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.

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).

Together, these filtering effects render it virtually impossible to classify individual echolocation clicks to species.

Researchers have addressed the classification task by averaging echolocation click characteristics across multiple clicks, click trains, and/or acoustic encounters. In doing so, group and species-specific features in echolocation clicks have been discovered. For example, Baumann-Pickering *et al.* (2013) compared the location of satellite tagged animals to passive acoustic recordings and was able to describe species-specific characteristics of false killer whale (*Pseudorca crassidens*) and short finned pilot whale (*Globicephala macrorhynchus*) echolocation clicks. Similarly, distributions of peak frequency, center frequency, click duration, inter-click interval (ICI) and bandwidth have been useful in discriminating between the echolocation clicks of melon-headed whales (*Peponocephala electra*), Gray's spinner dolphins (*Stenella longirostris longirostris*) and to a lesser extent, bottlenose dolphins (*Tursiops truncatus*) (Baumann-Pickering *et al.*, 2010).

In other studies, the structure of the frequency spectrum has proven useful in classifying click trains. In the Pacific, the echolocation clicks of white-sided dolphins *(Lagenorhynchus obliquidens)* and Risso's dolphins (*Grampus griseus*) have been shown to display consistent peaks and notches in spectral energy below 48 kHz (Roch *et al.*, 2007). Risso's dolphins click 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 kHz for white-sided dolphins. The spectral location was sufficient to discriminate between the two species but site and instrument-specific anomalies reduced the confidence of the classifications (Roch *et al.*, 2007). In the same habitat, bottlenose dolphin and common dolphin (*Delphinus delphis*) echolocation clicks were found to have a more uniform energy distribution between 40 and 80 kHz (Soldevilla *et al.*, 2008). Echolocation clicks from these species were nearly indistinguishable but easily discriminated from the peak and notch structure of Risso's and white-sided dolphins, especially when site and instrument specific parameters were accounted for (Roch *et al.*, 2011; Roch *et al.*, 2015). Uniform energy between 40-120 kHz was recorded for on-axis clicks of bottlenose dolphins in the Indian Ocean, and held for off axis angles up to ~13°, beyond which peaks and notches in energy were observed but were dependent on the angle between the animal and the recording system (Wahlberg *et al*. 2011). Similarly, in the North Atlantic Calderan *et al.* (2013) investigated whether the peaks and notches in spectral energy observed in Pacific animals were also present in clicks produced by Risso's and white-beaked dolphin (*Lagenorhynchus albirostris*), the latter having morphologically similar cranial structure to Pacific white-sided dolphins. Towed arrays in western Scottish waters suggested that a similar peak-and-notch structure was present in both species. Taken together, these studies suggest that the presence of stable peak-and-notches in spectral energy may be useful for increasing taxonomic resolution from acoustic recordings.

While significant progress has been made in classifying echolocation clicks in continuous recordings, little effort has been directed toward classifying echolocation clicks in click logging devices. C-PODs (Chelonia, Ltd.) are commercially available click logging devices popular in marine studies. The C-POD system returns a series of summary parameters related to detected clicks but does not save the waveform of the clicks themselves. Consequently, the volume of data collected by these systems is drastically less, while some of the click frequency/time information is preserved. Such systems are efficient, have low false positive detection rates, and produce generally consistent output between units (Dähne *et al.*, 2013; Roberts and Read, 2014). For these reasons, C-PODs are a popular tool used to study odontocete behavior and ecology worldwide (Carstensen *et al.*, 2006; Koschinski *et al.*, 2008; Bailey *et al.*, 2010; Pirotta *et al.*, 2014a; Jaramillo-Legorreta *et al.*, 2016). For species with mid- to high-frequency echolocation clicks, long-term and full spectrum (*fs* >200 kHz) continuous recordings are often impractical due to the high up-front cost of continuous recorders, high data volumes, time-consuming post-processing to extract echolocation clicks, and limited recording duration compared to click loggers.

Data collected by the C-POD data are generally processed to detect the presence of odontocete echolocation click trains with the accompanying KERNO classifier. The KERNO software is capable of discerning between dolphin and porpoise clicks based on the frequency and bandwidth of the detections. However, C-PODs currently lack the ability to discriminate between most dolphin species. Thus, where users can be relatively confident that only the target dolphin species is present, the use of C-PODs has proven to be both cost and time effective (Simon *et al.*, 2010; Pirotta *et al.*, 2015). However, where the scientific and/or regulatory concern focuses on a single species within a large habitat, the ability to discriminate between target and non-target species becomes a critical aspect of the research methodology.

The motivation for this study is the need to efficiently monitor the population of bottlenose dolphins resident along the eastern coast of Scotland. This population is protected by a variety of UK and EU regulations including the designation of special areas of conservation (SAC) in the Moray Firth and the Firth of Tay. However, in recent years the population appears to have undergone significant range expansion; while animals are consistently observed within the SAC's, a large proportion of the population partially or fully resides outside of the protected areas (Cheney *et al.*, 2014). Additionally, the construction of large offshore wind farms is planned off Eastern Scotland for the coming years. Determining what effect, if any, the construction, operation, and decommissioning of these structures will have on these animals is important for long term conservation goals. Thus, a better understanding of how the population uses the entire Eastern Scottish coast habitat is needed. One of the primary challenges to meet this objective using passive acoustic monitoring techniques lies in discriminating between target (bottlenose dolphin) and non-target species known to occur in the area. These include common dolphin, Risso's dolphin and white beaked dolphin (*Lagenorhynchus albirostris*) (Weir *et al.*, 2007; Quick *et al.*, 2014). Thompson *et al.* (2013) addressed the multi-species concern by integrating visual observations of various dolphin species and echolocation click detections from C-PODs. In their study, effort controlled visual survey data from 1980 through 2010 were combined with up to three seasons worth of C-POD detections from the Moray Firth. Results from their study strongly suggested that bottlenose dolphins primarily occupy the nearshore areas (<10 km from the coast) within the inner Moray Firth while a greater diversity of dolphin species were found in the offshore waters.

Discriminating between any dolphin species in C-POD data would represent a major step forward in the application of such systems in multi-species contexts. This challenge of species discrimination has been recognized and approached by researchers working with a similar group of species in Irish waters (Robbins *et al.*, 2015). In that study the authors used multi-dimensional scaling techniques to try and discriminate between visually-confirmed Risso's, common and bottlenose dolphin detections in C-POD data. The authors found that the limited metrics produced by the C-POD system in combination with their own post-processing metrics were insufficient to classify detections to species. This result is unsurprising given the difficulty in discriminating between common and bottlenose dolphin clicks even with continuous, full-spectrum recordings (Soldevilla *et al.*, 2008; Roch *et al.*, 2011).

In the present study we investigated the potential for discriminating between echolocation clicks with distinct peaks and notches, hereafter termed “frequency banded” and those that, when averaged across encounters, lack distinct peaks and troughs in spectral energy below 48 kHz, referred to hereafter as “broadband”. We denote this task as “categorization” rather than classification as we are not seeking to identify the exact species producing the click-types. We used data from acoustic recorders deployed alongside C-PODs to build a model that discriminated between broadband and frequency-banded clicks in C-POD data, and then used this model to classify data from a larger set of C-PODs for which there was no co-deployed recorder.

