

RESEARCH ARTICLE

Description and classification of echolocation clicks of Indian Ocean humpback (*Sousa plumbea*) and Indo-Pacific bottlenose (*Tursiops aduncus*) dolphins from Menai Bay, Zanzibar, East Africa

Liangliang Yang^{1,2}, Matt Sharpe¹, Andrew J. Temple¹, Narriman Jiddawi³, Xiaomei Xu^{2*}, Per Berggren^{1*}

1 School of Natural and Environmental Sciences, Newcastle University, Newcastle upon Tyne, England, United Kingdom, **2** Key Laboratory of Underwater Acoustic Communication and Marine Information Technology of the Ministry of Education, College of Ocean and Earth Sciences, Xiamen University, Xiamen, China, **3** Institute of Fisheries Research Zanzibar, Ministry of Agriculture, Natural Resources, Livestock and Fisheries, Zanzibar, Tanzania

* xmxu@xmu.edu.cn (XX); per.berggren@newcastle.ac.uk (PB)



OPEN ACCESS

Citation: Yang L, Sharpe M, Temple AJ, Jiddawi N, Xu X, Berggren P (2020) Description and classification of echolocation clicks of Indian Ocean humpback (*Sousa plumbea*) and Indo-Pacific bottlenose (*Tursiops aduncus*) dolphins from Menai Bay, Zanzibar, East Africa. PLoS ONE 15(3): e0230319. <https://doi.org/10.1371/journal.pone.0230319>

Editor: William David Halliday, Wildlife Conservation Society Canada, CANADA

Received: September 18, 2019

Accepted: February 26, 2020

Published: March 13, 2020

Copyright: © 2020 Yang et al. This is an open access article distributed under the terms of the [Creative Commons Attribution License](https://creativecommons.org/licenses/by/4.0/), which permits unrestricted use, distribution, and reproduction in any medium, provided the original author and source are credited.

Data Availability Statement: All relevant data are within the manuscript and its Supporting Information files.

Funding: This work was supported by the National Natural Science Foundation of China (41976178), the National Key Research and Development Program of China (Grant Number 2018YFC1406305), the Wildlife Conservation Society (WCS) and the Western Indian Ocean

Abstract

Passive acoustic monitoring (PAM) is a powerful method to study the occurrence, movement and behavior of echolocating odontocetes (toothed whales) in the wild. However, in areas occupied by more than one species, echolocation clicks need to be classified into species. The present study investigated whether the echolocation clicks produced by small, at-risk, resident sympatric populations of Indian Ocean humpback dolphin (*Sousa plumbea*) and Indo-Pacific bottlenose dolphin (*Tursiops aduncus*) in Menai Bay, Zanzibar, East Africa, could be classified to allow species specific monitoring. Underwater sounds of *S. plumbea* and *T. aduncus* groups were recorded using a SoundTrap 202HF in January and June-August 2015. Eight acoustic parameters, i.e. -10 dB duration, peak, centroid, lower -3 and lower -10 dB frequencies, and -3 dB, -10 dB and root-mean-squared bandwidth, were used to describe and compare the two species' echolocation clicks. Statistical analyses showed that *S. plumbea* clicks had significantly higher peak, centroid, lower -3 and lower -10 dB frequencies compared to *T. aduncus*, whereas duration and bandwidth parameters were similar for the two species. Random Forest (RF) classifiers were applied to determine parameters that could be used to classify the two species from echolocation clicks and achieved 28.6% and 90.2% correct species classification rates for *S. plumbea* and *T. aduncus*, respectively. Both species were classified at a higher rate than expected at random, however the identified classifiers would only be useful for *T. aduncus* monitoring. The frequency and bandwidth parameters provided most power for species classification. Further study is necessary to identify useful classifiers for *S. plumbea*. This study represents a first step in acoustic description and classification of *S. plumbea* and *T. aduncus* in the western Indian Ocean region, with potential application for future acoustic monitoring of species-specific temporal and spatial occurrence in these sympatric species.

Marine Science Association (WIOMSA) for funding project BYCAM (Grant Number MASMA/CP/2014/01). The funders had no role in study design, data collection and analysis, decision to publish, or preparation of the manuscript.

