Scottish Natural Heritage
Dualchas Nàdair na h-Alba
nature.scot

[redacted]

By email: [redacted]

Our Ref: SIR154980/A2934772 2 May 2019

Dear [redacted]

Information Request – SARF Low-frequency ADD Report

Thank you for your information request, which we received on 3 April. We have considered your request under the Environmental Information (Scotland) Regulations 2004 ('the EIRs').

Your Request

> "Please provide information on SARF112 – Influences of lower-frequency Acoustic Deterrent Devices (ADDs) on cetaceans in Scottish coastal waters.
>
> Please include any discussions on the report - including drafts and the final version - via emails, letters and other information.
>
> Please include any information on the publication of the report including any delays."

Our Response

We have carried out a detailed search of the information we hold, and the attached documents contain all the relevant information we have.

We have marked out (redacted) some personal data in the documents. The redactions include information that would identify one of the report's peer reviewers. SARF peer reviews all its reports, and always keeps reviewer identities confidential to encourage frank expression which, ultimately, improves the quality of the final product.

Releasing the personal data into the public domain in response to an access to information request would breach the Data Protection Act 2018. We are therefore withholding the information under EIRs Regulation 11(2) (Personal data).

How We Handled Your Request

We believe you have asked for environmental information as defined in the Environmental Information (Scotland) Regulations 2004 ('the EIRs'), so we are dealing with your request under those regulations. To be able to use the EIRs, we must apply an exemption under section 39(2) of the Freedom of Information (Scotland) Act 2002 ('FOISA'). The Scottish Information Commissioner's guidance recommends that public authorities apply this exemption to environmental information and handle requests under the EIRs.

If you would like to find out more about the access to information legislation, there is a guidance booklet available on the Scottish Information Commissioner's website:

http://www.itspublicknowledge.info/nmsruntime/saveasdialog.aspx?lID=5487&sID=5024.

Review and Appeal

I hope this information meets your requirements but if you are dissatisfied with how we have responded to your information request, please write to us within 40 working days explaining your concerns. You can contact us at Battleby, Redgorton, Perth, PH1 3EW or email us at FOI@nature.scot. We will carry out a review of our response and contact you with our findings within 20 working days.

If you are not satisfied following this, you can make an appeal to the Scottish Information Commissioner. The Scottish Information Commissioner can be contacted at:

Scottish Information Commissioner
Kinburn Castle
Doubledykes Road
St Andrews
Fife
KY16 9DS

Online appeal service: www.itspublicknowledge.info/Appeal

Website: http://www.itspublicknowledge.info/

Telephone: 01334 464610

Yours sincerely

Rhoda Davidson

Rhoda Davidson
Information Officer
FOI@nature.scot

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
SARF Secretariat
PO Box 7223
Pitlochry

PH16 9AF

Tel: 01738 479486

Website:
www.sarf.org.uk

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*			

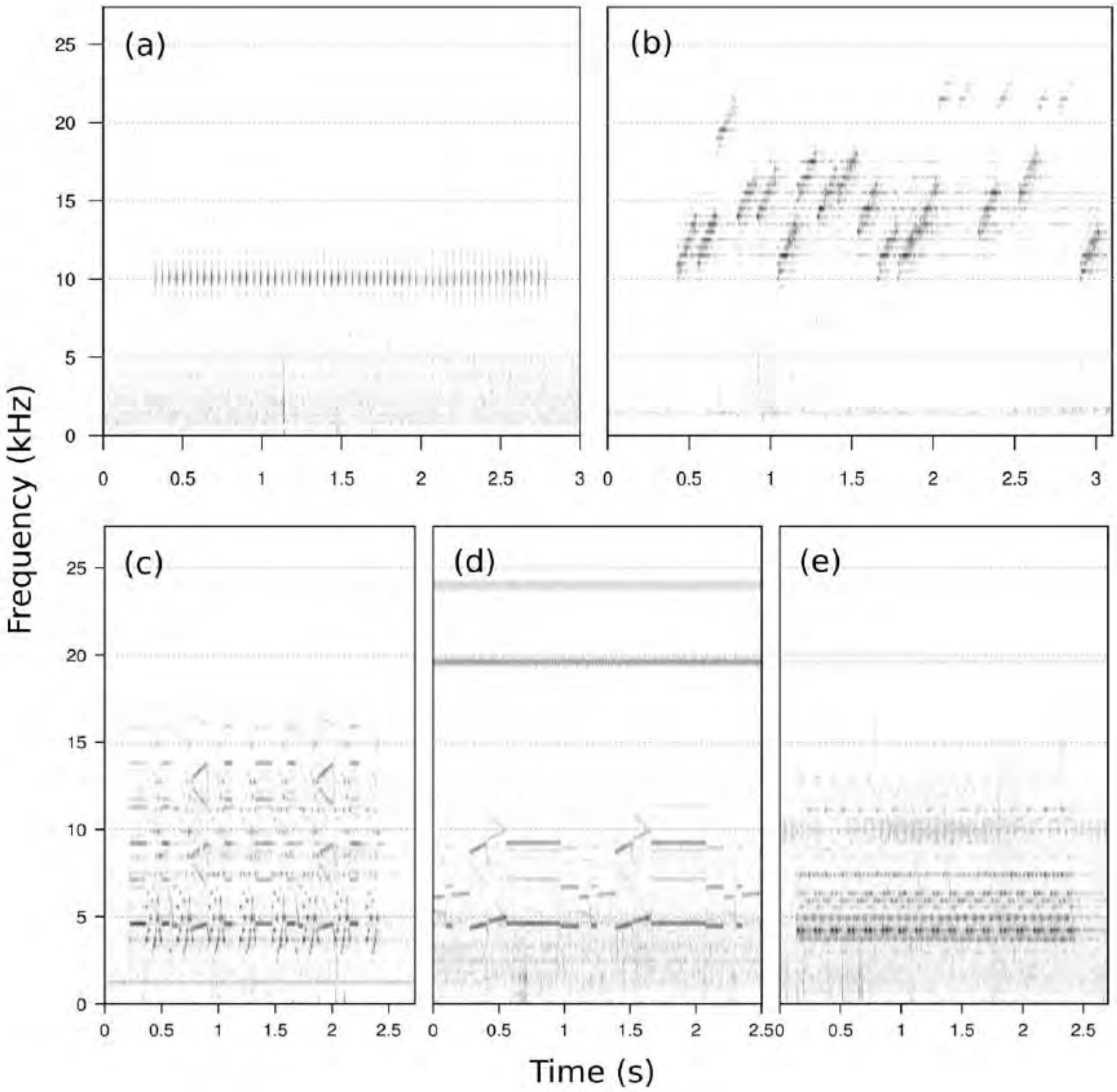


Figure 1. Examples of ADD spectrograms. Spectrogram parameters: FFT size = 1024 points, overlap = 50%, sample rate = 96 kHz; resulting in frequency and time resolution of 93.8 Hz and 10.67 ms, respectively. (a) Airmar™ (dB Plus II); (b) Ace Aquatec™ (US3); (c) Terecos™ (Type DSMS-4) Programme 4; (d) 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 $1\mu Pa^2s$ 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 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}. The closest observed approach in this study was at about 800 m (132 dB re 1μPa_{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 1μPa_{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 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).

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.

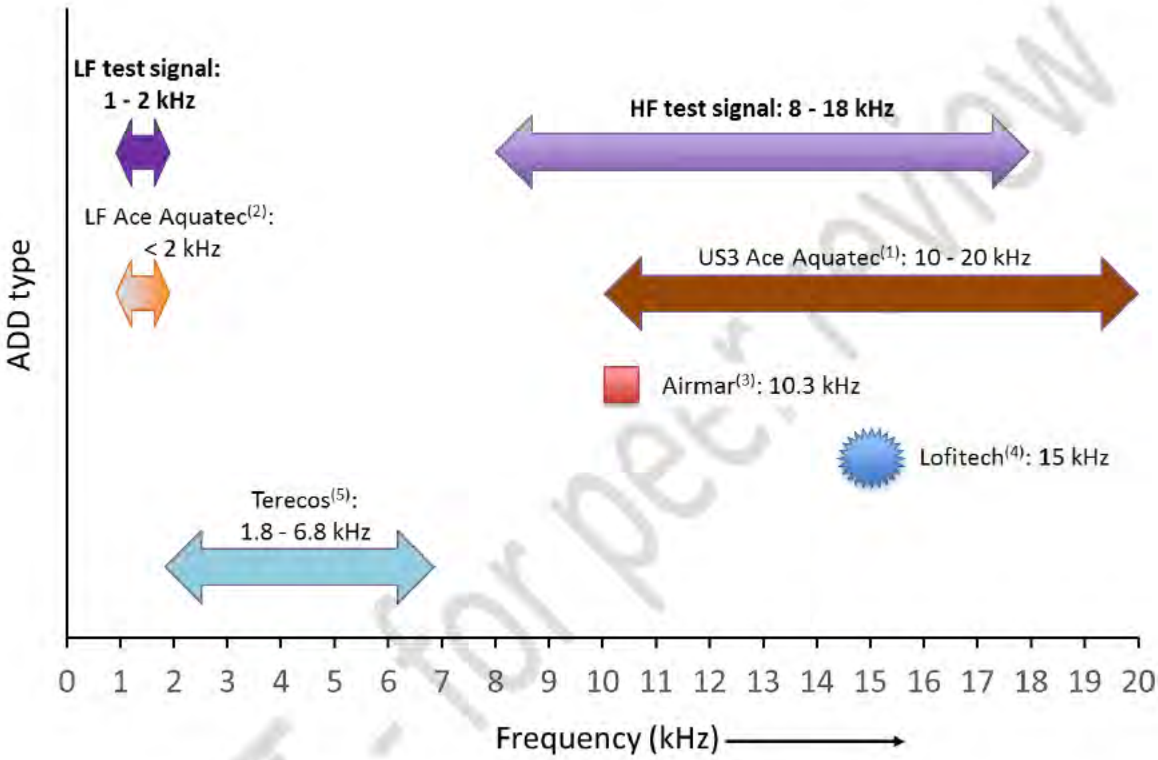


Figure 2. Output frequency ranges of the two test signals (LF and HF), compared to outputs from various existing ADD types (see Table 1 for details). Data on existing ADD outputs derived from 1) Ace Aquatec U3S manual (https://www.aceaquatec.com/us3specification); 2) Ace Aquatec pers. comm. (PL); 3)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

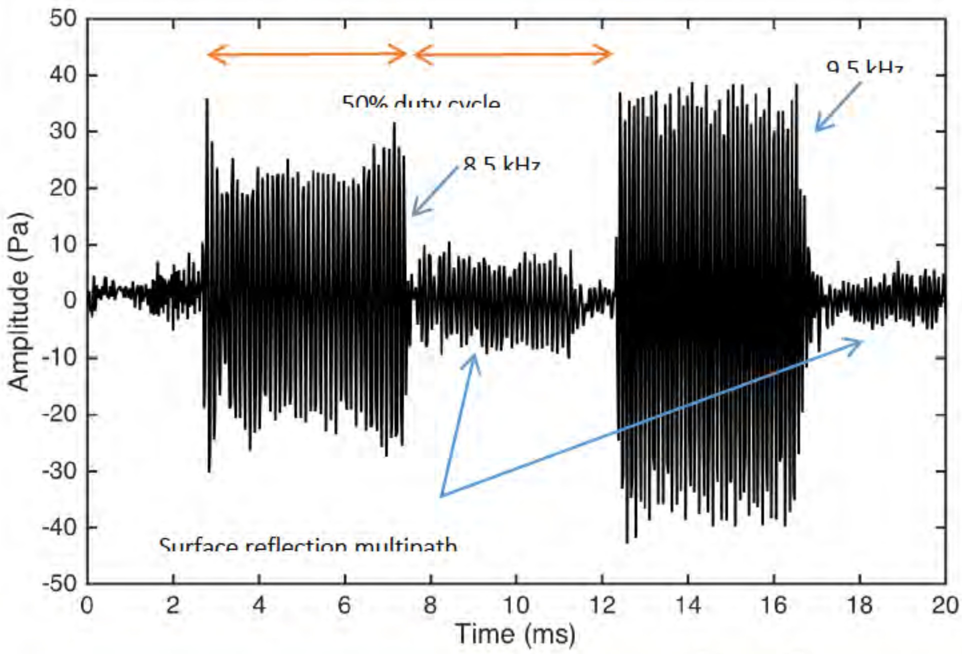


Figure 3. Time domain plot of two consecutive samples from the HF sequence – first pulse at 8.5 kHz and second at 9.5 kHz.

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

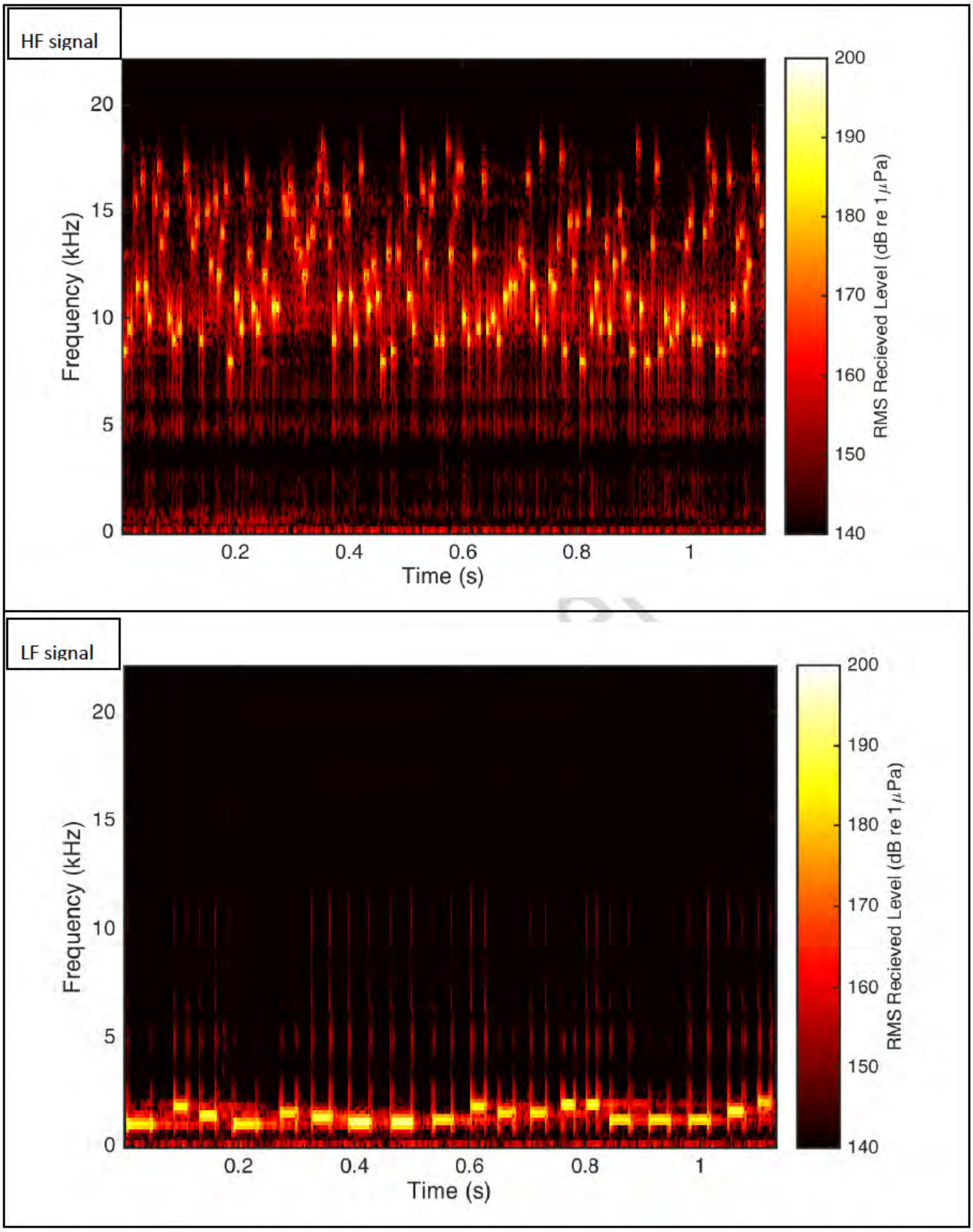


Figure 4. Spectral plot of a sample of the HF and LF signals received at a range of 8.5 m using a Reson 4014 balanced hydrophone. Analysis window was 256 FFT with 50 % overlap using a Hanning window. A 50 kHz low pass filter was applied. Original data were downsampled to a sample rate of 44.1 kHz.

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.

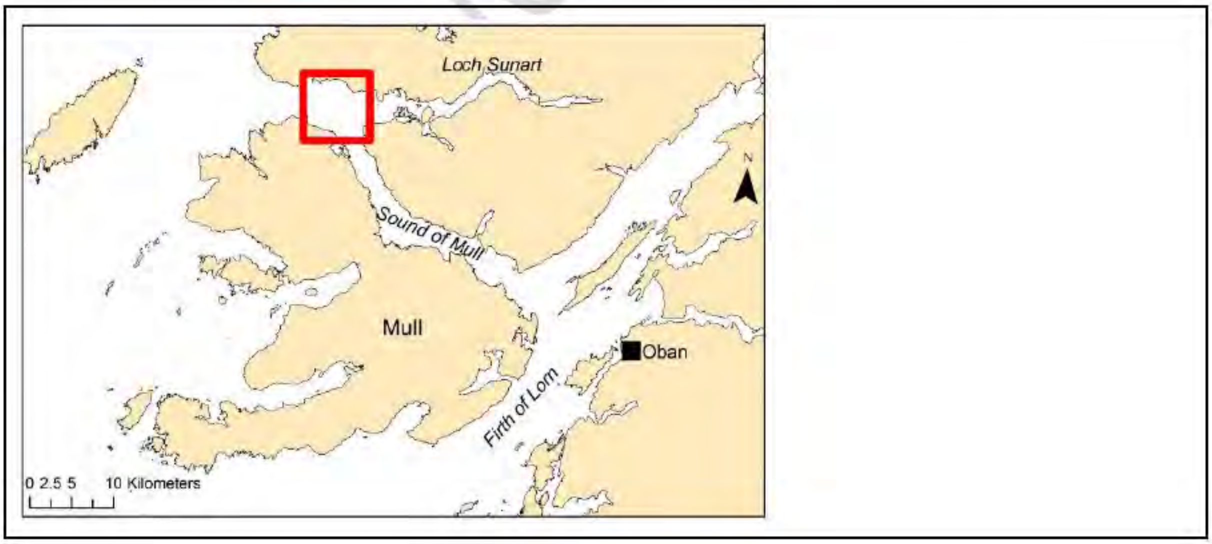
After several days of operation, it became apparent that the system drew more power when transmitting in Night mode than could be reliably replenished by the solar panels during the subsequent daytime, thus putting strain on the system's battery power supply. To preserve power throughout the experimental 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.



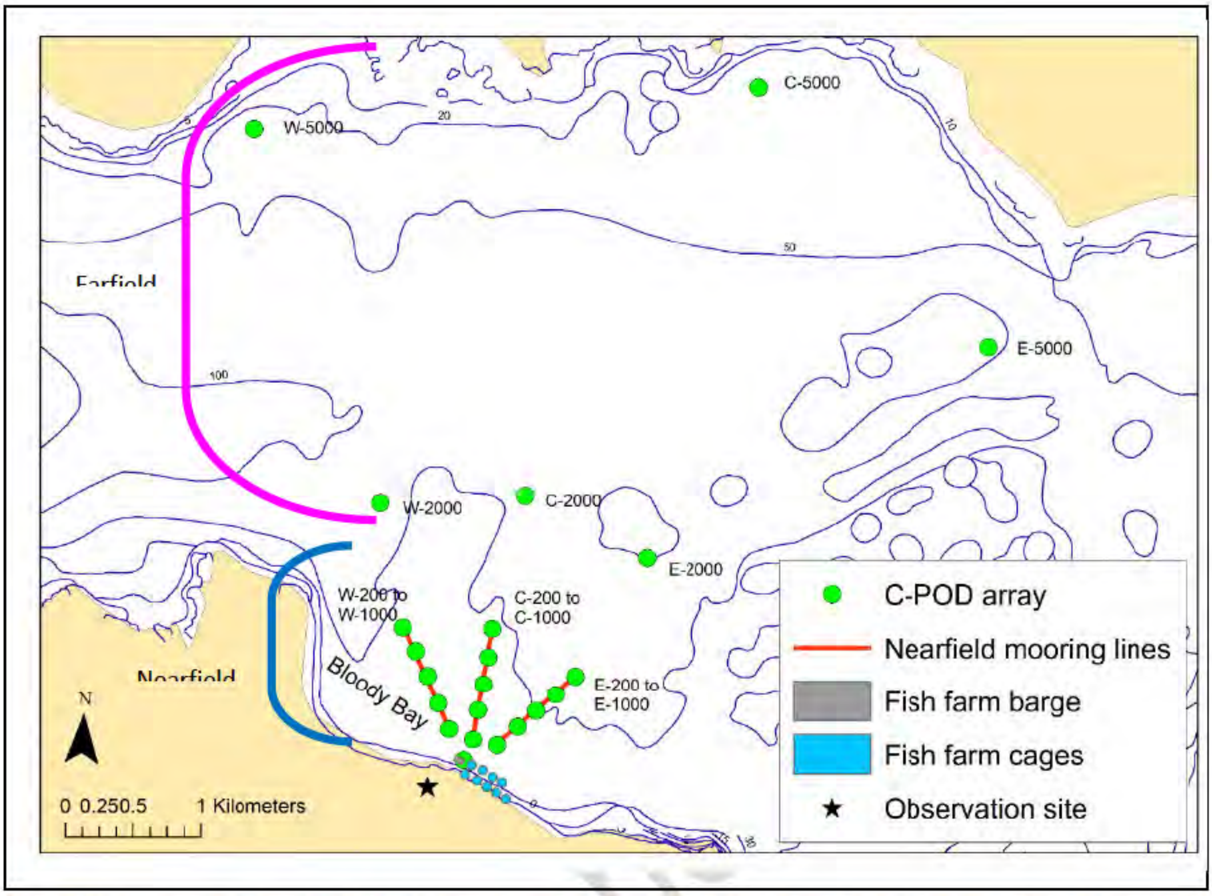


Figure 6. A) Overview of the Sound of Mull and adjacent areas. The Bloody Bay fieldwork site is indicated by the red box. B) Overview of LEAP passive acoustic mooring array in Bloody Bay and the northwestern Sound of Mull. Nearfield and Farfield components of the array are indicated. Note that the field 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.

