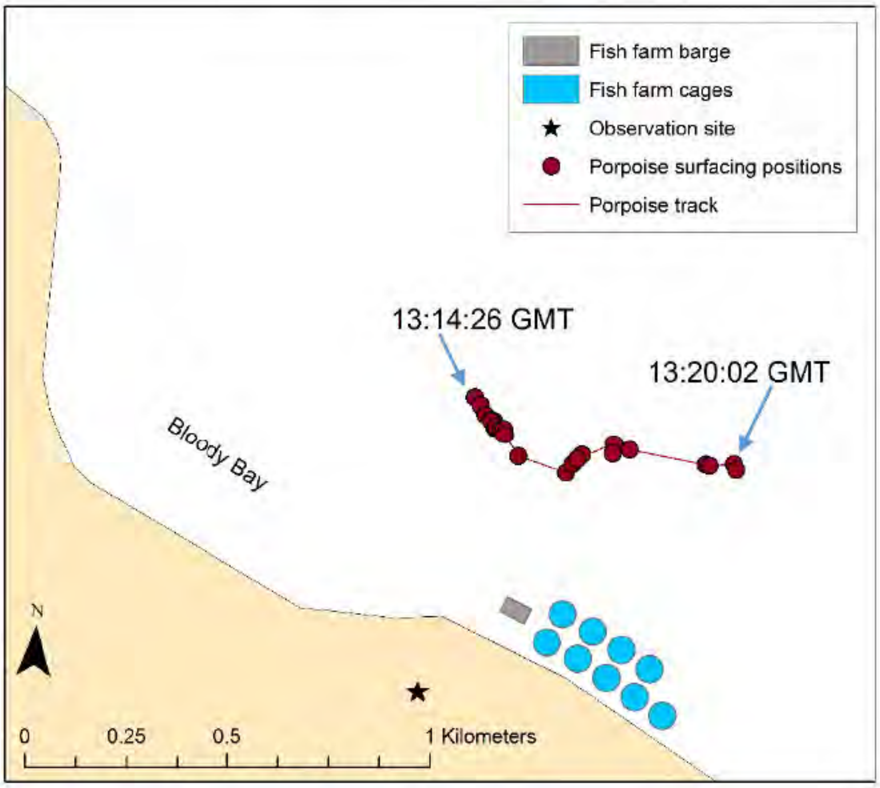

Figure 12. Example of tracked group of three porpoises observed on 14/09/2016, swimming from west to east.

4.6.3. Seal observations around the fish farm

Although not the main focus of this study, visual observations on seals surfacing around the fish farm allowed for some initial analysis of effects of the experimental ADD signals on them as well. Seals were observed during 17 experiments (Table 8).

*Table 8. Summary of seal sighting events during experimental transmissions of HF (n = 5) and LF signals (n = 7), as well as silent controls (n = 5; each experiment identified by number). Seal sightings have been divided into nearby and distant groups, based on approximate distances from the fish farm barge estimated from visual sighting data. Experiments marked with * were observed for <30 minutes and were excluded from subsequent analysis.*

Signal type	Experiment number	# 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

In three cases <30 minutes, or <25%, of the entire 2-hour transmission period was observed (Table 8), and these cases were excluded from further analysis. Data from the remaining 14 cases were used to assess the relationship, if any, between signal type and standardised sighting rate of individual seal sighting events per minute, using a linear modelling approach through the *lm* tool in the R package *stats* v.3.4.3. Results indicated that there was no obvious relationship between the signal being transmitted and standardised seal sighting rates, irrespective of whether sightings of nearby seals (d.f. = 12; p = 0.5461), more distant seals (d.f. = 12; p = 0.2213), or all seals (d.f. =12; p = 0.4637) were used to populate the model. Standardised seal sighting rates were lowest during silent controls, and highest during transmission of the HF signals (Table 8). These results are preliminary and should be interpreted with caution, but did not support the notion that either ADD signal used here was acting as an effective deterrent of seals from the immediate area around the fish farm.

4.7 C-POD DATA ANALYSIS

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

All C-POD data were initially analysed at a temporal resolution of whole minutes, with each minute classified as either 1 (a ‘Porpoise-Positive Minute’, or PPM) or 0 on the basis of presence/absence of porpoise click trains, as defined by the classifiers within the bespoke software *CPOD.exe* (Section 3.5; Table 9). Only click trains classified as “Moderate” or “High” quality were used in subsequent analyses (Carlström, 2005). Twenty unprocessed click trains from each C-POD (or all potential detections for C-

PODs where N<50) were checked visually to assess false positive rates on the basis of parameters such as frequency distribution, SPL and train duration, following Chelonia Ltd. (2013). False positive rates fell between 0-5% in all samples, suggesting that the risk of false positives affecting interpretation of the datasets was low.

*Table 9. Overview of porpoise detections across the C-POD array during 8/09-16/10/2016. * The C-5000 C-POD ceased to function on 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 '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

4.7.1 Experimental results of exposure experiments

Due to the randomised nature of transmission selection, the total number of HF and LF exposures and silent control trials was not equal (summarised in Section 4.1). PPM detection rates during the experimental period (08/09-11/10/2016) were standardised for each C-POD by dividing the number of PPMs by the total number of monitored minutes over each experimental transmission. For each signal type, all PPM detection rates were averaged across the array to produce an aggregate average. The maximum number of PPM observed during any experimental transmission was 19, representing approximately 15% of the total 2-hour experimental period. PPM detection results, aggregated by signal type, are summarised for each mooring in Table 10. At almost all moorings, the greatest number of PPMs was observed during silent control periods. Aggregate average PPM detection rates were highest in Silent Control exposures and lowest during transmission of HF signals (Figure 13). Based on aggregated results, LF signal transmissions also resulted in reduced PPM detection rates, contrary to original expectations that detection rates under these conditions would broadly resemble those observed under Silent Control exposures.

*Table 10. Summary of numbers of monitored minutes ($N_{MINUTES}$), number of PPMs (N_{PPM}), and average ratio of number of PPMs divided by total number of monitored minutes (F) during all experimental transmissions, detected by each C-POD between 08/09/2016 and 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
		$N_{MINUTES}$	N_{PPM}	F	$N_{MINUTES}$	N_{PPM}	F	$N_{MINUTES}$	N_{PPM}	F	N
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
	All Nearfield		39	0.00044		65	0.00093		127	0.00162	
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
	All Farfield		163	0.00580		152	0.00680		236	0.00911	
Entire Array		113188	202	0.00178	87624	217	0.00247	100676	363	0.00358	782

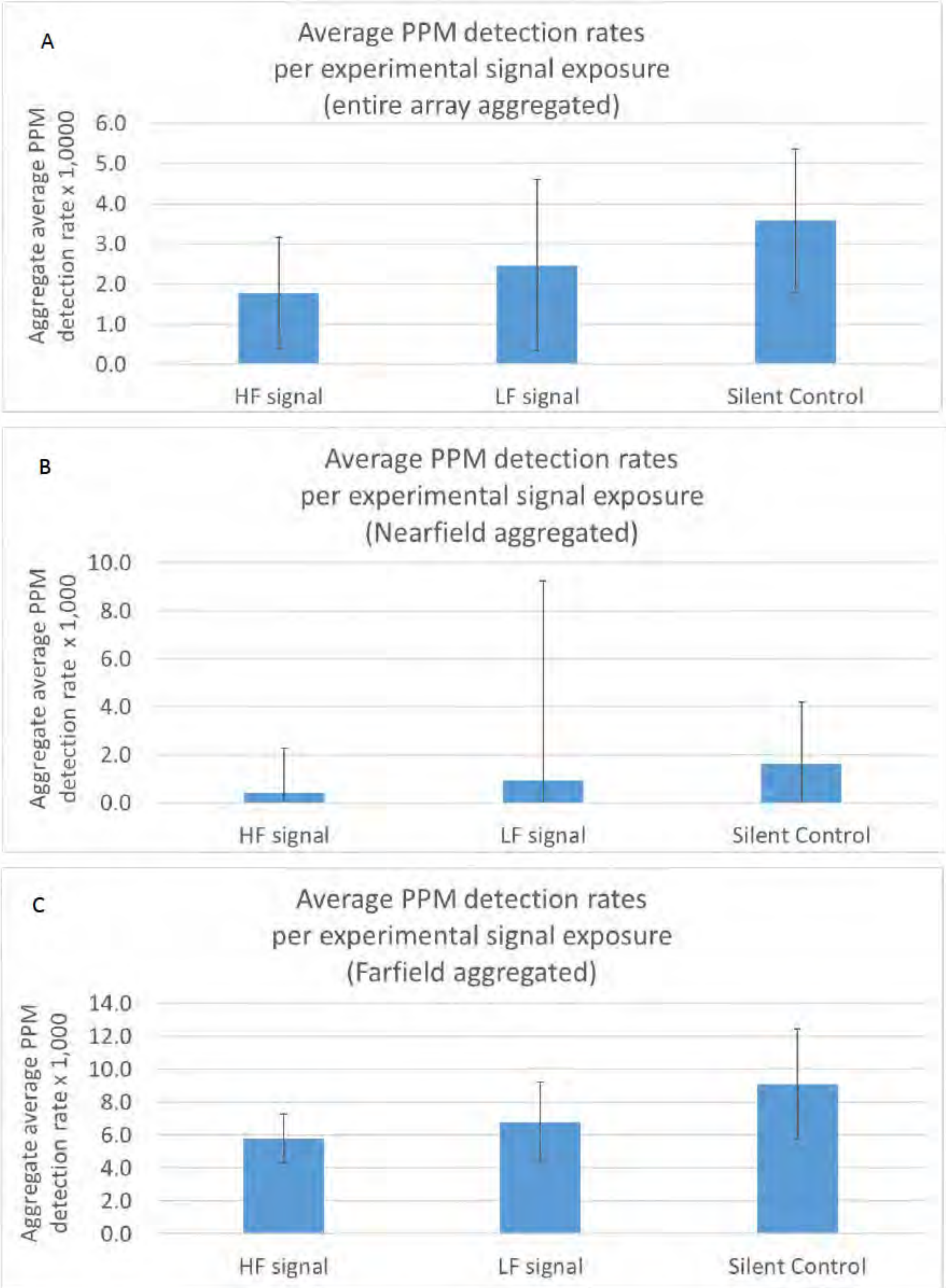

Figure 13. Aggregated average PPM detection rates (± SE) for (A) all C-PODs combined, (B) the Nearfield and (C) Farfield datasets, for the three different experimental transmissions (HF signal, LF signal, and 'Silent control'). Values were derived from Table 9 and multiplied by 1,000 for display purposes. Significant variability in detection rates is apparent, particularly in the Nearfield data.

Once moorings were assessed individually, however, considerable variability among standardised PPM detection rates became apparent (Table 10; Figure 14). PPM detection rates at Nearfield moorings closest to the fish farm barge were substantially lower during both HF and LF signal transmissions than during the silent control. This 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 the Nearfield component of the array (e.g. W-800 and W-1000), as well as the Farfield moorings, differences between one or both experimental treatment(s) and the silent controls were reduced (Table 10; Figure 14). While standardised detection rates were still highest overall during silent controls at each mooring (except W-1000 where detection rates under the LF signal exposure were relatively high, and almost non-existent under the HF signal exposure), only in one case (C-5000, along the opposite shore across the Sound of Mull) were HF-exposed detection rates notably higher than LF-exposed detection rates. There was an order of magnitude difference in terms of absolute numbers of PPMs detected at different C-PODs, even among adjacent ones (cf. results from C-600, C-800 and C-1000; Table 10). The reasons for these differences are presently unclear, but their occurrence suggests that the effects on porpoise detection of the signals themselves may be modulated by environmental parameters driving spatiotemporal heterogeneity across the array. Possible explanations for this heterogeneity include stochastic differences in individual porpoises' distribution, habitat use and/or echolocation rates (Linnenschmidt et al. 2013).

The degree of clumping of detections (i.e. multiple PPMs occurring in a few dense clusters within small numbers of experimental periods, rather than occasional PPMs spread out across multiple experimental periods) was examined to assess whether this might affect overall F-ratio values (Table 10). The variance associated with the average F-ratio values contained in Table 10 was compared across the array. High variance associated with clumping was noted in some cases, most notably W-1000 during the LF signal exposure, where 35 of 37 PPMs (>94%) occurred during only two experiments (N = 16 and 19 PPMs, respectively), resulting in a high F-ratio value (0.00796). Such results could have been caused by a single porpoise remaining near the mooring for an extended period. In the case of W-1000, the observed clumping of PPMs goes some way towards explaining the anomalously high score during the LF signal exposure experiments (see also Figure 14). This illustrates the substantial variability associated with this database.

Due to the large numbers of zero values in the data, a series of nonparametric Kruskal-Wallis tests, followed by Tukey-type nonparametric multiple comparisons analyses where appropriate, were performed to test for differences between signal treatments among different moorings (Zar 1984). Three separate Kruskal-Wallis tests were performed, for the entire array, the Nearfield and Farfield moorings respectively, based on F-values described in Table 10. To deal with tied ranks, correction factors were applied to the test parameter *H*, as described by Zar (1984). For the entire array, the Kruskal-Wallis test indicated significant differences between the three treatments ($n = 19$; $k = 3$; $H_c = 8.240039$; $H_{0\ 05,\ 19,\ 2} = 5.991$; $0.005 > p > 0.001$; Zar 1984), with the aggregate rank of the silent control (404.5) being substantially different from both HF and LF signal treatments (630 and 618.5, respectively). This was, however, not resolved through the subsequent Tukey-type multiple comparisons analysis, which could not identify a statistically significant difference between any category (Zar 1984). Suspicion that this result was largely driven by more homogenous Farfield mooring data was confirmed when the two subcategories were analysed separately. For the Nearfield data, the Kruskal-Wallis test again indicated significant differences between the three treatments ($n = 19$; $k = 3$; $H = 5.12$; $H_{0.05,\ 19,\ 2} = 5.991$; $0.005 > p > 0.001$; Zar 1984). The subsequent Tukey-type multiple comparisons analysis confirmed that there was no statistically significant difference between HF and LF signal treatments (aggregate rank scores of 353 and 367.5 respectively), but that both were significantly different from the silent control (aggregate rank score of 182.5). For the Farfield data, no statistically significant difference between treatments was apparent ($n = 19$; $k = 3$; $H_c = 12.33562$; $H_{0.05,\ 19,\ 2} = 5.991$; $0.010 > p > 0.05$; Zar 1984).

In summary, and acknowledging limited sample sizes and substantial inter-mooring variability, it appears that, close to the sound source (i.e. within 1 km), there was little difference between HF and LF signals in terms of their apparent effect on porpoise detection rates, which in both cases were significantly lower compared to silent control periods. Among more distant Farfield moorings, detection rates across all the treatments were generally higher and the effects of different signals were mixed; in most cases, differences in detection rates were limited and no obvious consistent patterns were observed (Figure 14).

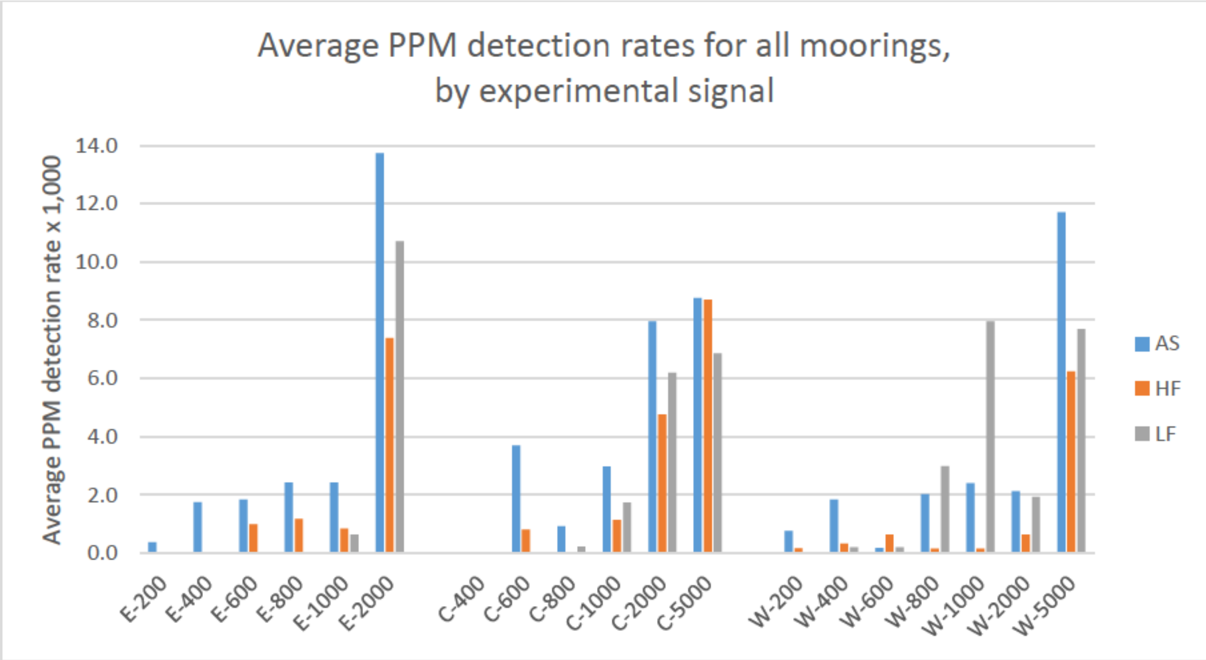

Figure 14. Average PPM detection rates (derived from Table 9, then multiplied by 1,000 for display purposes) across the experimental array under HF signal, LF signal, or Silent control (AS) control treatment.

4.7.2 Cross-array variability

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

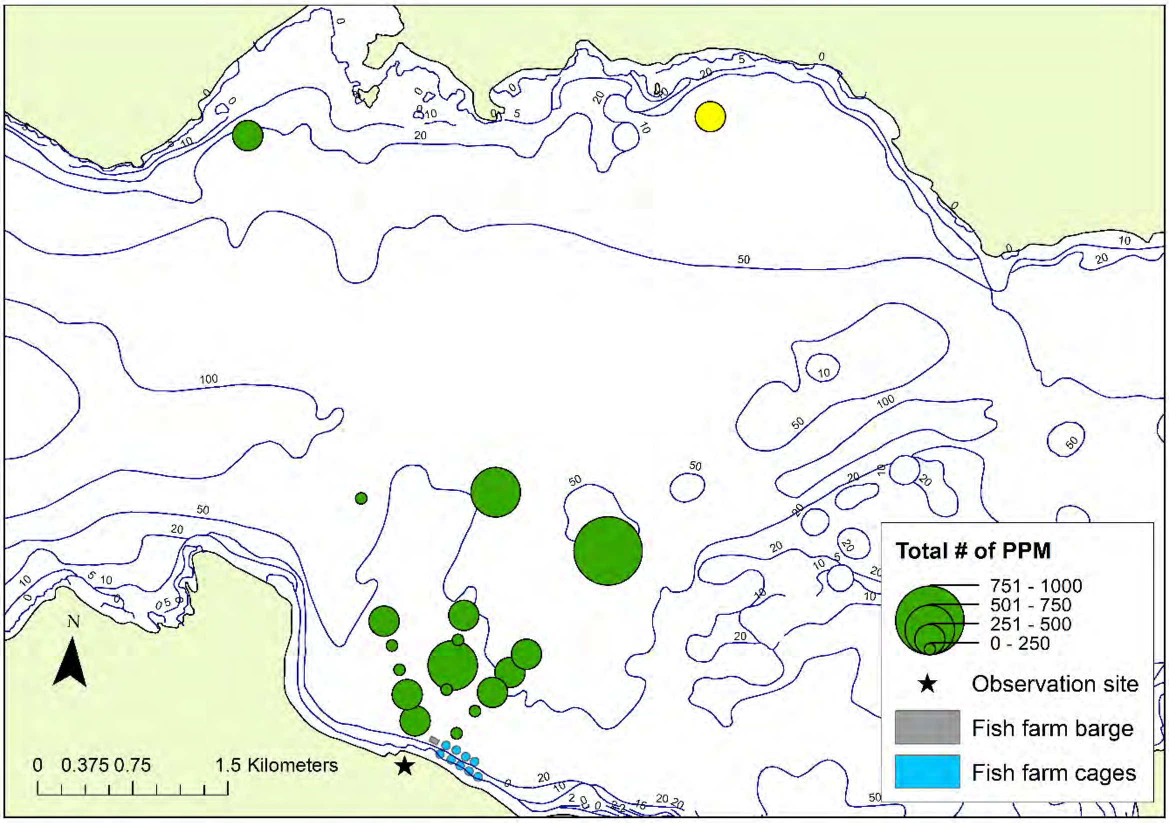

Figure 15. Summary of total numbers of PPMs reported during 8/09-16/10/2016. N.B.: the C-5000 C-POD (top right, yellow) was only operational up to 6/10/2016.

4.7.3 Environmental drivers of variability

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

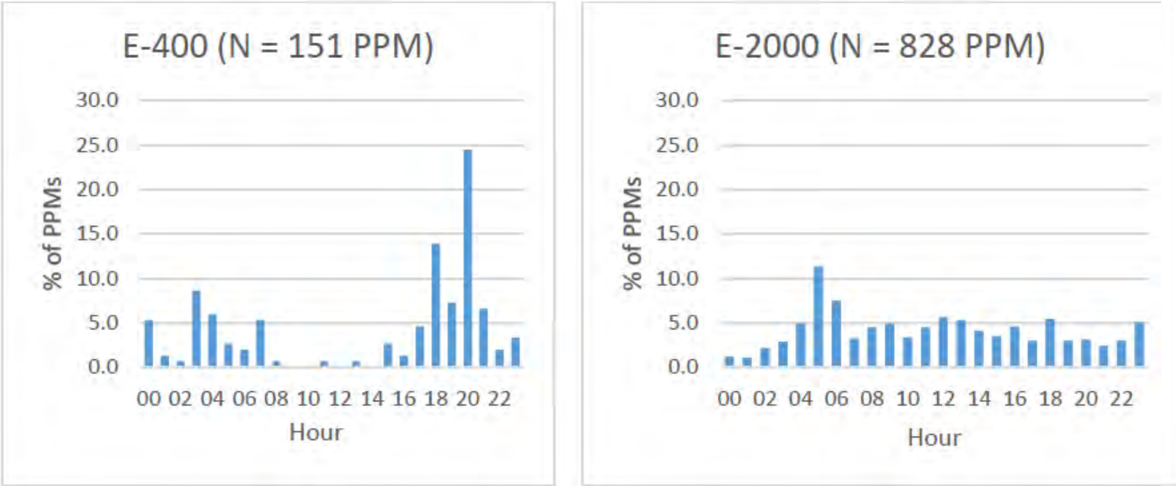

Figure 15. Examples of diurnal patterns of PPM detections from Nearfield (E-400) and Farfield (E-2000) C-PODs (data from 8/09-16/10/2016, aggregated).

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

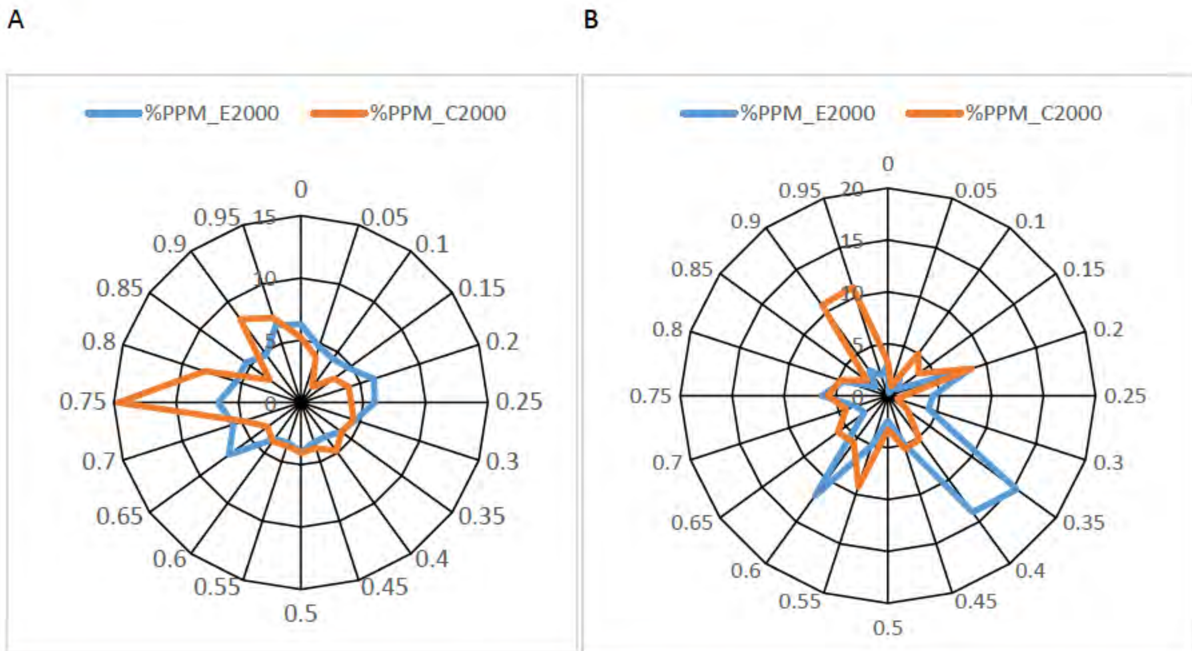

Figure 16. Examples of apparent variability in PPM detection rates at ebb-flood and spring-neap tidal scales. A) Normalised (% of total) PPM detections at locations E-2000 and C-2000 over the ebb-flood tidal cycle (0 = 1 = ebb at Tobermory tidal gauge); B) Normalised (% of total) PPM detections at locations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

4.7.4 Pre- and post-experimental context

C-POD data collected from the fish farm barge prior to the experiment indicated substantially higher average detection rates (0.00670 PPMs/total # of minutes monitored; SE = 0.00135) when compared to data collected by adjacent C-PODs E-200 and W-200 during the experimental period (specifically the silent control; Table 10). The pre-experiment baseline data indicated substantial daily variability in terms of total numbers of PPMs detected, with a decline in daily detection rates during the two weeks prior to starting transmissions (Appendix 2, Figure A2.1A). A strong diel pattern was once again apparent, with >80% of PPMs detected in the 7-hour period between 21:00 – 04:00, and very few PPM detections during daylight hours (Appendix 2, Figure A2.1B).

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

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

4.8 ADVANCED MODELLING

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

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

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

For comparative purposes, only data from September 8 up to October 6 2016, inclusive, were used for this modelling effort, as this facilitated aggregation of data from all moorings (including the abbreviated C-5000 deployment) within larger-scale models. As a result, PPM counts were generally lower than in previous analyses (Table 11).

Table 11. 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

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

The GAM-GEE modelling approach used here has allowed the relative significance of different covariates to be determined, thereby providing insight into the relative importance of the experimental signal transmissions versus a range of environmental variables in determining presence of echolocating porpoises. It is, however, important to interpret the modelling results with caution. In particular, each successive covariate included in the models referenced below and in Appendix 5 describes progressively less and less residual variability under the influence of all other previously assessed covariates. The PPM-covariate relationships observed should therefore not be taken out of that multi-covariate context and considered independently.

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

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

- Diel hour (HOUR) and Julian Day (JULDAY) were consistently among the most important covariates for nearly all models, confirming the apparent significance of diel and seasonal cycles in driving small-scale porpoise distribution.
- The spring-neap tidal cycle (SpringNeap) also appeared important in many cases, particularly for moorings further offshore, with ebb-flood tidal cycle (HiLoTide) generally less important.

- Signal_Type (HF vs. LF signals vs. silent control vs. 'other' non-experimental time) was of secondary significance (2^{nd} or 3^{rd} covariate) for a small number of single-mooring models (W-400, E-1000 and W-1000; Appendix 5). Responses were variable, with the greatest likelihood of porpoise detection often associated with periods of silence (either the silent controls or the intermediate non-experimental periods).
- Number of unprocessed clicks detected per minute (Nall_m) was a frequently occurring covariate although its relative importance varied across the array, ranking higher among more distant moorings (e.g. W-2000 and W-5000; Appendix 5).
- Time of Day (DAYTIMENum), a factorial covariate introduced to capture intermediate temporal patterns linked with daylight levels, turned out to be dismissed from most models due to strong collinearity with Diel Hour. In the four single-mooring models where it was retained (C-600, W-1000, E-2000 and C-5000; Appendix 5), all models but one (E-2000) indicated that most residual variability was explained by periods of darkness, particularly Night and Dawn.

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

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

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

5 DISCUSSION

The present experiment did not provide any evidence to support the hypothesis that LF signals impacted harbour porpoise detection rates any less than ‘standard’ HF signals. Instead, porpoise detection rates were, as a rule, greatest during silent control periods and declined similarly during both HF- and LF signal transmissions (Table 10; Figure 13, 14; Appendix 5), suggesting that porpoises were responding to both signal types. This was supported by the nonparametric Kruskal-Wallis test results, which indicated significant differences in porpoise detection rates between, on the one hand, the silent control dataset and, on the other hand, both the LF and HF signal exposure datasets; no statistically significant differences could be determined between the latter two datasets. ADD signals also did not feature as significant covariates in most individual GAM-GEE models (Appendix 5); instead, other factors, notably the day-night cycle, were typically more important in determining harbour porpoise presence. Porpoises appeared to seek out inshore waters after nightfall, with a particular peak around dusk and dawn, whereas open waters in the central Sound of Mull were occupied more consistently. Because so few porpoises were observed at the Bloody Bay fish farm site during daylight hours, no clear trends in porpoises’ immediate surface responses to signal transmission starts could be observed. The surface tracking approach using the SLR camera array was, however, confirmed to work as intended and can provide high-resolution observations if animals can be followed at ranges <1km from the observation site.

The experiment made use of bespoke HF and LF signals, designed to incorporate features of various different ADD types. Also, source levels of both HF and LF signals were lower due to experimental equipment limitations (up to approximately 170 dB re 1 µPa-m RMS, Table 3) than those of commercially available ADDs, which may exceed 190 dB re 1 µPa-m (RMS; Table 1). However, SoundTrap data confirmed that both signals were detectable at the C-5000 mooring, and that the entire area could thus be considered ensonified during all transmission experiments. Porpoises’ apparent responses to exposure to either HF or LF signals, in terms of reduced acoustic detection rates compared to silent control periods, could be explained in several ways, including animals’ ability to detect and respond to higher-frequency harmonics rather than the peak frequency of both signals. However, as Figure 4 illustrates for the tested experimental signals, potential higher-frequency harmonics are at significantly lower levels than the designed fundamental frequencies. Any such responses could potentially be reinforced by more general ‘neophobic’ tendencies to avoid novel stimuli often observed in porpoises (e.g. Dawson et al., 1998).

The observed porpoise detection rates during HF and LF signal transmissions may have been influenced by the fact that harbour porpoises along the west coast of Scotland were almost certainly not naïve in terms of previous ADD exposure. ADDs of one type or another have been used in many parts of western Scotland for many years (e.g. Northridge et al. 2010; Coram et al. 2014), and most porpoises alive today in western Scottish waters are likely to have encountered them regularly during their lives. Although the Bloody Bay fish farm itself is prevented by license from deploying ADDs, porpoises moving along the Sound of Mull would be exposed to numerous ADDs from other farms. The present experiment was set up to gather data around a real, operational fish farm, in the full knowledge of the potential for a degree of habituation towards ADD signals having occurred among western Scottish porpoises. In this light, the observation that both HF and LF ADD signals led to reduced porpoise detection rates relative to silent controls is interesting, as it suggests that any such habituation was at best incomplete. Future tests in areas without ADD-equipped fish farms, elsewhere within Scotland or further afield, would also be informative to better determine differences in responses of (presumed) naïve porpoises to the two signal types (following e.g. Mikkelsen et al. 2017).

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

Seasonal variation in porpoise detection rates, as evidenced by pre- and post-experimental data (Appendix 2), was substantial although its underlying causes remain unclear. The decline in daily porpoise detection rates at least 10 days prior to the commencement of the experiment suggests that, although the presence of artificial ADD signals might have had a negative impact on porpoise activity around the fish farm, this decline was not initiated by the experimental transmissions. The subsequent increase in daily detection rates during winter months was surprising and reinforces the importance of long-term monitoring to capture seasonal/interannual variability. These results indicate that porpoises did not exhibit long-term avoidance of the site following the completion of the experiment. These observations also confirm that porpoises were not deterred by the fish farm infrastructure per se. Official wildlife sighting reports and anecdotal observations collected by SSF staff suggested that porpoises could be observed within a few hundred metres of the Bloody Bay fish farm, although this was not reflected in the visual observations obtained during the experiment. Such observations are supported by reports from elsewhere (e.g. Haarr et al. 2009) suggesting that fish farm infrastructure without ADDs does not lead to long-term habitat exclusion of porpoises. Little is known about how porpoises might make use of marine infrastructure such as fish farms; potential reasons for actively approaching farms might include seeking shelter from storm conditions (as suggested by Haarr et al. 2009), or potentially feeding. Fish farms can attract a variety of wild fish species (e.g. Dempster et al. 2009, 2010), themselves attracted by excess food, fouling organisms on the cage structures etc., and such concentrations of wild fish might attract porpoises (or, indeed, seals; Coram et al. 2014; Callier et al. 2017). Individual porpoises' decisions to seek out the vicinity of fish farms will likely be influenced by animals' body condition, reproductive status, presence of predators, etc. Individuals who are sick, injured, nursing a calf, or otherwise nutritionally impaired may be more likely to seek out fish aggregations near fish farms, if present. Such attraction could inadvertently lead to increased exposure of these individuals to high levels of ADD noise with potential negative consequences (Lepper et al. 2014). Further work is needed to clarify the ecological role of fish farms in terms of their ability to attract harbour porpoise (and other top predators) through mediation of wild fish aggregations (Callier et al. 2017).

Although hampered by the limited number of exposure experiments that were visually observed (Section 4.6), the present results provide no evidence of either HF or LF ADD signal transmissions resulting in noticeably fewer seals being observed in the area around the fish farm. This was not the main focus of the present study and results should therefore be interpreted with caution. Nonetheless, the results presented here did not support the notion that either of the ADD signals used acted as an effective deterrent of seals from the immediate area around the fish farm. The apparently divergent responses of seals and porpoises to both HF and LF signals was contrary to what might have been expected if deterrence was assumed to be solely or largely driven by both groups' hearing capabilities at lower frequencies (e.g. Kastelein et al. 2002, 2010). Similar responses to an artificial ADD signal (resembling the output of a 12-kHz Lofitech unit) were observed by Mikkelsen et al. (2017), suggesting that other factors may be more important in determining time spent by different species in the vicinity of fish farms equipped with ADDs. This feeds into the ongoing discussion of precisely which component(s) of an ADD signal are important in initiating avoidance behaviour (Coram et al. 2014). Direct comparisons with responses to existing ADD types are hindered by continued lack of publicly available testing data. Testing other LF ADDs under rigorous experimental circumstances, as previously proposed (e.g. Northridge et al. 2013; Coram et al. 2014), would allow determination to what extent differences in signal characteristics might influence deterrence efficacy (as has been done by Götz & Janik 2015, 2016).

In summary, the present experiment did not provide any evidence to support the hypothesis that LF signals impacted harbour porpoise detection rates any less than 'standard' HF signals. Instead, the highest PPM detection rates occurred during silent control periods. Comparatively low PPM detection rates corresponding to LF signal transmission suggested that this type of signal was detectable by porpoises, contrary to original expectations. Substantial heterogeneity in PPM detection rates across the array suggested that environmental drivers, rather that ADD signal type, were important in determining spatiotemporal detection patterns. Sample sizes in the Nearfield component of the array immediately adjacent to the fish farm barge were limited for unknown reasons, but thought to be unrelated to the experiment itself.

6 RECOMMENDATIONS

Commercially available ADDs are in widespread use in the Scottish salmon aquaculture sector, but significant fundamental questions remain about the mechanisms and long-term efficacy of such ADDs in terms of their capacity in deterring seals (e.g. Yurk & Trites 2000; Jacobs & Terhune 2002; Quick et al. 2004; SMRU Ltd. 2007; Graham et al. 2009, 2011; Götz & Janik 2010; Harris et al. 2014). At the same time, these ADDs emit substantial amounts of noise pollution into Scotland's coastal waters, which may have both acute and chronic negative effects on cetaceans and other wildlife (e.g. Götz & Janik 2013).

Based on the results described above, and acknowledging substantial variability in detection rates across the array, the present study provides no strong evidence that use of commercial lower-frequency ADDs with signal characteristics similar to those tested would result in significantly reduced acoustic impacts on harbour porpoises, when compared to existing ADD signals. Instead, transmission of both HF and LF signals resulted in significantly reduced porpoise detection rates relative to silent control periods. This effect was most pronounced among the Nearfield moorings, i.e. within 1 km from the sound source. Results from the present study do not support the suggestion that widespread application of currently available lower-frequency ADDs, by themselves, will significantly reduce the risk of negative acoustic impacts on harbour porpoises in Scottish waters. Given these results, a number of recommendations can be made, in decreasing order of priority:

Recommendation # 1 (TOP PRIORITY): The effectiveness of alternative non-acoustic mitigation methods (e.g. appropriate fish husbandry, good net maintenance, improved net tensioning, and stronger net materials) should be investigated. These methods potentially harbour unrealised opportunities for successful mitigation of seal depredation but have not benefited from equivalent attention compared to ADDs. Preferably, and assuming that these methods are at least equally successful in mitigating depredation by seals, the use of one or more of these methods should be promoted over the use of ADDs.

Recommendation # 2: There is a need for improved understanding of ADD use and distribution in Scottish waters, to better document ADD-associated noise pollution in the context of other conservation activities such as the establishment of Marine Protected Areas. This improved understanding is also relevant in the light of other regulatory requirements to report noise pollution (e.g. under the EC Marine Strategy Framework Directive; EC 2008).

Recommendation # 3: If the continued use of ADDs is deemed to be unavoidable, there is a need to consider alternative ADD designs that both reduce overall noise output and are as species-specific as possible. The present study has shown reductions in porpoise detection rates during both LF and HF signal transmissions, implying that merely shifting the signal frequency downwards was insufficient to prevent impacts on porpoises.

Recommendation # 4: If the continued use of ADDs is deemed to be unavoidable, there is a need to:

1) establish definitively whether such ADDs actually work in terms of long-term, effective deterrence of seals,
2) which signal characteristics and/or modes of operation contribute to different ADD models' effectiveness, and
3) which other variables (e.g. time of year, weather, presence of fish farm staff) influence seal depredation events and apparent ADD effectiveness.

The key aim of these enquiries, and any further development of ADD design and/or deployment methods that might result from them, should be the long-term reduction of inadvertent noise pollution resulting from ADD use.

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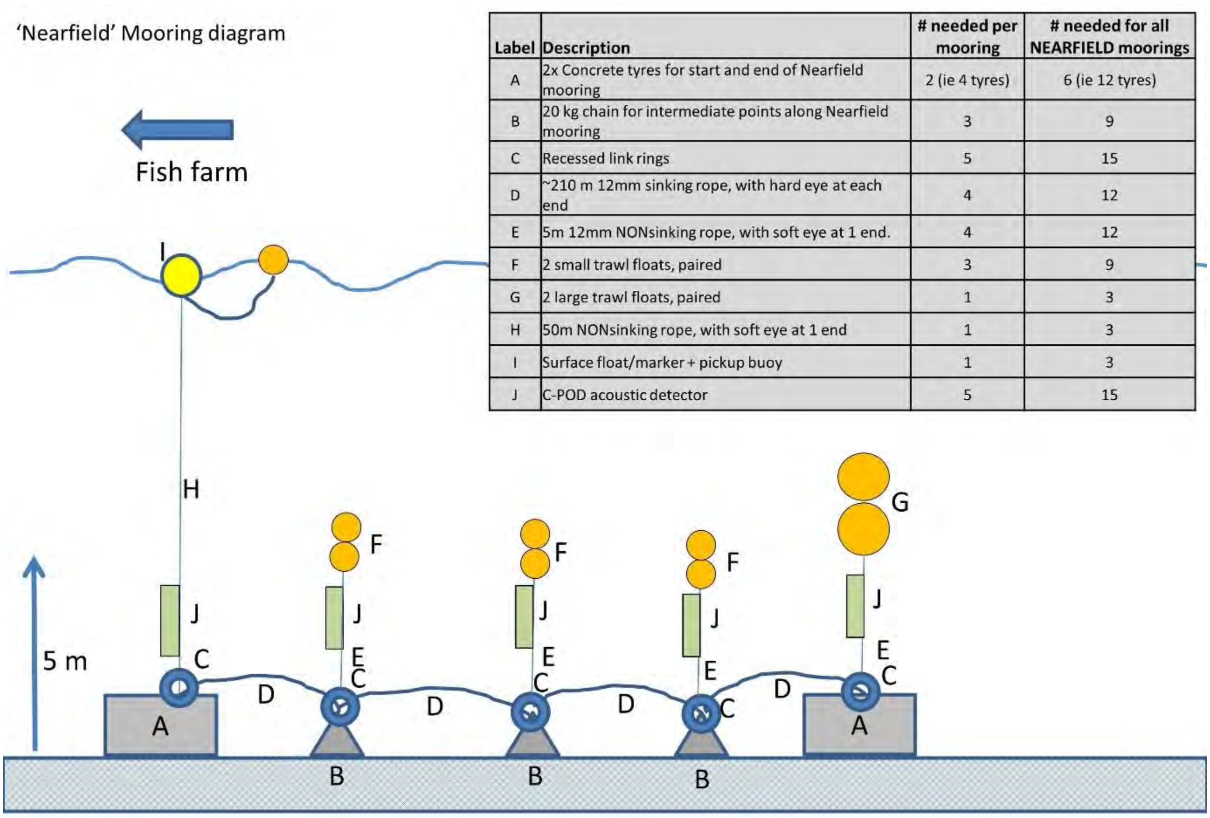
Appendix 1 - Mooring design

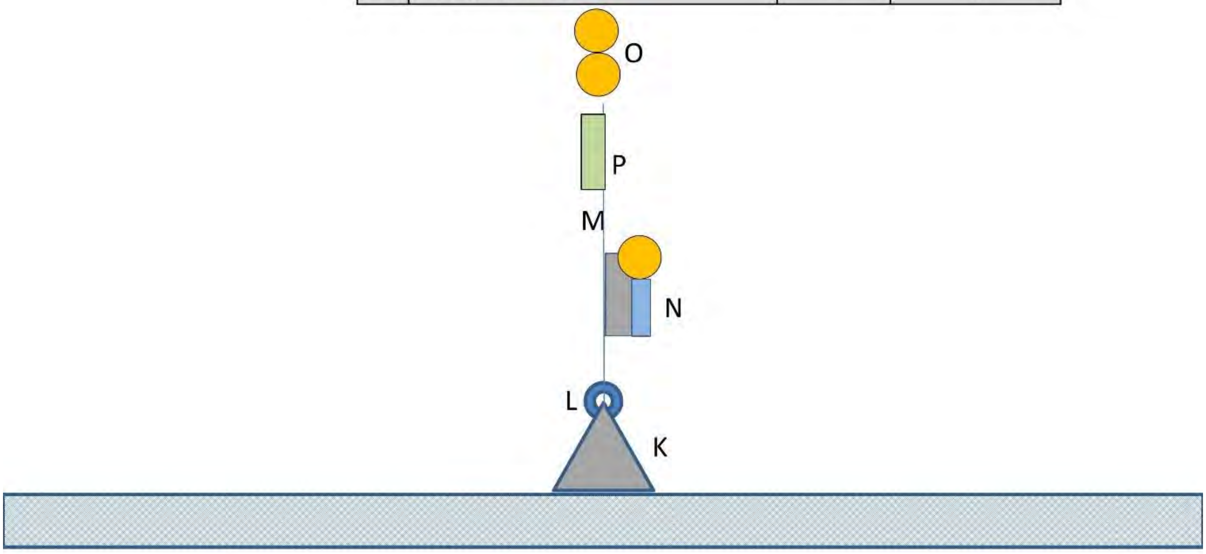
Overview of mooring structures used in Nearfield and Farfield moorings, respectively.



Label	Description	# needed per mooring	# needed for all NEARFIELD moorings
A	2x Concrete tyres for start and end of Nearfield mooring	2 (ie 4 tyres)	6 (ie 12 tyres)
B	20 kg chain for intermediate points along Nearfield mooring	3	9
C	Recessed link rings	5	15
D	~210 m 12mm sinking rope, with hard eye at each end	4	12
E	5m 12mm NONsinking rope, with soft eye at 1 end.	4	12
F	2 small trawl floats, paired	3	9
G	2 large trawl floats, paired	1	3
H	50m NONsinking rope, with soft eye at 1 end	1	3
I	Surface float/marker + pickup buoy	1	3
J	C-POD acoustic detector	5	15

‘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



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.

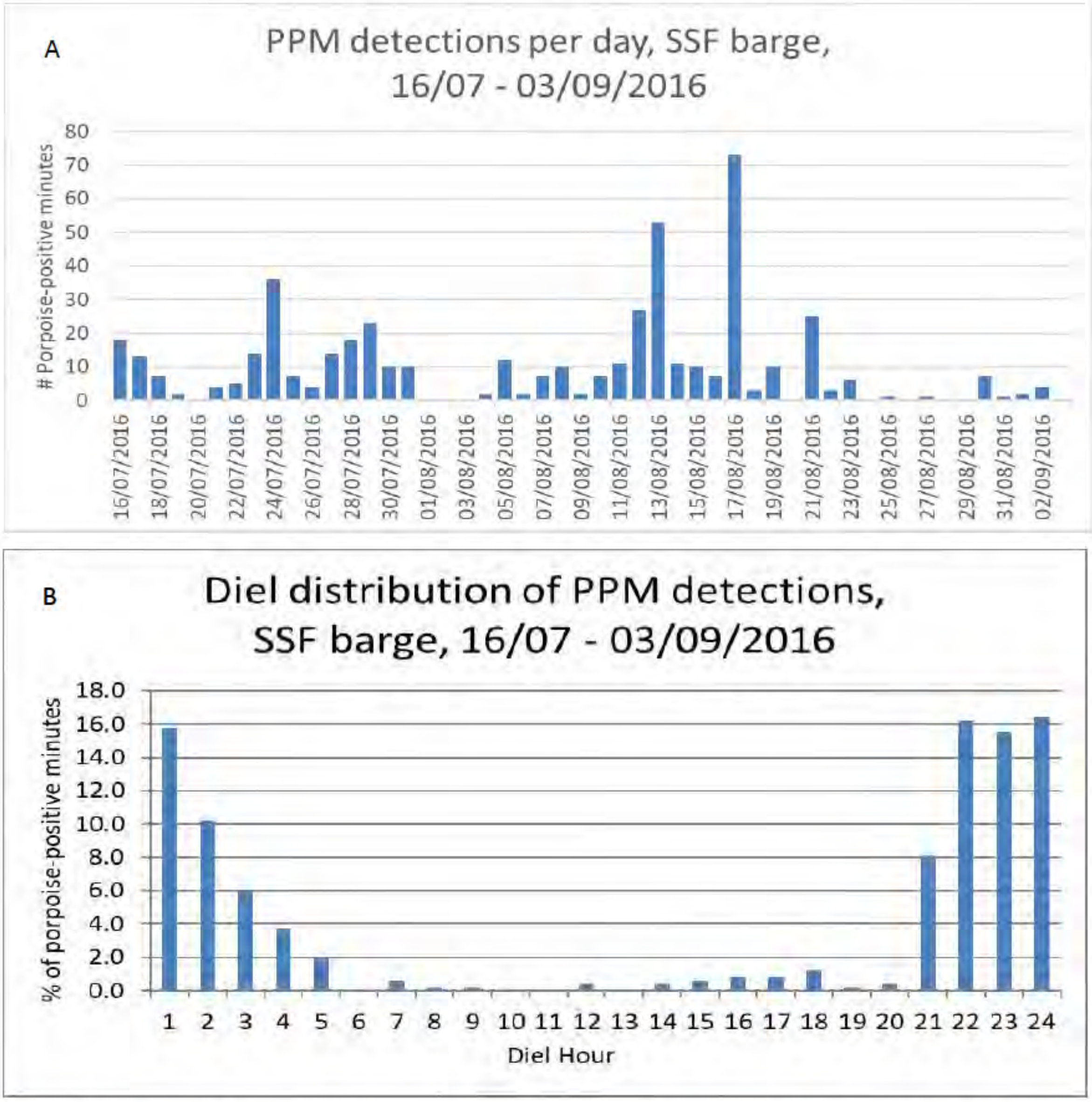


Figure A3.1. A) Overview of overall PPM numbers during pre-experimental deployment at the Bloody Bay fish farm, 16/07 – 3/09/2016 (partial start & end days excluded). B) Overview of distribution of PPMs by hour across a 24-hour day (data aggregated over 16/07 – 3/09/2016 (partial start & end days excluded).

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

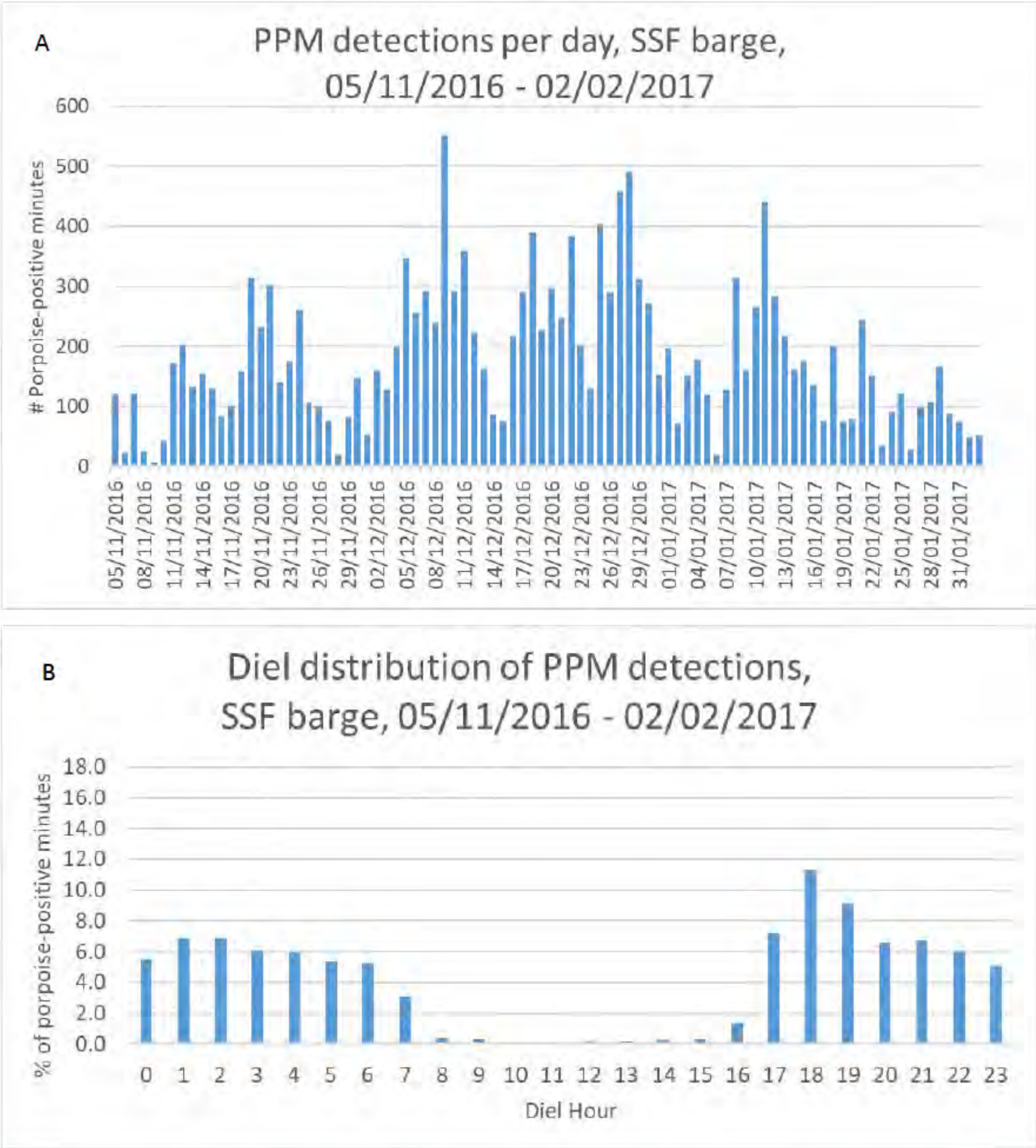


Figure A3.2. A) Overview of overall PPM numbers during pre-experimental deployment at the Bloody Bay fish farm, 05/11/2016 – 02/02/2017 (partial start & end days excluded). B) Overview of distribution of PPMs by hour across a 24-hour day (data aggregated over 05/11/2016 – 02/02/2017 (partial start &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

Appendix 3 - Overview of # PPM/day across array

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 are colour-coded with low values in green and high values in red.

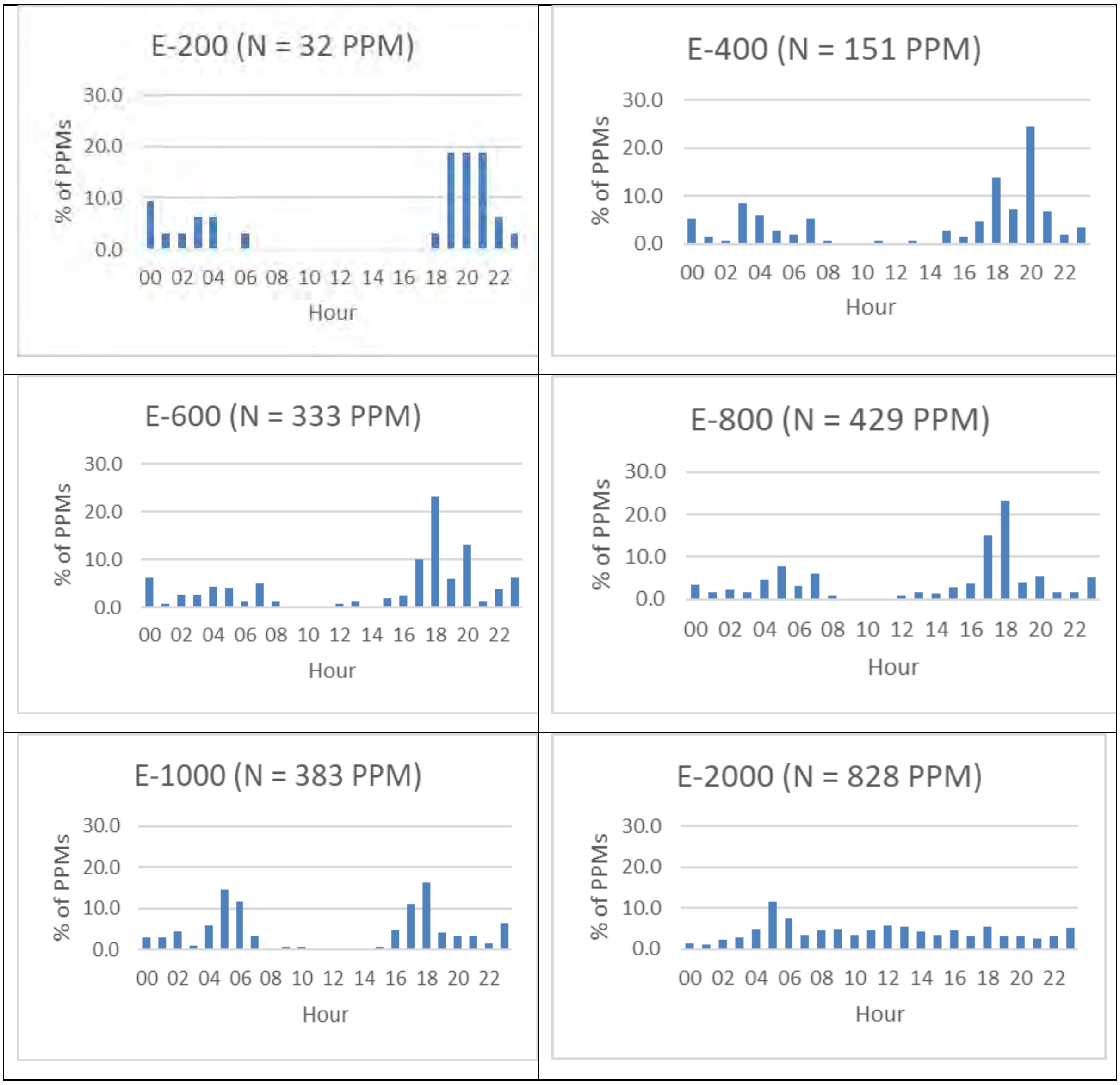
DATE	E-200	W-200	E-400	C-400	W-400	E-600	C-600	W-600	E-800	C-800	W-800	E-1000	C-1000	W-1000	E-2000	C-2000	W-2000	C-5000	W-5000
08/09/2016	0	0	3	3	0	2	0	0	1	0	0	6	6	0	28	0	1	9	18
09/09/2016	0	0	1	1	0	0	0	2	1	0	2	6	2	2	25	5	0	19	18
10/09/2016	0	0	1	1	0	7	1	0	10	0	0	4	5	0	5	10	0	119	55
11/09/2016	0	0	0	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

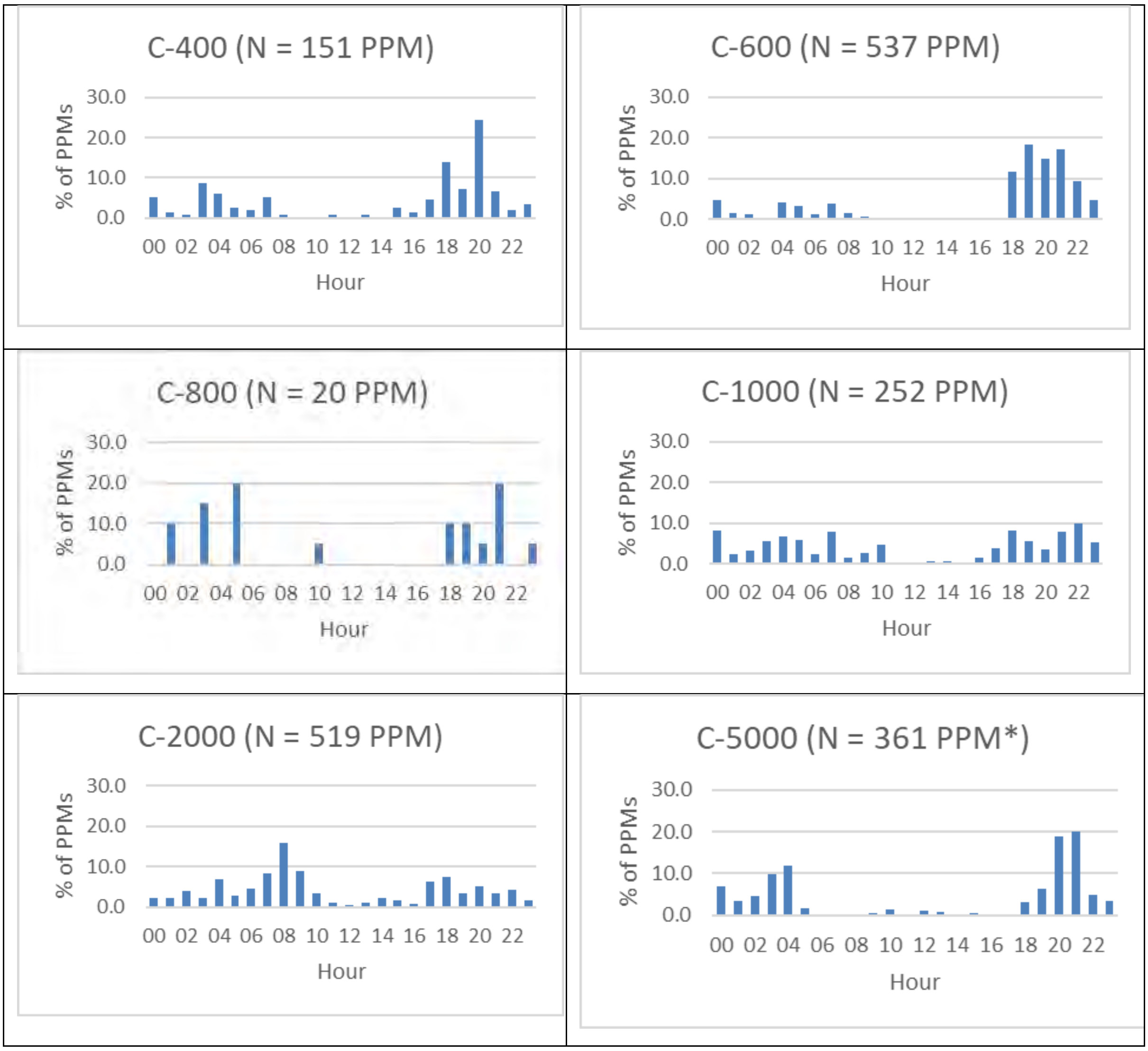
01/10/2016	3	0	2	2	0	1	0	0	3	0	1	3	0	4	4	2	3	1	3
02/10/2016	0	3	3	3	9	4	25	4	14	0	0	7	0	3	4	1	0	4	0
03/10/2016	0	0	0	0	2	0	0	1	1	0	0	1	1	0	0	4	1	20	14
04/10/2016	2	2	2	2	2	6	5	2	3	1	3	10	6	11	11	30	0	22	4
05/10/2016	1	9	2	2	6	3	5	0	0	0	6	0	22	22	19	32	2	7	1
06/10/2016	0	0	1	1	0	0	1	1	1	0	1	1	0	0	10	8	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

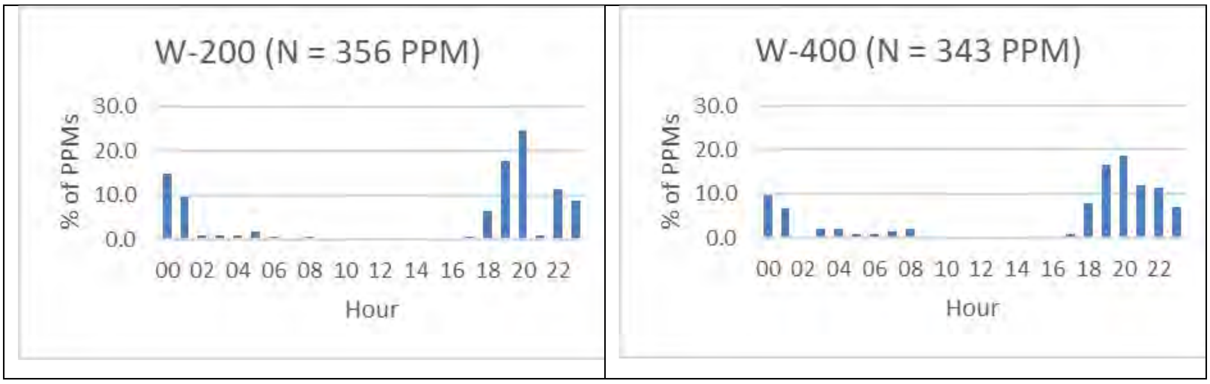
1944

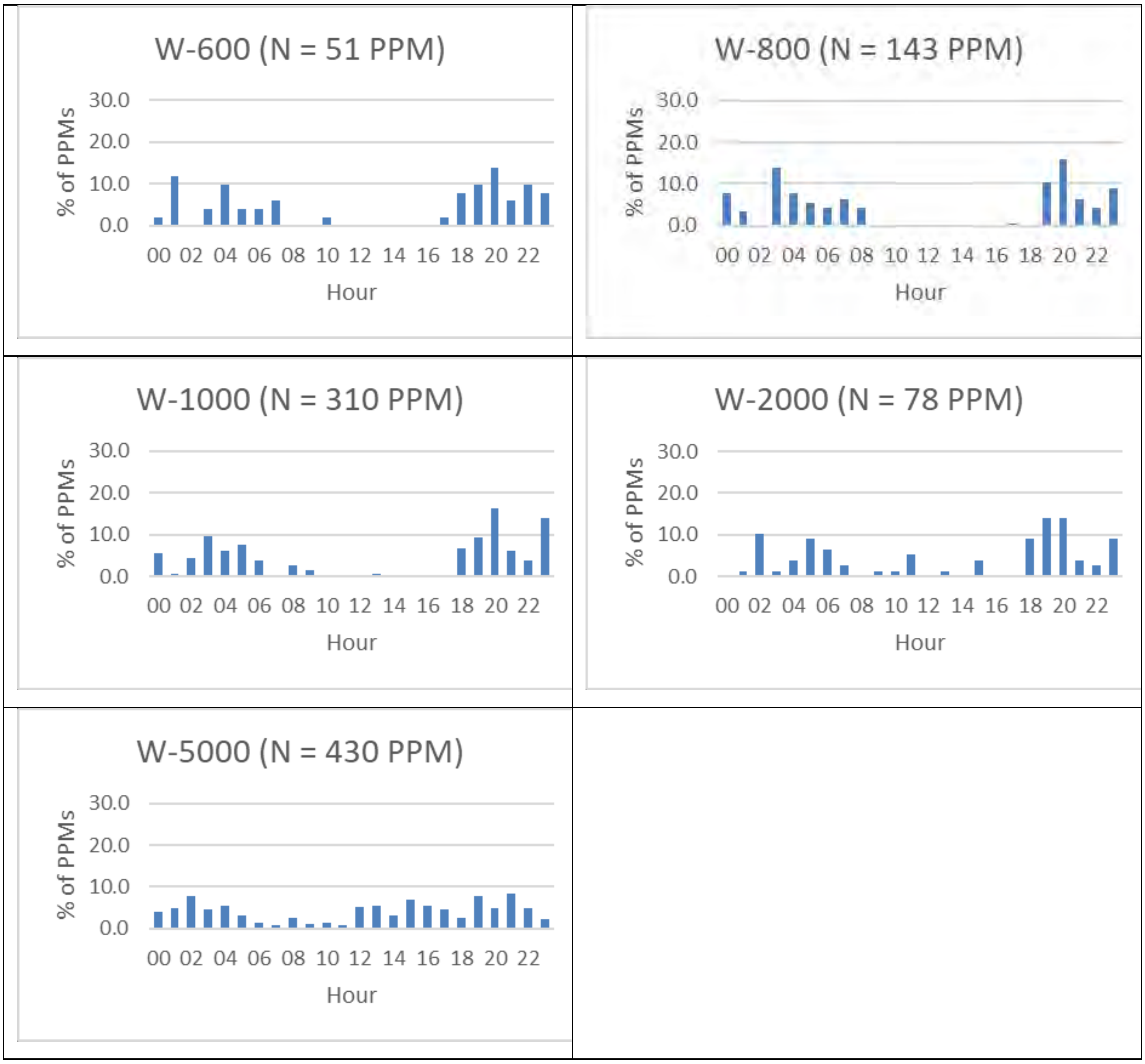
Appendix 4 – Diel variability in PPM detections

The following graphs illustrate, for each mooring, the diel patterns among PPM detections observed throughout the entire experimental period (8/09-16/10/2016). Total numbers of PPMs are indicated for each mooring. Moorings are aggregated according to their presence along the Eastern, Central and Western mooring lines. Detection rates were generally highest at night, particularly during evenings, except for Farfield moorings such as E-2000 and W-5000. *Note that mooring C-5000 was only deployed until 6/10/2016.




C-400 (N = 151 PPM)
% of PPMs
30.0
20.0
10.0
0.0
00 02 04 06 08 10 12 14 16 18 20 22
Hour
C-600 (N = 537 PPM)
% of PPMs
30.0
20.0
10.0
0.0
00 02 04 06 08 10 12 14 16 18 20 22
Hour
C-800 (N = 20 PPM)
% of PPMs
30.0
20.0
10.0
0.0
00 02 04 06 08 10 12 14 16 18 20 22
Hour
C-1000 (N = 252 PPM)
% of PPMs
30.0
20.0
10.0
0.0
00 02 04 06 08 10 12 14 16 18 20 22
Hour
C-2000 (N = 519 PPM)
% of PPMs
30.0
20.0
10.0
0.0
00 02 04 06 08 10 12 14 16 18 20 22
Hour
C-5000 (N = 361 PPM*)
% of PPMs
30.0
20.0
10.0
0.0
00 02 04 06 08 10 12 14 16 18 20 22
Hour


W-200 (N = 356 PPM)
% of PPMs
30.0
20.0
10.0
0.0
00 02 04 06 08 10 12 14 16 18 20 22
Hour
W-400 (N = 343 PPM)
% of PPMs
30.0
20.0
10.0
0.0
00 02 04 06 08 10 12 14 16 18 20 22
Hour


W-600 (N = 51 PPM)
W-800 (N = 143 PPM)
W-1000 (N = 310 PPM)
W-2000 (N = 78 PPM)
W-5000 (N = 430 PPM)
% of PPMs
0.0
10.0
20.0
30.0
00 02 04 06 08 10 12 14 16 18 20 22
Hour

Appendix 5 - GAM descriptors and outputs

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

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

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

*Table A8.1. List of available covariates considered for models. * Indicates covariates that were only considered for compound models.*

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	Broad 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 - intermediate time (no sound); 1 – silent control (no sound); 2 = HF signal; 3 = LF signal	Factor	5

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

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

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

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

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

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

Covariates were plotted independently to visualise the probabilistic relationship between each covariate and the binary response variable (porpoise detection) for each model. Covariates were plotted in declining order of significance in terms of their explanatory power. It is important to reiterate that while GAMs allowed the relative significance of different covariates to be determined, the results should be interpreted with care. Importantly, **less significant covariates’ relationships to the response variable were dependent upon the inclusion of more significant covariates in the**

model, and should therefore be interpreted as explaining residual amounts of variation in the presence of more significant covariates, rather than seen in isolation.