Competing interests: The authors have declared that no competing interests exist.

Introduction

Passive acoustic monitoring (PAM) is a powerful technique to study the occurrence, movement and behavior of odontocetes (toothed whales) in the wild [1–4]. Compared to traditional visual surveys for odontocetes, PAM detections are not affected by visibility, weather conditions, or human observer bias and may be used for long-term monitoring with minimal disturbance to the study animals [5]. Odontocetes predominantly use two types of sounds; tonal frequency-modulated sounds for communication, e.g. whistles, [6]; and high frequency pulsed clicks, e.g. echolocation clicks for navigation, orientation and prey detection [7], and burst pulses for communication [8]. Whistles are highly variable at an individual level [9] whereas echolocation clicks (here on referred to as “clicks”), are more consistent and can be used for species classification [10–13]. However, some sympatric species of odontocetes produce similar clicks which can limit the effectiveness of PAM for species-specific studies, as acoustic species classification can be challenging [14].

Acoustic parameters of odontocete clicks vary depending on their sound production morphology [14], with some species having the ability to optimize their clicks within the context of the specific habitat [15]. These parameters are further influenced by sound propagation [11], off-axis effects [16] and differences in recording systems [14]. Previous research has successfully classified clicks for some species groups, such as narrowband high frequency clicks of phocoenids [17] and non-whistling delphinids [10], and at species-specific level e.g. sperm whales (*Physeter microcephalus*) [18], pygmy sperm whales (*Kogia breviceps*) [19], Cuvier’s beaked whales (*Ziphius cavirostris*) [20], Blainville’s beaked whales (*Mesoplodon densirostris*) [21] and Franciscana river dolphins (*Pontoporia blainvillei*) [22]. However, classification of clicks for delphinids, especially sympatric species, has proved difficult due to overlaps in some acoustic parameters among species [14, 23, 24].

If the species identity is known when collecting acoustic data, then supervised classification techniques can be developed and employed to attempt species classification using only click data. Supervised machine learning techniques, such as logic-based techniques (e.g. decision tree and rule-based classifiers), perception-based techniques (e.g. neural networks) and statistical learning algorithms (e.g. Bayesian networks and instance-based learning), perform well in processing complex input tasks and may improve decision-making and prediction of unlabeled samples [25]. Considerable efforts have been devoted to analyzing the species-specific aspects of sympatric delphinid clicks using various supervised machine learning methods [26, 27]. For example, clicks of melon-headed whales (*Peponocephala electra*), common bottlenose (*Tursiops truncatus*) and Gray’s spinner (*Stenella longirostris longirostris*) dolphins were separated using spectral parameters and discriminant function analysis providing 93%, 75% and 54% correct classification rates for the three delphinid species, respectively [14]. Furthermore, clicks of seven delphinid species, striped dolphin (*Stenella coeruleoalba*), long-beaked common dolphin (*Delphinus capensis*), short-beaked common dolphin (*Delphinus delphis*), Risso’s dolphin (*Grampus griseus*), Pacific white-sided dolphin (*Lagenorhynchus obliquidens*), pilot whale (*Globicephala macrorhynchus*) and killer whale (*Orcinus orca*), off the coasts of Washington, Oregon and California were classified using the Random Forest classification model with overall correct classification score of 49%, which was significantly greater than that expected by chance for the seven species (14%) [12].

Eight species of delphinids have been identified around Zanzibar, East Africa [28, 29], but only the Indian Ocean humpback (*Sousa plumbea*) and the Indo-Pacific bottlenose dolphin (*T. aduncus*) are resident in Menai Bay off the southwest coast (Fig 1). Boat surveys using photographic identification and capture-recapture analyses have estimated population sizes of 19 (95% CI 14–25) *S. plumbea* and 136 (95% CI 124–172) *T. aduncus* in the southern portion of

the Menai Bay [30]. Both species are usually observed in small groups of 5–10 individuals, but social and foraging groups may be larger [30, 31]. *S. plumbea* is generally distributed closer to shore than *T. aduncus* in areas where the two species distributions overlap [32]. This is also true for Menai Bay, however the two species distributions overlap and are frequently encountered together in mixed-species groups [30]. Both species in Menai Bay are threatened by unsustainable fisheries bycatch [33, 34] and dolphin ecotourism [35–37].