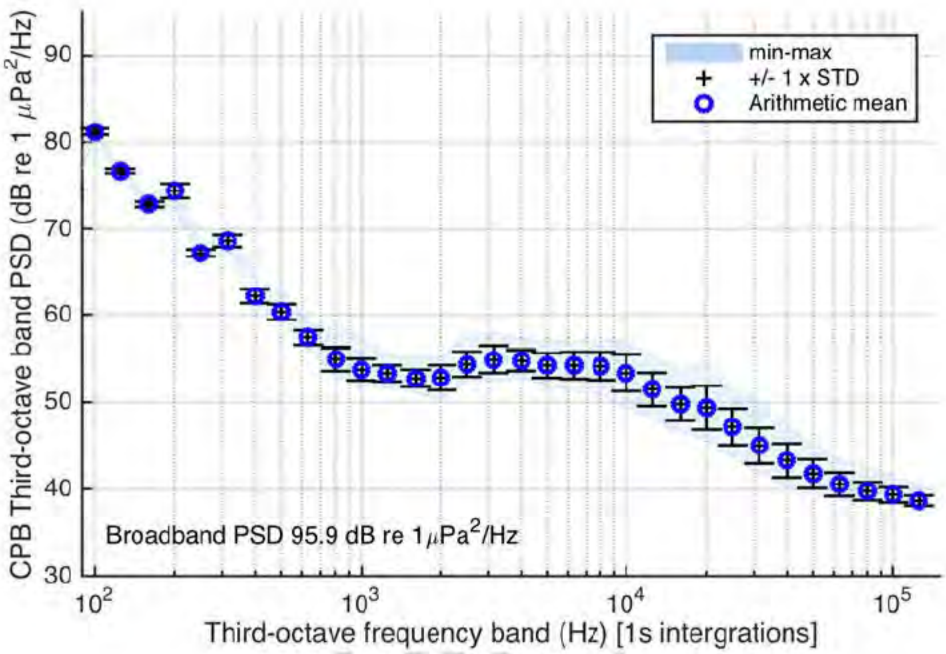


Figure 7. Power Spectral Density (PSD) in Third Octave Bands for a quiet period at 14:56 GMT on 11th October 2016. Total sample length 25 seconds, 1-second integration periods.

These levels are in line with similar sea-state noise levels at other sites with a broadband PSD of 95.9 dB re 1 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.

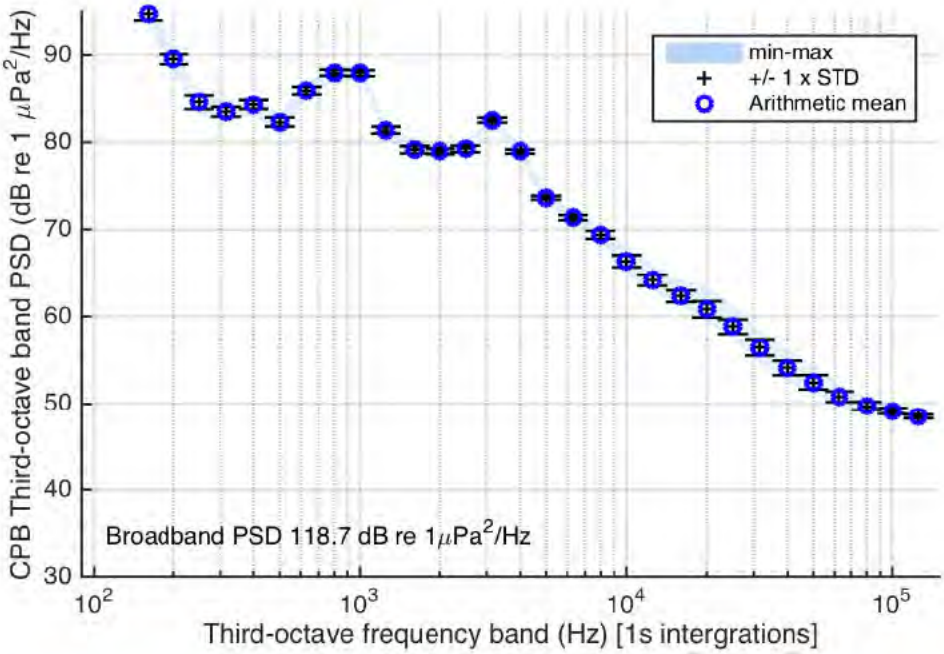


Figure 8. Power Spectral Density (PSD) in Third Octave Bands for low sea-state period at 15:01 GMT on 11th October 2016. Total sample length 25 seconds, 1-second integration periods. Likely contributions originated from specific barge or small boat operations.

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 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.

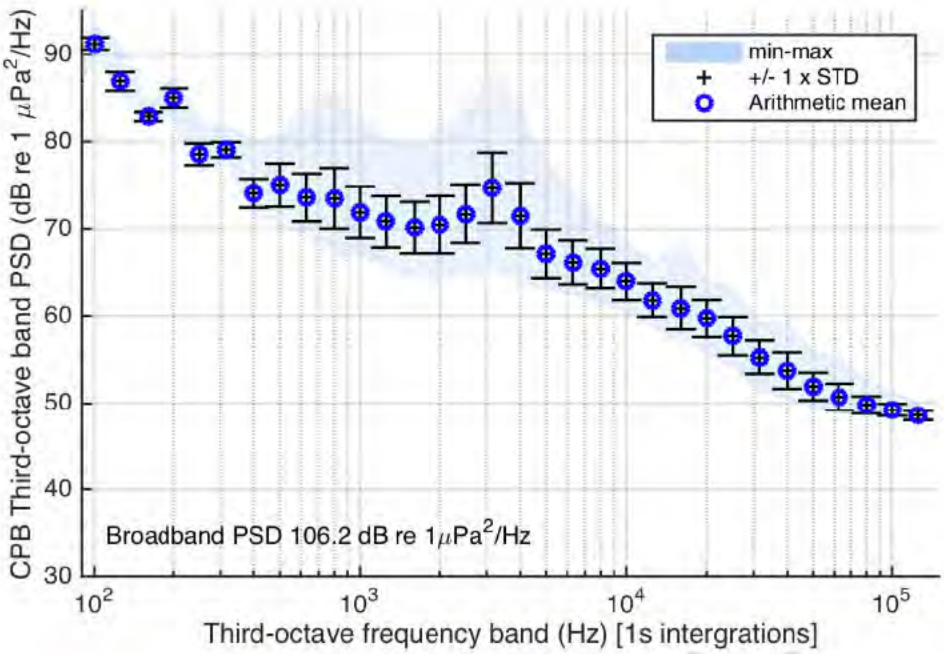


Figure 9. Power Spectral Density (PSD) in Third Octave Bands for low sea-state period. Consecutive 25s period from file started at 15:01 on 11th October 2016 compared to figure 9. Total sample length 25 seconds, 1-second integration periods. Transitory contributions from specific barge or small boat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

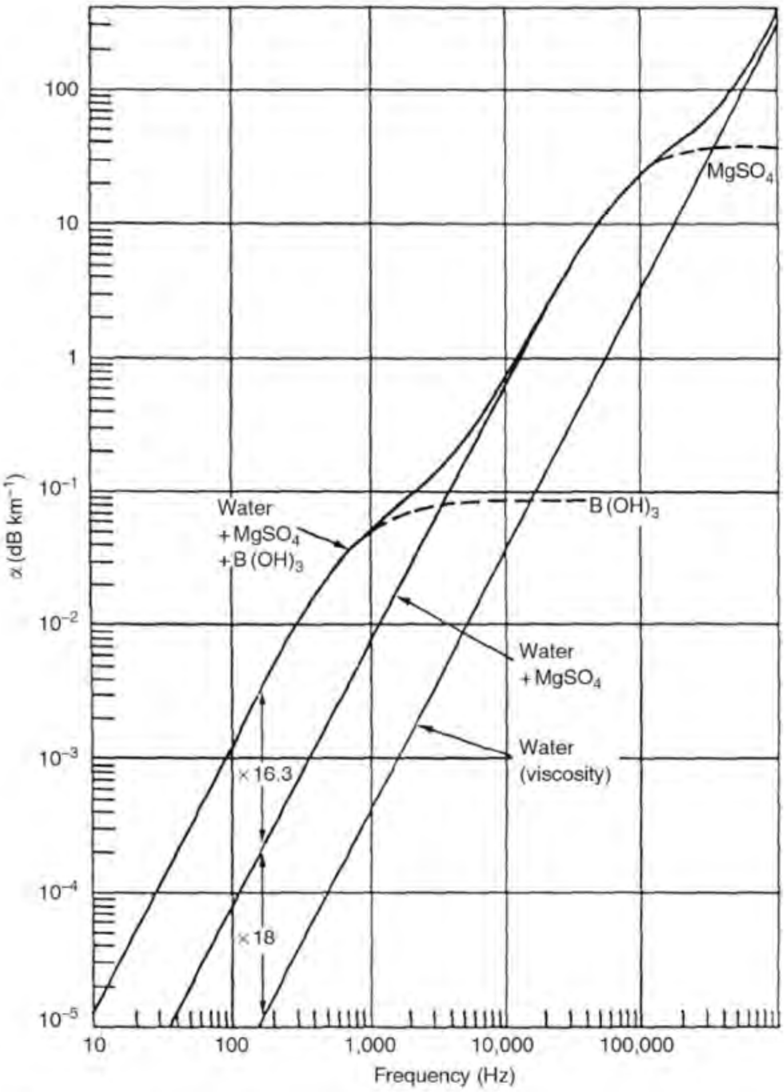


Figure 10. Underwater acoustic absorption versus frequency. Derived from Etter, 2003.

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.

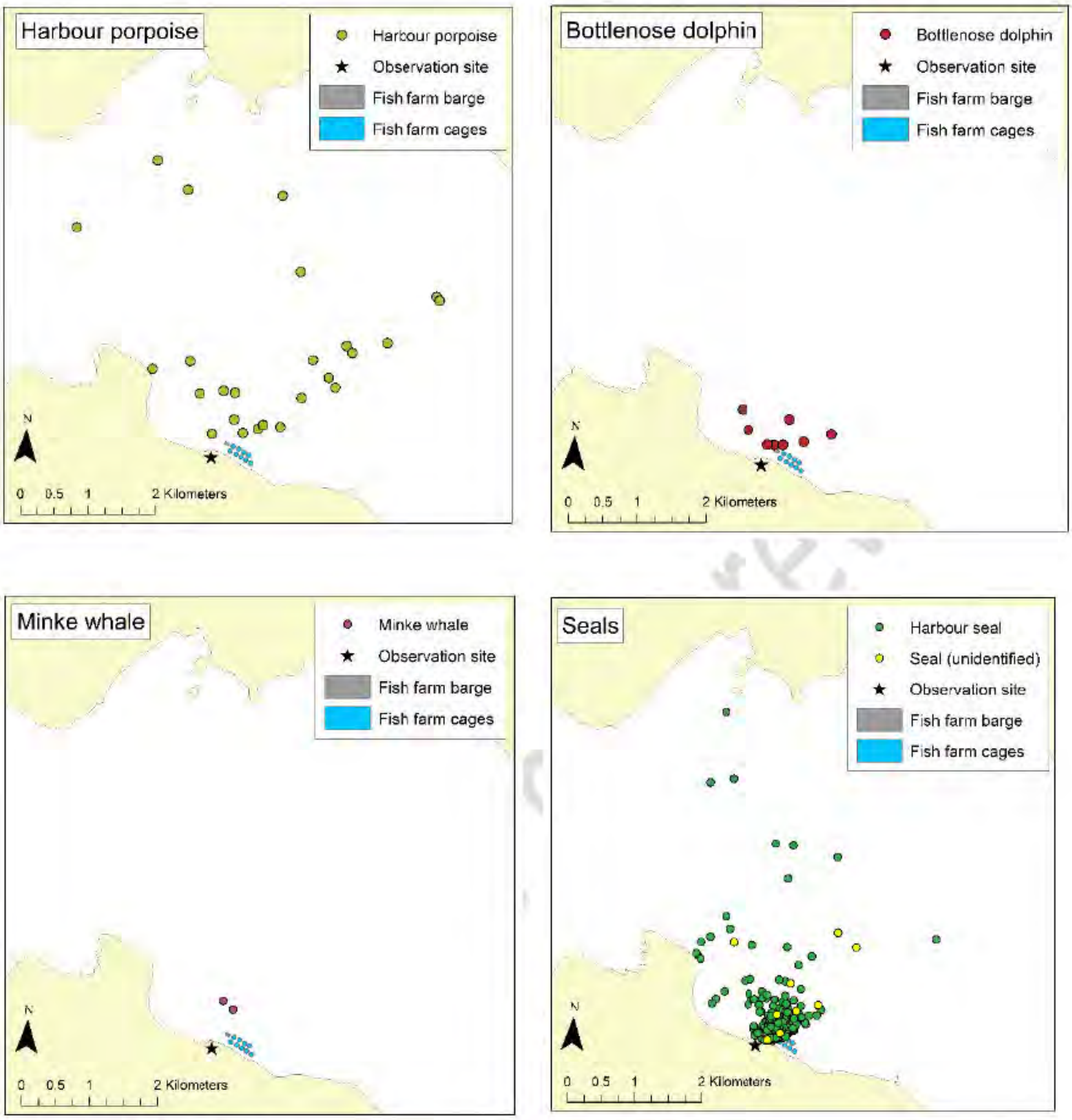


Figure 11. Approximate locations of sightings of different marine mammal species during the entire experimental period. Note that these positions are only approximations due to substantial variability in distance estimation among observers.

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.

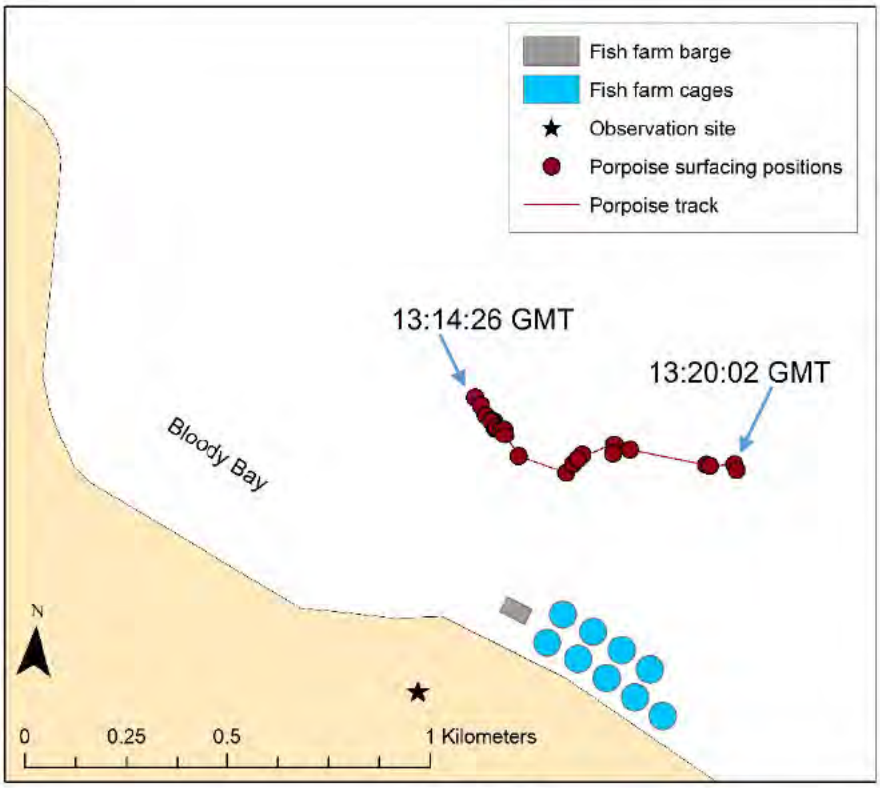


Figure 12. Example of tracked group of 3 porpoises observed on 14/09/2016, swimming from west to east.

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

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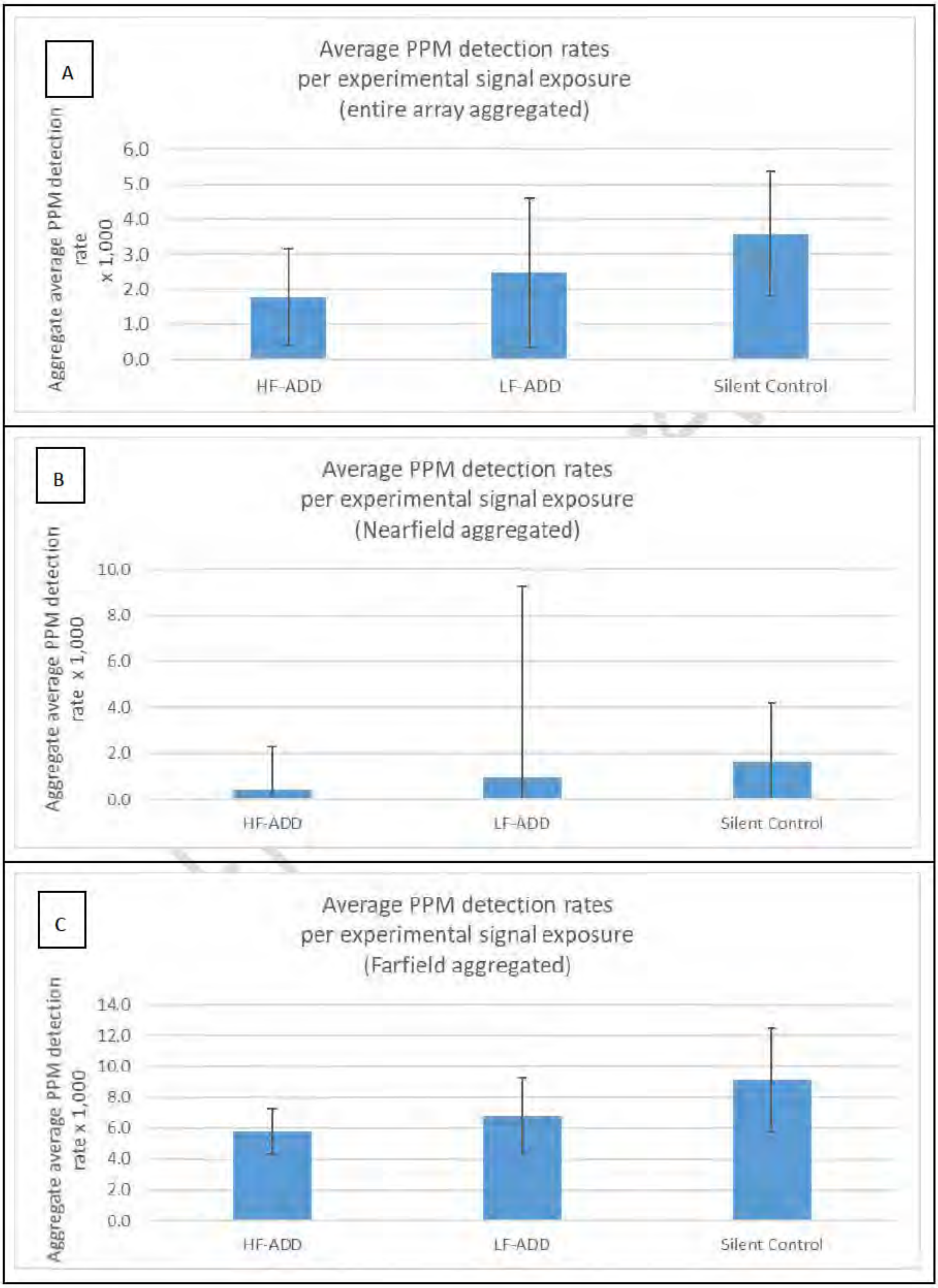
A
Average PPM detection rates
per experimental signal exposure
(entire array aggregated)
Aggregate average PPM detection rate x 1,000
6.0
5.0
4.0
3.0
2.0
1.0
0.0
HF-ADD
LF-ADD
Silent Control
B
Average PPM detection rates
per experimental signal exposure
(Nearfield aggregated)
Aggregate average PPM detection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

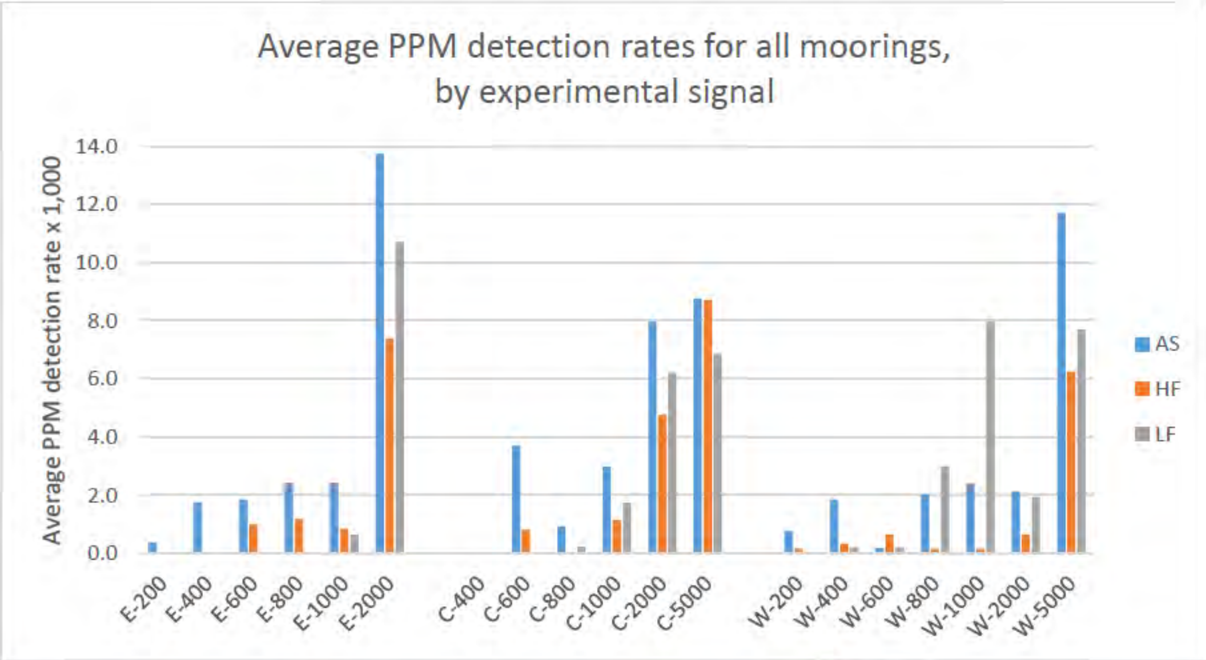

Figure 14. Average PPM detection rates (derived from Table 8, then multiplied by 1,000 for display purposes) across the experimental array under HF-signal, LF-signal, or Silent control (AS) control treatment.

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).