III. METHODS

A. Data Collection

In the spring of 2013, 30 C-PODs and 10 SM2M (Wildlife Acoustics) recorders were deployed along the eastern Scottish coast (Figure 1). Deployment locations were chosen to maximize acoustic coverage and minimize the likelihood of being displaced by storms or fishing activity. All units were moored to the seafloor using 100kg chain weights. Some were furnished with surface markers, while others had acoustic releases to facilitate recovery. The choice of mooring type was based upon vessel traffic in the deployment location. C-PODs were deployed in ten groups of three, with moorings within the group deployed approximately 5, 10 and 15 km from the coast. Moring locations are hereafter referred to as 5, 10, and 15 to indicate that distances from shore were approximate values only. One SM2M was co-deployed with one of the C-PODs at each group. The SM2M was attached to the same mooring line as the C-POD and the units were separated by more than one meter. This configuration allowed us to compare the continuous recordings from the SM2Ms, from which we could identify broadband and frequency banded echolocation click trains, to the C-POD detection logs. The C-PODs logged continuously from the deployment date, while SM2Ms were programmed to commence recording on Aug 13th 2013 with a 10 minute on/off duty cycle and sampling rate of 96 kHz and 12 dB gain. All units recorded until their battery capacity was exhausted and were recovered between October and November of the same year, as weather allowed (Table 1). For units displaced during the deployment, the C-POD outputs related to temperature, angle of the device and sonar detection were examined to determine the date on which the device was moved out of position. All data from midnight of that day onwards were removed from the analysis.

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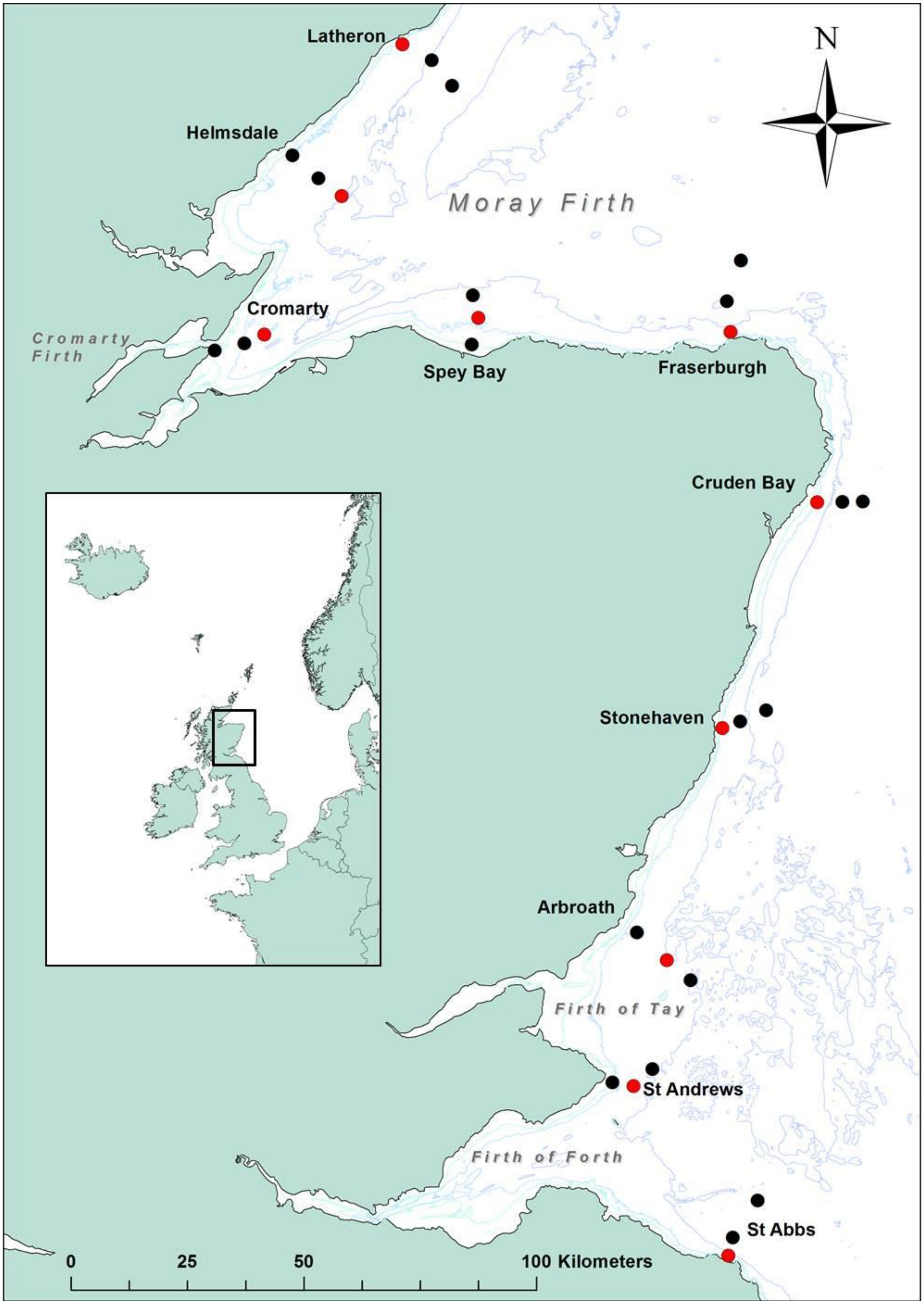
N
Latheron
Helmsdale
Moray Firth
Cromarty
Cromarty Firth
Spey Bay
Fraserburgh
Cruden Bay
Stonehaven
Arbroath
Firth of Tay
St Andrews
Firth of Forth
St Abbs
0
25
50
100 Kilometers

FIGURE 1 Survey locations for the ECOMMAS project C-POD and joint C-POD/SM2M deployment sites on the Eastern Scottish Coast. Deployment sites indicated by nearest large town: Latheron (Lat), Helmsdale (Hel), Cromarty (Cro), Spey Bay (Spe), Fraserburgh (Fra), Cruden Bay (Cru), Stonehaven (Sto), Arbroath (Abr), St Andrews (StA), St Abbs (Stb). All units were placed at approximately 5, 10, or 15km from the coast (color online).

TABLE I

Locations, dates and number of days for which usable data were obtained for all deployed devices (SM suffix indicates SM2M units, all others are C-PODs). For C-PODs, the number of click trains logged, the number of acoustic encounters, and the number of broadband or frequency banded click trains contributed to the training dataset, along with – in parentheses – the number of unique days represented by that contribution, are also given All dates are dd/mm in 2013. Five C-POD deployments that returned no usable data are omitted – Spey Bay 15, Fraserburgh 10 and 15, Cruden Bay 10, and Stonehaven 10.

						Training Data	
Location name (SM=SM2M unit)	**Data From**	**Data To**	**# Days**	**# Click Trains**	**# Encounters**	**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		

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” (narrowband high-frequency click trains often indicative of porpoise species), "Other Cet" (wideband clicks indicative of most dolphin species) and "Unk" (representing unclassified/unknown clicks). The C-POD software and KERNO classifier group "NBHF" and "Other Cet" signals into short "click trains" based on temporal proximity and assign a "click train ID" to each such group. The manufacturer states that this detection and classification system allows multiple clicking animals to be differentiated from each other. The KERNO classifier also assigns a quality class to each detection (high, moderate, or low) indicating the probability that the click train was correctly discriminated from other "non-train" sources such as snapping shrimp or rain (Tregenza, 2016).