Full array model

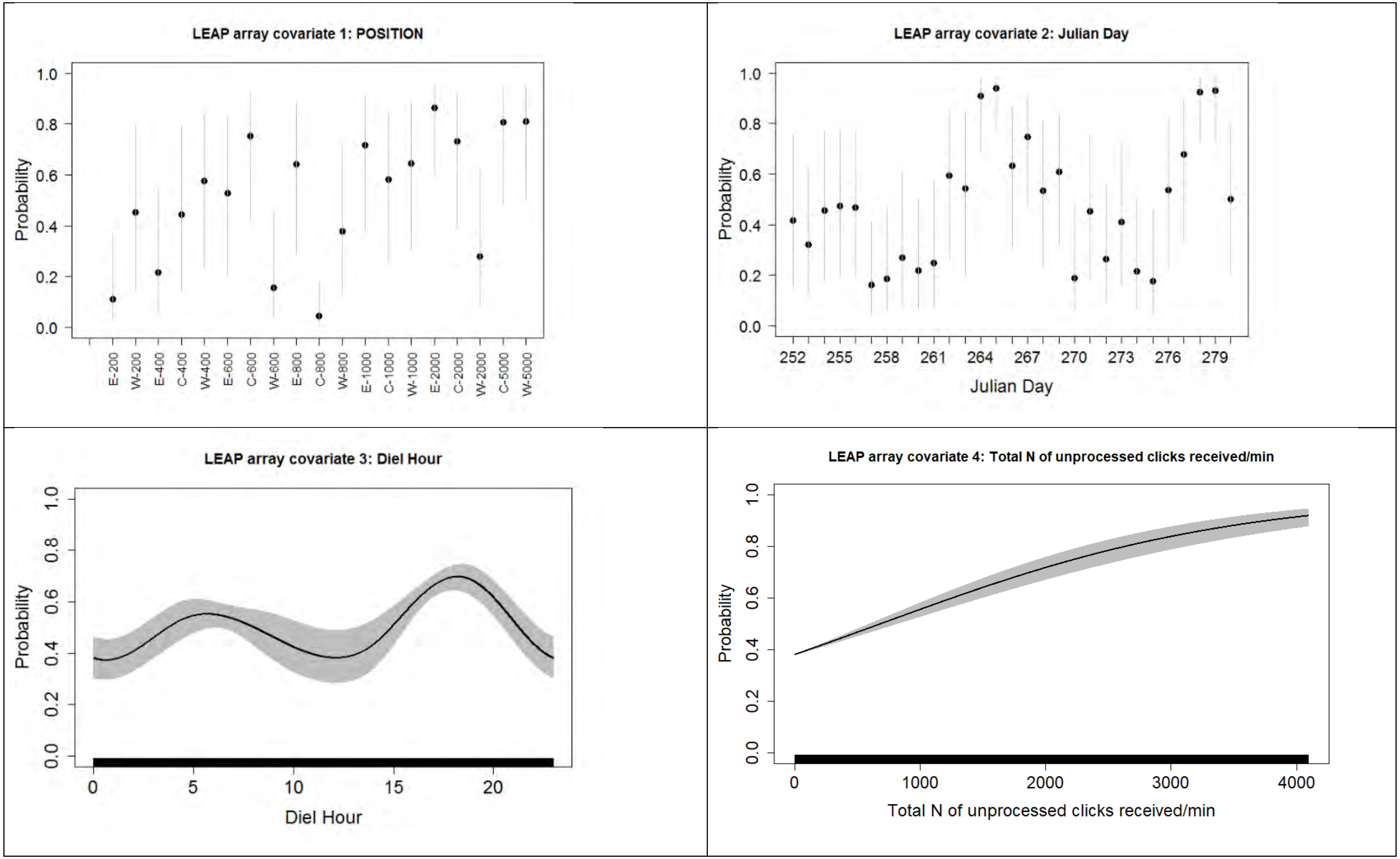
Model:	Entire array
Model structure:	POD2<-geeglm(PPM ~ as.factor(POSITION) + as.factor(JULDAY) + AvgHrBasisMat + Nall_m + as.factor(Signal_Type) + TideBasisMat + as.factor(DAYTIMENum) + SprNpBasisMat, family = binomial, corstr="independence", id=Panel, data=Array)
Confusion matrix:	(see below)
AUC value:	0.8436431

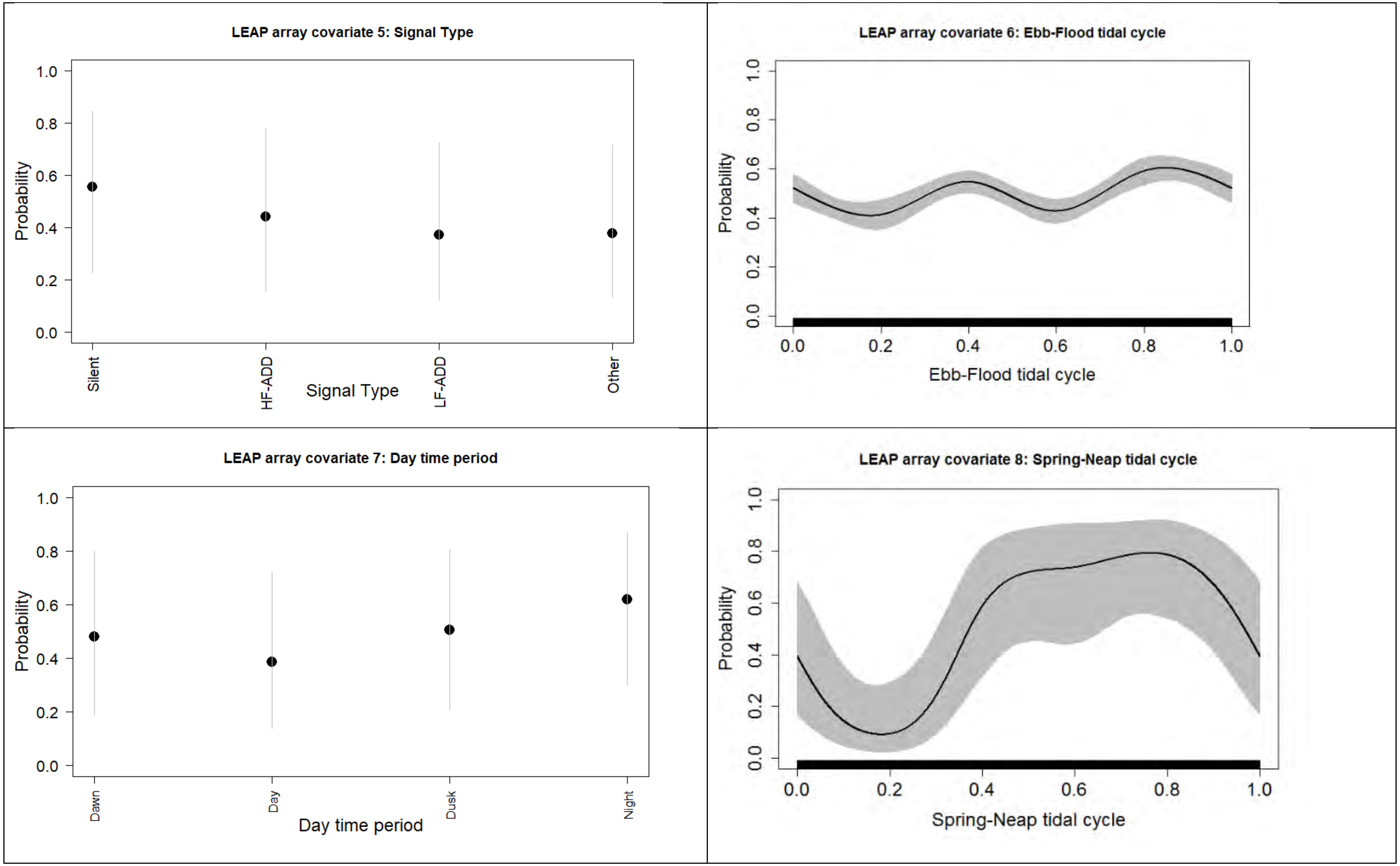
Confusion matrix:

		Expected	
		Porpoise	No porpoise
Observed	Porpoise	81.3%	27.3%
	No porpoise	18.7%	72.7%

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
SpringNeap	Cyclic B-spline	4	11.35	0.022868


LEAP array covariate 1: POSITION
Probability
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
LEAP array covariate 2: Julian Day
Julian Day
LEAP array covariate 3: Diel Hour
Diel Hour
LEAP array covariate 4: Total N of unprocessed clicks received/min
Total N of unprocessed clicks received/min



LEAP array covariate 5: Signal Type
Probability
1.0
0.8
0.6
0.4
0.2
0.0
Silent
HF-ADD
LF-ADD
Other
Signal Type
LEAP array covariate 6: Ebb-Flood tidal cycle
Probability
0.0
0.2
0.4
0.6
0.8
1.0
Ebb-Flood tidal cycle
LEAP array covariate 7: Day time period
Probability
Dawn
Day
Dusk
Night
Day time period
LEAP array covariate 8: Spring-Neap tidal cycle
Probability
Spring-Neap tidal cycle

Nearfield model

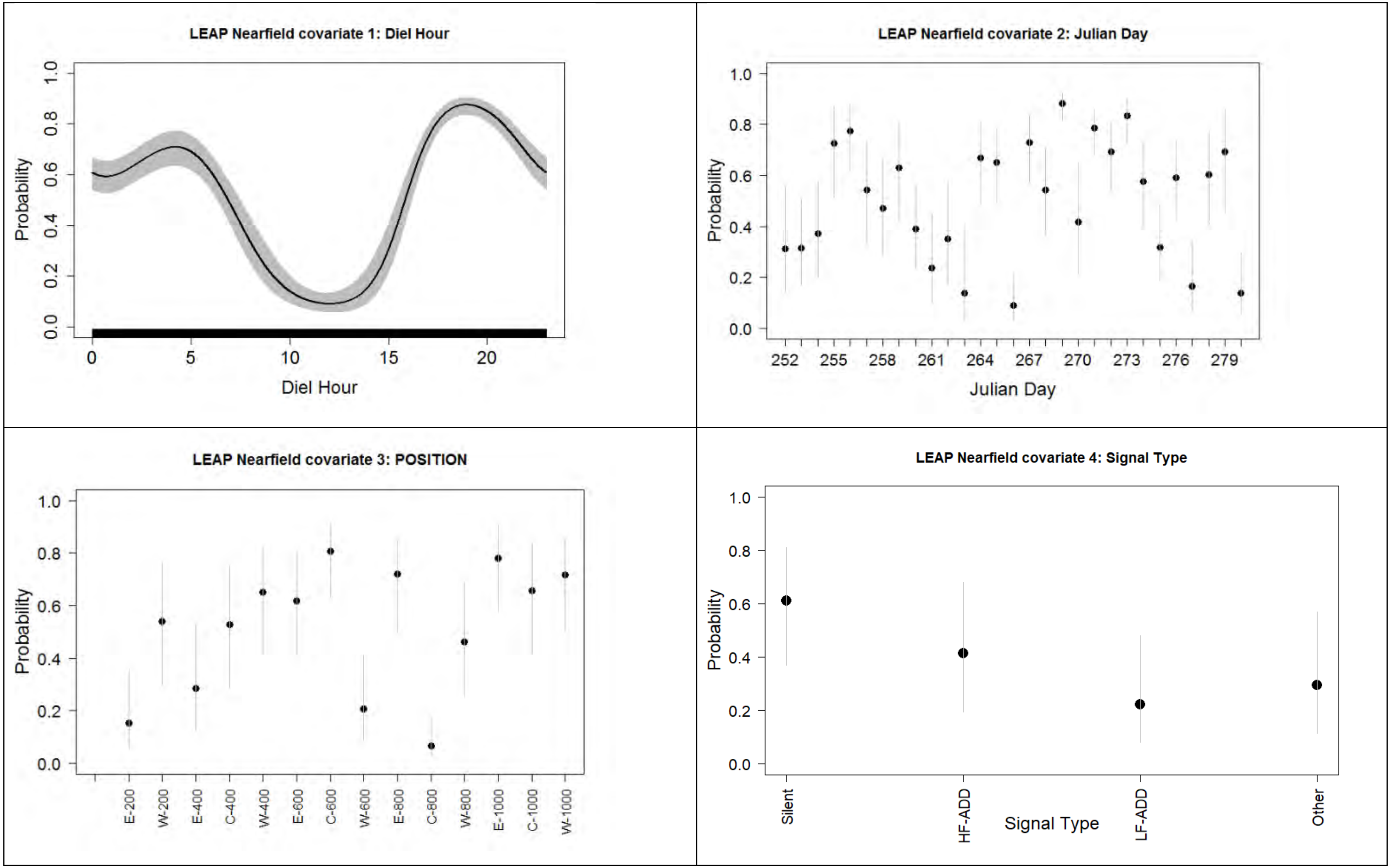
Model:	Nearfield moorings (E-200-E1000, C-400-1000, & W-200-1000)
Model structure:	POD3<-geeglm(PPM ~ AvgHrBasisMat + as.factor(JULDAY) + as.factor(POSITION) + as.factor(Signal_Type) + Nall_m + TideBasisMat, family = binomial, corstr="independence", id=Panel, data=Nearfield)
Confusion matrix:	

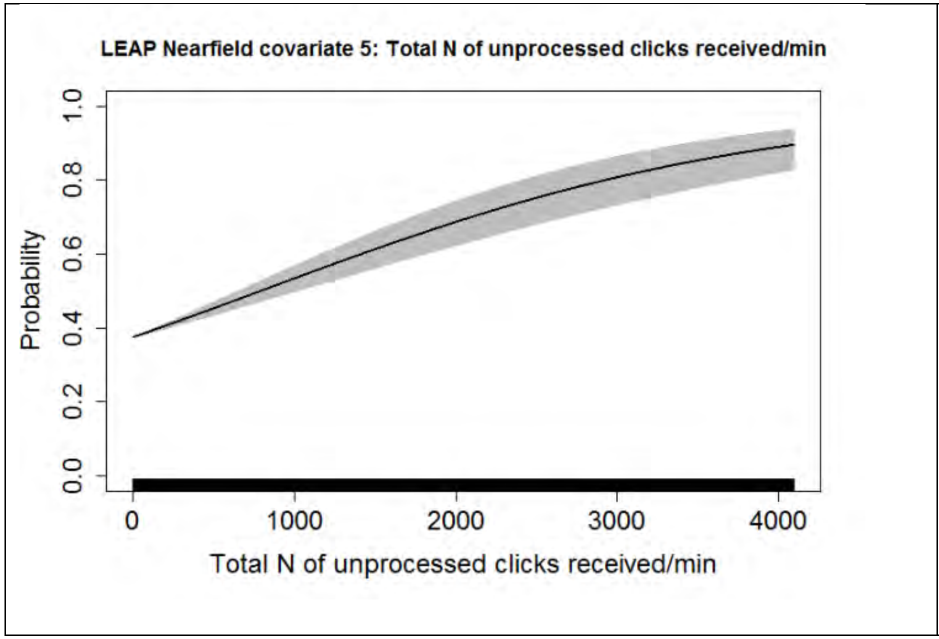
		Expected	
		Porpoise	No porpoise
Observed	Porpoise	80.6%	19.2%
	No porpoise	19.4%	80.8%

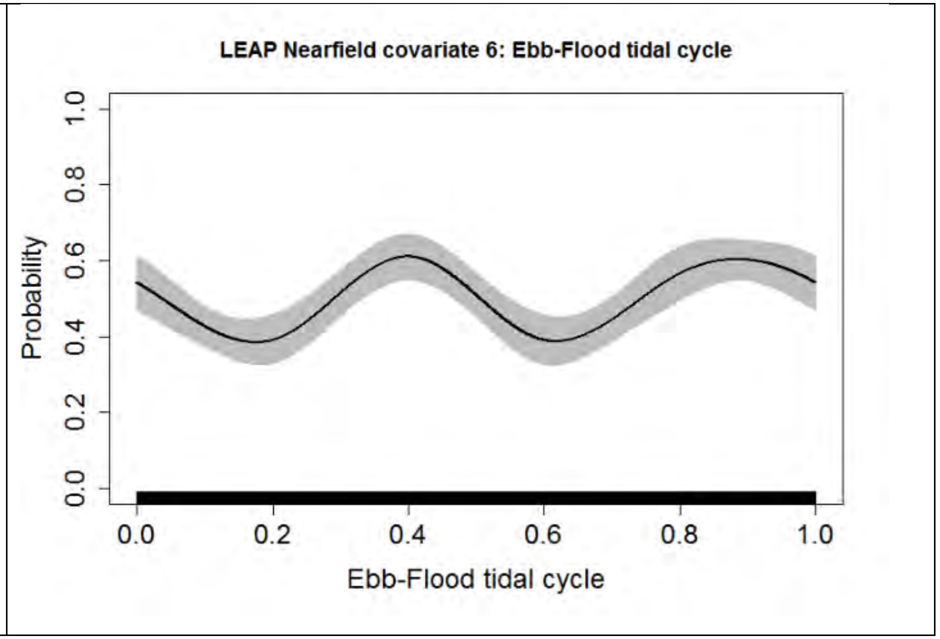
AUC value: 0.8893874

Results of Wald's tests for all significant covariates for the final model:

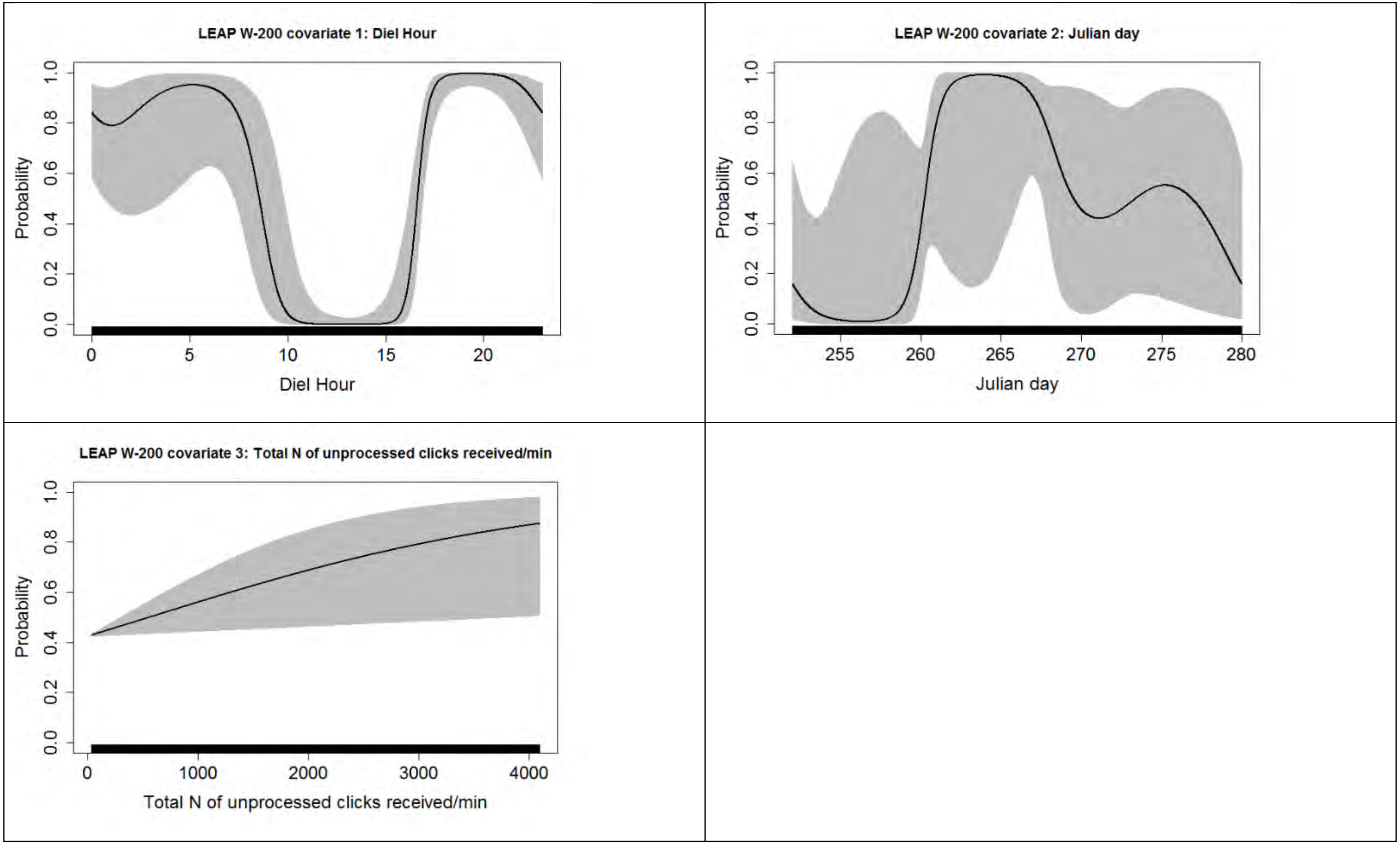
Covariates (in descending order of significance)	Form	Degrees of Freedom	χ^2 score	P-value
HOUR	Cyclic B-spline	4	165.23	$<2.2\cdot10^{-16}$
JULDAY	factor	28	367.38	$<2.2\cdot10^{-16}$
POSITION	factor	13	195.50	$<2.2\cdot10^{-16}$
Signal_Type	factor	3	61.93	$2.272\cdot10^{-13}$
Nall_m	linear	1	73.34	$<2.2\cdot10^{-16}$
HiLoTide	Cyclic B-spline	4	33.07	$1.158\cdot10^{-6}$


LEAP Nearfield covariate 1: Diel Hour
Probability
0.0
0.2
0.4
0.6
0.8
1.0
0
5
10
15
20
Diel Hour
LEAP Nearfield covariate 2: Julian Day
Probability
252
255
258
261
264
267
270
273
276
279
Julian Day
LEAP Nearfield covariate 3: POSITION
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
LEAP Nearfield covariate 4: Signal Type
Silent
HF-ADD
LF-ADD
Other
Signal Type


LEAP Nearfield covariate 5: Total N of unprocessed clicks received/min
Probability
0.0
0.2
0.4
0.6
0.8
1.0
0
1000
2000
3000
4000
Total N of unprocessed clicks received/min


LEAP Nearfield covariate 6: Ebb-Flood tidal cycle
Probability
0.0
0.2
0.4
0.6
0.8
1.0
0.0
0.2
0.4
0.6
0.8
1.0
Ebb-Flood tidal cycle

<table>
<tr><td>Model:</td><td colspan="4">W-200</td></tr>
<tr><td>Model structure:</td><td colspan="4">POD5<-geeglm(PPM ~ AvgHrBasisMat + bs(JULDAY , knots=mean(JULDAY)) + Nall_m, family = binomial, corstr="independence", id=Panel, data=W200)</td></tr>
<tr><td>Confusion matrix:</td><td colspan="4">
<table>
<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>
</td></tr>
<tr><td>AUC value:</td><td colspan="4">0.905853</td></tr>
<tr><td colspan="5">Results of Wald's tests for all significant covariates for the final model:</td></tr>
<tr><td>Covariates (in descending order of significance):</td><td>Form</td><td>Degrees of Freedom</td><td>χ^2 score</td><td>P-value</td></tr>
<tr><td>HOUR</td><td>Cyclic B-spline</td><td>4</td><td>24.6722</td><td>$5.855 \cdot 10^{-5}$</td></tr>
<tr><td>JULDAY</td><td>Cubic B-spline</td><td>4</td><td>9.9928</td><td>0.04055</td></tr>
<tr><td>Nall_m</td><td>linear</td><td>1</td><td>5.3750</td><td>0.02043</td></tr>
</table>


LEAP W-200 covariate 1: Diel Hour
Probability
0.0
0.2
0.4
0.6
0.8
1.0
0
5
10
15
20
Diel Hour
LEAP W-200 covariate 2: Julian day
Probability
0.0
0.2
0.4
0.6
0.8
1.0
255
260
265
270
275
280
Julian day
LEAP W-200 covariate 3: Total N of unprocessed clicks received/min
Probability
0.0
0.2
0.4
0.6
0.8
1.0
0
1000
2000
3000
4000
Total N of unprocessed clicks received/min

Model:	E-400
Model structure:	POD5<-geeglm(PPM ~ AvgHrBasisMat + SprNpBasisMat + Nall_m, family = binomial, corstr="independence", id=Panel, data=E400)

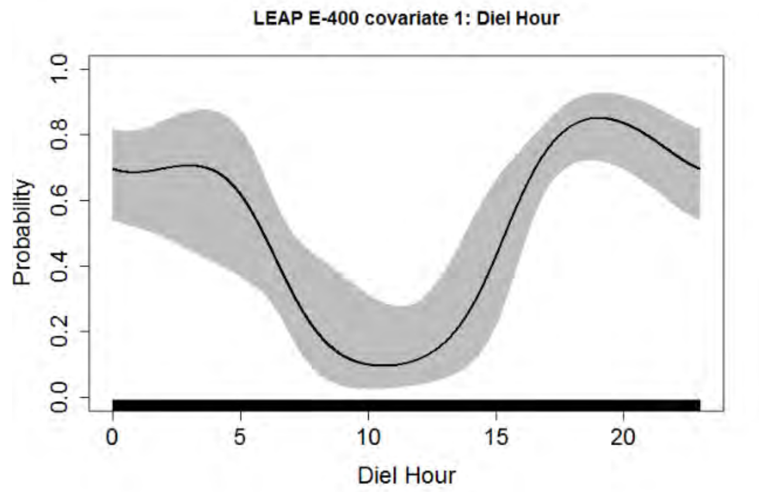
Confusion matrix:

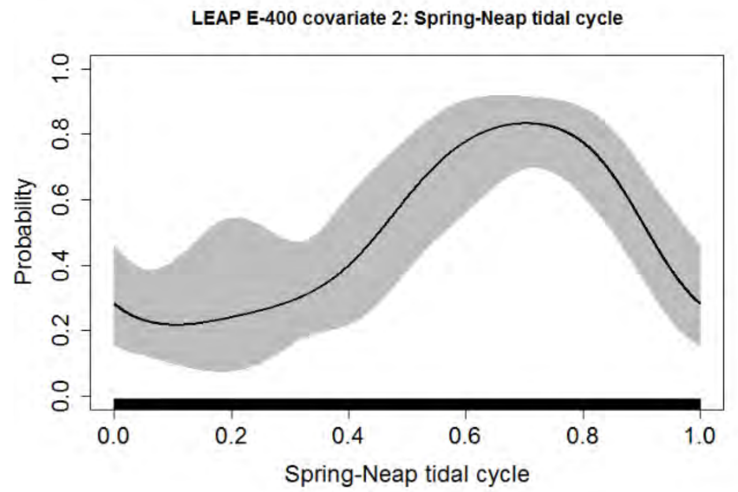
		Expected	
		Porpoise	No porpoise
Observed	Porpoise	74.7%	22.4%
	No porpoise	25.3%	77.6%

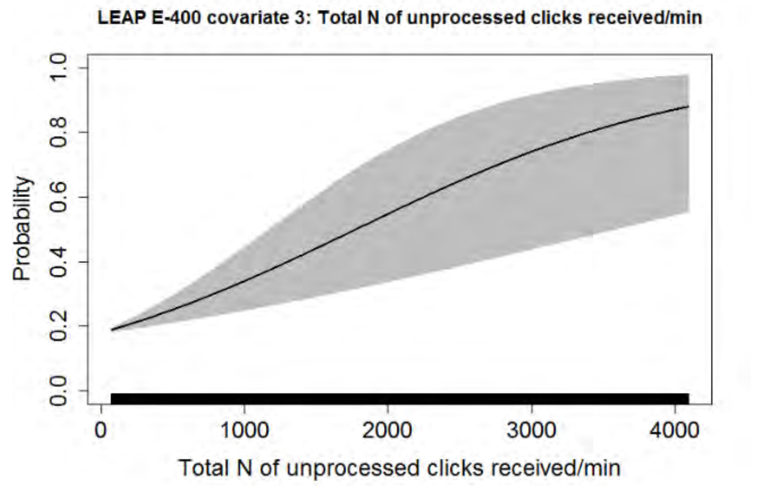
AUC value:	0.8263694

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


LEAP E-400 covariate 1: Diel Hour
Probability
0.0
0.2
0.4
0.6
0.8
1.0
0
5
10
15
20
Diel Hour


LEAP E-400 covariate 2: Spring-Neap tidal cycle
Probability
0.0
0.2
0.4
0.6
0.8
1.0
0.0
0.2
0.4
0.6
0.8
1.0
Spring-Neap tidal cycle


LEAP E-400 covariate 3: Total N of unprocessed clicks received/min
Probability
0.0
0.2
0.4
0.6
0.8
1.0
0
1000
2000
3000
4000
Total N of unprocessed clicks received/min

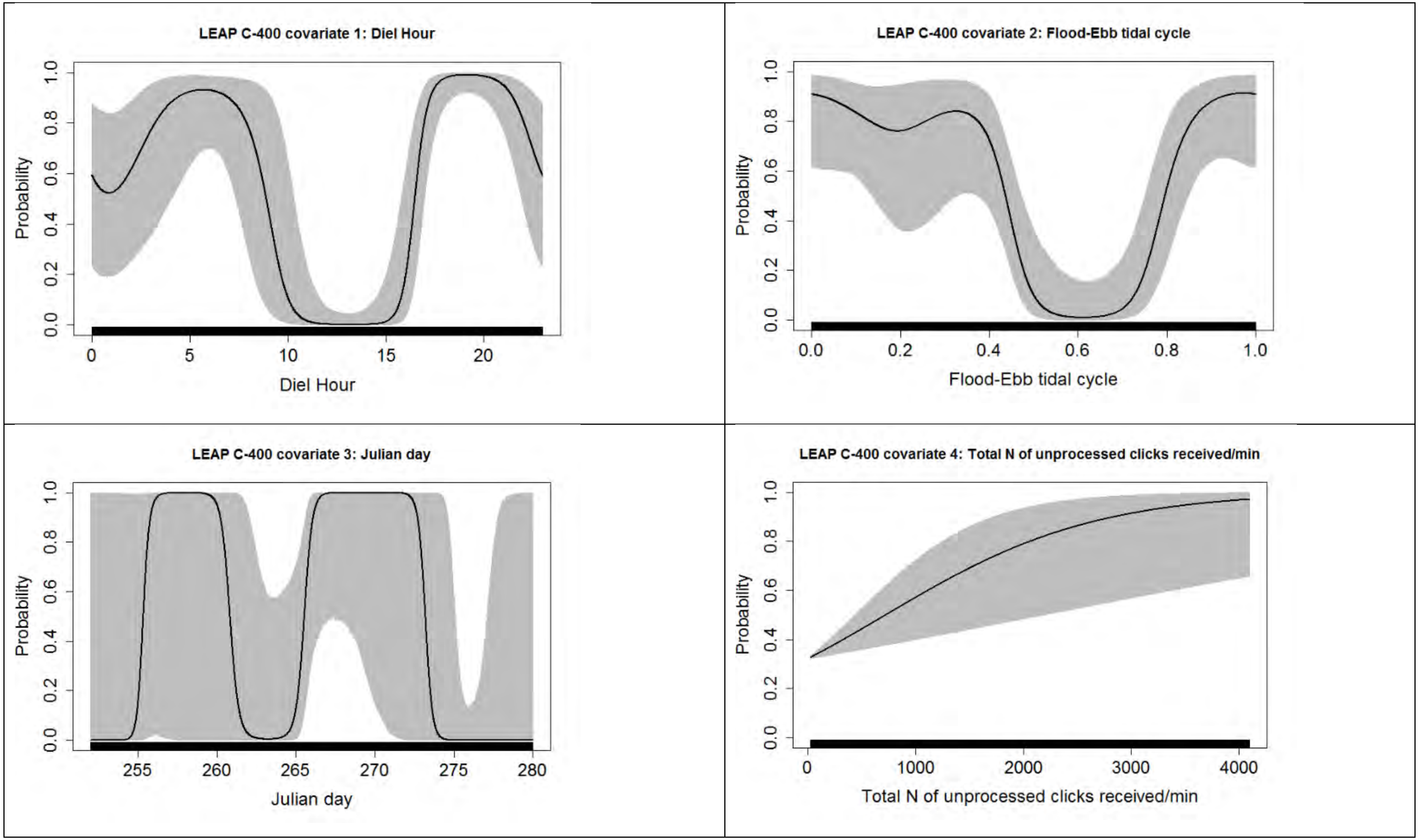
Model:	C-400
Model structure:	POD5<-geeglm(PPM ~ AvgHrBasisMat + TideBasisMat + bs(JULDAY , knots=mean(JULDAY)) + Nall_m, family = binomial, corstr="independence", id=Panel, data=C400)
Confusion matrix:	

		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


LEAP C-400 covariate 1: Diel Hour
Probability
0.0
0.2
0.4
0.6
0.8
1.0
0
5
10
15
20
Diel Hour
LEAP C-400 covariate 2: Flood-Ebb tidal cycle
Probability
0.0
0.2
0.4
0.6
0.8
1.0
Flood-Ebb tidal cycle
LEAP C-400 covariate 3: Julian day
Probability
255
260
265
270
275
280
Julian day
LEAP C-400 covariate 4: Total N of unprocessed clicks received/min
Probability
0
1000
2000
3000
4000
Total N of unprocessed clicks received/min

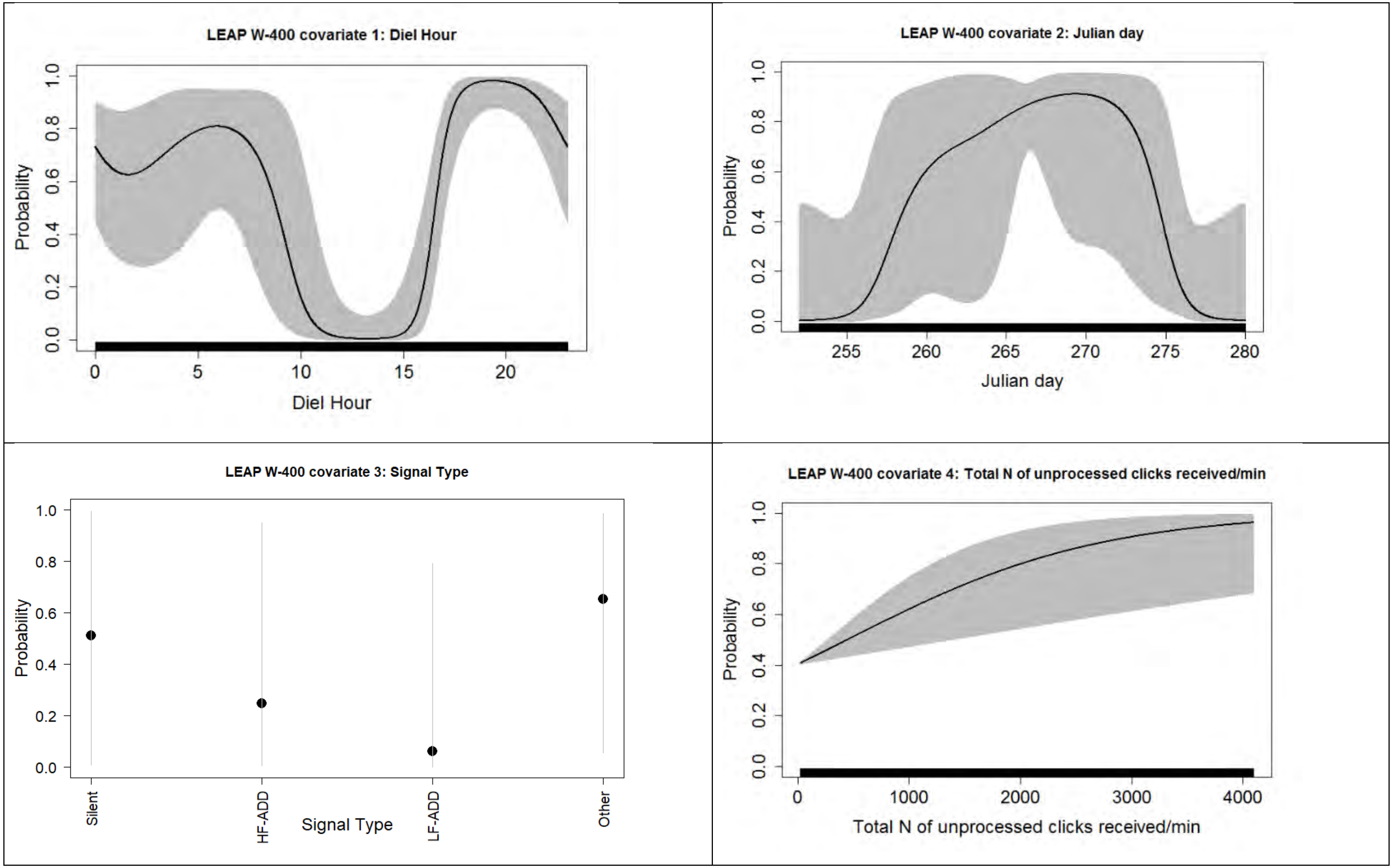
Model:	W-400
Model structure:	POD5<-geeglm(PPM ~ AvgHrBasisMat + bs(JULDAY , knots=mean(JULDAY)) + as.factor(Signal_Type) + Nall_m + TideBasisMat, family = binomial, corstr="independence", id=Panel, data=W400)
Confusion matrix:	

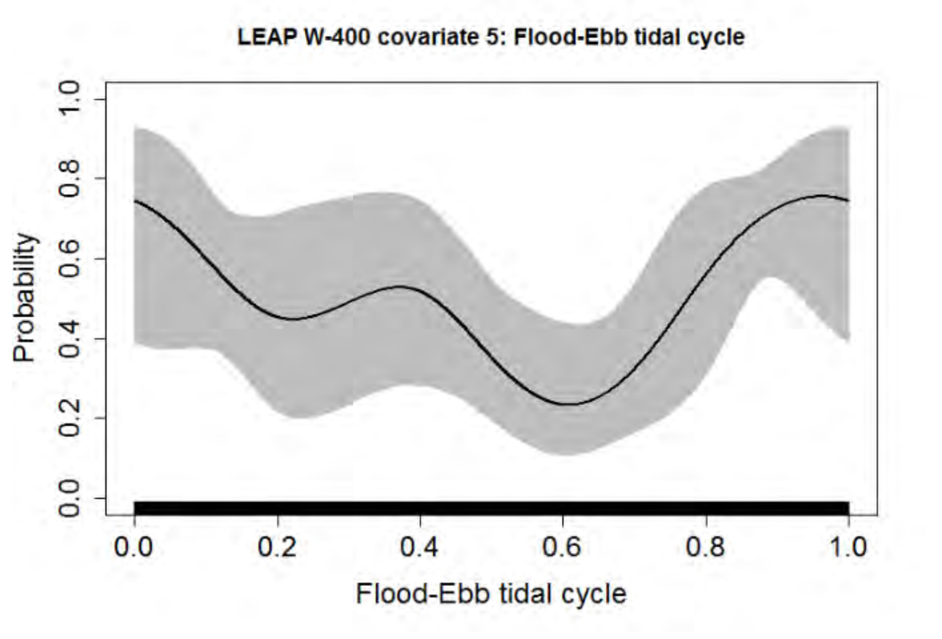
		Expected	
		Porpoise	No porpoise
Observed	Porpoise	88.4%	21.9%
	No porpoise	11.6%	78.1%

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


LEAP W-400 covariate 1: Diel Hour
Probability
Diel Hour
0.0
0.2
0.4
0.6
0.8
1.0
0
5
10
15
20
LEAP W-400 covariate 2: Julian day
Probability
Julian day
255
260
265
270
275
280
LEAP W-400 covariate 3: Signal Type
Probability
Signal Type
Silent
HF-ADD
LF-ADD
Other
LEAP W-400 covariate 4: Total N of unprocessed clicks received/min
Probability
Total N of unprocessed clicks received/min
0
1000
2000
3000
4000


LEAP W-400 covariate 5: Flood-Ebb tidal cycle
Probability
0.0
0.2
0.4
0.6
0.8
1.0
0.0
0.2
0.4
0.6
0.8
1.0
Flood-Ebb tidal cycle

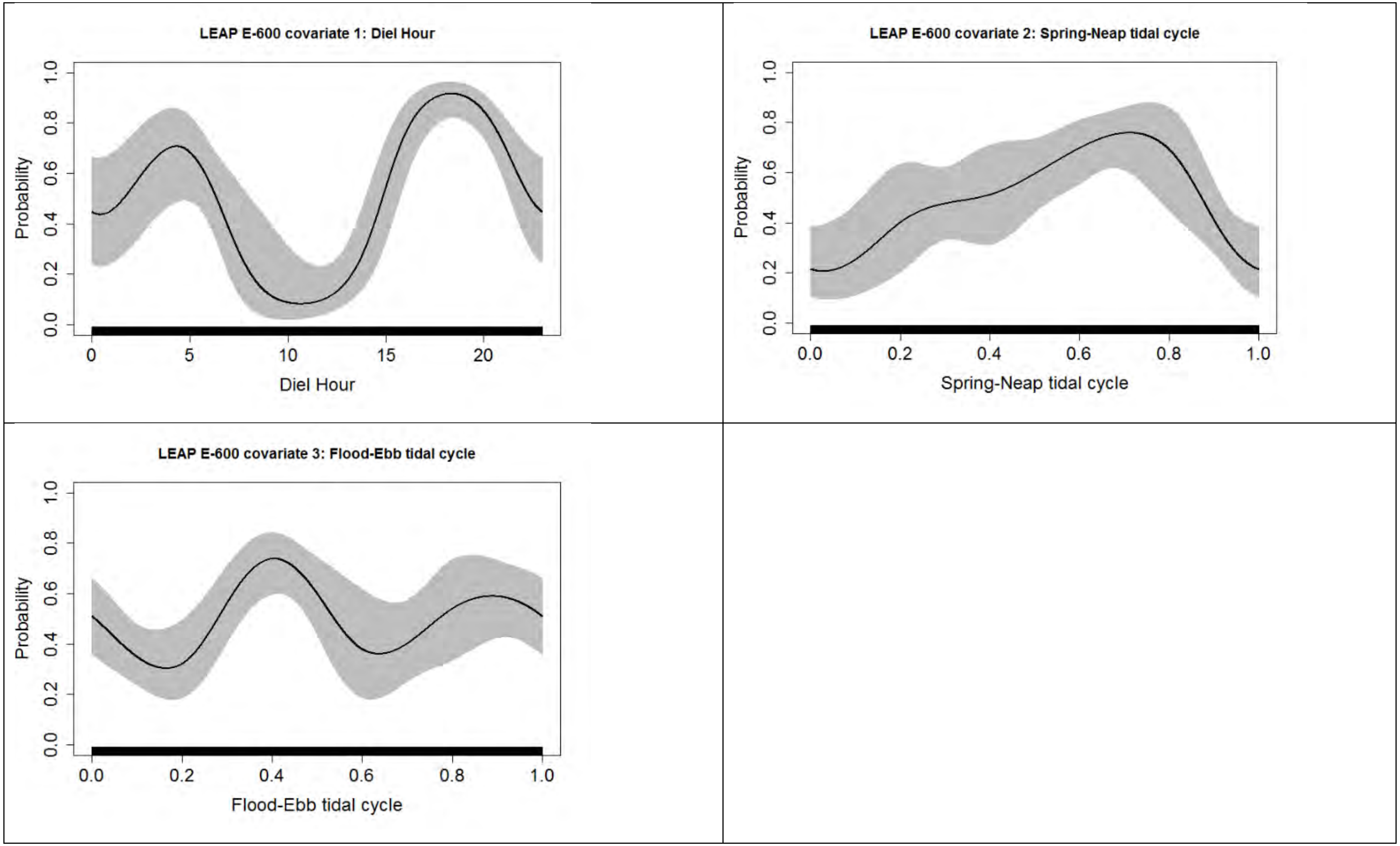
Model:	E-600
Model structure:	POD5<-geeglm(PPM ~ AvgHrBasisMat + bs(JULDAY , knots=mean(JULDAY)) + SprNpBasisMat + TideBasisMat, family = binomial, corstr="independence", id=Panel, data=E600)
Confusion matrix:	

		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


LEAP E-600 covariate 1: Diel Hour
Probability
Diel Hour
LEAP E-600 covariate 2: Spring-Neap tidal cycle
Probability
Spring-Neap tidal cycle
LEAP E-600 covariate 3: Flood-Ebb tidal cycle
Probability
Flood-Ebb tidal cycle

Model:	C-600
Model structure:	POD7<-geeglm(PPM ~ AvgHrBasisMat + bs(JULDAY , knots=mean(JULDAY)) + Nall_m + as.factor(DAYTIMENum), family = binomial, corstr="independence", id=Panel, data=C600)

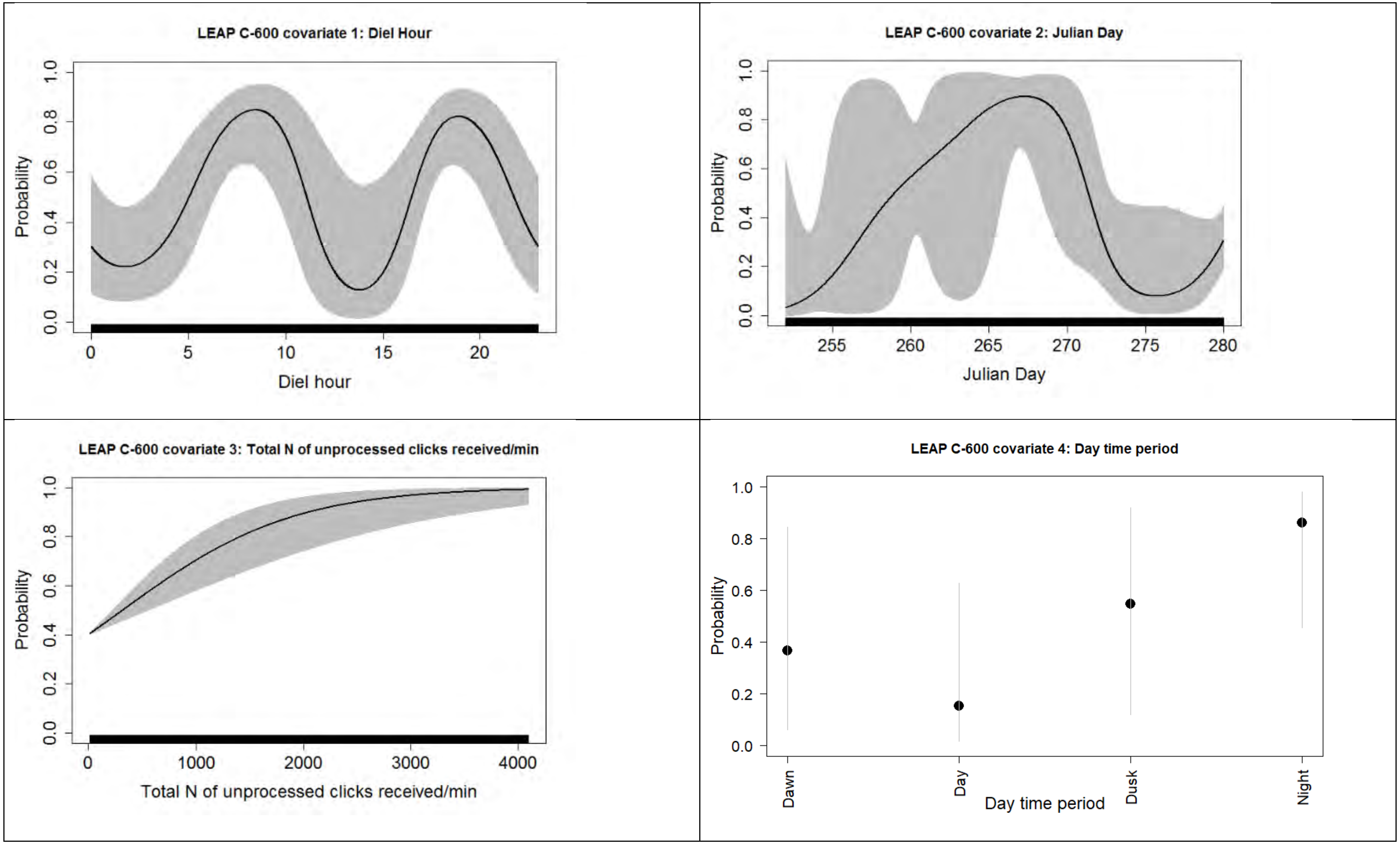
Confusion matrix:

		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


LEAP C-600 covariate 1: Diel Hour
Probability
0.0
0.2
0.4
0.6
0.8
1.0
0
5
10
15
20
Diel hour
LEAP C-600 covariate 2: Julian Day
Probability
0.0
0.2
0.4
0.6
0.8
1.0
255
260
265
270
275
280
Julian Day
LEAP C-600 covariate 3: Total N of unprocessed clicks received/min
Probability
0.0
0.2
0.4
0.6
0.8
1.0
0
1000
2000
3000
4000
Total N of unprocessed clicks received/min
LEAP C-600 covariate 4: Day time period
Probability
0.0
0.2
0.4
0.6
0.8
1.0
Dawn
Day
Dusk
Night
Day time period

Model:	E-800
Model structure:	POD7<-geeglm(PPM ~ AvgHrBasisMat + bs(JULDAY , knots=mean(JULDAY)), family = binomial, corstr="independence", id=Panel, data=E800)

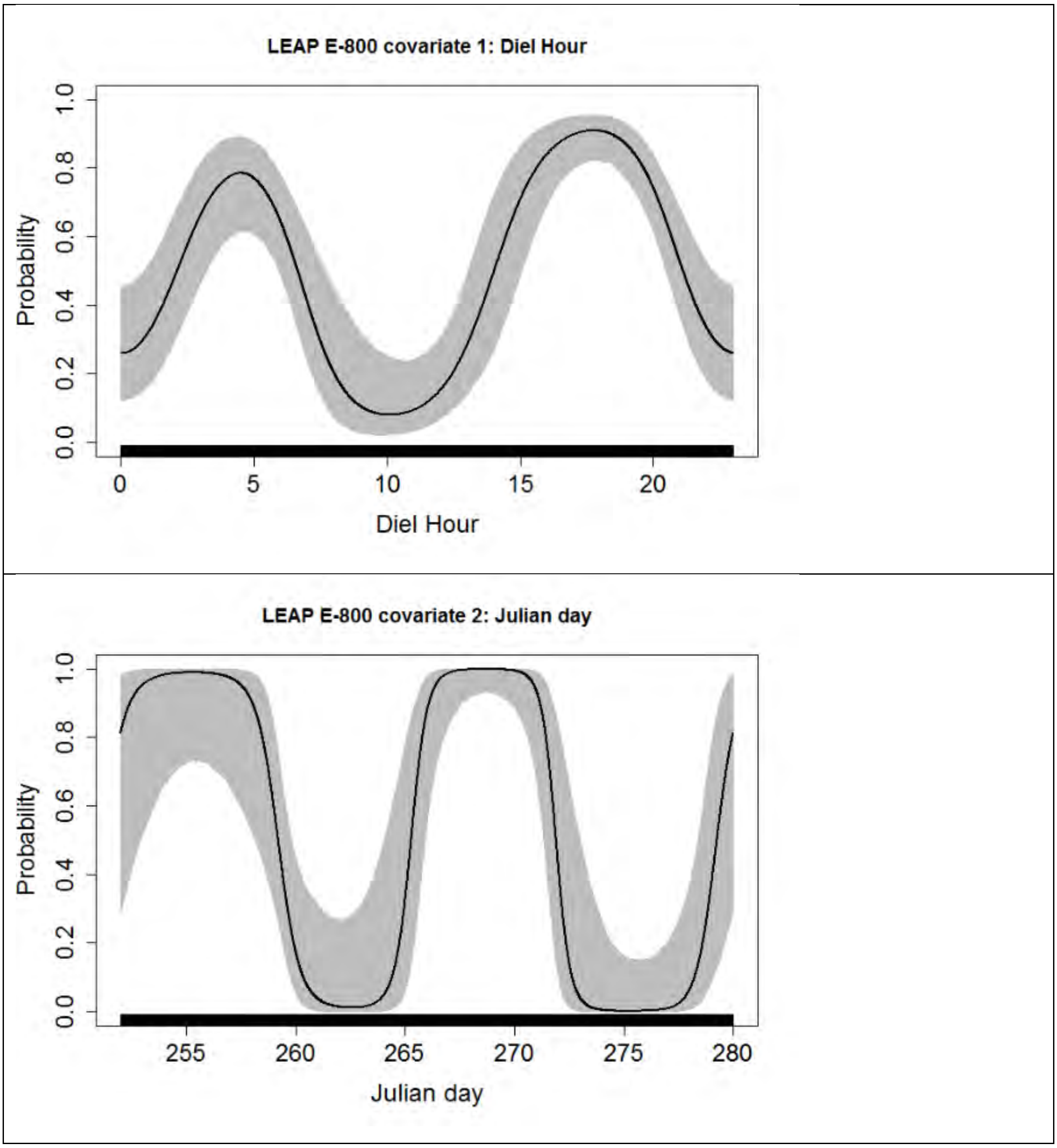
Confusion matrix:

		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


LEAP E-800 covariate 1: Diel Hour
Probability
0.0
0.2
0.4
0.6
0.8
1.0
0
5
10
15
20
Diel Hour
LEAP E-800 covariate 2: Julian day
Probability
0.0
0.2
0.4
0.6
0.8
1.0
255
260
265
270
275
280
Julian day

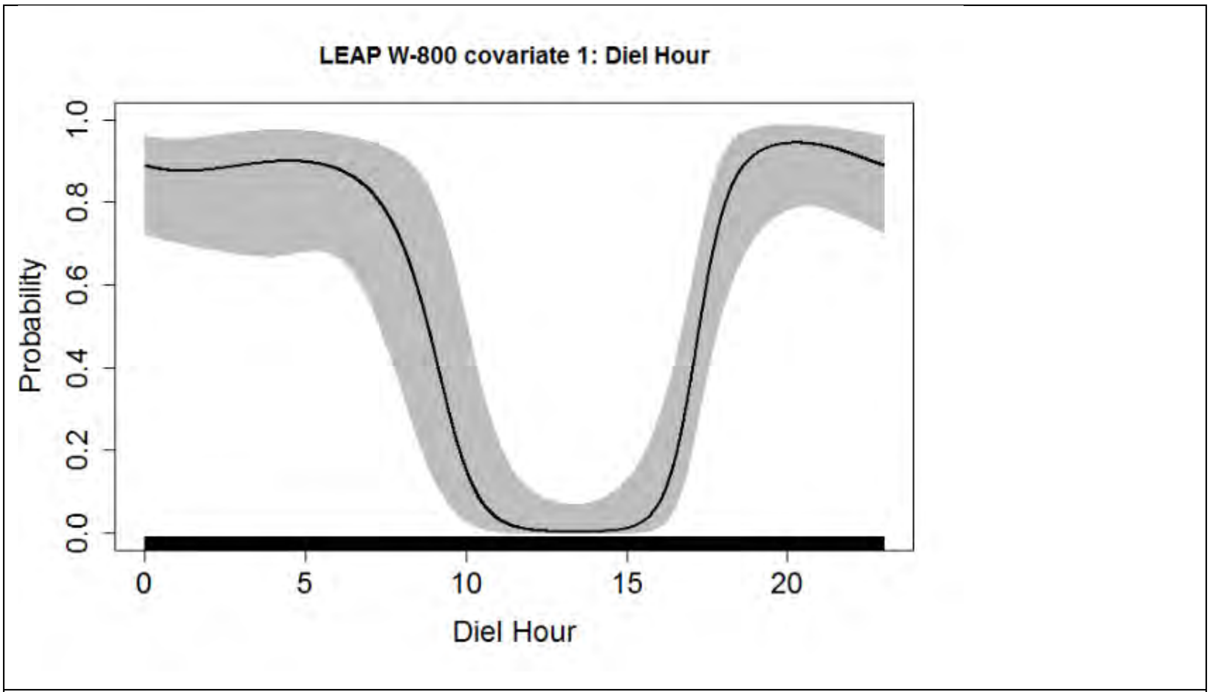
Model:	W-800
Model structure:	POD5<-geeglm(PPM ~ AvgHrBasisMat + Nall_m + as.factor(Signal_Type) , family = binomial, corstr="independence", id=Panel, data=W800)
Confusion matrix:	

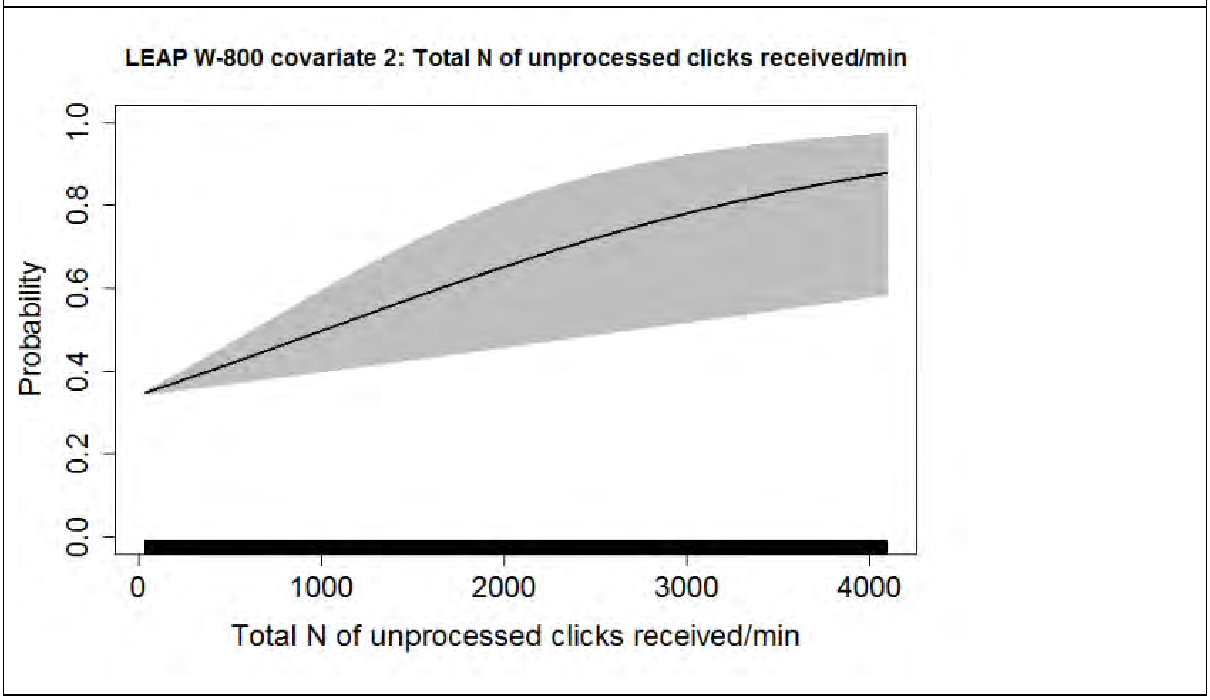
		Expected	
		Porpoise	No porpoise
Observed	Porpoise	90.9%	47.4%
	No porpoise	9.1%	52.6%

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


LEAP W-800 covariate 1: Diel Hour
Probability
0.0
0.2
0.4
0.6
0.8
1.0
0
5
10
15
20
Diel Hour


LEAP W-800 covariate 2: Total N of unprocessed clicks received/min
Probability
0.0
0.2
0.4
0.6
0.8
1.0
0
1000
2000
3000
4000
Total N of unprocessed clicks received/min

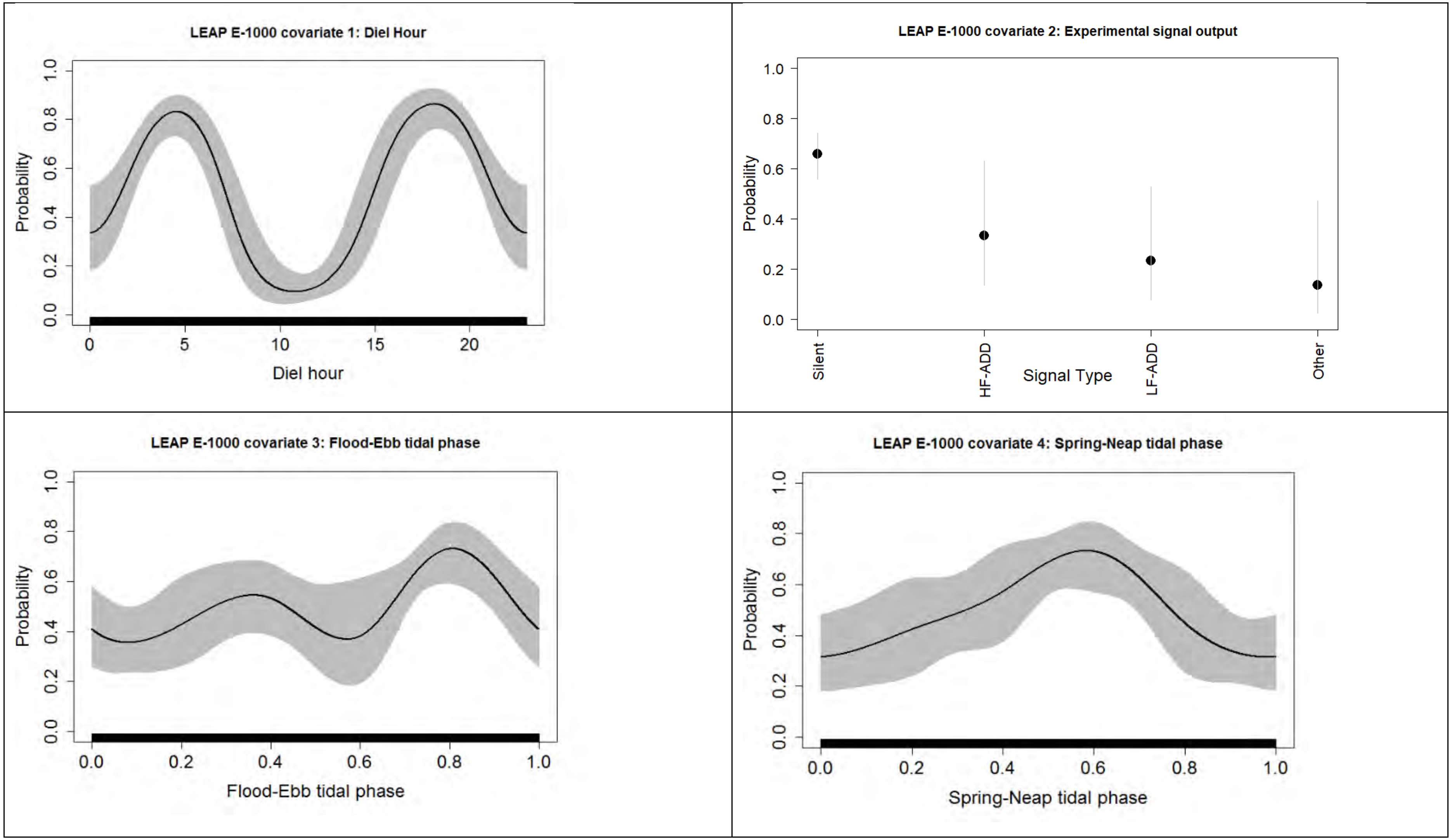
Model:	E-1000
Model structure:	POD4<-geeglm(PPM ~ AvgHrBasisMat + as.factor(Signal_Type)+ TideBasisMat + SprNpBasisMat, family = binomial, corstr="independence", id=Panel, data=E1000)
Confusion matrix:	

		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

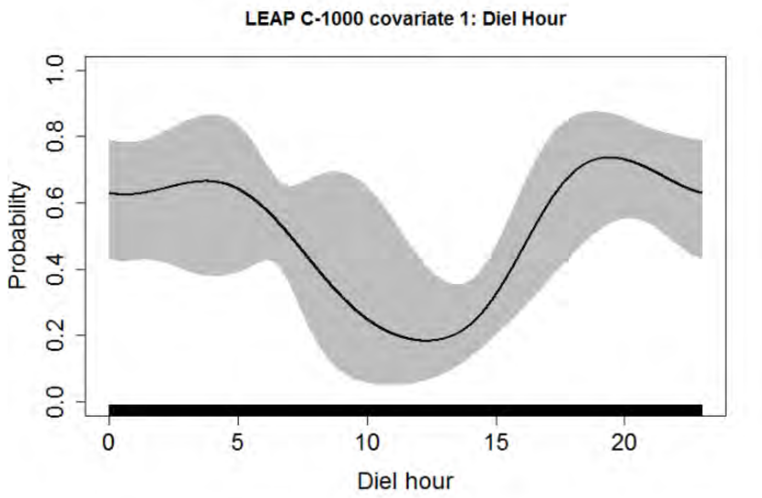


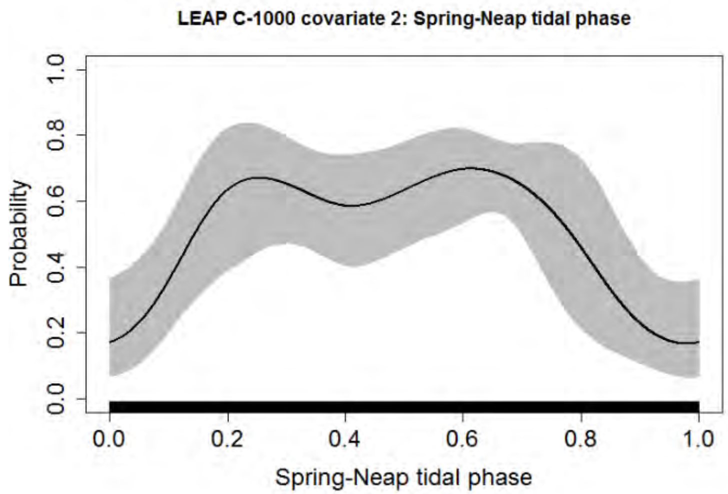
LEAP E-1000 covariate 1: Diel Hour
Probability
0.0
0.2
0.4
0.6
0.8
1.0
0
5
10
15
20
Diel hour
LEAP E-1000 covariate 2: Experimental signal output
Probability
0.0
0.2
0.4
0.6
0.8
1.0
Silent
HF-ADD
Signal Type
LF-ADD
Other
LEAP E-1000 covariate 3: Flood-Ebb tidal phase
Probability
0.0
0.2
0.4
0.6
0.8
1.0
Flood-Ebb tidal phase
LEAP E-1000 covariate 4: Spring-Neap tidal phase
Probability
0.0
0.2
0.4
0.6
0.8
1.0
Spring-Neap tidal phase

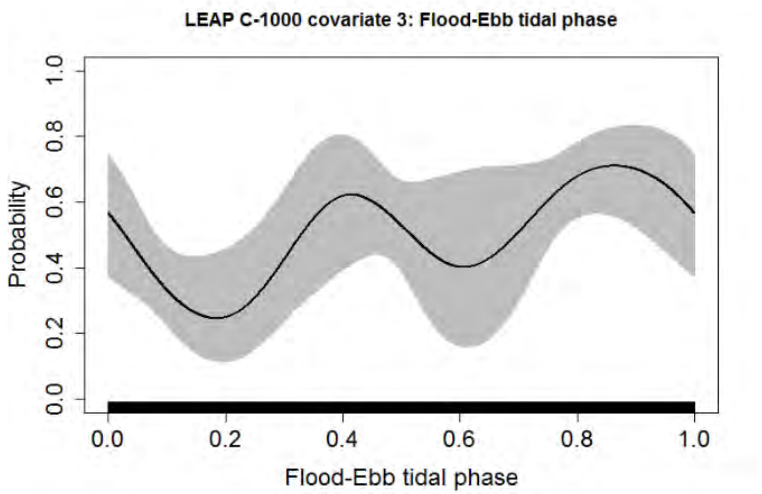
Model:	C-1000
Model structure:	POD5<-geeglm(PPM ~ AvgHrBasisMat + SprNpBasisMat + TideBasisMat, family = binomial, corstr="independence", id=Panel, data=C1000)
Confusion matrix:	

		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


LEAP C-1000 covariate 1: Diel Hour
Probability
0.0
0.2
0.4
0.6
0.8
1.0
0
5
10
15
20
Diel hour


LEAP C-1000 covariate 2: Spring-Neap tidal phase
Probability
0.0
0.2
0.4
0.6
0.8
1.0
0.0
0.2
0.4
0.6
0.8
1.0
Spring-Neap tidal phase


LEAP C-1000 covariate 3: Flood-Ebb tidal phase
Probability
0.0
0.2
0.4
0.6
0.8
1.0
0.0
0.2
0.4
0.6
0.8
1.0
Flood-Ebb tidal phase

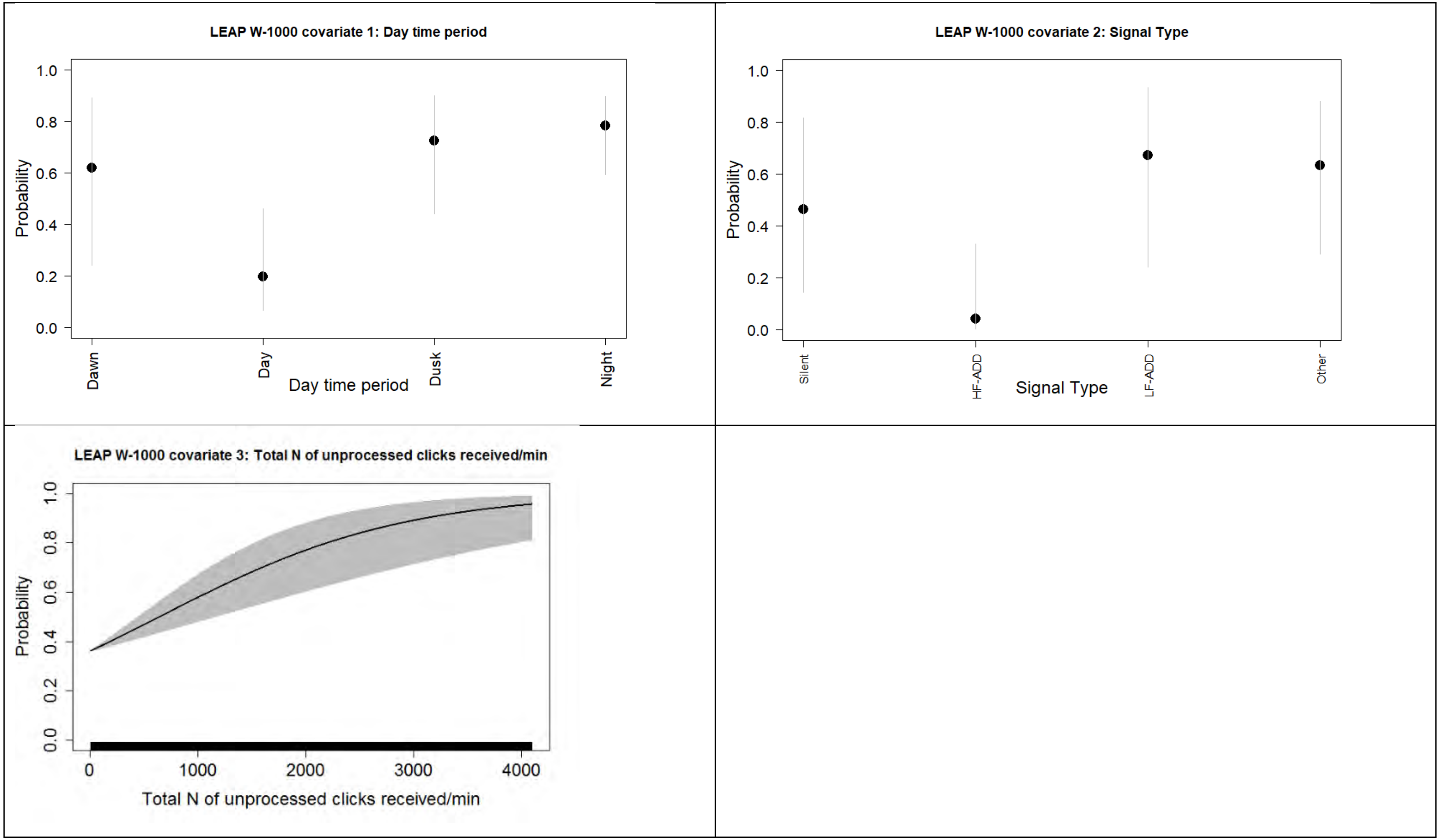
Model:	W-1000
Model structure:	POD5<-geeglm(PPM ~ as.factor(DAYTIMENum) + as.factor(Signal_Type) + Nall_m, family = binomial, corstr="independence", id=Panel, data=W1000)
Confusion matrix:	

		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	$6.547 \cdot 10^{-6}$


LEAP W-1000 covariate 1: Day time period
Probability
1.0
0.8
0.6
0.4
0.2
0.0
Dawn
Day
Dusk
Night
Day time period
LEAP W-1000 covariate 2: Signal Type
Probability
1.0
0.8
0.6
0.4
0.2
0.0
Silent
HF-ADD
LF-ADD
Other
Signal Type
LEAP W-1000 covariate 3: Total N of unprocessed clicks received/min
Probability
1.0
0.8
0.6
0.4
0.2
0.0
0
1000
2000
3000
4000
Total N of unprocessed clicks received/min

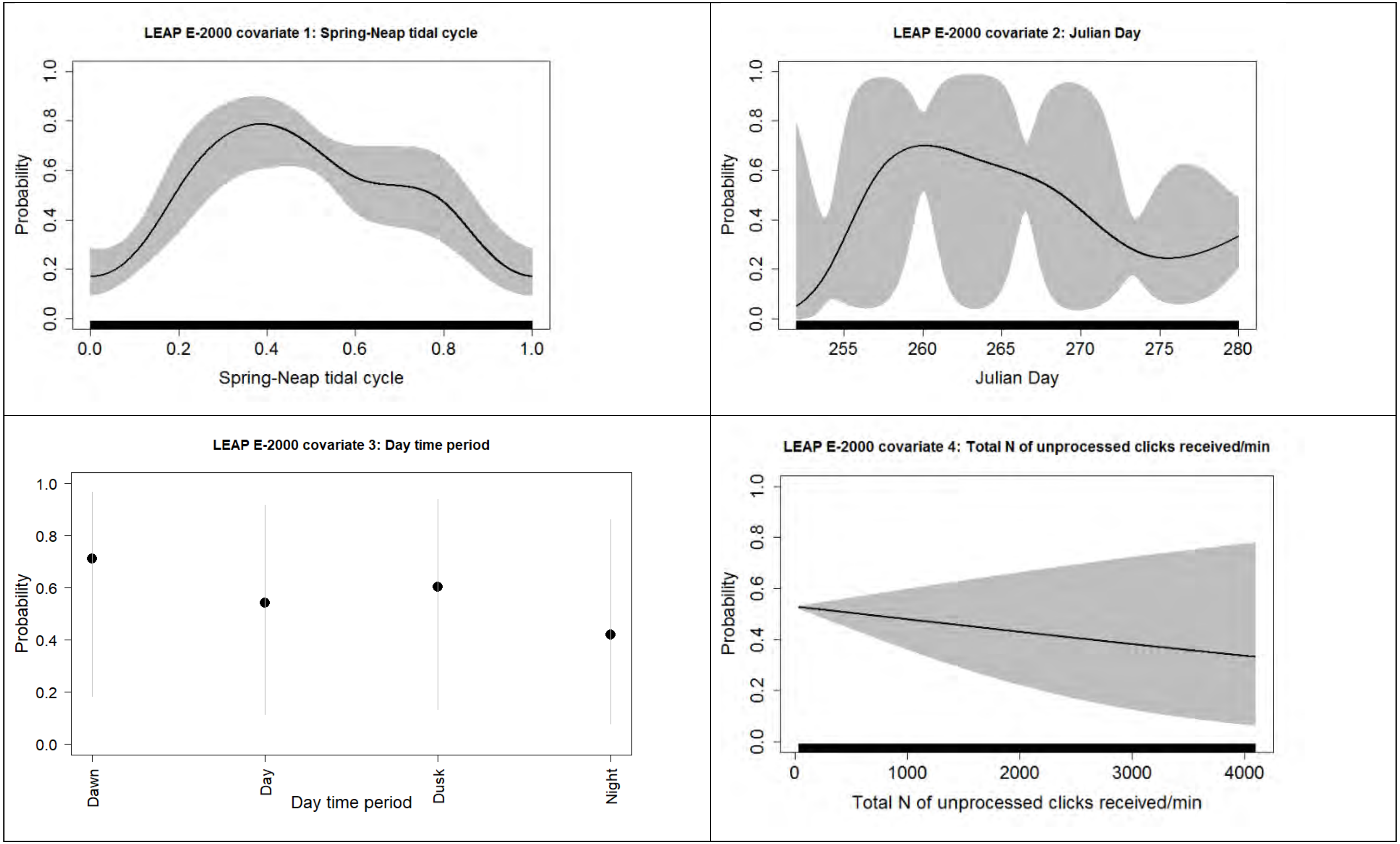
Model:	E-2000
Model structure:	POD5<-geeglm(PPM ~ SprNpBasisMat + bs(JULDAY , knots=mean(JULDAY)) + as.factor(DAYTIMENum) + bs(Nall_m , knots=mean(Nall_m)), family = binomial, corstr="independence", id=Panel, data=E2000)
Confusion matrix:	