The vocal repertoire of both *S. plumbea* and *T. aduncus* includes whistles and clicks, although to date only whistles of *T. aduncus* from Zanzibar have been described in detail [38]. A recent PAM study conducted in Menai Bay demonstrated broad scale spatio-temporal occurrence patterns for the delphinids [39]. However, that study was unable to acoustically classify the two species and therefore unable to assess species-specific spatio-temporal patterns, thus limiting the applications of the results. Yet, there is potential for species separation, with small but significant differences in some broadband click parameters demonstrated between *T. aduncus* and Australian humpback dolphins (*S. sahulensis*) [23], a sister taxon of *S. plumbea*.

The main objectives of this study are (1) to describe and quantify the source parameters of clicks produced by *S. plumbea* and *T. aduncus* in Menai Bay, Zanzibar, and (2) to investigate whether there are sufficient differences in the acoustic click parameters of *S. plumbea* and *T. aduncus* to classify recorded clicks to species.

Materials and methods

Data collection

Data were collected on 19 and 20 January, and between 28 June and 19 August 2015 in the Menai Bay Conservation Area, off the southwest coast of Unguja Island, Zanzibar (Fig 1). The study area was surveyed for dolphins using an outboard powered 8 m boat during daytime in Beaufort Sea state <4. The water depth at the recording locations was between 10 m and 15 m depending on the tide. The seabed sediment was sand with scattered small coralline rocks.

The time, date, location, species, group size and surface behavior were recorded for all encountered dolphin groups. The boat motored slowly ahead of the dolphin group, deployed the recording equipment, turned off the engine and drifted to reduce background noise. All acoustic recordings were made using a single SoundTrap (ST) 202HF (Ocean Instruments, New Zealand) with a flat frequency response from 20 Hz to 150 kHz (± 3 dB). Full-scale responses and sampling rates were set as 173 dB re 1 μ Pa and 576 kHz, respectively. The ST has an anti-aliasing filter at 150 kHz, resulting in a -6 dB roll-off per additional octave in frequency. The ST was deployed approximately 3 m below the sea surface, attached to a surface buoy and a small weight and tethered to the boat by a 50 m floating line. During recordings, dolphins passed or milled within 5–50 m from the boat. There was no apparent reaction by either species to the presence of the boat and the ST. Although some mixed species groups of *S. plumbea* and *T. aduncus* were encountered and recorded, for the purpose of this study only recordings from single species were used in the analyses. The temporal, spatial and species information for each recording session is given in Table 1.

Data analyses

Click train selection. Recordings were first visually and aurally inspected using waveforms and spectrograms [Hanning window, fast Fourier transform (FFT) size: 1024 points, 50% frequency overlap] produced in Adobe Audition (version 3.0, Adobe Systems Incorporated, CA). All sound files were digitally filtered with a 4-order Butterworth band pass-filter (10–200 kHz) in Audition to minimize the influence of whistles and ambient noise. Only