The click features (referred to as "details" in the accompanying software) logged by C-PODs are non-standard in the acoustics field and so require careful interpretation. Specifics of the click features are proprietary and defined by the manufacturer as the time of the click, measured with 5μs resolution, dominant zero-crossing frequency (fZC, which should not be confused with peak frequency), end zero-crossing frequency (derived from the last zero-crossing interval), bandwidth measured on an "arbitrary scale" (manufacturers description), and click duration measured as the number of cycles at the dominant frequency (NCycles). C-PODs also document a metric of amplitude which, though reported as sound pressure level, is not corrected for hydrophone frequency response (Dähne *et al.*, 2013). For this analysis, all "high" or "moderate" quality "Other Cet" detections were selected and the accompanying click features, referred to as "click details" by the manufacturer, were exported to a text file. For each click train (i.e. all clicks with the same "click train ID"), we also calculated the median inter-click-interval, mean 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 click trains were present on both instruments at the same time, we assumed that the echolocation click trains had originated from the same animal or group of animals.

Data from the SM devices were downloaded, converted to spectrograms (1024 point fast-Fourier transform , 10.67 ms window, and 50% overlap) and processed for echolocation clicks using PAMGuard click detecting software (Gillespie *et al.*, 2009). Click detection trigger was set to 10 dB and click detections were manually scanned for the presence of high signal-to-noise echolocation click encounters and annotated as such. Echolocation clicks from high SNR encounters containing at least 500 clicks were extracted and the average spectrum was inspected for the presence of either distinct peaks or notches in energy indicative of white-beaked or Risso's dolphins or unimodal energy between 20 and 40 kHz suggestive of bottlenose and/or common dolphins. While visually inspecting the continuous recordings for high SNR frequency banded click trains, we did not seek an exact match the location of the spectral energies as reported by reported by Calderan *et al.* (2013) or Soldevilla *et al.* (2008). Both environment and recording equipment impart site and equipment-specific filter effects on the received signals (Roch *et al.*, 2015). We expect some variation in the received characteristics of echolocation clicks. Neither did we attempt to differentiate between species within the two click encounter types (e.g. common vs bottlenose dolphin). Instead encounters where the average spectrum contained at least two peaks in energy between 35 and 43 kHz and with >3 dB peak-to-peak difference between successive peaks and notches were annotated as "frequency banded". Click encounters for which there was a unimodal peak in energy between 20 and 30 kHz were annotated as broadband (Figure 2).

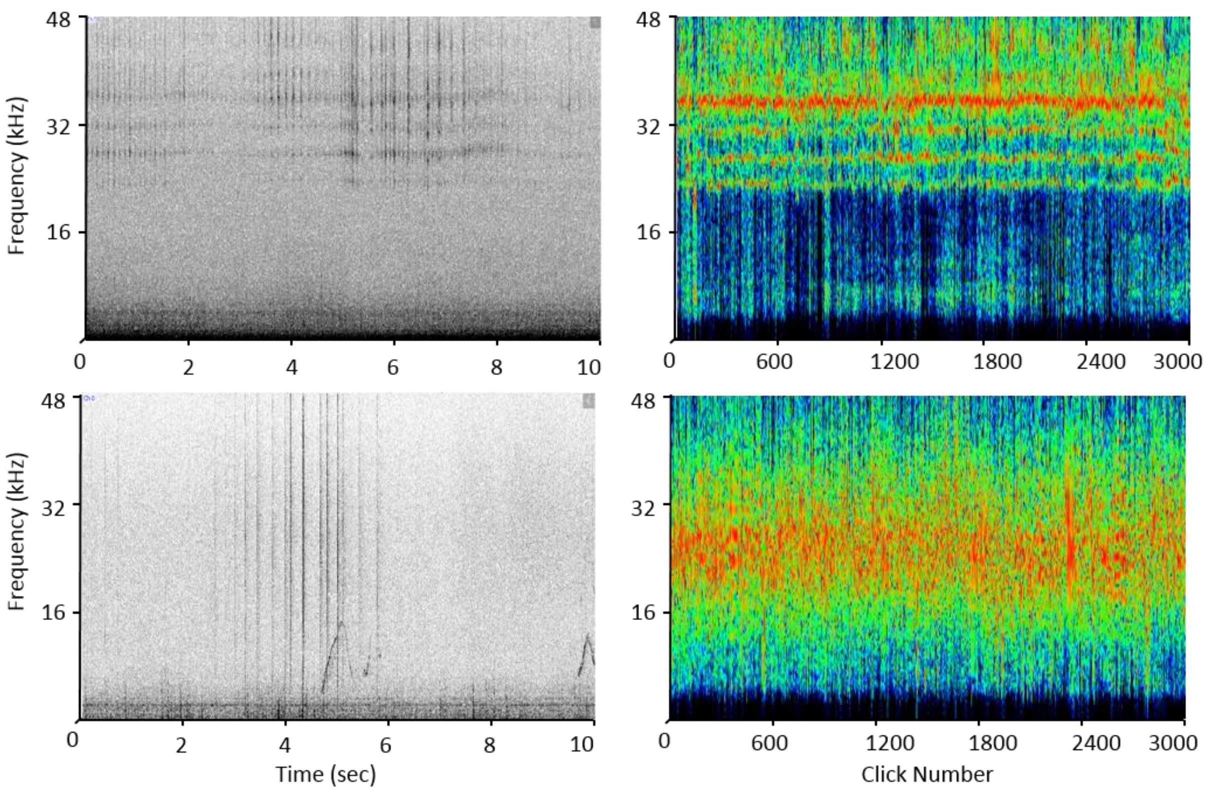

FIGURE 2 Spectrograms (left) (*fs* 96 kHz, 10.67 ms Hann window, 50% overlap) and concatenated click spectrums (right) of echolocation clicks within from frequency banded (top) and broadband (bottom) acoustic encounters. Top row: 10 seconds of recordings from a frequency banded encounter consistent with 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 recordings. The train features from “high” or “moderate” quality “other cetacean” trains coinciding with visually confirmed broadband and frequency banded encounters in the continuous recordings were used to build and train categorization models.

To increase the volume of C-POD click trains from broadband encounters, click train features from the Cromarty 5 C-POD, for which there was no adjacent SM2M recorder, were randomly selected for inclusion in the broadband training dataset. Despite the lack of concurrent acoustic recordings, we are confident that the vast majority of the click trains logged by the C-POD at this location were produced by bottlenose dolphins and as such represented our broadband category. The area in and around the Cromarty and inner Moray Firths has been continuously surveyed for the last 25 years and is a well-known bottlenose dolphin habitat that (Hammond and Thompson, 1991; Wilson *et al.*, 2004; Cheney *et al.*, 2013; Thompson *et al.*, 2014; Pirotta *et al.*, 2015). These studies strongly suggest that no dolphin species besides bottlenose regularly occupy the area. To further reduce the probability of including frequency banded click trains in the broadband training data, only click trains from the month of August, coinciding with the majority of visual surveys, were added to the training dataset.

Obtaining a representative sample of echolocation click behaviors is important in order to produce an accurate categorization system. Of the 1195 C-POD click trains that could be linked to trains in the adjacent SM recordings only 270 (22%) were broadband. We added only as many click trains from the Cromarty 5 site as needed to provide an equal number of broadband and frequency banded click trains for the categorization task. We could have reasonably included all of the data from the Cromarty 5 C-POD based on the overwhelming evidence showing that the area is primarily occupied by bottlenose dolphins. However, we chose to limit the number of auxiliary click trains included from this C-POD for two reasons. First, the Cromarty 5 unit contained almost as many “OtherCet” click trains as the other 25 recovered C-PODs combined. Therefore, we sought to reduce potential bias introduced by site-specific behavior present in the data from that unit. Second, the Cromarty Firth is a known “hot-spot” for bottlenose dolphin foraging activity (Hastie *et al.*, 2004; Hastie *et al.*, 2006; Pirotta *et al.*, 2014b). Thus, we would expect to document more clicks with shorter inter-click-interval (reflecting the production terminal buzzes characteristic of prey capture attempts) near that location (Pirotta *et al.*, 2014b). Including an excessive number of buzzes in the training data would introduce bias towards low ICI’s within the broadband category.