		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:

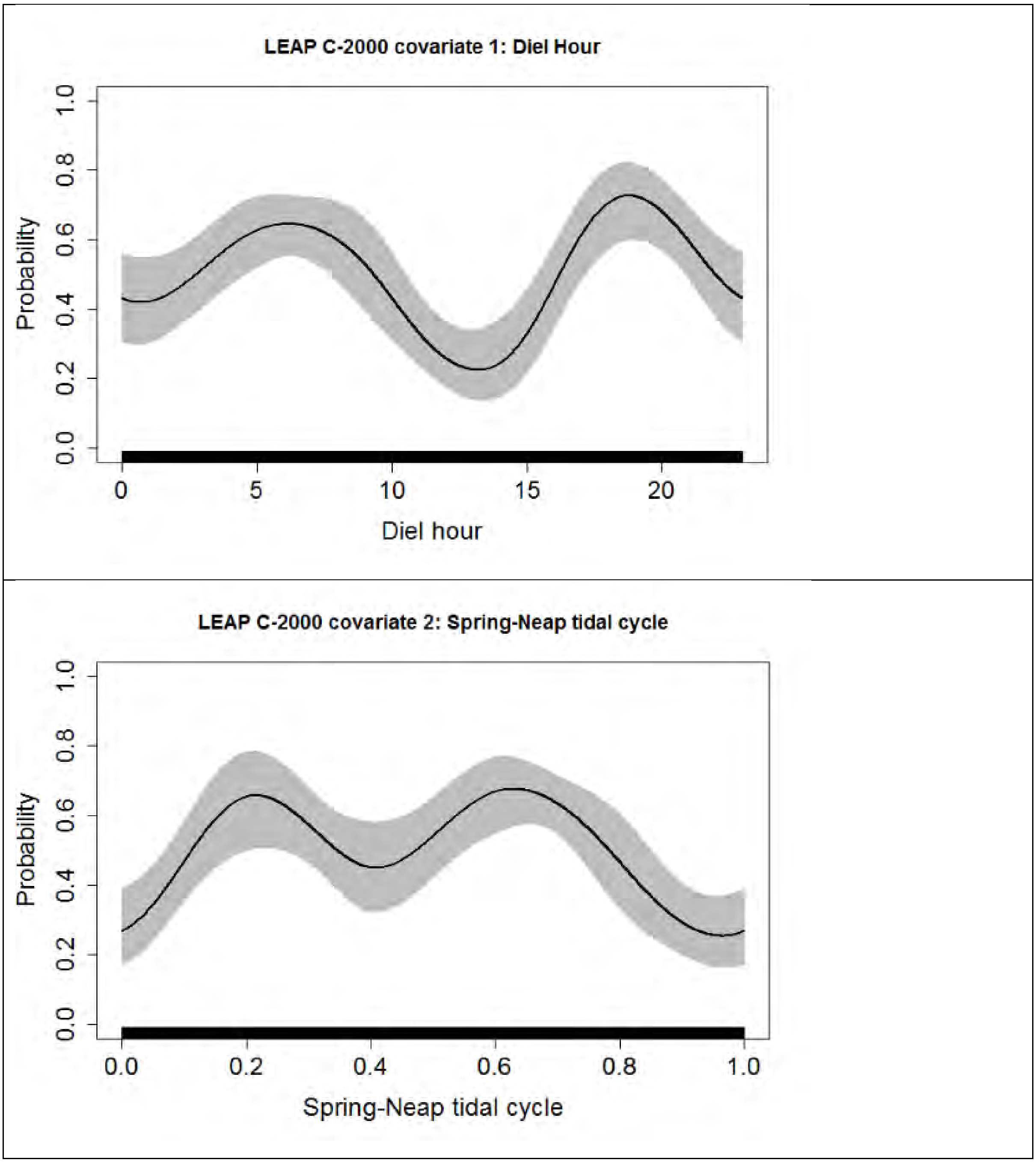
Covariates (in descending order of significance)	Form	Degrees of Freedom	χ^2 score	P-value
SpringNeap	Cyclic B-spline	4	37.671	$1.310 \cdot 10^{-7}$
JULDAY	Cubic B-spline	4	18.033	0.001216
DAYTIMENum	Factor	3	14.029	0.002866
Nall_m	Cubic B-spline	4	32.284	$1.674 \cdot 10^{-6}$


LEAP E-2000 covariate 1: Spring-Neap tidal cycle
Probability
Spring-Neap tidal cycle
LEAP E-2000 covariate 2: Julian Day
Probability
Julian Day
LEAP E-2000 covariate 3: Day time period
Probability
Dawn
Day
Dusk
Night
Day time period
LEAP E-2000 covariate 4: Total N of unprocessed clicks received/min
Probability
Total N of unprocessed clicks received/min

Model:	C-2000
Model structure:	POD5<-geeglm(PPM ~ bs(Nall_m , knots=mean(Nall_m)) + as.factor(DAYTIMENum) + AvgHrBasisMat + SprNpBasisMat, family = binomial, corstr="independence", id=Panel, data=C2000)
Confusion matrix:	(see below)

		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


LEAP C-2000 covariate 1: Diel Hour
Probability
0.0
0.2
0.4
0.6
0.8
1.0
0
5
10
15
20
Diel hour
LEAP C-2000 covariate 2: Spring-Neap tidal cycle
Probability
0.0
0.2
0.4
0.6
0.8
1.0
Spring-Neap tidal cycle

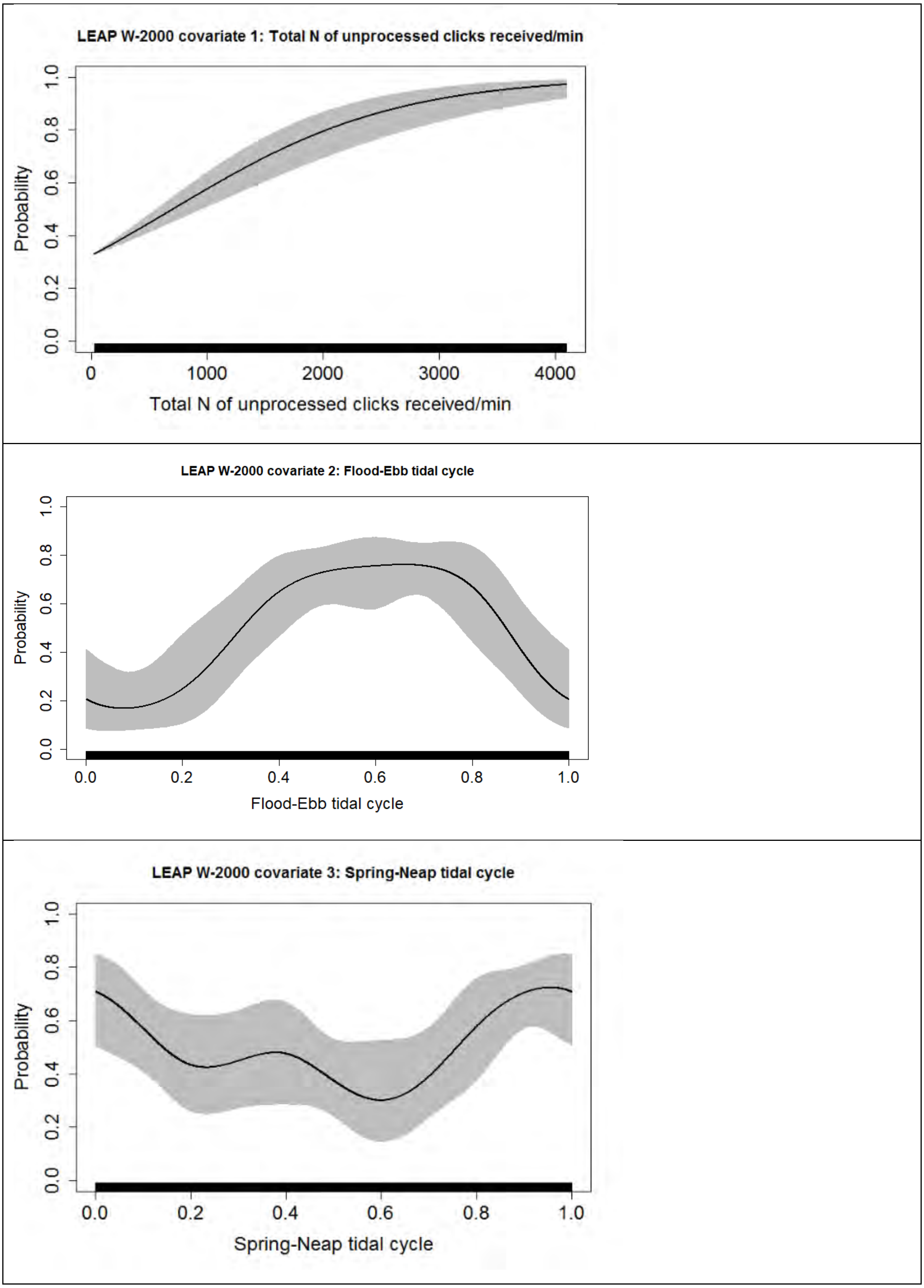
Model:	W-2000
Model structure:	POD5<-geeglm(PPM ~ Nall_m + TideBasisMat + SprNpBasisMat, family = binomial, corstr="independence", id=Panel, data=W2000)
Confusion matrix:	(see below)
AUC value:	0.7838515

Confusion matrix:

		Expected	
		Porpoise	No porpoise
Observed	Porpoise	88.5%	46.9%
	No porpoise	11.5%	53.1%

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	$<2.2\cdot10^{-16}$
HiLoTide	Cyclic B-spline	4	22.245	0.0001791
SpringNeap	Cyclic B-spline	4	10.022	0.0400520

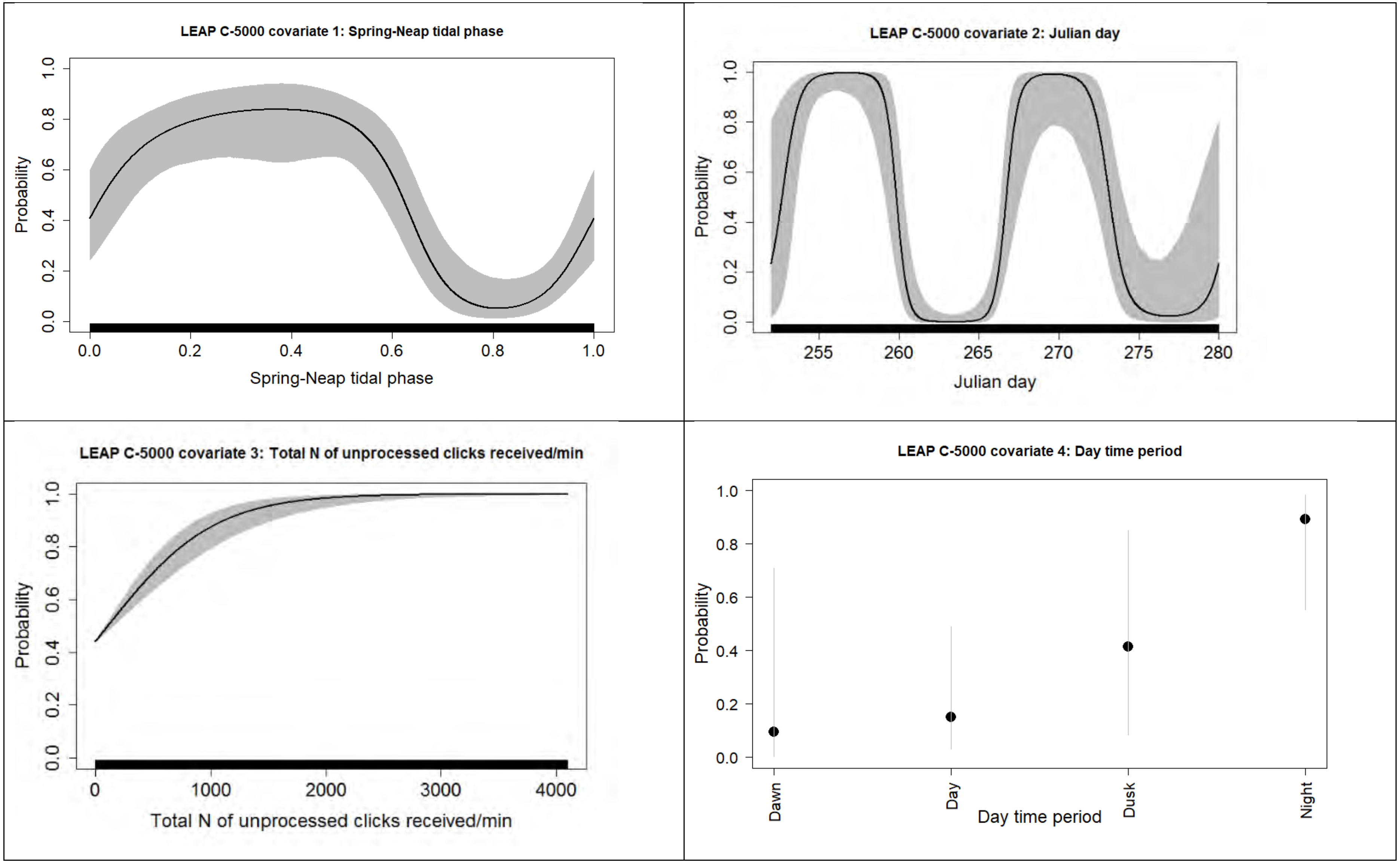

LEAP W-2000 covariate 1: Total N of unprocessed clicks received/min
Probability
0.0
0.2
0.4
0.6
0.8
1.0
0
1000
2000
3000
4000
Total N of unprocessed clicks received/min
LEAP W-2000 covariate 2: Flood-Ebb tidal cycle
Probability
0.0
0.2
0.4
0.6
0.8
1.0
0.0
0.2
0.4
0.6
0.8
1.0
Flood-Ebb tidal cycle
LEAP W-2000 covariate 3: Spring-Neap tidal cycle
Probability
0.0
0.2
0.4
0.6
0.8
1.0
0.0
0.2
0.4
0.6
0.8
1.0
Spring-Neap tidal cycle

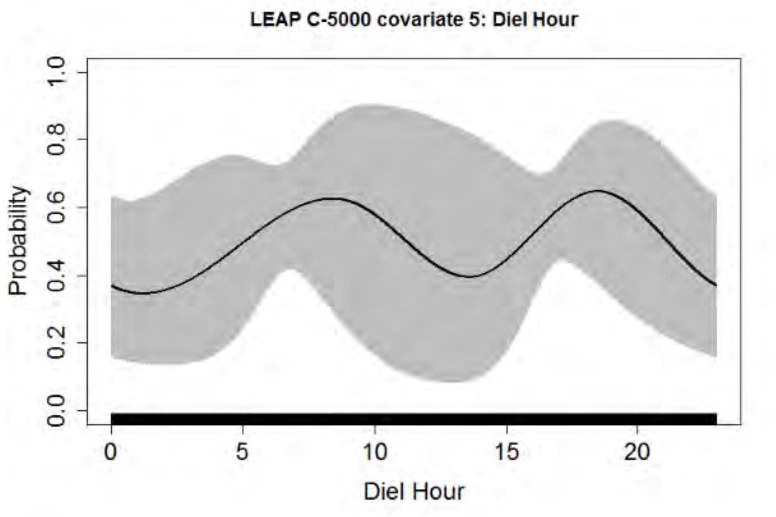
Model:	C-5000
Model structure:	POD5<-geeglm(PPM ~ SprNpBasisMat + bs(JULDAY , knots=mean(JULDAY)) + Nall_m + as.factor(DAYTIMENum) + AvgHrBasisMat, family = binomial, corstr="independence", id=Panel, data=C5000)
Confusion matrix:	(see below)

Confusion matrix:

		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	$3.291 \cdot 10^{-8}$


LEAP C-5000 covariate 1: Spring-Neap tidal phase
Probability
0.0
0.2
0.4
0.6
0.8
1.0
Spring-Neap tidal phase
LEAP C-5000 covariate 2: Julian day
Probability
255
260
265
270
275
280
Julian day
LEAP C-5000 covariate 3: Total N of unprocessed clicks received/min
Probability
0
1000
2000
3000
4000
Total N of unprocessed clicks received/min
LEAP C-5000 covariate 4: Day time period
Probability
Dawn
Day
Dusk
Night
Day time period

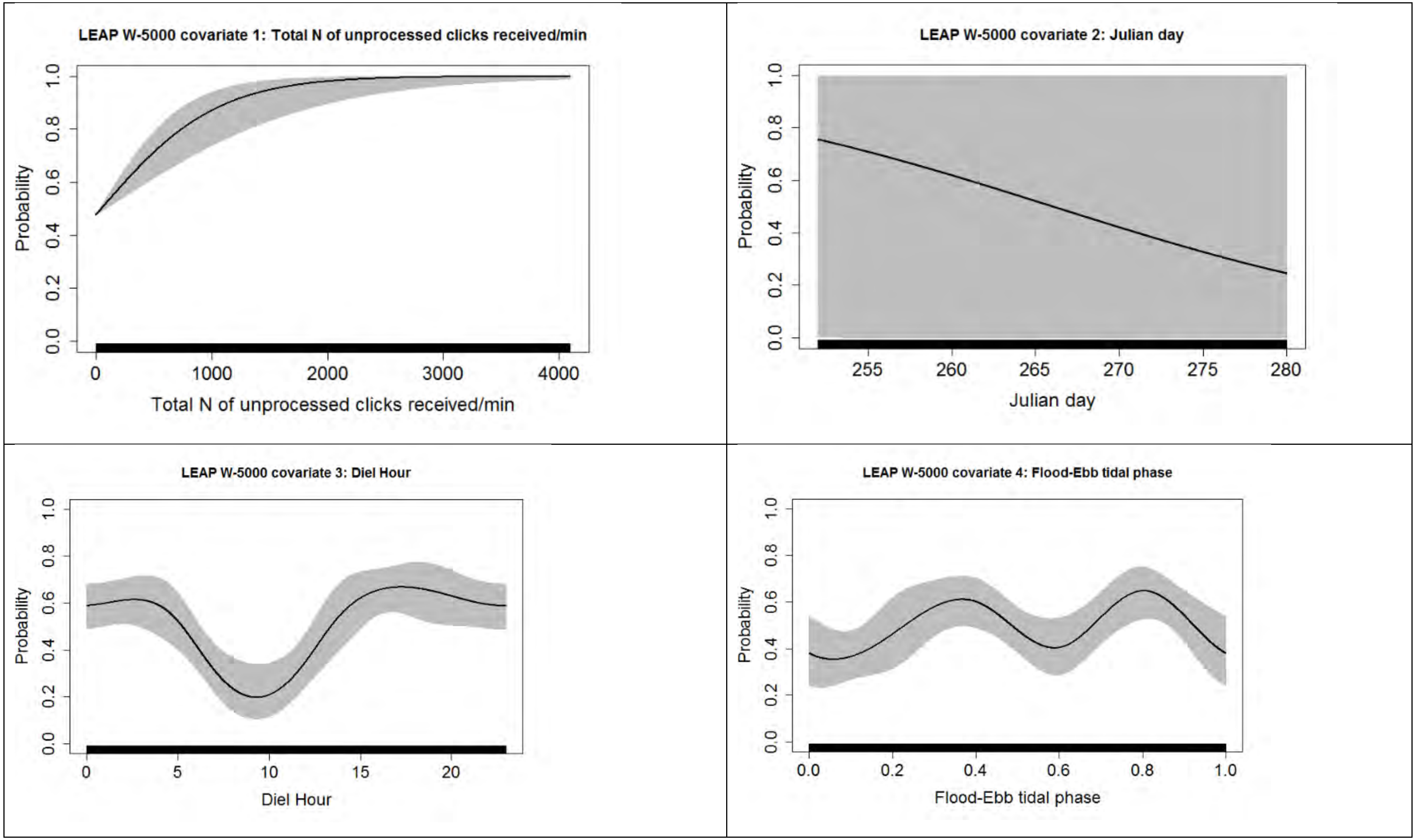

LEAP C-5000 covariate 5: Diel Hour
Probability
0.0
0.2
0.4
0.6
0.8
1.0
0
5
10
15
20
Diel Hour

2085

Model:	W-5000
Model structure:	POD5<-geeglm(PPM ~ Nall_m + JULDAY + AvgHrBasisMat + TideBasisMat, family = binomial, corstr="independence", id=Panel, data=W5000)
Confusion matrix:	

		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


LEAP W-5000 covariate 1: Total N of unprocessed clicks received/min
Probability
0.0
0.2
0.4
0.6
0.8
1.0
0
1000
2000
3000
4000
Total N of unprocessed clicks received/min
LEAP W-5000 covariate 2: Julian day
Probability
0.0
0.2
0.4
0.6
0.8
1.0
255
260
265
270
275
280
Julian day
LEAP W-5000 covariate 3: Diel Hour
Probability
0.0
0.2
0.4
0.6
0.8
1.0
0
5
10
15
20
Diel Hour
LEAP W-5000 covariate 4: Flood-Ebb tidal phase
Probability
0.0
0.2
0.4
0.6
0.8
1.0
0.0
0.2
0.4
0.6
0.8
1.0
Flood-Ebb tidal phase

From: Sandra Gray
To: r.slaski@sarf.org.uk; George Lees; Caroline Carter; "Craig Burton"
Cc: George Lees
Subject: FW: SARF 112
Date: 18 October 2018 13:10:29
Attachments: image001.png
image002.jpg
image003.jpg

As previous email, Ortaq concerns below & follow-up emails.
Regards
Sandra
SARF

From: Steven Benjamins <Steven.Benjamins@sams.ac.uk>
Sent: 02 July 2018 14:43
To: Richard Slaski <r.slaski@sarf.org.uk>
Cc: 'Sandra Gray' <s.gray@sarf.org.uk>
Subject: RE: SARF 112

Hello Richard,
Thank you again for your message earlier. I have discussed the matter with my co-authors and we agree that a mistake was made which we intend to rectify. Specifically, we have amended the Table 1 & associated text as follows:

- We have removed OTAQ from the 'AirMar' row at the top of the table so that this cell now reads "AirMar (Gael Force Marine Technology)", in line with the fact that Gael Force still makes use of the AirMar dB Plus II unit. This should hopefully address the concern stated by OTAQ that their device was unfairly lumped together with their competitors.

- The "Commercially Available" column has been removed entirely. This was originally intended to only refer to 'cetacean-friendly' systems but this was evidently unclear to the reader. This change should hopefully address OTAQ's comment concerning their device's commercial availability.

- The table caption used to read: "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 *, ** and *** symbols."

  This caption now more accurately reads (new text highlighted in yellow): "Table 1. Acoustic signal characteristics of different ADD types historically and currently used, or proposed for use, in Scottish finfish aquaculture. Table adapted from Götz & Janik (2013). Values from particular references are indicated using *, ** and *** symbols. †The term 'Cetacean-friendly' here refers to devices where changes in signal structure and/or duty cycle have been made to reduce acoustic impact on cetaceans. Other approaches, including 'Soft start' approaches, to reduce overall acoustic impacts were not considered in this report."

  This latter aspect is important as the report focuses on a specific approach to achieving 'cetacean-friendliness', namely one that changes the acoustic signal structure (in our case, frequency) to achieve reduced impact on cetaceans. To highlight the fact that other approaches such as soft starts exist, we have now also added a single sentence in Section 2.5, p.20, which reads "Other systems make use of 'soft starts' to slowly increase sound outputs.". Section 3.2 (page 20) then specifies that in the present report we are solely focusing on the potential effects of changing the frequency output.

- Concerning OTAQ's request that "*a clarificatory statement is included in the report that OTAQ products, whilst commercially available, were not tested as part of this research, and do not form part of any results of this research*", we feel this is already covered under the text in Section 3.2 (page 22), where we explain that no actual, existing ADD devices of any kind were used in the experiment, as per SARF's original stipulations. We are concerned that OTAQ may have inadvertently misinterpreted the first section of the report (notably Table 1) which was merely intended to provide a general overview of ADD types that have been, are being or may be used in the near future in Scottish aquaculture, and which makes no statement concerning their relevance to the study.

- Given the issues pointed out by OTAQ, we strongly feel that it would be beneficial for everyone involved if we contacted OTAQ directly to apologise for the mistake and explain the changes made. We have had personal conversations with the company in the past and we feel this issue can be readily resolved through a direct conversation.

I would like to discuss these changes with you, if possible, over the phone this afternoon, to confirm that these are acceptable.

Regards,
Steven

Dr. Steven Benjamins
Lecturer in Marine Vertebrate Ecology
SAMS (Scottish Association for Marine Science)
Oban
Argyll, Scotland, UK
PA37 1QA

Tel: +44(0)1631-559449 (office)
Tel: +44(0)1631-559000 (switchboard)
Fax: +44(0)1631-559001
E-mail address: Steven.Benjamins@sams.ac.uk
https://www.sams.ac.uk/people/researchers/benjamins-dr-steven/

From: Richard Slaski <r.slaski@sarf.org.uk>
Sent: 02 July 2018 09:49
To: Steven Benjamins <Steven.Benjamins@sams.ac.uk>
Cc: 'Sandra Gray' <s.gray@sarf.org.uk>
Subject: FW: SARF 112

Dear Steven,

Here is the detailed response from the commercial company concerning the SARF112 ADD report.

Could you please consider this very carefully, and let me know how you intend to address their concerns.

Kind regards,
Richard

Richard Slaski
Secretariat
Scottish Aquaculture Research Forum (SARF)
PO Box 7223 Pitlochry PH16 9AF
Tel: 01738 479486
Company Registered in Scotland - SC267177
Charity Registered in Scotland - SC035745
EU State Aid Registration No: X939 2009
Website: www.sarf.org.uk

From: Chris Hyde <Chris.Hyde@otaq.com>
Sent: 02 July 2018 09:29
To: Richard Slaski <r.slaski@sarf.org.uk>
Cc: 'Sandra Gray' <s.gray@sarf.org.uk>; Phil Newby <Phil.Newby@otaq.com>
Subject: SARF 112

Richard,

Further to our conversation on Thursday, we have significant concerns with some of the content within your latest published report SARF 112 . I have copied in our MD who is closely monitoring the response from SARF and the outcome.

Misleading / Incorrect Technical Information
As I said on the phone my primary concern here is with the misleading and incorrect technical information regarding our system. The report states…

"A review of commercially available ADD systems was carried out, with a summary provided in Table 1 of acoustic signal characteristics of the

most commonly used ADDs in the Scottish finfish aquaculture sector. The different models differ in terms of their acoustic characteristics (e.g. signal type, duty cycle, frequency range) as well as in terms of power supply and cost."

Table 1 on page 11 shows the following

- Our system (which is actually called OTAQ Sealfence) has been incorrectly bundled with several other devices on the same line under "Airmar" and all technical specifications quoted here for our system are incorrect.
- Please demonstrate how you arrived at RMS values for source level and why are you stating a 50% duty cycle.
- The column for "cetacean friendly" is extremely misleading and is without explanation.
- And despite being grouped with one of our only active competitors (Gael Force) we are not indicated as being "commercially available". As we now have over 500 systems deployed on around 40 sites in Scotland, it cannot be argued that the researchers have carried out a review that could be considered diligent on any level.

Action Required from you

We have consulted with our legal advisers, and request that you confirm to us by Friday 13 July 2018 that the following steps have been taken:-

1. OTAQ has been removed from the table on page 11; and

2. a clarificatory statement is included in the report that OTAQ products, whilst commercially available, were not tested as part of this research, and do not form part of any results of this research.

If you fail to provide such confirmation by the date requested, we will consult our lawyers further, and we fully reserve our position.

If you wish to discuss this please don't hesitate to give me a call on the mobile.

Yours sincerely,

Chris

Chris Hyde
Commercial Director

OTAQ Ltd
Scottish Marine Institute
Dunbeg, Oban, PA37 1QA
Scotland, UK

Tel +44 (0) 1631 559399
Direct +44 (0) 1631 692711
Mob [redacted]

VAT no 210802560
Company registration no SC498922

www.otaq.com

From: Richard Slaski <r.slaski@sarf.org.uk>
Sent: 28 June 2018 15:36
To: Info otaq <info@otaq.co.uk>
Cc: 'Sandra Gray' <s.gray@sarf.org.uk>
Subject: Re: For the attention of Chris Hyde PLEASE FORWARD

Dear Chris,

You haven't contacted me yet, so apologies for not knowing what your direct email address is – hope this gets to you.

You have raised a complaint about factual/technical accuracy in a SARF report – specifically SARF112. We take this very seriously indeed, and the following actions have been taken:

1. The report has been taken off our website
2. I have invited you to comment in writing about the specific issue that was inaccurate, so that I can share it with the author of the report. He would then ascertain the exact location of the problem, and make amendments to the report if he – in consultation with us – agrees with you. SARF would stress that neither our independent referees not any of our Board Members – all of whom saw the report prior to publication – noticed anything wrong. We would have taken action if we had done so. The error is therefore obviously very technical or specialised, and your clarification of its exact nature will be essential
3. I have contacted the author, and he is more than willing to do this. He is available for the remainder of this week and most of next week
4. I have contacted all Directors of SARF to outline the situation, and many have already replied:
    a. Broadly supporting the idea of making a technical amendment to the report, if that is warranted
    b. If that happens, putting a footnote in the amended report to stress that their had been an error in the first version.

I hope all this helps.

Kind regards,
Richard

Richard Slaski
Secretariat
Scottish Aquaculture Research Forum (SARF)
PO Box 7223 Pitlochry PH16 9AF
Tel: 01738 479486
Company Registered in Scotland - SC267177
Charity Registered in Scotland - SC035745
EU State Aid Registration No: X939 2009
Website: www.sarf.org.uk

From:	Sandra Gray
To:	r.slaski@sarf.org.uk; George Lees; Caroline Carter; "Craig Burton"
Cc:	George Lees
Subject:	FW: SARF112 ADD Report
Date:	18 October 2018 13:16:06
Attachments:	image001.png

As previous email, details of the conversations between Chris Hyde & SAMS & then SAMS & Richard.

One more to follow...

Regards

Sandra

SARF

From: Richard Slaski <r.slaski@sarf.org.uk>
Sent: 03 July 2018 10:29
To: 'Steven Benjamins' <Steven.Benjamins@sams.ac.uk>
Cc: 'Sandra Gray' <s.gray@sarf.org.uk>; [redacted]@sams.ac.uk>; ben.wilson@sams.ac.uk
Subject: Re: SARF112 ADD Report

Dear Steven,

I received an email from Chris Hyde yesterday late afternoon. He refers to a telephone call from [redacted] He itemises the main points of the conversation as follows:

- [redacted] explained that they had been alerted to our complaints about the report
- [redacted] apologised for getting technical points about our system wrong
- [redacted] asked if it would be possible to get the technical specifications for our system so that they could be included in the introduction
- I explained that we would not be providing the technical specifications and that we wanted all reference to our system removed from the report, save for the disclaimer as per our emailed request.
- [redacted] further explained that the introduction was a summary of systems currently in use and that they were very clear that the research detailed in the report specifically covered the LF system only
- I stated due to the nature of the conclusions made in the report (which cover all ADDs) that any mention of our system in the report inferred that we were implicated in their conclusions
- I further stated that I believed they had gone well beyond the stated remit in terms of expressing their opinions on ADDs and coming up with recommendations for ADD use in general; the report specification asked them to make recommendations on the use of Low frequency systems only.
- I reiterated my request for them to follow the instructions in the email

I was somewhat surprised by this, and have confirmed to Chris that you and I had spoken earlier in the day, and had agreed the following points:

- You would not ask the company for any further information about their product
- You would remove all reference to their product from the report
- You would amend the Table in question in other ways, which seemed very sensible
- You would insert a footnote in the new version of the report, to note that there had been an error in an earlier version
- You would be even more overt in the Section 3.2 pp 22 comments about the fact that this report has nothing to do with any commercially available devices of any sort, by promoting those comments right up to the front, into the Executive Summary
- You wondered if you should phone the company to apologise for the technical error, and whilst I left it up to you to decide on that, I did suggest that a modified report according to the terms of Chris' initial email would be 'sufficient unto the moment'

I would be grateful for an explanation of what transpired yesterday, and a confirmation that you intend to proceed along the lines we agreed, as itemised in the second set of bullet points above.

Kind regards,
Richard

Richard Slaski
Secretariat
Scottish Aquaculture Research Forum (SARF)
PO Box 7223 Pitlochry PH16 9AF
Tel: 01738 479486
Company Registered in Scotland - SC267177
Charity Registered in Scotland - SC035745
EU State Aid Registration No: X939 2009
Website: www.sarf.org.uk

From:	Sandra Gray
To:	r.slaski@sarf.org.uk; George Lees; Caroline Carter; "Craig Burton"
Cc:	George Lees
Subject:	SARF112 - Meeting 24th October at SAMS
Date:	18 October 2018 13:09:49

Dear All,

SARF112 – ADDs

In preparation for the additional steering group meeting for the above project, please find the following documents attached:

The revised version of the report after comments were received from Ortaq & Ace Aquatec.
The project teams detailed responses to Ace Aquatec.
The 3 referees' evaluations on the original report – they have not yet seen this revised report but will be asked to peer review this after your discussions next week.

The concerns from Ortaq came as an email & I will forward to you an email trail for your information.
I will also forward an email after a telephone conversation between Chris Hyde at Ortaq & two of the project team.

That should bring you all up to date prior to next weeks' meeting.

Should you need any further information, please do let Richard or I know.
Richard is available on the number in the footer below or on [redacted]

Kind regards,

Sandra Gray
SARF Secretariat
PO Box 7223
Pitlochry
PH16 9AF

Tel: 01738 479486

ACE AQUATEC

COMMENTS | WWW.ACEAQUATEC.COM

CONTACT

Nathan Pyne-Carter
Managing Director
[redacted]
Ace Aquatec Ltd.
16B City Quay, Camperdown Street,
Dundee. DD1 3JA

www.aceaquatec.com

PURPOSE OF DOCUMENT

The recent SARF report112 has been conducted to ascertain whether low frequency deterrents have an impact on cetaceans. The study uses a bespoke low frequency noise generator rather than a commercial system. In using this system, and failing to report sounds recorded up to 200khz, it is suspected that the equipment generates noise above 2khz which could be heard by cetaceans. If correct, the conclusions reached by this study are flawed.

Overview of the company

Ace Aquatec is a leading provider of innovative aquaculture equipment worldwide. We have developed an award winning range of triggered acoustic deterrents and electric nets to prevent seal, sea lion and shark attacks from farm cages (Scottish Aquaculture Innovation Centre's 2016 technology award 2016, Queen's Award 2018).

nathan@aceaquatec.com
www.aceaquatec.com
[redacted]
https://www.linkedin.com/company/ace-aquatec-ltd

CRITIQUE OF THE FOUR RECOMMENDATIONS OF SARF112:

The focus of the study does not provide grounds for the breadth of the recommendations in the summary and conclusion:

1. Recommendations for non acoustic deterrents:

Why should predator nets that kills seals and birds be promoted over triggered acoustic deterrents for example? The study has not demonstrated that a low frequency system operating at 1-2khz impacts cetaceans – only that their device has potentially impacted a few cetaceans, possibly due to broadband noise at higher levels, and with the possibility of other local deterrents impacting the bahaviour of the cetaceans detected.

2. "There is a need for improved understanding of ADD use and distribution in Scottish Waters".

We would welcome this – but central to such a study should be what manufacturers are already implementing to reduce noise – Ace Aquatec is rolling out sonar triggers and has a connected platform to bring all deterrents into duty cycle harmony to reduce overall sound on any one site. It has also developed electric fish and nets to allow the playing of low volume noise to act as a conditioned sound when paired with an electric shock. OTAQ has developed a PAM de-activation system to switch devices off when porpoises are detected. The studies do not seem to reflect the work and energy put in by manufacturers to use academic research to build upon and improve deterrent systems – nor are the current authors as balanced as other academics like Dr Simon Northridge on the benefits of deterrent systems. The current authors seem to want to push Scotland towards a BC Canadian model – without sharing the other side of the argument – for example farms in BC are trapping and moving animals – a model which is expensive, stressful and temporary in its effect.

3. Low frequency devices deter porpoises:

We dispute this finding – we believe had the study been conducted with our commercial system which has harmonics above 2khz removed, that the finding would not have been the same. This is reflected in the current results being obtained from our system which is being analyzed by St Andrew's university in Wyre.

4. A study on acoustic systems is required:

We would agree with point 4 – but whatever study is conducted needs to look at all mitigation measures being implemented. This should included sonar triggers, IOT (internet of things) devices co ordinating sound outputs, low frequency sound, electric fish and nets; PAM (Passive Acoustic Monitoring) deactivation etc.

SPECIFIC COMMENTS:

P11. While the low frequency system is derived from the US3, it has is own name: RT1.

P11. The systems referred to in the Northridge study in 2013 were only US3s in name. In 2014 out deterrent build was handed over to Neptune Sonar, and they created a completely different method of sound generation in the system, and at different volume levels. No systems in Scotland retain the physical properties described here. There are currently 290 US3s in Scotland – they share a central intelligent core which is monitored via a portal in Dundee. The systems can co ordinate their sound generation to reduce duty cycle across the site as a whole. Similarly, they are all built to be sonar activated; this triggering system has been tested at Loch Duart and is being rolled out to all our rental deterrents this year. This will dramatically reduce duty cycle to below 1%.

P12. Ferranti Thomson deterrents only exist in scientific labs – so I've no real idea why these are mentioned here. We stopped developing these back in 2004.

P20. Very little reference to why manufacturers have spent time and money investing in low frequency systems seems to be provided. It was in response to the last Marine Scotland report by Vincent Janik that we have sought government funding alongside our own funds to develop a low frequency system. That study used the research of Kasteline and the available knowledge at the time to suggest that deterrents should be pushed below 2khz as cetaceans hearing is not sensitive below these levels. The soundness of this research can be seen in the development of other cetacean friendly systems such as the Fauna Guard produced by Ron Kasteline who has extensively tested the most productive deterrent sounds for different marine mammal groups.

P20. Silent scrammer – Ace Aquatec has not produced the 'silent scrammer' triggers in 10 years. We have since developed a sonar trigger which is currently being used at Loch Duart and will be rolled out to all US3 devices over this year.

nathan@aceaquatec.com | www.aceaquatec.com | [redacted] | https://www.linkedin.com/company/ace-aquatec-ltd

P20. It seems very strange that the authors support a cetacean friendly device designed by academics Vincent Janik and Thomas Goetz) over various cetacean friendly devices developed elsewhere. Sonar triggers should reduce duty cycle, limit chances of habituation avoid non target species being impacted – but no attempt has been made to explore what measures Ace Aquatec or OTAQ are currently using. Similarly, electric nets receive a cursory mention when substantial work has been carried out by Dr David Thompson and his team to bring to bear a conditioned avoidance response in seals which is the holy grail of deterrent technology. I think the authors either need to focus on the remit of this study which is to look at 1-2khz noise or to conduct a complete study looking at all mitigation measures to avoid cetacean impact. A smattering of opinions on the subject does no justice to the time and effort of all companies working in this space.

P20. It states there is little scientific backing for producing a deterrent system operating at 1-2khz. The Marine Scotland report in 2012, plus Thomas Goetz's thesis 2008 recommended that deterrents should focus below 5khz and should preferentially make noise below 2khz to avoid cetaceans. Ron Kasteline has produced his own deterrent systems focused on this range in response to his own work in this area, and Dr Leppar has been in contact with Alex Coram of St Andrews's University - so he will know that another study is currently ongoing looking at the impact of our RT1 device on porpoises and that the results, while not yet published show the opposite results to this study. While of course he cannot reference the results, he can acknowledge that another academic study is currently being undertaken and therefore some conclusions from this study should be left on hold until corroborated or contradicted by that study.

p.21 suggests the startle response has been patented. It has not been patented. It is patent pending and all examination reports suggest the patent will be rejected on the basis that you cannot patent a reflex, that the argument for novelty is invalid given that 10ms rise time startle reflex is already described in papers from the 1960s in rats and upon the existence of air gun technology in seal deterrents which have utilized the effect of the 10ms rise time in this context before.

P22. Says no commercial ADD was used in order to retain impartiality. We would argue that this approach has invalidated the whole study.

When Ace Aquatec first built the RT1 device it was deployed at a site in Wyre with SNH approval and the sound production was assessed by Alex Coram of St Andrews University. Alex found that the electronics driving the system produced a noise above 2khz which was likely having an impact on cetaceans who are highly sensitive to novel sounds in higher frequencies. Ace Aquatec commissioned Neptune Sonar to develop a filter at great expense to remove this component. It seems improbable that engineers at Neptune Sonar have built a system costing over £100k to remove the system noise above 2khz whereas the academic system developed on this project has managed to achieve what we set out to do on a shoestring budget. To ascertain if this is the case, we would like access to all records from this device so that a full analysis of the sounds generated in the water can be conducted. It should be noted as well from the previous Janik studies that Airmar tried to build a deterrent below 2khz but failed to create a noise in the water that did not contain sounds above this level.

P26. If we compare the provided plot of the LF output used in the study we see sounds produced above 2khz all the way up to 12khz – well in the sensitive hearing range of porpoises. The authors mention the harmonics but point out they are probably too low an amplitude to bother porpoises. I would argue that Ron Kasteline's work on porpoise deterrent systems shows very good deterrent effects at low volume – so much so that they have been able to create a porpoise deterrent operating at volume levels not normally associated with deterrent systems. Similarly battery operated pinger devices rely on the highly sensitive nature of porpoise hearing and the flightiness of their response to new sounds.

The plot also does not show sounds produced above this level, and we would argue that the electronics themselves will be generating a sound around 70khz – again – in prime cetacean hearing ranges. Providing the original sound files to our engineers would be appreciated to confirm or discount this.

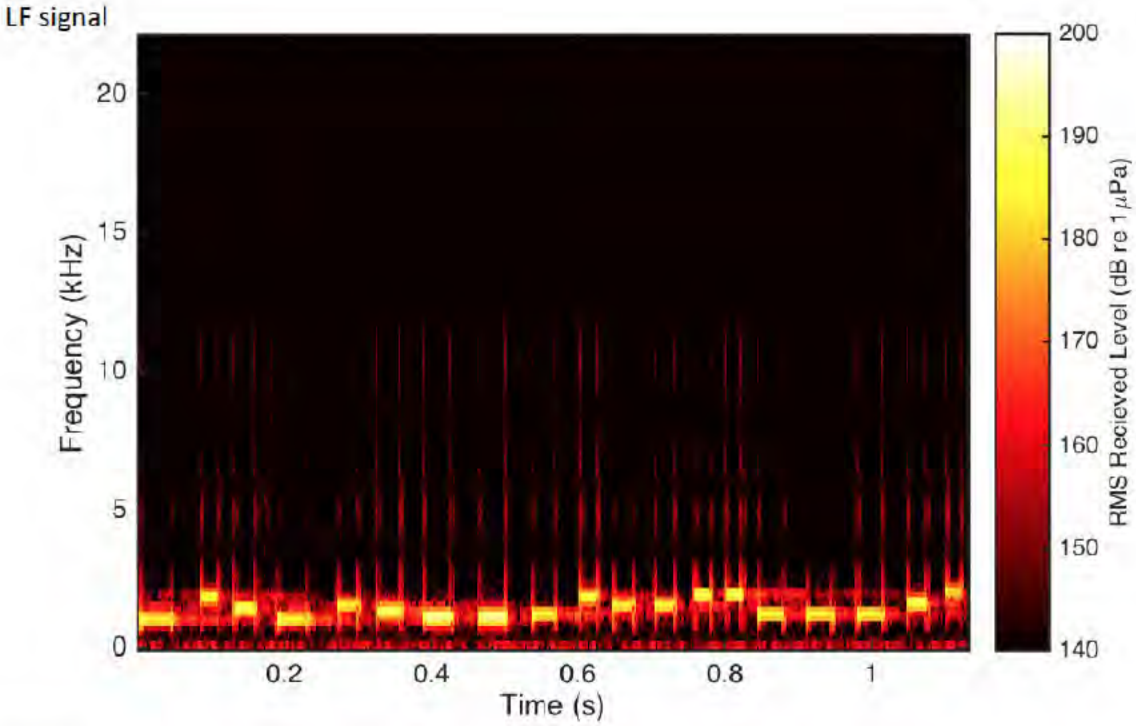


Figure 4. Spectral plot of a sample of the HF and LF signals received at a range of 8.5 m using a Reson 4014 balanced hydrophone. Analysis window was 256 FFT with 50 % overlap using a Hanning window. A 50 kHz low pass filter was applied. Original data were downsampled to a sample rate of 44.1 kHz.

The authors mention that they measured output up to 200khz, but they do not report it. We found with the original RT1 low frequency signal some high frequency electronic noise before developing the filter, so it is crucial that the measured outputs up to 200khz are provided to discount the same problem in their device. It is unfortunate that this study was not conducted with a 'real' commercial system to eliminate imperfections in the system as this is being used to validate or condemn much more sophisticated equipment.

Fig. 1 Early RT1 prototype – showing frequency harmonic at 70khz

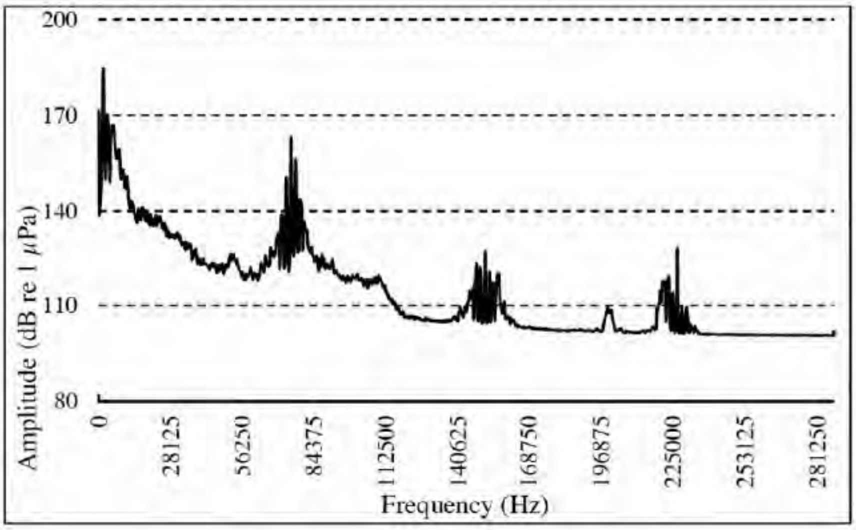


Figure 2 - Spectral frequency of the prototype RT1 ADD

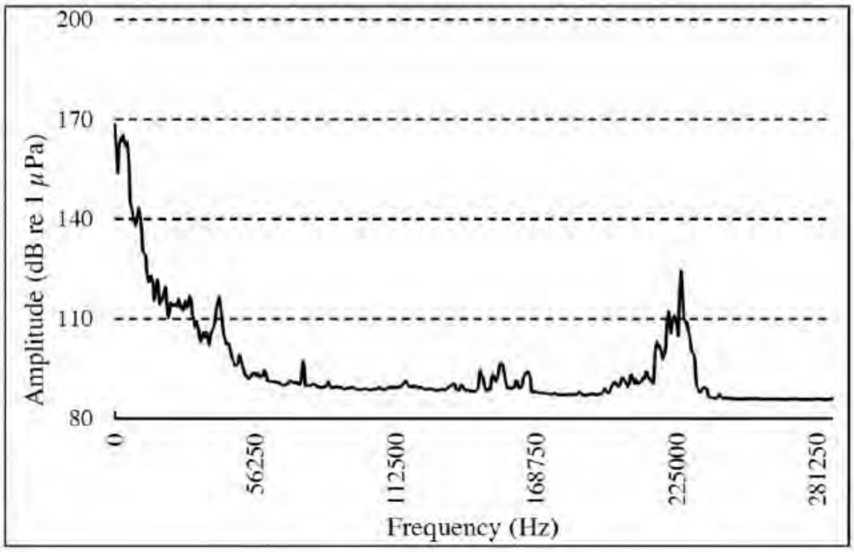


Figure 4 - Spectral frequency of the new RT1 signal

This new RT1 sound profile is very clean and we would want to see evidence that the LF sound produced in the SARF study has been as rigorously tested to remove broadband sounds.

P29. Field tests were carried out in the sound of Mull. The authors state quite flippantly that they cannot control for other seal deterrents operating in the area. When we conducted our own trials on our RT1 we were determined to find a site without other seal deterrents in operation so that impact from neighboring farms could be discounted. For this reason we chose Skapa flow where other mid frequency deterrents are banned from being used. Given the range described in table 2, and the fact that SSC and SSF all run mid frequency deterrents in the area, it seems peculiar that the authors would have chosen such a noisy environment to conduct studies where noise is so critical. We would argue that any number of local sites could be impacting both the presence (by driving cetaceans closer to shore) or the absence (by moving them away from farms) of cetaceans in the area. A site on Orkney with a larger protected range would have made a lot more sense.

SUMMARY:

This study's recommendations go well beyond the remit to advise on whether low frequency sound impacts cetaceans. By providing limited records of sound production up to 200khz it cannot be ascertained for sure that the system used to generate sounds is as clean above 2khz as our commercial RT1. Furthermore the test site is confounded by the presence of large quantities of mid frequency deterrent devices, and a more sensible approach would be to deploy an existing low frequency device into a protected area where there are no confounding mid frequency deterrents.

Response to Ace Aquatec (AA) comments to the previously published version of the SARF 112/LEAP final project report (now superseded):

AA1: The study uses a bespoke low frequency noise generator rather than a commercial system.

Response to AA1: The use of a bespoke sound transmission system was explicitly identified by SARF as a requirement within the scope of the project. We did discuss this with the project steering committee in the beginning, as we had similar concerns to those expressed by AA, but the board insisted on us using a generic rather than a specific commercial system.

AA2: In using this system, and failing to report sounds recorded up to 200khz, it is suspected that the equipment generates noise above 2khz which could be heard by cetaceans.

Response to AA2: We checked our data for higher harmonics and added a spectrogram showing the full broadband signal to the report (updated Figures 4 and 5 in the revised version). We are happy to share these recordings with AA, if requested. The spectrograms below, derived from SoundTrap recordings, show that, while there is some lower amplitude energy above 2 kHz (as stated and shown in the original report), energy is mostly concentrated below 10 kHz and is not detectable above background at 5 km distance. Peak energy is at about 2 kHz; the signal is described in more detail in the final report. The first spectrogram below (Figure 1A) is based on a recording made within 10 m of the loudspeaker (from the opposite side of the fish farm barge) and the second (Figure 1B) was made at 5 km distance from the loudspeaker (at mooring location C-5000).

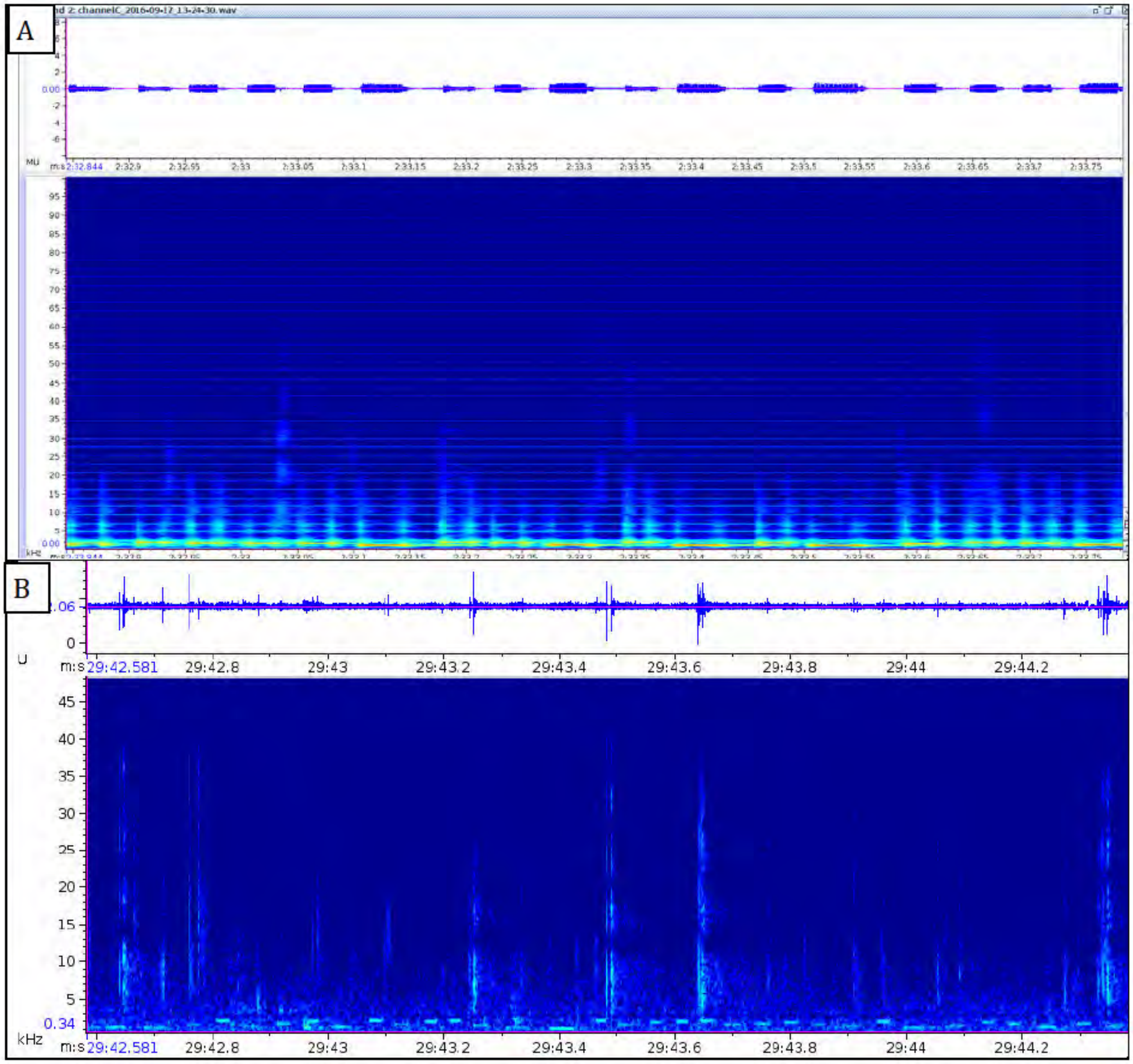


Figure 1. Soundtrap acoustic recordings of the LF signal at A) <10 m from the sound source, B) approximately 5000 m from the sound source (mooring C-5000).

AA3: Why should predator nets that kills seals and birds be promoted over triggered acoustic deterrents for example?

Response to AA3: We were proposing a benefit in reviewing current net materials and net tensioning methods as an alternative to continuous use of ADDs. Following comments on the final report we have slightly modified our final recommendations to focus on ADD use specifically, as this was the main topic of the report. However, we do still believe that all methods to prevent pinniped depredation, including non-acoustic ones, should be considered. In addition, if acoustic methods are being used in the future, there is an urgent need to establish their long-term efficiency in helping to prevent seal depredation, as well as reduce overall noise output and impacts on non-target species.

AA4: The study has not demonstrated that a low frequency system operating at 1-2khz impacts cetaceans – only that their device has potentially impacted a few cetaceans, possibly due to broadband noise at higher levels, and with the possibility of other local deterrents impacting the behaviour of the cetaceans detected.

Response to AA4: We disagree with this statement. Our results demonstrated more porpoise detections during periods with silent control versus periods with either high or low frequency signal playback. These results are clear and show a response by porpoises to the playback of our ADD-type signals regardless of signal type. As stated above, we are happy to provide access to recordings of our signals as requested by AA. As stated in the report, higher frequency signal harmonics, although present, were of much lower intensity than the peak frequency and are considered unlikely to, by themselves, have been the sole driver of the porpoises' responses observed. The potential presence of other background noise or ADD signals in the area from distant fish farm would have been there as part of the background noise (similarly to weather and ship noise) over all playback states and can therefore not explain on its own the different responses we observed towards the different playback signals. This has been discussed in the Discussion section of the report.

AA5: The studies do not seem to reflect the work and energy put in by manufacturers to use academic research to build upon and improve deterrent systems.

Response to AA5: The main scope of the project was to look at the impact of low-frequency versus high-frequency ADDs on porpoise detection rates and behaviour. We very much welcome and encourage the additional efforts by the manufacturers to reduce noise pollution beyond signal frequency adjustments and did not consciously seek to omit these from the report. However, efforts such as triggered sonar system or PAM de-activation of devices were beyond the scope of the current research project and were thus not discussed in detail. The wording of the report has been updated to better acknowledge the work going on in these areas; however, critical evaluation of these was unfortunately beyond the scope of the study.

AA6: We dispute this finding – we believe had the study been conducted with our commercial system which has harmonics above 2khz removed, that the finding would not have been the same. This is reflected in the current results being obtained from our system which is being analyzed by St Andrew's university in Wyre.

Response to AA6: We specifically state in our report that our results pertain to the signals tested in our study, i.e. an ADD-like signal centered at or below 2 kHz. As mentioned earlier, the decision to not use a commercially available system was made by the funders of this work and in discussion with the steering group. Our results comparing a lower versus a higher frequency ADD system stand as they are. If tests with other systems, e.g. RT1 tested in other environments, show different results then this is very interesting and worth discussing in more detail. However, this does not negate our finding that random playbacks of an ADD-like signal with peak frequencies at 2 kHz (as well as a 10 kHz signal) did result in fewer porpoise detections compared to silent control periods. Behavioural responses of animals are variable and often context-dependent. Hence conducting studies at different sites, different populations of animals and in different environmental contexts, is important and can highlight further research questions. In our original scope of work we for this reason proposed to also test the system on an ADD naive population of porpoises in the Netherlands. However, this work was deemed outside the scope of this study by funders and the steering group.

AA7: We would agree with point 4 – but whatever study is conducted needs to look at all mitigation measures being implemented. This should included sonar triggers, IOT (internet of things) devices co ordinating sound outputs, low frequency sound, electric fish and nets; PAM (Passive Acoustic Monitoring) deactivation etc.

Response to AA7: We agree.

AA8: While the low frequency system is derived from the US3, it has is own name: RT1.

Response to AA8: Thank you for this additional information. We will update the report accordingly.

AA9: The systems referred to in the Northridge study in 2013 were only US3s in name. In 2014 out deterrent build was handed over to Neptune Sonar, and they created a completely different method of sound generation in the system, and at different volume levels. No systems in Scotland retain the physical properties described here. There are currently 290 US3s in Scotland – they share a central intelligent core which is monitored via a portal in Dundee. The systems can co ordinate their sound generation to reduce duty cycle across the site as a whole. Similarly, they are all built to be sonar activated; this triggering system has been tested at Loch Duart and is being rolled out to all our rental deterrents this year. This will dramatically reduce duty cycle to below 1%.
Ferranti Thomson deterrents only exist in scientific labs – so I've no real idea why these are mentioned here. We stopped developing these back in 2004.

Response to AA9: Thank you for this additional information. We based our table on available information in the published and grey literature. In retrospect a questionnaire approach to different developers might have been the better solution, since as AA point out, a lot of current information does not seem to be in the public domain yet. Is the sonar triggering already being used on some sites? If so, what are the specifications for these systems? We would be very grateful if AA and other manufacturers would be willing to share their latest information on their devices with us so that the current table can be updated and reflect what is currently deployed. In the interim, we have elected to remove Table 1 altogether as it cannot be guaranteed to accurately reflect the present state of play in the industry.

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Response to AA10: We understand that a lot of effort has gone into developing these lower frequency systems by some of the manufacturers in an effort to reduce impacts on porpoises. However, we were asked by SARF to compare a lower frequency ADD system with a higher frequency ADD system, while not being able to use any one particular type of commercial system, and this comparison is what the report is based on. Our results showed that porpoises responded to both lower and higher frequency ADD-like systems and it is on these results that we base our recommendations.

AA11: Silent scrammer – Ace Aquatec has not produced the 'silent scrammer' triggers in 10 years. We have since developed a sonar trigger which is currently being used at Loch Duart and will be rolled out to all US3 devices over this year.

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AA12: It seems very strange that the authors support a cetacean friendly device designed by academics Vincent Janik and Thomas Goetz) over various cetacean friendly devices developed elsewhere.

Response to AA12: We are mentioning the Janik/Goetz method, since this method is described in the publicly accessible peer-reviewed literature, and hence part of the literature reviewed for this report, rather than an attempt to specifically endorse this method. We have since updated and revised the Section 2.3 in question in an attempt to dispel any notion of bias that may have existed. We are happy to add additional information on sonar trigger systems and PAM deactivation methods, which are currently not publicly available, if AA and other developers would be willing to share those. Also, since the main focus of our work and the report are acoustic deterrent we did not attempt a comprehensive review of seal depredation mitigation here.

AA13: It states there is little scientific backing for producing a deterrent system operating at 1-2khz.

Response to AA13: We are unsure which sentence in the report the above statement is referring to. We have tried to describe the currently available systems as known to us from a literature and web search. As stated earlier, we are happy to discuss additional methods related to ADD use that are currently used with AA and other developers.

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AA17: P26. If we compare the provided plot of the LF output used in the study we see sounds produced above 2khz all the way up to 12khz – well in the sensitive hearing range of porpoises. The authors mention the harmonics but point out they are probably too low an amplitude to bother porpoises.

Response to AA17: See comments about higher frequencies due to signal generation above.

AA18: P29. Field tests were carried out in the sound of Mull. The authors state quite flippantly that they cannot control for other seal deterrents operating in the area. We would argue that any number of local sites could be impacting both the presence (by driving cetaceans closer to shore) or the absence (by moving them away from farms) of cetaceans in the area. A site on Orkney with a larger protected range would have made a lot more sense.

Response to AA18: The site was selected for logistical reasons (access to infrastructure, expected likely presence of porpoises, reduced ship time/ability to deploy a large acoustic array to fit with overall project funding etc.). We agree that the potential presence of other ADDs in the area was not ideal. However, we would assume that if present, distant ADDs would collectively be continuously detectable, and thus the variable response of porpoises to ADD signals versus quiet periods would not be explained by the presence of distant ADDs. In our original project proposal we did suggest a control site in the Netherlands to test signals on a naive porpoise population; this was rejected by the funding body and steering committee, who wanted us to concentrate on sites in Scotland.

From:	Steven Benjamins
To:	Lepper, Paul; Ben Wilson; Denise Risch; Richard Slaski; Craig Burton; Caroline Carter; George Lees
Cc:	Sandra Gray
Subject:	Draft responses to OTAQ, Ace Aquatec
Date:	26 October 2018 11:03:10
Attachments:	Response to Ace Aquatec_FINAL DRAFT_20181026.docx Response to OTAQ_FINAL DRAFT 20181026.docx

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Hello all,
Please find attached the near-final versions of our responses to OTAQ and Ace Aquatec, which will be sent out to them by SARF once the final wording is approved, as discussed at Wednesday's Steering Group meeting. I have drafted the OTAQ response this morning on the basis of our previous email trail, so this represents a new document that none of you will have seen yet – your thoughts are very welcome! The AA response has also been slightly amended (using Track Changes) following our meeting, as I realised our original wording suggested that amendments to the report, based on information provided by them, might still be possible. I have elected to remove that notion from the text as it presently stands to prevent further delay to publication but I am open to discussion if anyone feels strongly about this. Please let me know if you feel there are still concerns about the wording of both these letters so that we can amend them as needed.

Many thanks,
Steven

Dr. Steven Benjamins
Lecturer in Marine Vertebrate Ecology
SAMS (Scottish Association for Marine Science)
Oban
Argyll, Scotland, UK
PA37 1QA

Tel: +44(0)1631-559449 (office)
Tel: +44(0)1631-559000 (switchboard)
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E-mail address: Steven.Benjamins@sams.ac.uk
https://www.sams.ac.uk/people/researchers/benjamins-dr-steven/

Response to Ace Aquatec (AA) comments to the previously published version of the SARF 112/LEAP final project report (now superseded):

AA1: The study uses a bespoke low frequency noise generator rather than a commercial system.

Response to AA1: The use of a bespoke sound transmission system was explicitly identified by SARF as a requirement within the scope of the project. We did discuss this with the project Steering Group in the beginning, as we had similar concerns to those expressed by AA, but the Steering Group directed us to use a generic rather than a specific commercial system.

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AA2: In using this system, and failing to report sounds recorded up to 200khz, it is suspected that the equipment generates noise above 2khz which could be heard by cetaceans.

Response to AA2: We checked our data for higher harmonics and added a spectrogram showing the full broadband signal to the report (updated Figures 4 and 5 in the revised version). We are happy to share these recordings with AA, if requested. The spectrograms below, derived from SoundTrap recordings, show that, while there is some lower amplitude energy above 2 kHz (as stated and shown in the original report), energy is mostly concentrated below 10 kHz and these high-frequency components are not detectable above background at 5 km distance. Peak energy is at about 2 kHz; the signal is described in more detail in the final report. The first spectrogram below (Figure 1A) is based on a recording made within 10 m of the loudspeaker (from the opposite side of the fish farm barge) and the second (Figure 1B) was made at 5 km distance from the loudspeaker (at mooring location C-5000).

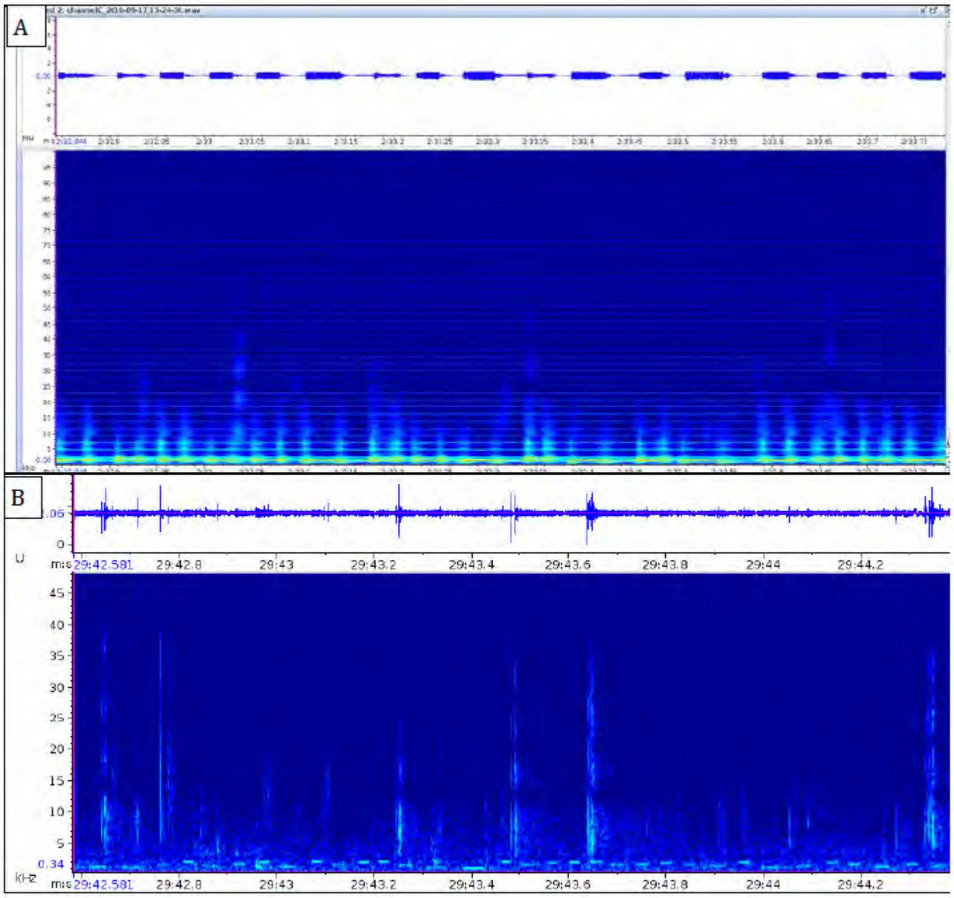

Figure 1. SoundTrap acoustic recordings of the LF signal at A) <10 m from the sound source, B) approximately 5000 m from the sound source (mooring C-5000).

AA3: Why should predator nets that kills seals and birds be promoted over triggered acoustic deterrents for example?

Response to AA3: We were proposing a benefit in reviewing current net materials and net tensioning methods as an alternative to continuous use of ADDs. Following comments on the final report we have slightly modified our final recommendations to focus on ADD use specifically, as this was the main topic of the report. However, we do still believe that all methods to prevent pinniped depredation, including non-acoustic ones, should be considered. In addition, if acoustic methods are going to be used, there is an urgent need to establish their long-term efficacy in helping to prevent seal depredation, as well as reducing overall noise output and impacts on non-target species.

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AA4: The study has not demonstrated that a low frequency system operating at 1-2khz impacts cetaceans – only that their device has potentially impacted a few cetaceans, possibly due to broadband noise at higher levels, and with the possibility of other local deterrents impacting the behaviour of the cetaceans detected.

Response to AA4: We disagree with this statement. Our results demonstrated more porpoise detections during periods with silent control versus periods with either high or low frequency signal playback. These results are clear and show a response by porpoises to the playback of our ADD-type signals regardless of signal type. As stated above, we are happy to provide access to recordings of our signals as requested by AA. As stated in the report, higher frequency signal harmonics, although present, were of much lower intensity than the peak frequency and are considered unlikely to, by themselves, have been the sole driver of the porpoises' responses observed. The potential presence of other background noise or ADD signals in the area from distant fish farm would have been there as part of the background noise (similarly to weather and ship noise) over all playback states and can therefore not explain on its own the different responses we observed towards the different playback signals. This has been discussed in the Discussion section of the report.

AA5: The studies do not seem to reflect the work and energy put in by manufacturers to use academic research to build upon and improve deterrent systems.

Response to AA5: The main scope of the project was to look at the impact of low-frequency versus high-frequency ADDs on porpoise detection rates and behaviour. We very much welcome and encourage the additional efforts by the manufacturers to reduce noise pollution beyond signal frequency adjustments and did not consciously seek to omit these from the report. However, efforts such as triggered sonar system or PAM de-activation of devices were beyond the scope of the current research project and were thus not discussed in detail. The wording of the report has been updated to better acknowledge the work going on in these areas; however, critical evaluation of these was unfortunately beyond the scope of the study.

AA6: We dispute this finding – we believe had the study been conducted with our commercial system which has harmonics above 2khz removed, that the finding would not have been the same. This is reflected in the current results being obtained from our system which is being analyzed by St Andrew's university in Wyre.

Response to AA6: We specifically state in our report that our results pertain to the signals tested in our study, i.e. an ADD-like signal centered at or below 2 kHz. As mentioned earlier, the decision to not use a commercially available system was made by the funders of this work and in discussion with the Steering

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Group. Our results comparing a lower versus a higher frequency ADD system stand as they are. If tests with other systems, e.g. RT1 tested in other environments, show different results then this is very interesting and worth discussing in more detail. However, this does not negate our finding that random playbacks of an ADD-like signal with peak frequencies at 2 kHz (as well as a 10 kHz signal) did result in fewer porpoise detections compared to silent control periods. Behavioural responses of animals are variable and often context-dependent; hence conducting studies at different sites, different populations of animals and in different environmental contexts, is important and can highlight further research questions. In our original scope of work we for this reason proposed to also test the system on an ADD naive population of porpoises in the Netherlands. However, this work was deemed outside the scope of this study by funders and the project Steering Group.

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AA7: We would agree with point 4 – but whatever study is conducted needs to look at all mitigation measures being implemented. This should included sonar triggers, IOT (internet of things) devices co ordinating sound outputs, low frequency sound, electric fish and nets; PAM (Passive Acoustic Monitoring) deactivation etc.

Response to AA7: We agree.

AA8: While the low frequency system is derived from the US3, it has is own name: RT1.

Response to AA8: Thank you for this additional information. We will update the report accordingly.

AA9: The systems referred to in the Northridge study in 2013 were only US3s in name. In 2014 out deterrent build was handed over to Neptune Sonar, and they created a completely different method of sound generation in the system, and at different volume levels. No systems in Scotland retain the physical properties described here. There are currently 290 US3s in Scotland – they share a central intelligent core which is monitored via a portal in Dundee. The systems can co ordinate their sound generation to reduce duty cycle across the site as a whole. Similarly, they are all built to be sonar activated; this triggering system has been tested at Loch Duart and is being rolled out to all our rental deterrents this year. This will dramatically reduce duty cycle to below 1%.
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Response to OTAQ comments to the previously published version of the SARF 112/LEAP final project report (now superseded):

The below comments illustrate how the various points raised by OTAQ have been addressed in the present version of the report:

1. Concerns had been raised that further clarity was needed about precisely which ADD systems had been used in the experiments described in this report. The use of a bespoke sound transmission system, rather than testing existing ADD systems, was identified by SARF as an important requirement within the scope of the project as well as being strongly supported by the project's Steering Group, and we have adhered to this requirement throughout. To make this point explicitly, the third bullet point in the Executive Summary now reads as follows:

   "The present experiment aimed to compare the effectiveness of this approach by comparing the acoustic and behavioural responses of wild harbour porpoises to two artificial signals: a high-frequency signal ('HF'; 8-18 kHz), and a low-Frequency signal ('LF'; 1-2 kHz). <u>To comply with the funder's original project brief, no actual ADDs of any particular brand were tested as part of this research, or form part of any results of this research, in order to maintain impartiality towards all suppliers</u>. The chosen field site was Bloody Bay (northern Sound of Mull, western Scotland), an area known to be frequented by porpoises, which contained a fish farm that did not use ADDs. Harbour porpoise presence within the ensonified area during repeat exposures was evaluated using visual and passive acoustic monitoring methods." [N.B.: text underlined for illustrative purposes].

