Categorizing click trains to increase taxonomic precision in echolocation click loggers.

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A. ABSTRACT

Passive acoustic monitoring is an efficient way to study acoustically active animals but species identification remains a major challenge. C-PODs are popular logging devices that automatically detect odontocete echolocation clicks. However, the accompanying analysis software does not distinguish between delphinid species. Click train features logged by C-PODs were compared to frequency spectra from adjacently deployed continuous recorders. A generalized additive model was then used to categorize C-POD click trains into three groups: broadband click trains, produced by bottlenose dolphin (*Tursiops truncatus*) or common dolphin (*Delphinus delphis*), frequency-banded click trains, produced by Risso's (*Grampus griseus*) or white beaked dolphins (*Lagenorhynchus albirostris*), and unknown click trains. Incorrect categorization rates for broadband and frequency banded clicks were 0.02 (SD 0.01), but only 30% of the click trains met the categorization threshold. To increase the proportion of categorized click trains, model predictions were pooled within acoustic encounters and a likelihood ratio threshold was used to categorize encounters. This increased the proportion of the click trains meeting either the broadband or frequency banded categorization threshold to 98%. Predicted species distribution at the 30 study sites matched well to visual sighting records from the region.

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II.   INTRODUCTION

Passive acoustic monitoring is an established method of studying the movement, distribution and behavior of acoustically active species (Fenton, 1982; Van Parijs *et al.*, 2009; Brookes *et al.*, 2013; Kalan *et al.*, 2015; Kloepper *et al.*, 2016). The field of cetacean ecology has especially benefited from advances in acoustic monitoring as these animals are largely visually inaccessible to researchers for the majority of their lives. Moreover, most cetaceans produce acoustic signals that can be detected by acoustic recorders and data loggers over large distances. Accordingly, passive acoustic monitoring has provided invaluable insights into the habitat use (Mellinger *et al.*, 2007; Van Parijs *et al.*, 2009), communication (Parks *et al.*, 2009), population size (Jaramillo-Legorreta and Rojas-Bracho, 2011; Harris *et al.*, 2013), and behavior (Buckstaff, 2004; Koschinski *et al.*, 2008; Nuuttila *et al.*, 2013; Pirotta *et al.*, 2014b) of multiple genera. Moreover, passive acoustic monitoring is directly involved in both long-term and real-time conservation efforts for protected cetacean species (Clark *et al.*, 2005; Van Parijs *et al.*, 2009; Jaramillo-Legorreta and Rojas-Bracho, 2011; Klinck *et al.*, 2012).

Taxonomic classification of the echolocation clicks of odontocetes is an ongoing problem in passive acoustic surveys. The received characteristics of any given click depend on the animal's behavior as well as the filtering effects of the cranial anatomy, the propagation environment and the parameters of the recording system (Au *et al.*, 1985; Au *et al*., 1995; Carlström, 2005; Johnson *et al*., 2006; DeRuiter *et al.*, 2009; Au et al., 2012a; Roch *et al.*, 2015). Since echolocation signals are highly directional, the received amplitude and spectral characteristics of echolocation clicks further depends on the orientation of the vocalizing animal with respect to the receiver (Rasmussen *et al.*, 2004; Wahlberg et al., 2011; Au *et al.*, 2012b).

42   Together, these filtering effects render it virtually impossible to classify individual echolocation

43   clicks to species.

44   Researchers have addressed the classification task by averaging echolocation click

45   characteristics across multiple clicks, click trains, and/or acoustic encounters. In doing so, group

46   and species-specific features in echolocation clicks have been discovered. For example,

47   Baumann-Pickering *et al.* (2013) compared the location of satellite tagged animals to passive

48   acoustic recordings and was able to describe species-specific characteristics of false killer whale

49   (*Pseudorca crassidens*) and short finned pilot whale (*Globicephala macrorhynchus*)

50   echolocation clicks. Similarly, distributions of peak frequency, center frequency, click duration,

51   inter-click interval (ICI) and bandwidth have been useful in discriminating between the

52   echolocation clicks of melon-headed whales (*Peponocephala electra*), Gray's spinner dolphins

53   (*Stenella longirostris longirostris*) and to a lesser extent, bottlenose dolphins (*Tursiops*

54   *truncatus*) (Baumann-Pickering *et al.*, 2010).

55   In other studies, the structure of the frequency spectrum has proven useful in classifying

56   click trains. In the Pacific, the echolocation clicks of white-sided dolphins *(Lagenorhynchus*

57   *obliquidens)* and Risso's dolphins (*Grampus griseus*) have been shown to display consistent

58   peaks and notches in spectral energy below 48 kHz (Roch *et al.*, 2007). Risso's dolphins click

59   trains contained peaks in energy at 22.4, 25.5, 30.5 and 38.7 kHz and at 22.2, 26.6, 33.7 and 37.3

60   kHz for white-sided dolphins. The spectral location was sufficient to discriminate between the

61   two species but site and instrument-specific anomalies reduced the confidence of the

62   classifications (Roch *et al.*, 2007). In the same habitat, bottlenose dolphin and common dolphin

63   (*Delphinus delphis*) echolocation clicks were found to have a more uniform energy distribution

64   between 40 and 80 kHz (Soldevilla *et al.*, 2008). Echolocation clicks from these species were

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65   nearly indistinguishable but easily discriminated from the peak and notch structure of Risso's

66   and white-sided dolphins, especially when site and instrument specific parameters were

67   accounted for (Roch *et al.*, 2011; Roch *et al.*, 2015). Uniform energy between 40-120 kHz was

68   recorded for on-axis clicks of bottlenose dolphins in the Indian Ocean, and held for off axis

69   angles up to ~13°, beyond which peaks and notches in energy were observed but were dependent

70   on the angle between the animal and the recording system (Wahlberg *et al*. 2011). Similarly, in

71   the North Atlantic Calderan *et al.* (2013) investigated whether the peaks and notches in spectral

72   energy observed in Pacific animals were also present in clicks produced by Risso's and white-

73   beaked dolphin (*Lagenorhynchus albirostris*), the latter having morphologically similar cranial

74   structure to Pacific white-sided dolphins. Towed arrays in western Scottish waters suggested that

75   a similar peak-and-notch structure was present in both species. Taken together, these studies

76   suggest that the presence of stable peak-and-notches in spectral energy may be useful for

77   increasing taxonomic resolution from acoustic recordings.

78   While significant progress has been made in classifying echolocation clicks in continuous

79   recordings, little effort has been directed toward classifying echolocation clicks in click logging

80   devices. C-PODs (Chelonia, Ltd.) are commercially available click logging devices popular in

81   marine studies. The C-POD system returns a series of summary parameters related to detected

82   clicks but does not save the waveform of the clicks themselves. Consequently, the volume of

83   data collected by these systems is drastically less, while some of the click frequency/time

84   information is preserved. Such systems are efficient, have low false positive detection rates, and

85   produce generally consistent output between units (Dähne *et al.*, 2013; Roberts and Read, 2014).

86   For these reasons, C-PODs are a popular tool used to study odontocete behavior and ecology

87   worldwide (Carstensen *et al.*, 2006; Koschinski *et al.*, 2008; Bailey *et al.*, 2010; Pirotta *et al.*,

88 2014a; Jaramillo-Legorreta *et al.*, 2016). For species with mid- to high-frequency echolocation

89 clicks, long-term and full spectrum (*fs* >200 kHz) continuous recordings are often impractical

90 due to the high up-front cost of continuous recorders, high data volumes, time-consuming post-

91 processing to extract echolocation clicks, and limited recording duration compared to click

92 loggers.

93   Data collected by the C-POD data are generally processed to detect the presence of

94 odontocete echolocation click trains with the accompanying KERNO classifier. The KERNO

95 software is capable of discerning between dolphin and porpoise clicks based on the frequency

96 and bandwidth of the detections. However, C-PODs currently lack the ability to discriminate

97 between most dolphin species. Thus, where users can be relatively confident that only the target

98 dolphin species is present, the use of C-PODs has proven to be both cost and time effective

99 (Simon *et al.*, 2010; Pirotta *et al.*, 2015). However, where the scientific and/or regulatory

100 concern focuses on a single species within a large habitat, the ability to discriminate between

101 target and non-target species becomes a critical aspect of the research methodology.

102   The motivation for this study is the need to efficiently monitor the population of

103 bottlenose dolphins resident along the eastern coast of Scotland. This population is protected by

104 a variety of UK and EU regulations including the designation of special areas of conservation

105 (SAC) in the Moray Firth and the Firth of Tay. However, in recent years the population appears

106 to have undergone significant range expansion; while animals are consistently observed within

107 the SAC's, a large proportion of the population partially or fully resides outside of the protected

108 areas (Cheney *et al.*, 2014). Additionally, the construction of large offshore wind farms is

109 planned off Eastern Scotland for the coming years. Determining what effect, if any, the

110 construction, operation, and decommissioning of these structures will have on these animals is

111 important for long term conservation goals. Thus, a better understanding of how the population

112 uses the entire Eastern Scottish coast habitat is needed. One of the primary challenges to meet

113 this objective using passive acoustic monitoring techniques lies in discriminating between target

114 (bottlenose dolphin) and non-target species known to occur in the area. These include common

115 dolphin, Risso's dolphin and white beaked dolphin (*Lagenorhynchus albirostris*) (Weir *et al.*,

116 2007; Quick *et al.*, 2014). Thompson *et al.* (2013) addressed the multi-species concern by

117 integrating visual observations of various dolphin species and echolocation click detections from

118 C-PODs. In their study, effort controlled visual survey data from 1980 through 2010 were

119 combined with up to three seasons worth of C-POD detections from the Moray Firth. Results

120 from their study strongly suggested that bottlenose dolphins primarily occupy the nearshore areas

121 (<10 km from the coast) within the inner Moray Firth while a greater diversity of dolphin species

122 were found in the offshore waters.