E. Model-based Prediction and Categorization

The above procedures generated a set of C-POD click trains, with measured features, for which we were reasonably confident of the species group producing the clicks. We used these acoustically verified click trains to build and characterize a binomial family generalized additive model (GAM) that output the predicted probability that each click train consisted of broadband clicks. The covariates for this model included: median inter-click-interval, mean zero-crossing frequency, mean click bandwidth and mean click duration. The GAM categorization model was created in R version 3.2.4 revised (R Core Team, 2016) with the MGCV package version 1.8-12 (Wood, 2006).

Here, our goal was to build and select the GAM model best able to discriminate between the two echolocation click types commonly documented on the eastern Scottish coast. Thus, a *k*-fold cross validation approach was used to characterize candidate GAM models and provide parameters for final model selection.

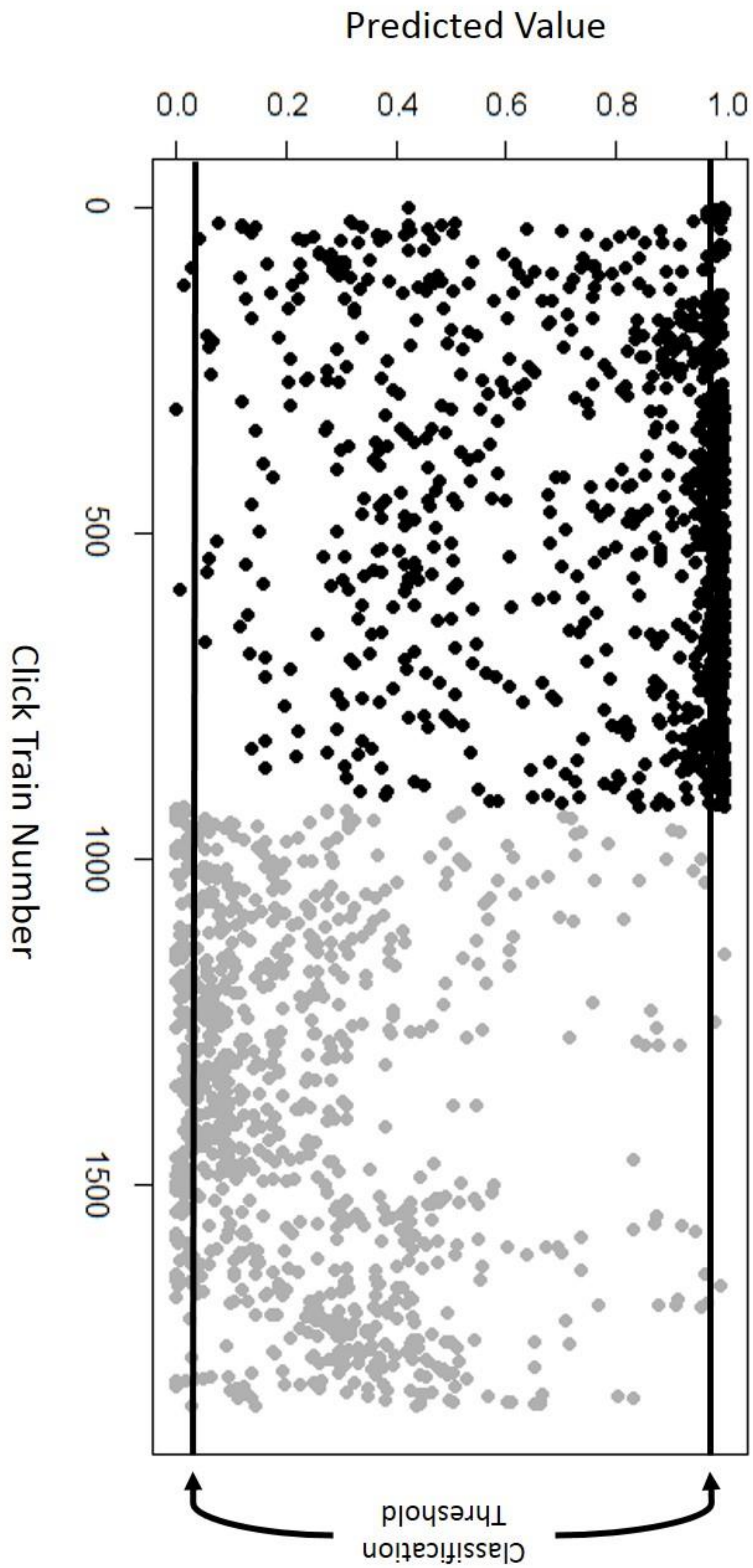
Predicted Value
0.0
0.2
0.4
0.6
0.8
1.0
Click Train Number
0
500
1000
1500
Classification Threshold

FIGURE 3 Predicted probability of a C-POD echolocation click train being associated with broadband encounter from the adjacent recordings (*P*, Equation 1). Points represent C-POD click trains associated with broadband (black) and frequency banded (grey) click encounters in the adjacent SM2M recordings. Horizontal lines represent the minimum classification threshold (*Tt*, Equation 2) above and below which click trains were classified as broadband and frequency banded, respectively. Click trains failing to meet the threshold (i.e. between the lines) were deemed too ambiguous to classify and left uncategorized.

For model comparison, all candidate GAMs were assessed using 200 iterations of a 5-fold cross-validation procedure and train categorization threshold of 0.425 (T_t; Equation 1). Thus, all click trains with predicted *P* exceeding 0.925 were categorized as broadband and those less than 0.075 were categorized as frequency banded (Equation 1, Figure 3). Click trains with predicted probabilities between 0.075 and 0.925 were considered too ambiguous to categorize and were therefore denoted as “unknown”.

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

For each model iteration 1/5th of the verified C-POD click trains were randomly selected and used as the validation set. The remaining 4/5ths of the verified C-POD click trains were used to build the GAM models. In this portion of the analysis acoustic encounters were not considered and all verified click trains were treated as independent. For each iteration, we calculated the following metrics: proportion of broadband and frequency banded click trains that met either categorization threshold (proportion classified), the proportion of correctly categorized click trains (correct categorization rate), and the proportion of incorrectly categorized click trains (incorrect categorization rate). Performance values for each GAM were calculated using the same train threshold for all models (T_t, Equation 1). We then calculated the mean and standard deviation of all performance metrics across the 200 iterations and used these values to select the model meeting our selection criteria.

Model selection focused on reducing the proportion of frequency banded click trains incorrectly categorized as broadband, and thereby minimize the chances of artificially inflating the bottlenose dolphin occupancy rates throughout the survey area. We also sought to categorize the highest proportion of click trains possible, regardless of type. Thus, our model selection criterion (SC) was defined as:

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

Where FP_f was the false positive rate for frequency banded click trains and U was the proportion of uncategorized click trains. We introduce a scalar value of three representing our qualitative decision to penalize frequency banded click trains incorrectly categorized as broadband over click trains left uncategorized. The selection criterion was calculated for all candidate models and the GAM with the lowest criterion score was used to predict the probability that each click train was comprised of broadband clicks.