   The underlined text above is based on wording proposed by OTAQ in previous communications and will hopefully allay any remaining concerns that any manufacturers of existing ADDs, including OTAQ, were in any way directly affiliated with the present report. The point is subsequently repeated in Section 3.3 (Acoustic Playback Signal Design, p.14), and in Section 6 (Recommendations, p.52).

2. Concerns had been raised about the accuracy of the information contained in Table 1 in the previous version of the report. This table attempted to aggregate signal characteristics of current, past and future ADD types to provide background context. This table was based on available information in the published and grey literature. It has since become apparent that a significant number of new developments re: ADD design have occurred that are not available in the public domain, potentially for reasons of commercial sensitivity. As a result, and to avoid inadvertent misrepresentation of any ADD product currently available, we have elected to remove Table 1 entirely from the report. We have also generally sought to reduce the number of times that actual ADD systems are referred to, apart from where such a reference is directly relevant (e.g., when describing the design of the generic signals in Section 3.3). Referring to the same concerns described above under Pt.1, a thorough review of the report text has been carried out and OTAQ is now not mentioned anywhere in the report.

We hope that these edits will serve to allay any residual concerns of inadvertent association of OTAQ and its products with the findings of the present SARF112/LEAP report.

From: Sandra Gray
To: [redacted]
Cc: "Sandra Gray"
Subject: SARF112 - ADD"s
Date: 06 December 2018 19:04:51
Attachments: SARF Final Report Evaluation Form - Directors.doc

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Dear [redacted]

Now that we have the revised report for SARF112 which addressed the concerns of industry on the original report, please could I trouble you to complete a fresh evaluation form.

Please find the evaluation form attached.

If you need anything further, please do let me know.

Many thanks,

Sandra Gray
SARF Secretariat
PO Box 7223
Pitlochry
PH16 9AF

Tel: 01738 479486

SARF - Company Registered in Scotland - SC267177
SARF - Charity Registered in Scotland - SC035745
EU State Aid Registration No: X939 2009

Website:
www.sarf.org.uk

From: Sandra Gray
To: Alastair Mitchell ; Alex Adrian; Craig Burton; David Sandison ; "Doug McLeod"; Douglas Sinclair; George Lees; Iain Berrill; Iain Sutherland; Nick Lake; Piers Hart ; rob.raynard@scotland.gsi.gov.uk
Cc: r.slaski@sarf.org.uk
Subject: SARF112 - ADDs
Date: 08 February 2019 15:35:18
Importance: High

Dear All,

SARF112 - Influence of low frequency ADDs on cetaceans in Scottish coastal waters

We have now completed a second peer review for the above project.

Please find attached the final report (revised in light of industry concerns) & the 2nd evaluation reports from the 3 reviewers.

Please could you let us have any comments that you might have by **Wednesday 20th February 2019.**

After this date the report will be published & final payment made to the contractor.

Kind regards,

Sandra Gray
SARF Secretariat
PO Box 7223
Pitlochry
PH16 9AF

Tel: 01738 479486

FINAL PROJECT REPORT EVALUATION FORM

Key - *** indicates reviewer comment added January 2019*

Project Number: SAR112	Completion Date: May 2018 ***updated Jan '19*

Project Title: INFLUENCES OF LOWER-FREQUENCY ACOUSTIC DETERRENT DEVICES (ADDS) ON CETACEANS IN SCOTTISH COASTAL WATERS

1. In your view have the scientific objectives been achieved. If not, does this need to be addressed by SARF?

Objectives 1 to 3 were achieved via a well planned and executed research programme.
*** I have downgraded the "collate data" objective (#1), based on the exchanges that have taken place since the original final report was submitted.*

Regarding Objective 4, it has proven difficult to discern the effects of "low" versus "high" frequency sounds on harbour porpoises during field experiments, thereby curtailing the primary goal of the project.

1. Collate data on key acoustic characteristics of ADD devices
    - Note, limited information available from manufacturers on specs of commercial devices
    - *** Stakeholder exchanges since April 2018 review clarify that this paucity of info stemmed from limited engagement with ADD manufacturers during early stages of the project. Related to this, the misperception by manufacturers, that failure to deploy commercial devices invalidates the project outcomes, could have been avoided if the brief had been conveyed clearly to stakeholders at the outset.*
2. Theoretically determine the sensitivity of harbour porpoises and bottlenose dolphins to 'lower frequency' ADD signals
    - Achieved via literature review
    - *** some positive edits have been made in response to manufacturer comments.*
3. Implement a robust field-based study on an active fish farm, comparing porpoise responses to simulated lower and "standard" ADD sounds
    - *** the complex issue of creating "clean" low frequency signals was not apparent within the original report. This has been aired extensively between Ace Aquatec and the authors, and a series of clarifications and additional data incorporated into the updated report. To the non-specialist, the authors appears to have addressed manufacturer concerns, 'though I defer to the engineering experts on this.*
    - Note, acoustic monitoring was partly compromised by failure (incl. battery exhaustion) and loss of some devices in the field. This was taken into account during data analysis and interpretation.
    - *** no change*
    - Note a potential confounding factor in reduced power output of the bespoke sound signals, when compared to commercial ADDs
    - *** no change*
    - The sub-objective of discerning effects of low frequency ADD on porpoise behaviour using video measurements was not met owing to few and distant sightings. This did not compromise the overall project.
    - *** no change*
4. Review and analyse results from ADD outputs and empirical field results, with respect to impact of lower frequency ADDs on cetaceans
    - Note the confounding effects of other variables, well described in the report.
    - *** improved description in updated report*

- o Note the absence of recommendations on use of ADDs in context of marine aquaculture and developing regulatory frameworks in Scottish waters. ***The discussion should be revised to address this.***
- o *** still not addressed (note that this aspect wasn't raised as a shortcoming by the ADD manufacturers)*

2. Comment on the overall results of the project, including their significance for SARF.

The LEAP project has yielded interesting findings on spatial, diurnal and seasonal behaviour differences among harbour porpoises in the Sound of Mull, as measured by acoustic monitoring.

However, the primary goal of comparing the effects of low frequency versus high frequency ADDs on cetaceans in the vicinity of fish farms has proven elusive. The authors have discussed potential reasons for this and have suggested further work aimed at reducing confounding factors.
*** methods, technical limitations, discussion and recommendations have been improved throughout*

An attempt has been made to include seals in the analysis of effects of low frequency ADDs and to compare the behavioural responses of seals versus porpoises. Noting that effects on seals were not part of the SARF call for proposals, that significant assumptions have been drawn from limited data, along with the various stakeholder sensitivities around the use and efficacy of ADDs, this reviewer urges caution on whether & how to refer to seal effects in the final report
*** this reservation has been taken into account in the updated report.*

Related to the previous comment, the authors should discuss to what extent recommendations can be made on the use of low frequency ADDs, based on the current findings. This was an important aspect of the original SARF Call (to guide regulation of ADDs, etc), which has not been addressed in the draft report.
*** still not addressed*

3. Is there a need for further work? If so, explain.

It is not clear that investing further funds to evaluate low frequency ADDs in the field would produce clearer results than in the current project, owing to the complexities involved.
*** knowledge gaps and proposed actions are better developed in the updated report, although it still appears to be a highly complex undertaking to obtain the sought-for information.*

Overall marking

1 - outstanding results
2 - results significantly above expectation
3 - satisfactory results
4 - results below expectation
5 - poor results

*** Amid the debate between the ADD manufacturers and the science team, the team's diligent efforts to fulfil the project brief should not be overlooked. A closer steer on industry engagement at the outset may well have yielded a less contentious outcome. Overall marking now closer to 3 than 2*

REFEREE ID: REF01

Date 13 May 2018 ** *31 January 2019*

Please indicate whether you wish to receive payment (Yes/No)   Y

Additional Comments**:**

SARF112 updated final report - Reviewer notes

OTAQ email

- Table 1 removed, and all references to OTAQ. **OK**

Ace Aquatec letter

  - AA1 - The study uses a bespoke low frequency noise generator rather than a commercial system. **OK** *(explained by scope of the Call)*
  - AA2 – AA suspect equipment generates noise above 200KHz. **OK?** *Detailed response in cover note, but unclear how much of this translates to final report*
  - AA4 – Study hasn't demonstrated that low frequency system at 1-2khz impacts cetaceans. **OK?** *Authors dispute & have referred to in the Discussion*
- Summary and Conclusions section
  - AA3 – why non acoustic deterrents? **Partially met**
  - AA5 – ADD use in Scotland needs to account for manufacturer activities **OK** *acknowledged, but beyond scope*
  - AA6 – Low frequent devices deter predators, disputed by AA. **Partially met** – *Explained in cover note, but has report text been updated to match?*
  - AA7 – a study on acoustic systems is needed – needs all implemented measures. **OK** *Agreed by authors, but this is a future action*
- Specific comments
  - P11/AA8 - RT1 name. **OK**
  - P11 & P12/AA9 - clarify not US3s; dispute Ferranti Thomson deterrents. **OK** *Table 1 removed and request made for cos. to share details*
  - P20/AA10 – refer to Mar Scotland Janik report. **Not done?**
  - P20/AA11 – correct silent scrammer. **OK**
  - P20/AA12 – dispute "academic" system. **OK**
  - P20/AA13 – acknowledge science evidence, low frequency. **OK?**
    - Reviewer unclear if the following is extract appropriate – "Questions do, however, remain more generally regarding the effects of low-frequency ADD signals on other non-target species, including fish as well as odontocete and mysticete cetaceans (baleen whales)."
  - P21/AA14 – startle response / patent. **OK** *Reference to patenting removed*
  - P22/AA15 – no commercial ADD = invalid? **OK**
  - P22/AA16 - Impacts of filter, Ace Aqua requests access to records. **Partially met**
    - *Authors updated report with extra data & expressed happy to share further data 1-2-1.*
  - P26 –
    - AA17 dispute whether or not low amplitude 12khz impacts porpoises. **Unclear**
      - *Authors refer AA to previous comments, higher frequencies due to signal generation*
    - request data to check for sounds above 12khz **OK**
    - request data on output up to 200khz **OK**

        - broadband sounds removed? Evidence requested. **Not done?**
    - p29/AA18 – Sound of Mull location, why? **OK**
        - Impacts of mid frequency devices? **Not done?** *Explained in cover note, but report text not updated to match?*

FINAL PROJECT REPORT EVALUATION FORM

Project Number: SARF112	Completion Date:

Project Title: Influences of lower-frequency Acoustic Deterrent Devices (ADDs) on cetaceans in Scottish coastal waters

1. In your view have the scientific objectives been achieved. If not, does this need to be addressed by SARF?

Yes. The project has achieved the scientific objectives that were set out in the brief. Furthermore – their findings have been presented in a neutral and factual way, as would be expected from a well-researched and executed project. This is important to emphasise in view of the level of criticism surrounding this project.

2. Comment on the overall results of the project, including their significance for SARF.

The main conclusion, that ADD's do not seem to work in deterring seals and may not actually be dolphin safe, is well argued and clearly justified. However, this conclusion was bound to generate criticism from the commercial manufacturers of ADD's. To that extent this project has been controversial but that in itself in not a bad thing and should not reflect badly on either the contractors or SARF.

I further understand that the contractors have undertaken considerable additional work in order to address some of the issues raised by the commercial manufacturers of ADD's

3. Is there a need for further work? If so, explain.

The main question in my mind is whether or not the commercial ADD's actually work while those devices made by the researchers do not – possibly reflecting the fact that the companies involved in ADD production have worked hard to perfect and refine their product whereas the researchers only used the most basic of equipment? An interesting piece of follow up work might be to compare the efficacy of commercial ADD's with the contractors' own kit

Overall marking 3

1 - outstanding results
2 - results significantly above expectation
3 - satisfactory results
4 - results below expectation
5 - poor results

REFEREE ID: REF02 Date 30 December 2018

Please indicate whether you wish to receive payment (Yes/No) Invoice to follow

Additional Comments**:**

As already indicated, I was concerned that I did not have the technical competence to challenge or even question the criticisms of this research made by the companies involved in ADD production.

However, on reflection, as a reviewer, I am not asked to provide technical comments or a critique. Instead I am asked to evaluate the project and this I have done.

FINAL PROJECT REPORT EVALUATION FORM

Project Number: 112	Completion Date: October 2018

NOTE. Following initial completion of this report in April 2018, and referee evaluation in May 2018, minor revisions to the report were implemented, as a consequence of issues raised by ADD developers cited in it. These revisions do not alter, significantly, the report content and merit, and so the review provided by this referee previously is retained, albeit updated slightly where justified by the revisions made.

Project Title: Low-frequency ADDS and Porpoises (LEAP); Influences of lower-frequency acoustic deterrents (ADDS) on cetaceans in Scottish coastal waters

1. In your view have the scientific objectives been achieved. If not, does this need to be addressed by SARF?

Yes; this is a thorough report that is consistent with the project scope. One proposed component of the field work (visual tracking of porpoises) proved not to be viable due to low porpoise numbers in the near-field area which could, readily, be tracked. But this was a subsidiary element of the work and does not detract significantly from the robustness of the rest of the study.

2. Comment on the overall results of the project, including their significance for SARF

The findings from this study were hindered by a relatively lower occurrence of harbour porpoise in the area than was expected. Monitoring conducted prior to the trial showed that the detections were already reducing before the trial commenced.

Notwithstanding the relatively low sample size, this study finds that there was a reduction of porpoise detections in the near-field when either the LF or HF signal was emitted, in comparison to the silent periods. There was not a discernible pattern in the far-field data. The data show a reduction in detections, they do not show a complete deterrence effect. Having said that, this shows that there is a localised deterrence effect from acoustic signals even with porpoise that are likely to be familiar with ADDs. The reduction in detections appears, generally, less during LF signal transmission than during HF signal transmission, but not significantly so. Though the study used replicated sound signals, rather than actual ADDs, this suggests caution about advocating ‘low frequency ADDs’ as a means of minimising or avoiding effects on cetaceans.

This study used a signal that is lower in volume than most commercially available ADDs; it is possible that the localised deterrence may be over a greater distance when the volume is increased.

This study also considers the environmental variables and finds that variation in detections is driven primarily by environmental variability rather than the experimental signal (in particular the day-night cycle) in the far field. Signal type appears important in the near field (out to 800m) This study notes the heterogeneity of habitat use by porpoise, and that diel and seasonal cycles may be more important here than an acoustic deterrent signal.

Although seals were not the focus for this study, their presence was noted in enough detail to consider their response to the acoustic trial. Here, seals were not noticeably deterred by either signal. This clearly has some bearing on the relevance of using ADDs to deter seals from fish-farms in the first place (again noting the caveat that the study employed replicated sound signals not commercial ADDs).

3. Is there a need for further work? If so, explain. This study adds to the debate on effects of ADDs on small cetaceans, however there are still uncertainties and therefore it does not conclusively elucidate the effect of ADDs. The overall abundance of harbour porpoise in the study area was lower than had been expected during project planning (possibly reflecting seasonal variations) and this precluded use of the 'visual tracking' approach as well as reducing overall sample size for the CPOD work. Re-running the monitoring earlier in the season, at this location (or applying it another suitable location), would be highly beneficial in terms of validating the results, especially given the unexpected findings, and elucidating near field behaviour of porpoises in response to signal transmission. Moreover, it would provide the opportunity to check more thoroughly the apparent absence of effects of signal transmission on seals, which would be of considerable significance in relation to the applicability of ADD use as seal deterrents. This study used a synthetic signal, as was recommended; however, it is not known what component of an acoustic signal causes an animal to alter its behaviour. It is difficult to look at this when there is a lack of publically available information on the commercial ADDs.
Overall marking   1 - outstanding results 2 - results significantly above expectation 3 - satisfactory results *(but see below)* 4 - results below expectation 5 - poor results
REFEREE ID: REF03   Date 18 January 2019

Additional comments

- **Overall marking**. As noted above, porpoise numbers in the study area proved far lower than expected during project planning, reducing the volume of CPOD data for analysis and precluding the use of the visual tracking approach. As a result it is difficult to rate the results as 'significantly above expectation' and hence the overall marking of 3. That said the authors have done an excellent job of analysing the data that were secured, considering the relevant issues and controlling factors that may have influenced these, and presenting a clearly written, illustrated and presented report.
- **HF / LF Response**. While the results illustrate a clear reduction in porpoise detection (relative to silent control periods) when either high or low frequency signals were being transmitted, the graphics (Figure 13 especially) suggest this reduction was less apparent during LF signal transmission than that of HF signals. Indeed, without a silent control, one could argue from these data that LF signals had a demonstrably lower impact on porpoise detections than did the HF signals. Little is made of this in the report, the difference in response seeming to be underplayed. While it is understood that the differences in response (to the two signals) were not statistically significant, it would have been of interest to see this issue discussed in more detail than it is.

SARF112: Low-Frequency ADDs and Porpoises (LEAP)

Influences of lower-frequency Acoustic Deterrent Devices (ADDs) on cetaceans in Scottish coastal waters

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EXECUTIVE SUMMARY

- Acoustic Deterrent Devices (ADDs) are widely used in the Scottish finfish aquaculture sector as a non-lethal means to deter depredation of Atlantic salmon (*Salmo salar*) 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, potentially impacting 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 10-20 kHz down to <2 kHz, where porpoises' hearing sensitivity is reduced compared to seals.

- The present experiment aimed to compare the effectiveness of this approach by comparing the acoustic and behavioural responses of wild harbour porpoises to two artificial signals: a high-frequency signal ('HF'; 8-18 kHz), and a low-Frequency signal ('LF'; 1-2 kHz). To comply with the funder's original project brief, no actual ADDs of any particular brand were tested as part of this research, or form part of any results of this research, in order to maintain impartiality towards all suppliers. The chosen field site was Bloody Bay (northern Sound of Mull, western Scotland), an area known to be frequented by porpoises, which contained a fish farm that did not use ADDs. Harbour porpoise presence within the ensonified area during repeat exposures was evaluated using visual and passive acoustic monitoring 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 deployed from the fish farm infrastructure. PAM data were collected using C-PODs (porpoise click train detectors), as well as several broadband recorders. Whenever conditions permitted, visual observers collected sightings of porpoises and other species as well as environmental data from an elevated onshore vantage point. An experimental video tracking procedure was implemented to record small-scale responsive movement of surfacing porpoises upon onset of signal transmission.

- Signal transmissions varied randomly between the HF signal, the LF signal and a silent control. All transmissions, including the silent 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 porpoises or other cetaceans were sighted. Outside regular observing hours (e.g., at night) or during periods of poor weather, the system could be set to Night mode, which involved transmission of a regular sequence of signals (including silent control) on a 50% duty cycle (2 hours on, 2 hours off) until actively interrupted. The system was controlled remotely through text messages over the GSM mobile phone network.

- The experimental period during which signals were transmitted lasted a total of 33 days (08/09 - 11/10/2016). During this period, 138 transmissions occurred, including 53 of the HF signal, 38 of the LF signal, and 47 silent controls. All the equipment, with the exception of 2 C-PODs and one broadband recorder, was recovered by 17/10/2016. One C-POD was found to

have malfunctioned, bringing the total number of C-POD datasets available for further analysis to 19.

- Visual observations of porpoises were infrequent (23 sighting events over 19 days of visual observations), despite generally good observing conditions. Most porpoises were sighted well outside Bloody Bay within the central and northern Sound of Mull, particularly towards the entrance to Loch Sunart. As a result, the video tracking procedure was often unable to resolve surfacing animals to assess responses to different ADD signals, although the validity of the method itself was confirmed. Groups of bottlenose dolphins were observed on four occasions and one minke whale was sighted. In contrast to the scarcity of cetacean sightings, harbour seals were observed on an almost daily basis, often in close proximity to the fish farm.

- The C-POD array provided a high-resolution dataset on presence of echolocating porpoises over the course of the experiment. Datasets were analysed using nonparametric statistical tests and GAM-GEE models to investigate the relative importance of different covariates, including signal transmission, in determining porpoise acoustic presence. Porpoise detections (defined as 'Porpoise-Positive Minutes' or PPMs) varied considerably across the array. Broadly speaking, PPM detection rates were higher in the central and northern Sound of Mull when compared to the Bloody Bay area, particularly compared to waters immediately surrounding the fish farm where detection rates were low.

- When assessing the effect of different signal transmissions, porpoise detection rates at most moorings were substantially lower during the signal transmissions than during silent control periods, suggesting that transmission of both HF and LF signals reduced the probability of porpoise detections. This was contrary to initial expectations that LF signal transmissions would have less of an impact on porpoise behaviour and therefore generate comparable detection rates to those observed during silent control periods. A statistically significant difference between porpoise detection rates during the different treatments was demonstrated for aggregated data from across the entire array as well as among the Nearfield moorings, although not among the Farfield moorings, using nonparametric Kruskal-Wallis tests. No significant differences in porpoise detection rates could be demonstrated between LF and HF signals, whereas detection rates during silent control periods were significantly higher than during transmissions of either signal. Higher-frequency signal components were present but were considered less likely to be the cause of the observed results due to their low signal strength compared to the main signal. The results of this study therefore suggest that LF signals, as defined here, may also affect harbour porpoise behaviour.

- To investigate relative importance of signal type and various environmental factors in more detail, C-POD data were also analysed using GAM-GEE modelling approaches. Two series of GAM-GEE models were run, one (Series A) only based on data collected during experimental transmissions, and one (Series B) based on all data (and therefore generally on a larger total number of porpoise detections). Models were run on datasets from individual moorings as well as on aggregations of data from multiple moorings, as long as the underlying datasets contained at least 50 PPMs.

- Based on Series A GAM-GEE modelling outcomes, ADD signal type was important in determining porpoise detection probability at distances up to 800 – 1000 m from the sound source. Once moorings deployed at greater distances were included, other covariates (such as the ebb-flood and spring-neap tidal cycle) became more important. For the moorings closer to the sound source (out to 800 m), modelling results confirmed large differences between silent control periods and both LF- and HF-signals, but no clear distinction between the two signals, in line with results from the nonparametric Kruskal-Wallis tests.

- Based on Series B GAM-GEE modelling outcomes, in all models across the array, observed 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 the night, 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 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 results. Pre-experimental PPM 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 for unknown reasons. 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 PPM detection rates at the fish farm barge. Pre- and post-experimental monitoring results both indicated continued strong influence of the day-night cycle on PPM detection rates, with the vast majority of detections occurring at night in both datasets.

- 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 numbers of seals observed at the surface. The results therefore did not support the assumption that either ADD signal, as defined in the present experiment, might result in seals leaving the immediate area around the fish farm.

- Based on the experimental results, the present study provides no strong evidence that widespread application of commercially available lower-frequency ADDs with signal characteristics similar to those tested would, by themselves, result in significantly reduced risk of acoustic impacts on harbour porpoises in Scottish waters, when compared to existing ADD signals.

- Given the results presented here, a number of recommendations can be made about use of LF-ADD signals, and ADDs more broadly, in Scottish finfish aquaculture:

  Recommendation 1: The present experiment has shown that use of continuous operation LF-ADD signals, with signal characteristics similar to the ones used in this experiment, cannot be assumed to entirely reduce collateral impacts of noise on non-target species such as porpoises. Further development and investigation of use of all non-lethal methods to address seal depredation is recommended.

  Recommendation 2: To improve understanding of ADD usage in Scottish aquaculture, it is recommended that a formal monitoring programme be developed to collect accurate information on ADD distribution and usage patterns. This will make it easier to document ADD-associated noise emissions and their potential impacts in the context of wider conservation activities such as the establishment of Marine Protected Areas. This improved understanding is also relevant in the light of other regulatory requirements to report marine noise pollution (e.g., under the EC Marine Strategy Framework Directive; EC 2008).

Recommendation #3: Given the results from this study and the current extent of ADD presence in Scottish coastal waters (Findlay et al. 2018), it is recommended that efforts be undertaken to 1) clearly establish the efficacy of ADDs in terms of long-term, successful deterrence of seals from impacting fish farms; 2) clarify which signal characteristics and/or modes of operation (e.g., loudness, frequency composition, duty cycle, signal repetitiveness) contribute to the effectiveness or otherwise of different ADD models, and 3) identify which other variables (e.g., time of year, weather, presence of fish farm staff) might affect the probability of seal depredation events and apparent ADD effectiveness.

1 INTRODUCTION: ADDS IN SCOTLAND

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

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

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

Over the years, several different ADD types have been developed, many of which are available commercially. While up to five different models of ADDs are known to have been used in Scottish finfish aquaculture (Northridge et al. 2010, 2013; Coram et al. 2014; Lepper et al. 2014), three of these (e.g., Airmar dB Plus, as well as models by Terecos and Ace Aquatec) appear to account for the majority of ADDs in current use in the sector (Findlay et al. 2018, Figure 1). The various models differ in terms of their acoustic characteristics (e.g., signal type, duty cycle, frequency range and amplitude) as well as in terms of power supply and cost (e.g., Lepper et al. 2004; Coram et al. 2014; Lepper et al. 2014). In general, most systems transmit single frequency (between approximately 5 – 30 kHz) tonal sinusoidal bursts, with source levels typically between 175 and 195 dB re 1 µPa (RMS; Lepper et al. 2014; Götz & Janik 2013). However, signal structure and source levels of ADDs often remain poorly described and field measurements do not always match information provided by manufacturers (Coram et al. 2014). Examples of ADD spectrograms recorded in Scottish coastal waters (Findlay et al. 2018) are provided in Figure 1 to illustrate the signal diversity among these devices.

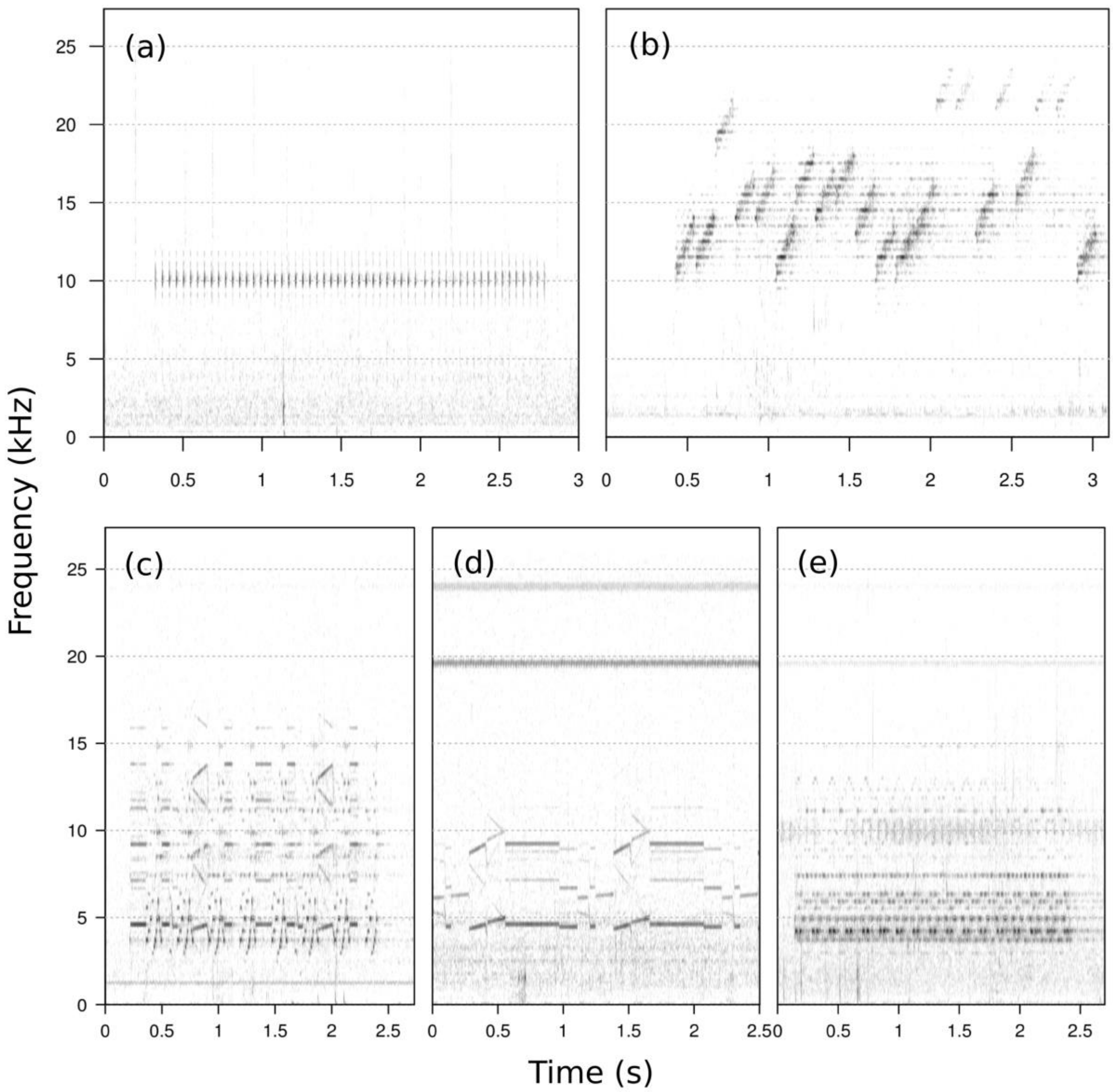

Figure 1. Examples of ADD signal types (figure amended from Findlay et al. [2018]; after Lepper et al. 2014). Spectrogram parameters: FFT size = 1024 points, overlap = 50%, sample rate = 96 kHz; resulting in frequency and time resolution of 93.8 Hz and 10.7 ms, respectively. (a) Airmar™ (dB Plus II); (b) Ace Aquatec™ (US3); (c) Terecos™ (Type DSMS-4) Programme 4; (d) Terecos™ (Type DSMS-4) Programme 2; (e) Terecos™ (Type DSMS-4) Programme 3.

2 IMPACTS OF ADDS ON CETACEANS

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

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

Both harbour porpoises and bottlenose dolphins are listed under Annex II of the EC Habitats Directive (EC 1992), which requires strict protection measures to be applied to both individuals and populations, including the establishment of Special Areas of Conservation (SACs) to protect habitats that are important for the survival of the species. SACs are intended to contribute to a coherent European ecological network of protected sites, and thereby ensure continued maintenance of Favourable Conservation Status (FCS) of the species involved. The recently designated 'Inner Hebrides and the Minches' candidate Special Area of Conservation (cSAC) for harbour porpoises encompasses a large part of the Scottish west coast, which also includes numerous finfish aquaculture sites (Scottish Natural Heritage 2016). Given harbour porpoises' potential sensitivity to ADD noise, current levels of ADD usage within and adjacent to the 'Inner Hebrides and the Minches' cSAC therefore potentially have a negative impact on FCS for this species.

2.1 PHYSIOLOGICAL EFFECTS

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

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

Long-term exposure to chronic noise pollution can have significant deleterious effects on the health of both humans and animals through a number of physiological pathways involving combinations of neural and endocrine systems (summarised by Wright et al. 2007a, 2007b). Such responses may be difficult to detect in free-living cetaceans, and most of our current knowledge is derived from studies using small numbers of captive animals (e.g., Thomas et al. 1990; Miksis et al. 2001; Romano et al. 2004). Elevated baseline levels of stress hormones measured in free-living baleen whales, indicating chronic stress, have been associated with long-term exposure to shipping noise, suggesting anthropogenic noise may have substantial impacts on health of wild cetacean populations (Rolland et al. 2012). The effects of aquaculture-associated ADDs on cetaceans in this regard remain poorly understood but merit further study in the light of currently available data on effects of other anthropogenic noise sources (Wright et al. 2007b).

2.2 BEHAVIOURAL RESPONSES AND HABITAT DISPLACEMENT

Beyond physical injury, another important potential impact of underwater noise concerns its ability to induce changes in animals' behavioural patterns and/or deter animals from ensonified areas, either temporarily or permanently (Nowacek et al. 2007; Götz & Janik 2013). Several behavioural response studies have attempted to either investigate behavioural effects of ADDs on cetaceans around fish farms or evaluate their potential to deter animals from construction sites (e.g., Olesiuk et al. 2002; Johnston 2002; Götz & Janik 2013; Lepper et al. 2014; Hermannsen et al. 2015). Airmar and Lofitech devices were the ADD types most often tested in these contexts.

Reported results suggested consistent deterrence of porpoises from the vicinity of the ADD sound source, but there was substantial variation in terms of the distances over which this deterrence was observed (Table 1). Summarizing and evaluating results from several studies, Hermannsen et al. (2015) estimated minimum absolute deterrence distances (within which all harbour porpoises could be expected to be deterred) of approx. 200 m and 350 m from source for Airmar and Lofitech devices, respectively. These distances typically corresponded to signal received levels of 130-150 dB re 1µPa$_{rms}$ depending on frequency range and device source level tested (Hermannsen et al. 2015). However, absolute deterrence effects can extend over much larger ranges. For example, Brandt et al. (2013a) reported avoidance responses by all observed porpoises within a range of 1.9 km from an active

Lofitech device, corresponding to estimated received levels ≥120 dB re 1µPa_{rms} (Table 1). Kastelein et al. (2015) tested the effect of Ace Aquatec and Lofitech ADDs on a captive harbour porpoise and found strong deterrence effects at 139 dB re 1µPa_{rms} for the former and 151 dB re 1µPa_{rms} for the latter. These results correspond to absolute deterrence distances of 380-590 m and 40-150 m for Ace Aquatec and Lofitech devices, respectively and a deterrence distance for most animals of 2-4 km (Hermannsen et al. 2015). The maximum reaction distance observed (involving a Lofitech ADD) was at least 7.5 km (Brandt et al. 2013b), corresponding to estimated received levels ≥110 dB re 1µPa_{rms} (Table 1). In summary, porpoises have been shown to be deterred from around ADDs at distances ranging from several hundred metres to several kilometres. It is worth noting that long-term use of ADDs may lead to habituation or reduced avoidance responses among porpoises, as indicated by results presented by Northridge et al. (2010).

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

Masking occurs when a sound is influenced by another sound of similar frequency, thereby interfering with reception and/or interpretation of the original sound of interest (Fletcher 1940). Broadband ADD signals, in particular, overlap with communication and echolocation signals of several marine mammal species, thereby raising the potential for communication masking in the vicinity of these devices (Götz & Janik 2013). Masking of marine mammal vocalizations by anthropogenic noise has primarily been considered in the context of shipping noise, which can result in a significant reduction of the space within which cetacean communication can occur (Clark et al. 2009; Jensen et al. 2009). This problem has not been directly investigated in the context of ADDs impacting species of concern in Scottish aquaculture and studies of the actual sound field around fish farms with active ADDs are needed to study this problem more thoroughly.

Table 1. Summary of minimum deterrence and reaction distances of harbour porpoises to ADD sounds reported in the literature. Note that substantial differences exist between these studies in terms of ADD types used, main frequencies and source levels, which account for some of the variability between studies. Table modified from Hermannsen et al. (2015).

Study	**Method**	**Type of ADD; Frequency; Source level**	**Deterrence distance for most animals**	**Absolute deterrence distance; Estimated received level**	**Maximum deterrence distance; Estimated received level**
Olesiuk et al. 2002	Visual observations	Airmar (model not provided); 10 kHz; 194 dB re 1µPa pp	Not estimated	200 m; 148 dB re 1µPa pp	3500 m (>90%); 106 dB re 1 µPa pp**
Johnston 2002	Visual surveys and theodolite tracking	Airmar dB II Plus; 10 kHz 181 dB re 1µPa pp	Not estimated	640 m (all); 128 dB re 1µPa pp	Not estimated
Northridge et al. 2010	T-PODs and hydrophone array	Airmar (model not provided); 10 kHz	~ 900 m	0 m (worst-case assumptions)	4000 m
Brandt et al. 2013a	Visual surveys and theodolite tracking	Lofitech (model not provided); 13.5-15 kHz; 189 dB re 1µPa pp	1300 m*	<768 m	2400 m; 129 dB re 1µPa pp**
Brandt et al. 2013b	C-PODs and aerial surveys	Lofitech (model not provided); 13.5-15 kHz; 189 dB re 1µPa pp	1900 m	350 m; 146 dB re 1µPa pp	7500 m; 113 dB re 1µPa
Kastelein et al. 2015	Visual study on captive porpoise	Ace Aquatec Seal Scrammer; 10-40 kHz; 193 dB re 1µPa rms	4 km; 117 dB re 1µPa (Ace Aquatec)***	Strong avoidance response: 380-590 m**** (Ace Aquatec)	Not estimated
		Lofitech Seal Scarer; 13.5-15 kHz; 189 dB re 1µPa pp	2 km; 121 dB re 1µPa (Lofitech)	Strong avoidance response: 40-150 m**** (Lofitech)	

**See Hermannsen et al. (2015) for details.*
***Derived from Tougaard et al. (2015).*
****Extrapolated from sound levels causing evasive reactions; see Hermannsen et al. (2015) for details.*
*****Extrapolated based on assumption of a spherical transmission loss and an absorption of 1 dB/km; see Hermannsen et al. (2015) for details.*

2.3 REDUCING ACOUSTIC IMPACTS OF ADD SYSTEMS ON NON-TARGET SPECIES

Concerns about potential impacts of ADD signals on non-target species such as harbour porpoise have encouraged the development of novel ADD systems seeking to minimize such impacts while still acting as effective seal deterrents. Considerable efforts have therefore been directed towards developing ADDs that reduce sound outputs in some manner, and/or modifying ADD deployment methods to reduce acoustic impacts on the surrounding environment.

One approach to reducing acoustic impacts of ADDs on non-target species is to reduce overall sound output. Changes to devices' duty cycles may reduce the amount of noise produced, although this effect is diminished when multiple ADDs are operating in close proximity with overlapping duty cycles. Total sound outputs can also vary depending on whether or not ADDs are left to operate continuously, or are only switched on temporarily in response to seal presence or attacks (Northridge et al. 2010; Coram et al. 2014); such decisions appear to be left largely to the discretion of individual farm managers. Some systems electronically link individual ADDs to a central control hub, from which devices' sound outputs can be regularly monitored and modified where necessary.

Triggered ADD systems, which only emit a signal when a predator is detected, also have the potential to significantly reduce total acoustic outputs (Northridge et al. 2010; Coram et al. 2014). Several systems have been developed, including those that rely on detecting the movements of salmon panicking in response to a predation attempt to trigger an ADD signal, as well as systems that detect the movements of seals directly. Alternative triggered approaches such as to remain silent when detecting acoustic signals from non-target species such as harbour porpoise have also been proposed.

Another option to reduce total acoustic outputs involves making ADD signals more specific to the target species in question, in this case harbour and grey seals. One potential means to reduce acoustic impacts on non-target species such as harbour porpoises relies on exploiting the differences in hearing sensitivities between seals and odontocete cetaceans at low frequencies. For example, harbour porpoise hearing has been shown to be relatively insensitive at frequencies <2.5 kHz even under low ambient noise levels, whereas harbour seals' hearing remains more sensitive to sounds down to frequencies <1 kHz under similar conditions (Kastelein et al. 2002, 2010). Some ADD systems exploiting this difference are already commercially available (e.g., Ace Aquatec 2016) using <2 kHz bespoke signal types. Evaluation of these systems are ongoing (Ace Aquatec, pers. comm. 2018). Another approach involves the use of short rapid-onset signals (peak frequency 1 kHz; received levels >145 dB re 1 μPa_{RMS}; <5 ms onset), which have been shown to elicit an autonomous startle reflex in seals, resulting in site avoidance (Götz & Janik 2011, 2012, 2015). The latter method, which at the time of writing was not yet commercially available, would significantly reduce the active duty cycle required to elicit avoidance responses in a similar manner to other methods such as triggered acoustic and non-acoustic systems. Questions do, however, remain more generally regarding the effects of low-frequency ADD signals on other non-target species, including fish as well as odontocete and mysticete cetaceans (baleen whales).

While several options to reduce acoustic impacts of ADDs are in development or already available as commercial systems, there is a dearth of experimental studies in the scientific literature evaluating the relative merits of different approaches. The scope of the present study was limited to a focus on one particular approach, namely evaluating the effects of lowering the signal frequencies to exploit the differences in hearing sensitivity between seals and odontocetes, specifically harbour porpoises.

3 EXPERIMENTAL METHODS

3.1 PROJECT AIMS

The present project was commissioned by the Scottish Aquaculture Research Forum (SARF) with the aim to investigate the potential impacts of ADDs emitting lower-frequency signals on harbour porpoises in Scottish waters. Little information is presently available in the scientific literature to evaluate the effects of lowering ADD signal frequencies on harbour porpoises and other high-frequency sensitive cetacean species for the purposes of long-term management.

The present project sought to undertake a controlled sound exposure experiment on an active fish farm on the west coast of Scotland to evaluate porpoises' responses (expressed as detection rates of porpoise echolocation calls). Simulated ADD sounds were transmitted by shore-based observers upon visual detection of porpoises, or at regular intervals during periods when visual surveys were impractical, such as at night or in poor weather. Signals were specifically designed for this project to take advantage of the difference in auditory sensitivity between seals and porpoises at frequencies <2.5 kHz. Responses of porpoises to ADD signal transmissions were recorded through an array of passive acoustic detectors, as well as visually through a team of onshore observers supported by an experimental camera-tracking array.

3.2 ACOUSTIC PLAYBACK SIGNAL DESIGN

Although several different ADD devices are presently available commercially, their signal output varies substantially in terms of source level, frequency range, duty cycle, repeatability etc. Despite being an active research area for both academic and industry groups, uncertainty still remains over which aspect(s) of the emitted signals (absolute loudness, frequency spectrum, duty cycle etc.) might lead to a deterrence effect, with trials into several new signal types ongoing at this time.

It is important to note that, in line with SARF's original tendering specifications, this research project was not able to test any specific signal types fully replicating any particular ADD brand. Accordingly, no actual ADDs of any particular brand were tested as part of this research, or form part of any results of this research, in order to maintain impartiality towards all ADD manufacturers and suppliers. Instead, generic bespoke signals were designed so as to encompass the approximate ranges of signals in terms of temporal and spectral characteristics commonly produced by a number of ADD types presently in commercial use in Scottish salmon aquaculture. These features included frequency range, pulse design, frequency switching and temporal characteristics. Due to limitations imposed by the overall experimental design, the specific ranges of signal features selected were limited to the use of pulsed continuous wave tone bursts of randomised tonal frequencies across different frequency ranges and standardized duty cycles. The test signals were designed to encompass common features of signals from as many ADD types in current use as possible, whilst not fully replicating any one of them in isolation. For this reason, the experimental paradigm for this study could not fully encompass all potential ADD signal type characteristics in current use or under development, for example pulse shape, in-pulse frequency modulation, simultaneous multi-frequency components, pulse rise time, amplitude modulation, variable/randomized duty cycles, triggered systems or other non-acoustic mitigation measures.

The difference between porpoises' and seals' hearing sensitivities to low-frequency sounds was exploited in the signal design process. A high frequency (hereafter referred to as HF) test signal was designed using single frequency tonal square envelope bursts, broadly similar to those produced by ADD brands representing many of the ADDs in current use in Scottish salmon aquaculture (Findlay et al. 2018). The random frequency sequencing and the pulse width and duty cycle of the Ace Aquatec Silent Scrammer (Lepper et al. 2004) were also adopted and adapted to the LF signal type. The overall fundamental frequency range of transmission was extended from 8-18 kHz to capture the full frequency spectrum of at least three commercially available systems (Figure 2). Specifically, the HF signal consisted of pulsed continuous wave sinusoidal tonal bursts at one of 21 randomly switching fundamental frequencies between 8 – 18 kHz at frequency intervals of 500 Hz. Each pulse contained 40 cycles of fundamental frequency with a rectangular pulse amplitude envelope, and the on – off duty cycle was 50%. Figure 3 illustrates the variation in pulse amplitude due to transducer response as well as pulse duration.

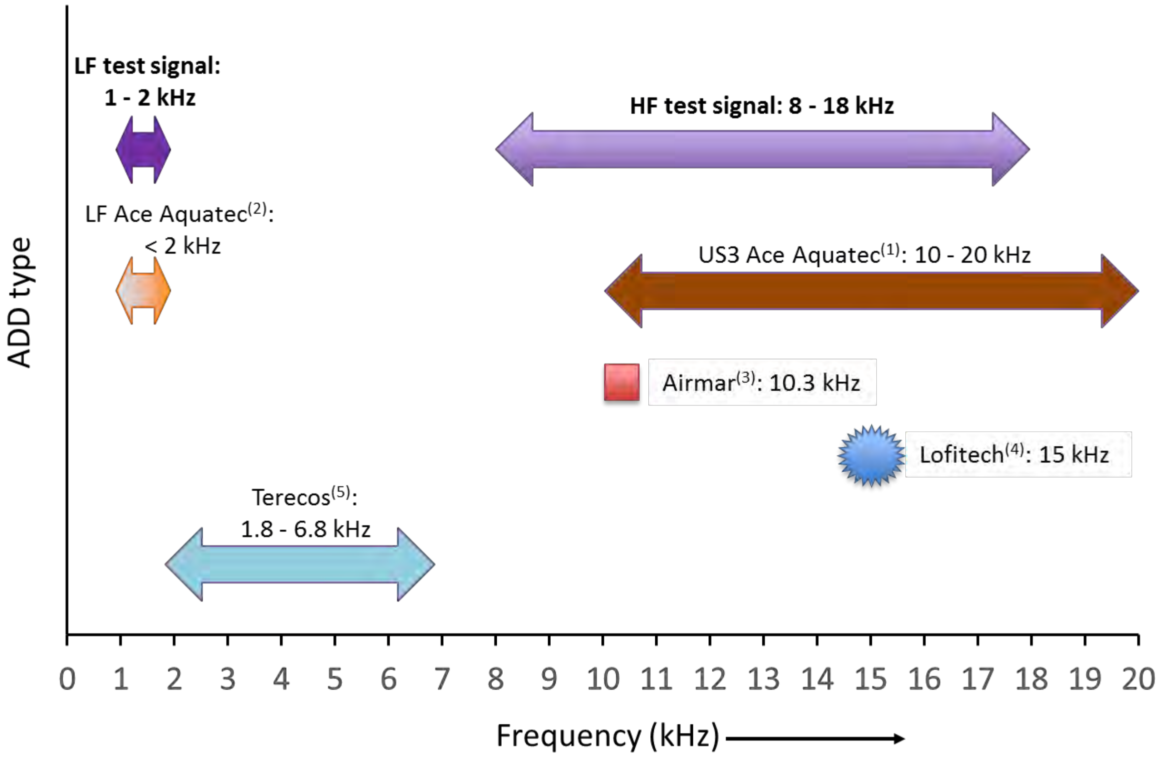

Figure 2. Output frequency ranges of the two test signals (LF and HF), compared to outputs from various existing ADD types. Data on existing ADD outputs derived from 1) Ace Aquatec U3S manual (https://www.aceaquatec.com/us3specification); 2) Ace Aquatec pers. comm. (PL); 3) Lepper et al. 2004, 2014;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

A low-frequency (hereafter referred to as LF) test signal was designed, consisting of pulsed continuous wave sinusoidal tonal bursts comparable to the HF signal, but in this case set at one of 11 randomly switching fundamental frequencies between 1 – 2 kHz and frequency intervals at 100 Hz. Each pulse was made up of 40 cycles of fundamental frequency with a rectangular pulse amplitude envelope, and the on – off duty cycle was 50%. This signal was designed to produce outputs comparable in designed fundamental drive frequency to those from the Ace Aquatec RT1 low frequency variant ADD design (Ace Aquatec, pers. comm. 2018; Figure 2).

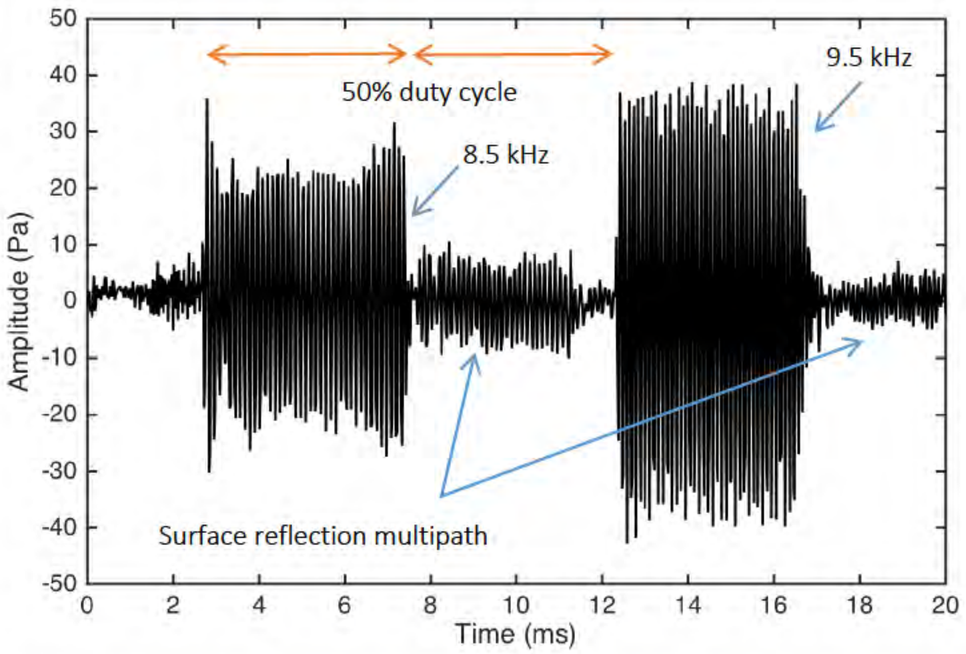

Figure 3. Time domain plot of two consecutive pulses from the HF sequence – first pulse at 8.5 kHz and second at 9.5 kHz.

It should be noted that the current RT1 low frequency signal, although replicated for fundamental frequency, also uses a variable pulse rise time not replicated in the current test, potentially resulting in a lower pulse turn on/off transient frequency response. The evaluation of the effects of these features within the design of the generic signal types was unfortunately beyond the scope of the current experiment.

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

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

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

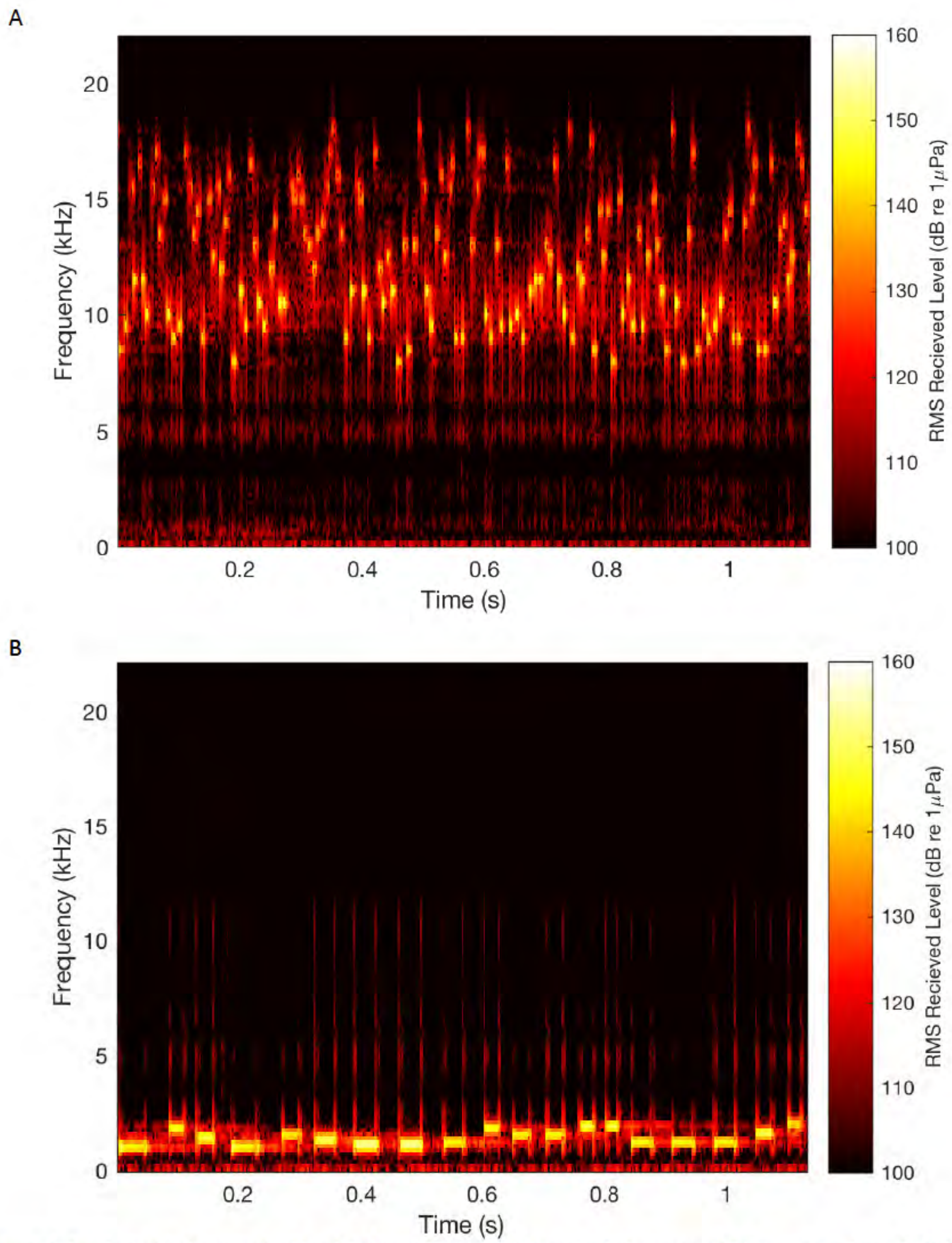

Figure 4. Spectral plot of a sample of the HF (A) and LF signals (B) received at a range of 8.5 m using a Reson 4014 balanced hydrophone. Analysis window was 256 FFT with 50 % overlap using a Hanning window. A 50 kHz low pass filter was applied. Original data were downsampled to a sample rate of 44.1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

Spectra of both HF and LF signals are presented in Figure 4A-B. Importantly, the LF signal data shown in Figure 4B do show that some higher frequency (>2 kHz) components above the designed fundamental frequencies (1-2 kHz) did exist. These were due to the turn- on/turn-off transient nature of the beginning and end of a square enveloped pulse shape commonly seen in the pulsed tonal signals currently under test and observed in many ADD signal types. Analyses of these components show that typical levels were 25-30 dB lower than the primary fundamental frequency at ~2.5 kHz, 40 dB lower at 5 kHz and 40-50 dB lower at 10 kHz. Above 12 kHz, these components were not detectable above ambient noise levels from the calibration data, and no other artificial signal relating to the experiment could be identified (Figure 5). Although these components are potentially within the hearing range of harbour porpoises, they were significantly below that of the fundamental drive signal being tested. The origin of these components was also typical of square envelope pulsed signal types used in many currently used ADD types.

3.3 SIGNAL TRANSMISSION

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

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

Calibration of the signal source from the Lubell speaker at each tonal frequency was undertaken in situ. Test trials recorded both signal types using a balanced RESON™ 4014 hydrophone with sensitivity of around -180 dB re 1V/µPa using a dedicated 20 dB balanced preamplifier. Measurements were made with preamplifiers/filters in the frequency range 10 Hz – 200 kHz and <50 kHz. Data acquisition was carried out using a 16-bit National Instruments 6521 DAQ system at a sample rate of 1.25 MSs^{-1} with a voltage range of +/- 5 V using bespoke data acquisition software. Both the DAQ and laptop (SurfacePro) were battery-powered. The RESON 4014 hydrophone was deployed from the front of the fish farm barge at 8.5 m directly in front of the sound source, at the same depth of 10.5 m. In post-experimental analysis, the free-field direct path of the signal was identified, allowing RMS levels to be calculated on this basis (Table 3). Free-field source levels were then calculated assuming spherical spreading.

Figure 5 shows a 4-second sequence recorded at a bandwidth of 1.25 Ms/s using a broadband 4014 hydrophone with band passed between 10 Hz and 200 kHz of the LF signal. Note that no significant signal-based components were observed above the fundamental signals' frequency range (<20 kHz) for frequencies up to 200 kHz covering the most sensitive frequencies of the harbour porpoise hearing range. The occasional broadband transients are attributed to barge-based noise that was not directly linked to the experimental signal source.

Transmissions were randomised between the HF signal, the LF signal and silence (hereafter termed 'silent control'), without any obvious indication to the fieldwork team which signal was being transmitted. Each signal transmission lasted for 2 hours and was followed by a 2-hour 'recovery' period during which no new transmission could be triggered, to allow time for any previously displaced animals to return to the ensonified area. Once this recovery period had passed, the system automatically reset itself so that it could be triggered to transmit again.

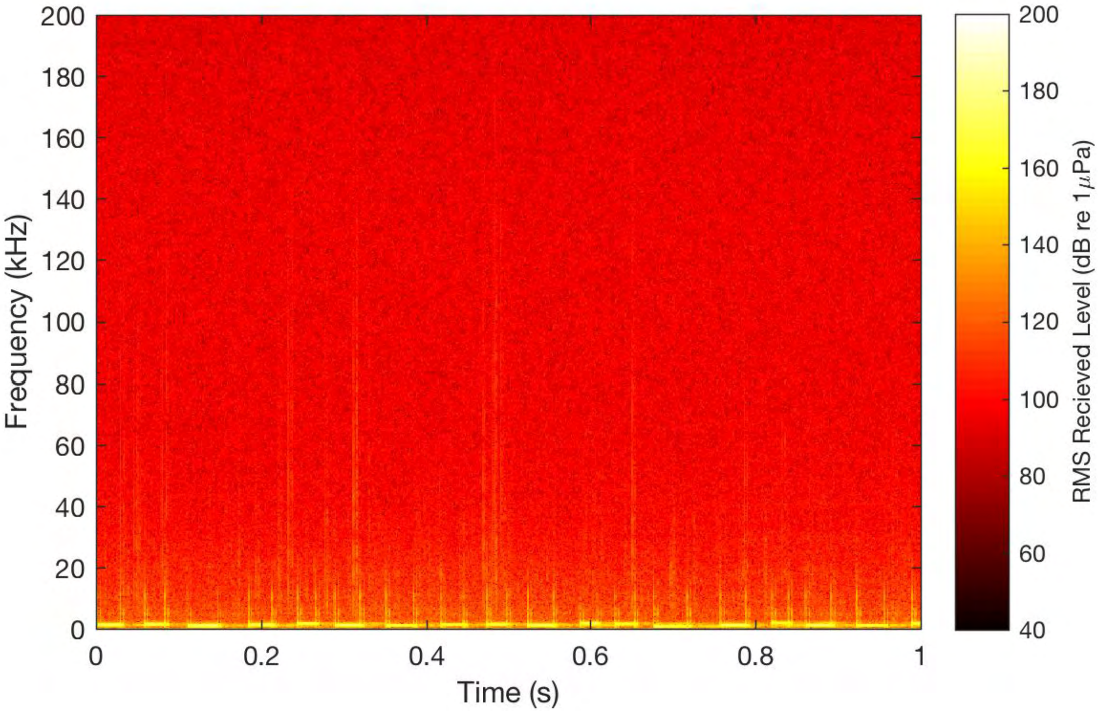

Figure 5. Spectral plot of a sample of the LF signal received at a range of 8.5 m using a Reson 4014 balanced hydrophone, (same signal as Figure 4B, but with expanded Y-axis and extended dynamic range to make weak background noise more apparent). Analysis window was 4096 FFT with 50 % overlap using a Hanning window. A 10 Hz – 200 kHz band pass filter was applied. Data were sampled at a rate of 1.25 MHz/s.

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

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

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

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

3.4 FIELDWORK LOCATION

The experiment took place in the Sound of Mull, on the west coast of Scotland, with observation efforts concentrated in Bloody Bay on the north shore of the Isle of Mull (56°38.626 N, 6°05.705 W; Figure 6). This location was chosen because it contained a salmon aquaculture site that operated under licensing restrictions preventing it from using ADDs (Scottish Natural Heritage, pers.comm. 2016). This meant that the experiment could be undertaken without interference from on-site operational ADDs, although effects of more distant ADDs deployed by other fish farms in the area could not be eliminated. Furthermore, Bloody Bay had previously been identified by various researchers as a good site to observe harbour porpoises regularly (Carlström 2005; Carlström et al. 2009; Götz & Janik 2016). The Bloody Bay fish farm barge was used as a platform from which to deploy the underwater loudspeaker and associated hardware as well as passive acoustic detectors. Water depths in the immediate area around the fish farm were approximately 35-40 m (based on GEBCO™ bathymetry data).

3.5 PASSIVE ACOUSTIC DETECTOR ARRAY

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

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

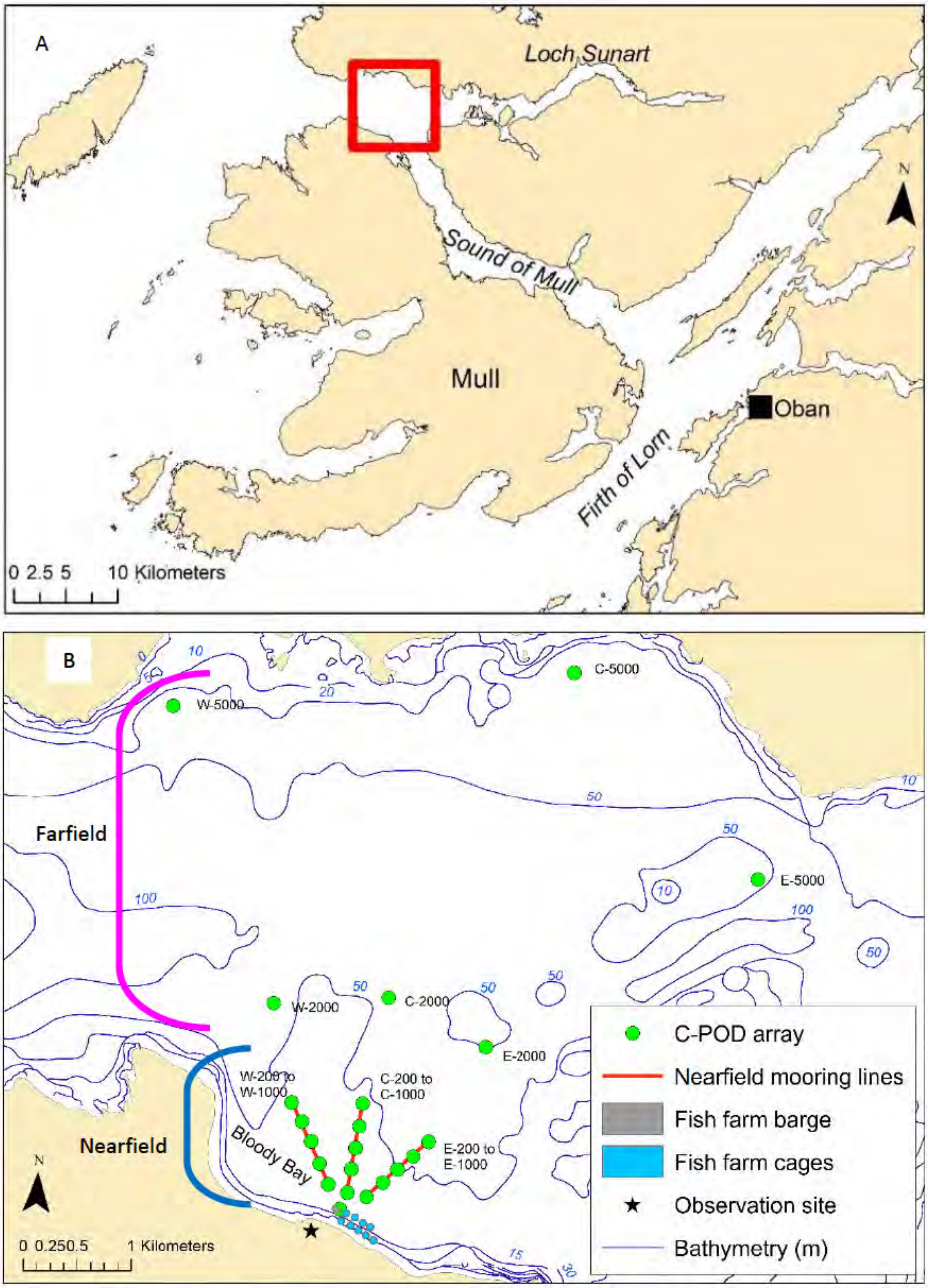

Figure 6. A) Overview of the Sound of Mull and adjacent areas. The Bloody Bay fieldwork site is indicated by the red box. B) Overview of LEAP passive acoustic mooring array in Bloody Bay and the northwestern Sound of Mull (red box within Figure 6A). Nearfield and Farfield components of the array are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

Table 4. Summary of mooring array components. Water depth was measured relative to Chart Datum (CD).

Array section	**Site name**	**Latitude**	**Longitude**	**Water depth (m rel. to CD)**	**Approximate distance to signal source (m)**	**Acoustic equipment at mooring**
NEARFIELD	Fish farm barge*	56°38.626 N	06°05.884 W	36	0	C-POD; RTSYS
NEARFIELD	E-200	56°38.691 N	06°05.600 W	35	270	C-POD
NEARFIELD	E-400	56°38.789 N	06°05.459 W	42	469	C-POD
NEARFIELD	E-600	56°38.838 N	06°05.334 W	51	647	C-POD
NEARFIELD	E-800	56°38.907 N	06°05.199 W	52	835	C-POD
NEARFIELD	E-1000	56°38.985 N	06°05.066 W	59	1032	C-POD; SoundTrap[1]
FARFIELD	E-2000	56°39.474 N	06°04.601 W	35	2020	C-POD
FARFIELD	E-5000	56°40.390 N	06°02.218 W	40	4941	C-POD
NEARFIELD	C-200	56°38.707 N	06°05.775 W	41	167	C-POD; SoundTrap[2]
NEARFIELD	C-400	56°38.827 N	06°05.752 W	43	386	C-POD
NEARFIELD	C-600	56°38.931 N	06°05.725 W	47	583	C-POD
NEARFIELD	C-800	56°39.042 N	06°05.700 W	36	788	C-POD
NEARFIELD	C-1000	56°39.156 N	06°05.685 W	39	1000	C-POD
FARFIELD	C-2000	56°39.692 N	06°05.508 W	39	2011	C-POD
FARFIELD	C-5000	56°41.371 N	06°03.992 W	40	5435	C-POD; SoundTrap[2]
NEARFIELD	W-200	56°38.743 N	06°05.952 W	49	252	C-POD
NEARFIELD	W-400	56°38.843 N	06°06.042 W	51	461	C-POD
NEARFIELD	W-600	56°38.951 N	06°06.129 W	47	680	C-POD
NEARFIELD	W-800	56°39.049 N	06°06.224 W	53	885	C-POD
NEARFIELD	W-1000	56°39.141 N	06°06.329 W	28	1085	C-POD
FARFIELD	W-2000	56°39.630 N	06°06.545 W	55	2005	C-POD
FARFIELD	W-5000	56°41.086 N	06°07.616 W	36	4920	C-POD

Each station contained a C-POD™ porpoise click detector, with some stations additionally being equipped with a SoundTrap™ or RTSYS™ sound recorder (Table 4). Detector selection was determined through a combination of unit battery capacity, price and availability among project partners. The main features of detectors were as follows:

- C-PODs are self-contained ultrasound monitors that select tonal clicks and record the time of occurrence, centre frequency, intensity, duration, bandwidth and frequency trend of tonal clicks within the frequency range 20 kHz - 160 kHz to 5-µs resolution. This allows them to monitor clicks from all odontocetes except sperm whales. Raw sound data are not stored, however, and the unit's design precludes manual configuration of click identification parameters. Maximum deployment times vary depending on environmental conditions but typically range over several months (Chelonia Ltd. 2011, 2013, 2014). This extended battery life makes them suitable for long-term monitoring experiments involving species such as

[1] High-Frequency SoundTrap™

[2] Low-Frequency SoundTrap™

harbour porpoise. A subset (n=8 units) of C-PODs' responses to artificial porpoise clicks had been tested previously as part of a different experiment, deploying an omnidirectional harbour porpoise click train synthesiser (PALv1; F^3 Maritime Technology 2012) at known distance. The PALv1 unit produced click trains with a centre frequency of 133 ± 0.5 kHz and source levels of 154 ± 2 dB (peak-to-peak; F^3 Maritime Technology 2012). Some variability in terms of C-PODs detecting PALv1 click trains was noted at the time; environmental factors (notably changes in C-POD orientation relative to the PALv1 sound source) were considered to be an important cause of this variability. No further calibration of C-PODs used in this experiment was performed.

Occasionally, under high ambient noise conditions, C-PODs temporarily stop logging when reaching a pre-set buffer limit of 4,096 clicks per minute, until the start of the next minute (Booth 2016). The proportion of each minute thus lost can be used as a crude proxy of ambient noise levels across the array. C-PODs also contained an onboard tilt sensor, recording their deflection from vertical (0° = vertical; 90° = horizontal).

- SoundTraps are compact self-contained broadband underwater sound recorders (Ocean Instruments 2017). Unlike C-PODs, they store raw sound data onboard for further study, but have a lesser battery capacity resulting in the need for sampling according to a pre-programmed duty cycle to extend recording duration. Two versions (SoundTrap 300 STD, with a working frequency range of 20 Hz-60 kHz, and SoundTrap 300 HF, with a working frequency range of 20 Hz-150 kHz) were available for the present experiment (N= 2 and 1 devices, respectively). The SoundTrap 300 units were included in the moorings to provide validation of the transmitted ADD signal across the array. Units were programmed to sample 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 acquiring signals from up to four broadband hydrophones simultaneously (RTSYS 2016). A single unit was deployed beneath the fish farm barge adjacent to the underwater loudspeaker to obtain information on signal output for subsequent modelling of transmission loss across the array. It recorded on one channel using a Reson TC4014, broadband omnidirectional hydrophone (sensitivity: -180 dB re 1 V/µPa, flat frequency response: 25 Hz-250 kHz), for a period of 4 days during 16-19/09/2016.

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

3.6 VISUAL OBSERVATIONS AND CAMERA ARRAY

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

The visual observation team also collected photogrammetric data using an array of DSLR cameras to establish the positions of surfacing harbour porpoises and other marine mammals relative to stationary coastal landmarks. This method had been developed by researchers at the Institute for Marine Resources and Ecosystem Studies (IMARES, part of Wageningen University-Research [WU-R], Den Helder, the Netherlands), and used coordinates of known reference points visible on the opposite shore to determine the 2-D positions of any surfacing marine mammals recorded by the cameras. This allowed their movements over time in response to transmitted ADD sounds to be tracked and plotted using GIS software (Hoekendijk et al. 2015). Following guidance from IMARES staff, an array of five DSLR cameras (Canon™ EOS 7D/600D using Sigma 70-200 mm/70-300 mm lenses) was mounted on a stationary frame such that cameras' fields of view overlapped, resulting in a total field of view of approximately 30° from the onshore vantage point. A sixth 'mobile' DSLR camera was mounted on a tripod and aligned with a pair of Swarowski™ 10 x 42 EL binoculars to scan and record the more distant parts of the survey area. At the start of each visual survey, the height of the mobile camera above ground level was measured to the nearest cm to be able to correct for small variations in vertical sighting angle. Additional parameters required for the analysis (e.g., exact geographical location of camera array, tidal height, cloud cover etc.) were collected according to the methods described by Hoekendijk et al. (2015). Tidal data were subsequently validated through comparison with high-resolution data from the nearby Tobermory tidal gauge (<5 km from Bloody Bay; part of the UK National Tidal Gauge Network, owned and operated by the Environment Agency [EA]). All cameras were switched on whenever a porpoise or other cetacean was observed, which was then tracked by visual observers using the binoculars and mobile camera until it was lost from view for more than 10 minutes or left the area. All DSLR cameras recorded video data in 10-minute blocks to facilitate data storage and subsequent analysis.