123   Discriminating between any dolphin species in C-POD data would represent a major step

124 forward in the application of such systems in multi-species contexts. This challenge of species

125 discrimination has been recognized and approached by researchers working with a similar group

126 of species in Irish waters (Robbins *et al.*, 2015). In that study the authors used multi-dimensional

127 scaling techniques to try and discriminate between visually-confirmed Risso's, common and

128 bottlenose dolphin detections in C-POD data. The authors found that the limited metrics

129 produced by the C-POD system in combination with their own post-processing metrics were

130 insufficient to classify detections to species. This result is unsurprising given the difficulty in

131 discriminating between common and bottlenose dolphin clicks even with continuous, full-

132 spectrum recordings (Soldevilla *et al.*, 2008; Roch *et al.*, 2011).

133   In the present study we investigated the potential for discriminating between echolocation

134   clicks with distinct peaks and notches, hereafter termed "frequency banded" and those that, when

135   averaged across encounters, lack distinct peaks and troughs in spectral energy below 48 kHz,

136   referred to hereafter as "broadband". We denote this task as "categorization" rather than

137   classification as we are not seeking to identify the exact species producing the click-types. We

138   used data from acoustic recorders deployed alongside C-PODs to build a model that

139   discriminated between broadband and frequency-banded clicks in C-POD data, and then used

140   this model to classify data from a larger set of C-PODs for which there was no co-deployed

141   recorder.

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III.   METHODS

A.   Data Collection

145   In the spring of 2013, 30 C-PODs and 10 SM2M (Wildlife Acoustics) recorders were

146   deployed along the eastern Scottish coast (Figure 1). Deployment locations were chosen to

147   maximize acoustic coverage and minimize the likelihood of being displaced by storms or fishing

148   activity. All units were moored to the seafloor using 100kg chain weights. Some were furnished

149   with surface markers, while others had acoustic releases to facilitate recovery. The choice of

150   mooring type was based upon vessel traffic in the deployment location. C-PODs were deployed

151   in ten groups of three, with moorings within the group deployed approximately 5, 10 and 15 km

152   from the coast. Moring locations are hereafter referred to as 5, 10, and 15 to indicate that

153   distances from shore were approximate values only. One SM2M was co-deployed with one of

154   the C-PODs at each group. The SM2M was attached to the same mooring line as the C-POD and

155   the units were separated by more than one meter. This configuration allowed us to compare the

156   continuous recordings from the SM2Ms, from which we could identify broadband and frequency

157   banded echolocation click trains, to the C-POD detection logs. The C-PODs logged continuously

158   from the deployment date, while SM2Ms were programmed to commence recording on Aug 13th

159   2013 with a 10 minute on/off duty cycle and sampling rate of 96 kHz and 12 dB gain. All units

160   recorded until their battery capacity was exhausted and were recovered between October and

161   November of the same year, as weather allowed (Table 1). For units displaced during the

162   deployment, the C-POD outputs related to temperature, angle of the device and sonar detection

163   were examined to determine the date on which the device was moved out of position. All data

164   from midnight of that day onwards were removed from the analysis.

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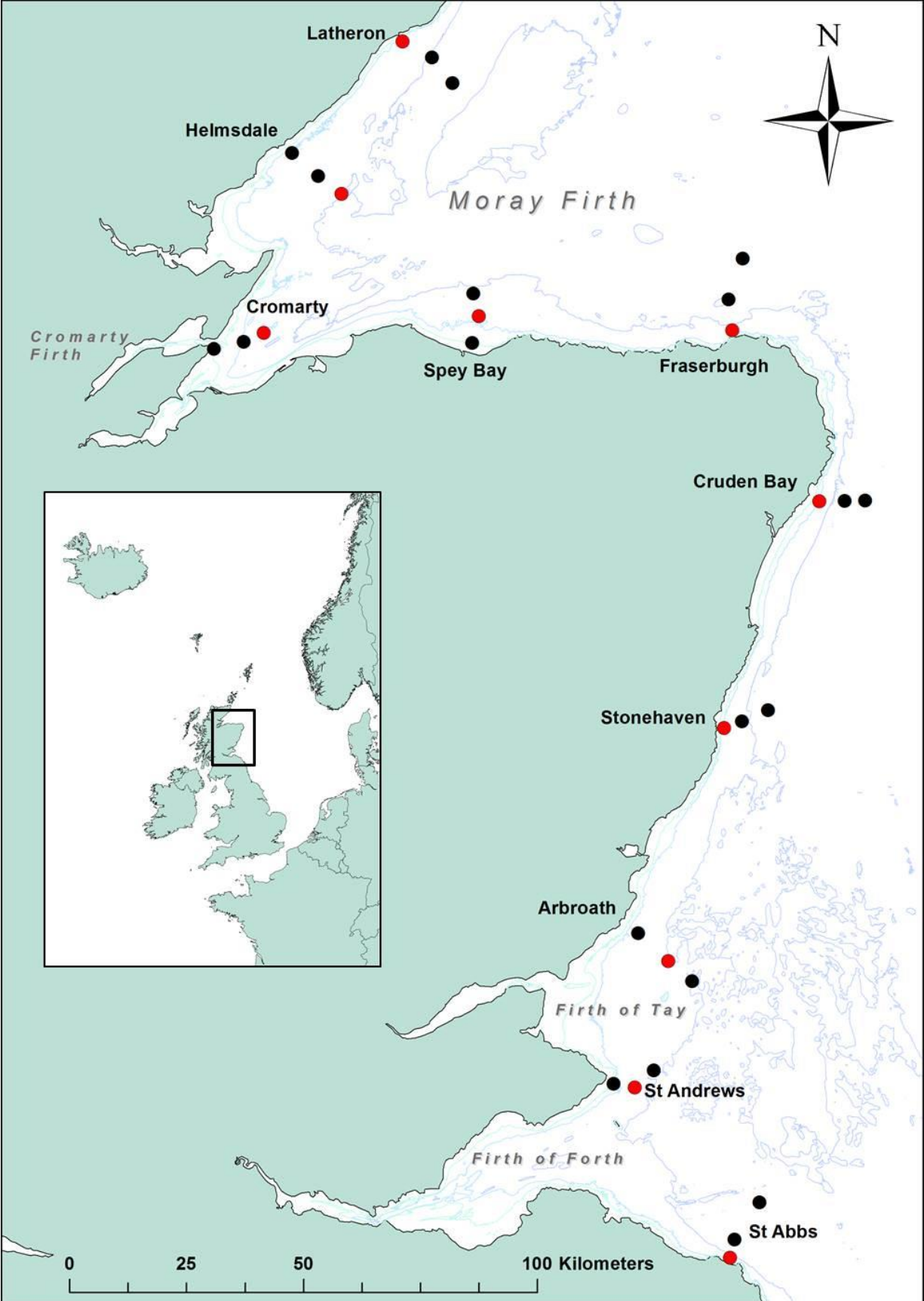
167   **FIGURE 1** Survey locations for the ECOMMAS project C-POD and joint C-POD/SM2M

168   deployment sites on the Eastern Scottish Coast. Deployment sites indicated by nearest large

169   town: Latheron (Lat), Helmsdale (Hel), Cromarty (Cro), Spey Bay (Spe), Fraserburgh (Fra),

170   Cruden Bay (Cru), Stonehaven (Sto), Arbroath (Abr), St Andrews (StA), St Abbs (Stb). All units

171   were placed at approximately 5, 10, or 15km from the coast (color online).

172

173   **TABLE I**

174   Locations, dates and number of days for which usable data were obtained for all deployed

175   devices (SM suffix indicates SM2M units, all others are C-PODs). For C-PODs, the number of

176   click trains logged, the number of acoustic encounters, and the number of broadband or

177   frequency banded click trains contributed to the training dataset, along with – in parentheses –

178   the number of unique days represented by that contribution, are also given All dates are dd/mm

179   in 2013. Five C-POD deployments that returned no usable data are omitted – Spey Bay 15,

180   Fraserburgh 10 and 15, Cruden Bay 10, and Stonehaven 10.

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Location name (SM=SM2M unit)	Data From	Data To	# Days	# Click Trains	# Encounters	Training Data	
						Broadband	Frequency-banded
Latheron 5	31/07	23/10	84	480	26		337 (9)
Latheron 5 SM	10/08	14/10	65				
Latheron 10	20/06	09/10	111	71	3		
Latheron 15	20/06	07/10	109	36	4		
Helmsdale 10	20/06	10/10	112	144	6		
Helmsdale 5	01/08	22/10	82	0	0		
Helmsdale 15	20/06	06/10	108	5	1		
Helmsdale 15 SM	10/08	25/09	46				
Cromarty 5	01/08	21/10	81	3680	199		
Cromarty 10	01/08	25/08	24	105	9		
Cromarty 15	01/08	23/10	83	23	4	22 (2)	