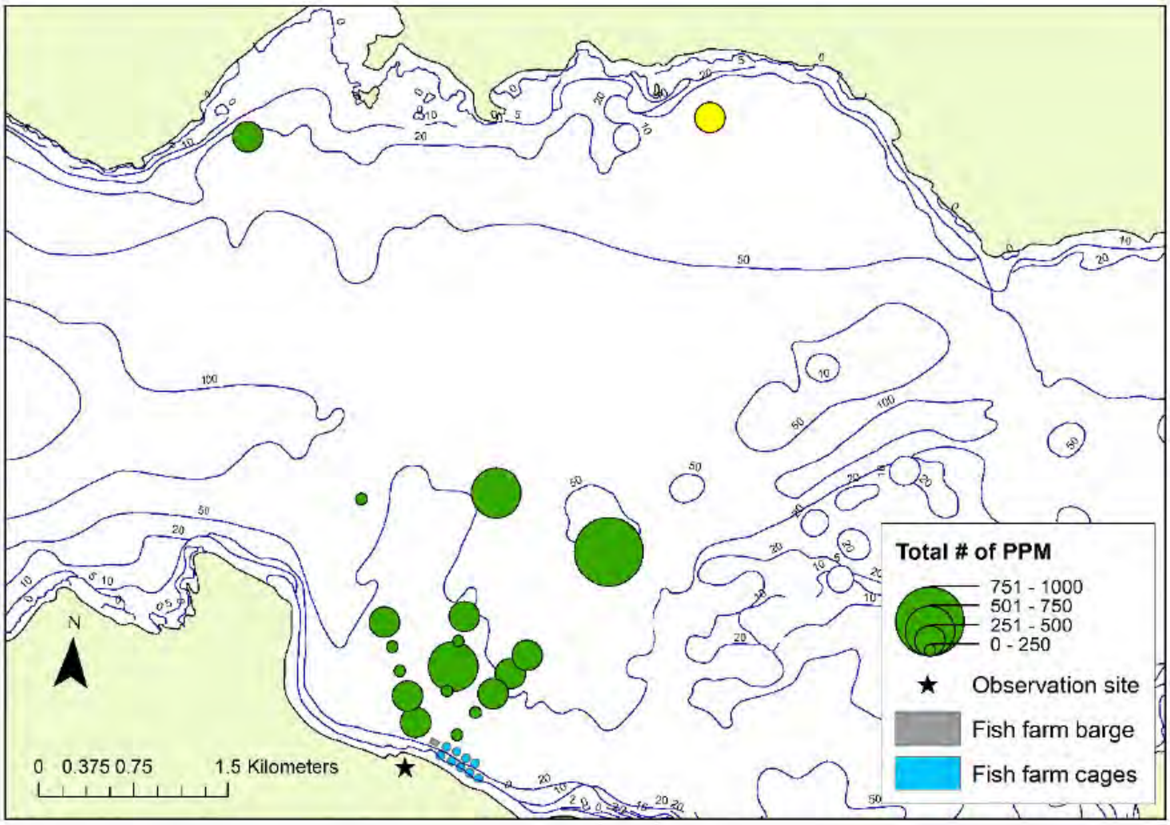

Figure 15. Summary of total numbers of PPMs reported during 8/09-16/10/2016. N.B.: the C-5000 C-POD (top right, yellow) was only operational up to 6/10/2016.

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.

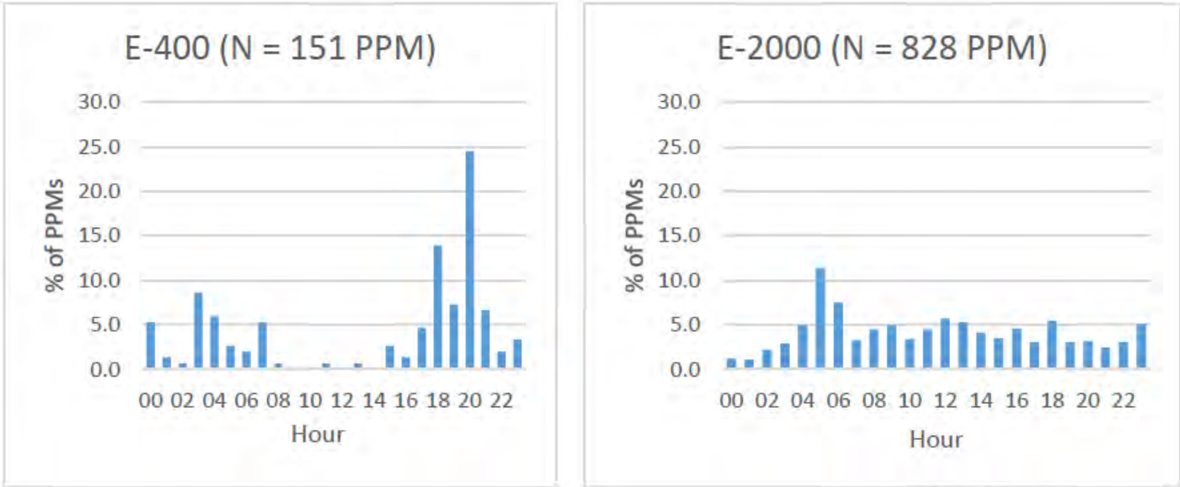

Figure 15. Examples of diurnal patterns of PPM detections from Nearfield (E-400) and Farfield (E-2000) C-PODs (data from 8/09-16/10/2016, aggregated).

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

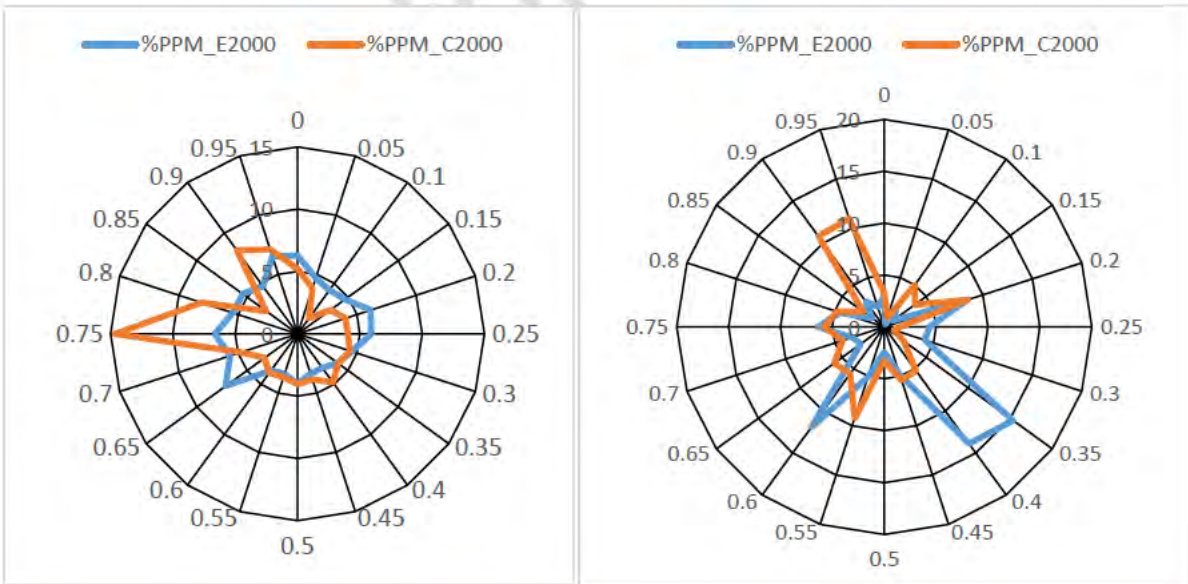

Figure 16. Examples of apparent variability in PPM detection rates at ebb-flood and spring-neap tidal scales. A) Normalised (% of total) PPM detections at locations E-2000 and C-2000 over the ebb-flood tidal cycle (0 = 1 = ebb at Tobermory tidal gauge); B) Normalised (% of total) PPM detections at locations 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 (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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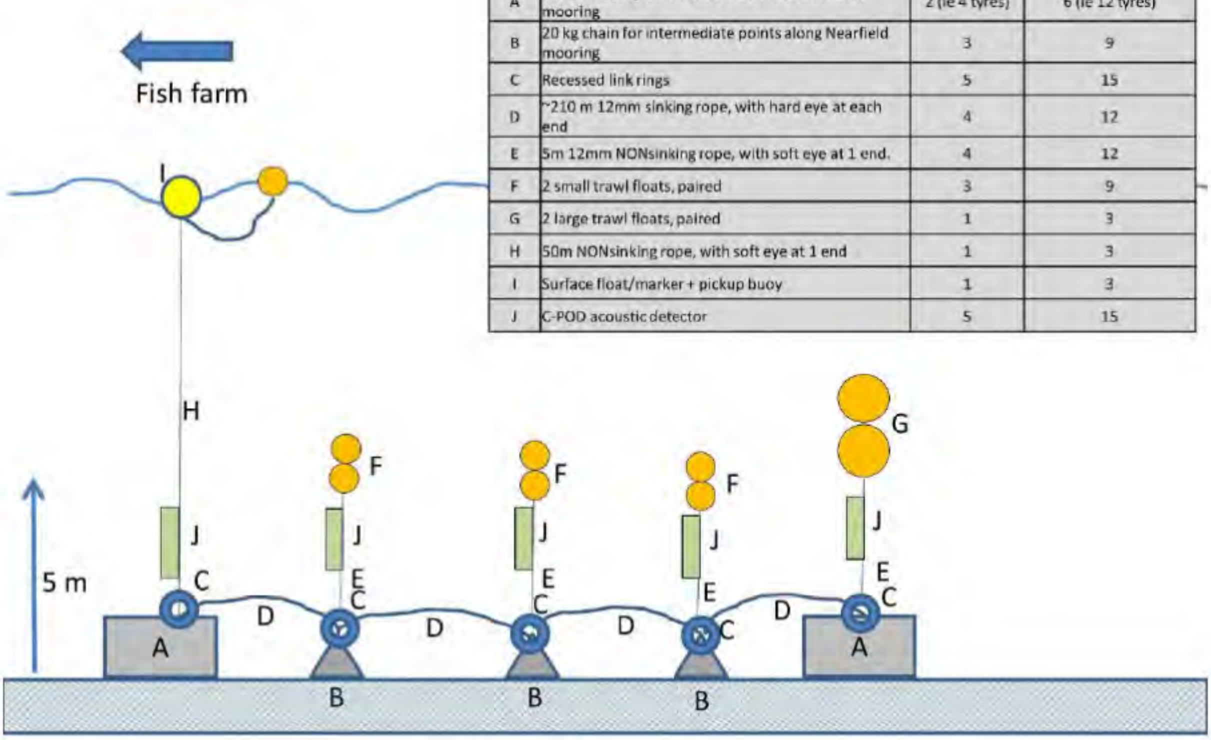
APPENDIX 1 - MOORING DESIGN

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

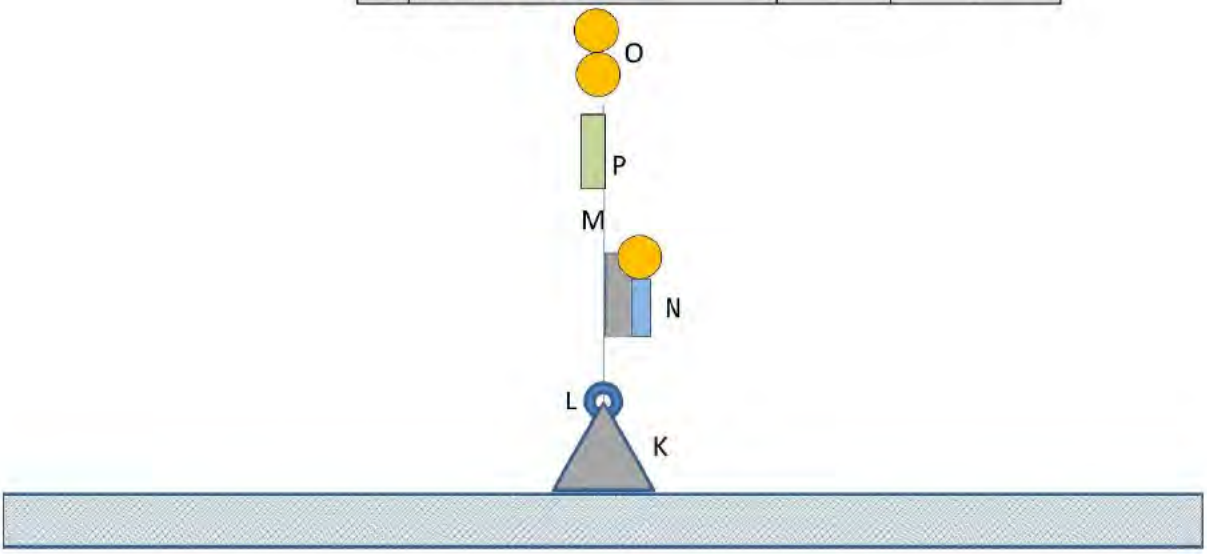
'Nearfield' Mooring diagram



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

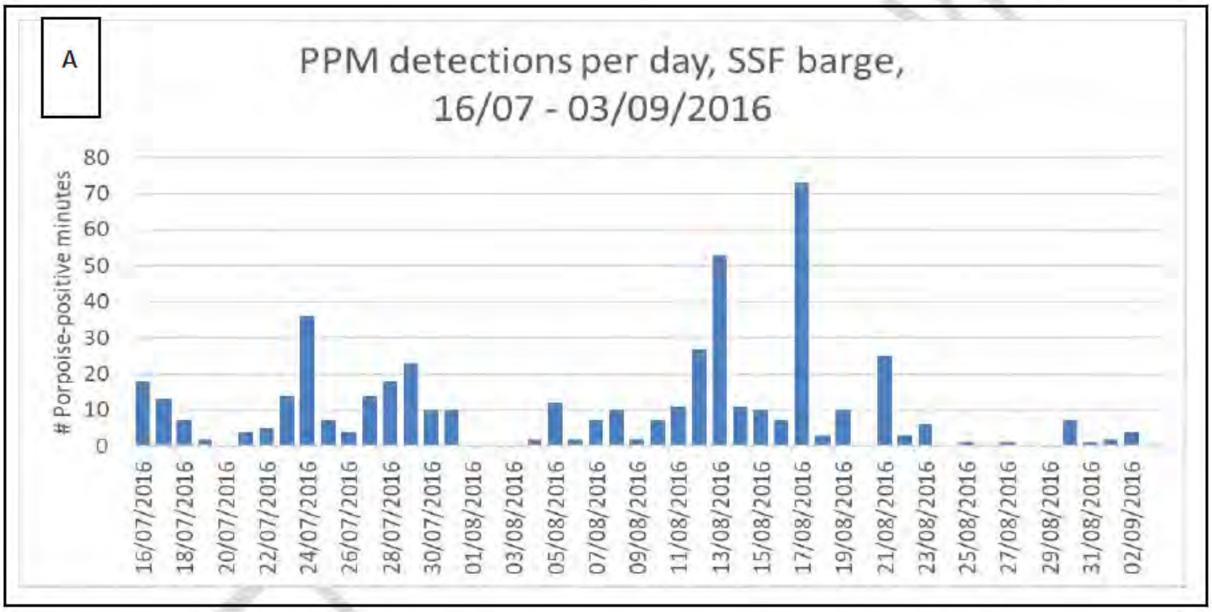
'Farfield' mooring diagram

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.



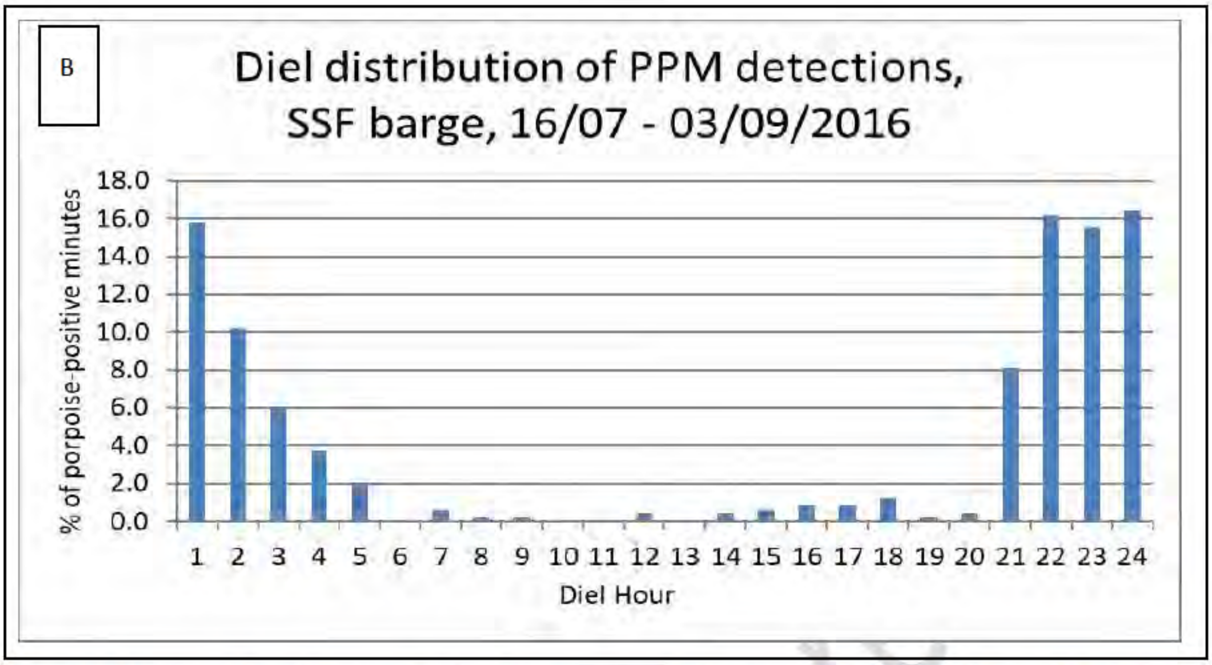


Figure A3.1. A) Overview of overall PPM numbers during pre-experimental deployment at the Bloody Bay fish farm, 16/07 – 3/09/2016 (partial start & end days excluded). B) Overview of distribution of PPMs by hour across a 24-hour day (data aggregated over 16/07 – 3/09/2016 (partial start & end days excluded).

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.