3.7 DATA MANAGEMENT

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

4 RESULTS

4.1 SIGNAL TRANSMISSION EXPERIMENTS

The signal transmission system described under Section 3.3 was installed onto the fish farm barge and activated on 6/09/2016, approximately 5 weeks later than planned following unexpectedly long delays in the licensing application process. Despite this, the project successfully completed a fieldwork campaign combining simulated ADD transmissions with concurrent acoustic and visual observations of porpoises. Following an initial test period, the actual experiment ran from 08/09/2016 until 11/10/2016 inclusive, equivalent to a total of 33 days. During this period, a total of 138 complete two-hour sound transmissions (including 53 HF signal transmissions, 38 LF signal transmissions, and 47 silent control "transmissions") were carried out. Transmissions were either triggered following visual detection of animals by the visual observations team or initiated on a random schedule (see Section 3.3: Signal Transmission). Of all transmissions, 62 ran during daylight hours (i.e., started during daytime or immediately before sunrise), while 76 transmissions overlapped partially or wholly with hours of darkness (i.e., started during darkness or immediately before sunset). Visual observations occurred on 18 days between 9/09/2017 and 10/10/2017, and included both data from human observers and video camera tracking data. There was no significant difference in terms of when particular signals were transmitted in relation to daylight hours. The resulting dataset will be described in more detail in the various sections below.

During the experiment, porpoises were seen less frequently in Bloody Bay than was expected given historical observations (Carlström 2005; Carlström et al. 2009; Götz & Janik 2016). The reasons for this were unclear but resulted in fewer opportunities for daytime ADD sound transmission experiments than had originally been anticipated. The system was manually triggered a total of nine times during visual observation periods as a direct result of sightings of porpoises or dolphins. On 18 days where no porpoises were detected by visual observers during the morning, the system was triggered at a random time during the day. This was done to account for the possibility that the C-PODs, particularly the more distant Farfield ones, might be detecting porpoises that were not reported by the visual observers, so that some relevant data might still be gathered.

4.2 HARDWARE RECOVERY

Anticipating a start date in early August 2016, a single C-POD was deployed in July 2016 below the fish farm barge to gather pre-experiment baseline data on porpoise presence near the fish farm. This C-POD was present from 15/07/2016 until recovery on 5/09/2016, immediately prior to the start of the experiment. Deployment of all remaining moorings occurred from 5-7/09/2016 using SAMS R/V *Seol Mara* with the exception of mooring C-5000, which had already been deployed on 17/08/2016 through a collaborative agreement with AlbaTern Wave Energy. The entire array was therefore functional by 07/09/2016; to facilitate analysis the effective start date and time used was 08/09/2016 at 00:00 GMT. Array recovery occurred on 18/10/2016 using SAMS R/V *Calanus*. The C-POD below the fish farm barge was later replaced with another unit to provide longer-term information of post-experiment site usage by porpoises. This second C-POD recorded data from 04/11/2016 until 3/02/2017.

All but three of the passive acoustic recorders were successfully recovered by SAMS R/V *Calanus* on 18/10/2016. On 13/09/2016, following a storm, the surface float of the central Nearfield mooring (position C-200) was noted to have disappeared. Because this was part of an 800 m long, complex mooring it was deemed unwise to lift and disrupt the mooring further. During retrieval of the full array on 18/10/2016, it became apparent that the earlier loss of the C-200 surface float had also resulted in the loss of the vertical riser below it, including the attached C-POD and SoundTrap detectors (Table 5). No monitoring data were therefore available from this particular location. In addition, the acoustic release of the solitary E-5000 Farfield mooring failed to respond to activation commands, preventing mooring recovery from this location as well. The reason for this was unclear but could involve a technical fault in the acoustic release unit or displacement of the mooring through interactions with commercial fishing gear. Subsequent efforts to contact this mooring's acoustic release unit, by surveying out as far as 2 km from its original deployment location, were unfortunately unsuccessful. An information campaign to alert the wider community to the fact of these losses and appeal for assistance in relocating the missing equipment did not yield any results, and these detectors were eventually considered lost (Table 5).

4.3 PASSIVE ACOUSTIC MONITORING

Following recovery of the PAM equipment, all C-PODS but one were found to have collected data. The exception was the C-POD deployed beneath the fish farm barge adjacent to the Lubell loudspeaker, which had malfunctioned for unknown reasons shortly after having been deployed at the very start of the experiment. No C-POD data were therefore available from this location during the experimental period. Fortunately, two adjacent C-PODs (E-200 and W-200) were successfully recovered and found to have recorded the entire experimental period. C-PODs' detection radii are generally considered to be on the order of 200-300 m (Brandt et al. 2013; Nuuttila et al. 2013), suggesting that data from the E-200 and W-200 C-PODs (located ~200 m from the sound source) could be used to indicate how porpoises might use the area near the fish farm barge. C-POD data from below the fish farm barge prior to and following the experiment (15/07 – 5/09/2016 and 04/11/2016 - 3/02/2017, respectively) indicated continued porpoise presence during these periods (Appendix 2).

As the C-5000 C-POD had been deployed before the other moorings on 17/08/2016, the subsequent delay in deploying the remainder of the array resulted in the C-5000 C-POD's batteries being depleted by 7/10/2016, about 10 days before the recovery of the array. Other C-PODs' batteries generally remained functional or suffered only minor losses in terms of recording time until they were recovered. The combined C-POD dataset available for analysis was therefore based on 18 out of 21 C-PODs (Table 5). Upon recovery, the HF-SoundTrap included in the E-1000 mooring was also found to have malfunctioned at some point during the deployment for unknown reasons.

C-POD datasets were truncated to exclude periods immediately after deployment and before recovery, such that the remaining datasets only contained entire days (1440 minutes per day). For this reason, the entire array (excluding the C-POD beneath the fish farm barge) was defined to be active from 8/09/2016 at 00:00 GMT until 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. All other C-PODs remained operational until at least 16/10/2017 at 23:59 GMT, equivalent to 39 full days.

*Table 5. Summary of periods monitored by moored C-POD units across the array. *These units stopped <24 hours prior to recovery. ** This 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	Fish farm 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

4.4 AMBIENT NOISE MONITORING

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

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

Figure 7 shows one of the quietest periods with no transmission at the fish farm barge in good sea-state conditions with a light breeze and no rain, taken on 11th October 2016 at 14:56 GMT. These levels are in line with similar sea-state noise levels at other sites with a broadband PSD of 95.9 dB re 1 µPa^2/Hz. The data also indicate relatively low variability during this period with only slightly increased standard deviations and maximum and minimum values for frequencies >10 kHz.

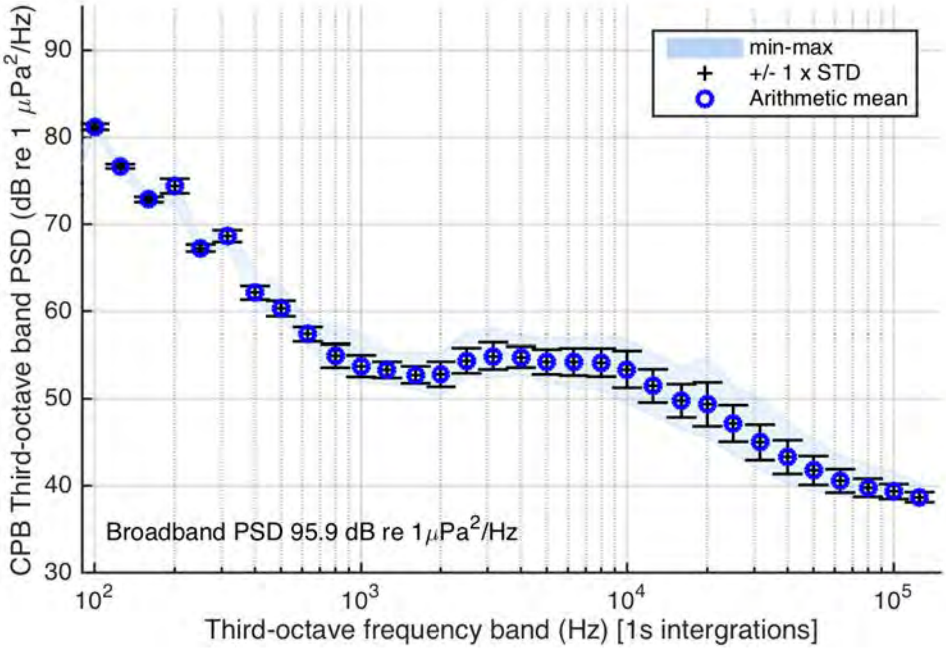

Figure 7. Power Spectral Density (PSD) in Third Octave Bands for a quiet period at 14:56 GMT on 11th October 2016. Total sample length 25 seconds, 1-second integration periods.

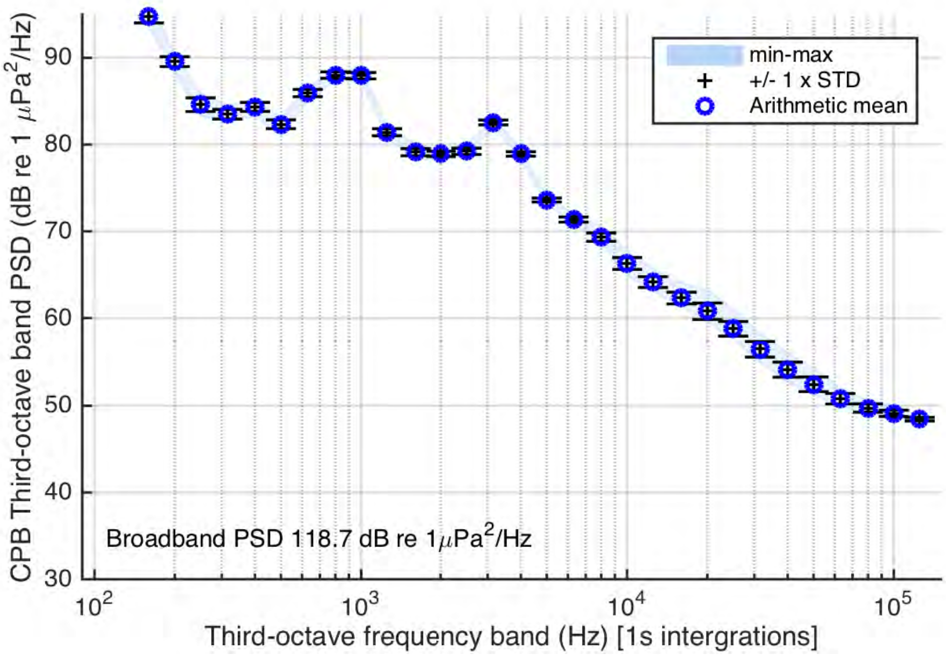

Figure 8. Power Spectral Density (PSD) in Third Octave Bands for low sea-state period at 15:01 GMT on 11th October 2016. Total sample length 25 seconds, 1-second integration periods. Likely contributions originated from specific activities aboard the barge or small boats.

By comparison, Figure 8 shows a 25-second period taken around 5 minutes later at 15:01 GMT. During this period, significantly elevated noise levels were observed at a range of frequencies. Most of this noise likely originated either from short-term barge-based activities or nearby small boat operations with a broadband response of 118.7 dB re 1 μPa^2/Hz with levels approximately 30 dB higher in some frequency bands. For further comparison, Figure 9 shows a consecutive 25-second sample period taken a few moments later with a lower broadband response of 106.2 dB re 1 μPa^2/Hz. These data show that, although levels dropped when compared to the previous sample, there was increased variation during the 25-second sample, most likely due to transitory noise from boat- or barge-based operations during this period.

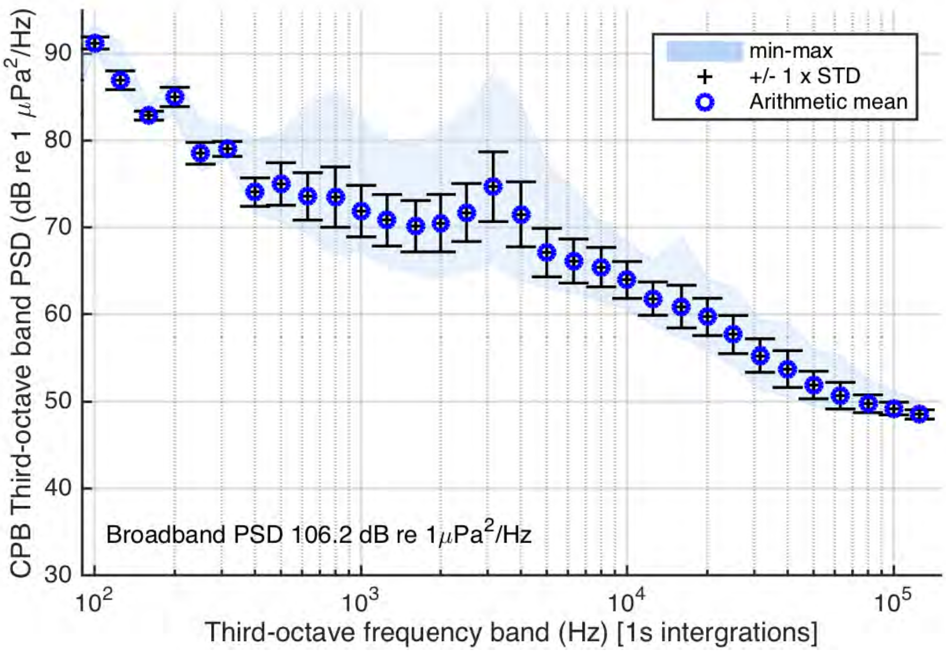

Figure 9. Power Spectral Density (PSD) in Third Octave Bands for low sea-state period. Consecutive 25s period from file started at 15:01 on 11th October 2016 compared to Figure 8. Total sample length 25 seconds, 1-second integration periods. Transitory contributions from specific barge-based or small boat operations.

These examples suggest that general noise levels at the fish farm barge and in the Sound of Mull could vary at short notice (occasionally varying by >40 dB within minutes), due to changing weather conditions (wind, sea-state, rain etc.) and contributions from nearby boat- and barge-based operations. Such operations were relatively infrequent and general background noise levels were in line with what might be expected within a relatively narrow waterway with a relatively low numbers of passing vessels. Further work is required to assess long-term variability in ambient noise levels at this site.

4.5 SIGNAL PROPAGATION MODELLING

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

Comparison to classic absorption data taken from various studies shown in Figure 10 (based on Etter 2003) shows that absorption rates of around 0.05 dB/km could be expected at 1 kHz, compared to rates of approximately 0.8 dB/km at 10 kHz and rates of approximately 2 dB/km at 20 kHz. At the Farfield sites, therefore, one might expect to observe more significant losses per km for the HF signal than for the LF signal, due to absorption across the intervening distance. At a distance of several km, the variation in losses of the signals' key frequency components would range from 0.2 dB in the 1-2 kHz range of the LF signal to approx. 1-2 dB at 10 kHz in the HF signal. This effect would increase towards the Farfield moorings with increasingly significant losses of higher frequency components expected at greater distance.

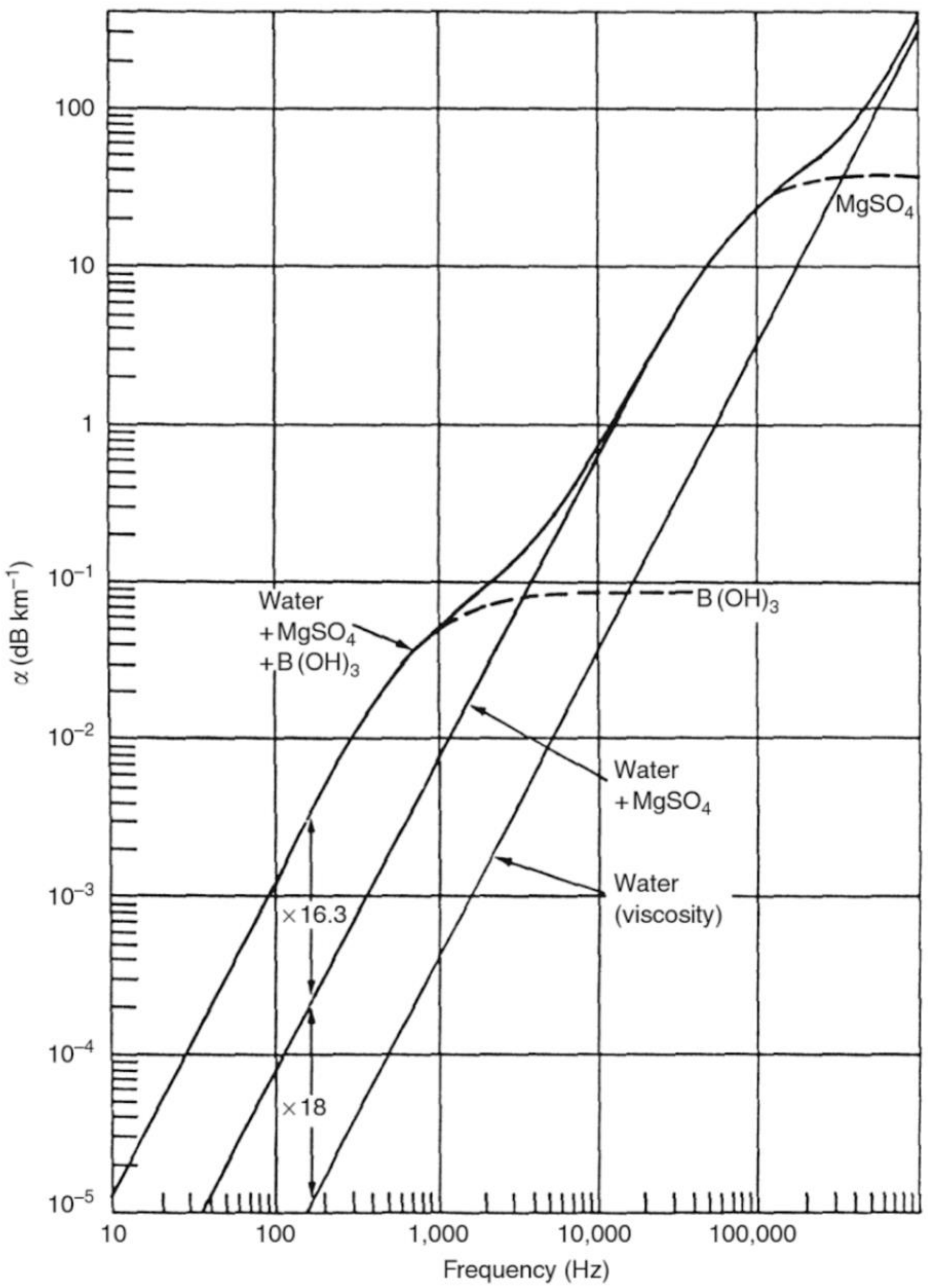

Figure 10. Underwater acoustic absorption versus frequency. Figure derived from Etter (2003).

Analysis of Farfield SoundTrap data from position C-5000 of both HF and LF signal types indicated that, despite the 5 km distance from the barge, both signals were nonetheless easily detectable above background noise levels. This suggested that the entire array was ensonified by the experimental signals, allowing direct comparison of porpoise detection rates between all C-PODs. Received levels would still be expected to be lower among the Farfield moorings, and hence behavioural response could be expected to be less pronounced; this aspect could not be investigated in the present experiment due to an absence of RL data from each individual mooring.

4.6 VISUAL OBSERVATIONS

Visual observations were collected on 18 days between 9/09/2016 and 10/10/2016 (or 56% of the total number of days in the experimental period). Visual observations only took place under relatively good weather conditions with low sea states that allowed clear views across the Sound of Mull. Due to the northward-facing aspect of the observation site, observations were not impeded by glare of sunlight reflected off the sea surface. Estimated daily Beaufort sea state during visual observation periods varied between approximately 0.5 and 2.5; however, sea state varied considerably over the course of a day due to local weather conditions. Bloody Bay was often more sheltered from prevailing winds than the central Sound of Mull, resulting in heterogeneous observation conditions across the Sound that were recorded by the field team. Observed vessel traffic was dominated by Caledonian MacBrayne ferries traversing the site, including both the local Tobermory/Kilchoan ferry crossing the Sound of Mull several times daily and the larger ferries on routes between Oban and Coll, Tiree and the Outer Hebrides. Other commonly observed vessel types included fishing vessels (mainly small inshore vessels targeting lobster and crab), tour boats and yachts. Trawling activity was noted to be mainly limited to nights and stormy conditions that prevented trawlers from accessing the main fishing grounds to the west of Mull.

4.6.1. Marine mammal sightings

Harbour porpoises were observed on 23 occasions across nine of 18 days (Table 6). Observations varied in duration from a single surfacing to extended sightings lasting 30 minutes or more. Porpoises were observed singly or in groups of up to four animals. Most porpoises were sighted outside Bloody Bay, i.e., >1 km away from the observation site within the central and northern Sound of Mull, and particularly towards the entrance to Loch Sunart (Figure 6); porpoises were sighted within approximately 1km from the fish farm on three occasions. Bottlenose dolphins were observed on four separate occasions (Table 6). As with porpoises, dolphin sightings varied in duration from a single brief surfacing event to extended observations for up to 30 minutes. Dolphins were generally observed closer to the observation site than porpoises, travelling singly or in groups of up to five individuals. Their active surface behaviour facilitated detection by the observers. Finally, a single minke whale was observed on 28/09/2016 in Bloody Bay (Table 6).

Seals were regularly observed on all but one day of the experimental period, with multiple observations throughout each day (Table 6). Because the focus of the study was on porpoises, signal transmissions were not initiated when a seal was sighted. Visual observers recorded occurrence, number and species of seals present and estimated location and surface behaviour, but no efforts were made to track individual seals or record surface interval durations. Seals were most often observed near the fish farm but were also seen throughout Bloody Bay and the wider Sound of Mull; no surface feeding behaviour was observed. All seals that were observed under sufficiently calm conditions to permit species identification were identified as harbour seals (Table 6). Seals were typically recorded as stationary or slowly swimming at the surface. Up to two seals were recorded at any given time by visual observers, confirming reports from the site staff that small numbers of seals might be present near the fish farm at any given moment. A single otter (*Lutra lutra*) was also observed in the water along the shoreline below the observation site on three days (Table 6). No efforts were made to assess effects of experimental transmissions on otters.

*Table 6. Overview of sightings of different marine mammal species during the experimental period. Sightings of porpoises and dolphins often involved >1 individual. *N.B.: Seal and otter sightings were not tracked over time and so numbers of sightings reflect the 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	-	-

Bearings of sightings for all species from the observation site (expressed in degrees) were initially estimated visually relative to the centre of the community of Kilchoan, on the far shore of the Sound of Mull, which deviated approximately 10° from true North from the observers' perspective. This deviation in bearings was subsequently corrected at the data processing stage. Distances of sightings to the observers, however, could only be estimated by comparison against stationary objects at known distances, e.g., the surface floats of the Nearfield C-POD array. This resulted in considerable uncertainty in terms of estimated positions of sightings at distances beyond several hundred metres from shore. It was nevertheless apparent that porpoises were typically sighted in the central and northern Sound of Mull, while seal sightings were mainly concentrated around the fish farm (Figure 11). Other species were sighted too infrequently to assess any heterogeneity in distribution.

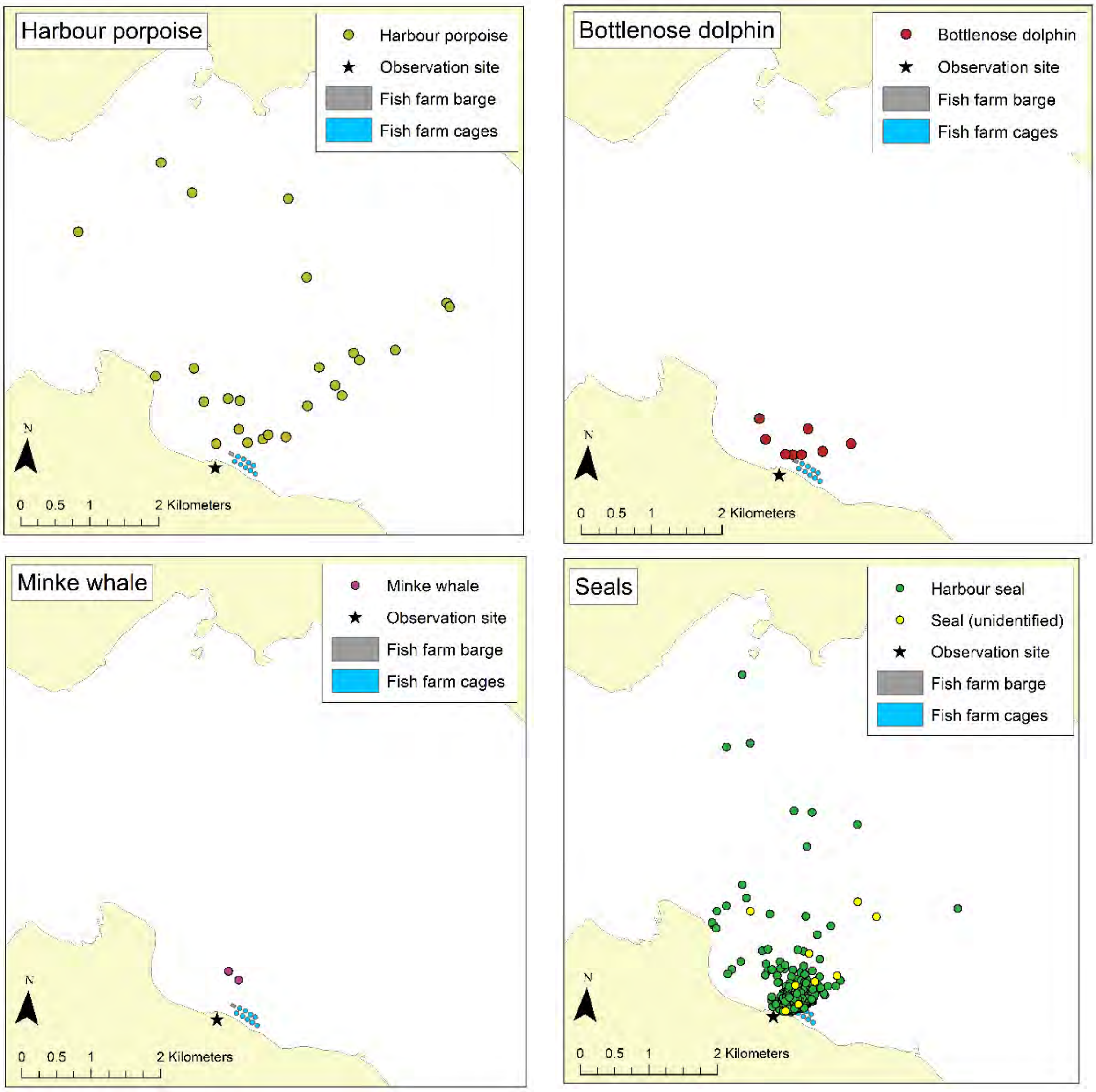

Figure 11. Approximate locations of sightings of different marine mammal species during the entire experimental period. Note that these positions are only approximations due to substantial variability in distance estimation among observers.

4.6.2 Visual tracking analysis

The visual tracking methodology (described in detail in Section 3.6) was designed to provide insight into porpoises' initial responses to the experimental signals by tracking their surface movements at high resolution. Unfortunately, the small number of visual sightings of porpoises made this difficult (Table 6). In addition to being infrequent, most porpoise sightings occurred at considerable distance from the observation site (notably in the northern half of the Sound of Mull towards the entrance to Loch Sunart, several km away). At such distances, the cameras' resolution proved to be inadequate for reliably recording porpoises for tracking. For this reason, very few sightings close to the fish farm were suitable for further analysis; the method was therefore unable to provide robust information on porpoises' responses to the experimental ADD signals. However, despite the small number of porpoises at the site in the autumn of 2016, we were able to demonstrate the general utility of the method and would encourage further development. An example of a tracked group of porpoises is shown in Figure 12.

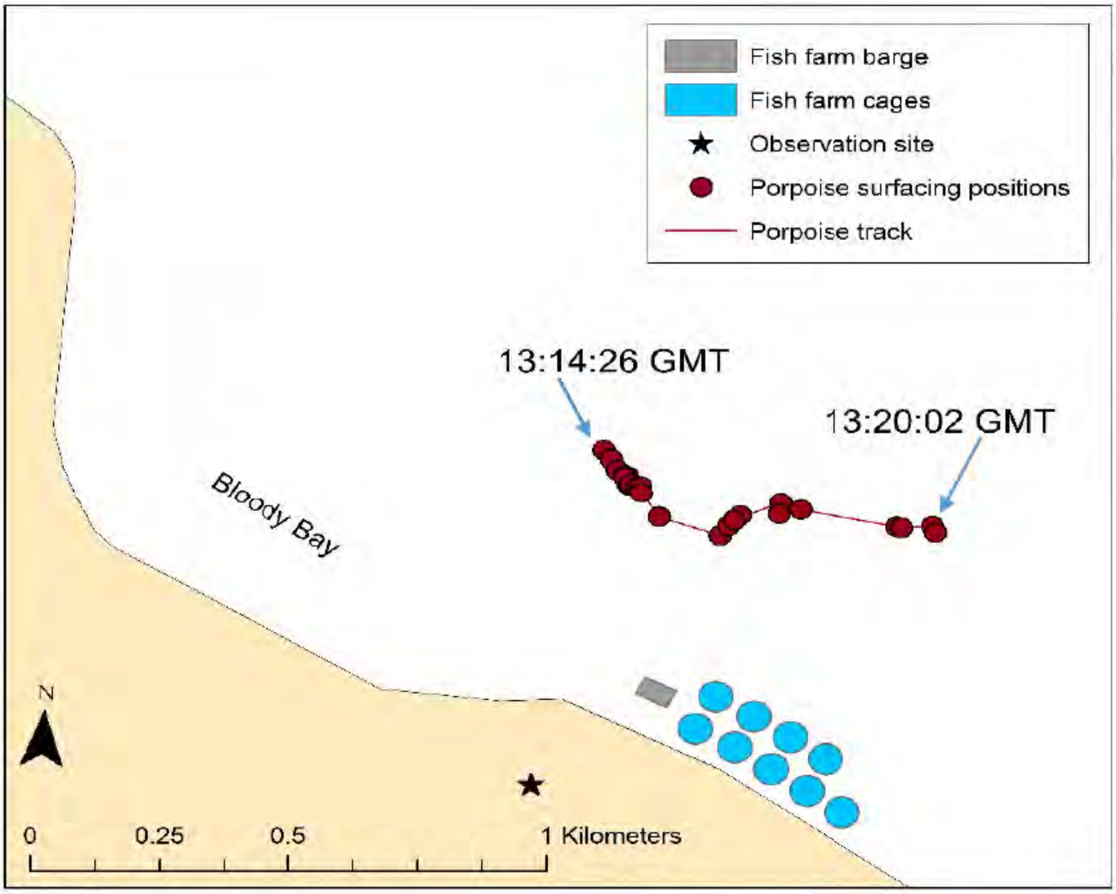

Figure 12. Example of tracked group of three porpoises observed on 14/09/2016, swimming from west to east.

4.6.3. Seal observations around the fish farm

Although not the main focus of this study, visual observations on seals surfacing around the fish farm allowed for some initial analysis of effects of the experimental ADD signals on them as well. Seals were observed during 17 experiments (Table 7). In three experiments, less than 30 minutes (or <25%) of the entire 2-hour transmission period were observed (Table 7), and these cases were excluded from further analysis. Data from the remaining 14 cases were used to assess the relationship between signal type and standardised seal sighting rates, using a linear modelling approach through the *lm* tool in the R package *stats* v.3.4.3. Results indicated that there was no obvious relationship between the signal being transmitted and standardised seal sighting rates, irrespective of whether sightings of nearby seals (d.f. = 11; p = 0.5461), more distant seals (d.f. = 11; p = 0.2213), or all seals (d.f. =11; p = 0.4637) were used to populate the model. Standardised seal sighting rates were lowest during silent controls, and highest during HF signal transmissions (Table 7). These preliminary results should be interpreted with caution, but they did not suggest that either ADD signal used in the present study acted as a significant deterrent to seals from the immediate area around the fish farm.

*Table 7. Summary of seal sighting events during experimental transmissions of HF (n = 5) and LF signals (n = 7), as well as silent controls (n = 5; each experiment identified by number). Seal sightings have been divided into nearby and distant groups, based on approximate distances from the fish farm barge estimated from visual sighting data. Experiments marked with * were observed for <30 minutes and were excluded from subsequent analysis.*

Signal type	Experiment number	Number of minutes observed (out of 120)	Number of nearby seal sightings (<500m from barge)	Sightings ratio (Near; # of sightings/# minutes observed)	Number of distant seal sightings (>500m from barge)	Sightings ratio (Distant; # of sightings/# minutes observed)	Total number of seal sightings
Silent control	14	42	1	0.02	0	0.00	1
	35	38	3	0.08	0	0.00	3
	40	75	0	0.00	0	0.00	0
	56	21*	0	0.00	0	0.00	0
	101	75	9	0.12	0	0.00	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

4.7 C-POD DATA ANALYSIS

Analysis of C-POD data began with a comprehensive review of data quality. By design, C-PODs exposed to noisy environments experience temporary memory buffer saturation, resulting in an inability to detect porpoise echolocation signals which resets at the beginning of the next minute (Chelonia Inc. 2011; Booth 2016). C-PODs in the present experiment experienced buffer saturation during <5% of the entire deployment period, typically as isolated minutes. This suggested that ambient noise had not unduly affected the functionality of the C-POD array. The buffer saturation effect was most pronounced among C-PODs near the fish farm barge and appeared largely associated with well-defined fish farm operations (notably during the salmon restocking process which occurred between 22-24/09/2016 and involved vessel activity well above normal levels). To ensure that these events would not confound the results, minutes from which more than 6 seconds (i.e., ≥10%) were lost (ranging from 65 to 2083 minutes, or 0.2% - 4.9% of total experimental period, for the various C-PODs across the array) were excluded from further analysis. Due to the removal of such 'noisy' minutes, some C-PODs' records of particular experimental sessions no longer equated to 120 minutes of monitored time. In 73 cases involving 11 experimental transmissions (2.8% of all 2606 C-POD-transmission combinations), individual C-PODs were found to have recorded <100 full minutes; these data were removed from further analysis to maintain approximately equal monitoring coverage across the array for all experiments.

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

*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 7/10/2016; the figures listed for this unit therefore were derived over a shorter period than the other units were. Note that this table includes 'off-effort' periods in between transmissions.*

Array section	Site name	# PPMs detected	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

4.7.1 Experimental results of exposure experiments

Due to the randomised nature of transmission selection, the total number of HF and LF exposures and silent control trials was not equal (summarised in Section 4.1). PPM detection rates during the experimental period (08/09-11/10/2016) were standardised for each C-POD by dividing the number of PPMs by the total number of monitored minutes over each experimental transmission. For each signal type, all PPM detection rates were averaged across the array to produce an aggregate average. The greatest number of PPMs observed during any experimental transmission was 19, representing approximately 15% of the total 2-hour experimental period. PPM detection results, aggregated by signal type, are summarised for each mooring in Table 9. At almost all moorings, the greatest number of PPMs was observed during silent control periods. Aggregate average PPM detection rates were highest in silent control exposures and lowest during transmission of HF signals (Figure 13). Based on aggregated results, LF signal transmissions also resulted in reduced PPM detection rates, contrary to original expectations that detection rates under these conditions might broadly resemble those observed under silent control exposures.

*Table 9. Summary of numbers of monitored minutes ($N_{MINUTES}$), number of PPMs (N_{PPM}), and average ratio of number of PPMs divided by total number of monitored minutes (F) during all experimental transmissions, detected by each C-POD between 08/09/2016 and 11/10/2016 inclusive. *N.B.: The C-5000 C-POD only collected data until 06/10/2016, inclusive. ** These values represent average F-ratios across all relevant C-PODs, and were multiplied by 1000 to generate values depicted in Figure 13.*

Array Element	Mooring	HF signal			LF signal			Silent control signal			TOTAL
		$N_{MINUTES}$	N_{PPM}	F	$N_{MINUTES}$	N_{PPM}	F	$N_{MINUTES}$	N_{PPM}	F	N
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
	All Nearfield		39	0.00044**		65	0.00093**		127	0.00162**	
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
	All Farfield		163	0.00580**		152	0.00680**		236	0.00911**	
Entire Array		113188	202	0.00178**	87624	217	0.00247**	100676	363	0.00358**	782

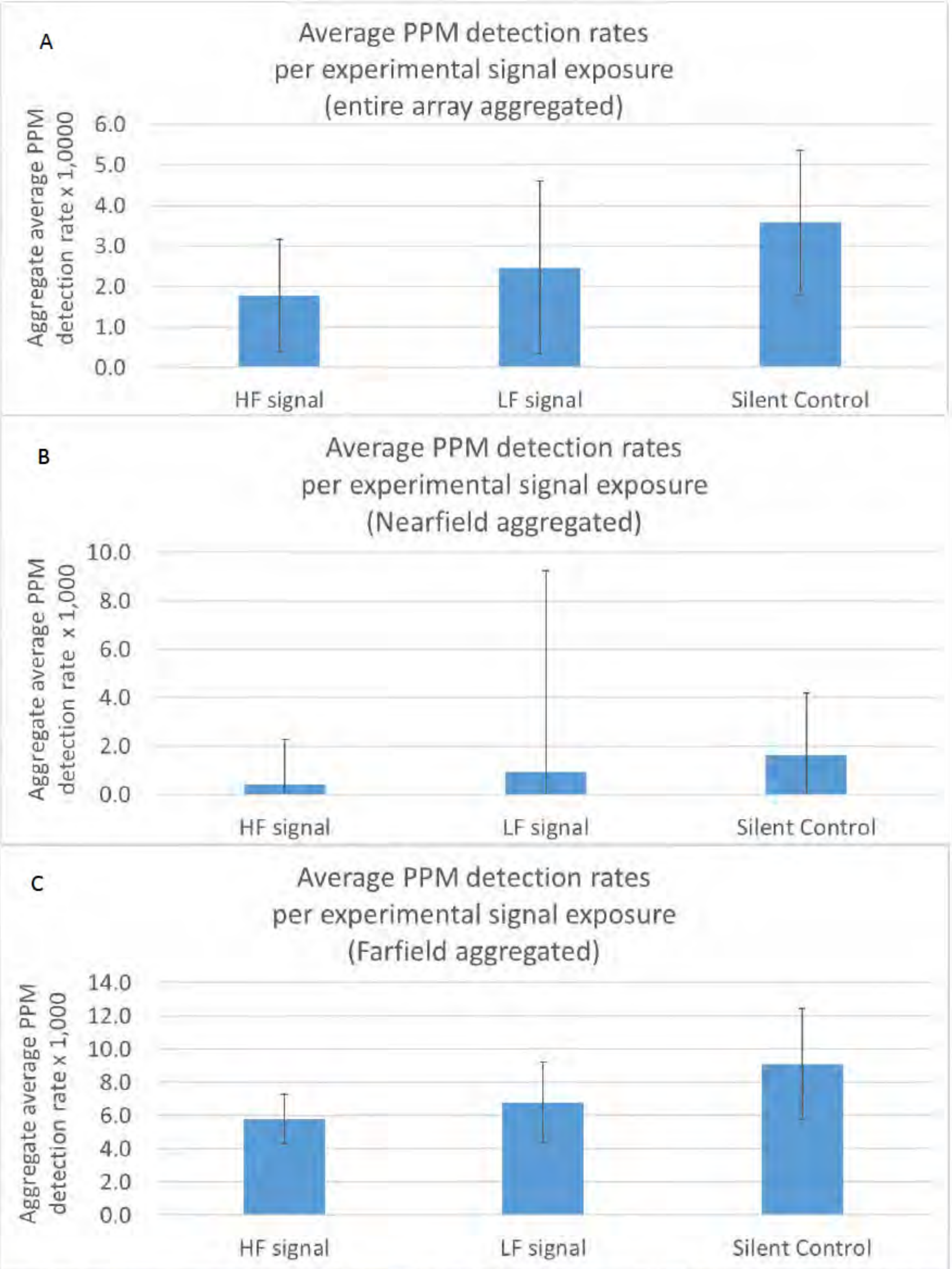

*Figure 13. Aggregated average PPM detection rates (± SE) for (A) all C-PODs combined, (B) the Nearfield and (C) Farfield datasets, for the three different experimental transmissions (HF signal, LF signal, and silent control). Average values were derived from Table 9 (identified by ** symbols) and multiplied by 1,000 for display purposes. Significant variability in detection rates is apparent, particularly in the Nearfield data.*

Once moorings were assessed individually, considerable variability among standardised PPM detection rates became apparent (Table 9; Figure 14). PPM detection rates at Nearfield moorings closest to the fish farm barge were substantially lower during both HF and LF signal transmissions than during silent control periods. This 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 the Nearfield component of the array (e.g., W-800 and W-1000), as well as the Farfield moorings, differences between one or both experimental treatment(s) and the silent controls were reduced (Table 9; Figure 14). While standardised detection rates were still highest overall during silent controls at each mooring (except W-1000 where detection rates under the LF signal exposure were relatively high, and almost non-existent under the HF signal exposure), only in one case (C-5000, along the opposite shore across the Sound of Mull) were HF-exposed detection rates notably higher than LF-exposed detection rates. There was an order of magnitude difference in terms of absolute numbers of PPMs detected at different C-PODs, even among adjacent ones (cf. results from C-600, C-800 and C-1000; Table 9). The reasons for these differences are presently unclear, but their occurrence suggests that any effects of the experimental signals on porpoise detection rates may be modulated by environmental parameters driving spatiotemporal heterogeneity of porpoise distribution across the array. Possible explanations for this heterogeneity include stochastic differences in individual porpoises' distribution, habitat use and/or echolocation rates (Linnenschmidt et al. 2013).

The extent to which PPM detections were clumped (i.e., multiple PPMs occurring in dense clusters within a few experimental periods, rather than occasional PPMs spread out across multiple experimental periods) was examined to assess whether this might affect overall F-ratio values (Table 9). The variance associated with average F-ratio values reported in Table 9 was compared across the array. High variance associated with clumping was noted at some moorings, most notably W-1000 during the LF signal experiments where 35 of 37 PPMs (>94%) occurred during only two experiments (N = 16 and 19 PPMs, respectively), resulting in a high F-ratio value (0.00796). Such results could have been caused by a single porpoise remaining near the mooring for an extended period. In the case of W-1000, the observed clumping of PPMs goes some way towards explaining the anomalously high score at this mooring during the LF signal exposure experiments (Table 9; see also Figure 14). This example illustrates the substantial variability associated with this database.

To take the frequent occurrence of zero values in the dataset into account, a series of nonparametric Kruskal-Wallis tests, followed by Tukey-type nonparametric multiple comparisons analyses where appropriate, were performed to test for differences between signal treatments among different moorings (following the method outlined in Zar 1984; p.176, 199). To deal with tied ranks among the Kruskal-Wallis test parameters, correction factors were applied as described by Zar (1984). Three separate Kruskal-Wallis tests were performed (for the entire array, the Nearfield and Farfield moorings respectively) based on F-values presented in Table 9. PPM sample sizes were considered too small to undertake further Kruskal-Wallis tests at the scale of individual moorings (Table 9).

For the entire array, the Kruskal-Wallis test indicated significant differences between the three treatments ($n = 19$; $k = 3$; $H_c = 8.240039$; $H_{0 05, 2} = 5.991$; $0.005 > p > 0.001$; Zar 1984), with the aggregate rank of the silent control (404.5) being substantially different from both HF and LF signal treatments (630 and 618.5, respectively). This was, however, not resolved through the subsequent Tukey-type multiple comparisons analysis, which could not identify a statistically significant difference between any category ($q_{0 05, \infty, 3} = 3.314$; $q_{HF\ vs.\ LF} = 0.1589$, $q_{HF\ vs.\ silent} = 3.1168$; $q_{LF\ vs.\ silent} = 2.9579$; Zar 1984). Suspicion that this result was largely driven by more homogenous Farfield mooring data was confirmed when the two subcategories were analysed separately. For the Nearfield data, the Kruskal-Wallis test again indicated significant differences between the three treatments ($n = 14$; $k = 3$; $H = 12.336$; $H_{0.05, 2} = 5.991$; $0.005 > p > 0.001$; Zar 1984). The subsequent Tukey-type multiple comparisons analysis confirmed that there was no statistically significant difference between HF and LF signal treatments (aggregate rank scores of 353 and 367.5 respectively; $q_{0 05, \infty, 3} = 3.314$;

$q_{HF\ vs\ LF}$ = 0.3159; Zar 1984), but that both were significantly different from the silent control (aggregate rank score of 182.5; $q_{0.05,\infty,3}$ = 3.314; $q_{HF\ vs.\ silent}$ = 3.7144; $q_{LF\ vs.\ silent}$ = 4.0303; Zar 1984). For the Farfield data, no statistically significant difference between treatments was apparent (n = 5; k = 3; H_c = 5.12; $H_{0.05,2}$ = 5.991; 0.10 > p > 0.05; Zar 1984).

In summary, and acknowledging limited sample sizes and substantial inter-mooring variability, it appears that, at the scale of the entire Nearfield array, there was little difference between HF and LF signals in terms of their apparent effect on porpoise detection rates, which in both cases were significantly lower compared to silent control periods. Resolving variability in responses to different signals at smaller scales proved problematic due to small sample sizes at moorings closer to the sound source. Among the more distant Farfield moorings, detection rates across all the treatments were generally higher and the effects of different signals were mixed; in most cases, differences in detection rates were limited and no obvious consistent patterns were observed (Figure 14).

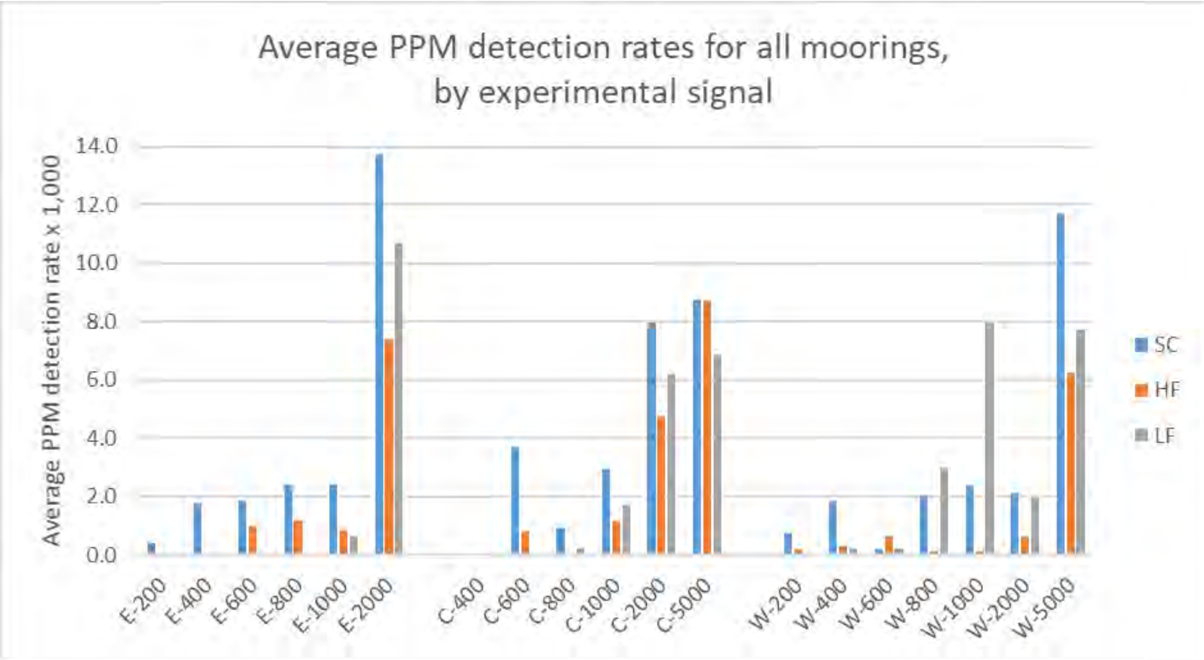

Figure 14. Average PPM detection rates (derived from Table 9, then multiplied by 1,000 for display purposes) across the experimental array when exposed to HF signal, LF signal, or silent control (SC) treatments.

4.7.2 Cross-array variability

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

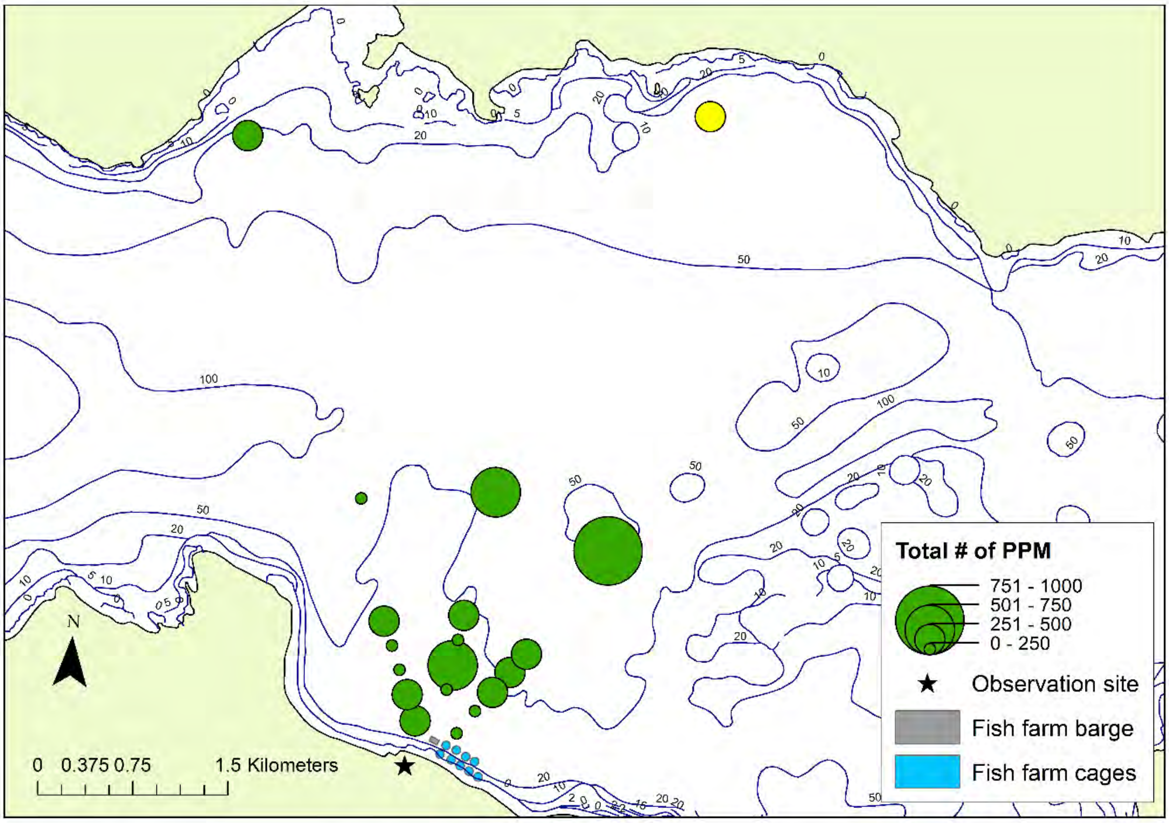

Figure 15. Summary of total numbers of PPMs reported at different mooring sites across the C-POD array during 8/09-16/10/2016. N.B.: the C-5000 C-POD (top right, yellow) was only operational up to 6/10/2016.

4.7.3 Environmental drivers of PPM detection variability

Considerable diel variability in PPM detection rates was observed at most C-PODs, with peaks in detection rates at night (particularly around dawn and dusk) contrasting with no or very few detections during daylight hours. This pattern was especially notable in C-PODs close to shore (e.g., E-400; Figure 16; Appendix 4, but also the C-5000 C-POD near the opposite shore), and reinforced the impression based on sighting rates from the visual observation team that porpoises did not regularly use the inshore waters of Bloody Bay during daylight hours. In contrast, porpoise click trains were detected throughout the day on most days at mooring E-2000, in line with visual observations of porpoises in that general area (Figure 16). These results suggested small-scale spatiotemporal heterogeneity in the use of the Sound of Mull by harbour porpoises, and indicated increased detection rates in inshore areas after dark. Additional variability in PPM detection rates across the array was noted over ebb-flood and spring-neap tidal cycles (Figure 17) but no consistent patterns were observed, again suggesting substantial heterogeneity in habitat usage.

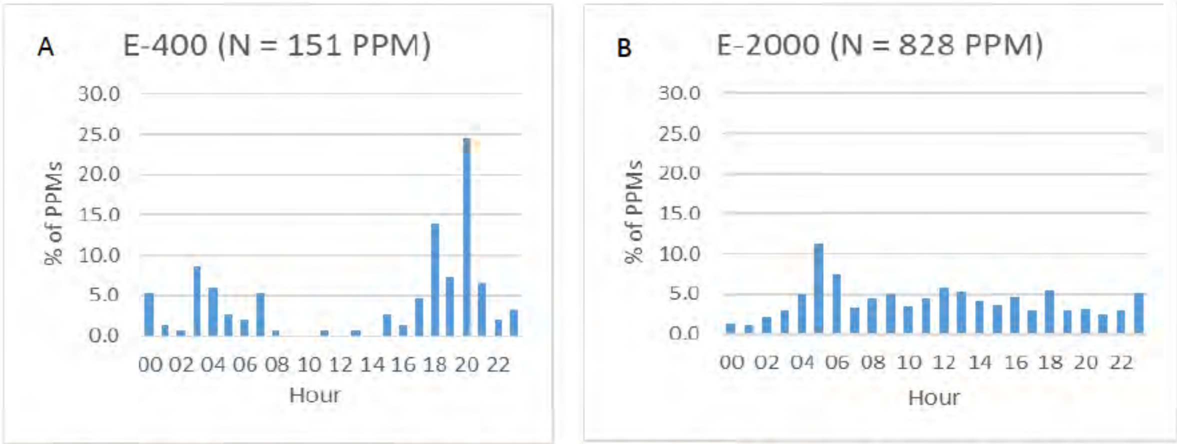

Figure 16. Examples of diurnal patterns of PPM detections from A) Nearfield (E-400) and B) Farfield (E-2000) C-PODs (data from 8/09-16/10/2016, aggregated).

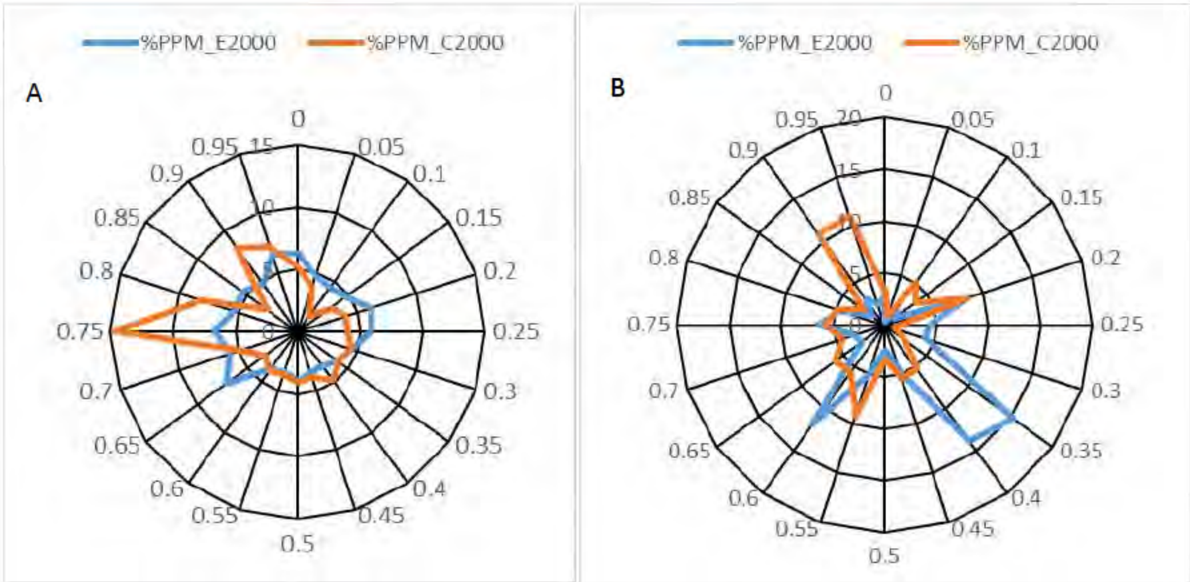

Figure 17. Examples of apparent variability in PPM detection rates at ebb-flood and spring-neap tidal scales. A) Normalised (% of total) PPM detections at locations E-2000 and C-2000 over the ebb-flood tidal cycle (0 = 1 = ebb at Tobermory tidal gauge). Detections appear mostly uniform at E-2000 (blue) but suggest a distinct increase in detection rates during falling tide at C-2000 (orange); B) Normalised (% of 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). These data suggest an increase in PPM detection rates approaching neap tide at E-2000 (blue), but an increase in detection rates approaching spring tide at C-2000 (orange). All data from 8/09-16/10/2016, aggregated.

4.7.4 Pre- and post-experimental context

C-POD data collected from below the fish farm barge prior to the experiment indicated high average PPM detection rates (0.00670 PPMs/# of minutes monitored; SE = 0.00135) when compared to the silent control data collected by adjacent C-PODs E-200 and W-200 during the experimental period (Table 9). The pre-experiment baseline data also indicated substantial daily variability in terms of total numbers of PPMs detected, with a decline in daily detection rates during the two weeks prior to starting transmissions (Appendix 2, Figure A2.1A). A strong diel pattern was apparent, with >80% of all PPMs detected in the 7-hour period between 21:00 and 04:00 GMT, and very few PPM detections during daylight hours (Appendix 2, Figure A2.1B).

PPM detection rates during the post-experimental winter deployment were significantly higher than both the pre-experimental and experimental datasets (Appendix 2). Despite ongoing daily variability, very high average PPM detection rates (0.13080 PPMs/# of minutes monitored; SE = 0.00881) were observed consistently throughout the deployment period (Appendix 2, Figure A2.2A). The diel pattern persisted with almost no detections during daytime, although the distribution of nocturnal detections was more spread out during the longer winter nights (>90% of PPMs detected in the 14-hour period between 17:00 – 06:00 GMT, Appendix 2, Figure A2.2B).

These results indicate that porpoises were using the area immediately surrounding the fish farm barge both before, during and after the experiment. There were, however, substantial differences in daily porpoise detection rates during the seven-month period covered by the various C-POD deployments described in the present study. Detection rates were significantly higher in winter when compared to both pre-deployment summer data and experimental data collected in September/October 2016; it is unclear what might have caused these differences. The same C-POD was used during both pre- and post-experimental monitoring, and deployments proceeded in a comparable fashion in terms of attachment and recovery, suggesting that the results do not represent an experimental artefact. Experimental results reported above therefore need to be viewed in the light of this apparent substantial seasonal variability in porpoise detection rates within Bloody Bay. Interestingly, the diel detection pattern observed during the experiment persisted from summer to winter, albeit more spread out across a longer period of darkness in winter. This could either suggest an increase in echolocating porpoises near the detector or a greater reliance on echolocation during seasonally low light levels.

4.8 ADVANCED MODELLING

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

Models were based on a binomial Generalised Additive Modelling (GAM) framework with an independent correlation structure and a logit-link function to determine explanatory relevance of environmental covariates, and were designed and run using the open-source programming language R (v.3.4.2; R Core Team, 2013). In these models, the response variable (PPM) was defined as a binary record (1 = presence, 0 = absence). Generalised Estimation Equations (GEEs; Liang & Zeger 1986) were used to address temporal autocorrelation, again following Pirotta et al. (2011). The independent correlation structure was used because the actual underlying correlation structure within the datasets was not known, and GEEs are considered to be robust against correlation structure misspecification (Liang & Zeger 1986; Pan 2001). The logit link function was chosen because it allowed the probability of porpoise detections to be modelled as a linear function of covariates, thereby satisfying a core assumption of GEEs (Zuur et al. 2009a; Garson 2013). Temporal autocorrelation was investigated using the *acf* autocorrelation function within the *stats* package in R (threshold = 0.05; Venables and Ripley 2002) to define blocks of data (here expressed in minutes) within which uniform autocorrelation was expected (Liang & Zeger 1986; Garson 2013). Block sizes varied from 5 to 145 minutes between moorings across the array.

Two broad series of models were run, hereafter referred to as Series A and Series B models (described in more detail in Appendix 5A & 5B). In Series A, only data collected during experiments were included, whereas in Series B, PPMs from the entire deployment (i.e., also including long periods of 'non-experimental' time and recovery time in between experiments) were included. This had the effect of increasing the sample size at many moorings and provided a broader context of which environmental factors were important in driving porpoise detection rates. Only datasets from moorings (or combinations of moorings) containing at least 50 PPM were modelled.

For comparative purposes, only data from September 8 up to October 6 2016, inclusive, were used for modelling, as this made it easier to aggregate data from all moorings including the abbreviated C-5000 deployment within larger-scale models. As a result, PPM counts used in the Series A models were either identical to, or marginally lower than, those used in previous analyses (Table 9); however, PPM counts used in the Series B models were typically much higher due to the longer time period covered (updated counts provided in Appendix 5B; Table A5B.1). The Series A models were explicitly intended to explore the role of different signal types during experiments, whereas the Series B models were used to provide longer-term context in terms of which covariates were most important in driving PPM detections.

Models were run at different spatial scales, depending on data availability (i.e., ≥50 PPM within the database). For Series A, the following models were run:

- Individual moorings (W-1000, E-2000, C-2000, C-5000 and W-5000); PPM sample sizes during experiments (Series A) were generally too small to reliably model at the scale of individual moorings, particularly within the Nearfield area.
- A series of aggregations of individual moorings, involving increasingly distant ones:
  - "200 – 600 m-A", involving data from all moorings out to 600 m from the sound source (E-200, W-200, E-400, W-400, E-600, C-600 and W-600);
  - "200 – 800 m-A", involving data from all moorings out to 800 m from the sound source (E-200, W-200, E-400, W-400, E-600, C-600, W-600, E-800, C-800 and W-800);
  - "Nearfield-A", involving data from all moorings out to 1000 m from the sound source (E-200, W-200, E-400, W-400, E-600, C-600, W-600, E-800, C-800, W-800, E-1000, C-1000, and W-1000);
  - "Nearfield-plus-A", involving data from all moorings out to 2000 m from the sound source (E-200, W-200, E-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 and W-2000);
  - "Whole array-A", involving data from all moorings out to 5000 m from the sound source (E-200, W-200, E-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 and W-5000).

No data from mooring C-400 were used in any Series A models due to an absence of any PPM detections during experimental periods at this mooring.

For Series B, many more models could be run due to the larger sample sizes available at most moorings. Accordingly, the following models were run for Series B:

- Individual moorings (W-200, E-400, C-400, W-400, E-600, C-600, E-800, W-800, E-1000, C-1000, W-1000, E-2000, C-2000, W-2000, C-5000 and W-5000);
- "Nearfield-B", involving data from all moorings out to 1000 m from the sound source (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, and W-1000);
- "Whole array-B", involving data from all moorings out to 5000 m from the sound source (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 and W-5000).

The various single-mooring models obtained during Series B illustrated the importance of different combinations of covariates among moorings, emphasizing the heterogeneity observed in PPM detection rates across the array.

Further details of the GAM-GEE modelling approach, a list of relevant covariates and individual model results are provided in Appendix 5A (for Series A models) and Appendix 5B (for Series B models). All covariates included in the final models were retained based on their ability to explain statistically significant amounts of residual variability within the datasets in question. Model quality varied considerably, with some models being substantially better at correctly predicting both presence and absence of PPMs than others (see Appendix 5A/5B for details). Poor model quality was likely driven by low numbers of PPMs detected in most models.

The GAM-GEE modelling approach used here has allowed an assessment of the relative significance of different covariates, notably experimental signal transmissions versus a range of unrelated environmental variables, in determining presence of echolocating porpoises. It is, however, important to interpret the modelling results with caution. In particular, each successive covariate included in the models referenced below and in Appendix 5A/5B describes progressively less and less residual variability under the influence of all other previously assessed covariates retained in the final models. The PPM-covariate relationships observed should therefore not be taken out of that multi-covariate context and should not be considered independently.

Overall, model outcomes across both Series A and Series B model runs aligned well with earlier observations described in Section 4.7, in terms of which covariates turned out to be relevant in predicting PPM detections. Importantly, the presence of an experimental signal (Signal_Type) was only retained as the primary covariate in models based on moorings close to the sound source, indicating that the presence of either LF or HF signal was typically not the main factor in determining presence of echolocating porpoises across the entire array.

The available Series A single-mooring models, all of which were based on moorings located 1 km or more from the sound source, can be summarised as follows (covariate abbreviations included in brackets; model-specific details in Appendix 5A):

- As expected (Figure 14), Signal type (HF vs. LF signals vs. silent control) was the most important covariate for one model (W-1000) but the reason for this is not clearly understood (see Section 4.7). Signal type was also included as a minor covariate in one other model (E-2000).
- Julian day (JULDAY) was the most important covariate in the two models where it occurred (E-2000 and W-5000), suggesting an increase in detection rates over time.
- Diel Hour (HOUR) occurred in three of five individual models, in each case suggesting an increase in detections during hours of darkness; this effect was most pronounced at nearshore sites (W-1000 and C-5000) and less so for E-2000.
- Number of unprocessed clicks detected per minute (Nall_m) was a frequently occurring covariate, although never of primary importance.
- The Spring-Neap tidal cycle (SpringNeap) was among the most important covariates in three of five individual models (E-2000, C-2000 and C-5000). In contrast, the Ebb-Flood tidal cycle (HiLoTide) only appeared in a single model (C-2000).
- C-POD angle relative to vertical (ANGLE) was included as a minor covariate in only one model (C-2000).

For the multi-mooring models created under Series A, the relative importance of different covariates changed between successive models, as data from increasingly distant moorings were included:

- Signal type (HF vs. LF signals vs. silent control) was the most important covariate for those models based solely on data from moorings near the sound source ("200m – 600m-A" and "200m – 800m-A"). Once moorings at greater distances were included, the importance of Signal type declined.
- Mooring location within the array (POSITION) was relatively unimportant for models that were only based on moorings close to the sound source, but became more important once more

distant moorings were included (e.g., the "Nearfield-A" model). However, mooring location was not included in the "whole array-A" model.

- The Ebb-Flood tidal cycle (HiLoTide) was important for inshore models up to and including the entire Nearfield array, but declined in significance once data from Farfield moorings in the central Sound of Mull were included. The Spring-Neap tidal cycle (SpringNeap), on the other hand, became much more important once these offshore moorings were included.
- Julian day (JULDAY) was the most important covariate for the "whole array-A" model, suggesting long-term variability in terms of PPM detection rates; it was not included in any of the other models.
- Number of unprocessed clicks detected per minute (Nall_m) occurred in all models as a minor covariate.
- Time of day was included as a minor covariate in the "whole array-A" model.

For Series B models, which included data from both experimental and non-experimental time periods, many more single-mooring models could be created. These can be summarised as follows (model-specific details in Appendix 5B):

- Diel hour (HOUR) and Julian Day (JULDAY) were consistently among the most important covariates for nearly all models, confirming the apparent significance of diel and seasonal cycles in driving small-scale porpoise distribution.
- The spring-neap tidal cycle (SpringNeap) also appeared important in many cases, particularly for moorings further offshore, with ebb-flood tidal cycle (HiLoTide) generally less important.
- Signal_Type (HF vs. LF signals vs. silent control vs. 'other' non-experimental time) was of secondary significance (2nd or 3rd covariate) for a small number of single-mooring models (W-400, E-1000 and W-1000; Appendix 5B). Responses were variable, with the greatest likelihood of porpoise detection often associated with periods of silence (either the silent controls or the intermediate non-experimental periods).
- Number of unprocessed clicks detected per minute (Nall_m) was a frequently occurring covariate although its relative importance varied across the array, ranking higher among more distant moorings (e.g., W-2000 and W-5000; Appendix 5B).
- Time of Day (DAYTIMENum), a factorial covariate introduced to capture intermediate temporal patterns linked with daylight levels, was dismissed from most models due to strong collinearity with Diel Hour. In the four single-mooring models where it was retained (C-600, W-1000, E-2000 and C-5000; Appendix 5B), all models but one (E-2000) indicated that most residual variability was explained by periods of darkness, particularly Night and Dawn.

For the "Nearfield-B" and "whole-array-B" models, the following patterns were observed, which were broadly similar to observations made for Series B's single-mooring models (Appendix 5B):

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

Modelling results, particularly those involving Nearfield moorings, were influenced by relatively low porpoise detection rates. Moreover, the available covariates are likely to act as proxies for more ephemeral factors such as prey abundance and distribution, which cannot be measured easily but are far more ecologically relevant to porpoises. Nonetheless, the modelling results provided support for the notion that porpoise distribution across the array during the experiment was mainly driven by environmental variability rather than by the experimental signals.

The differences between experimental treatments (HF- vs. LF-signals vs. silent control) were not very clear in most models. In Series A models where Signal type was retained as a covariate (W-1000, E-2000, as well as Nearfield and whole-array), use of LF-ADD signals generally resulted in comparable estimates of probability of PPM detection, relative to the silent control treatment. HF-ADD signals often resulted in a lower average likelihood of PPM detection (Appendix 5A). Confidence intervals around all average probability estimates were large, making it difficult to clearly determine which experimental signal had a stronger effect. Moreover, a different picture emerged once additional non-experimental data were included (Series B models; Appendix 5B). In these models, which included a fourth 'Other non-experimental' time category, the differences between HF- and LF-ADD signals were less pronounced, although both average probability estimates were lower than that of the silent control (but, interestingly, not always lower than the 'Other, non-experimental' category). It is also worth reiterating that each successive covariate included in the models described progressively less and less residual variability under the influence of all other previously included covariates. The PPM-covariate relationships observed should therefore not be taken out of that multi-covariate context and should not be considered independently.

In summary, results of both Kruskal-Wallis tests (Section 4.7) and advanced modelling (the present section; details in Appendix 5A/5B) indicated that both types of experimental ADD signals had some influence on porpoise echolocation detection rates when compared to the silent control treatment. However, small sample sizes across most of the Nearfield array, combined with apparent clumping of detections at particular moorings (notably W-1000) complicated attempts to obtain a clear picture in terms of which signal resulted in the strongest effect.

5 DISCUSSION

The present experiment did not provide evidence to support the hypothesis that LF-ADD signals, as defined in this report, had less of an impact on harbour porpoise detection rates than HF-ADD signals (again, as defined in this report). Instead, porpoise detection rates were greatest during silent control periods and declined during both HF- and LF signal transmissions (Table 9; Figure 13, 14; Appendix 5), suggesting that porpoises were responding to both signal types, at least within ~1km from the sound source. This was confirmed by the nonparametric Kruskal-Wallis test results (Section 4.7.1), which identified significant differences in porpoise detection rates between, on the one hand, the silent control dataset and, on the other hand, both the LF and HF signal datasets; no statistically significant differences were found between the latter two datasets. ADD signal type also featured as a significant covariate in GAM-GEE models based on data from moorings near the sound source (Appendix 5A); at greater distances, other factors, notably the day-night cycle and tidal cycles, were typically more important. As confirmed by the extended Series B GAM-GEE models, porpoise detection rates were often substantially higher in inshore waters at night, with a particular peak around dusk and dawn, whereas detection rates in open waters in the central Sound of Mull remained broadly constant throughout the day (Appendix 3). Because so few porpoises were observed visually at the Bloody Bay fish farm site, no clear trends in porpoises' immediate surface responses to signal transmission starts could be determined. The surface tracking approach using the SLR camera array has, however, been shown to work as intended and could provide high-resolution observations as part of future experiments if animals can be followed at ranges <1 km from the observation site.

Results from the experiments were unclear in terms of which type of signal had a stronger deterrent effect on porpoises. The strong response at mooring W-1000, where very few detections coincided with HF-ADD signals compared to LF-signals or silent control, was anomalous among the Nearfield moorings and may have resulted from 'data clumping', generated by only one or two extended visits by a porpoise. The reduced response to LF-signals observed in larger-scale models may therefore have been driven at least partially by the W-1000 data.

The responses by porpoises to both HF and LF signals, in terms of acoustic detection rates when compared to those during silent control periods suggest that the LF-signal had a similar effect on porpoises to the HF signal. The experiment made use of bespoke HF and LF signals, designed to incorporate features of various different ADD types. Also, source levels of both HF and LF signals were limited by the available equipment to approximately 170 dB re 1 µPa-m (RMS; Table 2) compared to source levels of commercially available ADDs, which may exceed 190 dB re 1 µPa (RMS; Götz & Janik 2013). However, broadband recordings confirmed that both signals were detectable at the C-5000 mooring, and that the entire area could thus be considered ensonified during all transmission experiments. It is possible that porpoises could have responded to some higher-frequency signal components rather than the peak frequency of both signals, but this is considered less likely because the higher-frequency signal components' source levels were significantly lower than the levels of the designed fundamental frequencies (Section 3.2; Figure 4, 5).

The observed porpoise detection rates during HF and LF signal transmissions may have been influenced by the fact that harbour porpoises along the west coast of Scotland were likely not naïve in terms of previous ADD exposure. ADDs of one type or another have been used in many parts of western Scotland for many years (e.g., Northridge et al. 2010; Coram et al. 2014), and most porpoises alive today in western Scottish waters are likely to encounter them regularly. Although the Bloody Bay fish farm itself is prevented by license from deploying ADDs, porpoises moving along the Sound of Mull would be exposed to numerous ADDs from other farms. It is likely that ADDs from adjacent farms would have been detectable within the Bloody Bay area (Findlay et al. 2018). However, the collective output of these more distant ADDs on other farms would have constituted a constant background to the experimental signals transmitted under the present study, and cannot explain the results reported here. The present experiment was set up to gather data around a real, operational fish farm, in the full knowledge of the potential for a degree of habituation towards ADD signals having occurred among western Scottish porpoises. In this light, the observation that both HF and LF ADD signals led to reduced porpoise detection rates relative to silent controls is interesting, as it suggests that habituation might be incomplete. Future tests in areas without other fish farms equipped with ADDs, elsewhere within Scotland or abroad, would also be informative to determine differences in responses of (presumed) naïve porpoises to the two signal types (following Mikkelsen et al. 2017).