Cromarty 15 SM	10/08	15/10	66				
Spey Bay 5	24/07	22/10	90	330	24		
Spey Bay 10	20/06	06/10	108	0	0		
Spey Bay 10 SM	10/08	12/10	63				
Spey Bay 15	-	-	-				
Fraserburgh 5	25/07	24/10	91	859	21		303 (8)
Fraserburgh 5 SM	10/08	07/10	58				
Fraserburgh 10	-	-	-				
Fraserburgh 15	-	-	-				
Cruden Bay 5	26/07	26/11	123	910	29		
Cruden Bay 5 SM	10/08	12/10	63				
Cruden Bay 10	-	-	-				
Cruden Bay 15	19/06	26/11	160	541	31		
Stonehaven 5	26/07	26/11	123	955	34	226 (7)	32 (2)
Stonehaven 5 SM	10/08	03/10	54				
Stonehaven 10	-	-	-				
Stonehaven 15	19/06	26/11	160	1047	77		
Arbroath 5	27/07	26/10	91	224	16		
Arbroath 10	27/07	25/10	90	20	2		
Arbroath 10 SM	10/08	11/10	62				
Arbroath 15	21/06	27/11	159	887	44		
St Andrews 5	27/07	28/10	93	183	22		
St Andrews 10	27/07	28/10	93	0	0		
St Andrews 10 SM	10/08	18/10	69				
St Andrews 15	21/06	10/10	111	55	3		
St Abbs 5	27/07	27/11	123	55	6	5 (1)	
St Abbs 5 SM	10/08	03/10	54				
St Abbs 10	27/07	25/10	90	71	4		
St Abbs 15	20/06	27/11	160	72	8		

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B.   *C-POD Click Detection and Feature Extraction*

C-POD data were downloaded and processed for echolocation click detections using the

manufacturer's software and accompanying KERNO classifier (v2.042). The KERNO software

classifies impulsive detections into one of the following four groups: "Sonar", "NBHF"

190   (narrowband high-frequency click trains often indicative of porpoise species), "Other Cet"

191   (wideband clicks indicative of most dolphin species) and "Unk" (representing

192   unclassified/unknown clicks). The C-POD software and KERNO classifier group "NBHF" and

193   "Other Cet" signals into short "click trains" based on temporal proximity and assign a "click

194   train ID" to each such group. The manufacturer states that this detection and classification

195   system allows multiple clicking animals to be differentiated from each other. The KERNO

196   classifier also assigns a quality class to each detection (high, moderate, or low) indicating the

197   probability that the click train was correctly discriminated from other "non-train" sources such as

198   snapping shrimp or rain (Tregenza, 2016).

199   The click features (referred to as "details" in the accompanying software) logged by C-PODs

200   are non-standard in the acoustics field and so require careful interpretation. Specifics of the click

201   features are proprietary and defined by the manufacturer as the time of the click, measured with

202   5µs resolution, dominant zero-crossing frequency (fZC, which should not be confused with peak

203   frequency), end zero-crossing frequency (derived from the last zero-crossing interval),

204   bandwidth measured on an "arbitrary scale" (manufacturers description), and click duration

205   measured as the number of cycles at the dominant frequency (NCycles). C-PODs also document

206   a metric of amplitude which, though reported as sound pressure level, is not corrected for

207   hydrophone frequency response (Dähne *et al.*, 2013). For this analysis, all "high" or "moderate"

208   quality "Other Cet" detections were selected and the accompanying click features, referred to as

209   "click details" by the manufacturer, were exported to a text file. For each click train (i.e. all

210   clicks with the same "click train ID"), we also calculated the median inter-click-interval, mean

211   dominant zero-crossing frequency, mean bandwidth and mean click duration (NCycles).

C. C-POD Data Quality

Initial data exploration was undertaken to identify collinearity between click train features documented by the C-POD. The distributions of all train features were visually inspected and we excluded all click trains for which there were insufficient data to produce reliable models (i.e. the tails of the distributions). Thus, all click trains with median inter-click-intervals greater than or equal to 0.4 seconds, mean click durations greater than or equal to 11 cycles (NCycles), mean bandwidths greater than or equal to 7 (manufacturers arbitrary units), or dominant frequencies less than 30 kHz were excluded from the categorization portion of the analysis (resulting in the removal of ~1% of all logged click trains).

We then grouped C-POD click trains into "acoustic encounters," consisting of all click trains on the same C-POD occurring within 30 minutes of another click train (Thompson *et al.*, 2011). In this process we assume that each encounter was produced by the same animal or group of animals and that groups of acoustically dissimilar species (e.g., Risso's and bottlenose dolphins) were not represented in the data. This is consistent with visual observations indicating that mixed odontocete groups, especially any containing bottlenose dolphins, are extremely rare in Scottish coastal waters (Ross and Wilson, 1996; Hammond *et al.*, 2002).

### D. Identifying Broadband and Frequency Banded Click Trains in the C-POD Detections

The few click features documented by the C-POD system are not sufficient to allow users to visually discriminate between click trains matching the broadband and frequency banded categories described above. Thus, we used continuous recordings to identify time periods with clearly identifiable bouts of broadband or frequency banded click trains. These periods were compared to the click log produced by the C-POD at to the same mooring. Where echolocation

236   click trains were present on both instruments at the same time, we assumed that the echolocation

237   click trains had originated from the same animal or group of animals.

238   Data from the SM devices were downloaded, converted to spectrograms (1024 point fast-

239   Fourier transform , 10.67 ms window, and 50% overlap) and processed for echolocation clicks

240   using PAMGuard click detecting software (Gillespie *et al.*, 2009). Click detection trigger was set

241   to 10 dB and click detections were manually scanned for the presence of high signal-to-noise

242   echolocation click encounters and annotated as such. Echolocation clicks from high SNR

243   encounters containing at least 500 clicks were extracted and the average spectrum was inspected

244   for the presence of either distinct peaks or notches in energy indicative of white-beaked or

245   Risso's dolphins or unimodal energy between 20 and 40 kHz suggestive of bottlenose and/or

246   common dolphins. While visually inspecting the continuous recordings for high SNR frequency

247   banded click trains, we did not seek an exact match the location of the spectral energies as

248   reported by reported by Calderan *et al.* (2013) or Soldevilla *et al.* (2008). Both environment and

249   recording equipment impart site and equipment-specific filter effects on the received signals

250   (Roch *et al.*, 2015). We expect some variation in the received characteristics of echolocation

251   clicks. Neither did we attempt to differentiate between species within the two click encounter

252   types (e.g. common vs bottlenose dolphin). Instead encounters where the average spectrum

253   contained at least two peaks in energy between 35 and 43 kHz and with >3 dB peak-to-peak

254   difference between successive peaks and notches were annotated as "frequency banded". Click

255   encounters for which there was a unimodal peak in energy between 20 and 30 kHz were

256   annotated as broadband (Figure 2).

257
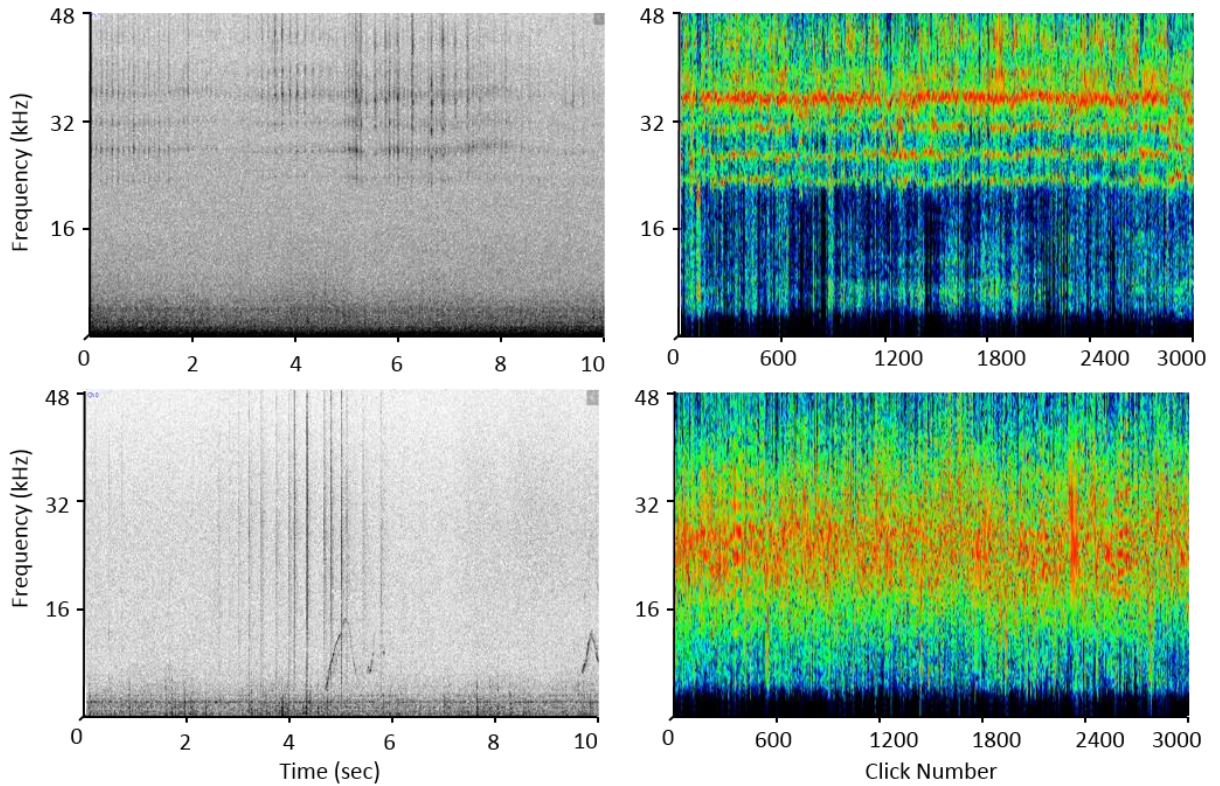
FIGURE 2 Spectrograms (left) (*fs* 96 kHz, 10.67 ms Hann window, 50% overlap) and concatenated click spectrums (right) of echolocation clicks within from frequency banded (top) and broadband (bottom) acoustic encounters. Top row: 10 seconds of recordings from a frequency banded encounter consistent with white beaked and/or Risso's dolphins and 3000 concatenated echolocation clicks from the frequency banded encounter. Bottom row: 10 seconds of recordings from a broadband encounter containing whistles and echolocation clicks consistent with bottlenose and/or common dolphins (color online).