F. Encounter Likelihood

By itself, the GAM model could not account for the fact that click trains recorded in close succession were most likely produced by the same individual or group of animals (Quick *et al.*, 2014). To incorporate this information and increase the proportion of categorized click trains, we calculated the joint likelihood of each acoustic encounter by taking the product of all GAM predictions within the acoustic encounter. We then calculated the joint likelihood that all click trains comprising each encounter were either broadband or frequency banded. The two likelihoods were then combined into a likelihood ratio (*LR*; Equation 3) calculated as;

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

where P_i is the predicted probability from the GAM categorization model that the i^{th} of n click trains in the acoustic encounter was broadband. Since the model was binary, the likelihood that an encounter was comprised of frequency banded click trains was calculated by simply replacing P_i with $(1 - P_i)$ to give the denominator of Equation 3. As with the click train analysis, a minimum likelihood encounter threshold (T_e; Equation 4) was chosen above and below which all trains within acoustic encounters were categorized as broadband or frequency banded:

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

In this portion of the analysis we therefore needed to choose a minimum likelihood threshold (T_e) that balanced the risk of incorrectly classifying encounters against the risk of failing to classify most encounters. We compared the encounter categorization produced by the likelihood ratios to the validated training data to determine the correct and incorrect encounter classification rates. Through a process of trial and error we found that T_e=5, so that the evidence had to be five times as strong for one option than the other for a positive classification to be made, produced the optimal balance of maximizing classification rates while minimizing classification errors. Thus all encounters with likelihood ratios above 5 were classified as broadband and encounters with likelihood ratios below 1/5 were classified as frequency banded. All click trains from encounters with likelihood ratios (*LR*) between 1/5 and 5 were deemed too ambiguous for categorization and were left uncategorized. Finally, the GAM and the encounter analysis were applied to the full C-POD data set for which simultaneous acoustic recordings were not available.

IV. RESULTS

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

All SM2M units were successfully recovered in late 2013, but four C-PODs were not recovered, while four others were on moorings that had been displaced, or had stopped recording early, and subsequently excluded from the analysis (Table 1, Figure 6).The number of usable recording days varied considerably between units based on battery life and/or displacement during the survey period. The median number of usable days for the C-PODs was 108 (range 24-160). Due to the increased power and storage requirements, the SM2M units recorded for fewer days than the C-PODs, with a median number of recording days of 62.5 (range 46 -69; Table 1).

Together the C-PODs identified 10,753 high or moderate quality “Other Cet” click trains, representing undetermined delphinid species (Table 1). The number of “Other Cet” click trains logged by each C-POD varied from zero (recorded by the Helmsdale 10, Spey Bay 10 and St Andrews 10 units; Figure 1) to a maximum of 3662 (recorded by the Cromarty 5 unit). Of these, 1% represented click trains from the tails of the click feature distributions where there therefore excluded from the analysis. Data exploration indicated that dominant frequency and end frequency were collinear and so the latter was excluded from the categorization analysis.

B. C-POD Echolocation Click Features

Five of the 10 C-PODs deployed with adjacent SM2Ms registered click trains that were also identifiable in the full spectrum SM2M recordings (Table 1). The lack of concurrent detections in the other five C-POD/SM2M pairs could partly be attributed to the very few echolocation click detections by either the SM2M or the C-POD those locations (e.g., Spey Bay and St Andrews 10). In other cases, such as Cruden Bay 5, the failure to detect clicks on the adjacent SM2M likely arose from the duty cycle of the SM2M units which precluded visual categorization of the echolocation clicks. Last, differences in detection probability between the C-PODs and SM2M units may result in fewer click trains overall being recorded by the C-PODs.

In total, 925 click trains detected by the KERNO classifier occurred concurrently with visually confirmed broadband (n=253) or frequency banded (n=672) click train encounters in the continuous recordings. The vast majority of verifiable broadband click trains (89%) were extracted from the Stonehaven 5 deployment. This distribution was therefore not representative of either the spatial or temporal scale of the survey. To obtain a more representative sample of broadband click features, 419 click trains were randomly selected from the Cromarty 5 C-POD, where long term sighting records confirm the overwhelming presence of bottlenose dolphins, and added to the broadband training. Four hundred and nineteen were used so as to include an equal number of frequency banded and broadband click trains with which we built the GAM for 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

TABLE III

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

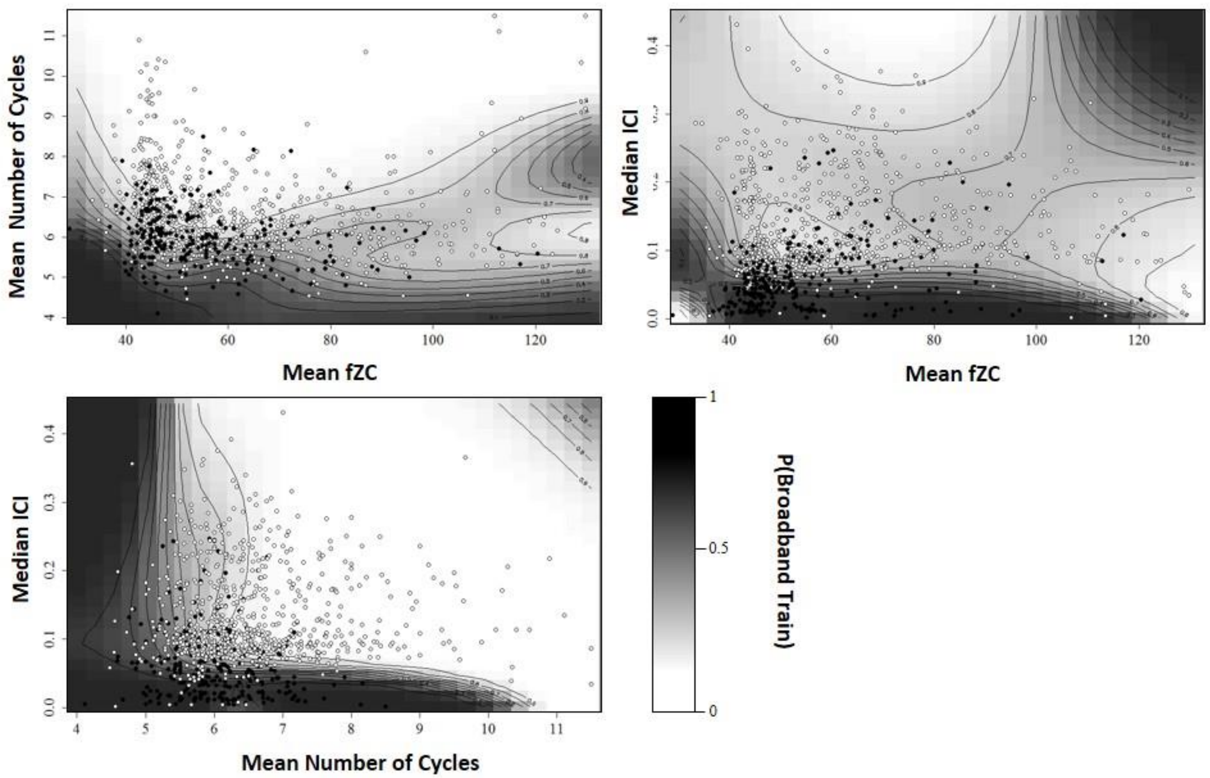

FIGURE 4 Two dimensional representations of the for-dimensional tensor-smooth binomial classification GAM. Shade indicates the probability that a given click train was broadband (black) or frequency banded (white) based on the mean inter-click-interval (Median ICI), mean number of cycles (e.g. duration) 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.

When applied to the full C-POD dataset (minus the training data), the model categorized a total of 3968 (37%) of the click trains, of which 2737 were identified as broadband and 1231 frequency banded. The remaining 63% of the click trains failed to meet either categorization threshold (T_t). As expected, the proportion of click train types varied across the deployment sites. C-PODs near the inner Moray Firth (Cromarty and Spey Bay) contained primarily broadband click trains and units to the north and south (Helmsdale and Fraserburgh) contained primarily frequency banded click trains. Uncategorized click trains were present on all units and, with the exception of the Cromarty locations, generally represented the majority of the click trains detected at each deployment site (Figure 5).