Heterogeneity among PPM detection rates across the array was considerable, with detection rates being both higher and more consistent in deeper waters in the central Sound of Mull. Inshore moorings within the Nearfield component of the array reported lower numbers of detections, often with a strong bias towards periods after sunset/before sunrise. These patterns suggested heterogeneous use of habitats by harbour porpoises across the Sound of Mull. Such cyclical dawn/dusk patterns among harbour porpoise detections have been reported previously (e.g., Schaffeld et al. 2016; Benjamins et al. 2017; Nuuttila et al. 2017; Williamson et al. 2017), including at the Bloody Bay field site (Carlström 2005). The present study did not investigate which possible environmental drivers might be underpinning the observed patterns in the Sound of Mull, but the diurnal/nocturnal activity patterns of prey items in nearshore areas are potential candidates.

Responses by porpoises to either experimental signal might have been underpinned by the species' general 'neophobic' tendencies to avoid novel stimuli (e.g., Dawson et al., 1998), as loud ADD signals of any kind would normally have been absent within Bloody Bay. However, pre-experimental observations (Appendix 2) illustrate that daily porpoise detection rates began to decline at least 10 days prior to the commencement of the experiment, suggesting that although the presence of artificial ADD signals might have had a temporary negative impact on porpoise activity in Bloody Bay, this was not initiated by the experimental signal transmissions. Post-experimental data further illustrated a substantial increase in daily detection rates during winter months. This outcome was surprising and highlighted the importance of long-term monitoring to capture seasonal/interannual variability. These results indicated that porpoises did not exhibit long-term avoidance of the site following the completion of the experiment.

These results also confirmed that porpoises were not deterred by the fish farm infrastructure per se. Official wildlife sighting reports and anecdotal observations collected by fish farm staff suggested that porpoises could be observed within a few hundred metres of the Bloody Bay fish farm, although this was not confirmed by the visual observations obtained during the experiment. Such observations are supported by studies from elsewhere (Haarr et al. 2009), suggesting that the presence of fish farm infrastructure without ADDs did not result in long-term habitat exclusion of porpoises. Little is presently known about how porpoises behave around marine infrastructure such as fish farms; potential reasons for actively approaching farms might include seeking shelter from storm conditions (as suggested by Haarr et al. 2009) or feeding. Fish farms can attract a variety of wild fish species through the presence of excess food and/or protection among cages, moorings and other infrastructure (Dempster et al. 2009, 2010). Such concentrations of wild fish might subsequently attract porpoises and/or other top predators (including seals; Coram et al. 2014; Callier et al. 2017). Individual porpoises' decisions to seek out fish farms may be influenced by animals' body condition, reproductive status, awareness of predators, etc. It can be hypothesized that porpoises that are sick, injured, nursing a calf or otherwise nutritionally stressed might potentially be more inclined to seek out predictable wild fish aggregations near fish farms, if present. This could inadvertently result in increased exposure to high levels of ADD noise with potential negative consequences for these individuals (Lepper et al. 2014). Further work is needed to clarify the ecological role of fish farms in terms of their indirect effects on harbour porpoises and other top predators, modulated through wild fish aggregations (Callier et al. 2017).

Although the number of exposure experiments that were visually observed was limited (Section 4.6), the present results provide no evidence that either HF- or LF-ADD signal transmissions resulted in noticeably fewer seals being observed in the area around the fish farm. Seal presence was not the main focus of the present study and results reported here should therefore be interpreted with caution. Similar responses to an artificial ADD signal were observed by Mikkelsen et al. (2017), suggesting that other factors may also be important in determining time spent by different species in the vicinity of fish farms equipped with ADDs. This feeds into the ongoing discussion of precisely which component(s) of an ADD signal are important in initiating avoidance behaviour (Coram et al. 2014). Direct comparisons with responses to existing ADD types are hindered by continued lack of publicly available testing data. Testing other LF ADDs under rigorous experimental circumstances, as previously proposed (e.g., Northridge et al. 2013; Coram et al. 2014; Götz & Janik 2015, 2016), would allow determination to what extent differences in signal characteristics might influence deterrence efficacy.

In summary, results from the present experiment did not support the original hypothesis that LF-ADD signals, as defined in this report, would affect harbour porpoise detection rates less than HF-ADD signals (again, as defined in this report). Instead, the highest PPM detection rates occurred during silent control periods. Comparatively low PPM detection rates during LF signal transmissions suggested that this type of signal was detectable by porpoises, contrary to original expectations. There was substantial heterogeneity in PPM detection rates across the array, which indicated the additional importance of environmental factors such as the day-night and tidal cycles in determining spatiotemporal detection patterns. PPM detection rates in the Nearfield component of the array, especially next to the fish farm barge, were limited for unknown reasons, but this was likely unrelated to the experiment itself based on pre- and post-experimental data (Section 4.7; Appendix 2).

6 RECOMMENDATIONS

Commercially available ADDs are in widespread use in the Scottish salmon aquaculture sector. However, significant fundamental questions remain about the mechanisms and long-term efficacy of such systems in terms of their capacity in deterring seals (Yurk & Trites 2000; Jacobs & Terhune 2002; Quick et al. 2004; SMRU Ltd. 2007; Graham et al. 2009, 2011; Götz & Janik 2010; Harris et al. 2014). At the same time, ADDs emit noise that extends well beyond the footprint of individual fish cages (Findlay et al., 2018), with associated potential for acute and/or chronic negative effects on cetaceans and other wildlife (Götz & Janik 2013; Lepper et al. 2014).

This study tested the impact of higher- and low-frequency ADD signals on the occurrence of harbour porpoises on the west coast of Scotland. As requested by the project's funding body (SARF) and Steering Group, the present study did not compare the effects of signals from different commercially available ADDs on harbour porpoises, but instead tested custom-made signals exemplifying the generalities of ADDs currently used in Scottish aquaculture. Successful field trials involving experimental transmission of both signals were undertaken in September 2016 in the Sound of Mull in western Scotland.

While acknowledging substantial variability in porpoise detection rates across the array, results from the present study suggest that using an ADD signal with a lower peak frequency at approximately 1-2 kHz in this case did not result in significantly reduced impacts on harbour porpoises' habitat use, when compared to higher-frequency ADD signals, which have been used traditionally. Instead, transmission of either HF or LF signals resulted in significantly reduced porpoise detection rates relative to silent control periods. This effect was most pronounced among the Nearfield moorings, i.e., within 1 km from the sound source. Higher-frequency signal components were present but were considered less likely to be the cause of the observed results due to their low signal strength compared to the main signal. Given these results, a number of recommendations can be made about use of LF-ADD signals, and ADDs more broadly, in Scottish finfish aquaculture:

Recommendation 1: The present experiment has shown that use of continuous operation LF-ADD signals, with signal characteristics similar to the ones used in this experiment, cannot be assumed to entirely reduce collateral impacts of noise on non-target species such as porpoises. Further development and investigation of use of all non-lethal methods to address seal depredation is recommended.

Recommendation 2: To improve understanding of ADD usage in Scottish aquaculture, it is recommended that a formal monitoring programme be developed to collect accurate information on ADD distribution and usage patterns. This will make it easier to document ADD-associated noise emissions and their potential impacts in the context of wider conservation activities such as the establishment of Marine Protected Areas. This improved understanding is also relevant in the light of other regulatory requirements to report marine noise pollution (e.g., under the EC Marine Strategy Framework Directive; EC 2008).

Recommendation #3: Given the results from this study and the current extent of ADD presence in Scottish coastal waters (Findlay et al. 2018), it is recommended that efforts be undertaken to 1) clearly establish the efficacy of ADDs in terms of long-term, successful deterrence of seals from impacting fish farms; 2) clarify which signal characteristics and/or modes of operation (e.g., loudness, frequency composition, duty cycle, signal repetitiveness) contribute to the effectiveness or otherwise of different ADD models, and 3) identify which other variables (e.g., time of year, weather, presence of fish farm staff) might affect the probability of seal depredation events and apparent ADD effectiveness.

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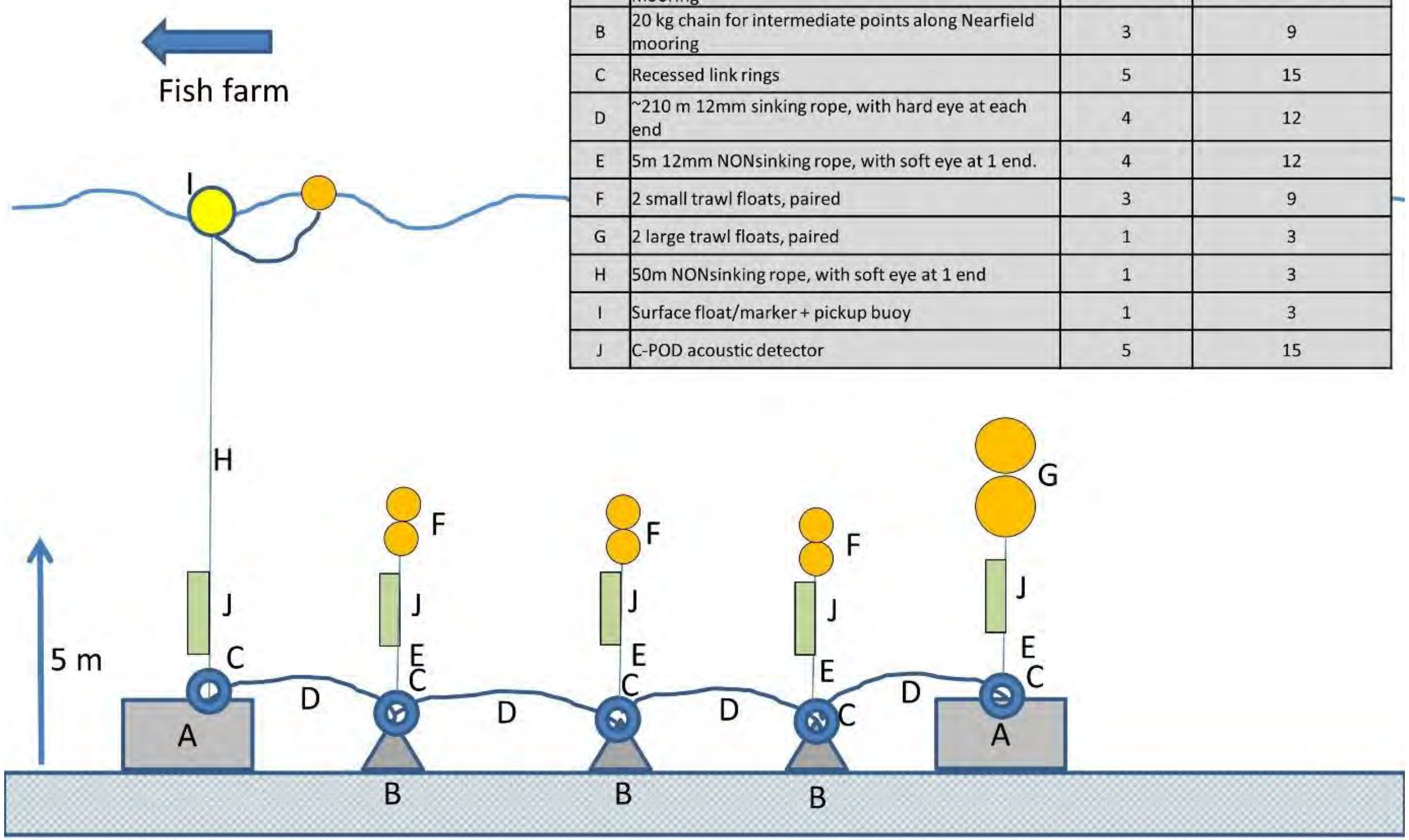
Appendix 1 - Mooring design

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

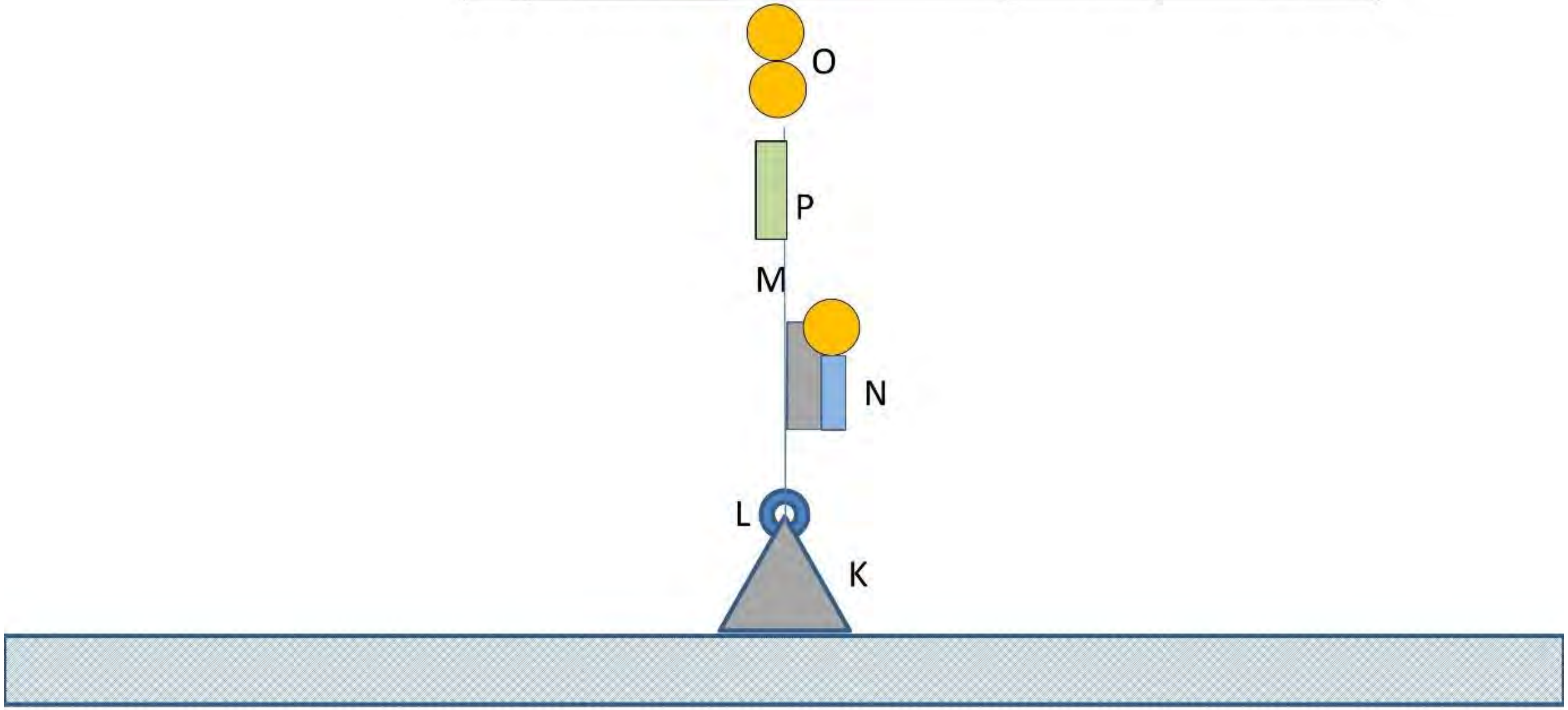
'Nearfield' Mooring diagram



Label	Description	# needed per mooring	# needed for all NEARFIELD moorings
A	2x Concrete tyres for start and end of Nearfield mooring	2 (ie 4 tyres)	6 (ie 12 tyres)
B	20 kg chain for intermediate points along Nearfield mooring	3	9
C	Recessed link rings	5	15
D	~210 m 12mm sinking rope, with hard eye at each end	4	12
E	5m 12mm NONsinking rope, with soft eye at 1 end.	4	12
F	2 small trawl floats, paired	3	9
G	2 large trawl floats, paired	1	3
H	50m NONsinking rope, with soft eye at 1 end	1	3
I	Surface float/marker + pickup buoy	1	3
J	C-POD acoustic detector	5	15

‘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



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.

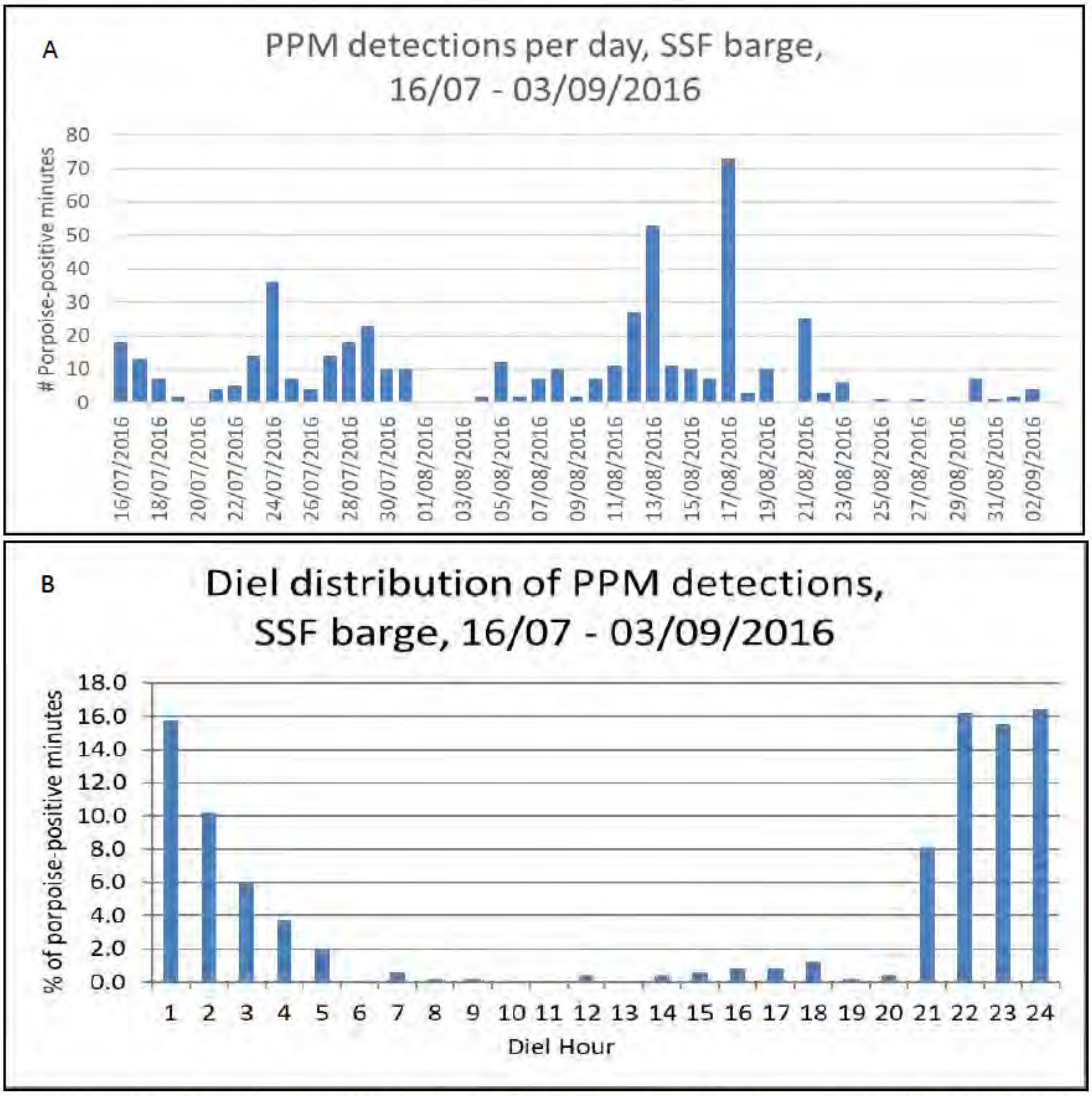


Figure A3.1. A) Overview of overall PPM numbers during pre-experimental deployment at the Bloody Bay fish farm, 16/07 – 3/09/2016 (partial days at beginning and end excluded). B) Overview of distribution of PPMs by hour across a 24-hour day (data aggregated over 16/07 – 3/09/2016; partial days at beginning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

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

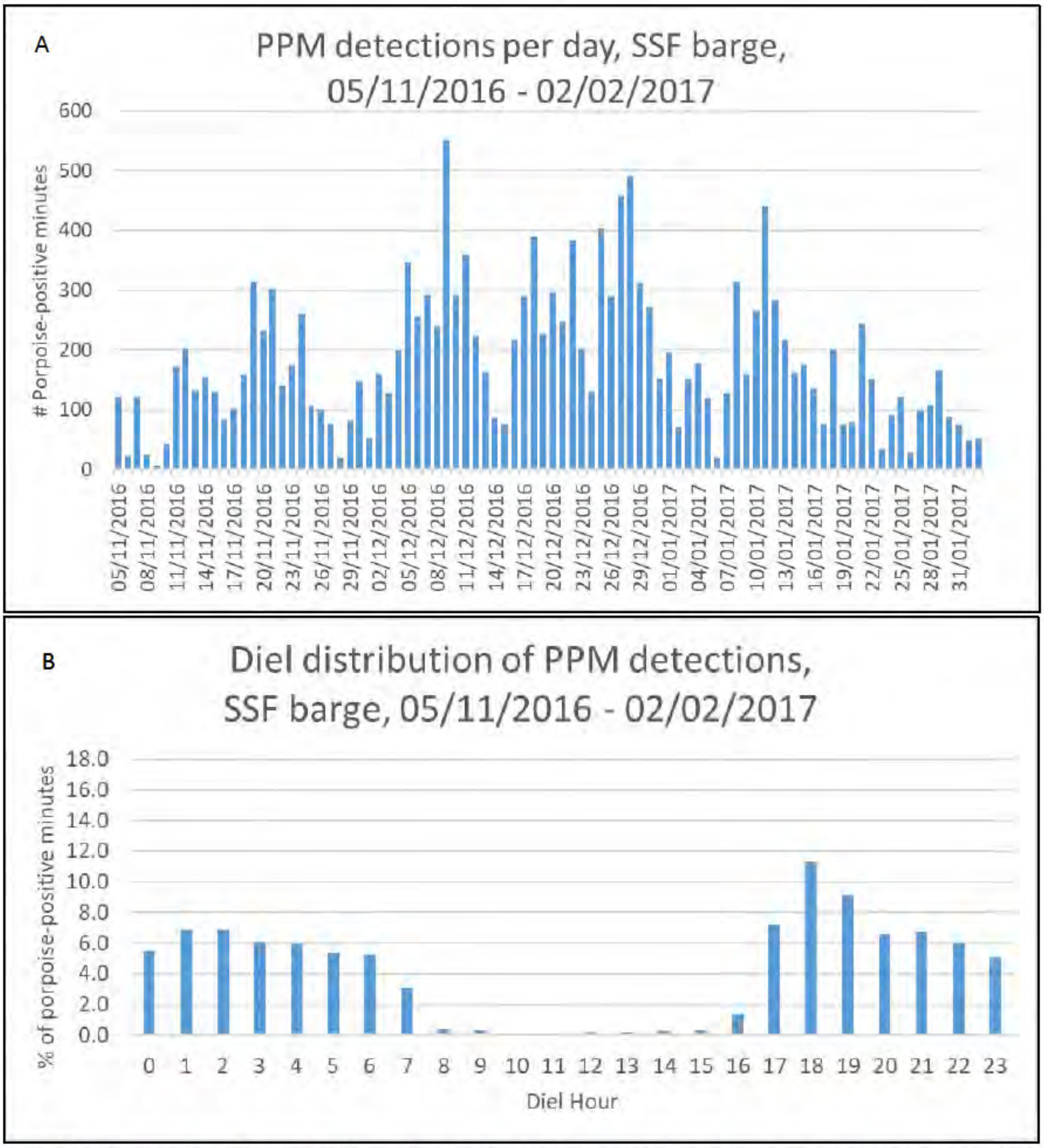


Figure A3.2. A) Overview of overall PPM numbers during pre-experimental deployment at the Bloody Bay fish farm, 05/11/2016 – 02/02/2017 (partial days at beginning and end excluded). B) Overview of distribution of PPMs by hour across a 24-hour day (data aggregated over 05/11/2016 – 02/02/2017; partial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

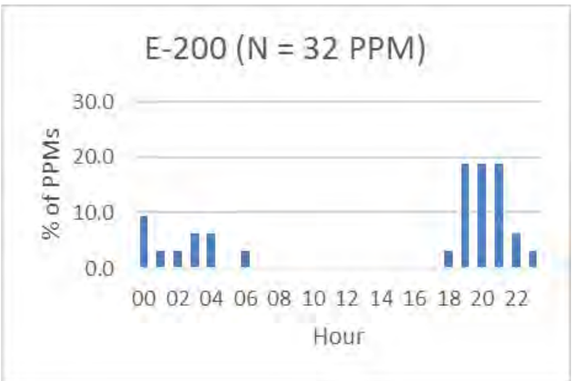
Appendix 3 - Overview of # PPM/day across array

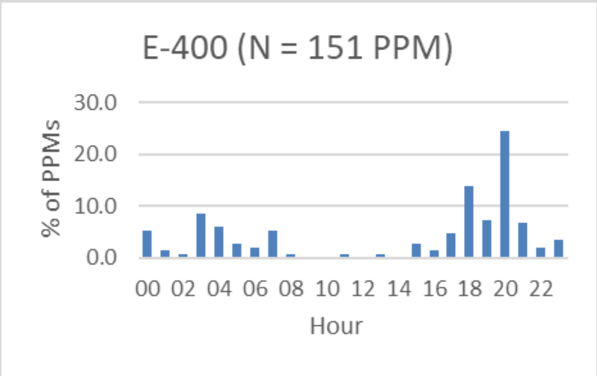
Summary of total daily PPM detection counts per mooring, at increasing distance from the sound source below the fish farm barge (reading from left to right, from E-200 out to W-5000). Cells are coloured according to a gliding scale from zero detections per day (dark green) to >100 detections per day (dark red).

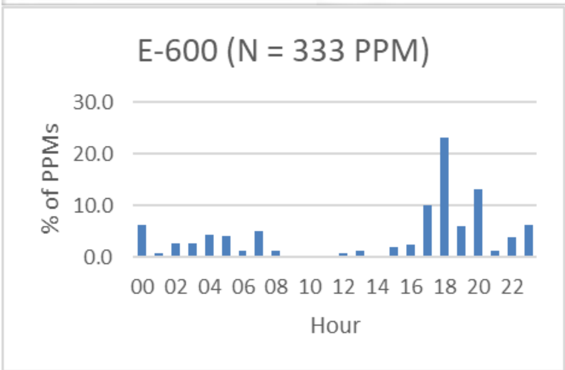
DATE	E-200	W-200	E-400	C-400	W-400	E-600	C-600	W-600	E-800	C-800	W-800	E-1000	C-1000	W-1000	E-2000	C-2000	W-2000	C-5000	W-5000
08/09/2016	0	0	3	3	0	2	0	0	1	0	0	6	6	0	28	0	1	9	18
09/09/2016	0	0	1	1	0	0	0	2	1	0	2	6	2	2	25	5	0	19	18
10/09/2016	0	0	1	1	0	7	1	0	10	0	0	4	5	0	5	10	0	119	55
11/09/2016	0	0	0	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

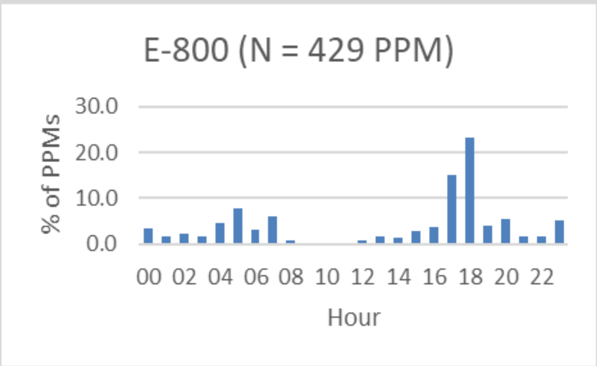
Appendix 4 – Diel variability in PPM detections

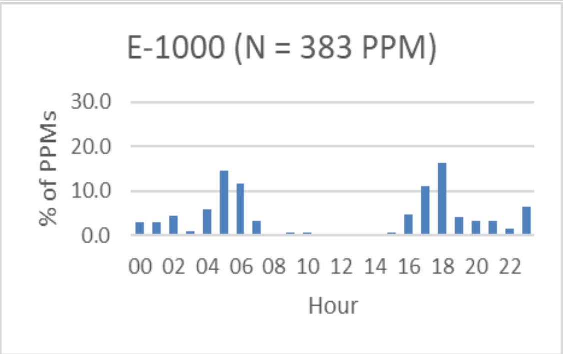
The following graphs illustrate, for each mooring, the diel patterns in PPM detections observed throughout the entire experimental period (8/09-16/10/2016; NB: mooring C-5000 was only deployed until 6/10/2016.). Total numbers of PPMs detected during this period are indicated for each mooring. Moorings are aggregated by distance from the sound source and according to their location along the Eastern, Central and Western mooring lines. Detection rates were generally highest at night, particularly during evenings, except for Farfield moorings such as E-2000 and W-5000.

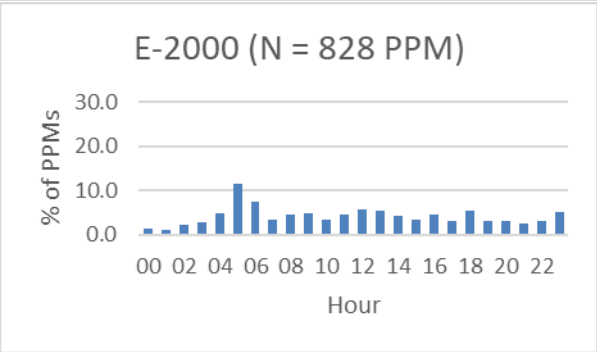


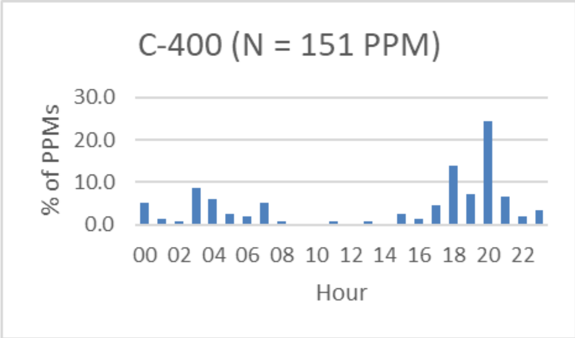


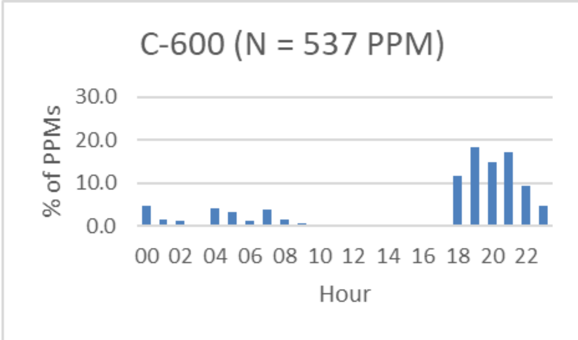


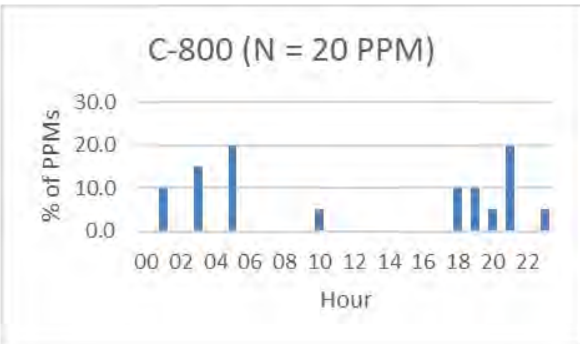


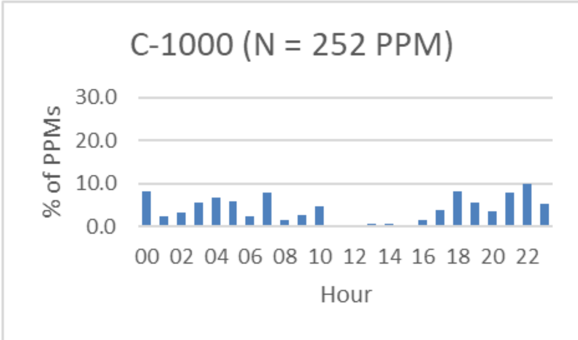


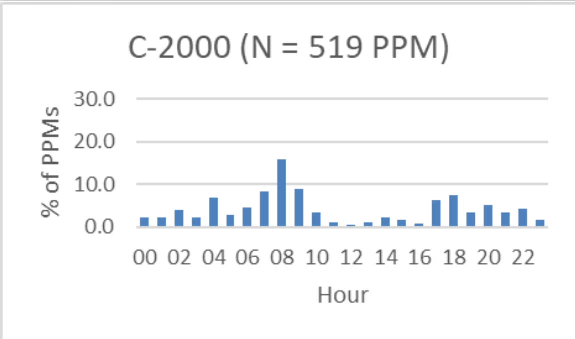


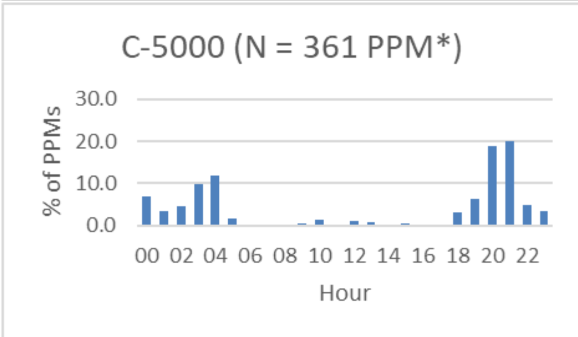

C-400 (N = 151 PPM)
% of PPMs
30.0
20.0
10.0
0.0
00 02 04 06 08 10 12 14 16 18 20 22
Hour

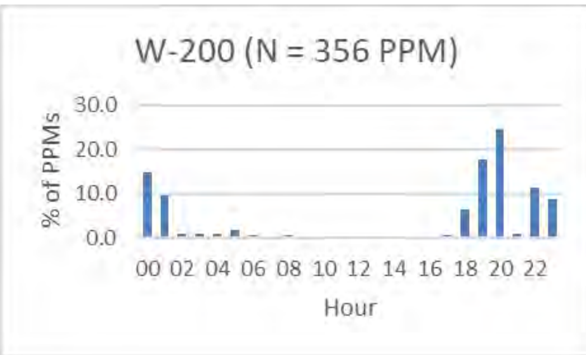

C-600 (N = 537 PPM)
% of PPMs
30.0
20.0
10.0
0.0
00 02 04 06 08 10 12 14 16 18 20 22
Hour

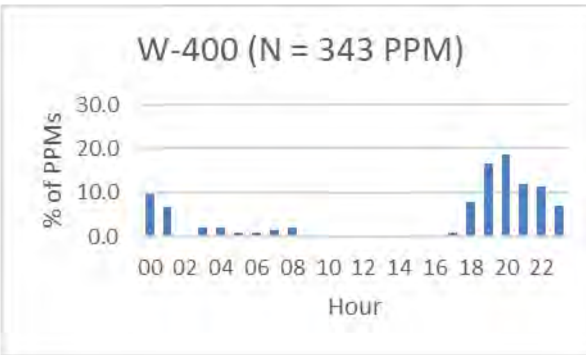

C-800 (N = 20 PPM)
% of PPMs
30.0
20.0
10.0
0.0
00 02 04 06 08 10 12 14 16 18 20 22
Hour

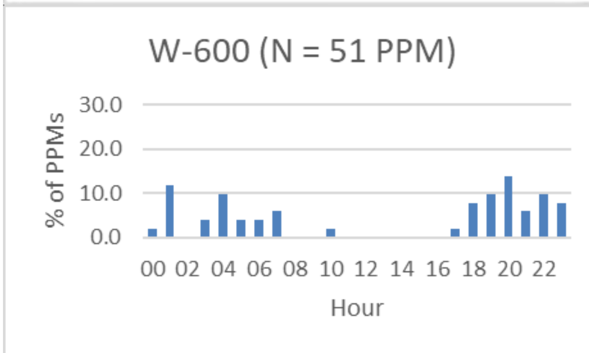

C-1000 (N = 252 PPM)
% of PPMs
30.0
20.0
10.0
0.0
00 02 04 06 08 10 12 14 16 18 20 22
Hour

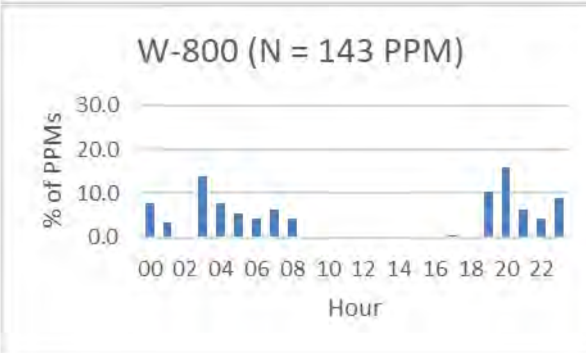

C-2000 (N = 519 PPM)
% of PPMs
30.0
20.0
10.0
0.0
00 02 04 06 08 10 12 14 16 18 20 22
Hour

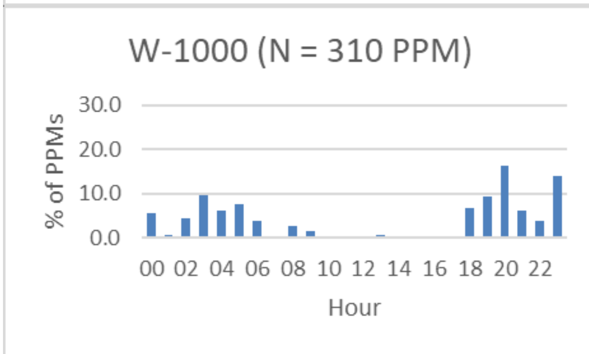

C-5000 (N = 361 PPM*)
% of PPMs
30.0
20.0
10.0
0.0
00 02 04 06 08 10 12 14 16 18 20 22
Hour

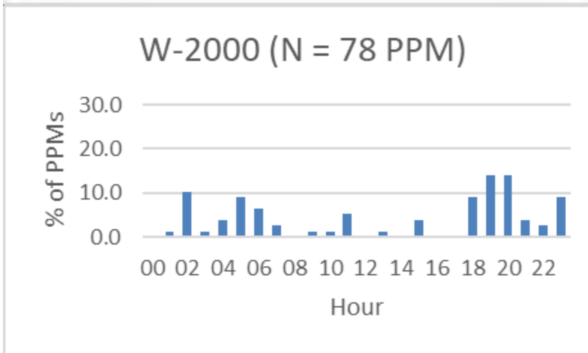

W-200 (N = 356 PPM)
% of PPMs
30.0
20.0
10.0
0.0
00 02 04 06 08 10 12 14 16 18 20 22
Hour

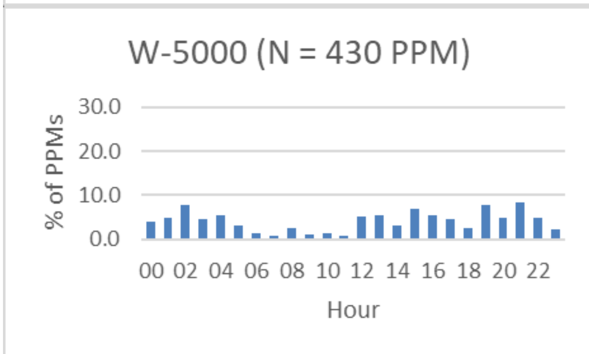

W-400 (N = 343 PPM)
% of PPMs
30.0
20.0
10.0
0.0
00 02 04 06 08 10 12 14 16 18 20 22
Hour


W-600 (N = 51 PPM)
% of PPMs
30.0
20.0
10.0
0.0
00 02 04 06 08 10 12 14 16 18 20 22
Hour


W-800 (N = 143 PPM)
% of PPMs
30.0
20.0
10.0
0.0
00 02 04 06 08 10 12 14 16 18 20 22
Hour


W-1000 (N = 310 PPM)
% of PPMs
30.0
20.0
10.0
0.0
00 02 04 06 08 10 12 14 16 18 20 22
Hour


W-2000 (N = 78 PPM)
% of PPMs
30.0
20.0
10.0
0.0
00 02 04 06 08 10 12 14 16 18 20 22
Hour


W-5000 (N = 430 PPM)
% of PPMs
30.0
20.0
10.0
0.0
00 02 04 06 08 10 12 14 16 18 20 22
Hour

Appendix 5A – GAM design, descriptors and outputs – Series A models

This Appendix contains Series A model outputs for 1) individual moorings, and 2) a sequence of models containing increasing numbers of moorings moving outward from the fish farm, up to containing the entire array. Modelling was only attempted in cases where the underlying dataset contained at least 50 PPMs. All Series A models described in this Appendix were based solely on data associated with actual experimental transmission periods. The modelling method described here was used for both Series A and Series B models; therefore, this section will provide a generic description of the modelling approach applicable to both Appendices.

Porpoise presence was modelled using binomial-based GAM-GEEs with an independent correlation structure and a logit link function to describe the relationship between covariates and porpoise click train detection presence (the response variable, described in a binary presence/absence format). This approach closely follows the one initially described by Pirotta et al. (2011) and the following text is adapted from an in-depth description of this method by Benjamins et al. (2016, 2017). Models are only intended to describe available records and should not be extrapolated to other datasets.

Data exploration protocols described by Zuur et al. (2010) and Zuur (2012) were used to identify outliers, data variability, relationships between covariates and response variable, and collinearity between covariates. Modelling was initiated using a basic GLM as a means to assess collinearity of covariates, following Zuur (2012). Collinear and non-significant covariates were removed during subsequent analyses. Collinearity among covariates was investigated using the GVIF^(1/(2*Df)) output of the R function *vif* (part of the *car* package; Fox & Weisberg 2011), to account for combinations of linear, cyclic and factorial covariates. A list of available covariates is included in Table A5A.1. The POSITION covariate was found to be collinear with numerous descriptive covariates (e.g., bathymetry, sediment type, distance from shore) and was therefore retained as a means to capture the residual variability derived from all these other covariates, which were subsequently removed. HiLoTide and SpringNeap covariates were defined based on data obtained from the Tobermory tidal gauge (part of the UK National Tidal Gauge Network).

Table A5A.1. List of available covariates considered for Series A and Series B models.

Covariate	Unit	Scale	Description	Use in model
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
JULDAY	Number	252 - 280	Julian day number	Factor, linear or cubic B-spline
HOUR	Hour	0 - 23	Number of hour per day	Cyclic spline
Temp	°C	1.6 - 19 degrees	POD temp logger (not calibrated)	Linear or cubic B-spline
Angle	Degree (°)	0 - 180°	Avg. deflection from vertical, where 0° = CPOD pointing straight up	Linear or cubic B-spline
Nall_m	Number	0 - 4096	Number of raw clicks received each minute	Linear or cubic B-spline
D_Source_m	Number	252 - 5435	Estimated distance (in m) from sound source	Linear or cubic B-spline
D_Shore_m	Number	362 - 2107	Estimated shortest distance (in m) from any shore	Linear or cubic B-spline
Angle_shore	Degree (°)	-56.161179 - -176.885639	Angle to closest shore (0° = North; -180° = 180° = South; 90° = East; -90° = West)	Cyclic spline
Est_depth_m	Number	28 - 59	Estimated depth (m, rel. to CD) at site	Linear or cubic B-spline
Sed_type	Number	1-3	Broad sediment type (1 = mud, 2 = sandy mud, 3 = sand)	Factor
HiLoTide	Fraction	0 - 1	Cyclic variable denoting ebb-flood tide (0 = 1 = Low Tide as measured at Tobermory tidal gauge)	Cyclic B-spline
SpringNeap	Fraction	0 - 1	Cyclic variable denoting spring-neap tide (0 = 1 = Spring Low as measured at Tobermory tidal gauge)	Cyclic spline
DAYTIMENum	Number	1 - 4	Numeric descriptor of period of day (relevant for daylight levels; 1 = Dawn, 2 = Day, 3 = Dusk, 4 = Night)	Factor
Exper_ON	Binary	0 - 1	Binary variable indicating whether each minute was part of an experiment or time in between	Factor
Signal_Type	Number	0 - 3	Numeric descriptor of experimental status; 0 - intermediate time (no sound); 1 – silent control (no sound); 2 = HF signal; 3 = LF signal	Factor

GAMs offer the ability to incorporate nonlinear responses to variables and therefore can provide a more flexible and powerful tool than Generalised Linear Models (GLMs) to study the interactions between animals and their environment (Hastie et al. 2005). GAMs assume independence between model residuals, which is likely to be violated where conditions at time *t* may closely resemble those at *t* - 1 and *t* + 1 (such as might be expected in the present case). This temporal autocorrelation could cause the uncertainty surrounding model estimates to be underestimated. To address this problem, autocorrelation in the data was investigated using the R autocorrelation function *acf* (Venables & Ripley 2002). These results were used to define blocks of data within which autocorrelation was present, using Generalised Estimation Equations (GEEs; Liang & Zeger 1986). Using this approach, uniform autocorrelation was expected within the blocks but not between them (Garson 2013). This is appropriate when studying population-level effects (in contrast to animal-specific response patterns, e.g., GAMMs; Fieberg et al. 2009, 2010) and particularly suitable for binomial distributions. GEEs are considered to be relatively robust even if block sizes are misspecified (Hardin & Hilbe 2003). Block sizes were specified for each model in Table A5A.2.

Table A5A.2. Overview of block sizes used for individual and compound models to address temporal autocorrelation in Series A models.

Array section	**Site name**	**Block size (minutes)**
NEARFIELD	E-200	1
NEARFIELD	E-400	1
NEARFIELD	E-600	5
NEARFIELD	E-800	9
NEARFIELD	E-1000	8
FARFIELD	E-2000	41
NEARFIELD	C-400	1
NEARFIELD	C-600	8
NEARFIELD	C-800	3
NEARFIELD	C-1000	8
FARFIELD	C-2000	28
FARFIELD	C-5000	14
NEARFIELD	W-200	1
NEARFIELD	W-400	8
NEARFIELD	W-600	2
NEARFIELD	W-800	9
NEARFIELD	W-1000	34
FARFIELD	W-2000	8
FARFIELD	W-5000	20

Covariates were considered as either 1) linear terms, 2) factors, or 3) 1-dimensional smooth terms with 4 degrees of freedom. The latter were modelled as either cubic B- splines with one internal knot positioned at the average value of each variable, or as cyclic penalized cubic regression splines (specifically those covariates identified as ‘cyclic’ in Table A5A.1).

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

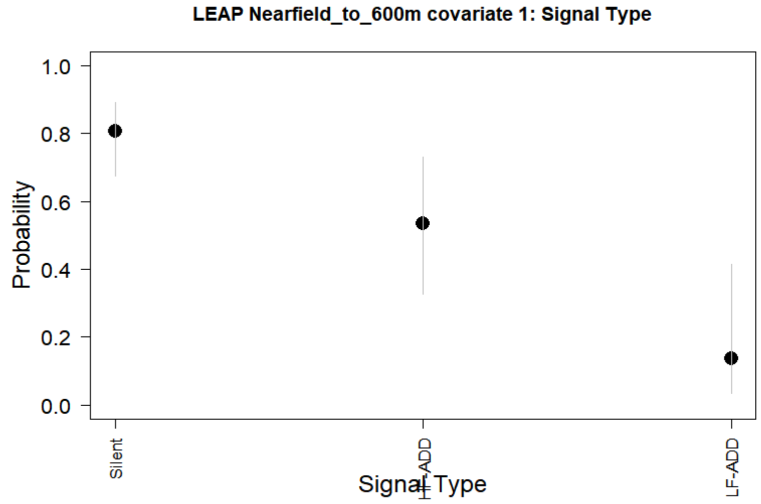
Model quality was expressed through a combination of confusion matrices and Area under the Curve (*auc*) calculations. Each model summary below contains a Confusion Matrix, which describes how well the binary model predictions matched observed values (i.e., how often an observed detection was predicted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

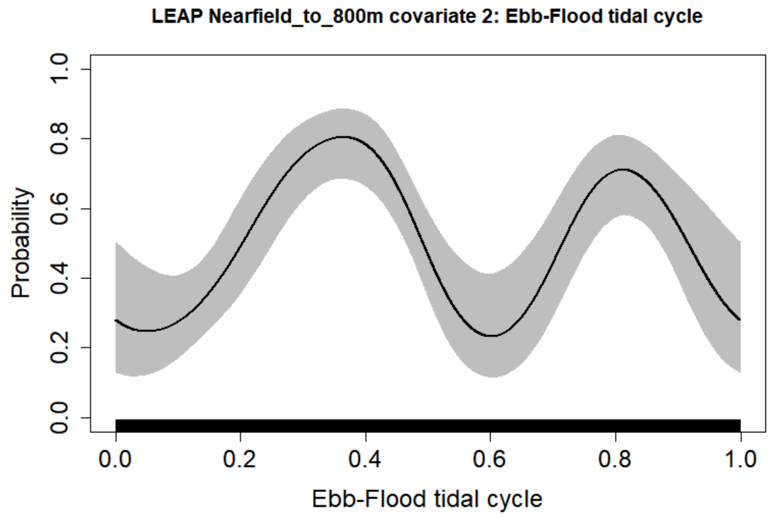
Following identification of the final model, plots were generated describing the probabilistic relationship between each contributing explanatory covariate and the model response variable (PPM presence/absence). Confidence intervals around these plots were based on the standard errors of the GAM-GEE model. Covariates were plotted independently to visualise the probabilistic relationship (expressed as "Probability on the Y-axis of each graph) between each covariate and the binary response variable (porpoise detection) for each model. Each model summary below contains all graphs of relevant covariates, plotted in declining order of significance in terms of their explanatory power.

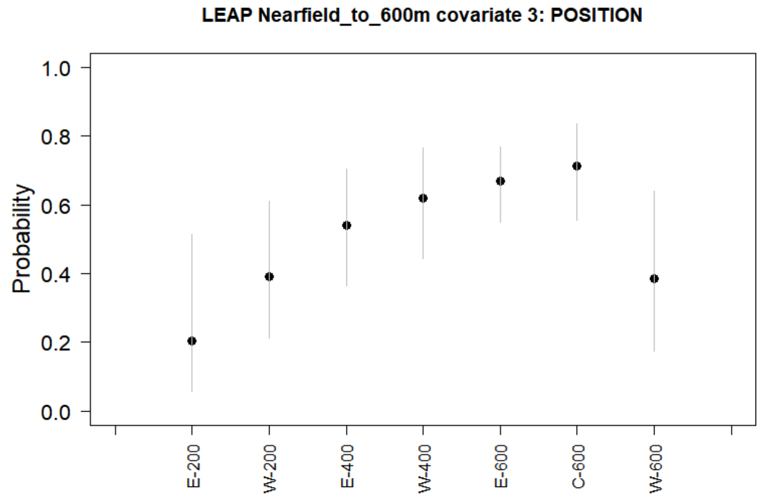
It is important to reiterate that while GAMs allowed the relative significance of different covariates to be determined, the results should be interpreted with care. Importantly, **less significant covariates' relationships to the response variable were dependent upon the inclusion of more significant covariates in the model, and should therefore be interpreted as explaining residual amounts of variation in the presence of more significant covariates, rather than seen in isolation.**

Model:	200m-to-600m (A) (E-200-600, C-600, W200-600)			
Model structure:	POD5<-geeglm(DPM ~ as.factor(Signal_Type) + TideBasisMat + as.factor(POSITION), family = binomial, corstr="independence", id=Panel, data=Array)			
Confusion matrix:			Expected	
			Porpoise	No porpoise
	Observed	Porpoise	85.7%	33.7%
		No porpoise	14.2%	66.2%
AUC value:	0.816902			
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
Signal_Type	Factor	2	26.302	$1.944 \cdot 10^{-6}$
HiLoTide	Cyclic spline	4	23.568	$9.748 \cdot 10^{-5}$
POSITION	Factor	6	16.516	0.01124

Model: 200m-to-600m (A) (E-200-600, C-600, W200-600)

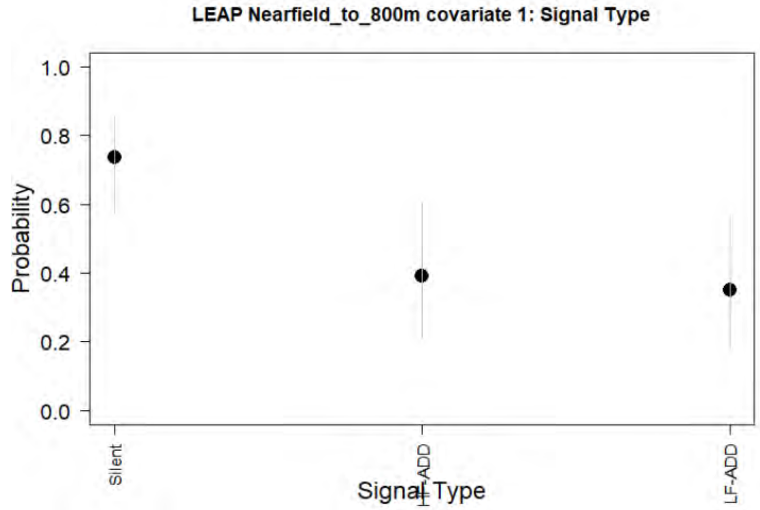


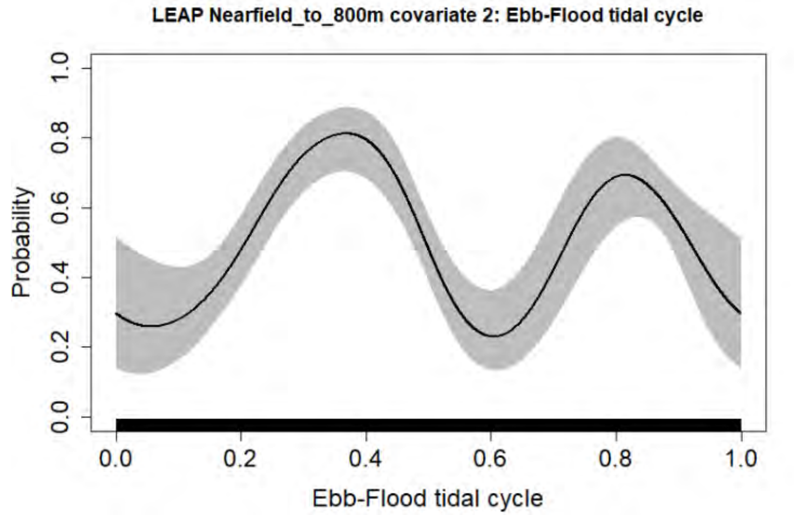


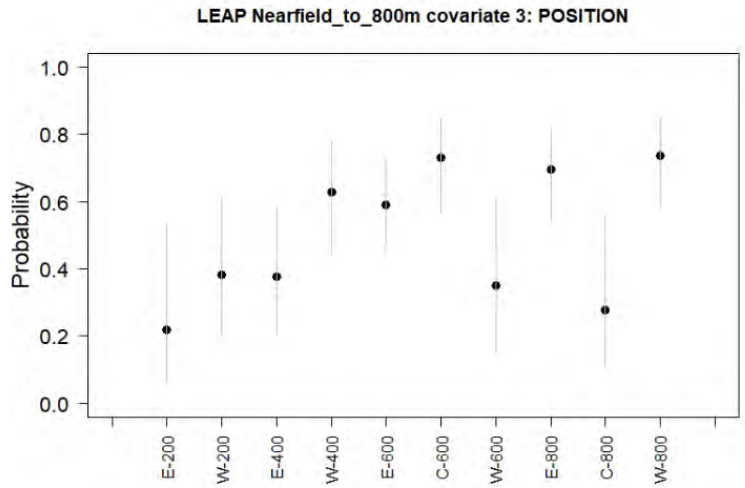


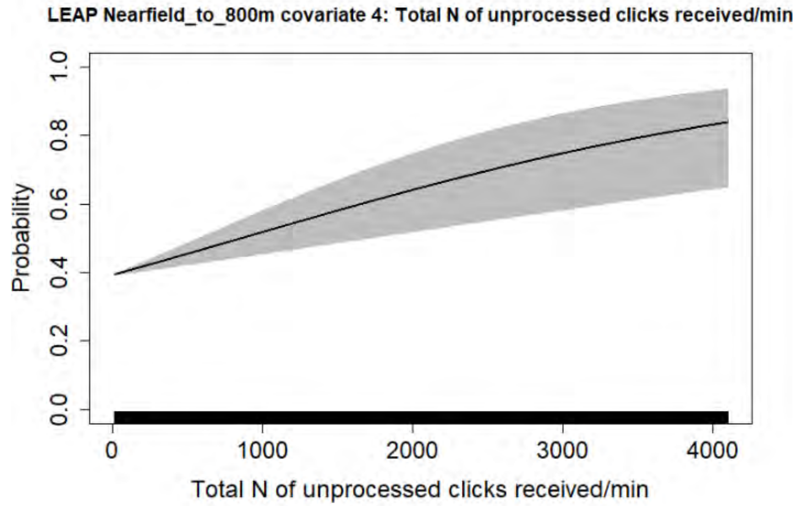
Model:	200m-to-800m (A) (E-200-800, C-600-800, W200-800)			
Model structure:	POD5<-geeglm(DPM ~ as.factor(Signal_Type) + TideBasisMat + as.factor(POSITION) + Nall_m, family = binomial, corstr="independence", id=Panel, data=Array)			
Confusion matrix:			Expected	
			Porpoise	No porpoise
	Observed	Porpoise	89.8%	42.9%
		No porpoise	10.2%	57.1%
AUC value:	0.8077915			
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
Signal_Type	Factor	2	28.837	$5.473\cdot10^{-7}$
HiLoTide	Cyclic	4	28.200	$1.136\cdot10^{-5}$
POSITION	Factor	9	29.472	0.0005393
Nall_m	Linear	1	15.630	$7.701\cdot10^{-5}$

Model: 200m-to-800m (A) (E-200-800, C-600-800, W200-800)



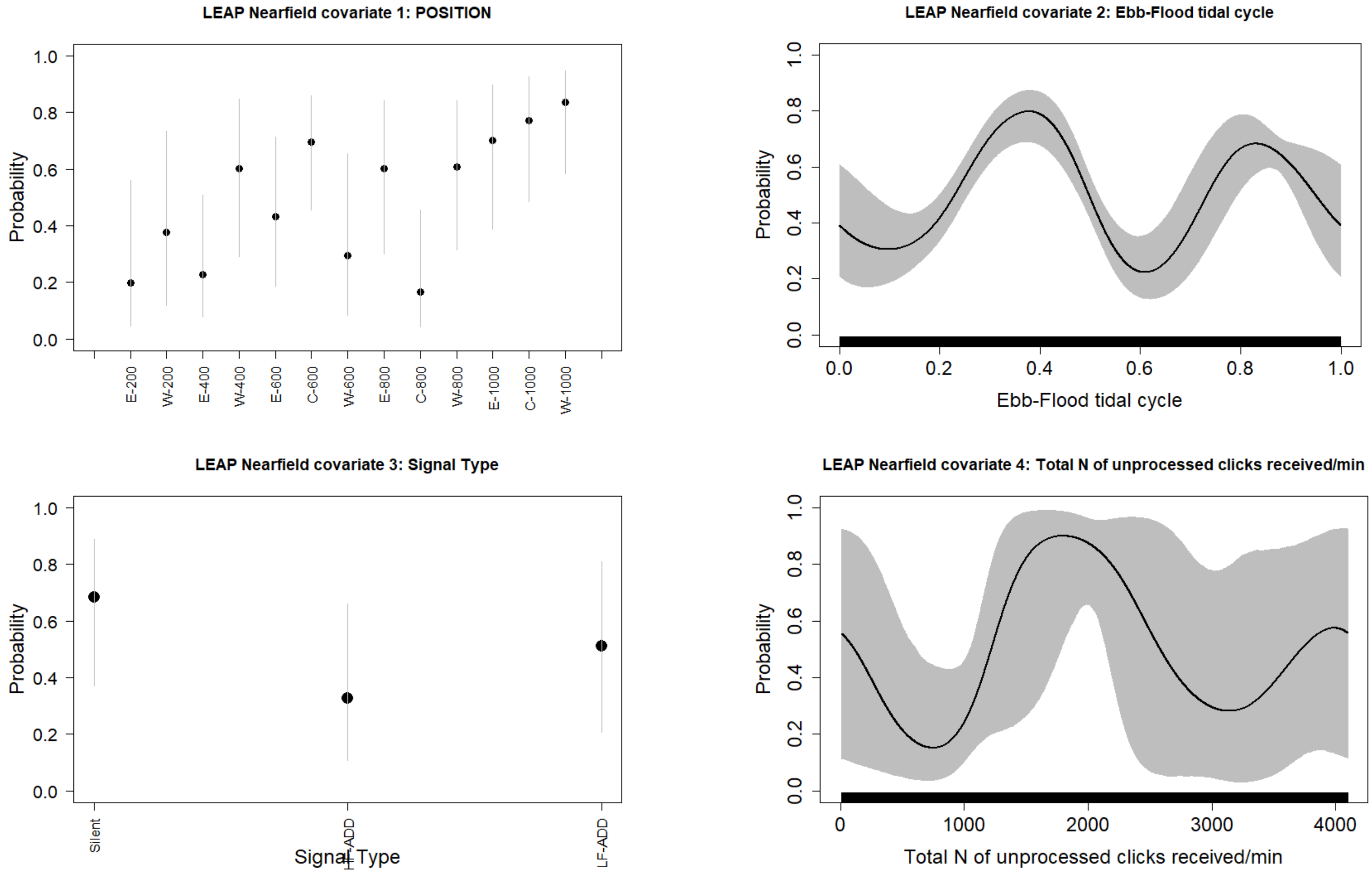






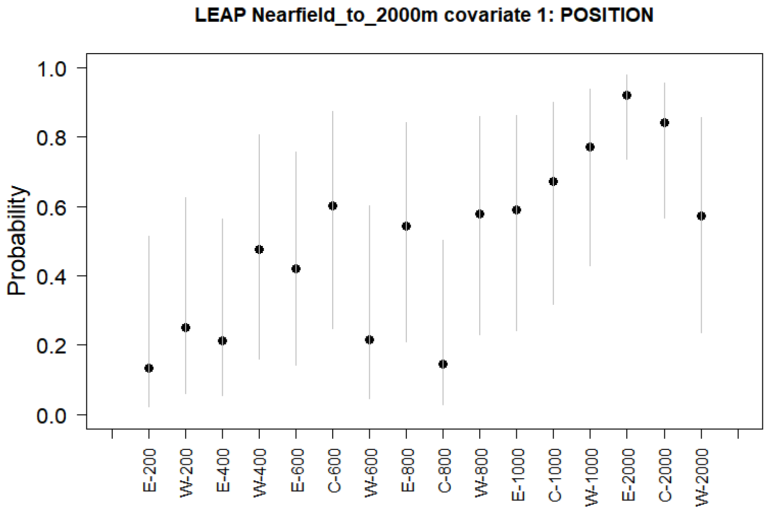
<table>
<tr><td>Model:</td><td colspan="4">Nearfield (A) (E-200-1000, C-600-1000, W200-1000)</td></tr>
<tr><td>Model structure:</td><td colspan="4">POD5<-geeglm(DPM ~ as.factor(POSITION) + TideBasisMat + as.factor(Signal_Type) + bs(Nall_m, knots=mean(Nall_m)), family = binomial, corstr="independence", id=Panel, data=Array)</td></tr>
<tr><td>Confusion matrix:</td><td colspan="4"><table>
<tr><td colspan="2"></td><td colspan="2">Expected</td></tr>
<tr><td colspan="2"></td><td>Porpoise</td><td>No porpoise</td></tr>
<tr><td rowspan="2">Observed</td><td>Porpoise</td><td>69.8%</td><td>24.8%</td></tr>
<tr><td>No porpoise</td><td>30.2%</td><td>75.2%</td></tr>
</table></td></tr>
<tr><td>AUC value:</td><td colspan="4">0.7999681</td></tr>
<tr><td colspan="5">Results of Wald's tests for all significant covariates for the final model:</td></tr>
<tr><td>Covariates (in descending order of significance)</td><td>Form</td><td>Degrees of Freedom</td><td>χ^2 score</td><td>P-value</td></tr>
<tr><td>POSITION</td><td>Factor</td><td>12</td><td>47.785</td><td>$3.406 \cdot 10^{-6}$</td></tr>
<tr><td>HiLoTide</td><td>Cyclic</td><td>4</td><td>29.682</td><td>$5.681 \cdot 10^{-6}$</td></tr>
<tr><td>Signal_Type</td><td>Factor</td><td>2</td><td>41.211</td><td>$1.125 \cdot 10^{-9}$</td></tr>
<tr><td>Nall_m</td><td>Cubic spline</td><td>4</td><td>22.182</td><td>0.0001844</td></tr>
</table>

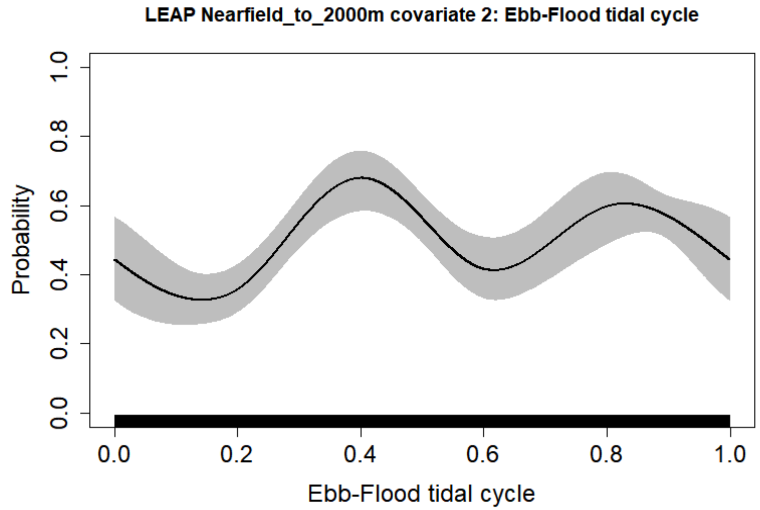
Model: Nearfield (A) (E-200-1000, C-600-1000, W200-1000)

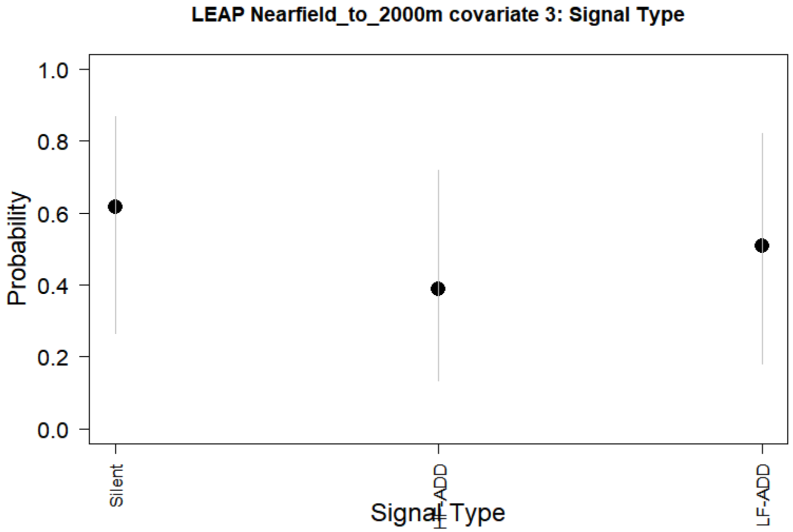


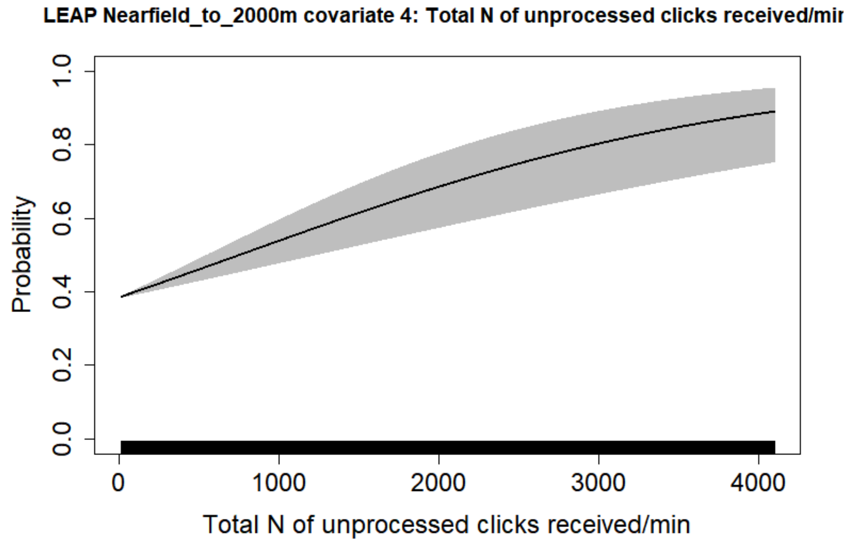
Model:	Nearfield-Plus (A) (E-200-2000, C-600-2000, W200-2000)			
Model structure:	POD6<-geeglm(DPM ~ as.factor(POSITION) + TideBasisMat + as.factor(Signal_Type) + Nall_m + as.factor(DAYTIMENum), family = binomial, corstr="independence", id=Panel, data=Array)			
Confusion matrix:			Expected	
			Porpoise	No porpoise
	Observed	Porpoise	77.9%	19.9%
		No porpoise	22.1%	80.1%
AUC value:	0.8425368			
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	15	221.169	$<2.2\cdot10^{-16}$
HiLoTide	Cyclic spline	4	21.186	0.0002908
Signal_Type	Factor	2	19.061	$7.262\cdot10^{-5}$
Nall_m	Linear	1	30.472	$3.388\cdot10^{-8}$
DAYTIMENum	Factor	3	11.660	0.0086417

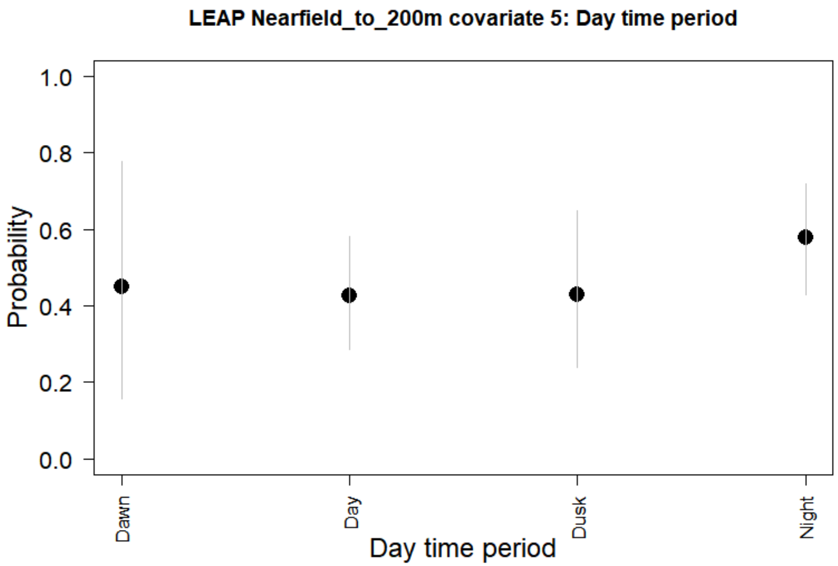
Model: Nearfield-Plus (A) (E-200-2000, C-600-2000, W200-2000)











LEAP Nearfield_to_200m covariate 5: Day time period
Probability
1.0
0.8
0.6
0.4
0.2
0.0
Dawn
Day
Dusk
Night
Day time period

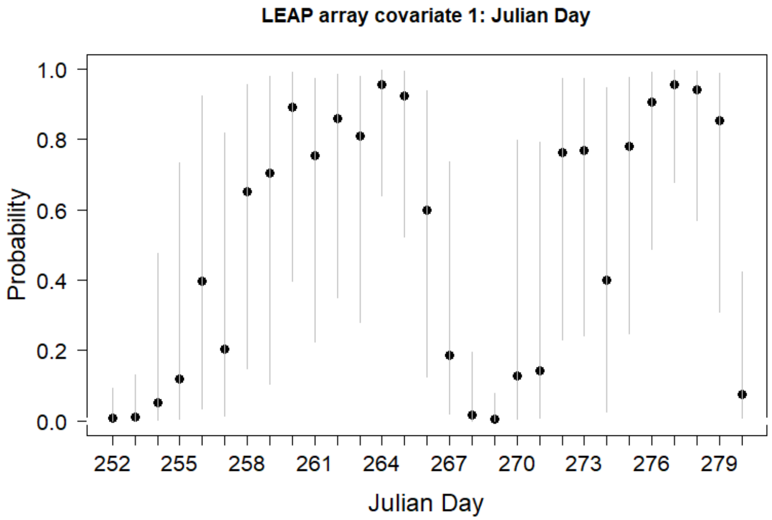
Model:	Whole Array (A) (E-200-5000, C-600-5000, W200-5000)
Model structure:	POD2<-geeglm(DPM ~ as.factor(JULDAY) + SprNpBasisMat + as.factor(DAYTIMENum) + as.factor(Signal_Type) + Nall_m + TideBasisMat, family = binomial, corstr="independence", id=Panel, data=Array)