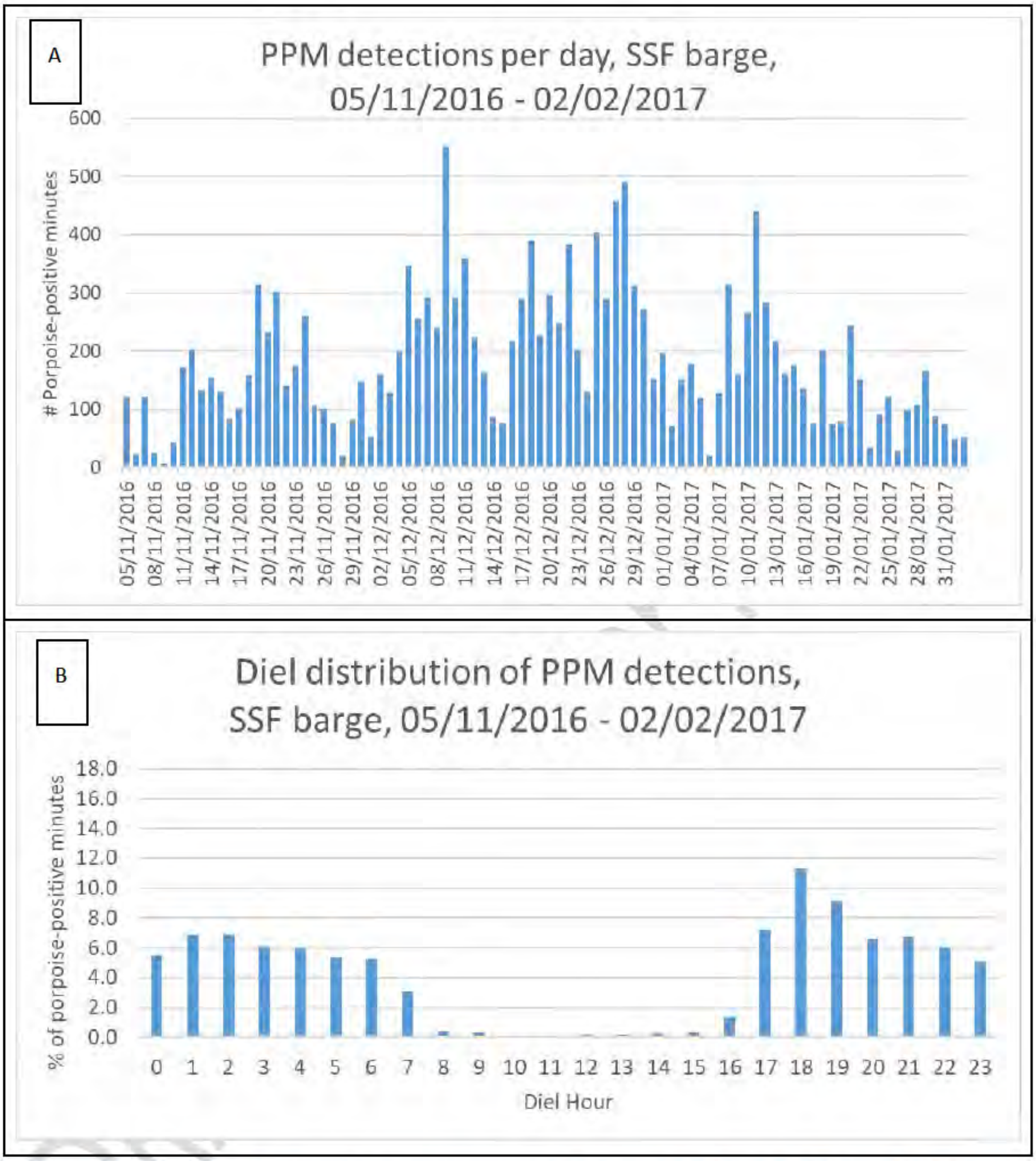


Figure A3.2. A) Overview of overall PPM numbers during pre-experimental deployment at the Bloody Bay fish farm, 05/11/2016 – 02/02/2017 (partial start & end days excluded). B) Overview of distribution of PPMs by hour across a 24-hour day (data aggregated over 05/11/2016 – 02/02/2017 (partial start & 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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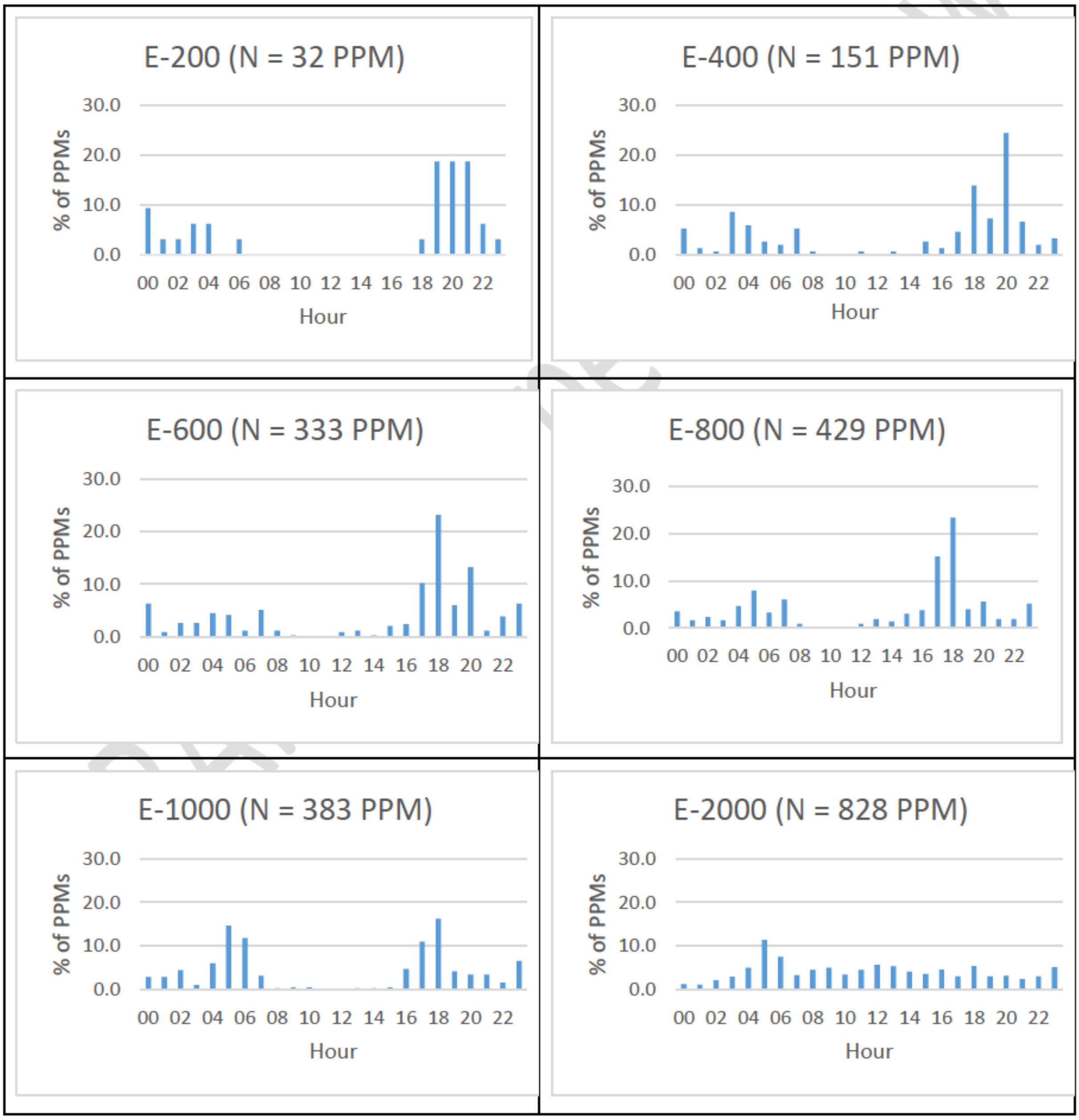
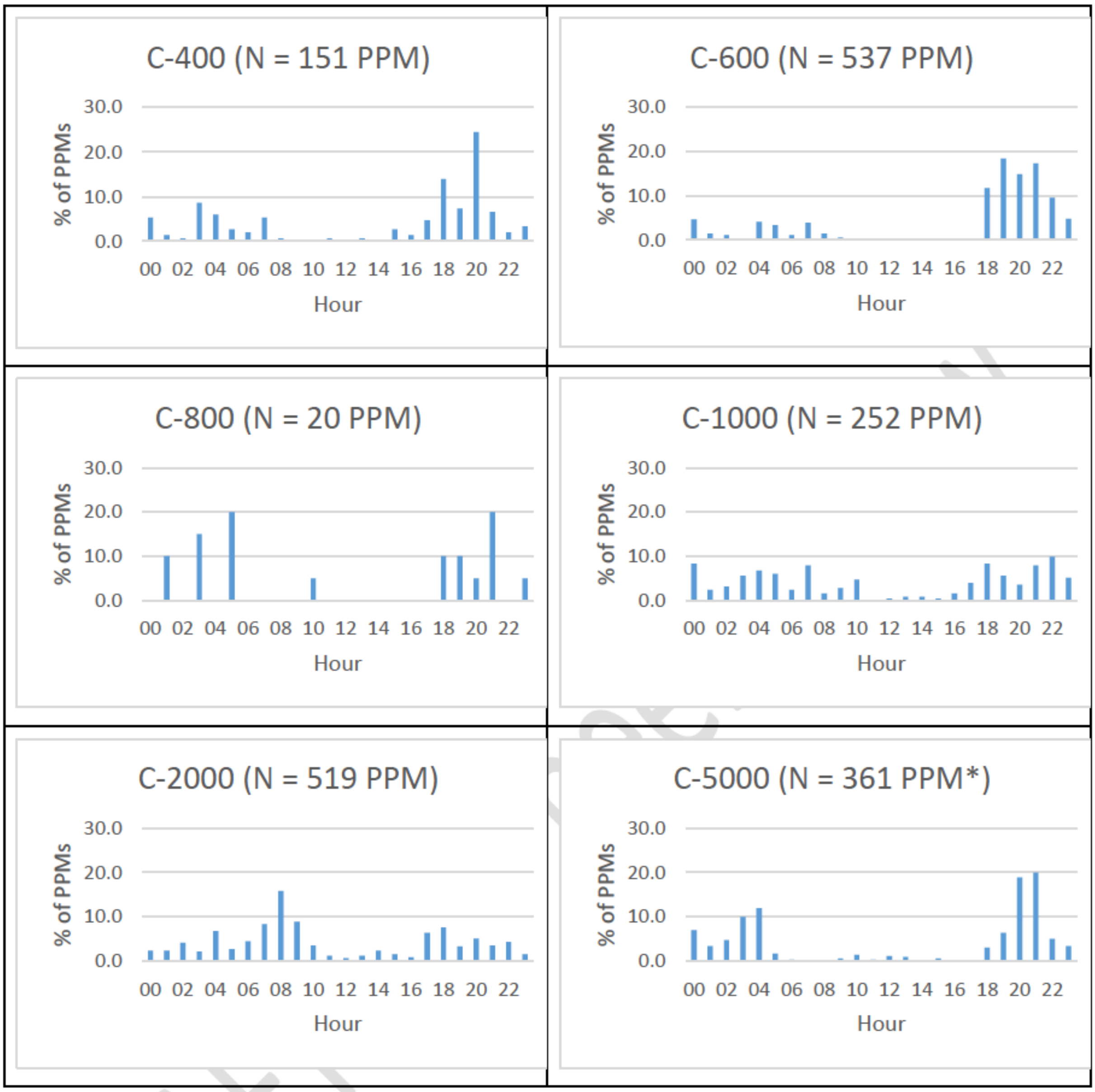
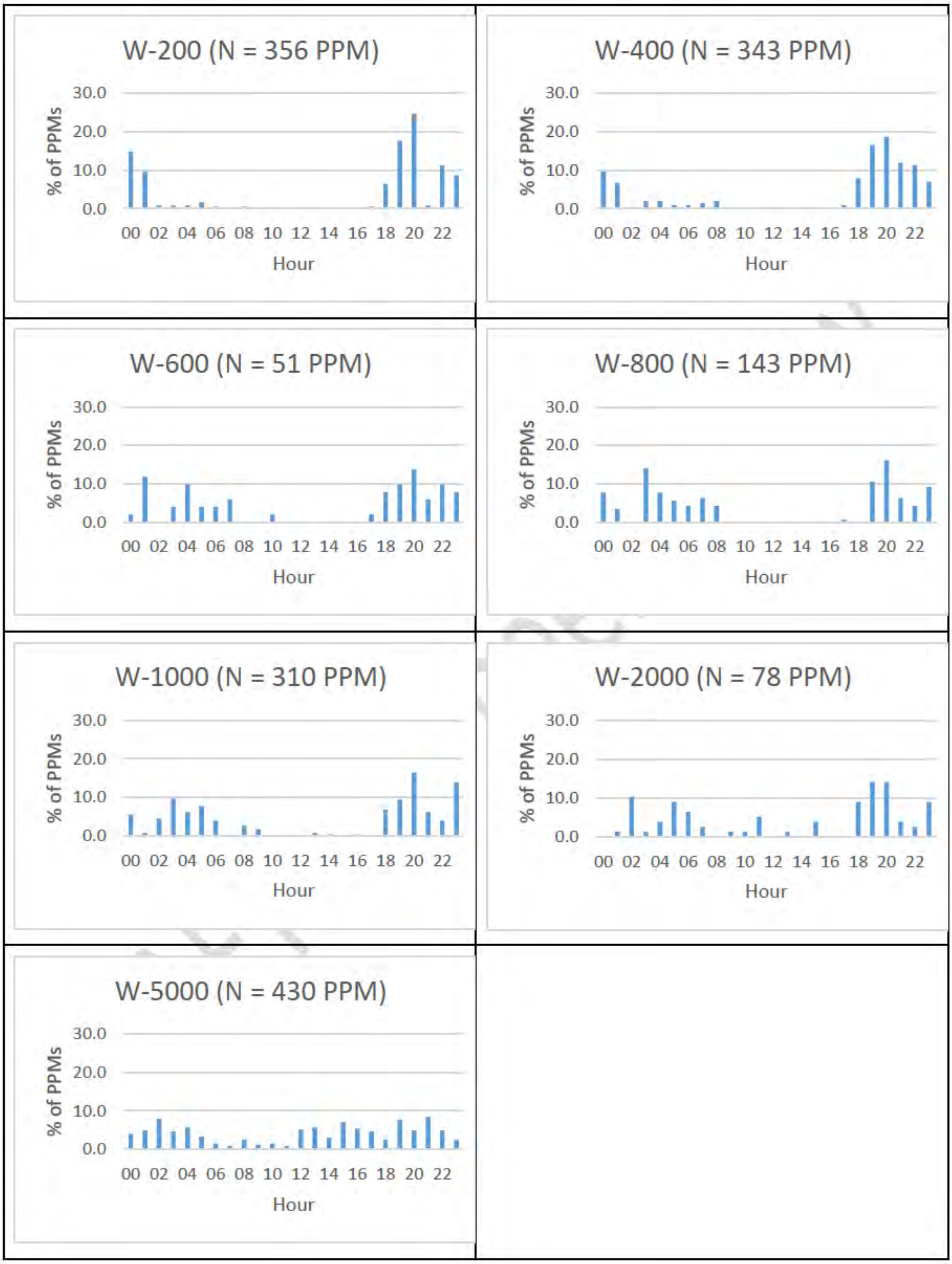
APPENDIX 4 – DIEL VARIABILITY IN PPM DETECTIONS

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
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	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)

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

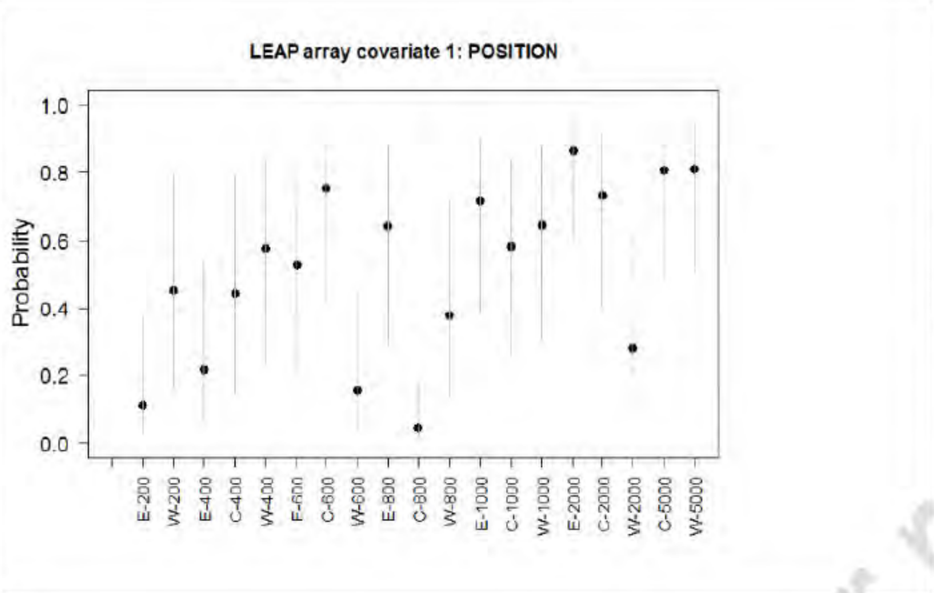
AUC value:	0.8436431

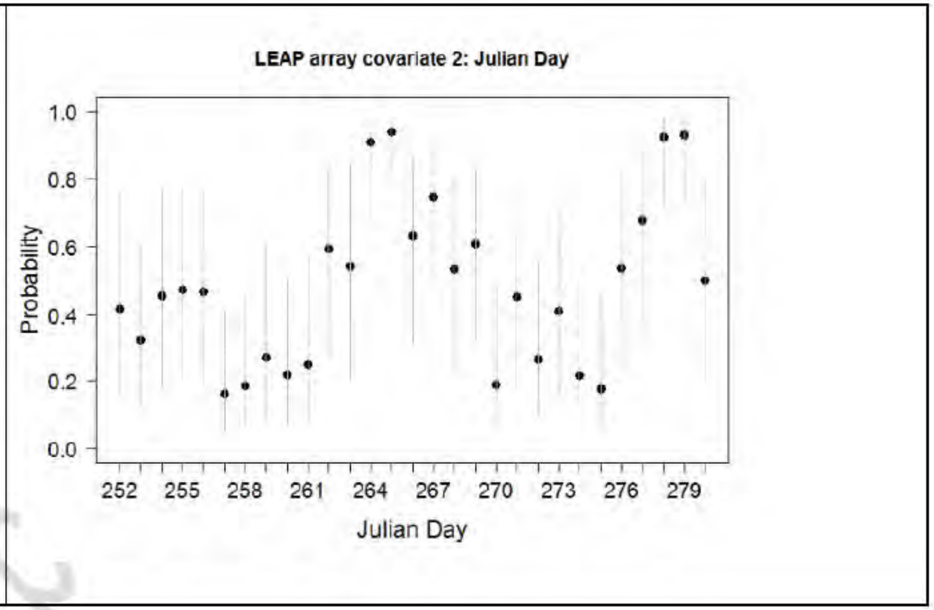
Results of Wald's tests for all significant covariates for the final model:

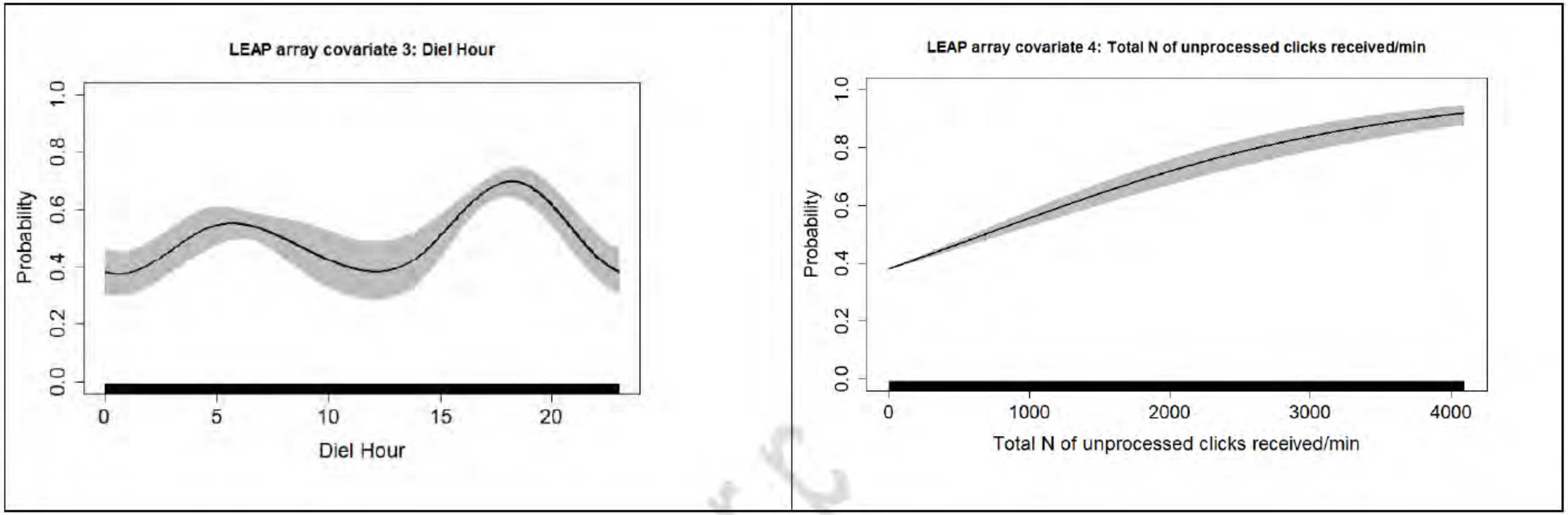
Covariates (in descending order of significance)	Form	Degrees of Freedom	χ^2 score	P-value
POSITION	factor	18	423.14	$<2.2\cdot10^{-16}$
JULDAY	factor	28	273.52	$<2.2\cdot10^{-16}$
HOUR	Cyclic B-spline	4	138.73	$<2.2\cdot10^{-16}$
Nall_m	linear	1	169.23	$<2.2\cdot10^{-16}$
Signal_Type	factor	3	37.69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

DAYTIMENum	factor	3	15.00	0.001819

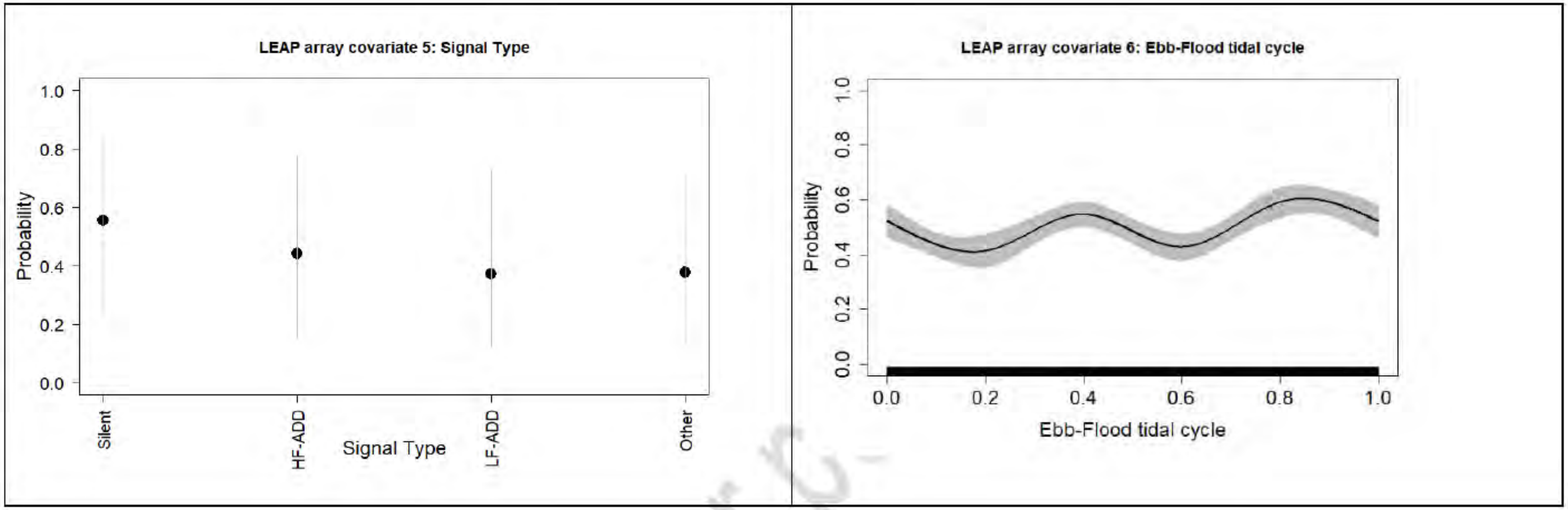
SpringNeap	Cyclic B-spline	4	11.35	0.022868

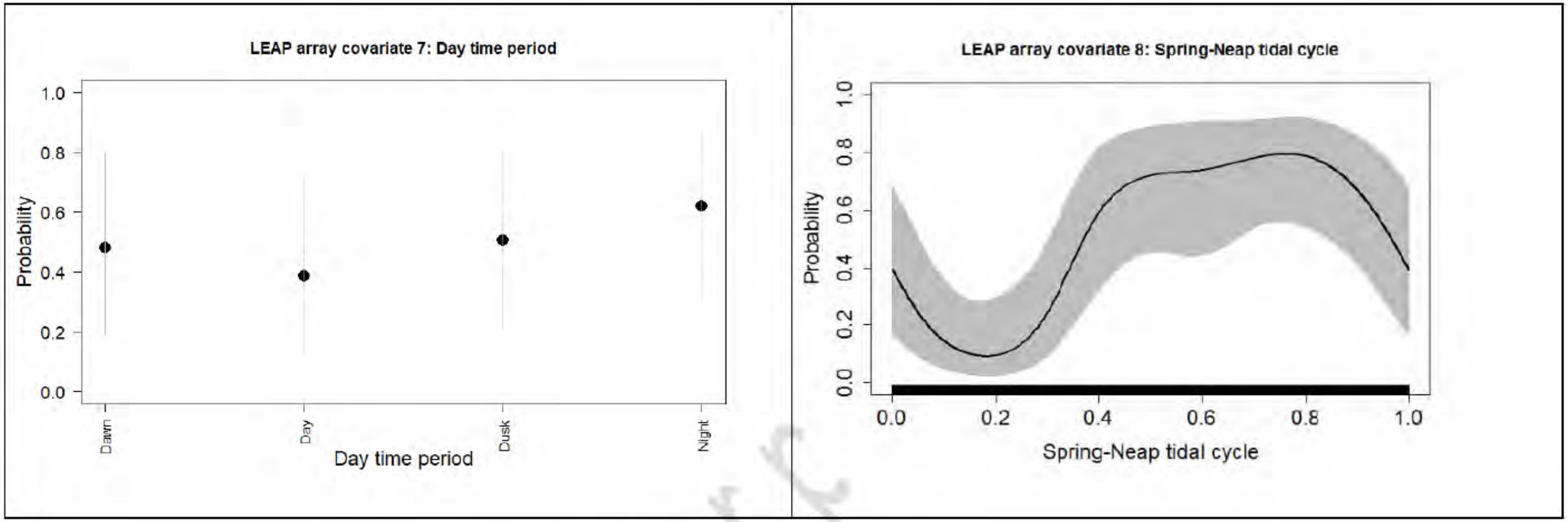

LEAP array covariate 1: POSITION
Probability
1.0
0.8
0.6
0.4
0.2
0.0
E-200
W-200
E-400
C-400
W-400
E-600
C-600
W-600
E-800
C-800
W-800
E-1000
C-1000
W-1000
E-2000
C-2000
W-2000
C-5000
W-5000