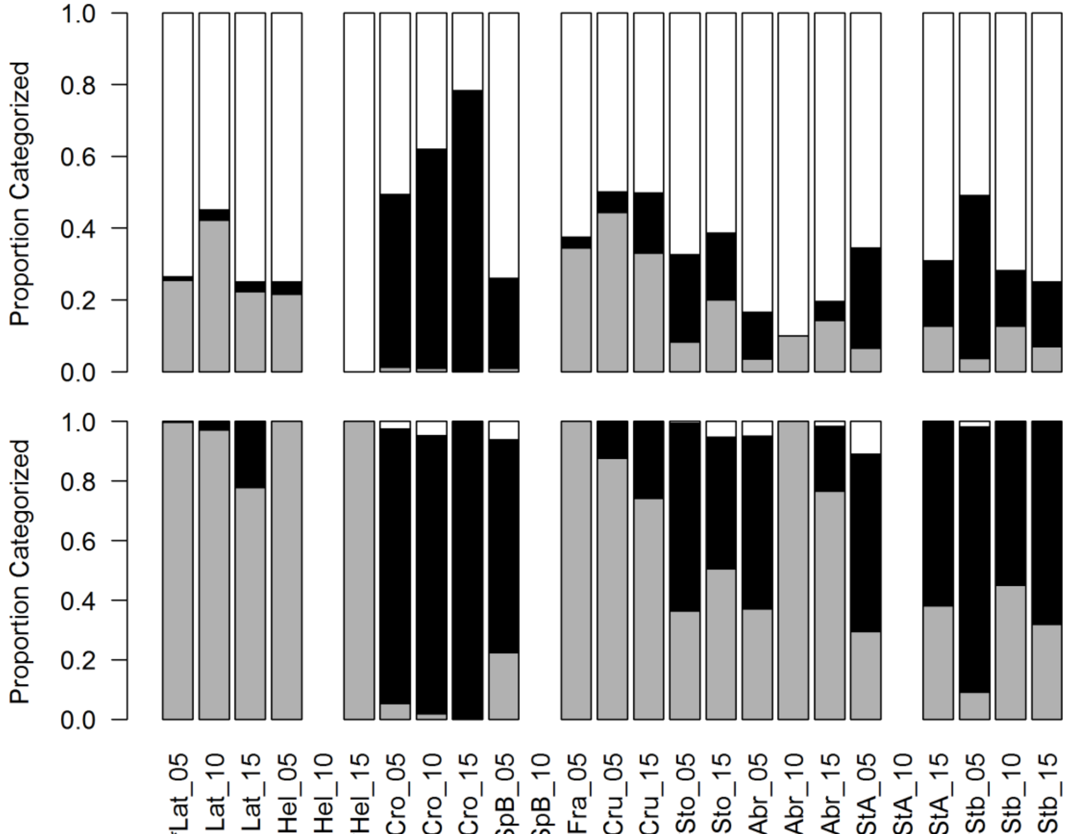

FIGURE 5 Upper Panel: The proportion of click trains classified as broadband (black), frequency banded (gray) or unknown (white) by the GAM classification model with a minimum classification threshold of ±0.425(Tt Equation 1). Lower Panel: The proportion of click trains classified as broadband, frequency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

encounter likelihood ratio. Asterisks indicate joint C-POD/SM2M deployment locations from which training data were derived. Displaced units (SpB 05, Fra 10, Fra 15, Cru 10, Sto 10) not shown.

D. Encounter Likelihood

The 10,753 click trains documented by the 26 recovered C-PODs represented 573 encounters. Twelve encounters coincided with visually verified broadband trains recorded by the adjacent SM2M recordings and 27 encounters coincided with visually verified frequency-banded click trains in the SM2M recordings (Table 1). Using a minimum likelihood ratio of five ($T_e = 5$ in Equation 4), 10 of the verified broadband click-train encounters were correctly categorized, two were incorrectly categorized as frequency banded encounters and none were left unclassified, while 24 of the 27 verified frequency banded encounters were correctly categorized, none were incorrectly categorized and three were left unclassified. When the likelihood model was applied to the remaining data, 264 (43%) total encounters were categorized as broadband, 273 (45%) as frequency banded and the remaining 75 (12%) were left unclassified (Figure 5). The Helmsdale 15 unit contained a single acoustic encounter for which no click trains met the GAM categorization threshold, but the likelihood ratio of the encounter was less than 1/5 allowing classification, therefore the proportion of click trains classified on the Helmsdale unit was 0 in the GAM only model, but 100% when the encounter likelihood ratio was applied.

The highest daily occupancy rates were observed at the Cromarty 5 deployment location, with other peaks around the Latheron, Fraserburgh, Arbroath and St Andrews sites (Figure 6). No encounters of either type were documented by the Helmsdale 10, Spey Bay 10 and St Andrews 10 units. The daily occupancy rates of broadband and frequency banded click encounters differed between locations. Deployments near the inner Moray Firth showed higher broadband daily occupancy rates while the converse was true for the Latheron, Fraserburgh and Cruden Bay sites. These results are consistent with long-term studies in the area that have shown regular bottlenose dolphin presence in and around the SAC (Hammond and Thompson, 1991; Wilson *et al.*, 1997; Quick *et al.*, 2014). Interestingly, encounters in Stonehaven, Arbroath, and to a lesser degree St Andrews and St Abbs, showed similar rates of detection positive days for both broadband and frequency-banded click types, indicating the presence of multiple species.