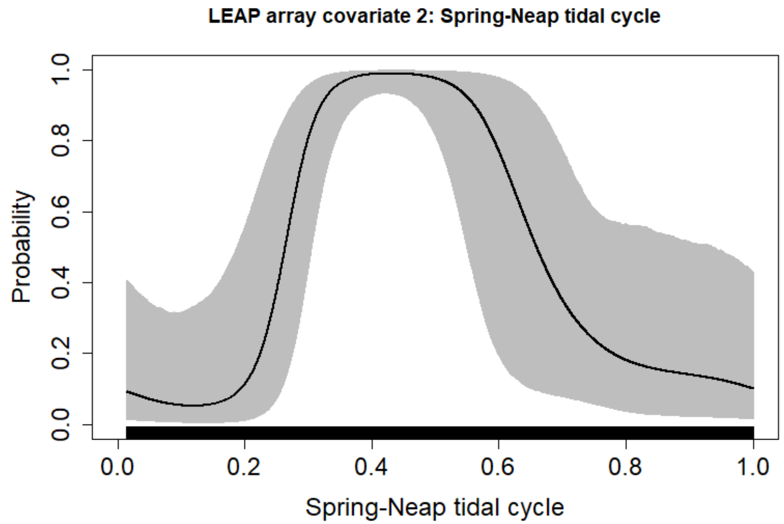
Confusion matrix:

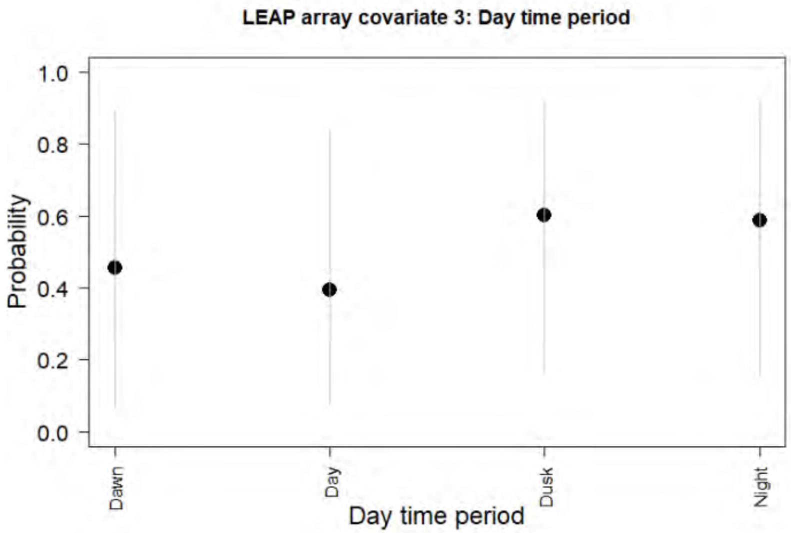
		Expected	
		Porpoise	No porpoise
Observed	Porpoise	64.3%	28.8%
	No porpoise	35.7%	71.25

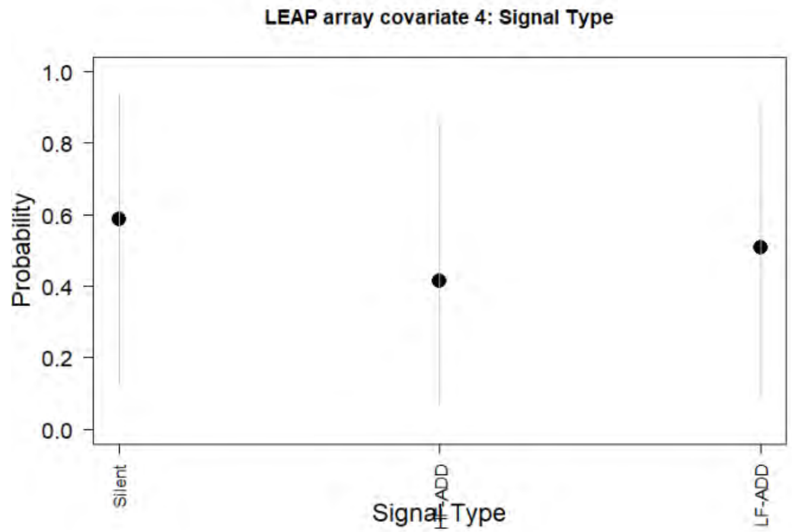
AUC value:	0.7477562			
Results of Wald's tests for all significant covariates for the final model:				
Covariates (in descending order of significance)	Form	Degrees of Freedom	χ^2 score	P-value
JULDAY	Factor	28	112.725	$3.996 \cdot 10^{-12}$
SpringNeap	Cyclic spline	4	27.007	$1.981 \cdot 10^{-5}$
DAYTIMENum	Factor	3	26.698	$6.811 \cdot 10^{-6}$
Signal_Type	Factor	2	9.261	0.0097486
Nall_m	Linear	1	12.171	0.0004854
HiLoTide	Cyclic spline	4	14.032	0.0071933

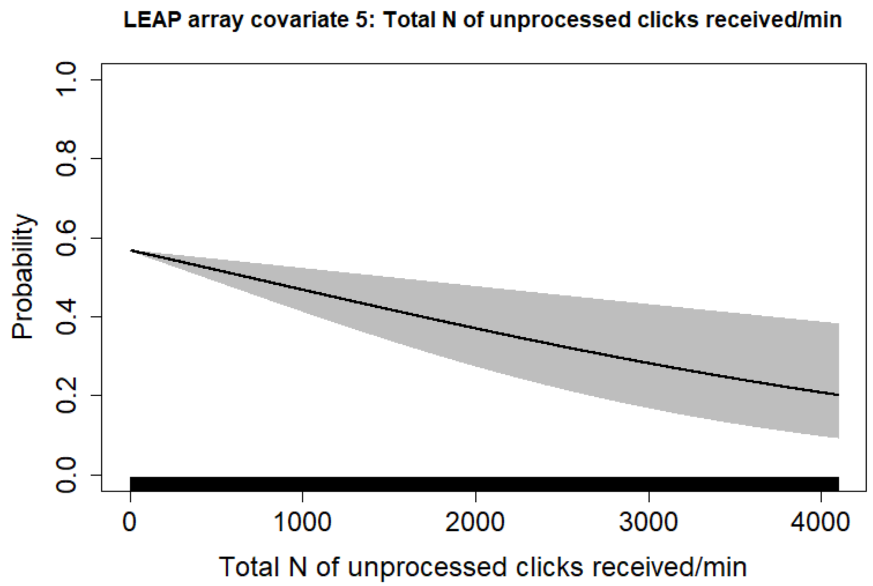
Model: Whole Array (A) (E-200-5000, C-600-5000, W200-5000)

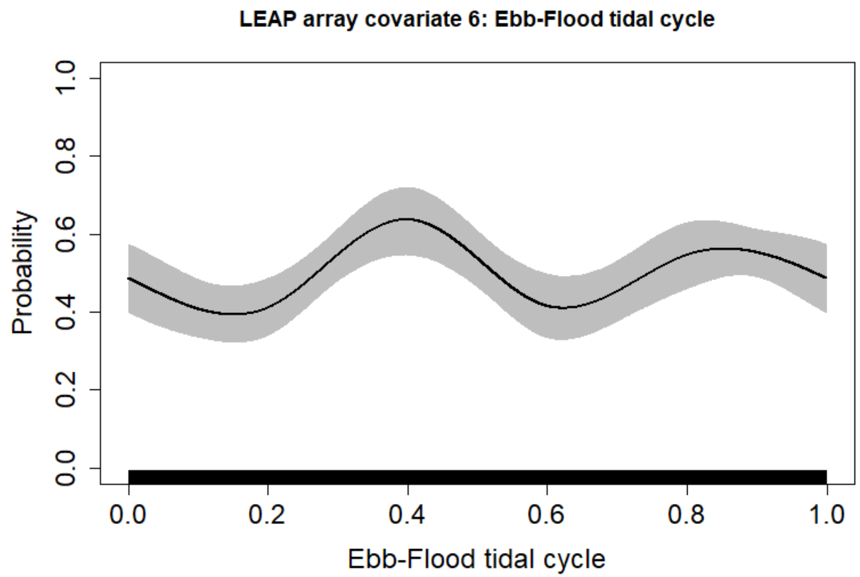






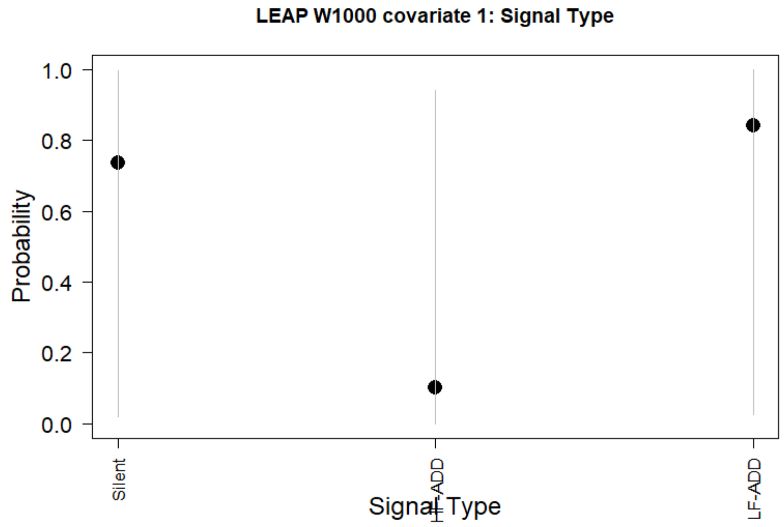


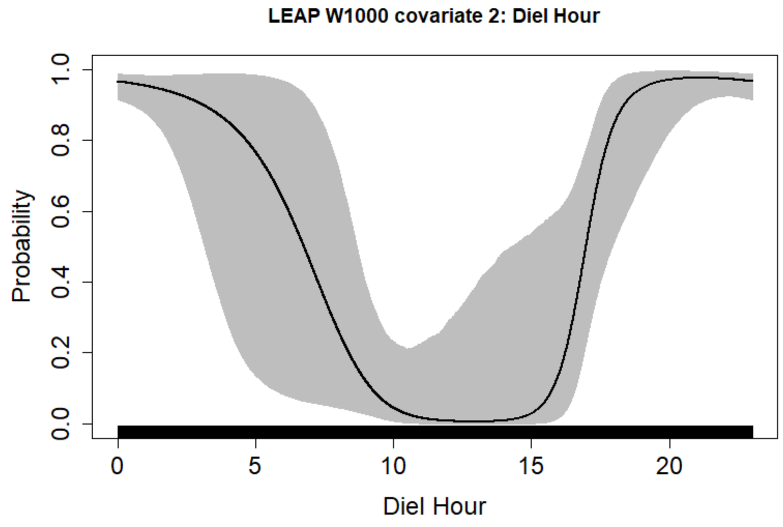

LEAP array covariate 5: Total N of unprocessed clicks received/min
Probability
0.0
0.2
0.4
0.6
0.8
1.0
0
1000
2000
3000
4000
Total N of unprocessed clicks received/min

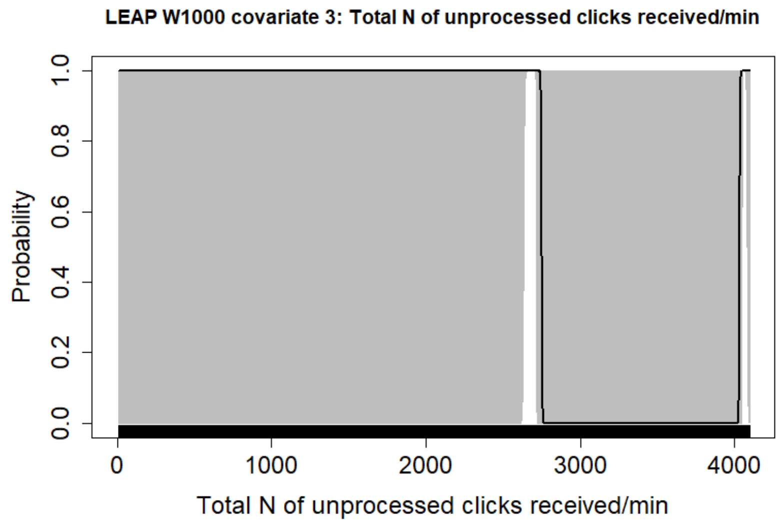

LEAP array covariate 6: Ebb-Flood tidal cycle
Probability
0.0
0.2
0.4
0.6
0.8
1.0
0.0
0.2
0.4
0.6
0.8
1.0
Ebb-Flood tidal cycle

<table>
<tr><td>Model:</td><td colspan="4">W-1000 (A)</td></tr>
<tr><td>Model structure:</td><td colspan="4">POD5<-geeglm(DPM ~ as.factor(Signal_Type) + AvgHrBasisMat + bs(Nall_m, knots=mean(Nall_m)), family = binomial, corstr="independence", id=Panel, data=Array)</td></tr>
<tr><td rowspan="4">Confusion matrix:</td><td colspan="2" rowspan="2"></td><td colspan="2">Expected</td></tr>
<tr><td>Porpoise</td><td>No porpoise</td></tr>
<tr><td rowspan="2">Observed</td><td>Porpoise</td><td>91.1%</td><td>21.1%</td></tr>
<tr><td>No porpoise</td><td>8.9%</td><td>78.9%</td></tr>
<tr><td>AUC value:</td><td colspan="4">0.9039284</td></tr>
<tr><td colspan="5">Results of Wald's tests for all significant covariates for the final model:</td></tr>
<tr><td>Covariates (in descending order of significance)</td><td>Form</td><td>Degrees of Freedom</td><td>χ^2 score</td><td>P-value</td></tr>
<tr><td>Signal_Type</td><td>Factor</td><td>2</td><td>11.813</td><td>0.0027221</td></tr>
<tr><td>Diel Hour</td><td>Cyclic spline</td><td>4</td><td>39.237</td><td>$6.223 \cdot 10^{-8}$</td></tr>
<tr><td>Nall_m</td><td>Cubic spline</td><td>4</td><td>19.991</td><td>0.0005014</td></tr>
</table>

Model: W-1000 (A)







Model:	E-2000 (A)
Model structure:	POD5<-geeglm(DPM ~ bs(JULDAY, knots=mean(JULDAY)) + SprNpBasisMat + AvgHrBasisMat + as.factor(Signal_Type), family = binomial, corstr="independence", id=Panel, data=Array)
Confusion matrix:	

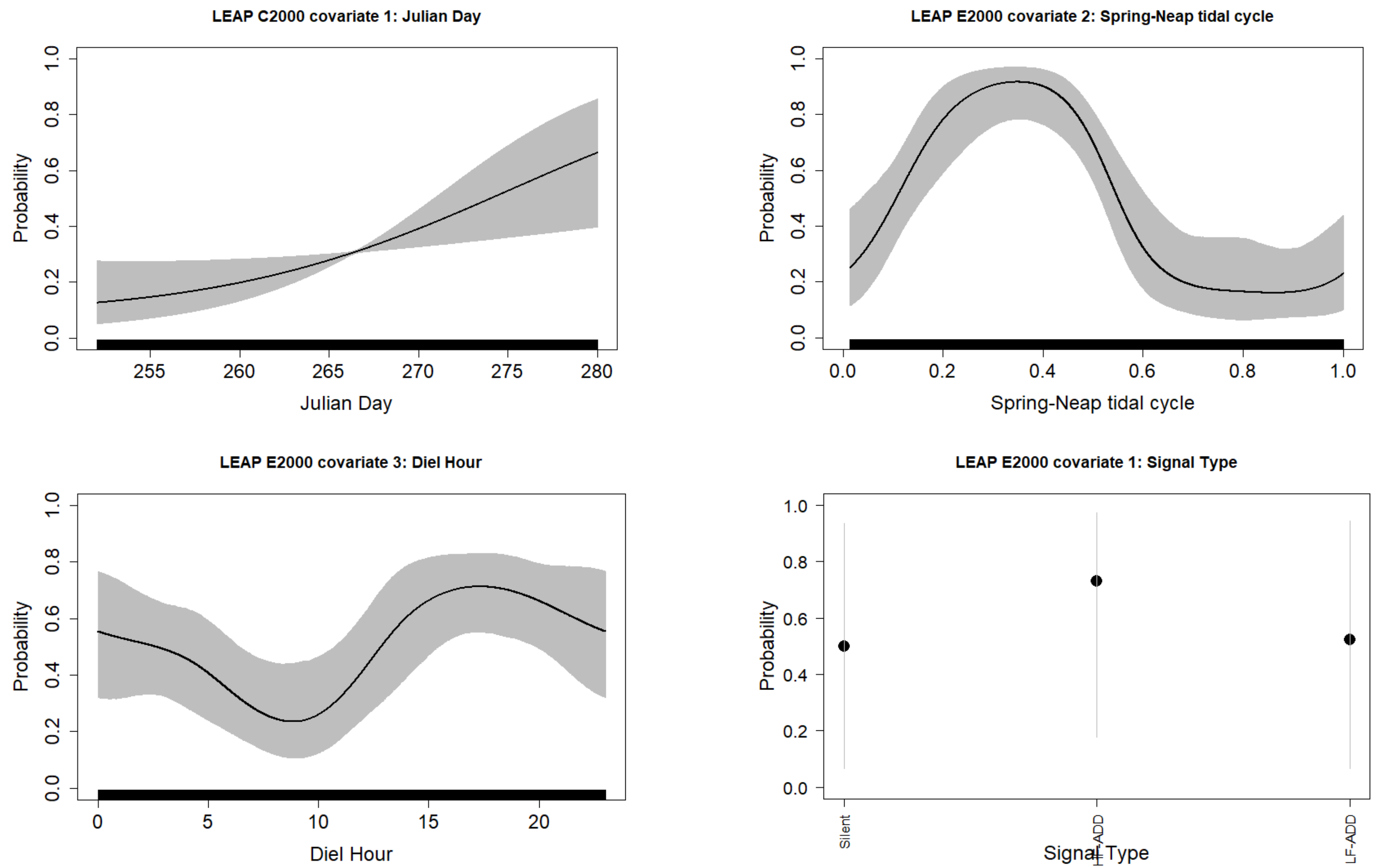
		Expected	
		Porpoise	No porpoise
Observed	Porpoise	62.4%	20.4%
	No porpoise	37.6%	79.6%

AUC value:	0.7656189

Results of Wald's tests for all significant covariates for the final model:

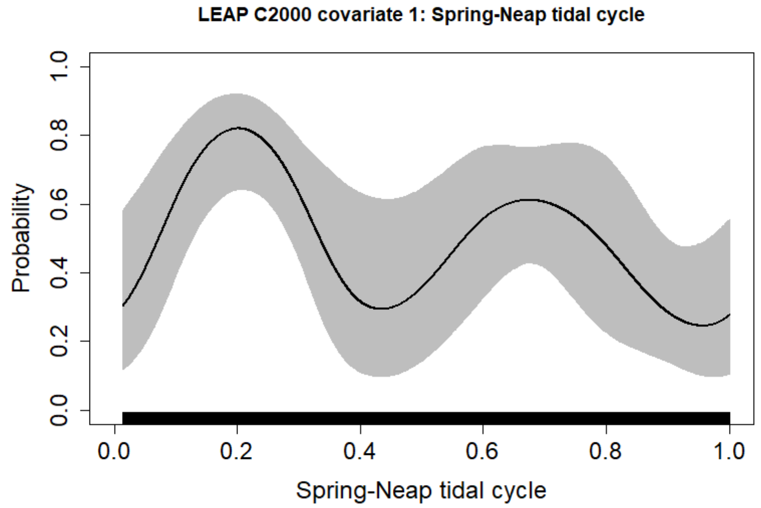
Covariates (in descending order of significance)	Form	Degrees of Freedom	χ^2 score	P-value
JULDAY	Cubic spline	4	11.5337	0.021177
SpringNeap	Cyclic spline	4	16.6861	0.002224
Diel Hour	Cyclic spline	4	10.4193	0.033927
Signal_Type	Factor	2	7.2264	0.026965

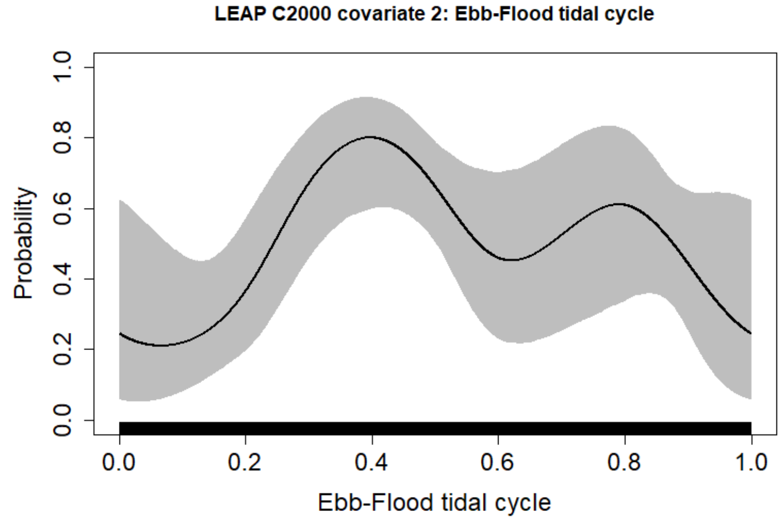
Model: E-2000 (A)

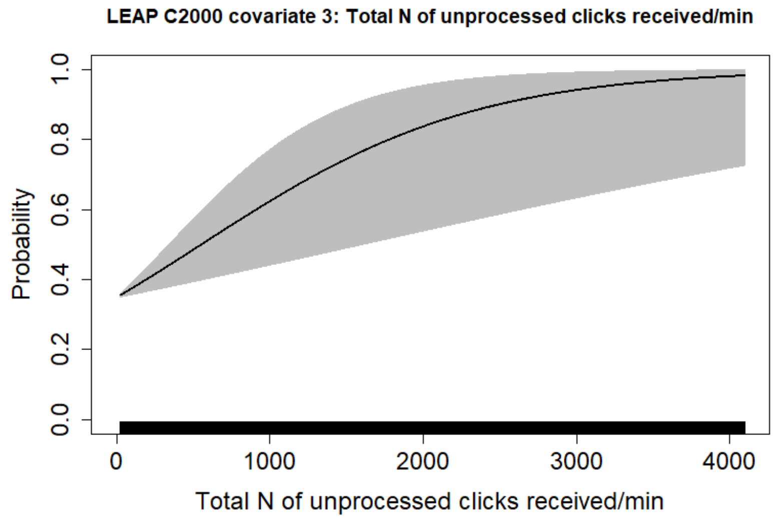


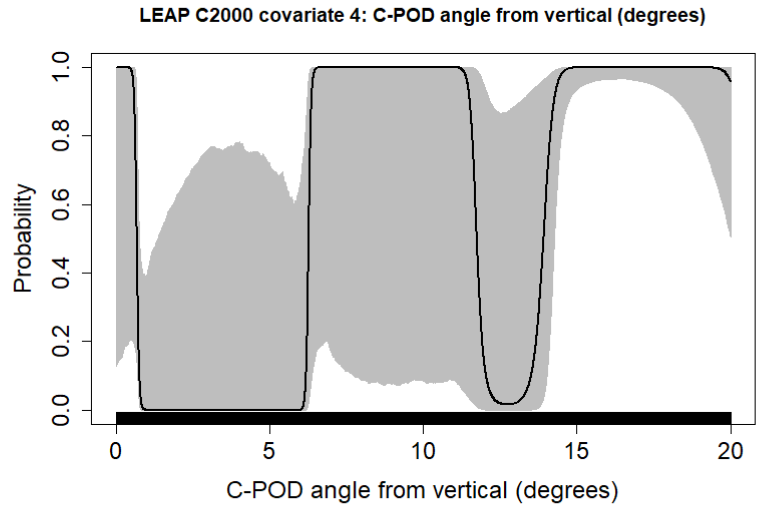
Model:	C-2000 (A)			
Model structure:	POD5<-geeglm(DPM ~ SprNpBasisMat + TideBasisMat + Nall_m + bs(Angle, knots=mean(Angle)), family = binomial, corstr="independence", id=Panel, data=Array)			
Confusion matrix:			Expected	
			Porpoise	No porpoise
	Observed	Porpoise	63.0%	23.2%
		No porpoise	37.0%	76.8%
AUC value:	0.7702981			
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 spline	4	9.7232	0.045358
HiLoTide	Cyclic spline	4	9.6518	0.046720
Nall_m	Linear	1	9.6253	0.001919
ANGLE	Cubic spline	4	26.3417	$2.7 \cdot 10^{-5}$

Model: C-2000 (A)



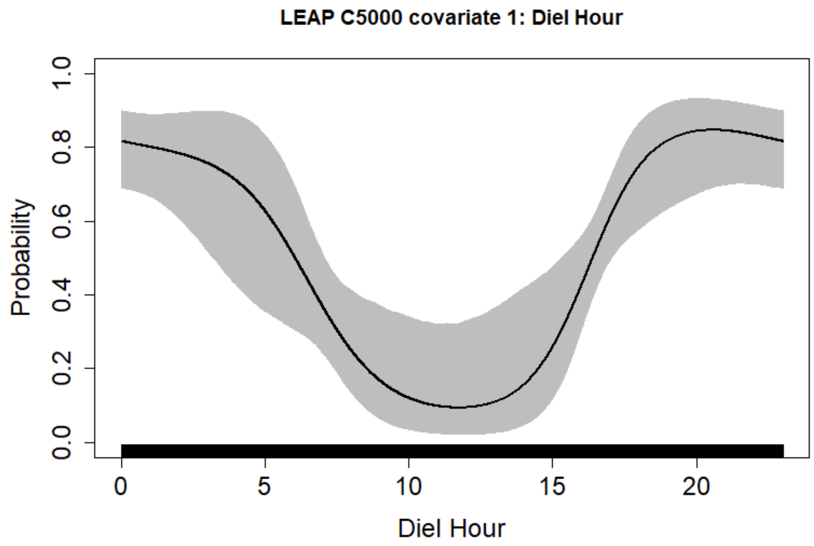


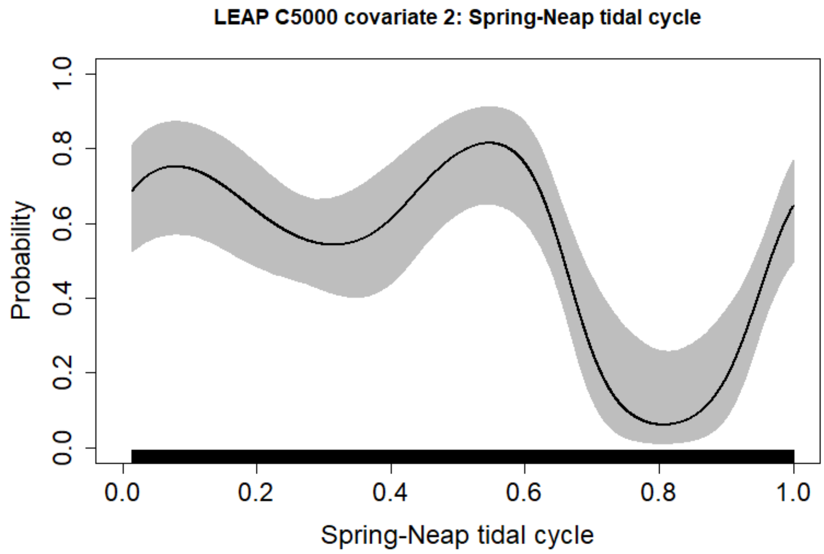


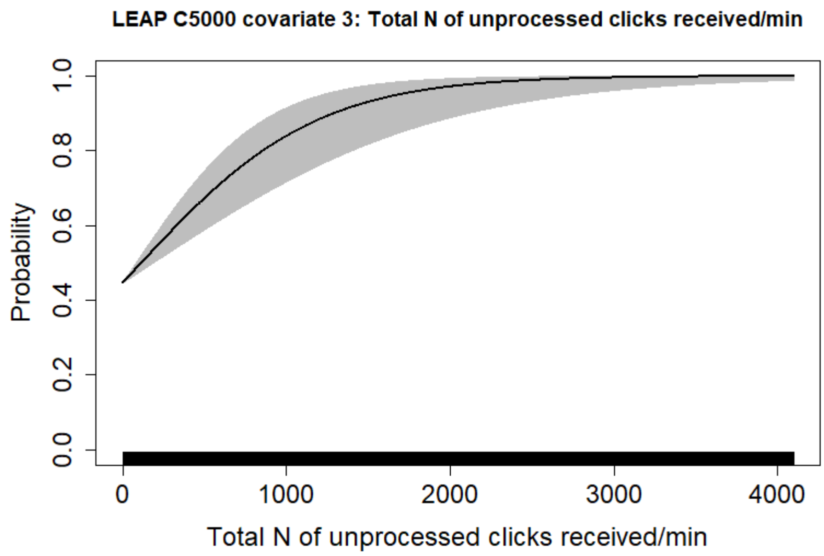


Model:	C-5000 (A)			
Model structure:	POD6<-geeglm(DPM ~ AvgHrBasisMat + SprNpBasisMat + Nall_m, family = binomial, corstr="independence", id=Panel, data=Array)			
Confusion matrix:			Expected	
			Porpoise	No porpoise
	Observed	Porpoise	82.8%	21.1%
		No porpoise	17.2%	78.9%
AUC value:	0.8495685			
Results 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
Diel Hour	Cyclic spline	4	24.422	$6.574 \cdot 10^{-5}$
SpringNeap	Cyclic spline	4	12.986	0.01134
Nall_m	Linear	1	26.615	$2.483 \cdot 10^{-7}$

Model: C-5000 (A)







Model:	W-5000 (A)
Model structure:	POD8<-geeglm(DPM ~ bs(JULDAY, knots=mean(JULDAY)), family = binomial, corstr="independence", id=Panel, data=Array)

Confusion matrix:

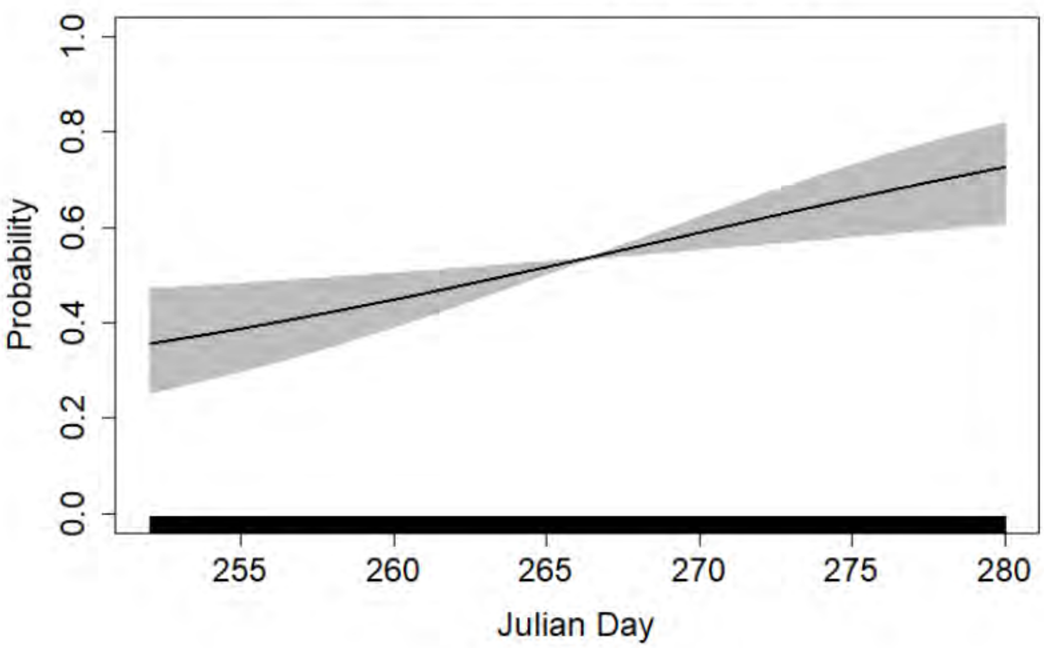
		Expected	
		Porpoise	No porpoise
Observed	Porpoise	48.6%	24.6%
	No porpoise	51.4%	75.4%

AUC value: 0.6707535

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
JULDAY	Cubic spline	4	20.1	0.0004773

LEAP W5000 covariate 1: Julian Day



Appendix 5B - GAM design, descriptors and outputs – Series B models

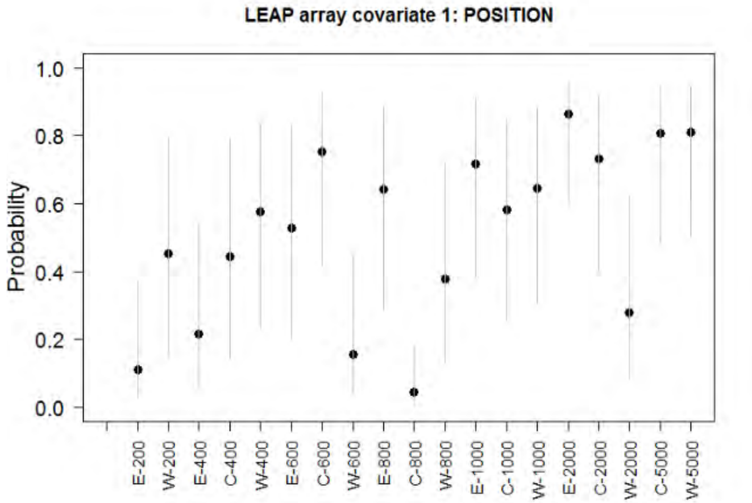
This Appendix contains Series B model outputs for 1) the entire LEAP array, 2) for the Nearfield component only, and 3) for all individual C-PODs where at least 50 PPMs were detected during the experimental period, this time using all data across the entire deployment period. Porpoise presence was modelled using binomial-based GAM-GEEs with an independent correlation structure and a logit link function to describe the relationship between covariates and porpoise click train detection presence (the response variable, described in a binary presence/absence format). This approach closely follows the one initially described by Pirotta et al. (2011) and the following text is adapted from an in-depth description of this method by Benjamins et al. (2016, 2017). Model outputs, expressions of model quality etc. are presented in exactly the same manner as described in Appendix 5A; details about the employed modelling approach can also be found there. Because greater numbers of PPM detections were available, daily PPM detection rates and block sizes were different from those described in Sections 4.7, 4.8 and Appendix 5A (Table A5B.1).

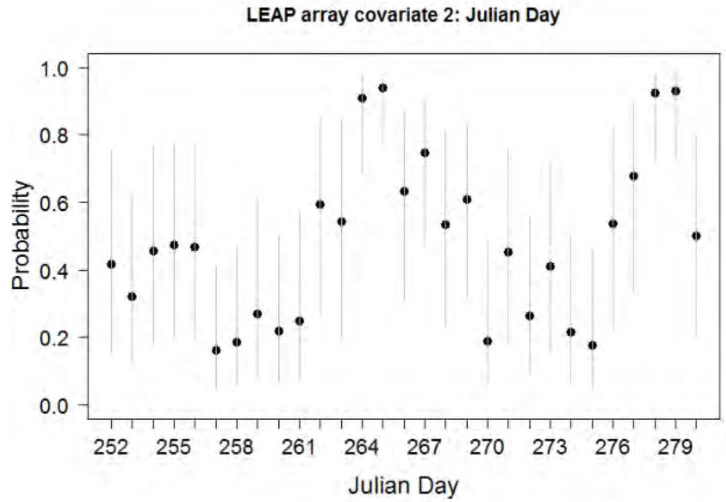
Table A5B.1. Overview of PPM detections during period used for Series B modelling efforts, covering the period 8/09 – 6/10/2016. Information is provided on block sizes used for individual and compound models to address temporal autocorrelation.

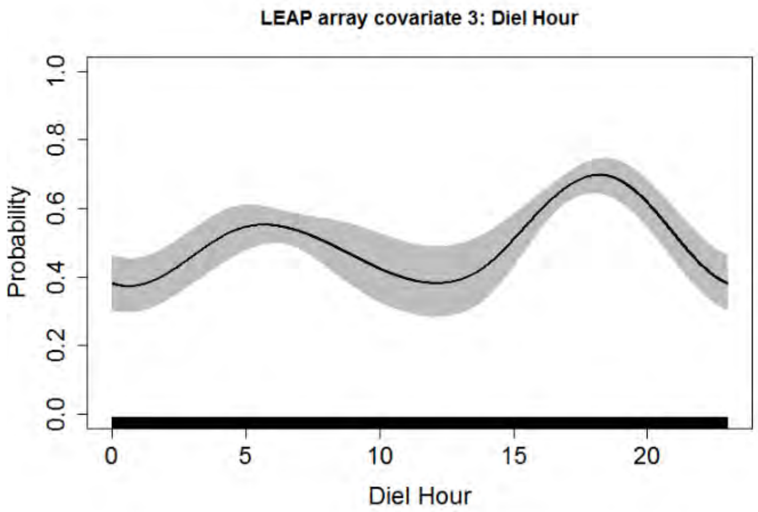
Array section	Site name	#PPM	Daily PPM detection rate (#PPM/day)	Block size (minutes)
NEARFIELD	E-200	15	0.51	5
NEARFIELD	E-400	97	3.33	30
NEARFIELD	E-600	204	7.00	118
NEARFIELD	E-800	263	9.02	137
NEARFIELD	E-1000	283	9.71	117
FARFIELD	E-2000	748	25.66	145
NEARFIELD	C-400	97	3.33	72
NEARFIELD	C-600	309	10.60	100
NEARFIELD	C-800	15	0.51	5
NEARFIELD	C-1000	159	5.45	40
FARFIELD	C-2000	319	10.94	45
FARFIELD	C-5000	361	12.38	121
NEARFIELD	W-200	111	3.81	45
NEARFIELD	W-400	155	5.32	71
NEARFIELD	W-600	30	1.03	6
NEARFIELD	W-800	110	3.77	17
NEARFIELD	W-1000	238	8.16	64
FARFIELD	W-2000	53	1.82	10
FARFIELD	W-5000	352	12.07	55

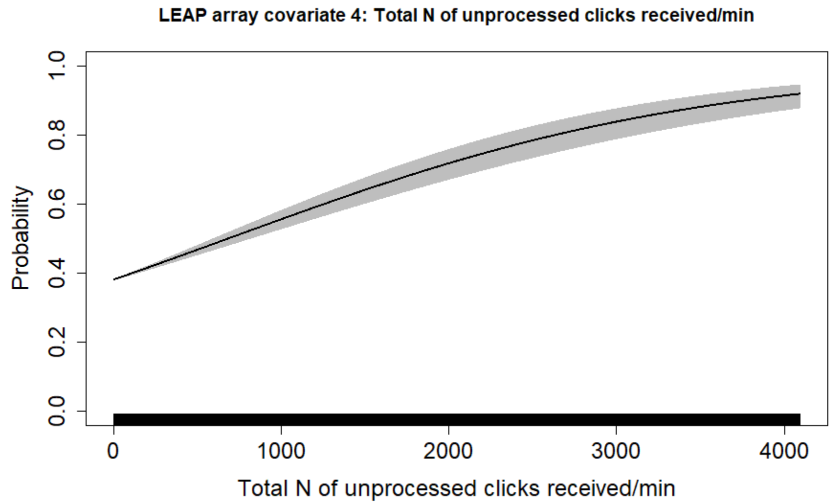
Model:	Whole array (B) (E-200-5000, C-400-5000, W200-5000)			
Model structure:	POD2<-geeglm(PPM ~ as.factor(POSITION) + as.factor(JULDAY) + AvgHrBasisMat + Nall_m + as.factor(Signal_Type) + TideBasisMat + as.factor(DAYTIMENum) + SprNpBasisMat, family = binomial, corstr="independence", id=Panel, data=Array)			
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	$<2.2\cdot10^{-16}$
JULDAY	factor	28	273.52	$<2.2\cdot10^{-16}$
HOUR	Cyclic spline	4	138.73	$<2.2\cdot10^{-16}$
Nall_m	linear	1	169.23	$<2.2\cdot10^{-16}$
Signal_Type	factor	3	37.69	$3.291\cdot10^{-8}$
HiLoTide	Cyclic spline	4	27.66	$1.462\cdot10^{-5}$
DAYTIMENum	factor	3	15.00	0.001819
SpringNeap	Cyclic spline	4	11.35	0.022868

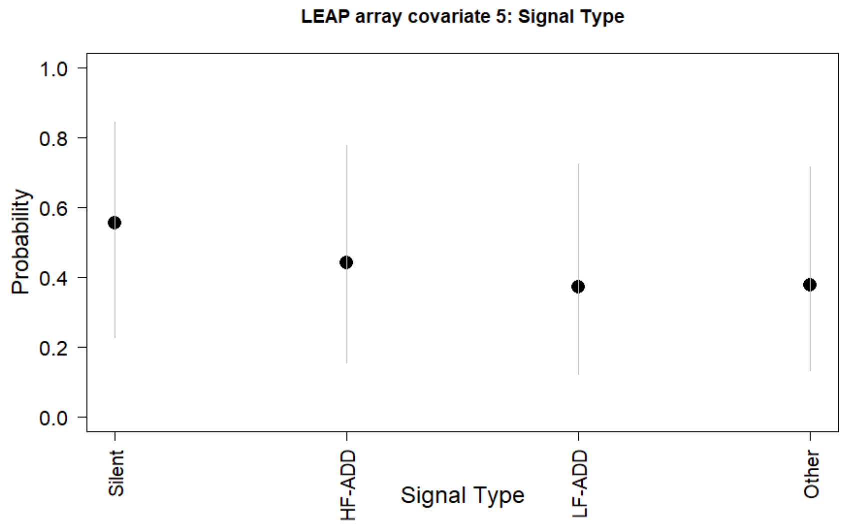
Model: Whole array (B) (E-200-5000, C-400-5000, W200-5000)

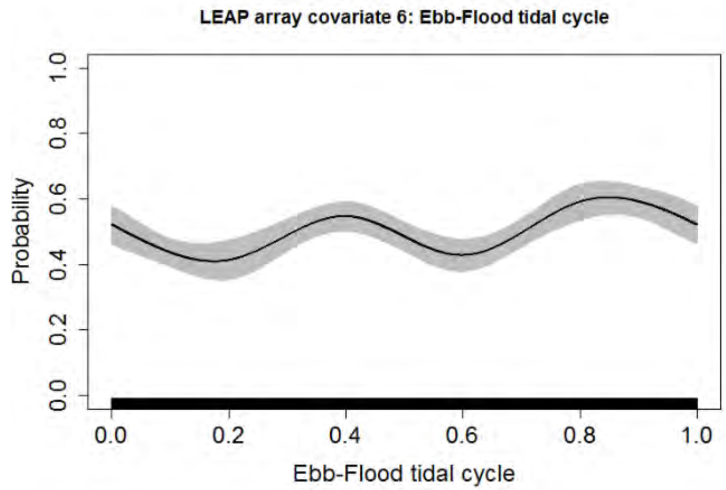


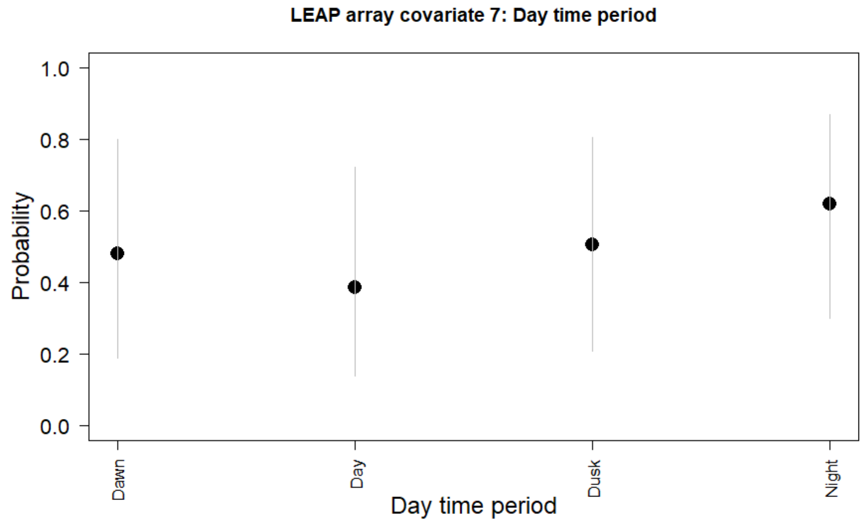


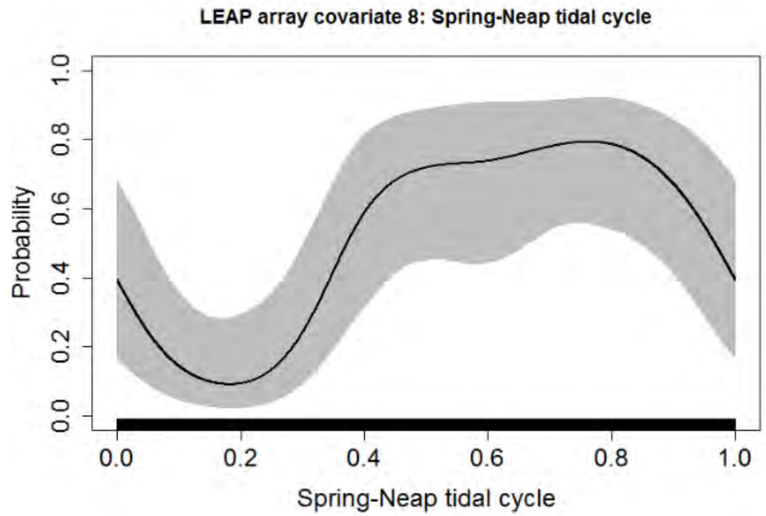





LEAP array covariate 5: Signal Type
Probability
1.0
0.8
0.6
0.4
0.2
0.0
Silent
HF-ADD
LF-ADD
Other
Signal Type


LEAP array covariate 6: Ebb-Flood tidal cycle
Probability
0.0
0.2
0.4
0.6
0.8
1.0
Ebb-Flood tidal cycle


LEAP array covariate 7: Day time period
Probability
1.0
0.8
0.6
0.4
0.2
0.0
Dawn
Day
Dusk
Night
Day time period


LEAP array covariate 8: Spring-Neap tidal cycle
Probability
0.0
0.2
0.4
0.6
0.8
1.0
Spring-Neap tidal cycle

Model:	Nearfield (B) (E-200-1000, C-400-1000, W200-1000)
Model structure:	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)
Confusion matrix:	

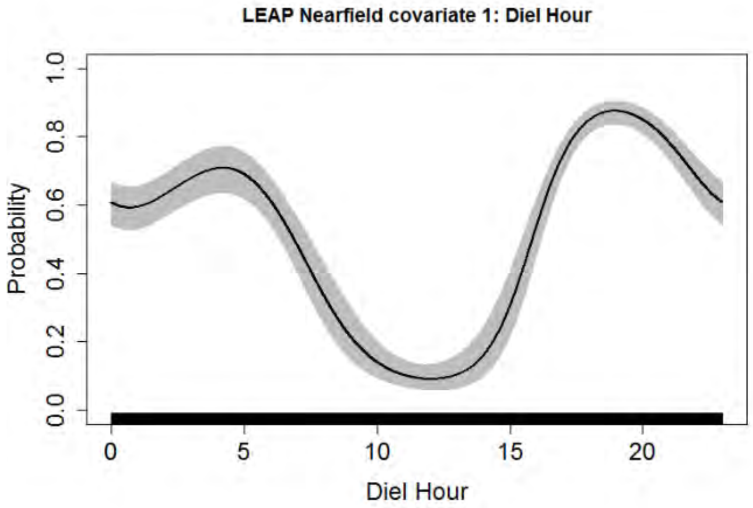
		Expected	
		Porpoise	No porpoise
Observed	Porpoise	80.6%	19.2%
	No porpoise	19.4%	80.8%

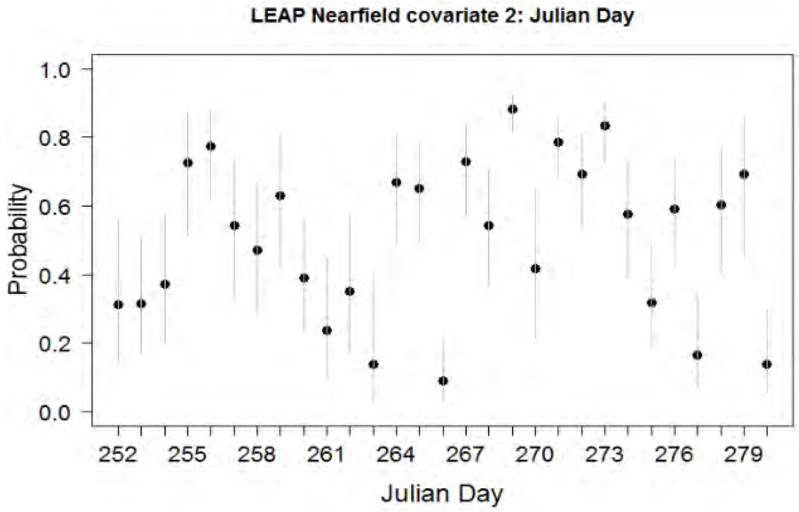
AUC value:	0.8893874

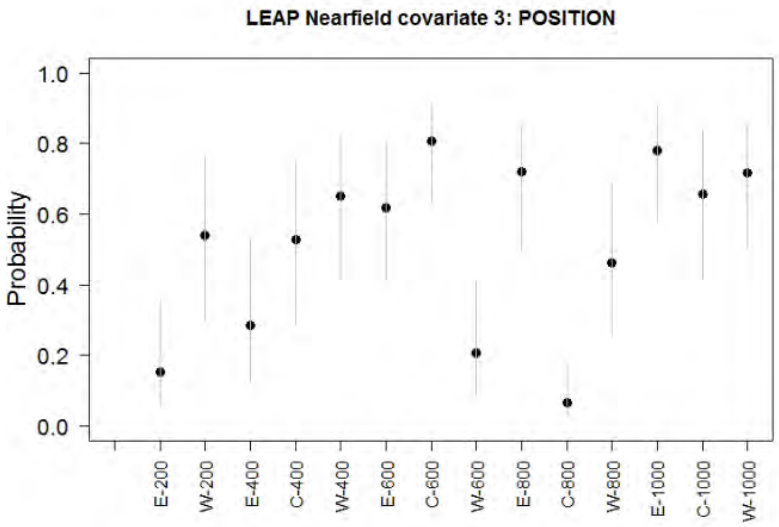
Results of Wald's tests for all significant covariates for the final model:

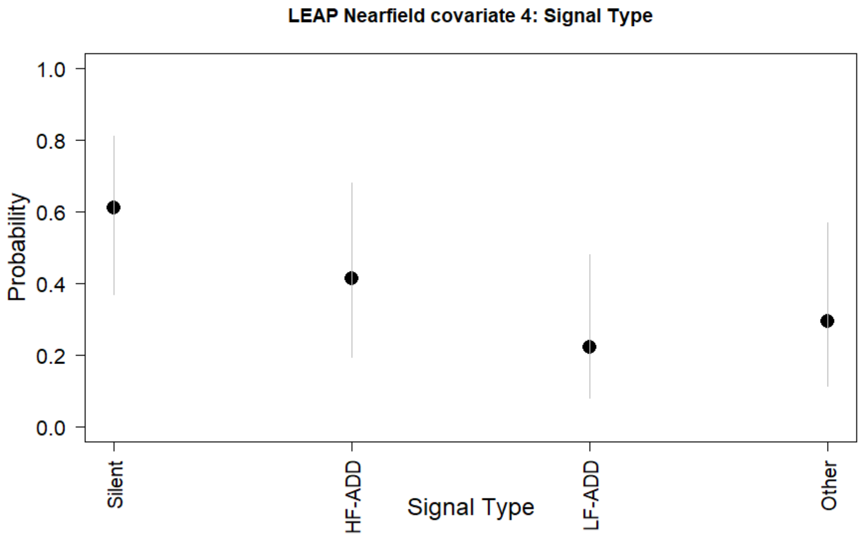
Covariates (in descending order of significance)	Form	Degrees of Freedom	χ^2 score	P-value
HOUR	Cyclic spline	4	165.23	$<2.2\cdot10^{-16}$
JULDAY	factor	28	367.38	$<2.2\cdot10^{-16}$
POSITION	factor	13	195.50	$<2.2\cdot10^{-16}$
Signal_Type	factor	3	61.93	$2.272\cdot10^{-13}$
Nall_m	linear	1	73.34	$<2.2\cdot10^{-16}$
HiLoTide	Cyclic spline	4	33.07	$1.158\cdot10^{-6}$

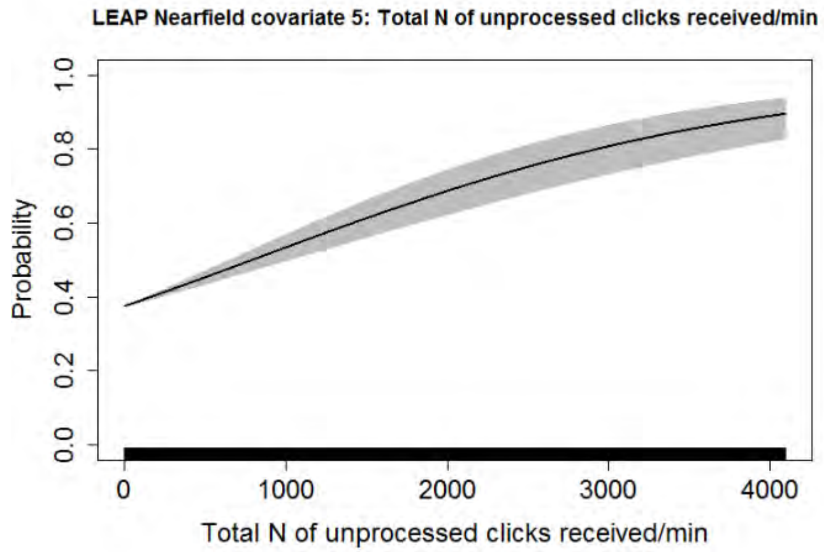
Model: Nearfield (B) (E-200-1000, C-400-1000, W200-1000)

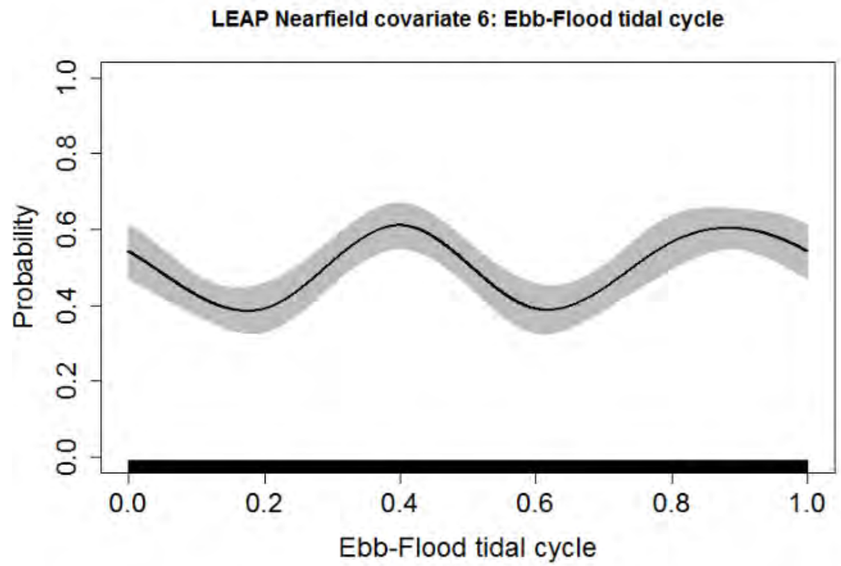









LEAP Nearfield covariate 5: Total N of unprocessed clicks received/min
Probability
0.0
0.2
0.4
0.6
0.8
1.0
0
1000
2000
3000
4000
Total N of unprocessed clicks received/min

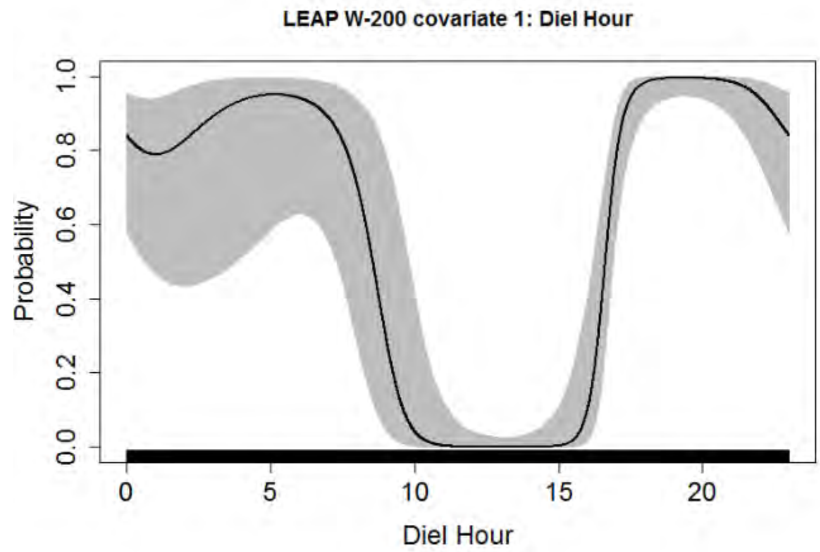

LEAP Nearfield covariate 6: Ebb-Flood tidal cycle
Probability
0.0
0.2
0.4
0.6
0.8
1.0
0.0
0.2
0.4
0.6
0.8
1.0
Ebb-Flood tidal cycle

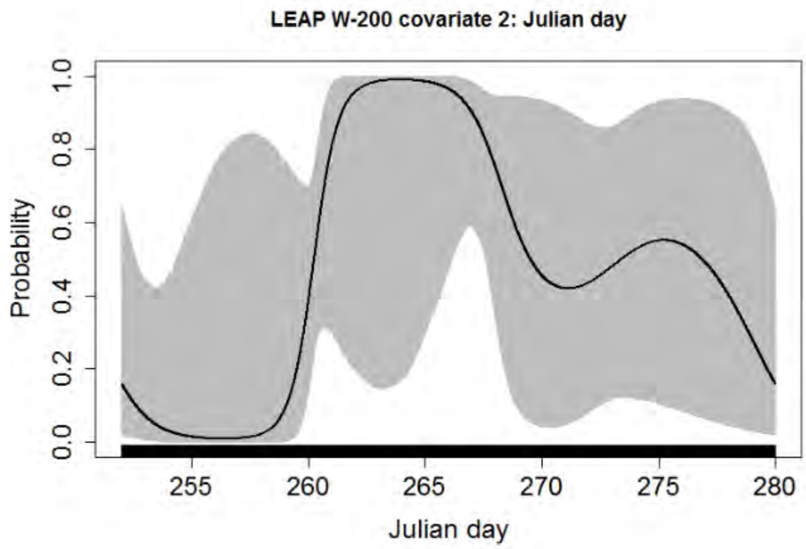
Model:	W-200 (B)			
Model structure:	POD5<-geeglm(PPM ~ AvgHrBasisMat + bs(JULDAY, knots=mean(JULDAY)) + Nall_m, family = binomial, corstr="independence", id=Panel, data=W200)			
Confusion matrix:				
AUC value:	0.905853			
Results of Wald's tests for all significant covariates for the final model:				
Covariates (in descending order of significance):	Form	Degrees of Freedom	χ^2 score	P-value
HOUR	Cyclic 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

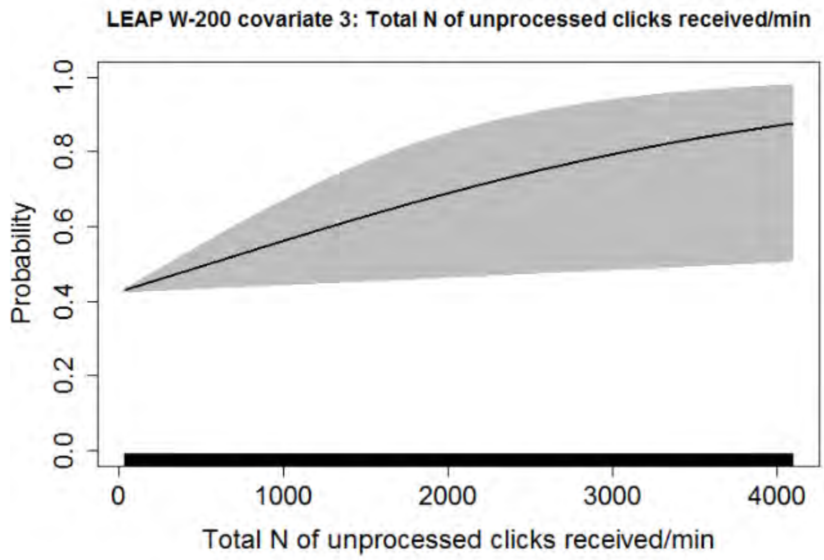
Confusion matrix:

		Expected: Porpoise	Expected: No porpoise
Observed	Porpoise	77.5%	6.8%
	No porpoise	22.5%	93.2%

Model: W-200 (B)


LEAP W-200 covariate 1: Diel Hour
Probability
0.0
0.2
0.4
0.6
0.8
1.0
0
5
10
15
20
Diel Hour


LEAP W-200 covariate 2: Julian day
Probability
0.0
0.2
0.4
0.6
0.8
1.0
255
260
265
270
275
280
Julian day


LEAP W-200 covariate 3: Total N of unprocessed clicks received/min
Probability
0.0
0.2
0.4
0.6
0.8
1.0
0
1000
2000
3000
4000
Total N of unprocessed clicks received/min

Model:	E-400 (B)
Model structure:	POD5<-geeglm(PPM ~ AvgHrBasisMat + SprNpBasisMat + Nall_m, family = binomial, corstr="independence", id=Panel, data=E400)

Confusion matrix:

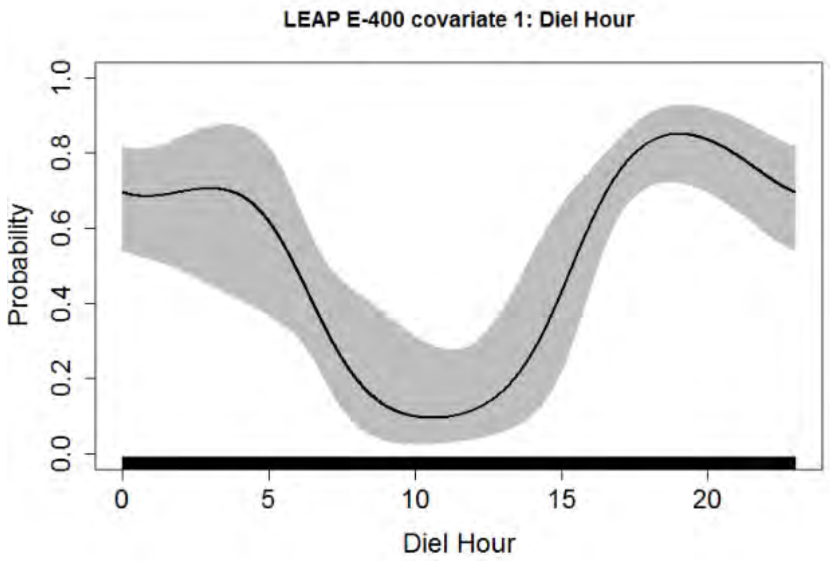
		Expected	
		Porpoise	No porpoise
Observed	Porpoise	74.7%	22.4%
	No porpoise	25.3%	77.6%

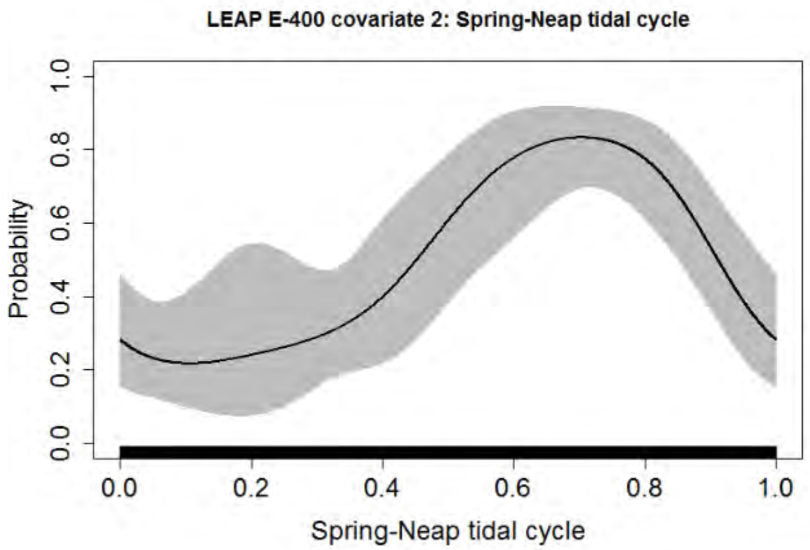
AUC value: 0.8263694

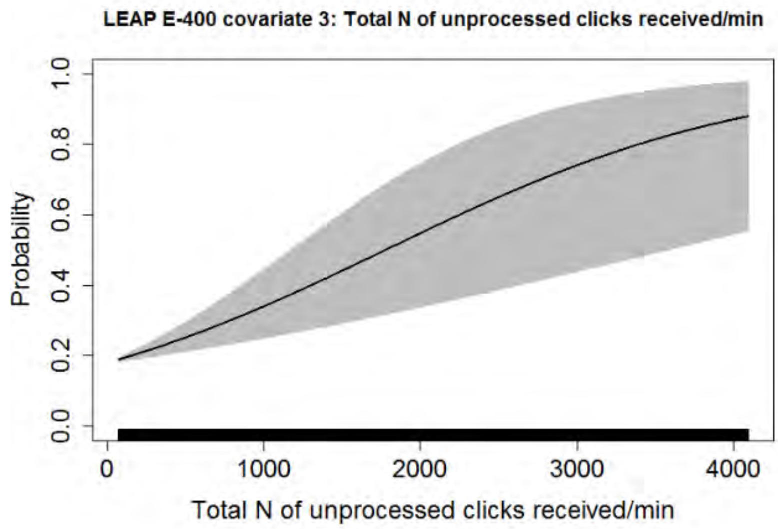
Results of Wald's tests for all significant covariates for the final model:

Covariates (in descending order of significance)	Form	Degrees of Freedom	χ^2 score	P-value
HOUR	Cyclic spline	4	25.635	$3.749 \cdot 10^{-5}$
SpringNeap	Cyclic spline	4	17.091	0.0018557
Nall_m	linear	1	14.680	0.0001274

Model: E-400 (B)


LEAP E-400 covariate 1: Diel Hour
Probability
0.0
0.2
0.4
0.6
0.8
1.0
0
5
10
15
20
Diel Hour


LEAP E-400 covariate 2: Spring-Neap tidal cycle
Probability
0.0
0.2
0.4
0.6
0.8
1.0
0.0
0.2
0.4
0.6
0.8
1.0
Spring-Neap tidal cycle


LEAP E-400 covariate 3: Total N of unprocessed clicks received/min
Probability
0.0
0.2
0.4
0.6
0.8
1.0
0
1000
2000
3000
4000
Total N of unprocessed clicks received/min

Model:	C-400 (B)
Model structure:	POD5<-geeglm(PPM ~ AvgHrBasisMat + TideBasisMat + bs(JULDAY, knots=mean(JULDAY)) + Nall_m, family = binomial, corstr="independence", id=Panel, data=C400)

Confusion matrix:

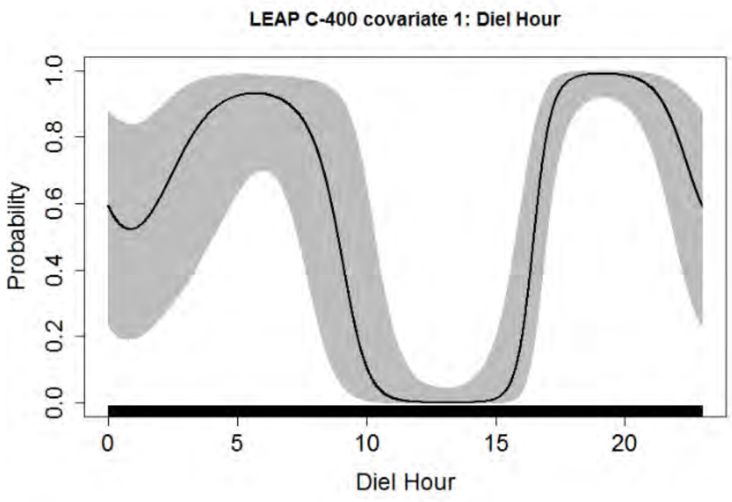
		Expected	
		Porpoise	No porpoise
Observed	Porpoise	89.3%	10.8%
	No porpoise	10.7%	89.2%

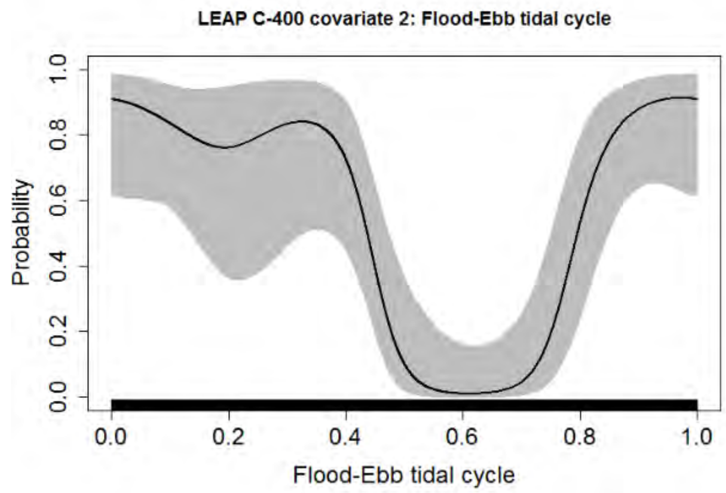
AUC value:	0.943135

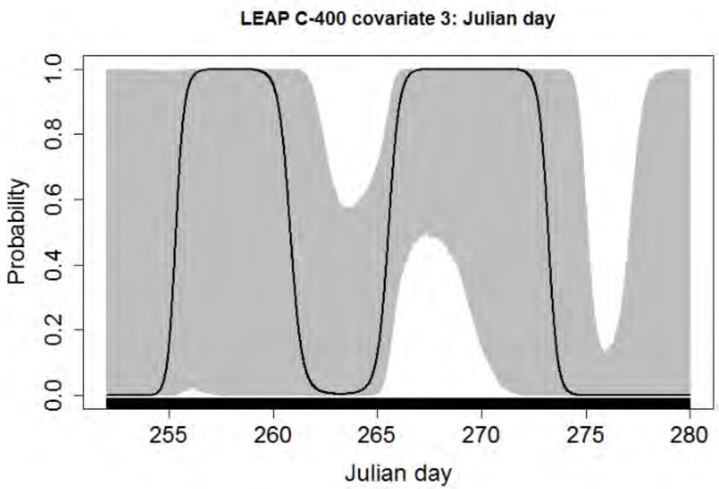
Results of Wald's tests for all significant covariates for the final model:

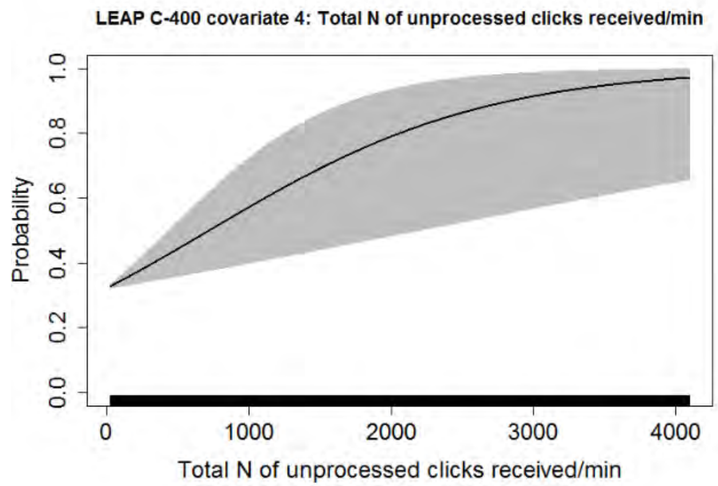
Covariates (in descending order of significance)	Form	Degrees of Freedom	χ^2 score	P-value
HOUR	Cyclic spline	4	14.0194	0.007233
HiLotide	Cyclic spline	4	13.7363	0.008186
JULDAY	Cubic B-spline	4	15.3708	0.003991
Nall_m	linear	1	8.5291	0.003495

Model: C-400 (B)