The timing of acoustic encounters documented by the C-PODs were compared with the times of broadband and frequency banded click trains observed in the continuous SM2M

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270   recordings. The train features from "high" or "moderate" quality "other cetacean" trains

271   coinciding with visually confirmed broadband and frequency banded encounters in the

272   continuous recordings were used to build and train categorization models.

273   To increase the volume of C-POD click trains from broadband encounters, click train

274   features from the Cromarty 5 C-POD, for which there was no adjacent SM2M recorder, were

275   randomly selected for inclusion in the broadband training dataset. Despite the lack of concurrent

276   acoustic recordings, we are confident that the vast majority of the click trains logged by the C-

277   POD at this location were produced by bottlenose dolphins and as such represented our

278   broadband category. The area in and around the Cromarty and inner Moray Firths has been

279   continuously surveyed for the last 25 years and is a well-known bottlenose dolphin habitat that

280   (Hammond and Thompson, 1991; Wilson *et al.*, 2004; Cheney *et al.*, 2013; Thompson *et al.*,

281   2014; Pirotta *et al.*, 2015). These studies strongly suggest that no dolphin species besides

282   bottlenose regularly occupy the area. To further reduce the probability of including frequency

283   banded click trains in the broadband training data, only click trains from the month of August,

284   coinciding with the majority of visual surveys, were added to the training dataset.

285   Obtaining a representative sample of echolocation click behaviors is important in order to

286   produce an accurate categorization system. Of the 1195 C-POD click trains that could be linked

287   to trains in the adjacent SM recordings only 270 (22%) were broadband. We added only as many

288   click trains from the Cromarty 5 site as needed to provide an equal number of broadband and

289   frequency banded click trains for the categorization task. We could have reasonably included all

290   of the data from the Cromarty 5 C-POD based on the overwhelming evidence showing that the

291   area is primarily occupied by bottlenose dolphins. However, we chose to limit the number of

292   auxiliary click trains included from this C-POD for two reasons. First, the Cromarty 5 unit

293   contained almost as many "OtherCet" click trains as the other 25 recovered C-PODs combined.

294   Therefore, we sought to reduce potential bias introduced by site-specific behavior present in the

295   data from that unit. Second, the Cromarty Firth is a known "hot-spot" for bottlenose dolphin

296   foraging activity (Hastie *et al.*, 2004; Hastie *et al.*, 2006; Pirotta *et al.*, 2014b). Thus, we would

297   expect to document more clicks with shorter inter-click-interval (reflecting the production

298   terminal buzzes characteristic of prey capture attempts) near that location (Pirotta *et al.*, 2014b).

299   Including an excessive number of buzzes in the training data would introduce bias towards low

300   ICI's within the broadband category.

301   *E.   Model-based Prediction and Categorization*
302   The above procedures generated a set of C-POD click trains, with measured features, for

303   which we were reasonably confident of the species group producing the clicks. We used these

304   acoustically verified click trains to build and characterize a binomial family generalized additive

305   model (GAM) that output the predicted probability that each click train consisted of broadband

306   clicks. The covariates for this model included: median inter-click-interval, mean zero-crossing

307   frequency, mean click bandwidth and mean click duration. The GAM categorization model was

308   created in R version 3.2.4 revised (R Core Team, 2016) with the MGCV package version 1.8-12

309   (Wood, 2006).

310   Here, our goal was to build and select the GAM model best able to discriminate between the

311   two echolocation click types commonly documented on the eastern Scottish coast. Thus, a *k*-fold

312   cross validation approach was used to characterize candidate GAM models and provide

313   parameters for final model selection.

314

Predicted Value

Click Train Number

Classification Threshold
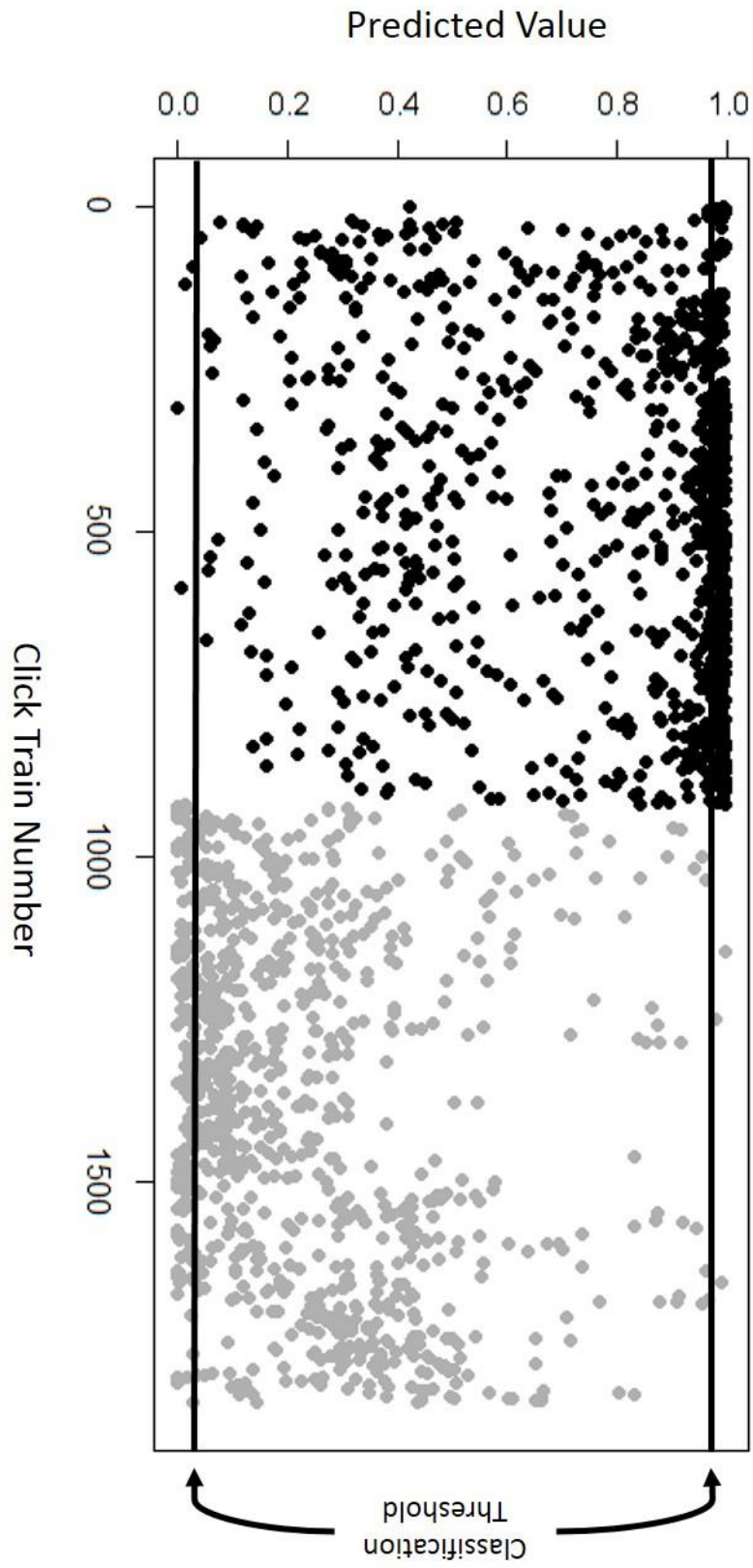
315

316   **FIGURE 3** Predicted probability of a C-POD echolocation click train being associated with

317   broadband encounter from the adjacent recordings (*P*, Equation 1). Points represent C-POD click

318   trains associated with broadband (black) and frequency banded (grey) click encounters in the

319   adjacent SM2M recordings. Horizontal lines represent the minimum classification threshold (*Tt*,

320   Equation 2) above and below which click trains were classified as broadband and frequency

321   banded, respectively. Click trains failing to meet the threshold (i.e. between the lines) were

322   deemed too ambiguous to classify and left uncategorized.

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324

325   For model comparison, all candidate GAMs were assessed using 200 iterations of a 5-fold

326   cross-validation procedure and train categorization threshold of 0.425 (*Tt*; Equation 1). Thus, all

327   click trains with predicted *P* exceeding 0.925 were categorized as broadband and those less than

328   0.075 were categorized as frequency banded (Equation 1, Figure 3). Click trains with predicted

329   probabilities between 0.075 and 0.925 were considered too ambiguous to categorize and were

330   therefore denoted as "unknown".

331

332

333    $$Train\ Classification(P) = \begin{cases} P \geq 0.5 + T_t \rightarrow Broadband \\ P \leq 0.5 - T_t \rightarrow Frequency\ banded \\ 0.5 - T_t < P < 0.5 + T_t \rightarrow Unclassified \end{cases} \quad \text{(Equation 1)}$$

334

335

336   For each model iteration 1/5th of the verified C-POD click trains were randomly selected and

337   used as the validation set. The remaining 4/5ths of the verified C-POD click trains were used to

20

338   build the GAM models. In this portion of the analysis acoustic encounters were not considered

339   and all verified click trains were treated as independent. For each iteration, we calculated the

340   following metrics: proportion of broadband and frequency banded click trains that met either

341   categorization threshold (proportion classified), the proportion of correctly categorized click

342   trains (correct categorization rate), and the proportion of incorrectly categorized click trains

343   (incorrect categorization rate). Performance values for each GAM were calculated using the

344   same train threshold for all models (T_t, Equation 1). We then calculated the mean and standard

345   deviation of all performance metrics across the 200 iterations and used these values to select the

346   model meeting our selection criteria.