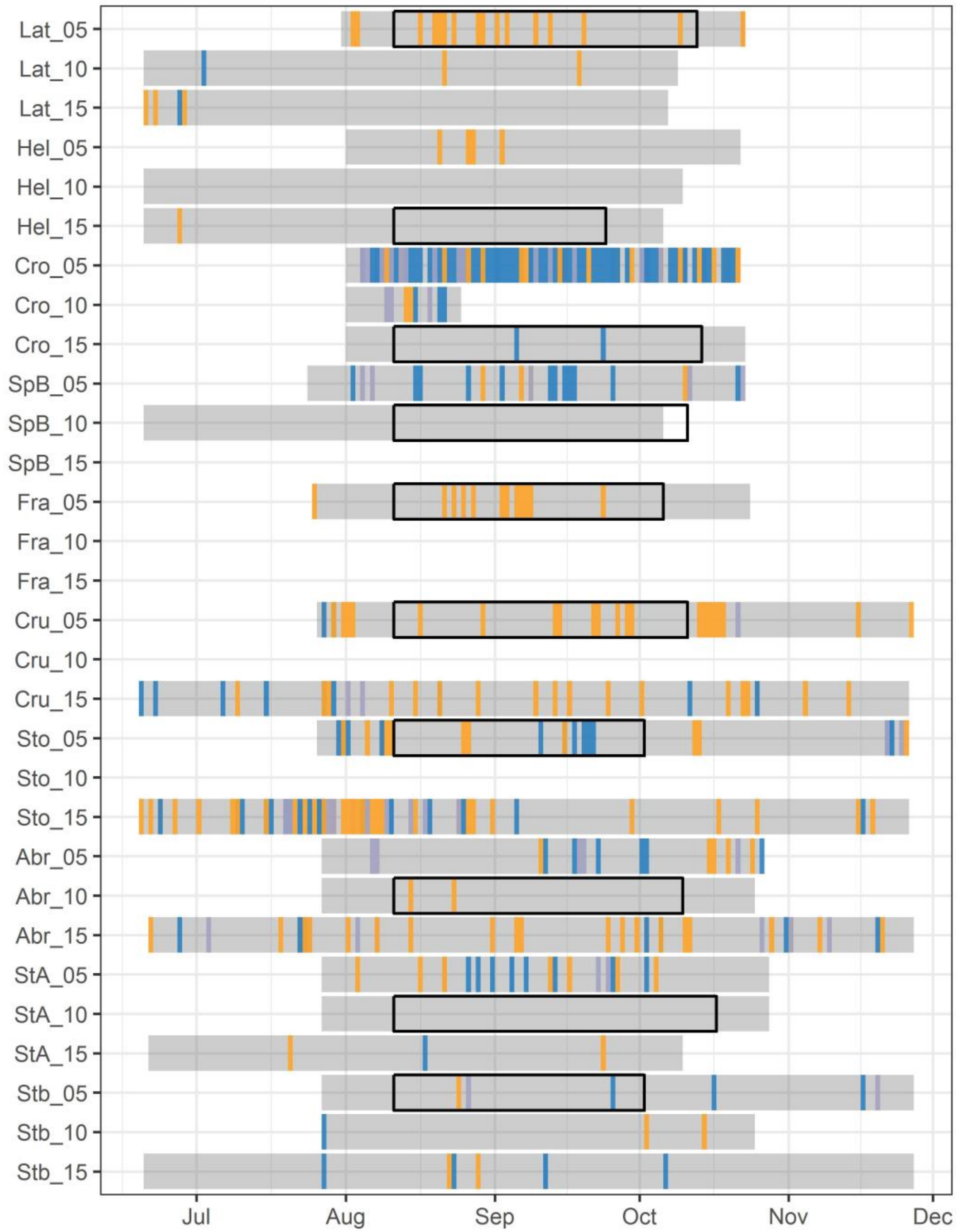
Lat_05
Lat_10
Lat_15
Hel_05
Hel_10
Hel_15
Cro_05
Cro_10
Cro_15
SpB_05
SpB_10
SpB_15
Fra_05
Fra_10
Fra_15
Cru_05
Cru_10
Cru_15
Sto_05
Sto_10
Sto_15
Abr_05
Abr_10
Abr_15
StA_05
StA_10
StA_15
Stb_05
Stb_10
Stb_15
Jul
Aug
Sep
Oct
Nov
Dec

FIGURE 6 Daily occupancy of broadband echolocation click encounters (blue), frequency banded echolocation click encounters (yellow) and uncategorized echolocation click train encounters (dark gray). Gray blocks indicate times when the C-PODs were recording (see also table 1) and

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

V. DISCUSSION

The categorization results reported here for C-POD detections are consistent with the few visual surveys available for areas outside of the Moray Firth. This study identified primarily broadband encounters in the data from all three Cromarty C-PODs. This finding is unsurprising given that a portion of the broadband training detections were derived from the Cromarty 5 unit. However, the prevalence of broadband click trains at the other two Cromarty deployment sites is consistent with previous studies in the area. Similarly, broadband encounters were more prevalent than frequency banded click trains in the C-POD detections at the St Andrews and St Abbs sites, where bottlenose dolphins are the most frequently sighted species (Cheney *et al.*, 2013). Approximately equal numbers of broadband and frequency banded detections occurred through the Grampian region (Cruden Bay, Stonehaven and Arbroath), which agrees well with reported sighting rates for bottlenose and white-beaked dolphins between Cruden Bay and Stonehaven (Anderwald and Evans (2010). Similarly, Weir *et al.* (2007) report multiple sightings of white-beaked dolphins in and around the Aberdeen area (between Cruden Bay and Stonehaven).

Daily occupancy rates from the C-POD data suggest a degree of spatial partitioning between species producing broadband and frequency-banded clicks. Broadband click encounters comprised the vast majority of the detection positive days logged by the C-PODs deployed in the inner Moray Firth (Cromarty). Contrary to our expectations, the acoustic encounters on the Helmsdale C-PODs, which were located within the Moray Firth SAC, were dominated by frequency banded click trains. This suggests that, over the 2013 deployment period, bottlenose dolphins were not the most common species using this portion of the SAC.

Outside of the SAC, both broadband and frequency banded click encounters were frequently observed. However, for each deployment group (e.g., St Andrews, Arbroath etc.) broadband click trains were more common in the nearshore (~5 km) than the offshore deployment sites (~10 and 15 km). This is consistent with previous studies that suggest bottlenose dolphins preferentially use nearshore areas (Arso Civil, 2014; Quick *et al.*, 2014). The Stonehaven C-PODs contained a mix of broadband and frequency banded encounters, matching visual surveys indicating that both bottlenose and white beaked dolphins are commonly sighted in that area (Weir *et al.*, 2007; Anderwald and Evans, 2010). These results hint at the possibility of areas along the eastern Scottish coast having different ecological importance for the two groups. This has been confirmed for bottlenose dolphins in the inner Moray Firth where foraging buzzes are more frequently documented near known "hot-spots" (Hastie *et al.*, 2004; Pirotta *et al.*, 2014b). However, fewer data are available for the other species present in the area and/or outside of the Moray Firth.

The similarity between our results and previously published sightings data indicates that the C-POD encounter categorization system presented here works well for eastern Scottish waters. However, it would be inappropriate to directly apply this categorization tool to C-POD detections collected from other regions. Recent classification studies on similar species groups using full spectrum recording (*fs* = 200 kHz) have shown that deployment location and instrument type can adversely affect the performance of click train classifiers (Roch *et al.*, 2015). It is unclear whether this might be the case with C-POD data for which fewer click features are collected. While it is possible that the zero-crossing method combined with the limited click parameters are more robust to site and/or instrument specific variations, it could just as easily be the case that the limited click features recorded by the C-PODs are *more* susceptible to such variations. Thus, future studies seeking to use this classifier or these methods must not omit a validation process. Ideally this would involve comparing C-POD detections with concurrent visual sightings (e.g., Roberts and Read 2014, Robbins *et al.* 2015, Nuutilia *et al.* 2013). However, where visual observations are not possible or practical, pairing C-PODs with continuous recorders is an alternative method.

The use of C-POD data processed only with the KERNO classifier is justified in surveys where the researchers can be confident that the majority of detections represent single dolphin and/or porpoise species. This is the case for the dolphin detections within the inner Moray Firth where bottlenose dolphins represent the principle dolphin species. Similarly, throughout the North Sea, harbor porpoise (*Phocoena phocoena*) represent the only resident cetacean capable of producing "NBHF" clicks and are, therefore, unlikely to be confused with other species. In such contexts, C-PODs and similar devices can directly inform studies of cetacean abundance and behavior (Jaramillo-Legorreta and Rojas-Bracho, 2011; Kyhn *et al.*, 2012; Brookes *et al.*, 2013; Wilson *et al.*, 2013; Pirotta *et al.*, 2014b; Williamson *et al.*, 2016). However, where multiple odontocete species with similar click features are present, additional methods are needed to increase taxonomic resolution. This study highlights the benefits of developing methods to increase taxonomic precision in detections from low-cost click loggers when full acoustic audits are impossible or impractical. This is especially pertinent given that C-PODs and their predecessor T-PODs are widely used for monitoring an mitigation associated with offshore industrial activities (Carstensen *et al.*, 2006; Scheidat *et al.*, 2011).