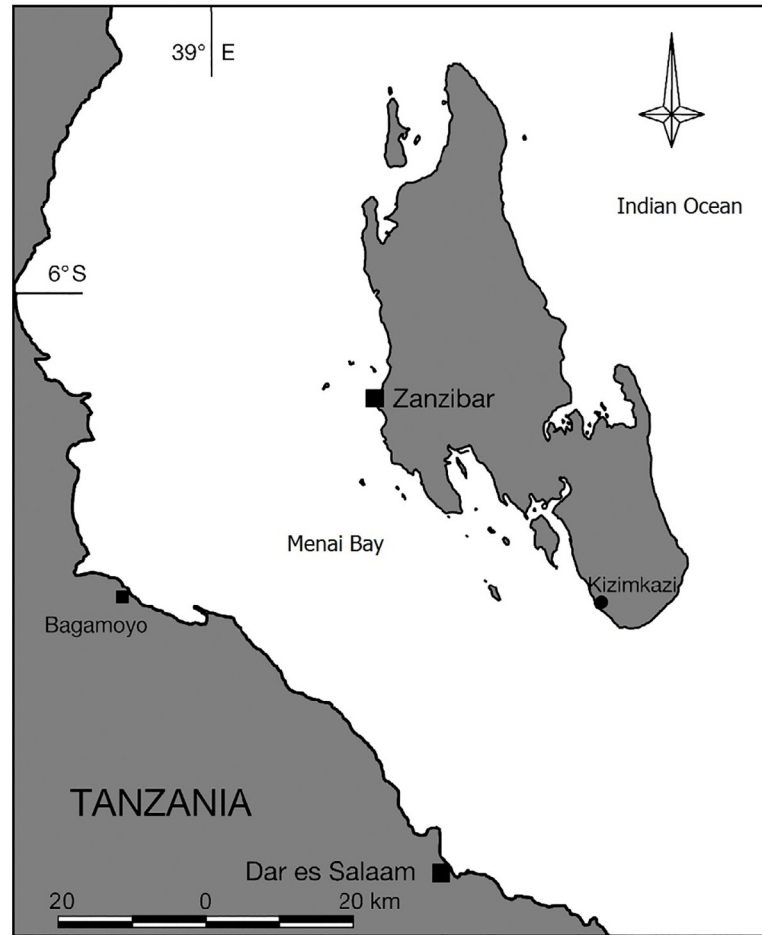


Fig 1. Map of study area. Menai Bay study area ($6^{\circ}31'S$ to $6^{\circ}17'S$, $39^{\circ}11'E$ to $39^{\circ}33'E$) off the southwest coast of Zanzibar, East Africa, where recordings of *S. plumbea* and *T. aduncus* echolocation clicks were conducted in 2015.

<https://doi.org/10.1371/journal.pone.0230319.g001>

Table 1. Temporal, spatial and species information of acoustic recordings made during 2015 in Menai Bay, Zanzibar, East Africa during single species group encounters of *S. plumbea* and *T. aduncus*. Number of click trains, selected trains and individual clicks are presented for each recording session and species.

| Species | Recording session | Date | Start time | Latitude (S), Longitude (E) | Group size | Click trains | Selected trains | selected clicks |
|-------------------|-------------------|--------|------------|-------------------------------------|------------|--------------|-----------------|-----------------|
| <i>S. plumbea</i> | 1 | 19 Jan | 2:12 PM | $6^{\circ}27'0", 39^{\circ}27'36"$ | 5 | 61 | 10 | 10 |
| | 2 | 28 Jun | 6:46 AM | $6^{\circ}28'48", 39^{\circ}29'24"$ | 5 | 9 | 9 | 9 |
| | 3 | 1 Jul | 8:21 AM | $6^{\circ}26'24", 39^{\circ}27'36"$ | 4 | 3 | 3 | 3 |
| | 4 | 20 Jul | 12:06 AM | $6^{\circ}27'36", 39^{\circ}28'12"$ | 8 | 13 | 13 | 13 |
| <i>T. aduncus</i> | 1 | 20 Jan | 7:09 AM | $6^{\circ}27'36", 39^{\circ}28'12"$ | 25 | 40 | 40 | 40 |
| | 2 | 28 Jun | 9:47 AM | $6^{\circ}27'0", 39^{\circ}27'36"$ | 14 | 1 | 1 | 1 |
| | 3 | 4 Jul | 9:26 AM | $6^{\circ}28'48", 39^{\circ}29'24"$ | 27 | 4 | 4 | 4 |
| | 4 | 17 Jul | 7:03 AM | $6^{\circ}28'48", 39^{\circ}30'36"$ | 5 | 24 | 10 | 10 |
| | 5 | 1 Aug | 7:28 AM | $6^{\circ}28'12", 39^{\circ}32'60"$ | 7 | 2 | 2 | 2 |
| | 6 | 9 Aug | 9:07 AM | $6^{\circ}28'12", 39^{\circ}28'12"$ | 17 | 2 | 2 | 2 |
| | 7 | 11 Aug | 8:59 AM | n. a. | 36 | 30 | 30 | 30 |
| | 8 | 19 Aug | 11:54 AM | $6^{\circ}28'48", 39^{\circ}28'48"$ | 14 | 3 | 3 | 3 |