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
Dawn
Day
Dusk
Night
Day time period
LEAP array covariate 8: Spring-Neap tidal cycle
Probability
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:

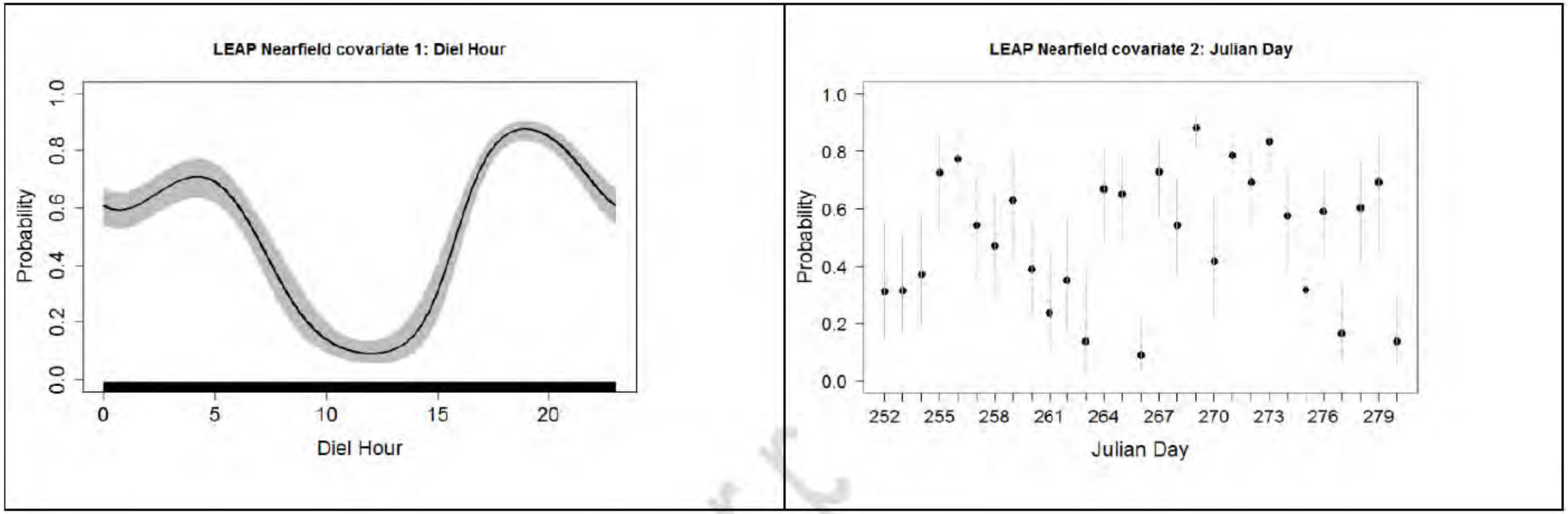
		Expected	
		Porpoise	No porpoise
Observed	Porpoise	80.6%	19.2%
	No porpoise	19.4%	80.8%

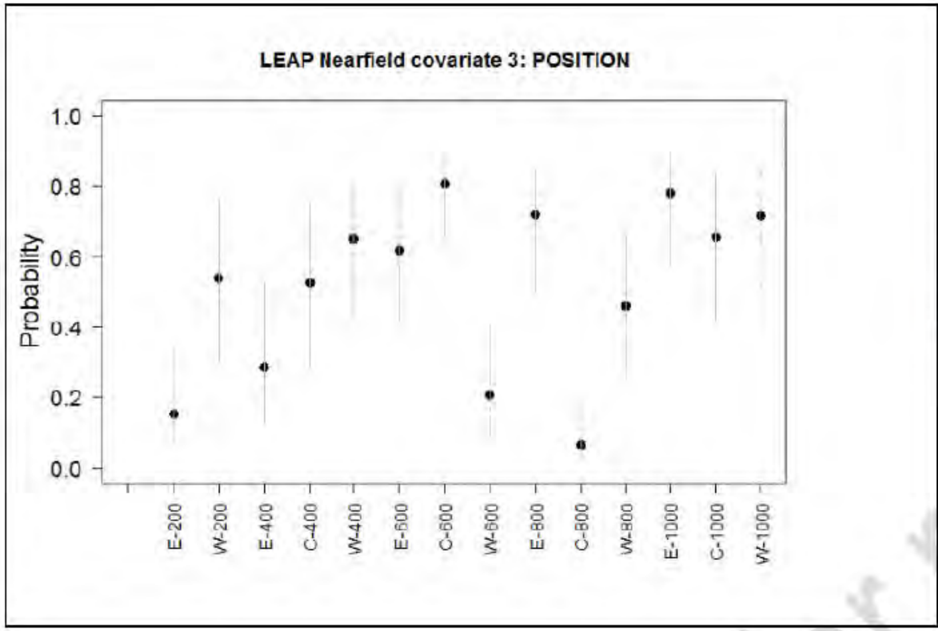
AUC value:	0.8893874

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

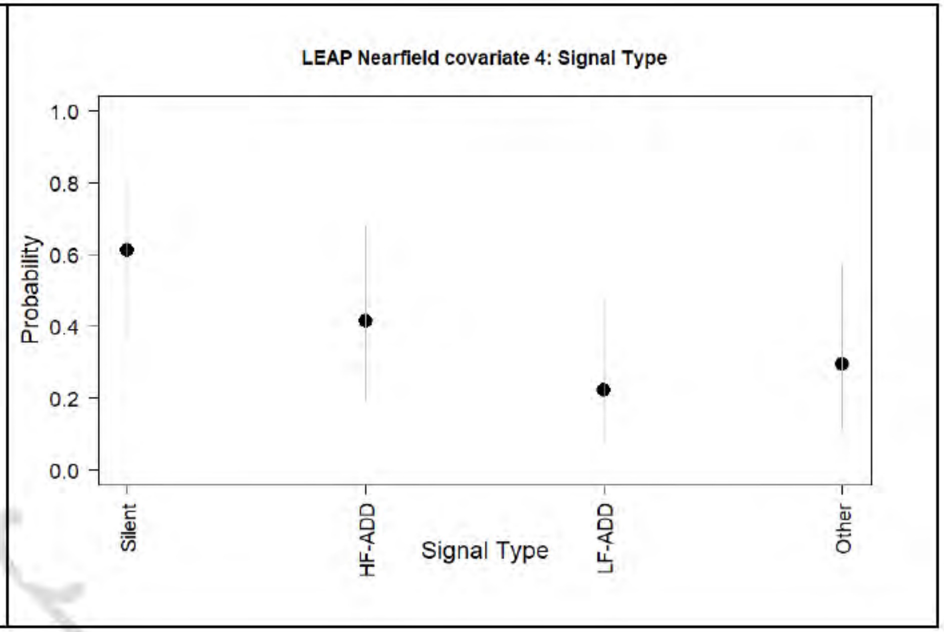
Covariates (in descending order of significance)	Form	Degrees of Freedom	χ^2 score	P-value
HOUR	Cyclic B-spline	4	165.23	$<2.2\cdot10^{-16}$
JULDAY	factor	28	367.38	$<2.2\cdot10^{-16}$
POSITION	factor	13	195.50	$<2.2\cdot10^{-16}$
Signal_Type	factor	3	61.93	$2.272\cdot10^{-13}$
Nall_m	linear	1	73.34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

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

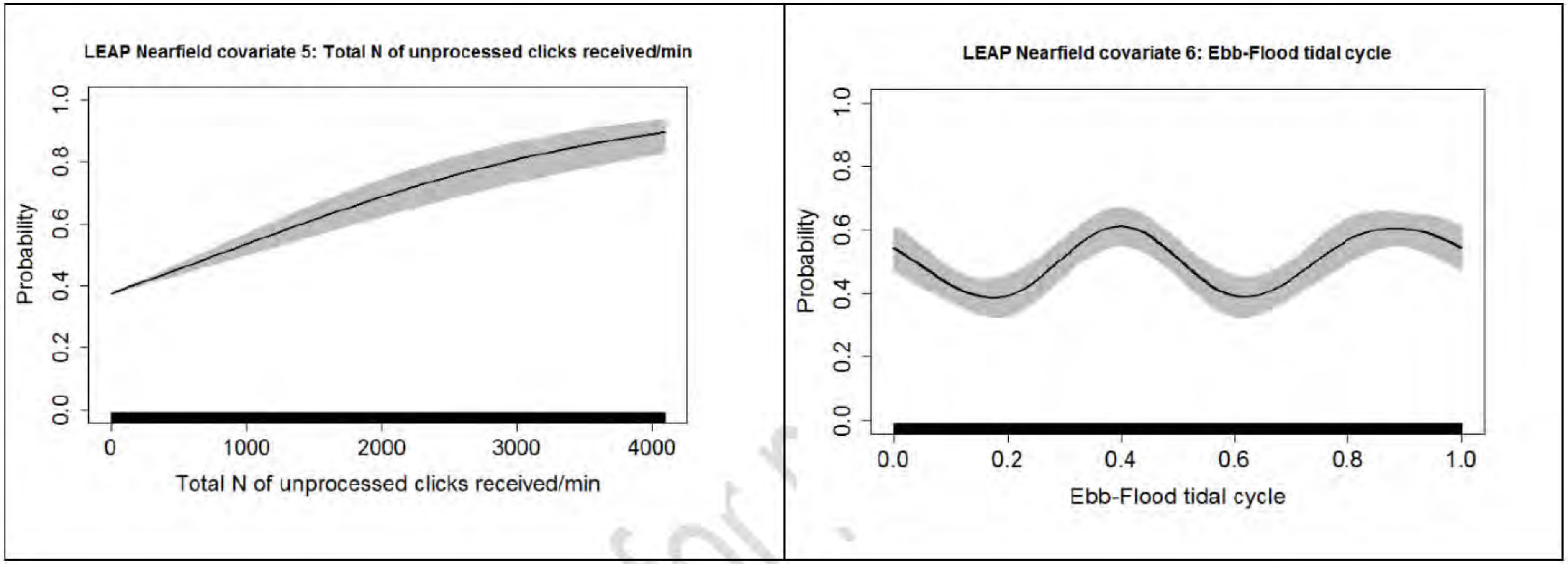

LEAP Nearfield covariate 1: Diel Hour
Probability
0.0
0.2
0.4
0.6
0.8
1.0
0
5
10
15
20
Diel Hour
LEAP Nearfield covariate 2: Julian Day
Probability
0.0
0.2
0.4
0.6
0.8
1.0
252
255
258
261
264
267
270
273
276
279
Julian Day



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
Ebb-Flood tidal cycle

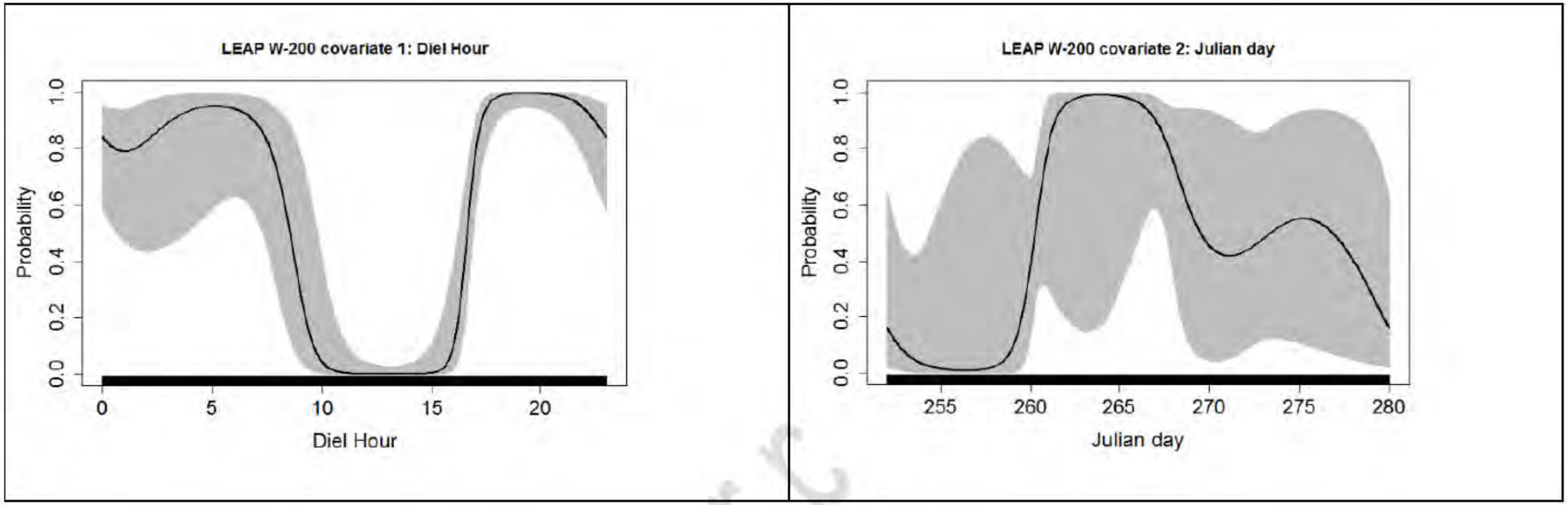
Model:	W-200
Model structure:	POD5<-geeglm(PPM ~ AvgHrBasisMat + bs(JULDAY , knots=mean(JULDAY)) + Nall_m, family = binomial, corstr="independence", id=Panel, data=W200)
Confusion matrix:	

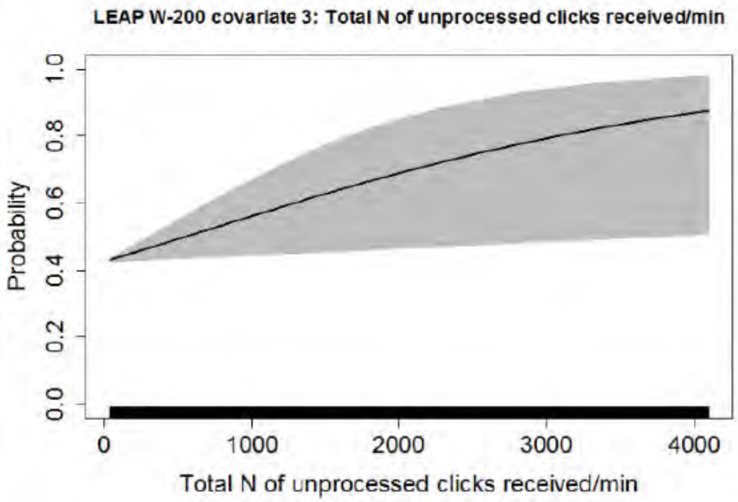
		Expected	
		Porpoise	No porpoise
Observed	Porpoise	77.5%	6.8%
	No porpoise	22.5%	93.2%

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

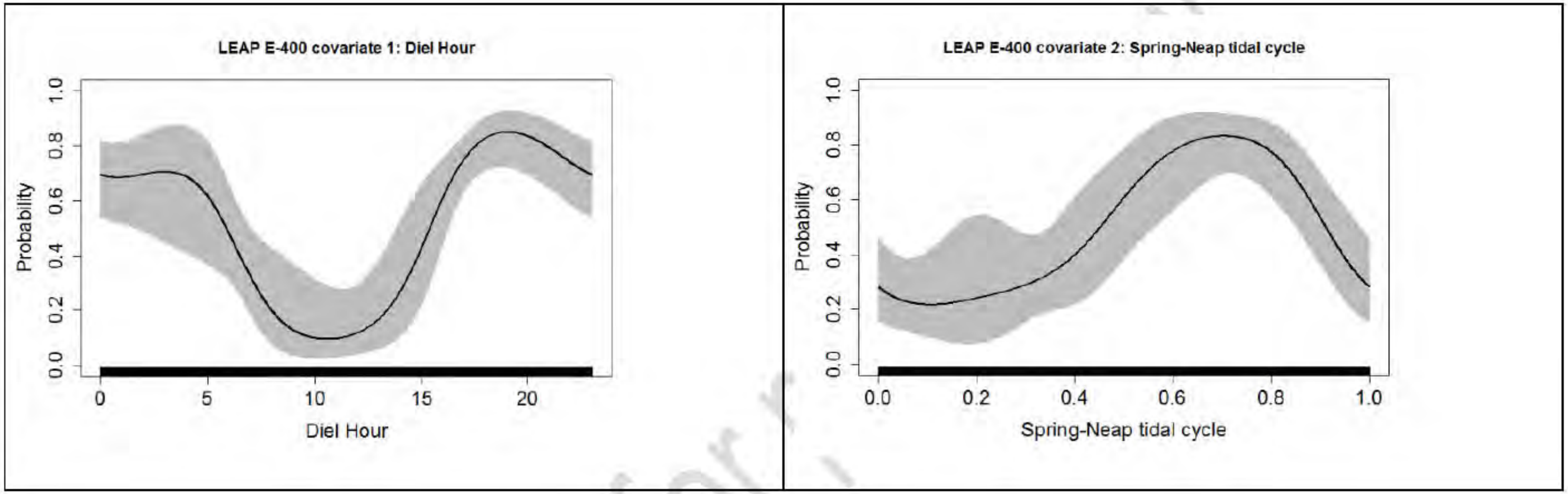
Model:	E-400
Model structure:	POD5<-geeglm(PPM ~ AvgHrBasisMat + SprNpBasisMat + Nall_m, family = binomial, corstr="independence", id=Panel, data=E400)
Confusion matrix:	

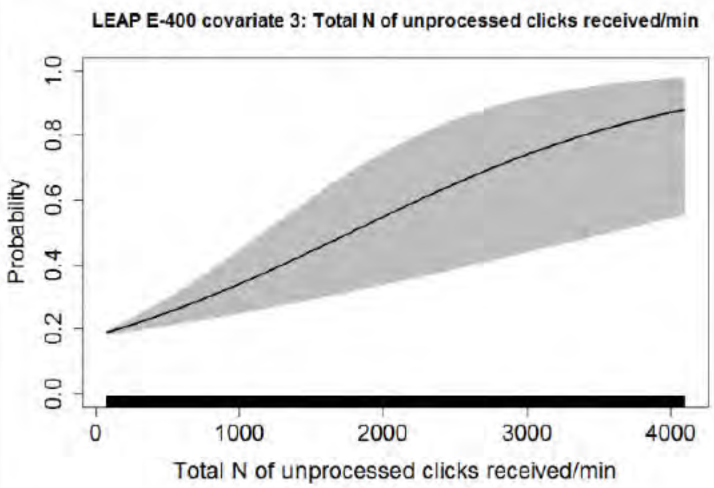
		Expected	
		Porpoise	No porpoise
Observed	Porpoise	74.7%	22.4%
	No porpoise	25.3%	77.6%

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
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

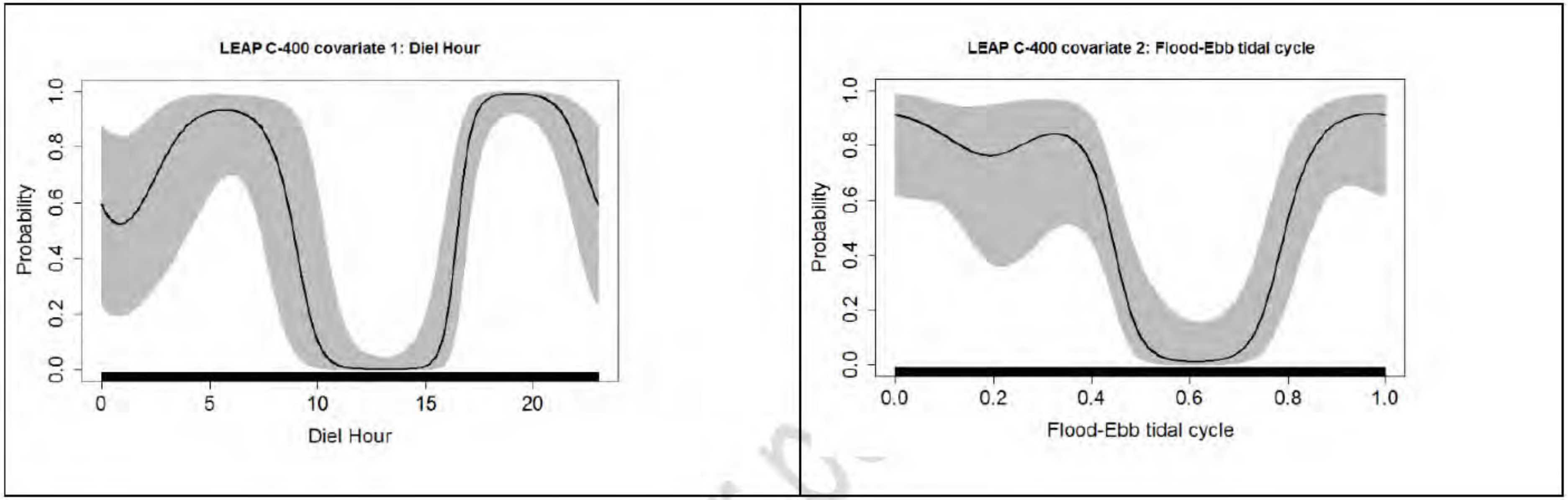
Model:	C-400
Model structure:	POD5<-geeglm(PPM ~ AvgHrBasisMat + TideBasisMat + bs(JULDAY , knots=mean(JULDAY)) + Nall_m, family = binomial, corstr="independence", id=Panel, data=C400)
Confusion matrix:	(see below)