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 one of the four most common species seen in the area. C-PODs are capable of recording echolocation clicks from all odontocetes with the exception of sperm whales (*Physeter macrocephalus*) for which the energy is below the sensitivity of the instruments (Dähne *et al.*, 2013). This includes clicks from species that, while infrequent, are known to visit the eastern Scottish coast including killer whales (*Orcinus orca*), long-finned pilot whales (*Globicephala melas*), and Atlantic white sided dolphins (*Lagenorhynchus acutus*). Based on published click characteristics (Deecke *et al.*, 2005; Eskesen *et al.*, 2011), click trains from these species would likely be classified as broadband click encounters by this categorization system. Thus, it is possible that some of the "Other Cet" click trains detected by the C-PODs represented one or more of these species. However, previous visual surveys indicate that such species are infrequent visitors to the eastern Scottish coast and could therefore contribute only a trivial amount of noise to the encounter rates presented here. Regardless, the ambiguity in dolphin detections reiterates the need to inform acoustic-only methods with other sources of information about the study system.

The interpretation of these results assumed that stable frequency banding, or the lack thereof, in echolocation clicks was diagnostic of the species-group producing them. This assumption is debated in the literature, with several authors providing evidence of species discrimination based on the spectral location of peaks and notches (Houser et al., 1999; Soldevilla et al., 2008; Calderan et al., 2013), while others have postulated that spectral banding cannot be diagnostic of species (Wahlberg et al., 2011). While an in-depth analysis of this debate is outside of the scope of this study, careful consideration is prudent to understand the validity of the categorization analysis presented here. Currently two hypotheses exist regarding how frequency banding might be produced. Wahlberg et al. (2011) and Rasmussen et al. (2004) measured on-axis clicks from free-ranging bottlenose and white sided dolphins, respectively. Both studies fitted a baffled piston model to the received clicks, and Wahlberg et al. (2011) suggested that the banding found in other species was attributed to the off-axis banding effects dictated by the piston aperture size. However, these studies primarily analyzed clicks from 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 preclude the independent documentation of stable spectral peaks and notches in the spectra of clicks recorded off-axis from a number of species with similar cranial morphology (Soldevilla *et al.*, 2008; Au *et al.*, 2012b).

The off-axis spectral characteristics of echolcoation clicks have been measured for bottlenose dolphins. Au *et al.* (2012b) measured the entire biosonar field around captive bottlenose dolphins and found that, off-axis, echolocation clicks degraded into discrete pulses most likely produced by the phonic lips and internal reflections from within the animal's head (Au et al., 2012b). Multiple pulses, when processed with an FFT or DFT algorithm, result in "ripples" in the spectrum consistent with the peaks and notches described by Soldevilla *et al.* (2008). However, as with sperm whales, the inter-pulse-interval in bottlenose dolphin echolocation clicks is highly sensitive to the off-axis angle (Goold, 1996). Therefore, when energy is averaged across multiple clicks collected from a variety of angles relative to the animal, the peaks and notches in spectral energy from this species become less distinct.

Unfortunately, detailed studies of off-axis clicks from “frequency banded” species including Risso’s, white-beaked and white-sided dolphins are lacking. However, it is possible that differences in cranial morphology between the species groups could account for differences in the stability of spectral peaks and notches. For example, assuming the multi-pulse model of echolocation click propagation, more uniform path lengths between the phonic lips and melon for frequency banded species would result in consistent inter-pulse-intervals. This would subsequently lead to less variation in the spectral location in peak and notch energy for off-axis clicks in these species. Additional studies are needed to determine whether or not this is the case.

Assuming the presence of stable spectral peaks and notches is diagnostic of species group, on-axis clicks will necessarily confound our ability to discriminate between broadband and frequency banded click trains in both the SM2M recordings and the C-POD encounter categorization model (Au *et al.*, 1974; Au *et al.*, 1999; Rasmussen and Miller, 2002; Rasmussen *et al.*, 2004; Wahlberg *et al.*, 2011; Au *et al.*, 2012a). Moreover, if a disproportionately large selection of on-axis click trains were included in the training data, this would add considerable noise to the final categorization task. We limited this outcome by restricting the selection of C-POD click trains used to build the GAM to periods during which more than 500 high SNR click trains could be identified in the adjacent SM2M recordings. This conservative selection criterion reduced the probability of creating a biased sample of clicks from any particular beam angle and thereby increased our confidence in the accuracy of the categorization task.

Our categorization model included ICI as a predictor, yet it is known that odontocetes modify their inter-click-interval depending on their behavioral state (Janik, 2000; Johnson *et al.*, 2006; Pirotta *et al.*, 2014b). This has the potential to introduce two confounding factors into the analysis presented here. First, there is question of whether ICI can be used to discriminate between different species (or groups) of dolphins. Additionally, there is the potential that the categorization task is describing behavior (e.g. foraging vs. travel) rather than species group.

In addressing whether ICI can be used for species discrimination we note that the GAM model selected here used a tensor smooth across all three click train features recorded by the C-POD. Thus, ICI itself did not predict the click-train category. Instead, prediction was based on the relationship between median ICI, mean zero-crossing frequency and mean bandwidth. Accordingly, while ICI itself has not been widely used to discriminate between species, Johnson *et al.* (2006) note that in Blainsville's beaked whales (*Mesoplodon densirostris*) there is a species-specific relationship between ICI, peak frequency and bandwidth of the individual clicks. For this species, as the animal approaches a prey target decreasing ICI's are linked with decreasing click durations and increasing click bandwidths and peak frequencies. Thus, while inter click interval, bandwidth or peak frequency alone would be inadequate to categorize echolocation clicks, the relationship between these variables may be sufficiently different in some species to allow for categorization and/or classification.

Concerning whether our sample of echolocation clicks represented a biased distribution of clicking behaviors (e.g. primarily click trains associated with foraging or travelling), we note that the training data were obtained from multiple times and locations throughout the survey. Therefore, click trains associated with foraging, travelling and socializing activities should all be represented in the training data for both echolocation click types (Pirotta *et al.*, 2014b). *K*-fold cross validation involved subsetting trains from multiple acoustic encounters. This methodology was necessary as very few acoustic encounters could be correlated with the adjacent

SM2M recordings (10 broadband and 17 frequency banded encounters; Table 1). This also meant we were forced to train and test our model on the same data - with more verified acoustic encounters we could have better characterized in vs. out of sample model performance, and this should still be the aim for future studies.

As with any acoustic classifier, ours is not immune to miscategorization. There are a number of ways in which future studies may account for this misclassification error. First, the performance of this categorization system should be tailored to the research objectives by modifying encounter thresholds based on cost functions derived from study objectives. For example, in this study a single encounter threshold was set above and below which encounters were categorized as broadband or frequency banded. However, studies for which there is a high cost to false negative detections may wish to take a more conservative approach. In such cases, the likelihood categorization threshold (T_e) could be either decreased or excluded altogether; opting instead to include all click trains with a GAM prediction score above a given threshold (T_p) in the final analysis. Alternatively, future studies may seek to incorporate misclassification error directly into the analysis. Bayesian occupancy models, in particular, offer sufficient flexibility to allow for the incorporation of correct and incorrect classification rates across all categories (Miller *et al.*, 2011).

Provided the above considerations are kept in mind, it would be worthwhile to investigate whether this categorization system might perform comparably to C-POD detections collected from other habitats. Similar dolphin species compositions have been observed in western Scotland (MacLeod *et al.*, 2005), Ireland (Robbins *et al.*, 2015), California (Soldevilla *et al.*, 2008), and in the Mediterranean sea (Frantzis and Herzing, 2002). If the C-POD categorization system derived here performs comparably in other habitats, it suggests a wider application of these GAM/likelihood methods may be possible.

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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