LEAP C-400 covariate 1: Diel Hour
Probability
0.0
0.2
0.4
0.6
0.8
1.0
0
5
10
15
20
Diel Hour

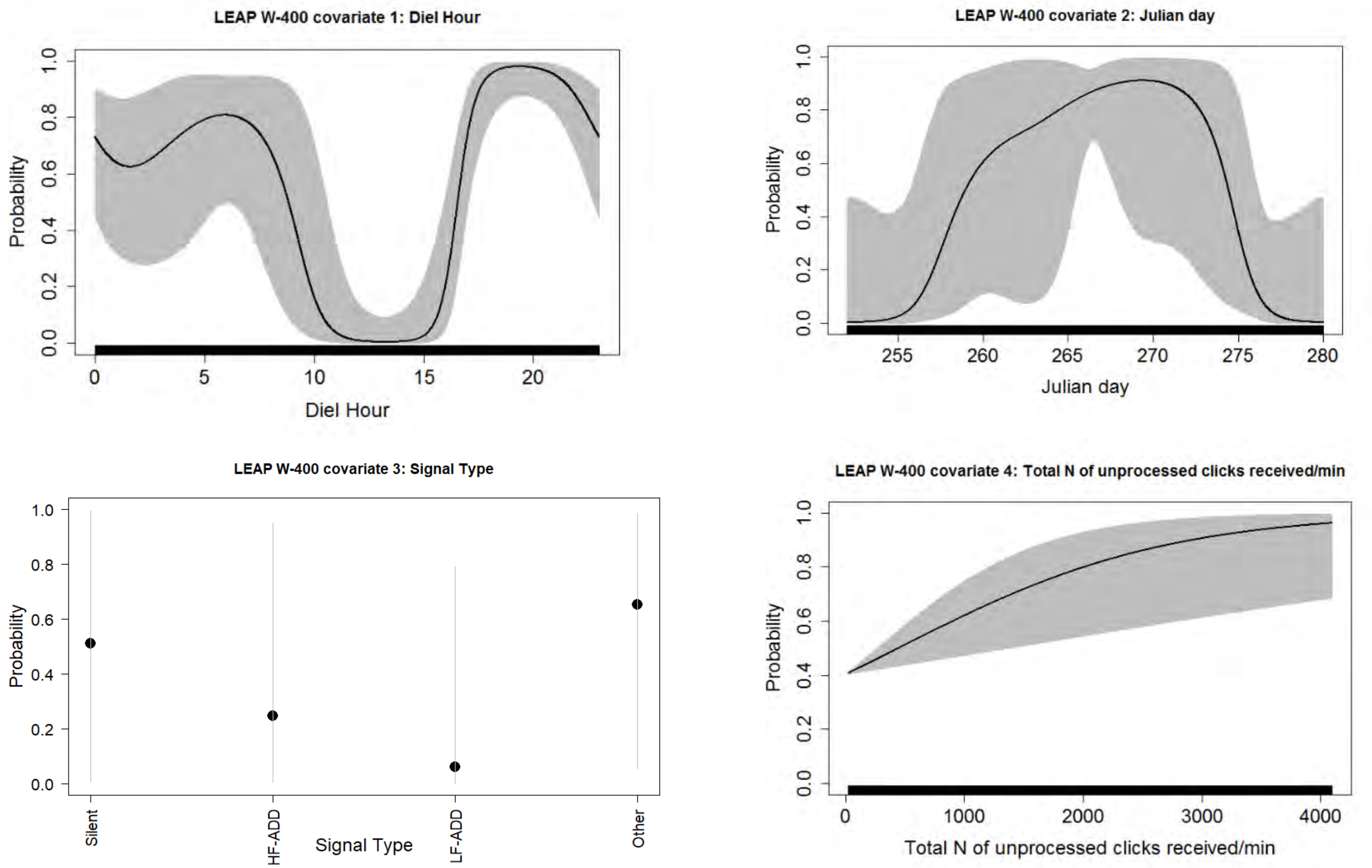

LEAP C-400 covariate 2: Flood-Ebb tidal cycle
Probability
0.0
0.2
0.4
0.6
0.8
1.0
0.0
0.2
0.4
0.6
0.8
1.0
Flood-Ebb tidal cycle


LEAP C-400 covariate 3: Julian day
Probability
0.0
0.2
0.4
0.6
0.8
1.0
255
260
265
270
275
280
Julian day

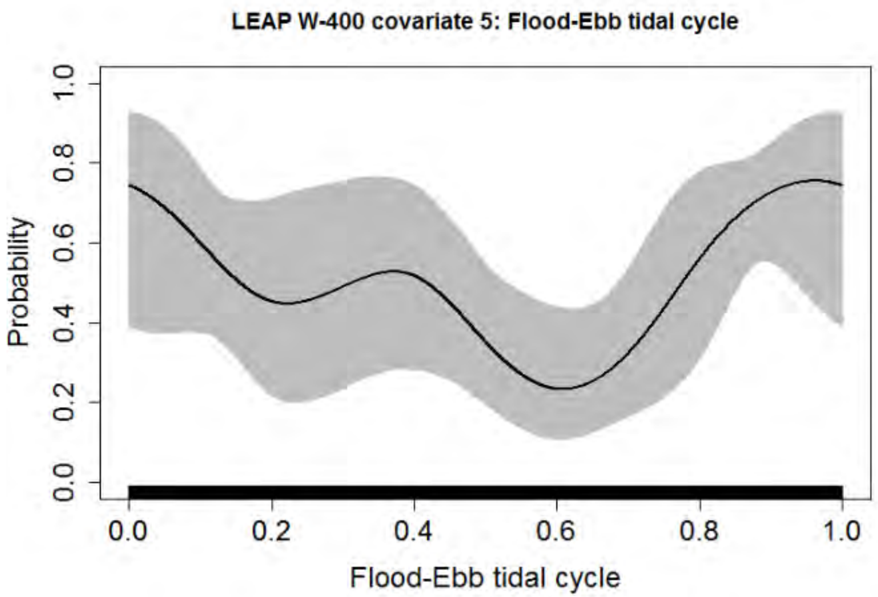

LEAP C-400 covariate 4: Total N of unprocessed clicks received/min
Probability
0.0
0.2
0.4
0.6
0.8
1.0
0
1000
2000
3000
4000
Total N of unprocessed clicks received/min

<table>
<tr><td>Model:</td><td colspan="4">W-400 (B)</td></tr>
<tr><td>Model structure:</td><td colspan="4">POD5<-geeglm(PPM ~ AvgHrBasisMat + bs(JULDAY, knots=mean(JULDAY)) + as.factor(Signal_Type) + Nall_m + TideBasisMat, family = binomial, corstr="independence", id=Panel, data=W400)</td></tr>
<tr><td>Confusion matrix:</td><td colspan="4"><table>
<tr><td></td><td></td><td colspan="2">Expected</td></tr>
<tr><td></td><td></td><td>Porpoise</td><td>No porpoise</td></tr>
<tr><td rowspan="2">Observed</td><td>Porpoise</td><td>88.4%</td><td>21.9%</td></tr>
<tr><td>No porpoise</td><td>11.6%</td><td>78.1%</td></tr>
</table></td></tr>
<tr><td>AUC value:</td><td colspan="4">0.9068351</td></tr>
<tr><td colspan="5">Results of Wald’s tests for all significant covariates for the final model:</td></tr>
<tr><td>Covariates (in descending order of significance)</td><td>Form</td><td>Degrees of Freedom</td><td>χ^2 score</td><td>P-value</td></tr>
<tr><td>HOUR</td><td>Cyclic spline</td><td>4</td><td>21.8619</td><td>0.0002135</td></tr>
<tr><td>JULDAY</td><td>Cubic B-spline</td><td>4</td><td>17.9475</td><td>0.0012636</td></tr>
<tr><td>Signal_Type</td><td>Factor</td><td>3</td><td>13.8378</td><td>0.0031345</td></tr>
<tr><td>Nall_m</td><td>Linear</td><td>1</td><td>7.2002</td><td>0.0072895</td></tr>
<tr><td>HiLoTide</td><td>Cyclic spline</td><td>4</td><td>11.4568</td><td>0.0218828</td></tr>
</table>

Model: W-400 (B)



LEAP W-400 covariate 1: Diel Hour
Probability
0.0
0.2
0.4
0.6
0.8
1.0
0
5
10
15
20
Diel Hour
LEAP W-400 covariate 2: Julian day
Probability
0.0
0.2
0.4
0.6
0.8
1.0
255
260
265
270
275
280
Julian day
LEAP W-400 covariate 3: Signal Type
Probability
0.0
0.2
0.4
0.6
0.8
1.0
Silent
HF-ADD
LF-ADD
Other
Signal Type
LEAP W-400 covariate 4: Total N of unprocessed clicks received/min
Probability
0.0
0.2
0.4
0.6
0.8
1.0
0
1000
2000
3000
4000
Total N of unprocessed clicks received/min


LEAP W-400 covariate 5: Flood-Ebb tidal cycle
Probability
0.0
0.2
0.4
0.6
0.8
1.0
0.0
0.2
0.4
0.6
0.8
1.0
Flood-Ebb tidal cycle

Model:	E-600 (B)
Model structure:	POD5<-geeglm(PPM ~ AvgHrBasisMat + bs(JULDAY, knots=mean(JULDAY)) + SprNpBasisMat + TideBasisMat, family = binomial, corstr="independence", id=Panel, data=E600)
Confusion matrix:	

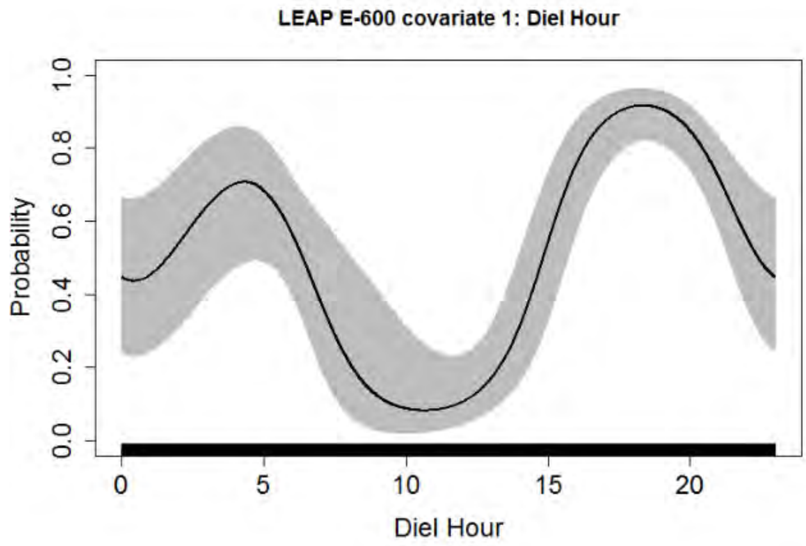
		Expected	
		Porpoise	No porpoise
Observed	Porpoise	75.5%	23.6%
	No porpoise	24.5%	76.4%

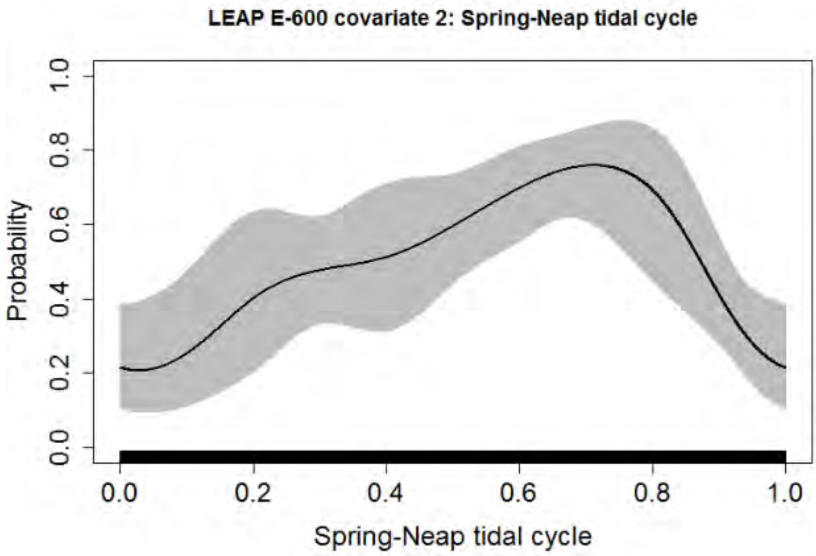
AUC value:	0.8365278

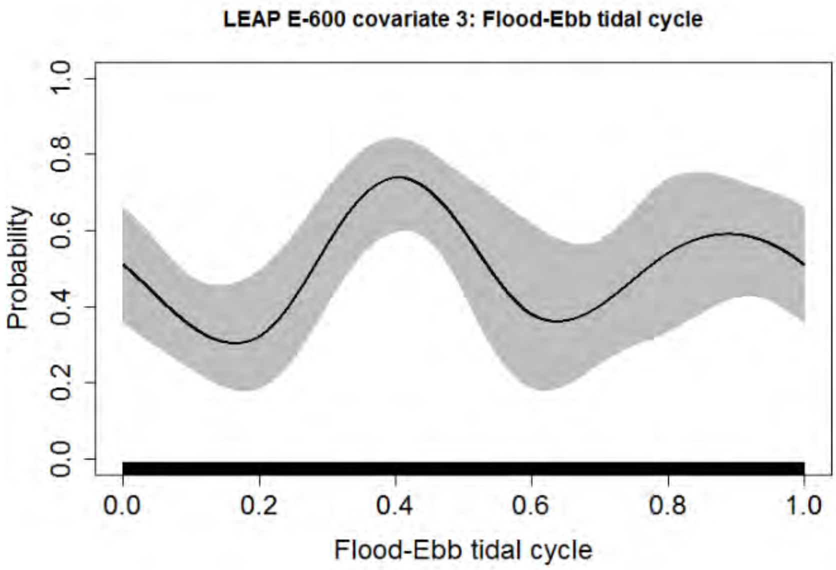
Results of Wald's tests for all significant covariates for the final model:

Covariates (in descending order of significance)	Form	Degrees of Freedom	χ^2 score	P-value
HOUR	Cyclic spline	4	34.277	$6.538 \cdot 10^{-7}$
SpringNeap	Cyclic spline	4	14.105	0.006967
HiLoTide	Cyclic spline	4	13.362	0.009636

Model: E-600 (B)

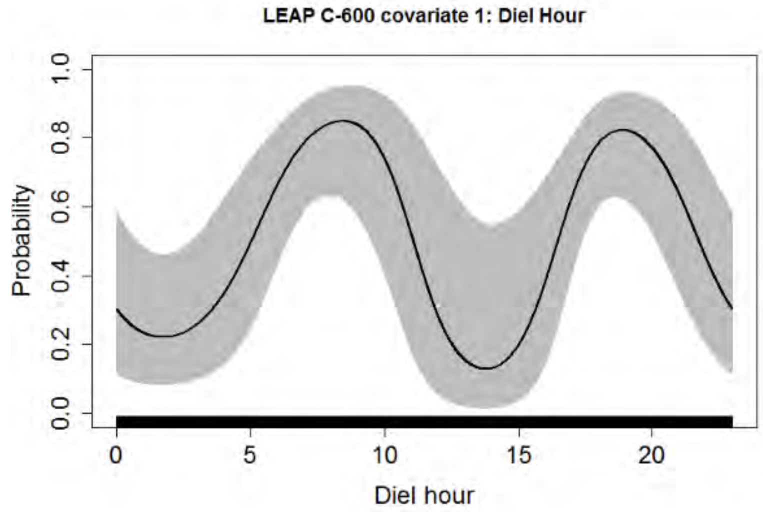

LEAP E-600 covariate 1: Diel Hour
Probability
0.0
0.2
0.4
0.6
0.8
1.0
0
5
10
15
20
Diel Hour

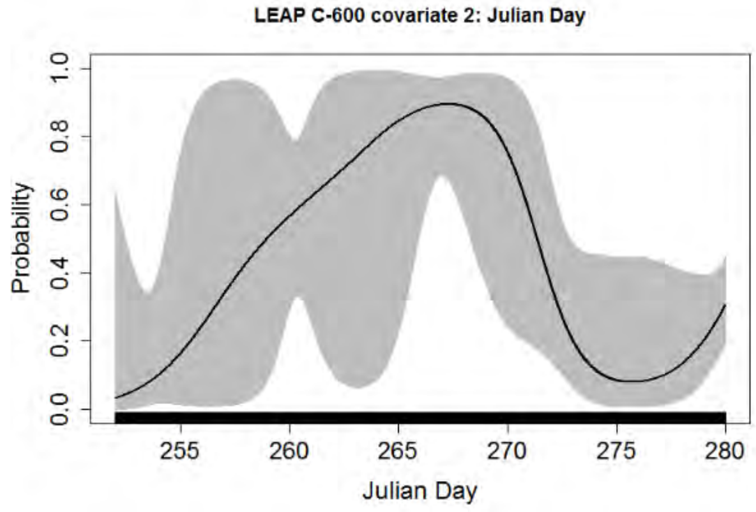

LEAP E-600 covariate 2: Spring-Neap tidal cycle
Probability
0.0
0.2
0.4
0.6
0.8
1.0
0.0
0.2
0.4
0.6
0.8
1.0
Spring-Neap tidal cycle

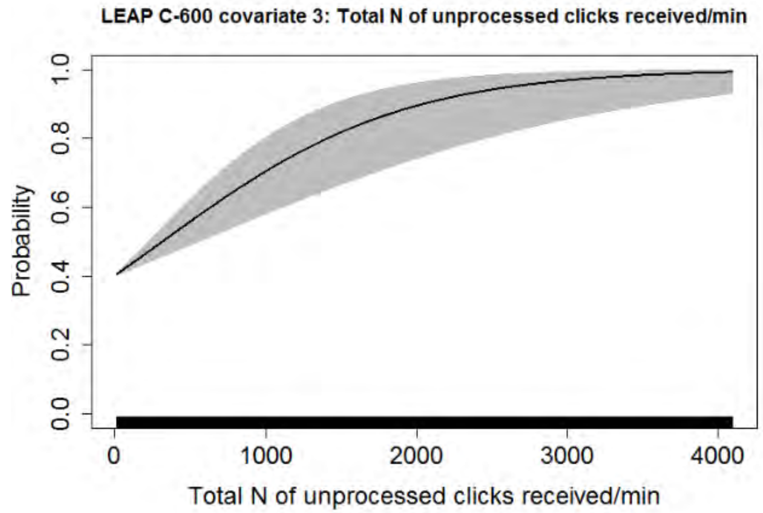

LEAP E-600 covariate 3: Flood-Ebb tidal cycle
Probability
0.0
0.2
0.4
0.6
0.8
1.0
0.0
0.2
0.4
0.6
0.8
1.0
Flood-Ebb tidal cycle

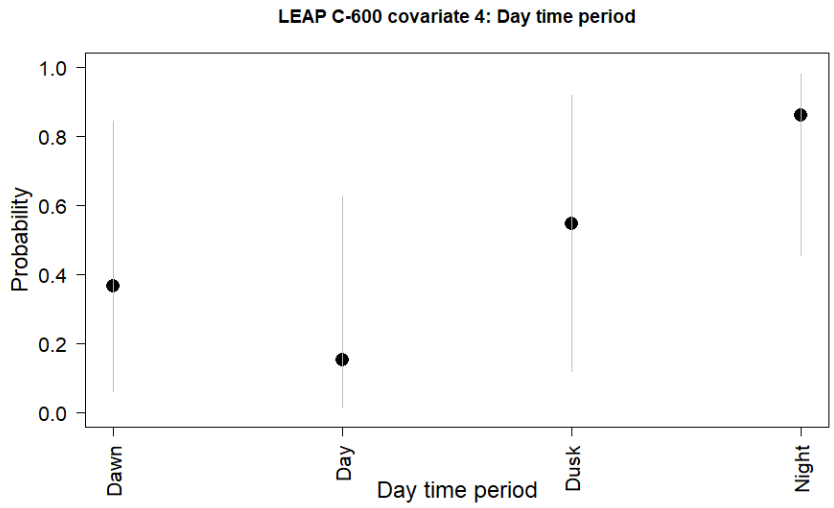
<table>
<tr><td>Model:</td><td colspan="4">C-600 (B)</td></tr>
<tr><td>Model structure:</td><td colspan="4">POD7<-geeglm(PPM ~ AvgHrBasisMat + bs(JULDAY, knots=mean(JULDAY)) + Nall_m + as.factor(DAYTIMENum), family = binomial, corstr="independence", id=Panel, data=C600)</td></tr>
<tr><td rowspan="4">Confusion matrix:</td><td colspan="2" rowspan="2"></td><td colspan="2">Expected</td></tr>
<tr><td>Porpoise</td><td>No porpoise</td></tr>
<tr><td rowspan="2">Observed</td><td>Porpoise</td><td>77.0%</td><td>15.6%</td></tr>
<tr><td>No porpoise</td><td>23.0%</td><td>84.4%</td></tr>
<tr><td>AUC value:</td><td colspan="4">0.8862971</td></tr>
<tr><td colspan="5">Results of Wald’s tests for all significant covariates for the final model:</td></tr>
<tr><td>Covariates (in descending order of significance)</td><td>Form</td><td>Degrees of Freedom</td><td>χ^2 score</td><td>P-value</td></tr>
<tr><td>HOUR</td><td>Cyclic spline</td><td>4</td><td>33.592</td><td>$9.034 \cdot 10^{-7}$</td></tr>
<tr><td>JULDAY</td><td>Cubic B-spline</td><td>4</td><td>32.976</td><td>$1.208 \cdot 10^{-6}$</td></tr>
<tr><td>Nall_m</td><td>Linear</td><td>1</td><td>23.235</td><td>$1.434 \cdot 10^{-6}$</td></tr>
<tr><td>DAYTIMENum</td><td>Factor</td><td>3</td><td>20.308</td><td>0.0001465</td></tr>
</table>

Model: C-600 (B)


LEAP C-600 covariate 1: Diel Hour
Probability
0.0
0.2
0.4
0.6
0.8
1.0
0
5
10
15
20
Diel hour


LEAP C-600 covariate 2: Julian Day
Probability
0.0
0.2
0.4
0.6
0.8
1.0
255
260
265
270
275
280
Julian Day


LEAP C-600 covariate 3: Total N of unprocessed clicks received/min
Probability
0.0
0.2
0.4
0.6
0.8
1.0
0
1000
2000
3000
4000
Total N of unprocessed clicks received/min


LEAP C-600 covariate 4: Day time period
Probability
0.0
0.2
0.4
0.6
0.8
1.0
Dawn
Day
Dusk
Night
Day time period

Model:	E-800 (B)
Model structure:	POD7<-geeglm(PPM ~ AvgHrBasisMat + bs(JULDAY, knots=mean(JULDAY)), family = binomial, corstr="independence", id=Panel, data=E800)

Confusion matrix:

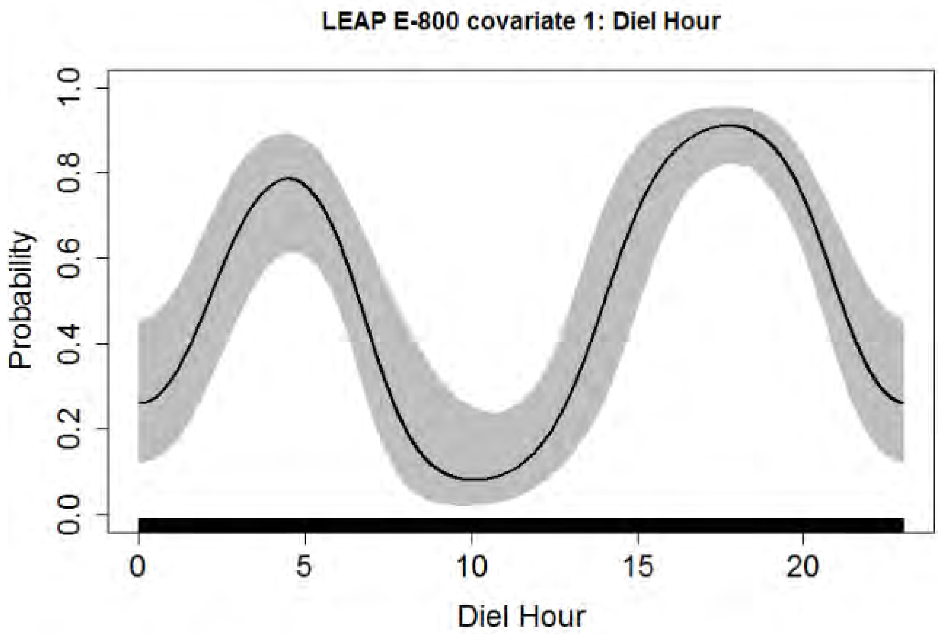
		Expected	
		Porpoise	No porpoise
Observed	Porpoise	80.2%	25.6%
	No porpoise	19.8%	74.4%

AUC value:	0.841899

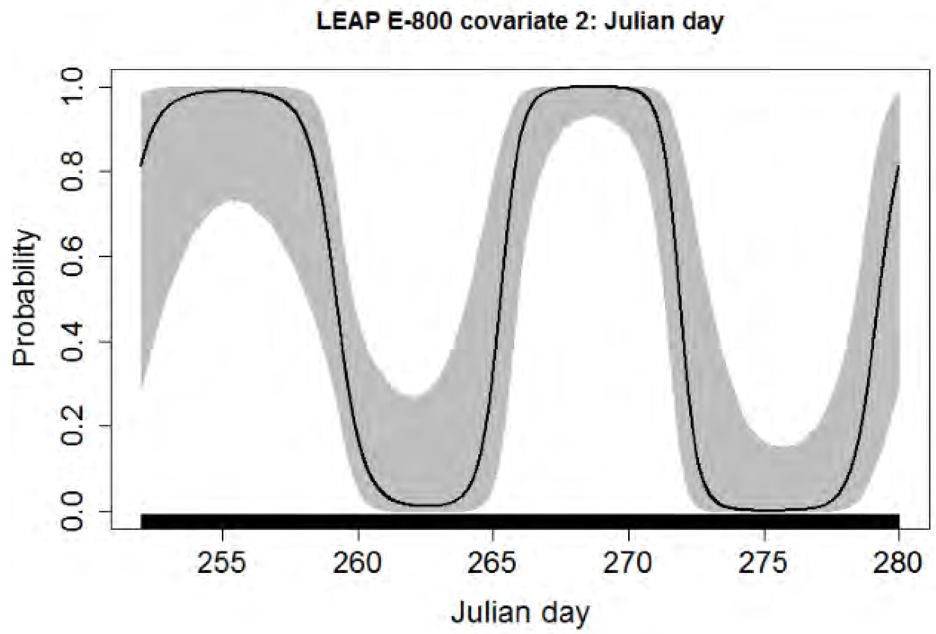
Results of Wald's tests for all significant covariates for the final model:

Covariates (in descending order of significance)	Form	Degrees of Freedom	χ^2 score	P-value
HOUR	Cyclic spline	4	31.865	$2.039 \cdot 10^{-6}$
JULDAY	Cubic B-spline	4	11.591	0.02067

Model: E-800 (B)



LEAP E-800 covariate 1: Diel Hour
Probability
0.0
0.2
0.4
0.6
0.8
1.0
0
5
10
15
20
Diel Hour



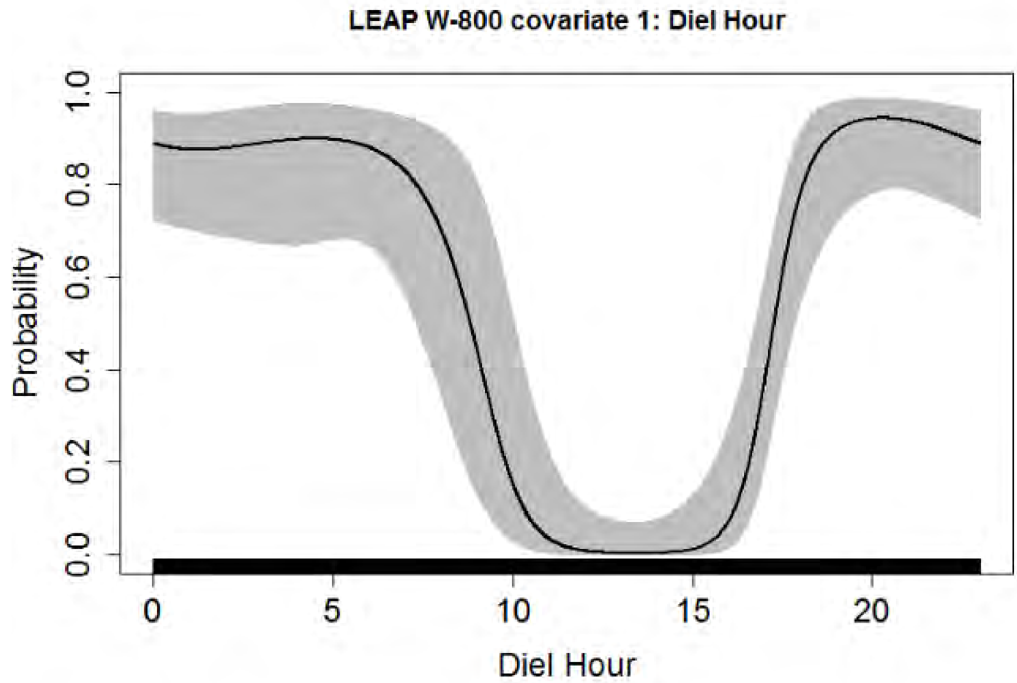
LEAP E-800 covariate 2: Julian day
Probability
0.0
0.2
0.4
0.6
0.8
1.0
255
260
265
270
275
280
Julian day

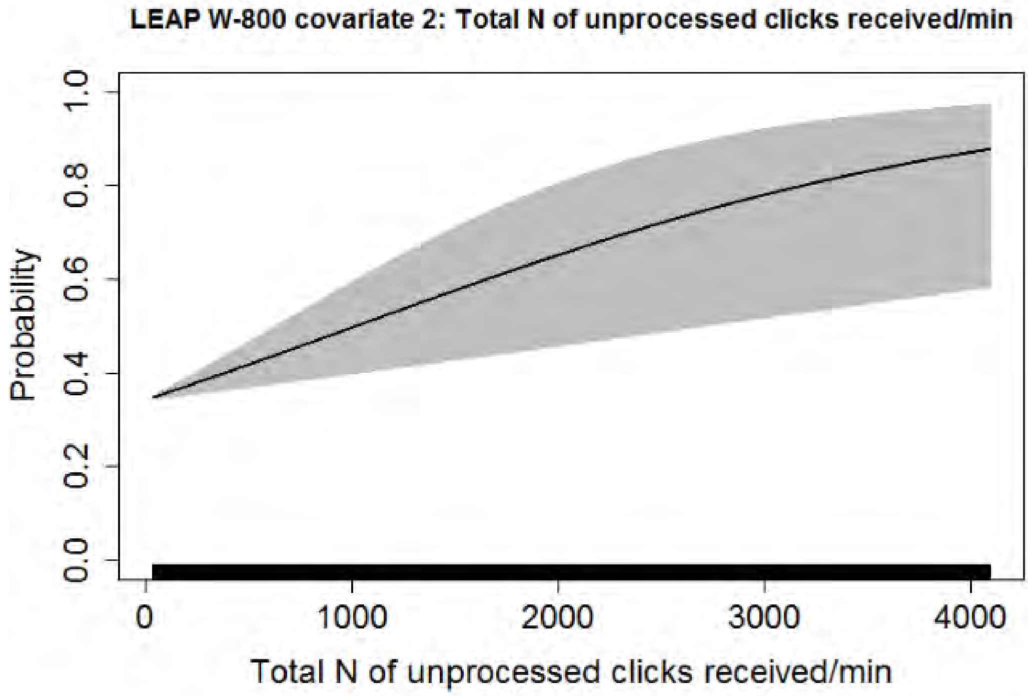
Model:	W-800 (B)			
Model structure:	POD5<-geeglm(PPM ~ AvgHrBasisMat + Nall_m + as.factor(Signal_Type), family = binomial, corstr="independence", id=Panel, data=W800)			
Confusion matrix:	(see below)			

		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 spline	4	16.0326	0.002976
Nall_m	linear	1	9.9207	0.001634

Model: W-800 (B)


LEAP W-800 covariate 1: Diel Hour
Probability
0.0
0.2
0.4
0.6
0.8
1.0
0
5
10
15
20
Diel Hour


LEAP W-800 covariate 2: Total N of unprocessed clicks received/min
Probability
0.0
0.2
0.4
0.6
0.8
1.0
0
1000
2000
3000
4000
Total N of unprocessed clicks received/min

Model:	E-1000 (B)
Model structure:	POD4<-geeglm(PPM ~ AvgHrBasisMat + as.factor(Signal_Type)+ TideBasisMat + SprNpBasisMat, family = binomial, corstr="independence", id=Panel, data=E1000)
Confusion matrix:	
AUC value:	0.8554172

Confusion matrix:

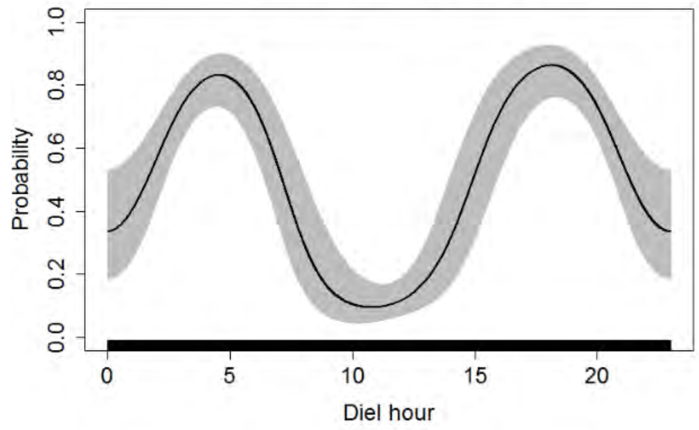
		Expected	
		Porpoise	No porpoise
Observed	Porpoise	83.7%	26.7%
	No porpoise	16.3%	73.3%

Results of Wald's tests for all significant covariates for the final model:

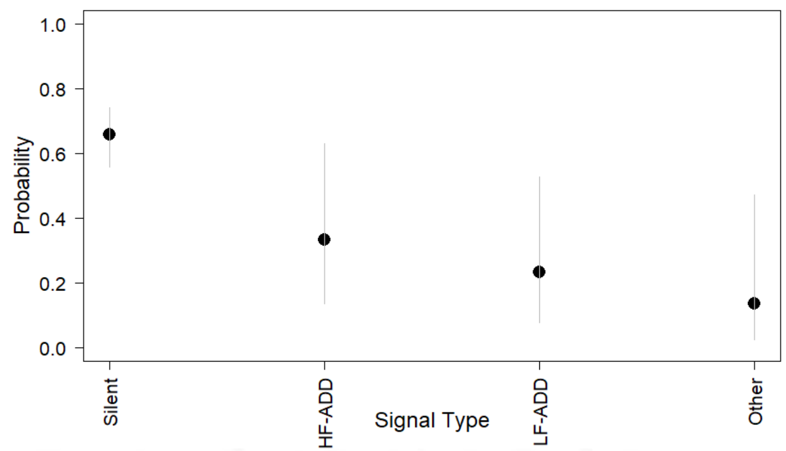
Covariates (in descending order of significance)	Form	Degrees of Freedom	χ^2 score	P-value
HOUR	Cyclic spline	4	76.904	$7.772 \cdot 10^{-16}$
Signal_Type	Factor	1	25.397	$1.276 \cdot 10^{-5}$
HiLoTide	Cyclic spline	4	16.484	0.002434
SpringNeap	Cyclic spline	4	14.722	0.005313

Model: E-1000 (B)

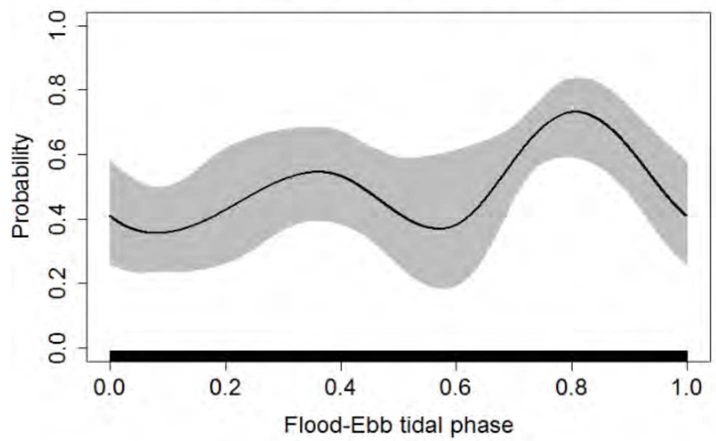
LEAP E-1000 covariate 1: Diel Hour



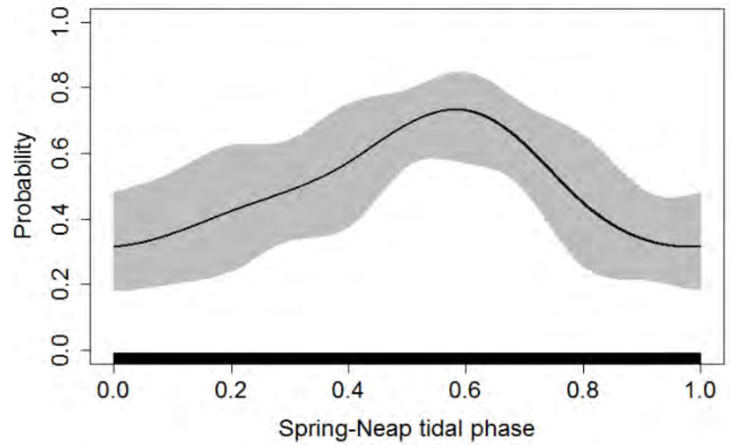
LEAP E-1000 covariate 2: Experimental signal output



LEAP E-1000 covariate 3: Flood-Ebb tidal phase



LEAP E-1000 covariate 4: Spring-Neap tidal phase



Model:	C-1000 (B)
Model structure:	POD5<-geeglm(PPM ~ AvgHrBasisMat + SprNpBasisMat + TideBasisMat, family = binomial, corstr="independence", id=Panel, data=C1000)

Confusion matrix:

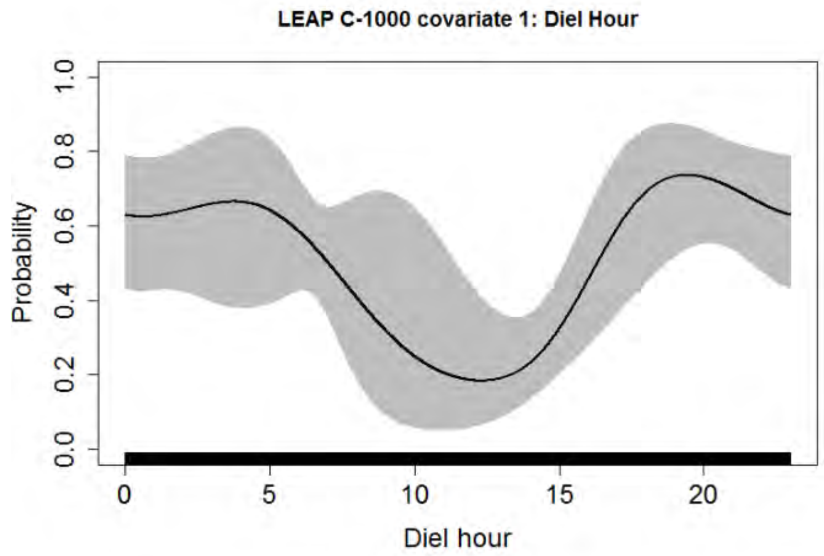
		Expected	
		Porpoise	No porpoise
Observed	Porpoise	73.0%	27.9%
	No porpoise	27.0%	72.1%

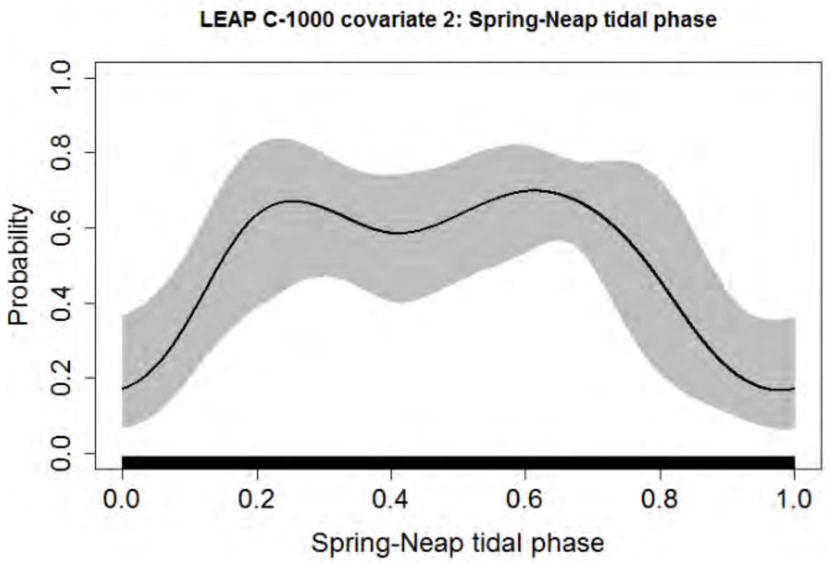
AUC value: 0.7798787

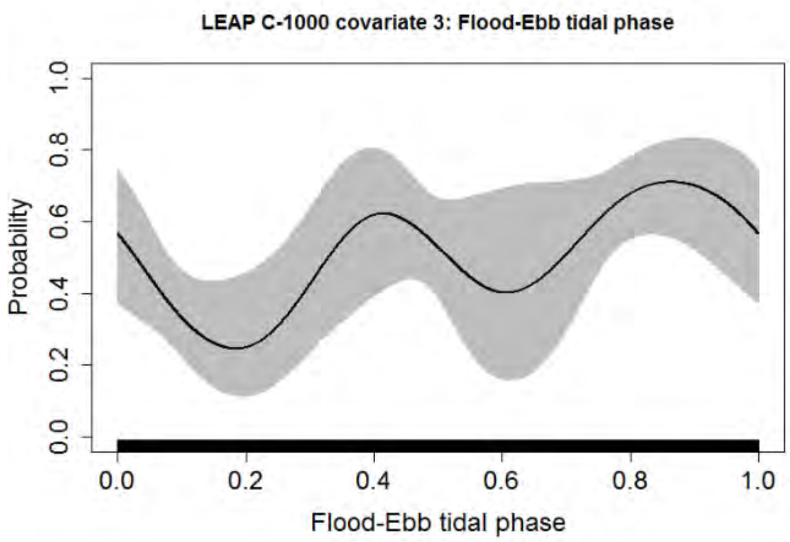
Results of Wald's tests for all significant covariates for the final model:

Covariates (in descending order of significance)	Form	Degrees of Freedom	χ^2 score	P-value
HOUR	Cyclic spline	4	19.7491	0.0005597
SpringNeap	Cyclic spline	4	18.3390	0.0010594
HiLoTide	Cyclic spline	4	9.9507	0.0412661

Model: C-1000 (B)

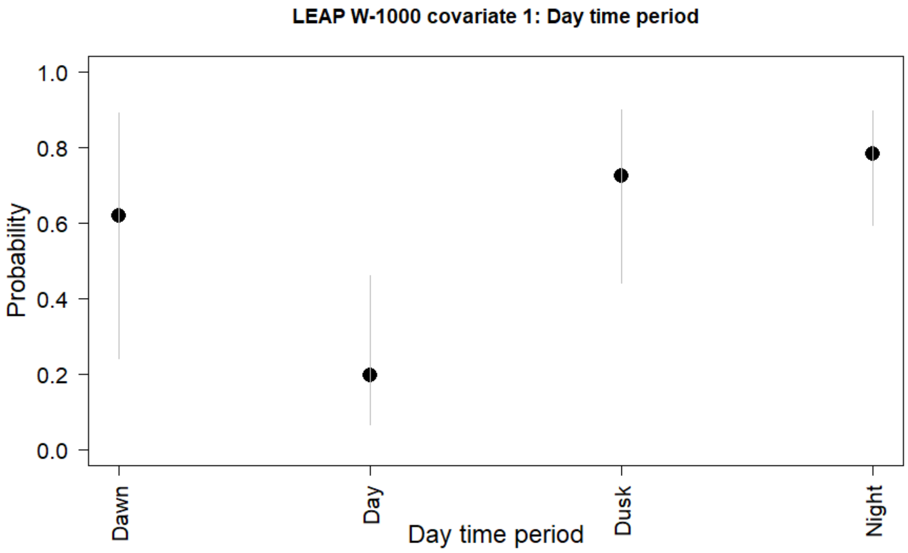


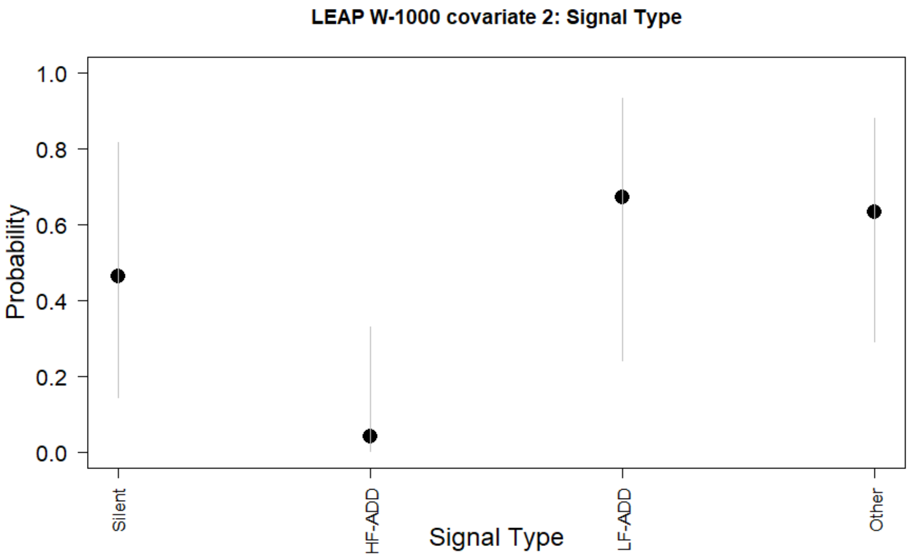


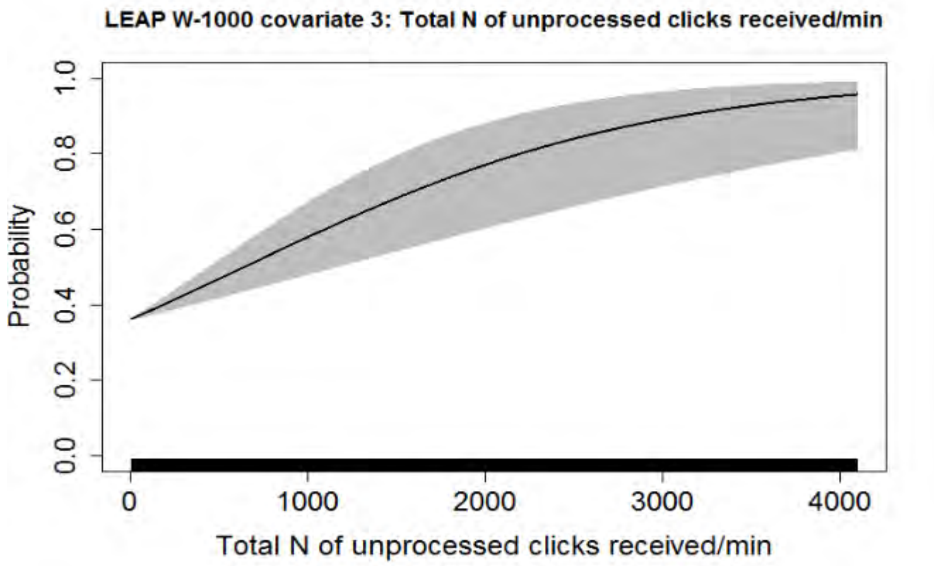


Model:	W-1000 (B)			
Model structure:	POD5<-geeglm(PPM ~ as.factor(DAYTIMENum) + as.factor(Signal_Type) + Nall_m, family = binomial, corstr="independence", id=Panel, data=W1000)			
Confusion matrix:			Expected	
			Porpoise	No porpoise
	Observed	Porpoise	87.8%	37.7%
		No porpoise	12.2%	62.3%
AUC value:	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	$6.547 \cdot 10^{-6}$

Model: W-1000 (B)

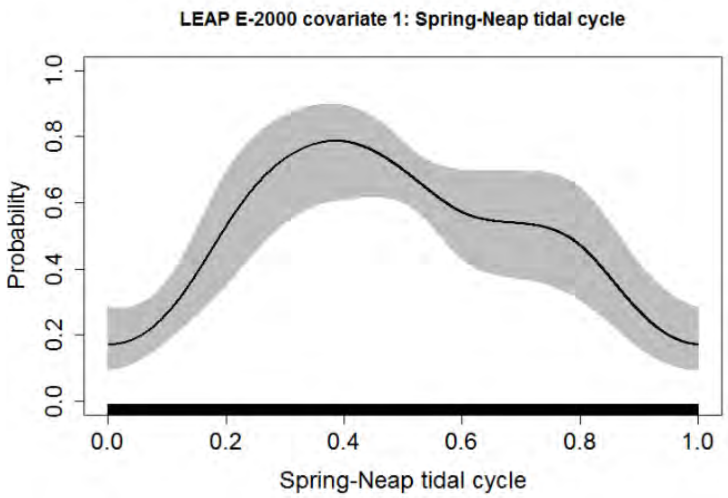


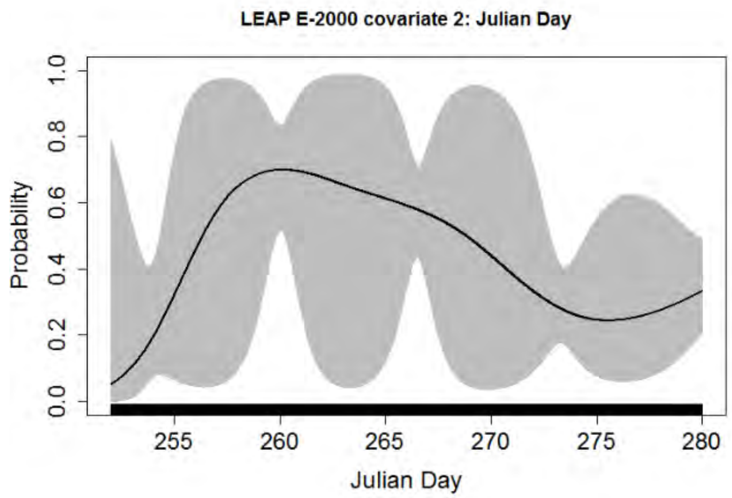


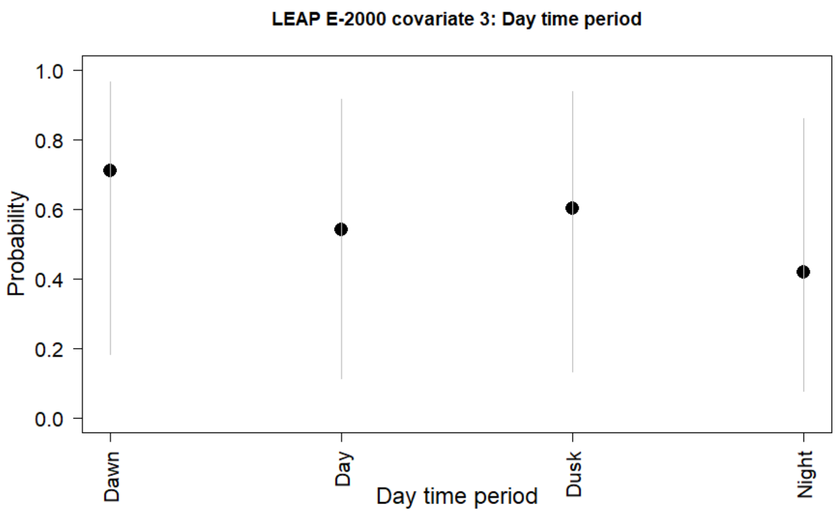


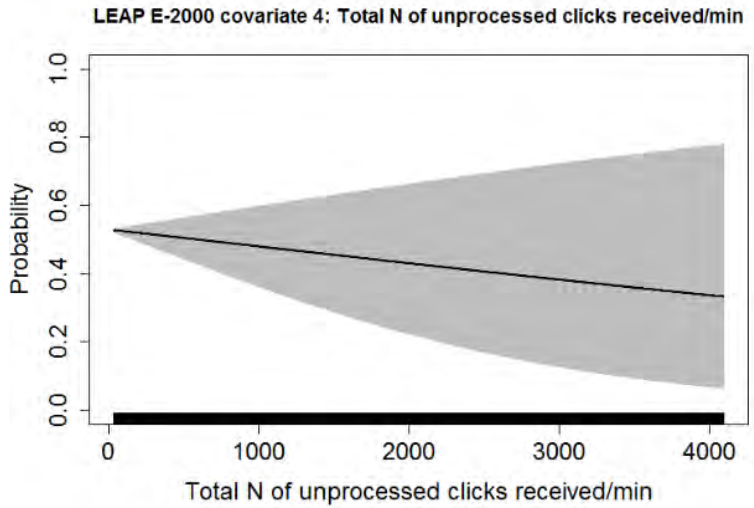
<table>
<tr><td>Model:</td><td colspan="4">E-2000 (B)</td></tr>
<tr><td>Model structure:</td><td colspan="4">POD5<-geeglm(PPM ~ SprNpBasisMat + bs(JULDAY, knots=mean(JULDAY)) + as.factor(DAYTIMENum) + bs(Nall_m, knots=mean(Nall_m)), family = binomial, corstr="independence", id=Panel, data=E2000)</td></tr>
<tr><td>Confusion matrix:</td><td colspan="4"><table>
<tr><td></td><td></td><td colspan="2">Expected</td></tr>
<tr><td></td><td></td><td>Porpoise</td><td>No porpoise</td></tr>
<tr><td rowspan="2">Observed</td><td>Porpoise</td><td>75.5%</td><td>32.1%</td></tr>
<tr><td>No porpoise</td><td>24.5%</td><td>67.9%</td></tr>
</table></td></tr>
<tr><td>AUC value:</td><td colspan="4">0.7766977</td></tr>
<tr><td colspan="5">Results of Wald's tests for all significant covariates for the final model:</td></tr>
<tr><td>Covariates (in descending order of significance)</td><td>Form</td><td>Degrees of Freedom</td><td>χ^2 score</td><td>P-value</td></tr>
<tr><td>SpringNeap</td><td>Cyclic spline</td><td>4</td><td>37.671</td><td>$1.310 \cdot 10^{-7}$</td></tr>
<tr><td>JULDAY</td><td>Cubic B-spline</td><td>4</td><td>18.033</td><td>0.001216</td></tr>
<tr><td>DAYTIMENum</td><td>Factor</td><td>3</td><td>14.029</td><td>0.002866</td></tr>
<tr><td>Nall_m</td><td>Cubic B-spline</td><td>4</td><td>32.284</td><td>$1.674 \cdot 10^{-6}$</td></tr>
</table>

Model: E-2000 (B)









Model:	C-2000 (B)
Model structure:	POD5<-geeglm(PPM ~ bs(Nall_m, knots=mean(Nall_m)) + as.factor(DAYTIMENum) + AvgHrBasisMat + SprNpBasisMat, family = binomial, corstr="independence", id=Panel, data=C2000)

Confusion matrix:

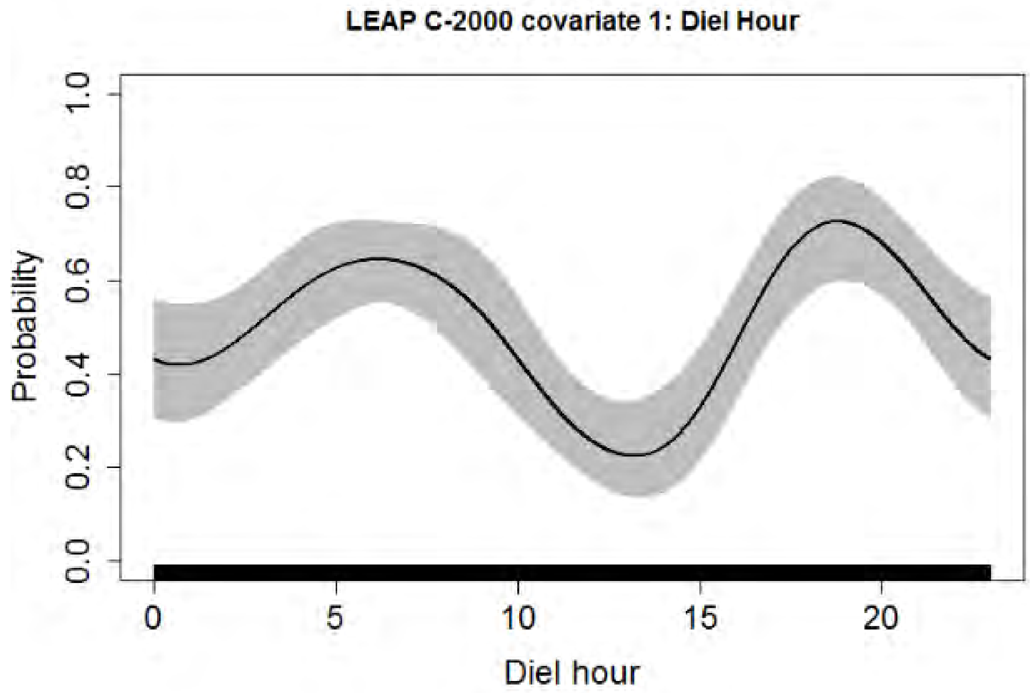
		Expected	
		Porpoise	No porpoise
Observed	Porpoise	74.9%	32.2%
	No porpoise	25.1%	67.8%

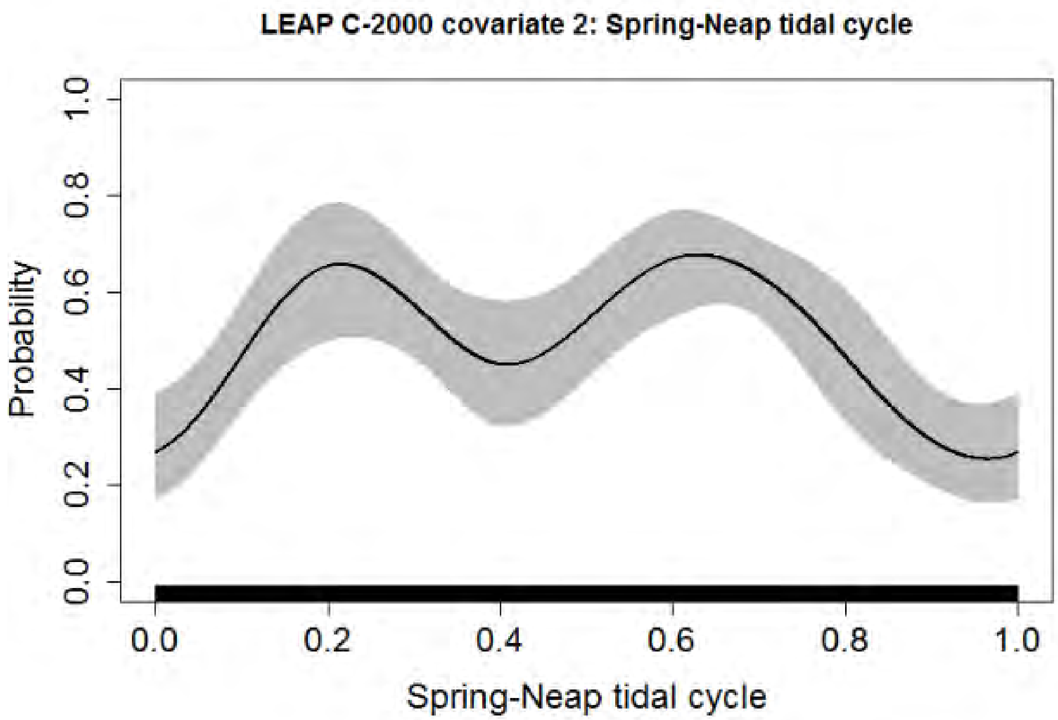
AUC value:	0.7749851

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 spline	4	22.842	0.0001362
SpringNeap	Cyclic spline	4	19.751	0.0005593

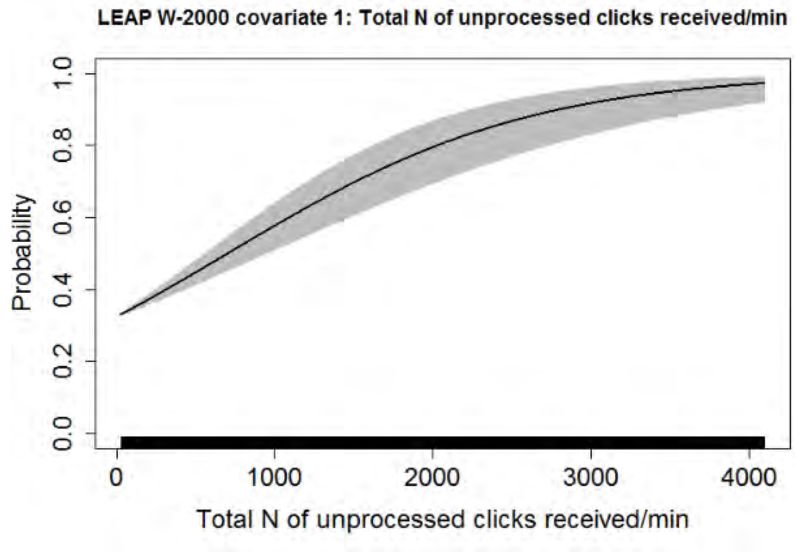
Model: C-2000 (B)

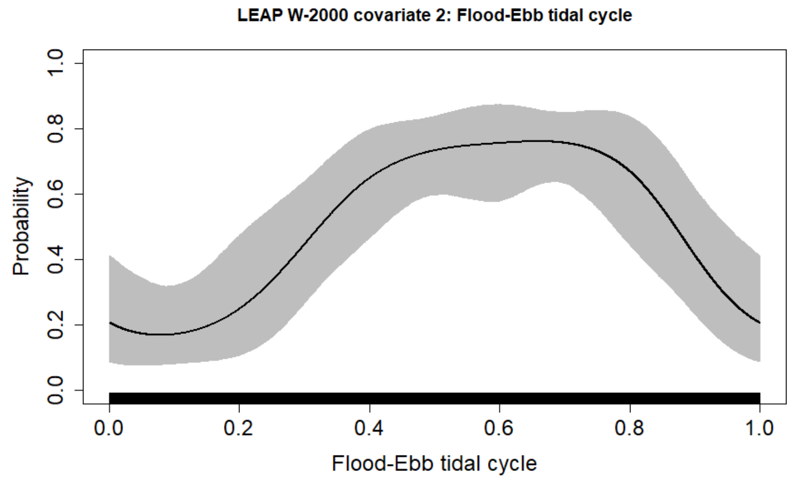


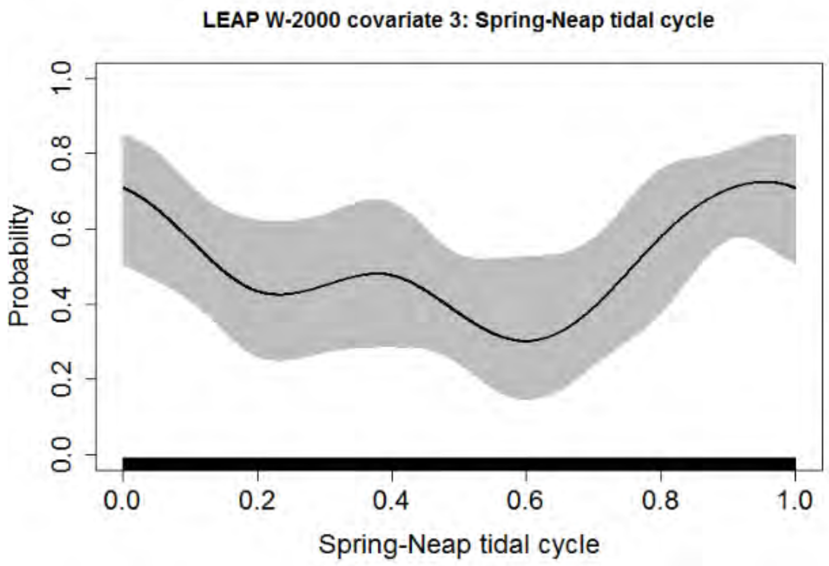


Model:	W-2000 (B)			
Model structure:	POD5<-geeglm(PPM ~ Nall_m + TideBasisMat + SprNpBasisMat, family = binomial, corstr="independence", id=Panel, data=W2000)			
Confusion matrix:			Expected	
			Porpoise	No porpoise
	Observed	Porpoise	88.5%	46.9%
		No porpoise	11.5%	53.1%
AUC value:	0.7838515			
Results 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	$<2.2\cdot10^{-16}$
HiLoTide	Cyclic spline	4	22.245	0.0001791
SpringNeap	Cyclic spline	4	10.022	0.0400520

Model: W-2000 (B)







Model:	C-5000 (B)
Model structure:	POD5<-geeglm(PPM ~ SprNpBasisMat + bs(JULDAY, knots=mean(JULDAY)) + Nall_m + as.factor(DAYTIMENum) + AvgHrBasisMat, family = binomial, corstr="independence", id=Panel, data=C5000)

Confusion matrix:

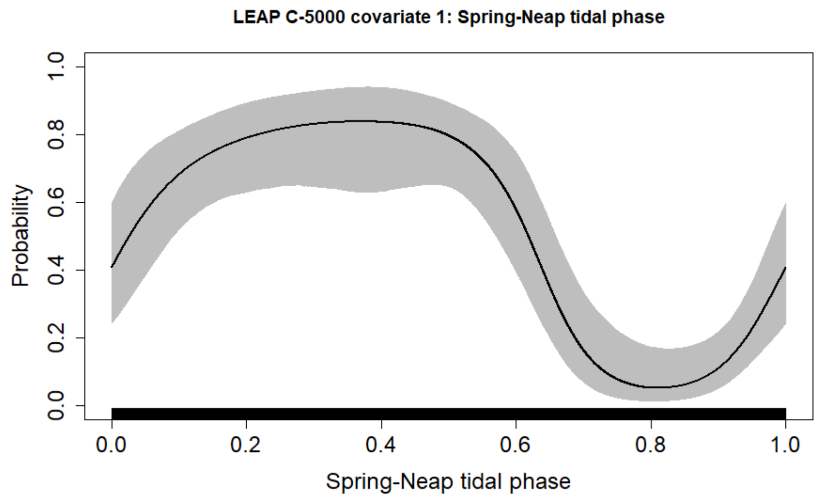
		Expected	
		Porpoise	No porpoise
Observed	Porpoise	80.1%	15.5%
	No porpoise	19.9%	84.5%

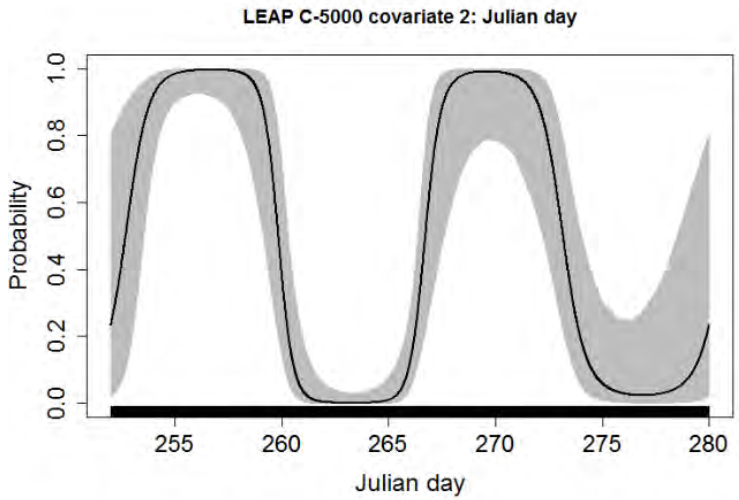
AUC value:	0.8861703

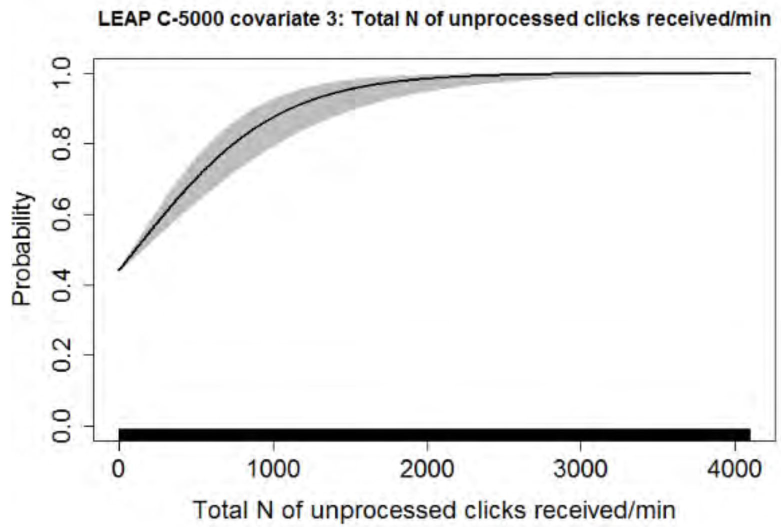
Results of Wald's tests for all significant covariates for the final model:

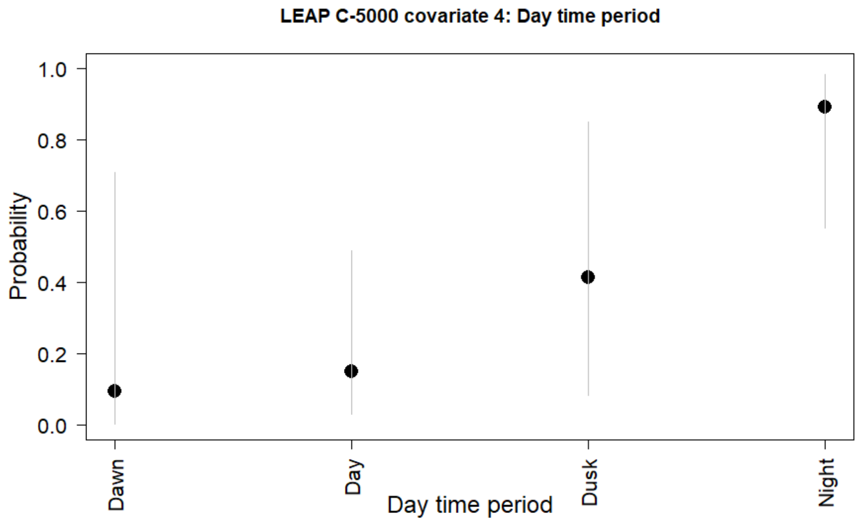
Covariates (in descending order of significance)	Form	Degrees of Freedom	χ^2 score	P-value
SpringNeap	Cyclic spline	4	14.806	0.005121
JULDAY	Cubic B-spline	4	15.829	0.003036
Nall_m	Linear	1	49.829	$1.678 \cdot 10^{-12}$
DAYTIMENum	Factor	3	40.503	$8.335 \cdot 10^{-9}$
HOUR	Cyclic spline	4	12.875	$3.291 \cdot 10^{-8}$

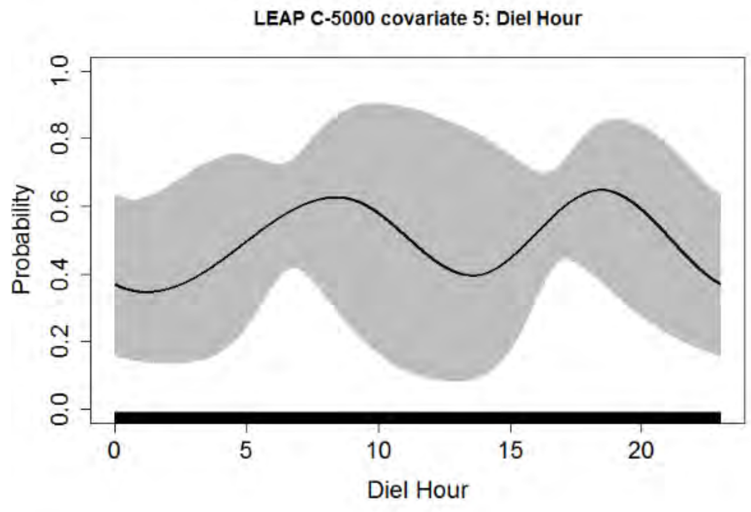
Model: C-5000 (B)










LEAP C-5000 covariate 5: Diel Hour
Probability
0.0
0.2
0.4
0.6
0.8
1.0
0
5
10
15
20
Diel Hour

Model:	W-5000 (B)			
Model structure:	POD5<-geeglm(PPM ~ Nall_m + JULDAY + AvgHrBasisMat + TideBasisMat, family = binomial, corstr="independence", id=Panel, data=W5000)			
Confusion matrix:			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 spline	4	16.7938	0.00212
HiLoTide	Cyclic spline	4	9.6231	0.04728

Model: W-5000 (B)