347   Model selection focused on reducing the proportion of frequency banded click trains

348   incorrectly categorized as broadband, and thereby minimize the chances of artificially inflating

349   the bottlenose dolphin occupancy rates throughout the survey area. We also sought to categorize

350   the highest proportion of click trains possible, regardless of type. Thus, our model selection

351   criterion (SC) was defined as:

352

353    $$SC = 3FP_f + U \qquad\qquad \text{(Equation 2)}$$

354

355   Where FP_f was the false positive rate for frequency banded click trains and U was the

356   proportion of uncategorized click trains. We introduce a scalar value of three representing our

357   qualitative decision to penalize frequency banded click trains incorrectly categorized as

358   broadband over click trains left uncategorized. The selection criterion was calculated for all

359   candidate models and the GAM with the lowest criterion score was used to predict the

360   probability that each click train was comprised of broadband clicks.

361 ### *F.   Encounter Likelihood*

362 By itself, the GAM model could not account for the fact that click trains recorded in close

363 succession were most likely produced by the same individual or group of animals (Quick *et al.*,

364 2014). To incorporate this information and increase the proportion of categorized click trains, we

365 calculated the joint likelihood of each acoustic encounter by taking the product of all GAM

366 predictions within the acoustic encounter. We then calculated the joint likelihood that all click

367 trains comprising each encounter were either broadband or frequency banded. The two

368 likelihoods were then combined into a likelihood ratio (*LR*; Equation 3) calculated as;

369

370
$$LR = \frac{\prod_{i=1}^{n} P_i}{\prod_{i=1}^{n}(1-P_i)}$$
(Equation 3)

371

372 where P_i is the predicted probability from the GAM categorization model that the ith of n click

373 trains in the acoustic encounter was broadband. Since the model was binary, the likelihood that

374 an encounter was comprised of frequency banded click trains was calculated by simply replacing

375 P_i with $(1 - P_i)$ to give the denominator of Equation 3. As with the click train analysis, a

376 minimum likelihood encounter threshold (T_e; Equation 4) was chosen above and below which all

377 trains within acoustic encounters were categorized as broadband or frequency banded:

378

379
$$Encounter\ Classification = \begin{cases} Broadband,\ LR \geq T_e \\ Frequency\ Banded,\ LR \leq 1/T_e \\ Unclassified,\ 1/T_e < LR < T_e \end{cases}$$
(Equation 4)

380

381 In this portion of the analysis we therefore needed to choose a minimum likelihood threshold

382 (T_e) that balanced the risk of incorrectly classifying encounters against the risk of failing to

383   classify most encounters. We compared the encounter categorization produced by the likelihood

384   ratios to the validated training data to determine the correct and incorrect encounter classification

385   rates. Through a process of trial and error we found that T_e=5, so that the evidence had to be five

386   times as strong for one option than the other for a positive classification to be made, produced

387   the optimal balance of maximizing classification rates while minimizing classification errors.

388   Thus all encounters with likelihood ratios above 5 were classified as broadband and encounters

389   with likelihood ratios below 1/5 were classified as frequency banded. All click trains from

390   encounters with likelihood ratios (*LR*) between 1/5 and 5 were deemed too ambiguous for

391   categorization and were left uncategorized. Finally, the GAM and the encounter analysis were

392   applied to the full C-POD data set for which simultaneous acoustic recordings were not

393   available.

394

IV.   RESULTS

A.   *Echolocation Click Encounters in C-PODs and Continuous Recordings*

398   All SM2M units were successfully recovered in late 2013, but four C-PODs were not

399   recovered, while four others were on moorings that had been displaced, or had stopped recording

400   early, and subsequently excluded from the analysis (Table 1, Figure 6).The number of usable

401   recording days varied considerably between units based on battery life and/or displacement

402   during the survey period. The median number of usable days for the C-PODs was 108 (range 24-

403   160). Due to the increased power and storage requirements, the SM2M units recorded for fewer

404   days than the C-PODs, with a median number of recording days of 62.5 (range 46 -69; Table 1).

405   Together the C-PODs identified 10,753 high or moderate quality "Other Cet" click trains,

406   representing undetermined delphinid species (Table 1). The number of "Other Cet" click trains

23

407   logged by each C-POD varied from zero (recorded by the Helmsdale 10, Spey Bay 10 and St

408   Andrews 10 units; Figure 1) to a maximum of 3662 (recorded by the Cromarty 5 unit).

409   Of these, 1% represented click trains from the tails of the click feature distributions where there

410   therefore excluded from the analysis. Data exploration indicated that dominant frequency and

411   end frequency were collinear and so the latter was excluded from the categorization analysis.

412   ## B.   C-POD Echolocation Click Features
413   Five of the 10 C-PODs deployed with adjacent SM2Ms registered click trains that were also

414   identifiable in the full spectrum SM2M recordings (Table 1). The lack of concurrent detections

415   in the other five C-POD/SM2M pairs could partly be attributed to the very few echolocation

416   click detections by either the SM2M or the C-POD those locations (e.g., Spey Bay and St

417   Andrews 10). In other cases, such as Cruden Bay 5, the failure to detect clicks on the adjacent

418   SM2M likely arose from the duty cycle of the SM2M units which precluded visual

419   categorization of the echolocation clicks. Last, differences in detection probability between the

420   C-PODs and SM2M units may result in fewer click trains overall being recorded by the C-PODs.

421   In total, 925 click trains detected by the KERNO classifier occurred concurrently with

422   visually confirmed broadband (n=253) or frequency banded (n=672) click train encounters in the

423   continuous recordings. The vast majority of verifiable broadband click trains (89%) were

424   extracted from the Stonehaven 5 deployment. This distribution was therefore not representative

425   of either the spatial or temporal scale of the survey. To obtain a more representative sample of

426   broadband click features, 419 click trains were randomly selected from the Cromarty 5 C-POD,

427   where long term sighting records confirm the overwhelming presence of bottlenose dolphins, and

428   added to the broadband training. Four hundred and nineteen were used so as to include an equal

429   number of frequency banded and broadband click trains with which we built the GAM for

430   categorization (see Methods).

C.   Categorization Model Performance

The model with the best categorization score was a tensor product smooth with mean zero-crossing frequency, mean bandwidth and median inter-click interval (Table 2). Tensor smooths are multi-variate functions that allow for interactions between inputs with different units (e.g. frequency in kHz, and Number of Cycles). Five-fold cross validation resulted in a mean false categorization rate of 1.4% for verified frequency banded click trains and, on average, categorized 40% of the training data (Figure 4, Table 3).