<https://doi.org/10.1371/journal.pone.0230319.t001>

sound files with “loud and clear” click trains were extracted, labeled by hand, and used in subsequent analyses. Click trains were considered to be “loud and clear”, if they were at least 10 dB re 1 μ Pa louder than background noise [40] and had no overlap with other strong pulsed sound. The click trains were inspected and potentially confounding sounds (e.g. snapping shrimp and bubble/sediment entrainment noise) were removed by hand. Furthermore, the chosen click trains were required to contain at least eight clicks per train with average inter-click interval (ICI) of > 10 ms and < 0.1 s using a playback rate of 0.01 [41, 42], thus excluding echolocation buzzes (click trains with high repetition rates used during prey capture) and burst pulses, to avoid introducing additional variance in the dataset. The total number of click trains used per recording session was limited to twice the estimated group size to reduce over-representation of a single recording session [13]. Click trains were randomly selected until all available trains were selected or the limit was reached (Table 1).

Click detection. Clicks were automatically detected from each chosen click train using an energy detector to identify impulse signals [43]. Click trains were first divided into several 5 ms segments. Clicks were detected in the spectra domain (frequency vs spectral power, Hanning window, FFT size: 576 points, 50% overlap) and calculated from each segment. When 13% or more of the frequency bins between 15 kHz and 95 kHz had signal-to-noise ratios over 15 dB [13], the segments were considered to contain a click candidate.

An automated algorithm was used to remove false positive detections, including vessel noise and clipped clicks. Specifically, click candidates with a peak frequency less than 20 kHz [44] and with a maximum amplitude more than 80% of the maximum system capability [14] were considered as false positive detections. Given that only a single hydrophone was used during the field recordings, it was impossible to determine whether a click was recorded on the acoustic axis [45]. To mitigate against the impact of off-axis click use, only the highest amplitude click from each click train was extracted, following the methods for on-axis click analysis [46]. The aforementioned click detections and false positive removal were performed using customized routines in MATLAB (version R2016a, Mathworks, Natick, MA).

Acoustic parameters. A 32-point rectangular window around the peak of the signal envelop was utilized for all selected clicks in order to minimize the risk of reflected clicks and background noise being included in the analysis. To assess potential differences in clicks between *S. plumbea* and *T. aduncus*, eight acoustic parameters, i.e. -10 dB duration, peak frequency, centroid frequency, lower -3 dB frequency, lower -10 dB frequency, -3 dB bandwidth, -10 dB bandwidth and RMS bandwidth, were calculated using custom written scripts in MATLAB R2016a (Mathworks, Natick, MA). The chosen parameters (Table 2) have been used

Table 2. Description of eight acoustic parameters for echolocation clicks of *S. plumbea* and *T. aduncus* recorded in Menai Bay, Zanzibar, East Africa. Abbreviation used are shown in the parenthesis.

| Acoustic parameters | Description |
|--|--|
| -10 dB duration (D_{-10dB}) | Click duration in 10 dB below the peak of the envelope of the waveform [46]. |
| Peak frequency (F_p) | Frequency value of maximum energy in the spectrum [7]. |
| Centroid frequency (F_c) | Average power distributed across the frequency bins in the spectrum [48]. |
| Lower -3dB frequency (F_{L3}) | Lower cut-off frequency of -3dB bandwidth [14]. |
| Lower -10dB frequency (F_{L10}) | Lower cut-off frequency of -10dB bandwidth [14]. |
| -3dB bandwidth (BW_{-3dB}) | Frequency width between the $1/\sqrt{2}$ of amplitude points of the spectrum on the linear scale [46]. |
| -10dB bandwidth (BW_{-10dB}) | Frequency width between the 1/10 of amplitude points of the spectrum on the linear scale [46]. |
| Root-mean-squared bandwidth (BW_{RMS}) | Spectral standard deviation around the centroid frequency of the spectrum [48]. |