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

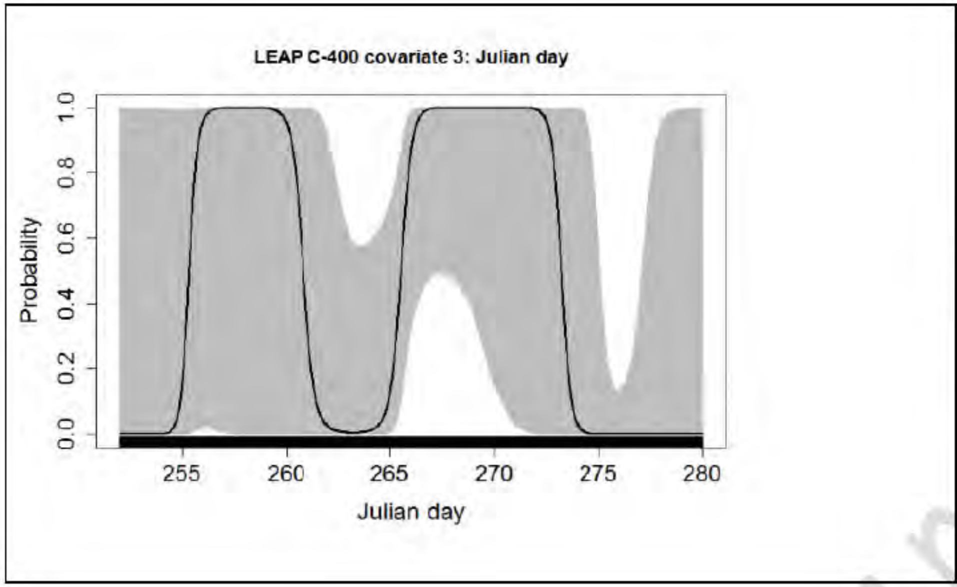
AUC value:	0.943135

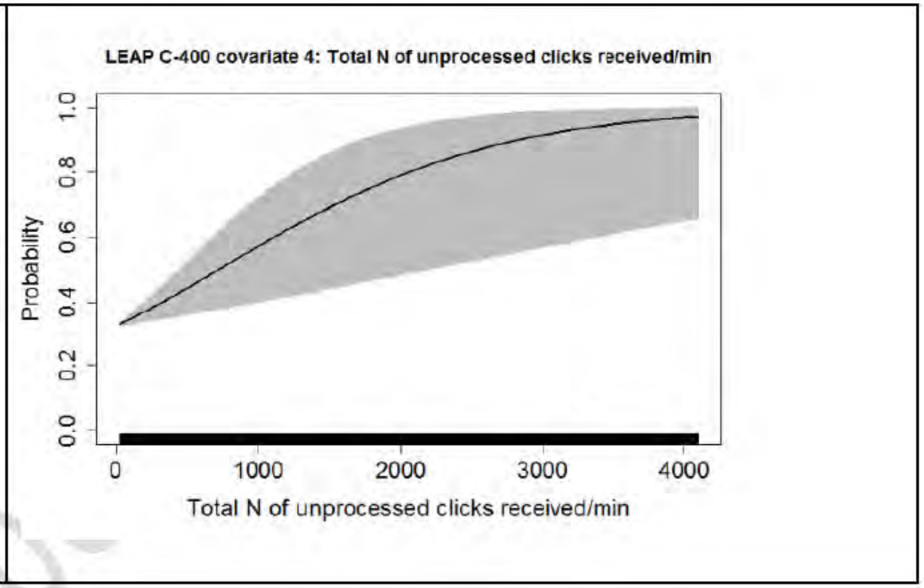
Results of Wald's tests for all significant covariates for the final model:

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
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

1800

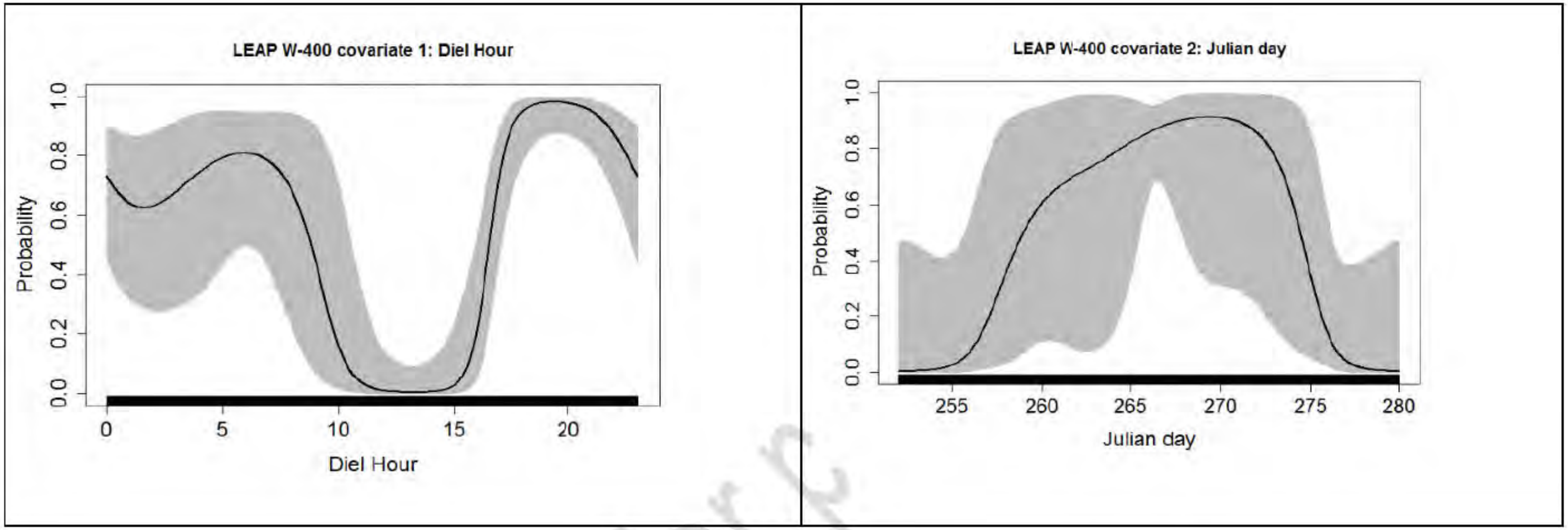
Model:	W-400
Model structure:	POD5<-geeglm(PPM ~ AvgHrBasisMat + bs(JULDAY , knots=mean(JULDAY)) + as.factor(Signal_Type) + Nall_m + TideBasisMat, family = binomial, corstr="independence", id=Panel, data=W400)
Confusion matrix:	

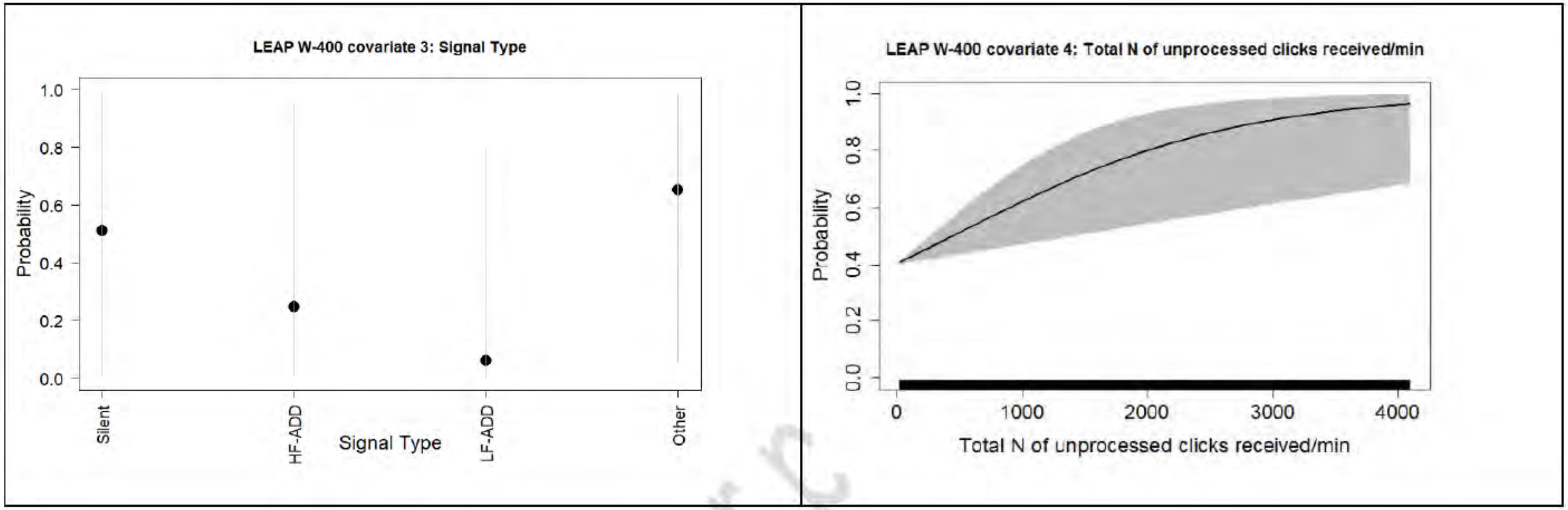
		Expected	
		Porpoise	No porpoise
Observed	Porpoise	88.4%	21.9%
	No porpoise	11.6%	78.1%

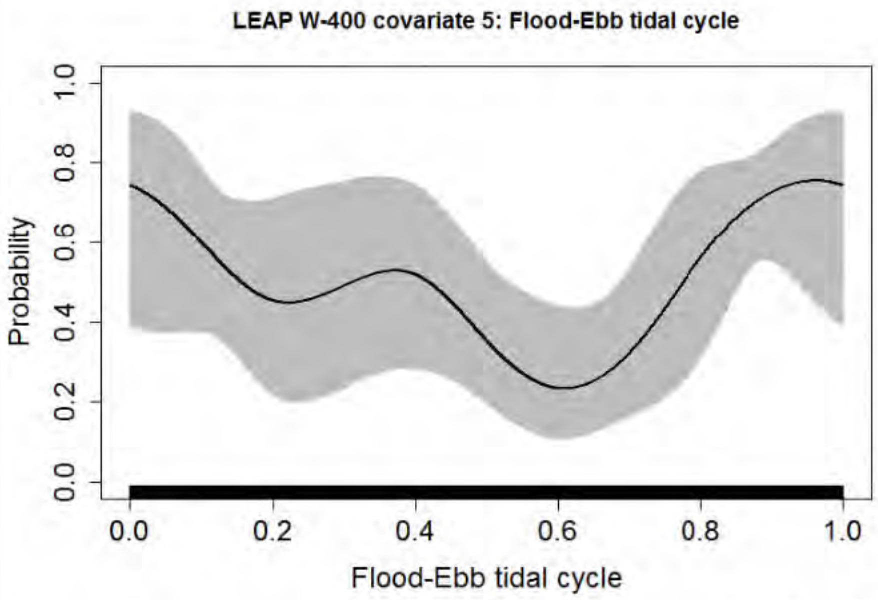
AUC value:	0.9068351

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
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
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

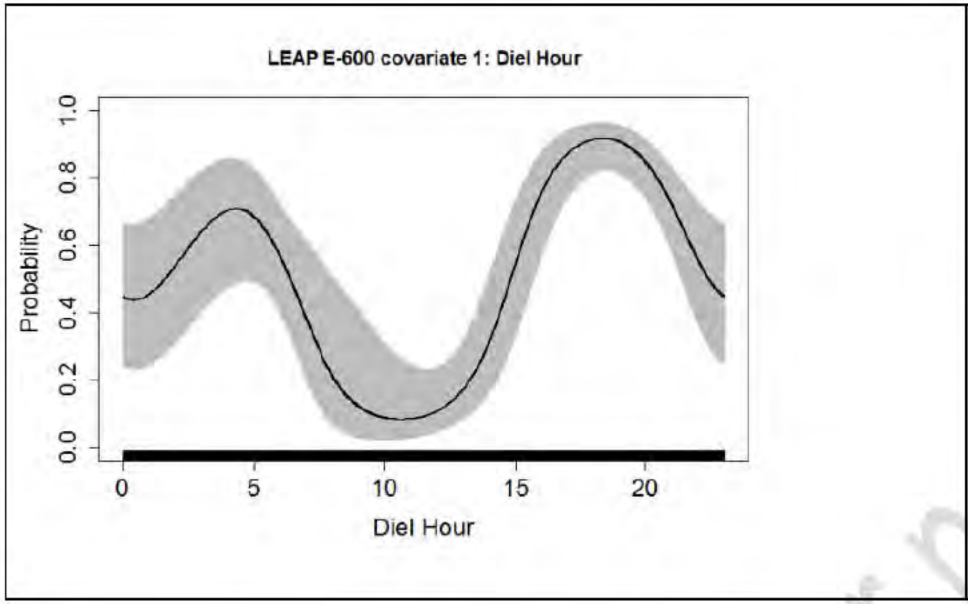
Model:	E-600
Model structure:	POD5<-geeglm(PPM ~ AvgHrBasisMat + bs(JULDAY , knots=mean(JULDAY)) + SprNpBasisMat + TideBasisMat, family = binomial, corstr="independence", id=Panel, data=E600)
Confusion matrix:	

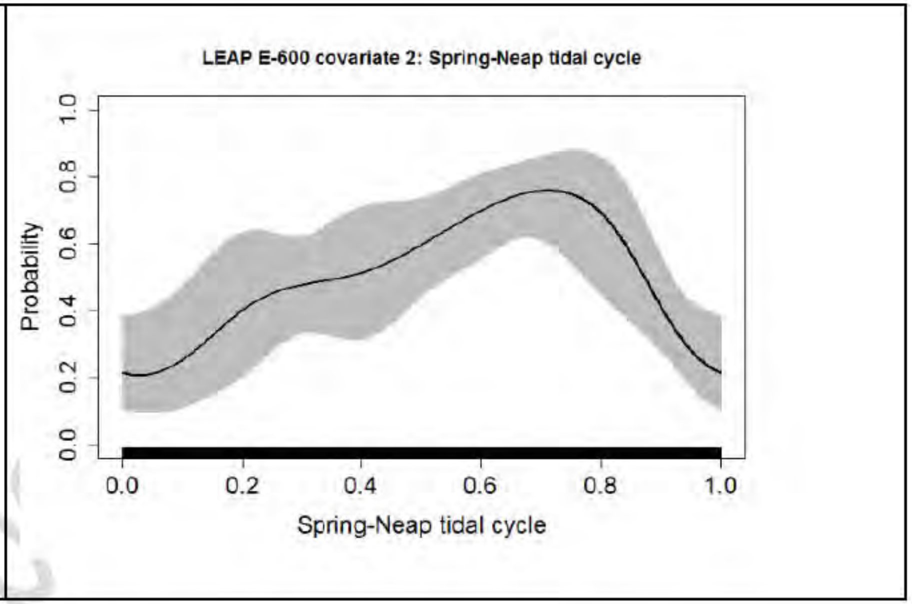
		Expected	
		Porpoise	No porpoise
Observed	Porpoise	75.5%	23.6%
	No porpoise	24.5%	76.4%

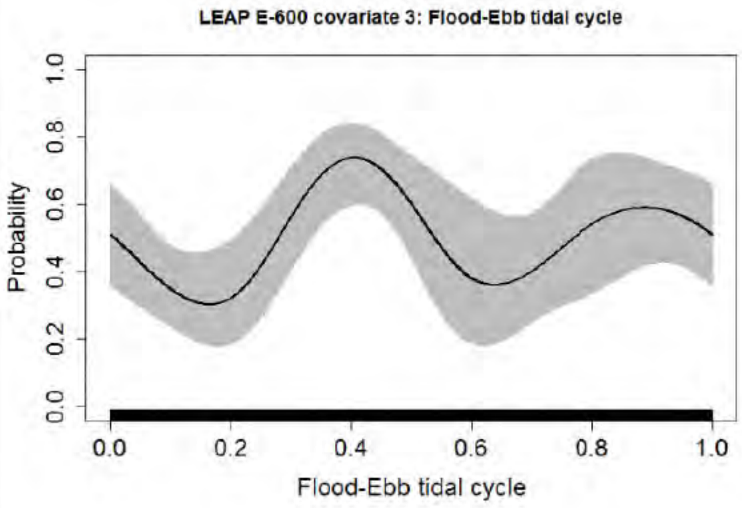
AUC value:	0.8365278

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

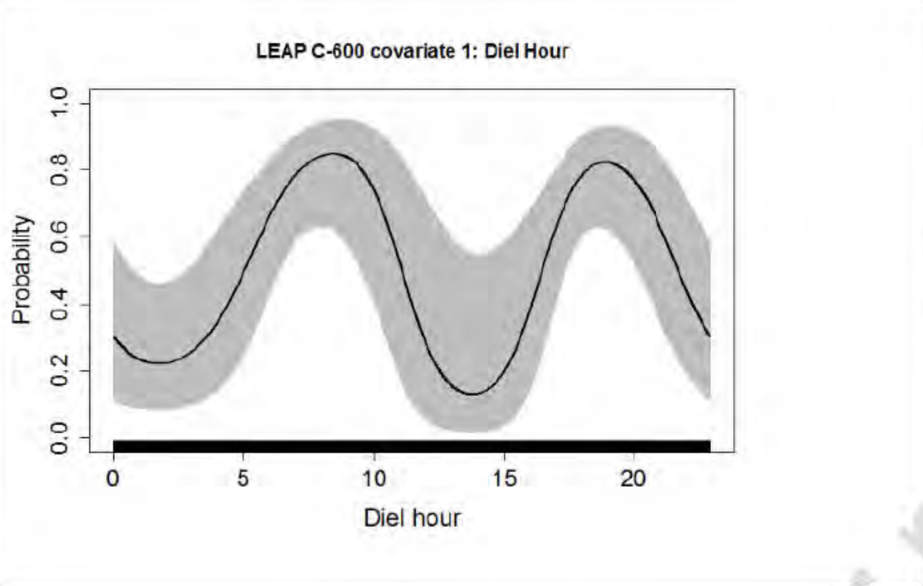
Model:	C-600
Model structure:	POD7<-geeglm(PPM ~ AvgHrBasisMat + bs(JULDAY , knots=mean(JULDAY)) + Nall_m + as.factor(DAYTIMENum), family = binomial, corstr="independence", id=Panel, data=C600)
Confusion matrix:	(see below)
AUC value:	0.8862971

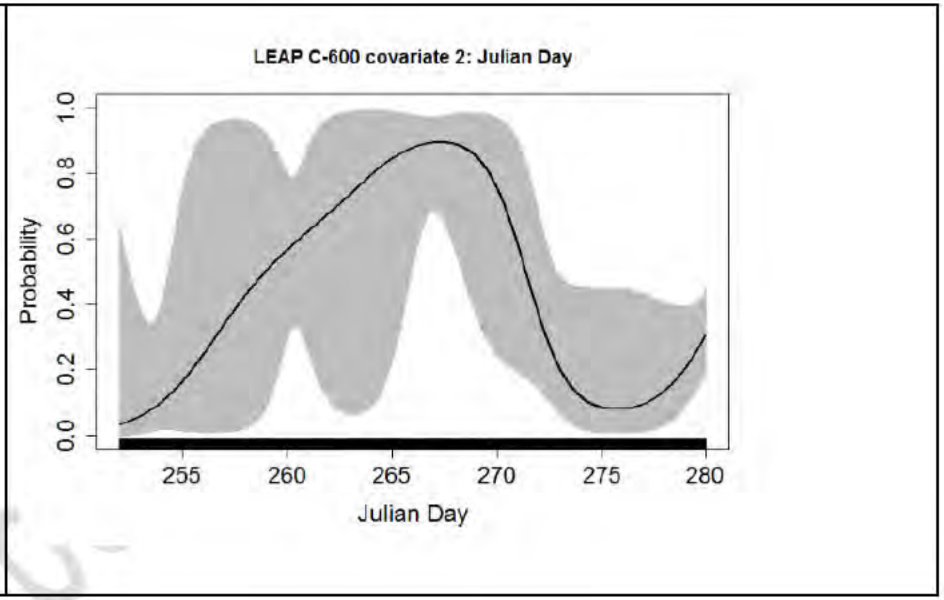
Confusion matrix:

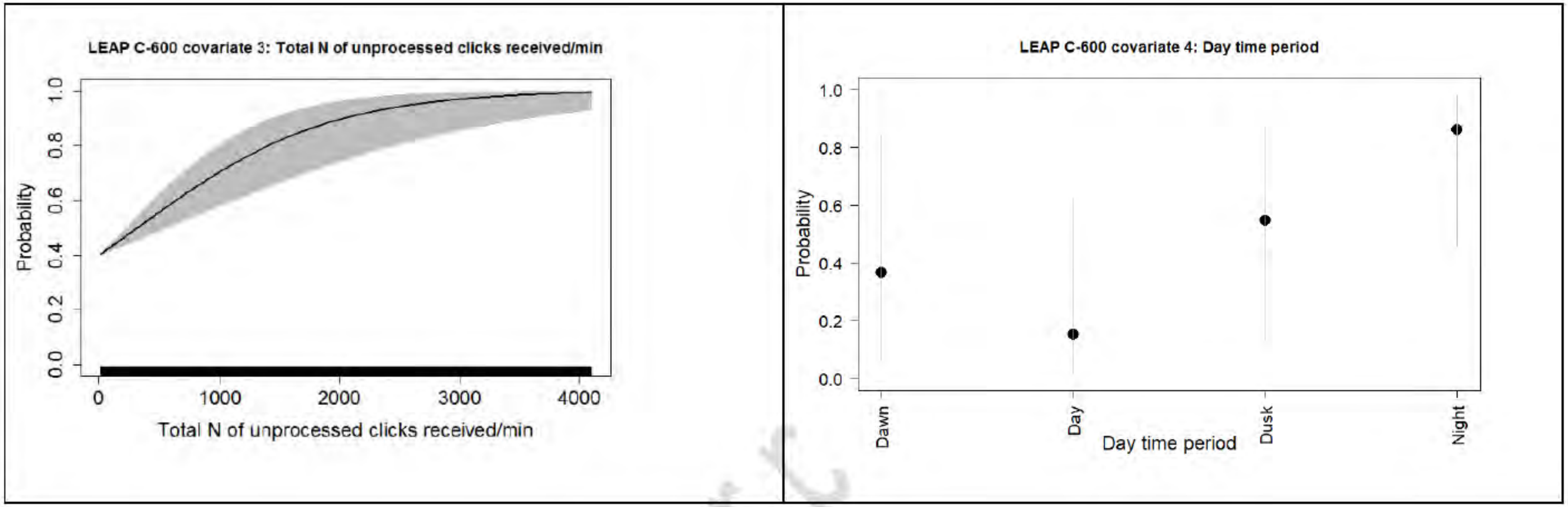
		Expected	
		Porpoise	No porpoise
Observed	Porpoise	77.0%	15.6%
	No porpoise	23.0%	84.4%