TABLE II

Mean and standard deviation for the true classification rate (TCR), false classification rate (FCR), and proportion of unclassified click trains for each model as estimated by the k-fold cross validation. Mean and standard deviation of the GAM classification model performance metrics for the top 15 models using a classification threshold (T_t, Equation 2) of ±0.425. Grey highlight indicates model selected for this analysis and (*) indicates the initial 'best guess' model used to establish a classification threshold (T_t) for all analysis. (Equation 1)
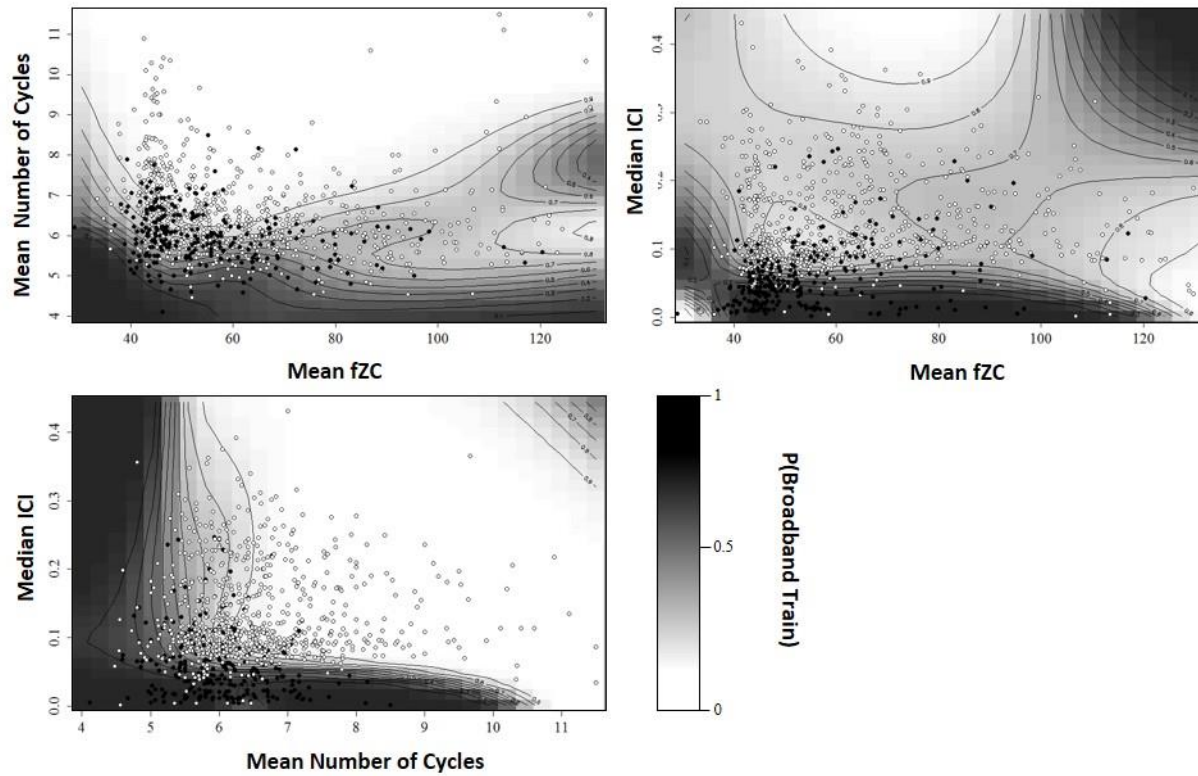
Formula	Broadband Click Trains		Frequency Banded Click Trains			
	TCR	FCR	TCR	FCR	Unclassified	Selection Criterion
Speciesid~te(MedICI, MeanNCycles, Meanzfc)	0.49 ± 0.02	0.02 ± 0.01	0.29 ± 0.02	0.01 ± 0.01	0.60 ± 0.01	0.638
Speciesid~te(MedICI, MeanNCycles, Meanzfc)+s(MeanBW)	0.49 ± 0.02	0.02 ± 0.01	0.29 ± 0.02	0.02 ± 0.01	0.59 ± 0.01	0.640
Speciesid~te(MedICI, MeanNCycles, MeanBW)+s(Meanzfc)	0.48 ± 0.03	0.03 ± 0.01	0.28 ± 0.04	0.02 ± 0.01	0.60 ± 0.03	0.644
Speciesid~te(MedICI, MeanNCycles, MeanBW, Meanzfc)	0.47 ± 0.03	0.03 ± 0.01	0.27 ± 0.03	0.02 ± 0.01	0.61 ± 0.02	0.658
Speciesid~te(MedICI, MeanNCycles, MeanBW)	0.47 ± 0.03	0.03 ± 0.01	0.27 ± 0.03	0.02 ± 0.01	0.61 ± 0.02	0.659
Speciesid~te(MedICI, MeanBW, Meanzfc)+s(MeanNCycles)	0.52 ± 0.03	0.02 ± 0.02	0.20 ± 0.05	0.02 ± 0.01	0.62 ± 0.05	0.681
Speciesid~te(MedICI,MeanNCycles)+s(MeanBW)+s(Meanzfc)	0.48 ± 0.03	0.02 ± 0.01	0.19 ± 0.03	0.02 ± 0.01	0.65 ± 0.02	0.693
Speciesid~s(MedICI)+te(MeanNCycles, MeanBW, Meanzfc)	0.48 ± 0.03	0.01 ± 0.01	0.21 ± 0.03	0.02 ± 0.01	0.64 ± 0.03	0.693
Speciesid~te(MedICI, MeanNCycles)+s(Meanzfc)	0.49 ± 0.03	0.02 ± 0.01	0.19 ± 0.03	0.02 ± 0.01	0.65 ± 0.02	0.698
Speciesid~te(MedICI, MeanNCycles)+s(MeanBW)	0.48 ± 0.03	0.02 ± 0.01	0.18 ± 0.02	0.02 ± 0.01	0.65 ± 0.02	0.704
Speciesid~s(MedICI)+te(MeanNCycles, Meanzfc)+s(MeanBW)	0.48 ± 0.03	0.01 ± 0.01	0.18 ± 0.02	0.02 ± 0.01	0.66 ± 0.02	0.717
Speciesid~te(MeanNCycles, Meanzfc)+s(MedICI)	0.47 ± 0.03	0.01 ± 0	0.16 ± 0.02	0.02 ± 0.01	0.67 ± 0.02	0.728
Speciesid~te(MedICI, Meanzfc)+s(MeanNCycles)+s(MeanBW)	0.47 ± 0.02	0.01 ± 0.01	0.14 ± 0.02	0.02 ± 0.01	0.68 ± 0.02	0.729
Speciesid~s(MedICI)+te(MeanNCycles, MeanBW)+s(Meanzfc)	0.47 ± 0.03	0.01 ± 0.01	0.14 ± 0.03	0.02 ± 0.01	0.68 ± 0.02	0.734
Speciesid~s(MedICI)+s(MeanNCycles)+te(Meanzfc, MeanBW)	0.46 ± 0.03	0.01 ± 0.01	0.15 ± 0.03	0.02 ± 0.01	0.68 ± 0.02	0.735

447

448 **TABLE III**

449 Results of the binomial GAM used to analyze click type (ClickTrain) using a tensor smooth of median inter-click interval (MedICI),

450 mean number of cycles in clicks (MeanNCycles) and mean zero crossing frequency (meanzfc).

Parametric Coefficients Formula: ClickTrain~te(*MedICI, MeanNCycles, Meanzfc,* family=*Binomial* ,link=*logit*)			
Intercept Estimate	**Standard Error**	**z-value**	**Pr(>|z|)**
-0.3500	0.1254	-2.791	0.00525
Approximate Significance of Smooth Terms			
Est. df	**Reference df**	**Chi squared**	**P-value**
69.28	79.31	612	<.001

451

452

FIGURE 4 Two dimensional representations of the for-dimensional tensor-smooth binomial classification GAM. Shade indicates the

probability that a given click train was broadband (black) or frequency banded (white) based on the mean inter-click-interval (Median

ICI), mean number of cycles (e.g. duration) of the clicks, and mean zero-crossing frequency (Mean fZC) of the click trains. Points

represent training data for broadband (black) and frequency banded (light gray) click trains.

457

458

459   When applied to the full C-POD dataset (minus the training data), the model categorized a total of 3968 (37%) of the click

460   trains, of which 2737 were identified as broadband and 1231 frequency banded. The remaining 63% of the click trains failed to meet

461   either categorization threshold (T_t). As expected, the proportion of click train types varied across the deployment sites. C-PODs near

462   the inner Moray Firth (Cromarty and Spey Bay) contained primarily broadband click trains and units to the north and south

463   (Helmsdale and Fraserburgh) contained primarily frequency banded click trains. Uncategorized click trains were present on all units

464   and, with the exception of the Cromarty locations, generally represented the majority of the click trains detected at each deployment

465   site (Figure 5).
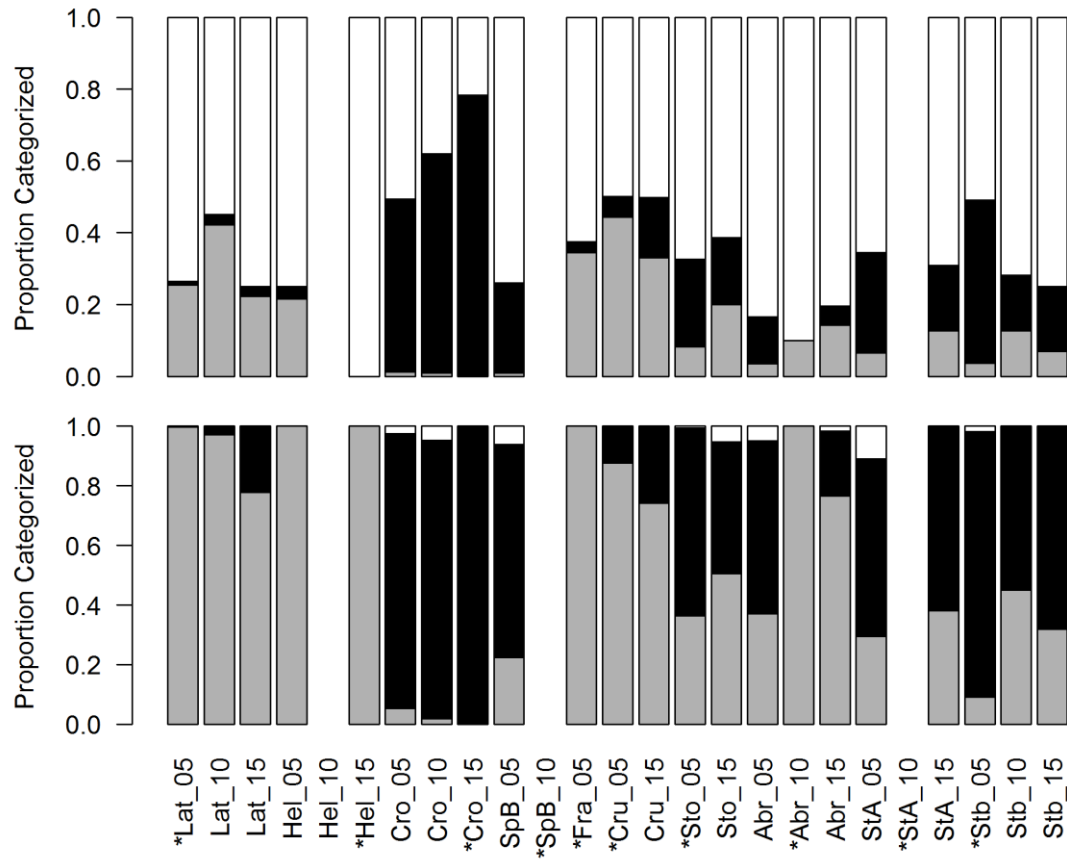
FIGURE 5 Upper Panel: The proportion of click trains classified as broadband (black), frequency banded (gray) or unknown (white) by the GAM classification model with a minimum classification threshold of ±0.425(Tt Equation 1). Lower Panel: The proportion of click trains classified as broadband, frequency banded or unknown by the combination of the GAM click-train classification and the

471   encounter likelihood ratio. Asterisks indicate joint C-POD/SM2M deployment locations from which training data were derived.

472   Displaced units (SpB 05, Fra 10, Fra 15, Cru 10, Sto 10) not shown.

473

D.   Encounter Likelihood

475   The 10,753 click trains documented by the 26 recovered C-PODs represented 573 encounters. Twelve encounters coincided with

476   visually verified broadband trains recorded by the adjacent SM2M recordings and 27 encounters coincided with visually verified

477   frequency-banded click trains in the SM2M recordings (Table 1). Using a minimum likelihood ratio of five ($T_e = 5$ in Equation 4), 10

478   of the verified broadband click-train encounters were correctly categorized, two were incorrectly categorized as frequency banded

479   encounters and none were left unclassified, while 24 of the 27 verified frequency banded encounters were correctly categorized, none

480   were incorrectly categorized and three were left unclassified. When the likelihood model was applied to the remaining data, 264

481   (43%) total encounters were categorized as broadband, 273 (45%) as frequency banded and the remaining 75 (12%) were left

482   unclassified (Figure 5). The Helmsdale 15 unit contained a single acoustic encounter for which no click trains met the GAM

483   categorization threshold, but the likelihood ratio of the encounter was less than 1/5 allowing classification, therefore the proportion of

484   click trains classified on the Helmsdale unit was 0 in the GAM only model, but 100% when the encounter likelihood ratio was applied.