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

1806

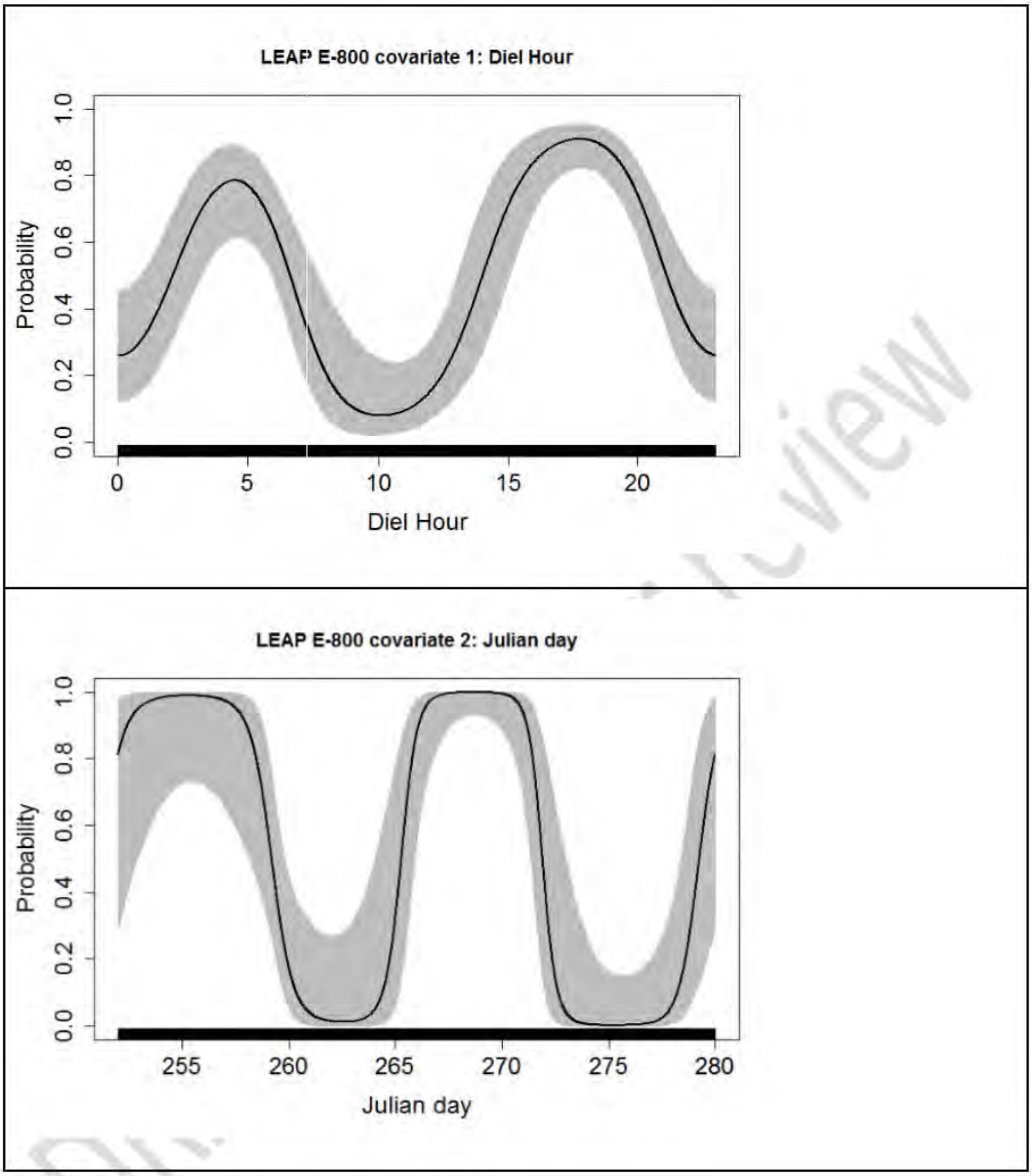
Model:	E-800
Model structure:	POD7<-geeglm(PPM ~ AvgHrBasisMat + bs(JULDAY , knots=mean(JULDAY)), family = binomial, corstr="independence", id=Panel, data=E800)
Confusion matrix:	

		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

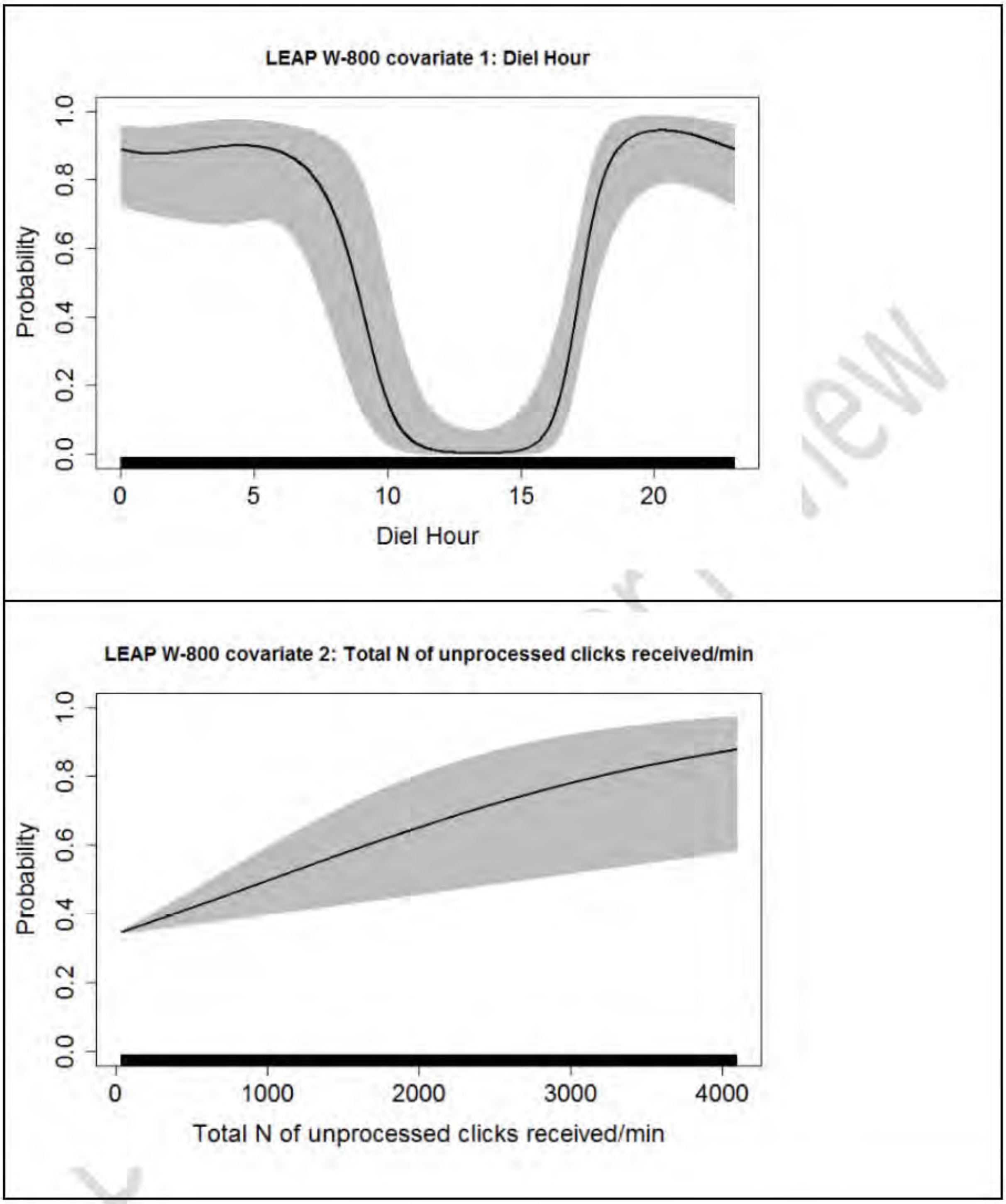
Model:	W-800
Model structure:	POD5<-geeglm(PPM ~ AvgHrBasisMat + Nall_m + as.factor(Signal_Type) , family = binomial, corstr="independence", id=Panel, data=W800)
Confusion matrix:	

		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:

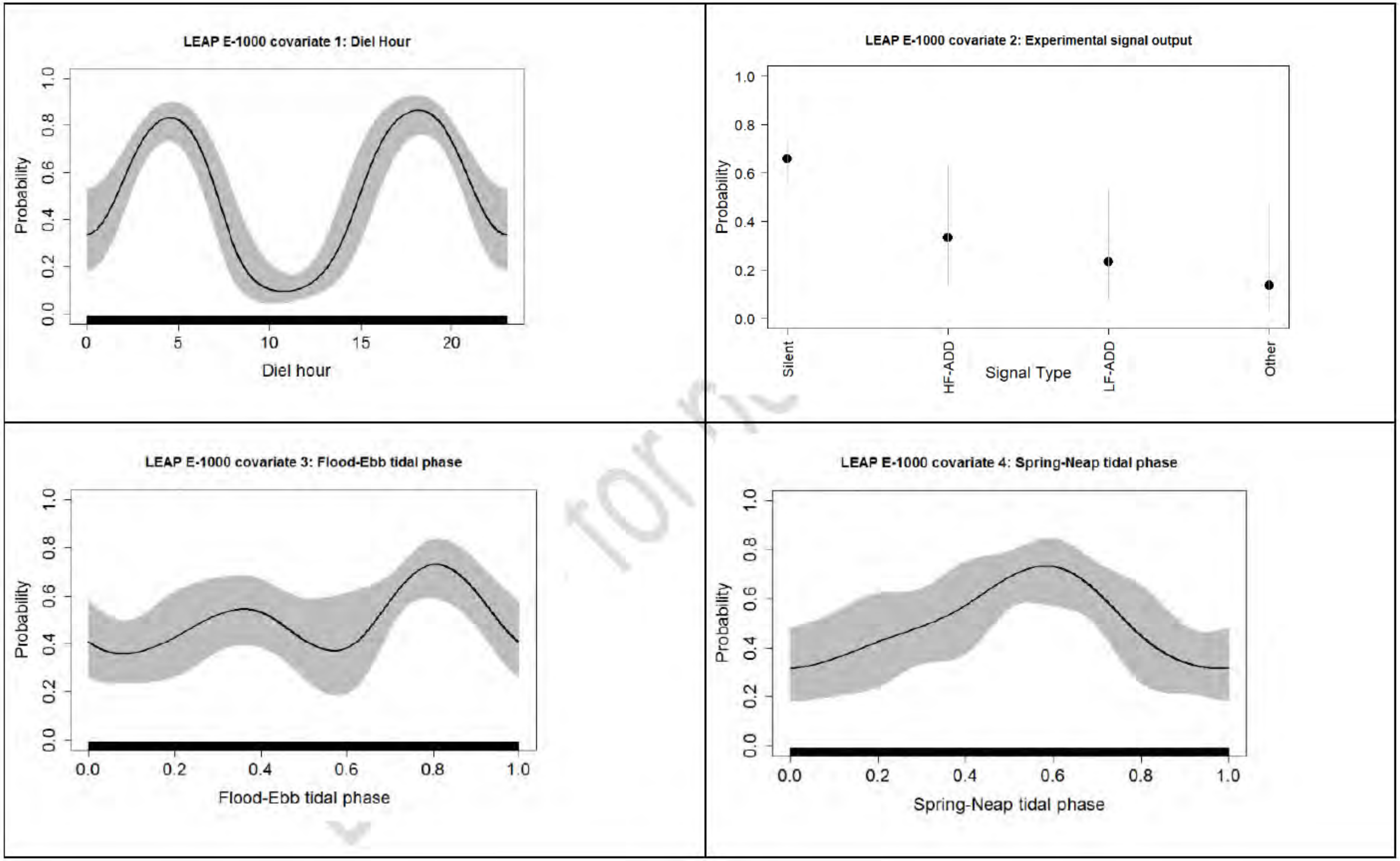
Covariates (in descending order of significance)	Form	Degrees of Freedom	χ^2 score	P-value
HOUR	Cyclic B-spline	4	16.0326	0.002976
Nall_m	linear	1	9.9207	0.001634


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:	(see below)			
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

Confusion matrix:

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


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
LF-ADD
Other
Signal Type
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

1814

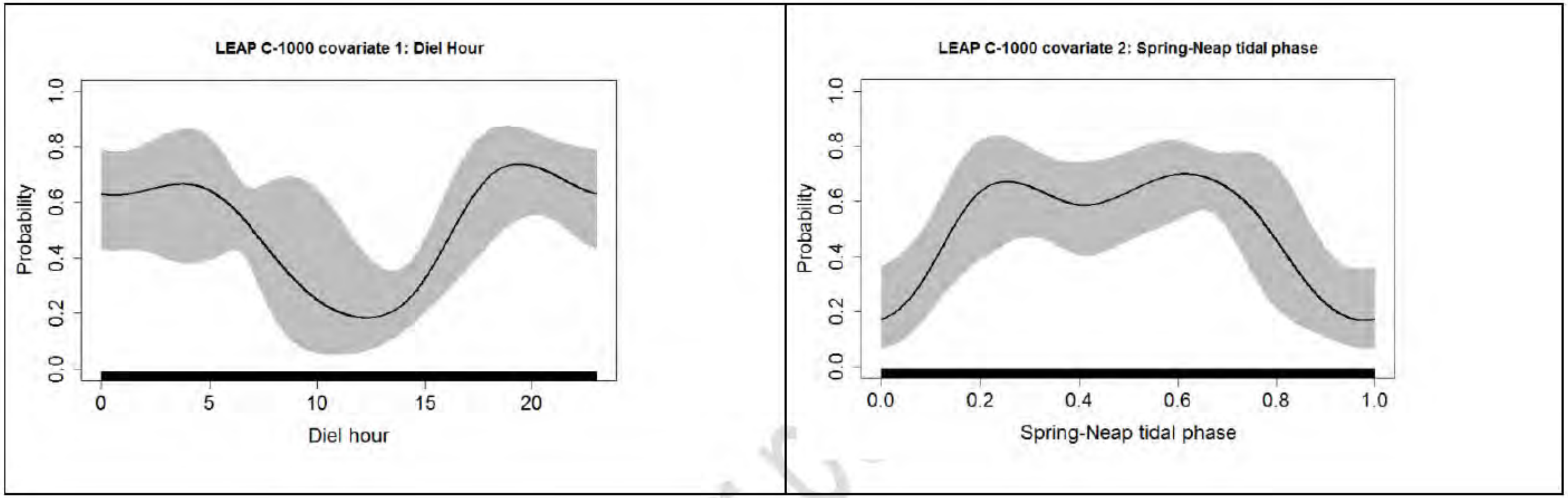
Model:	C-1000
Model structure:	POD5<-geeglm(PPM ~ AvgHrBasisMat + SprNpBasisMat + TideBasisMat, family = binomial, corstr="independence", id=Panel, data=C1000)
Confusion matrix:	

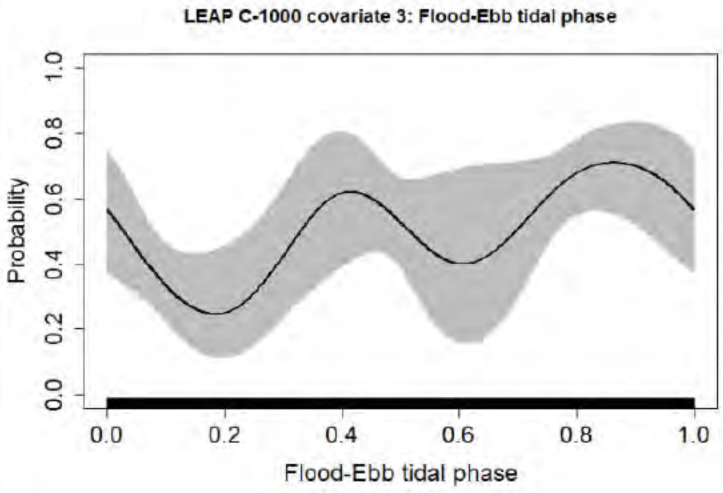
		Expected	
		Porpoise	No porpoise
Observed	Porpoise	73.0%	27.9%
	No porpoise	27.0%	72.1%

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
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

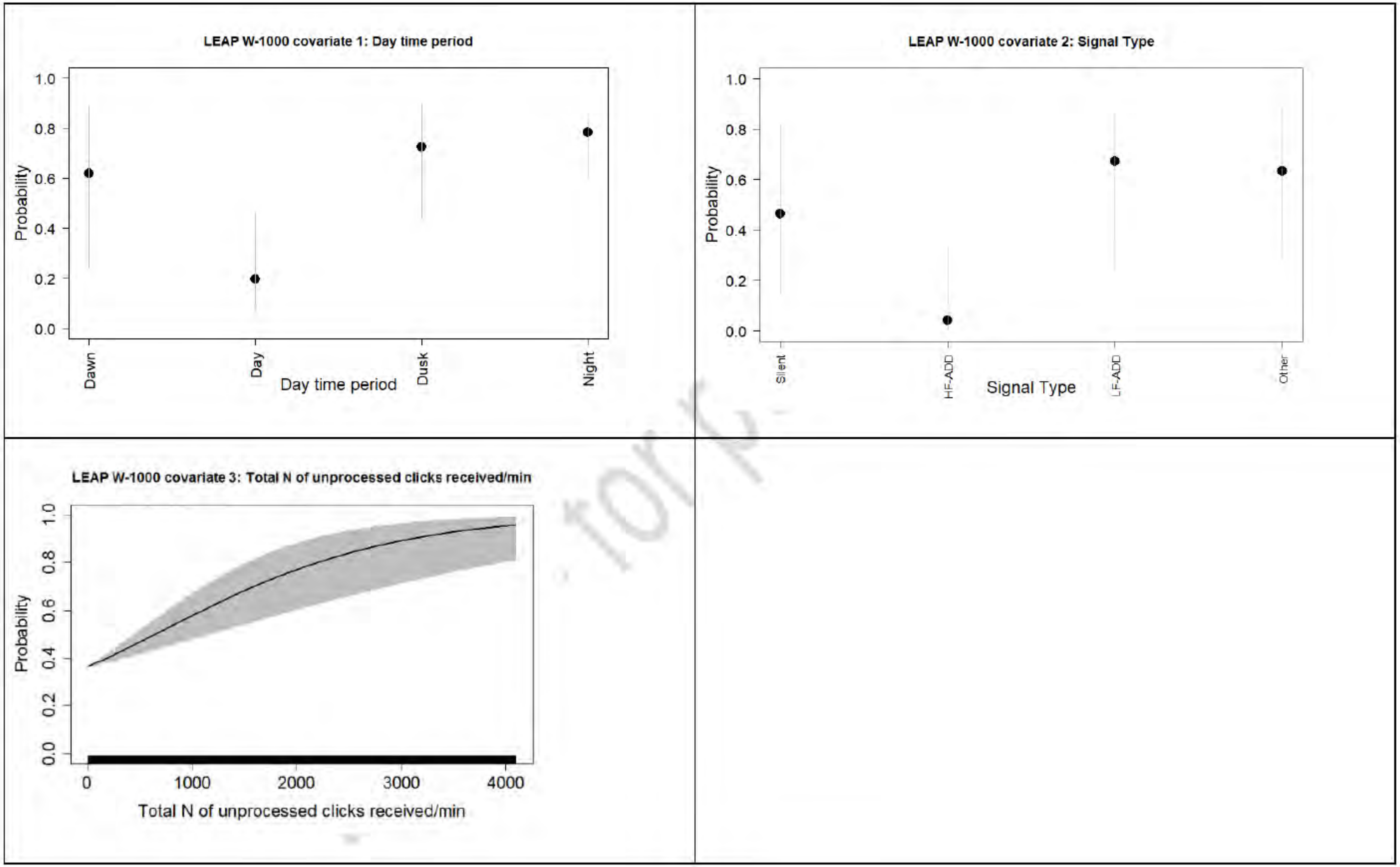
Model:	W-1000
Model structure:	POD5<-geeglm(PPM ~ as.factor(DAYTIMENum) + as.factor(Signal_Type) + Nall_m, family = binomial, corstr="independence", id=Panel, data=W1000)
Confusion matrix:	

		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

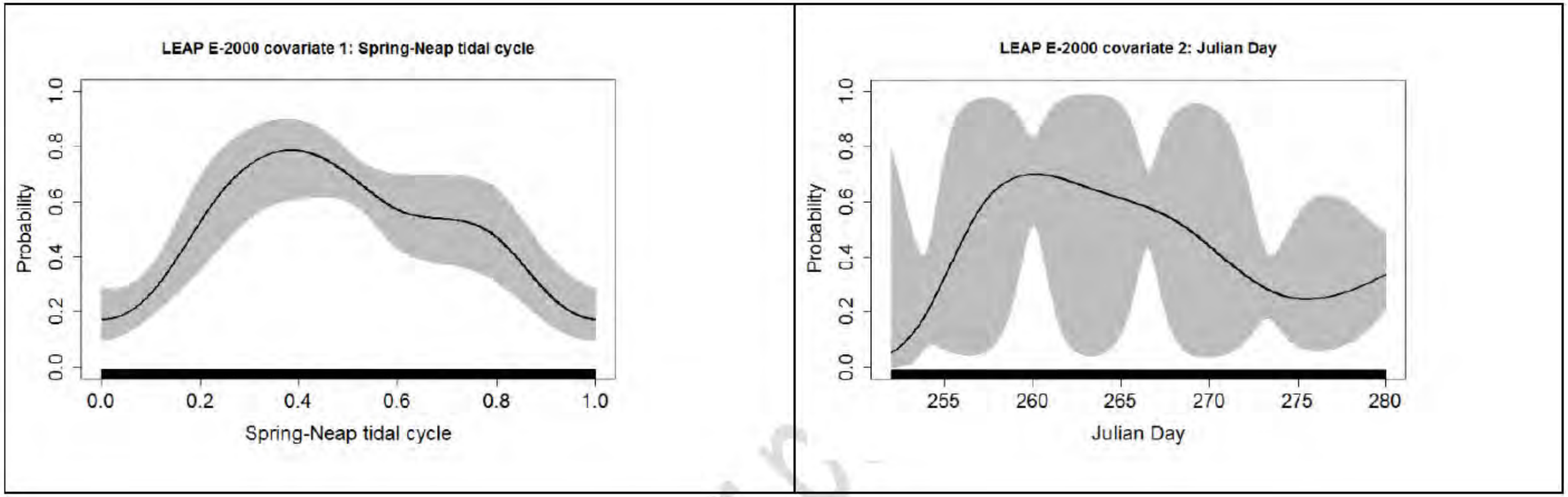
Model:	E-2000
Model structure:	POD5<-geeglm(PPM ~ SprNpBasisMat + bs(JULDAY , knots=mean(JULDAY)) + as.factor(DAYTIMENum) + bs(Nall_m , knots=mean(Nall_m)), family = binomial, corstr="independence", id=Panel, data=E2000)
Confusion matrix:	

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

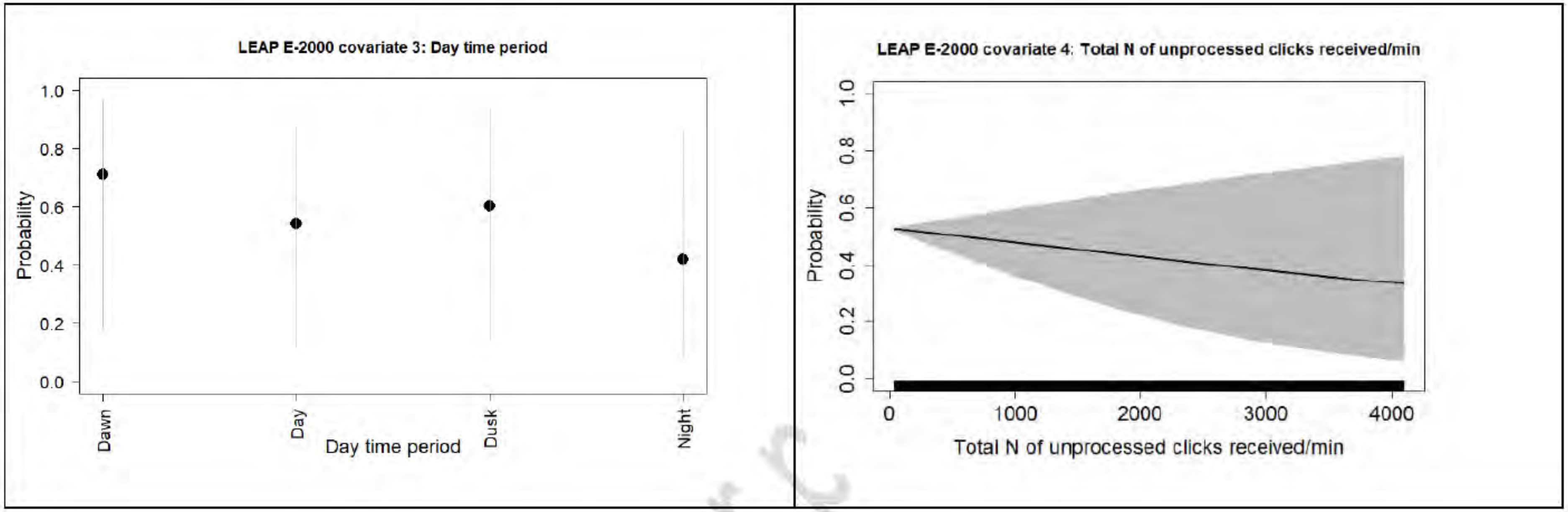
AUC value:	0.7766977

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
0.0
0.2
0.4
0.6
0.8
1.0
Spring-Neap tidal cycle
LEAP E-2000 covariate 2: Julian Day
Probability
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
1.0
0.8
0.6
0.4
0.2
0.0
0
1000
2000
3000
4000
Total N of unprocessed clicks received/min

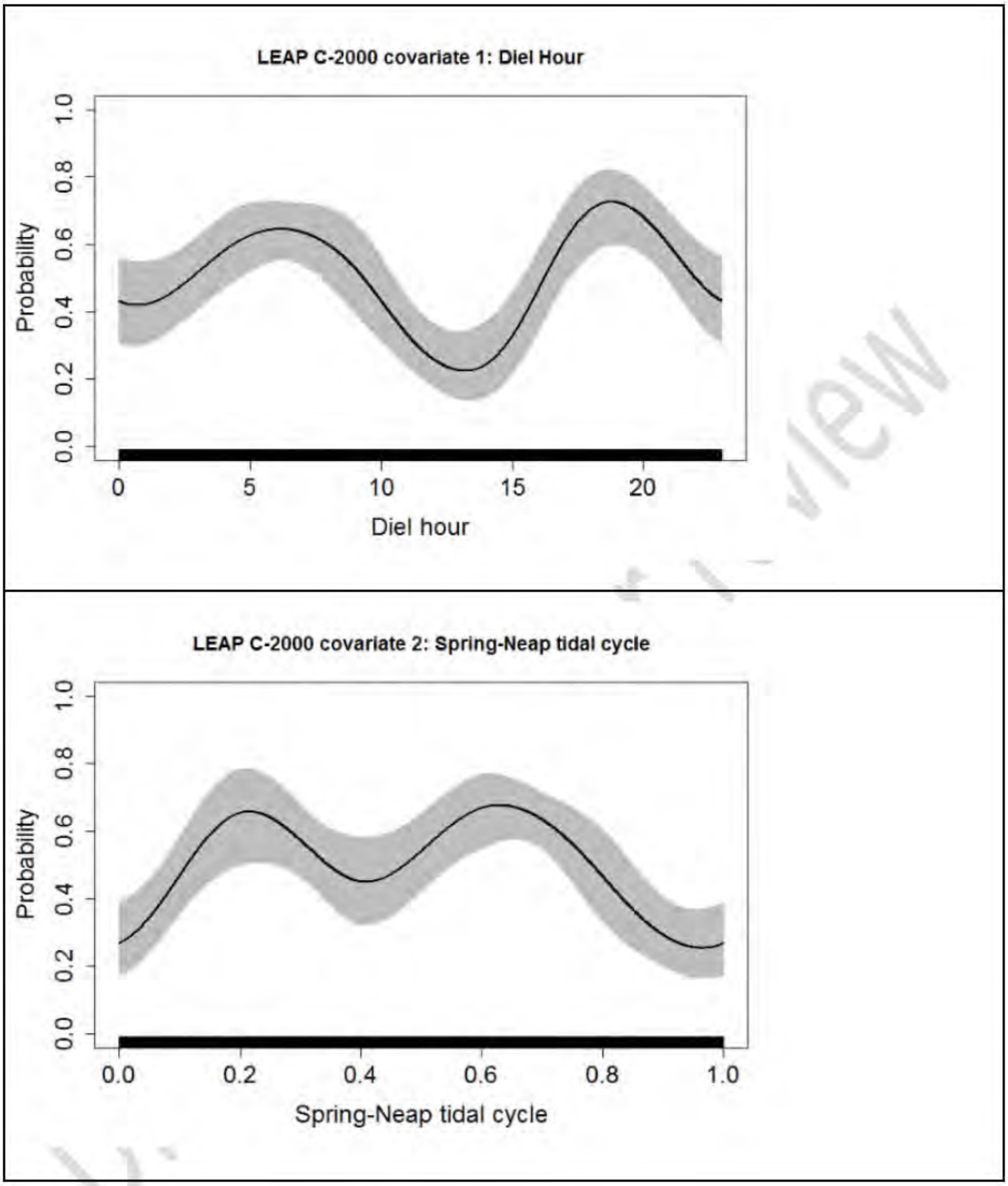
Model:	C-2000
Model structure:	POD5<-geeglm(PPM ~ bs(Nall_m , knots=mean(Nall_m)) + as.factor(DAYTIMENum) + AvgHrBasisMat + SprNpBasisMat, family = binomial, corstr="independence", id=Panel, data=C2000)
Confusion matrix:	
AUC value:	0.7749851

Confusion matrix:

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

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

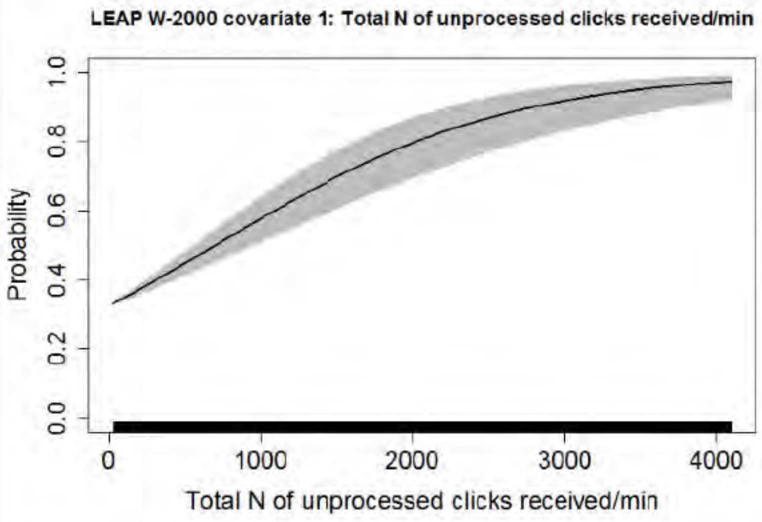
Model:	W-2000
Model structure:	POD5<-geeglm(PPM ~ Nall_m + TideBasisMat + SprNpBasisMat, family = binomial, corstr="independence", id=Panel, data=W2000)
Confusion matrix:	(see below)
AUC value:	0.7838515

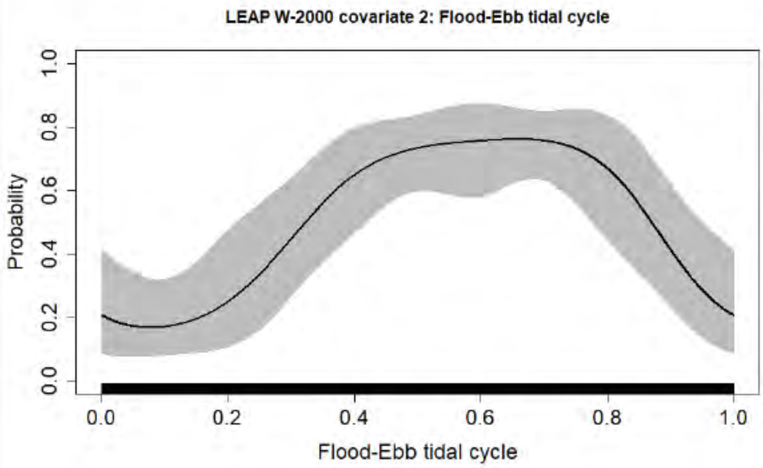
Confusion matrix:

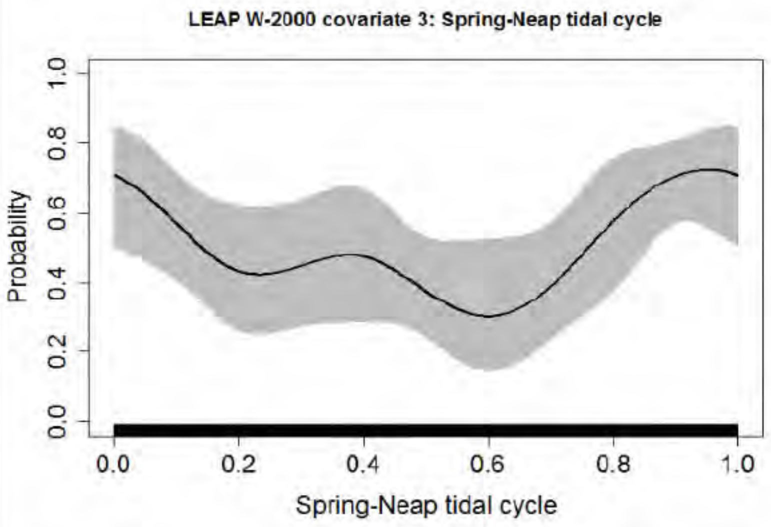
		Expected	
		Porpoise	No porpoise
Observed	Porpoise	88.5%	46.9%
	No porpoise	11.5%	53.1%

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	$<2.2 \cdot 10^{-16}$
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

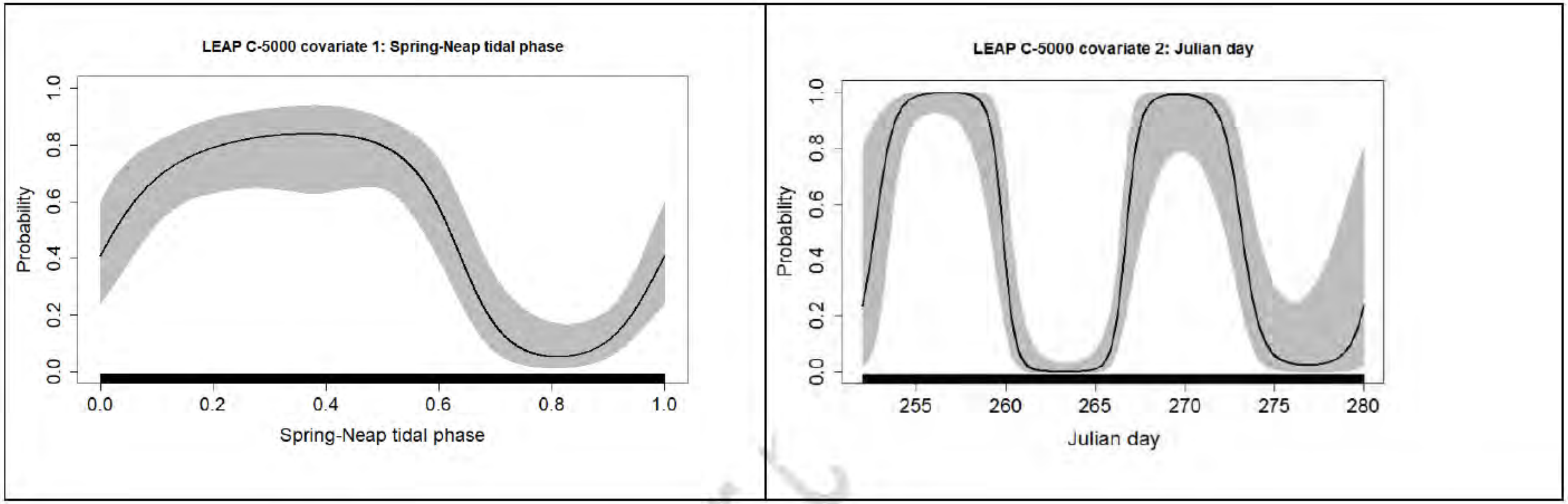
Model:	C-5000
Model structure:	POD5<-geeglm(PPM ~ SprNpBasisMat + bs(JULDAY , knots=mean(JULDAY)) + Nall_m + as.factor(DAYTIMENum) + AvgHrBasisMat, family = binomial, corstr="independence", id=Panel, data=C5000)
Confusion matrix:	(see below)

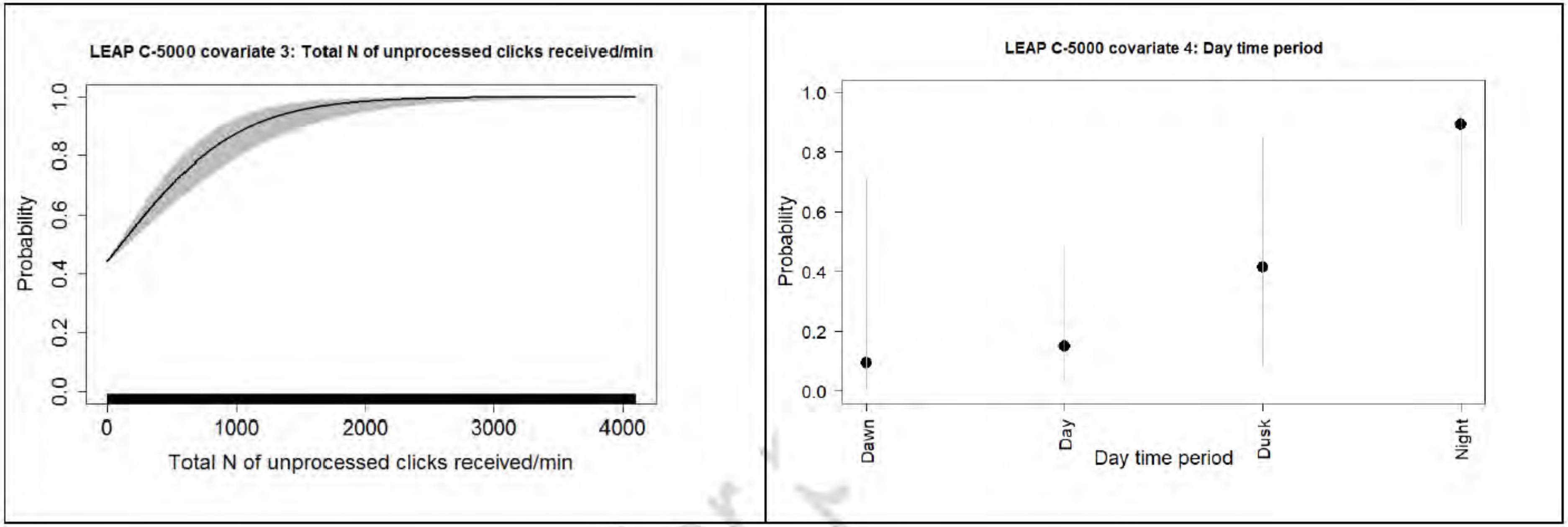
		Expected	
		Porpoise	No porpoise
Observed	Porpoise	80.1%	15.5%
	No porpoise	19.9%	84.5%

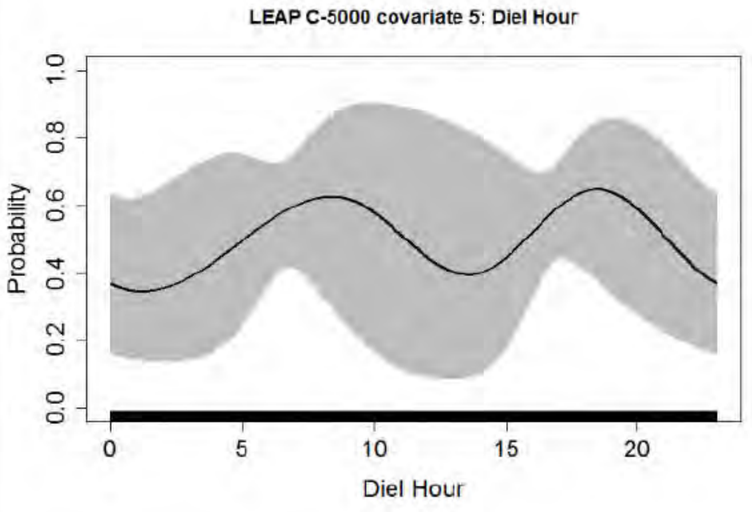
AUC value:	0.8861703

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	$1.678\cdot10^{-12}$
DAYTIMENum	Factor	3	40.503	$8.335\cdot10^{-9}$
HOUR	Cyclic B-spline	4	12.875	$3.291\cdot10^{-8}$


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


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

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

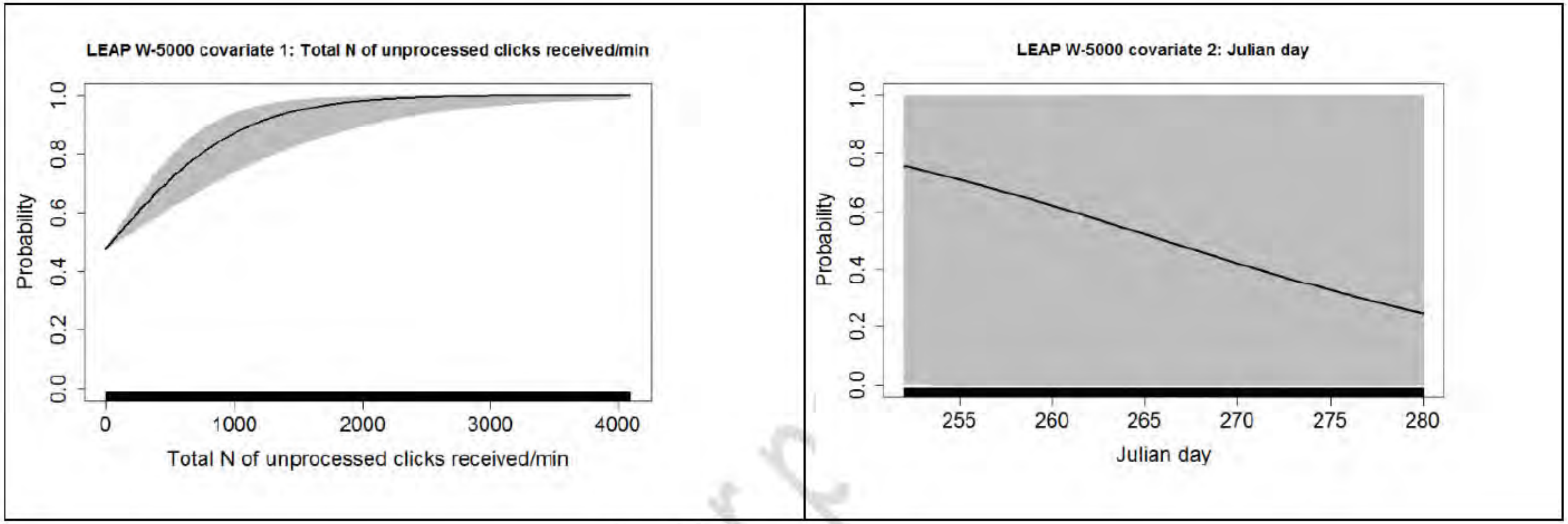
Confusion matrix:

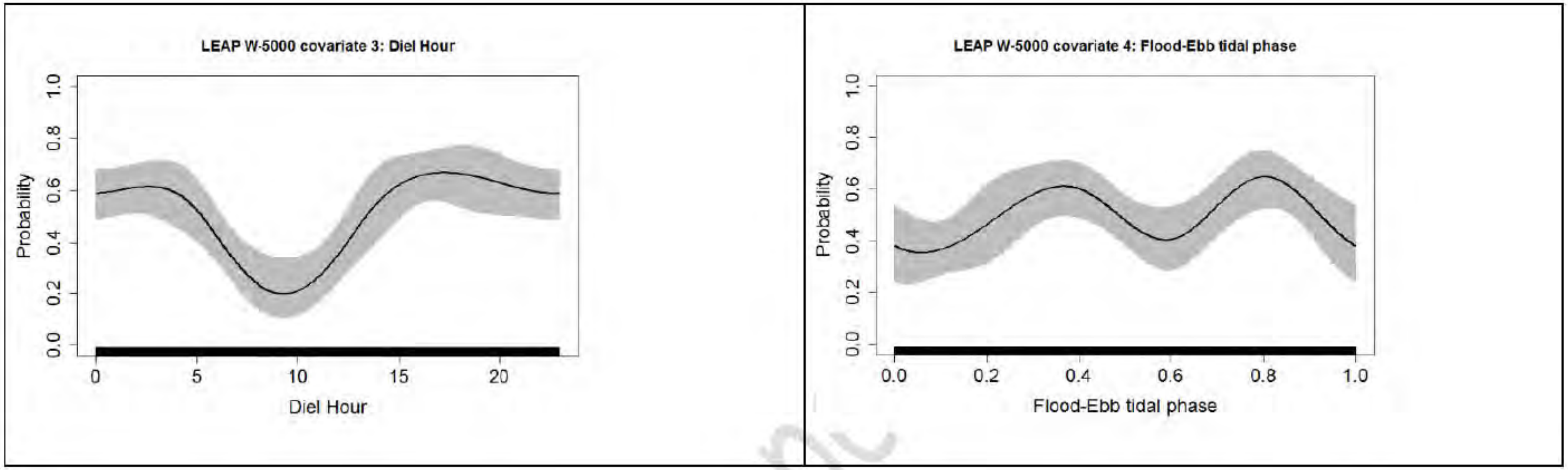
		Expected	
		Porpoise	No porpoise
Observed	Porpoise	58.8%	13.2%
	No porpoise	41.2%	86.6%

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
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

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