485   The highest daily occupancy rates were observed at the Cromarty 5 deployment location, with other peaks around the Latheron,

486   Fraserburgh, Arbroath and St Andrews sites (Figure 6). No encounters of either type were documented by the Helmsdale 10, Spey Bay

487   10 and St Andrews 10 units. The daily occupancy rates of broadband and frequency banded click encounters differed between

31

488   locations. Deployments near the inner Moray Firth showed higher broadband daily occupancy rates while the converse was true for

489   the Latheron, Fraserburgh and Cruden Bay sites. These results are consistent with long-term studies in the area that have shown

490   regular bottlenose dolphin presence in and around the SAC (Hammond and Thompson, 1991; Wilson *et al.*, 1997; Quick *et al.*, 2014).

491   Interestingly, encounters in Stonehaven, Arbroath, and to a lesser degree St Andrews and St Abbs, showed similar rates of detection

492   positive days for both broadband and frequency-banded click types, indicating the presence of multiple species.

493

494
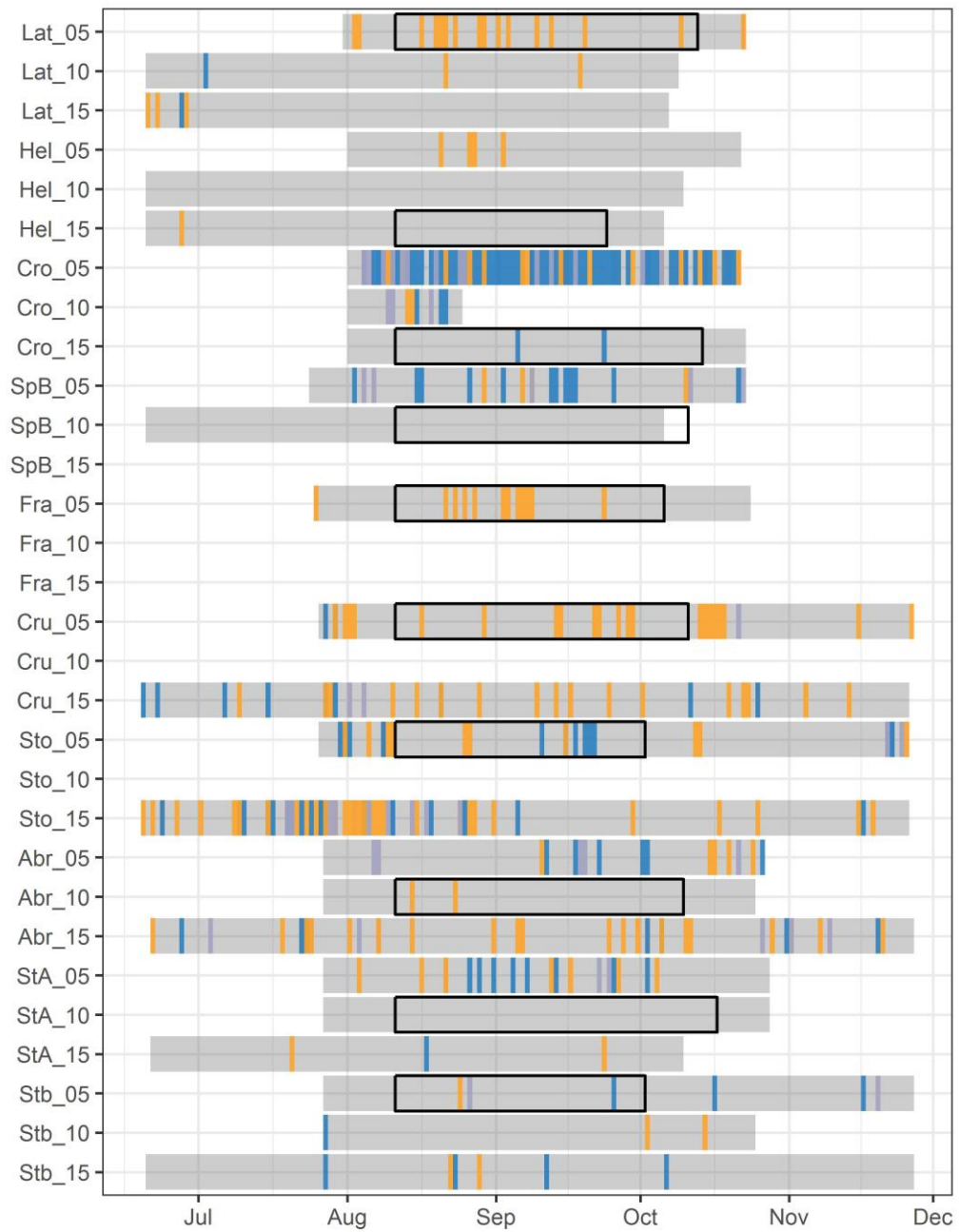
495 **FIGURE 6** Daily occupancy of broadband echolocation click encounters (blue), frequency banded echolocation click encounters

496 (yellow) and uncategorized echolocation click train encounters (dark gray). Gray blocks indicate times when the C-PODs were recording

497 (see also table 1) and

498 black rectangles indicate periods for which there were simultaneous SM2M recordings (color online).

499

V.   DISCUSSION

501   The categorization results reported here for C-POD detections are consistent with the few visual surveys available for areas

502 outside of the Moray Firth. This study identified primarily broadband encounters in the data from all three Cromarty C-PODs. This

503 finding is unsurprising given that a portion of the broadband training detections were derived from the Cromarty 5 unit. However, the

504 prevalence of broadband click trains at the other two Cromarty deployment sites is consistent with previous studies in the area.

505 Similarly, broadband encounters were more prevalent than frequency banded click trains in the C-POD detections at the St Andrews

506 and St Abbs sites, where bottlenose dolphins are the most frequently sighted species (Cheney *et al.*, 2013). Approximately equal

507 numbers of broadband and frequency banded detections occurred through the Grampian region (Cruden Bay, Stonehaven and

508 Arbroath), which agrees well with reported sighting rates for bottlenose and white-beaked dolphins between Cruden Bay and

509 Stonehaven (Anderwald and Evans (2010). Similarly, Weir *et al.* (2007) report multiple sightings of white-beaked dolphins in and

510 around the Aberdeen area (between Cruden Bay and Stonehaven).

34

511   Daily occupancy rates from the C-POD data suggest a degree of spatial partitioning between species producing broadband and

512   frequency-banded clicks. Broadband click encounters comprised the vast majority of the detection positive days logged by the C-

513   PODs deployed in the inner Moray Firth (Cromarty). Contrary to our expectations, the acoustic encounters on the Helmsdale C-PODs,

514   which were located within the Moray Firth SAC, were dominated by frequency banded click trains. This suggests that, over the 2013

515   deployment period, bottlenose dolphins were not the most common species using this portion of the SAC.

516   Outside of the SAC, both broadband and frequency banded click encounters were frequently observed. However, for each

517   deployment group (e.g., St Andrews, Arbroath etc.) broadband click trains were more common in the nearshore (~5 km) than the

518   offshore deployment sites (~10 and 15 km). This is consistent with previous studies that suggest bottlenose dolphins preferentially use

519   nearshore areas (Arso Civil, 2014; Quick *et al.*, 2014). The Stonehaven C-PODs contained a mix of broadband and frequency banded

520   encounters, matching visual surveys indicating that both bottlenose and white beaked dolphins are commonly sighted in that area

521   (Weir *et al.*, 2007; Anderwald and Evans, 2010). These results hint at the possibility of areas along the eastern Scottish coast having

522   different ecological importance for the two groups. This has been confirmed for bottlenose dolphins in the inner Moray Firth where

523   foraging buzzes are more frequently documented near known "hot-spots" (Hastie *et al.*, 2004; Pirotta *et al.*, 2014b). However, fewer

524   data are available for the other species present in the area and/or outside of the Moray Firth.

525   The similarity between our results and previously published sightings data indicates that the C-POD encounter categorization

526   system presented here works well for eastern Scottish waters. However, it would be inappropriate to directly apply this categorization

527   tool to C-POD detections collected from other regions. Recent classification studies on similar species groups using full spectrum

35

528   recording (*fs* = 200 kHz) have shown that deployment location and instrument type can adversely affect the performance of click train

529   classifiers (Roch *et al.*, 2015). It is unclear whether this might be the case with C-POD data for which fewer click features are

530   collected. While it is possible that the zero-crossing method combined with the limited click parameters are more robust to site and/or

531   instrument specific variations, it could just as easily be the case that the limited click features recorded by the C-PODs are *more*

532   susceptible to such variations. Thus, future studies seeking to use this classifier or these methods must not omit a validation process.

533   Ideally this would involve comparing C-POD detections with concurrent visual sightings (e.g., Roberts and Read 2014, Robbins *et al.*

534   2015, Nuutilia *et al.* 2013). However, where visual observations are not possible or practical, pairing C-PODs with continuous

535   recorders is an alternative method.

536   The use of C-POD data processed only with the KERNO classifier is justified in surveys where the researchers can be confident

537   that the majority of detections represent single dolphin and/or porpoise species. This is the case for the dolphin detections within the

538   inner Moray Firth where bottlenose dolphins represent the principle dolphin species. Similarly, throughout the North Sea, harbor

539   porpoise (*Phocoena phocoena*) represent the only resident cetacean capable of producing "NBHF" clicks and are, therefore, unlikely

540   to be confused with other species. In such contexts, C-PODs and similar devices can directly inform studies of cetacean abundance

541   and behavior (Jaramillo-Legorreta and Rojas-Bracho, 2011; Kyhn *et al.*, 2012; Brookes *et al.*, 2013; Wilson *et al.*, 2013; Pirotta *et al.*,

542   2014b; Williamson *et al.*, 2016). However, where multiple odontocete species with similar click features are present, additional

543   methods are needed to increase taxonomic resolution. This study highlights the benefits of developing methods to increase taxonomic

544   precision in detections from low-cost click loggers when full acoustic audits are impossible or impractical. This is especially pertinent

36

545   given that C-PODs and their predecessor T-PODs are widely used for monitoring an mitigation associated with offshore industrial

546   activities (Carstensen *et al.*, 2006; Scheidat *et al.*, 2011).

547   In this work we relied on several assumptions, but a key one was that all click trains detected by the C-PODs were produced by

548   one of the four most common species seen in the area. C-PODs are capable of recording echolocation clicks from all odontocetes with

549   the exception of sperm whales (*Physeter macrocephalus*) for which the energy is below the sensitivity of the instruments (Dähne *et*

550   *al.*, 2013). This includes clicks from species that, while infrequent, are known to visit the eastern Scottish coast including killer whales

551   (*Orcinus orca*), long-finned pilot whales (*Globicephala melas*), and Atlantic white sided dolphins (*Lagenorhynchus acutus*). Based on

552   published click characteristics (Deecke *et al.*, 2005; Eskesen *et al.*, 2011), click trains from these species would likely be classified as

553   broadband click encounters by this categorization system. Thus, it is possible that some of the "Other Cet" click trains detected by the

554   C-PODs represented one or more of these species. However, previous visual surveys indicate that such species are infrequent visitors

555   to the eastern Scottish coast and could therefore contribute only a trivial amount of noise to the encounter rates presented here.

556   Regardless, the ambiguity in dolphin detections reiterates the need to inform acoustic-only methods with other sources of information

557   about the study system.

558   The interpretation of these results assumed that stable frequency banding, or the lack thereof, in echolocation clicks was diagnostic

559   of the species-group producing them. This assumption is debated in the literature, with several authors providing evidence of species

560   discrimination based on the spectral location of peaks and notches (Houser et al., 1999; Soldevilla et al., 2008; Calderan et al., 2013),

561   while others have postulated that spectral banding cannot be diagnostic of species (Wahlberg et al., 2011). While an in-depth analysis

562   of this debate is outside of the scope of this study, careful consideration is prudent to understand the validity of the categorization

563   analysis presented here. Currently two hypotheses exist regarding how frequency banding might be produced. Wahlberg et al. (2011)

564   and Rasmussen et al. (2004) measured on-axis clicks from free-ranging bottlenose and white sided dolphins, respectively. Both studies

565   fitted a baffled piston model to the received clicks, and Wahlberg et al. (2011) suggested that the banding found in other species was

566   attributed to the off-axis banding effects dictated by the piston aperture size. However, these studies primarily analyzed clicks from

567   on-axis angles and may therefore have missed the filter effects caused by the cranial anatomy. If this is the case then it does not

568   preclude the independent documentation of stable spectral peaks and notches in the spectra of clicks recorded off-axis from a number

569   of species with similar cranial morphology (Soldevilla *et al.*, 2008; Au *et al.*, 2012b).

570   The off-axis spectral characteristics of echolcoation clicks have been measured for bottlenose dolphins. Au *et al.* (2012b)

571   measured the entire biosonar field around captive bottlenose dolphins and found that, off-axis, echolocation clicks degraded into

572   discrete pulses most likely produced by the phonic lips and internal reflections from within the animal's head (Au et al., 2012b).

573   Multiple pulses, when processed with an FFT or DFT algorithm, result in "ripples" in the spectrum consistent with the peaks and

574   notches described by Soldevilla *et al.* (2008). However, as with sperm whales, the inter-pulse-interval in bottlenose dolphin

575   echolocation clicks is highly sensitive to the off-axis angle (Goold, 1996). Therefore, when energy is averaged across multiple clicks

576   collected from a variety of angles relative to the animal, the peaks and notches in spectral energy from this species become less

577   distinct.

578   Unfortunately, detailed studies of off-axis clicks from "frequency banded" species including Risso's, white-beaked and white-

579   sided dolphins are lacking. However, it is possible that differences in cranial morphology between the species groups could account

580   for differences in the stability of spectral peaks and notches. For example, assuming the multi-pulse model of echolocation click

581   propagation, more uniform path lengths between the phonic lips and melon for frequency banded species would result in consistent

582   inter-pulse-intervals. This would subsequently lead to less variation in the spectral location in peak and notch energy for off-axis

583   clicks in these species. Additional studies are needed to determine whether or not this is the case.

584   Assuming the presence of stable spectral peaks and notches is diagnostic of species group, on-axis clicks will necessarily confound

585   our ability to discriminate between broadband and frequency banded click trains in both the SM2M recordings and the C-POD

586   encounter categorization model (Au *et al.*, 1974; Au *et al.*, 1999; Rasmussen and Miller, 2002; Rasmussen *et al.*, 2004; Wahlberg *et*

587   *al.*, 2011; Au *et al.*, 2012a). Moreover, if a disproportionately large selection of on-axis click trains were included in the training data,

588   this would add considerable noise to the final categorization task. We limited this outcome by restricting the selection of C-POD click

589   trains used to build the GAM to periods during which more than 500 high SNR click trains could be identified in the adjacent SM2M

590   recordings. This conservative selection criterion reduced the probability of creating a biased sample of clicks from any particular beam

591   angle and thereby increased our confidence in the accuracy of the categorization task.

592   Our categorization model included ICI as a predictor, yet it is known that odontocetes modify their inter-click-interval depending

593   on their behavioral state (Janik, 2000; Johnson *et al.*, 2006; Pirotta *et al.*, 2014b). This has the potential to introduce two confounding

39

594   factors into the analysis presented here. First, there is question of whether ICI can be used to discriminate between different species

595   (or groups) of dolphins. Additionally, there is the potential that the categorization task is describing behavior (e.g. foraging vs. travel)

596   rather than species group.

597   In addressing whether ICI can be used for species discrimination we note that the GAM model selected here used a tensor smooth

598   across all three click train features recorded by the C-POD. Thus, ICI itself did not predict the click-train category. Instead, prediction

599   was based on the relationship between median ICI, mean zero-crossing frequency and mean bandwidth. Accordingly, while ICI itself

600   has not been widely used to discriminate between species, Johnson *et al.* (2006) note that in Blainsville's beaked whales (*Mesoplodon*

601   *densirostris*) there is a species-specific relationship between ICI, peak frequency and bandwidth of the individual clicks. For this

602   species, as the animal approaches a prey target decreasing ICI's are linked with decreasing click durations and increasing click

603   bandwidths and peak frequencies. Thus, while inter click interval, bandwidth or peak frequency alone would be inadequate to

604   categorize echolocation clicks, the relationship between these variables may be sufficiently different in some species to allow for

605   categorization and/or classification.

606   Concerning whether our sample of echolocation clicks represented a biased distribution of clicking behaviors (e.g. primarily click

607   trains associated with foraging or travelling), we note that the training data were obtained from multiple times and locations

608   throughout the survey. Therefore, click trains associated with foraging, travelling and socializing activities should all be represented in

609   the training data for both echolocation click types (Pirotta *et al.*, 2014b). *K*-fold cross validation involved subsetting trains from

610   multiple acoustic encounters. This methodology was necessary as very few acoustic encounters could be correlated with the adjacent

611　SM2M recordings (10 broadband and 17 frequency banded encounters; Table 1). This also meant we were forced to train and test our

612　model on the same data - with more verified acoustic encounters we could have better characterized in vs. out of sample model

613　performance, and this should still be the aim for future studies.

614　　As with any acoustic classifier, ours is not immune to miscategorization. There are a number of ways in which future studies may

615　account for this misclassification error. First, the performance of this categorization system should be tailored to the research

616　objectives by modifying encounter thresholds based on cost functions derived from study objectives. For example, in this study a

617　single encounter threshold was set above and below which encounters were categorized as broadband or frequency banded. However,

618　studies for which there is a high cost to false negative detections may wish to take a more conservative approach. In such cases, the

619　likelihood categorization threshold (T_e) could be either decreased or excluded altogether; opting instead to include all click trains with

620　a GAM prediction score above a given threshold (T_p) in the final analysis. Alternatively, future studies may seek to incorporate

621　misclassification error directly into the analysis. Bayesian occupancy models, in particular, offer sufficient flexibility to allow for the

622　incorporation of correct and incorrect classification rates across all categories (Miller *et al.*, 2011).

623　　Provided the above considerations are kept in mind, it would be worthwhile to investigate whether this categorization system

624　might perform comparably to C-POD detections collected from other habitats. Similar dolphin species compositions have been

625　observed in western Scotland (MacLeod *et al.*, 2005), Ireland (Robbins *et al.*, 2015), California (Soldevilla *et al.*, 2008), and in the

626　Mediterranean sea (Frantzis and Herzing, 2002). If the C-POD categorization system derived here performs comparably in other

627　habitats, it suggests a wider application of these GAM/likelihood methods may be possible.

628

VI.   CONCLUSIONS

Our study indicates that it is possible to increase the taxonomic resolution of low-cost click loggers by using statistical methods to

discriminate between acoustically similar species groups. By comparing continuous recordings to logged C-POD detections we were

able to identify and discriminate between the broadband and frequency banded click trains produced by the two pairs of dolphin

species most commonly encountered in Eastern Scottish coastal waters.

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VIII. REFERENCES

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