<https://doi.org/10.1371/journal.pone.0230319.t002>

by several other studies to characterize dolphin clicks [7, 14, 46]. The -10 dB duration was determined from the interpolated (10 times linear interpolation) waveform for an individual click. The remaining seven frequency and bandwidth parameters were computed from the power spectra. The power spectrum of each detected click was calculated based on Welch method [47] using 32-point fast Fourier transform with a Hanning window, and interpolated with a factor of 10 using low-pass interpolation, resulting in a spectral resolution of 1.8 kHz. These settings allow direct comparison to previous published acoustic parameter measurements for the two species [23]. Inter-click interval (ICI) and Q (quality factor) parameters were not deemed appropriate for use in the analyses and so were not considered. ICIs are adjusted by the echolocating animal and shortened when approaching a target to facilitate close distance tracking and capture [14]. The Q parameter has been used to describe the relative bandwidth of click signals in previous research [23]. However, the Q parameter does not provide useful information for classification, as it is defined as the ratio of centroid frequency to RMS bandwidth.

Statistical analyses

The click train selection criteria used identified 35 *S. plumbea* (S1 Audio) and 92 *T. aduncus* (S2 Audio) click trains as “loud and clear”, and thus suitable for analysis. All data of the highest amplitude clicks selected from each click train used for statistical analysis are available in supporting information (S1 Table). None of the analyzed parameters conformed to a normal distribution (Kolmogorov-Smirnov tests, $\alpha = 0.05$), had equal variance (Levene’s tests, $\alpha = 0.05$) or could be successfully log-transformed. Median with 5th and 95th percentile values were used as the descriptive statistics for each parameter. Non-parametric Mann-Whitney U-tests were used to statistically compare the acoustic parameters between *S. plumbea* and *T. aduncus*. Significance level was set at $\alpha = 0.05$. All parameters were used in subsequent classification analyses, with parameters showing significant differences between species expected to provide greatest classification power.

Random Forest (RF) was used to separate echolocation clicks between *S. plumbea* and *T. aduncus* using all acoustic parameters. RF, as a supervised classification method, has demonstrated excellent performance in bio-acoustic studies [49]. The RF is an ensemble classifier, developed by Breiman [50], consisting of many independent classification trees [51], where each tree is generated by a randomly selected subset of the original training data (e.g. 92 *T. aduncus* clicks and 35 *S. plumbea* clicks used here) with replacement [50, 52]. At each split approximately 37% of the training data, named as “out of bag” (OOB) samples, are not selected when constructing each tree but used to assess the performance of the RF [50, 53]. The remaining samples, named as “in-bag” samples, are used to construct each tree using a random subset of all features (e.g. the eight acoustic parameters here) to split the node [50, 53]. Once the forest is built, individual trees are combined through a majority voting process to assign new candidates to a class [50].

The OOB error rate ($OOB_{\text{error rate}}$) was calculated as the median of the error rates from the constructed trees in the RF using OOB samples [50]. The percentage, i.e. $1 - OOB_{\text{error rate}}$, and its 5th and 95th quantiles are reported as a measure of the correct classification rate [54]. There are two significant parameters in the RF [53]: (1) the number of trees to construct (n_{tree}), and (2) the number of randomly chosen variables (e.g. acoustic parameters in this case) used to split each node (m_{try}), which can be optimized via the OOB error estimation. As a result, the n_{tree} and m_{try} were set to 3000 and \sqrt{M} based on the OOB error, where M represents the total number of input variables.

The above parameter comparison and RF model construction were all implemented in R (version 3.3.3, R Core Team, 2018) using the *asht* and *randomForest* packages, respectively.

Table 3. The median with the 5th and 95th percentile values of eight acoustic parameters for echolocation clicks of *S. plumbea* and *T. aduncus* in Menai Bay, Zanzibar, East Africa. Species comparisons of click parameters were conducted using Mann-Whitney U tests. Note: * = $p < 0.05$.

| Acoustic parameters | <i>S. plumbea</i> (n = 35) | | <i>T. aduncus</i> (n = 92) | | p-value |
|------------------------------|----------------------------|-----------|----------------------------|----------|---------|
| | median | (5–95%) | median | (5–95%) | |
| -10 dB duration (μ s) | 13 | (11–22) | 14 | (11–23) | 0.514 |
| Peak frequency (kHz) | 97 | (52–119) | 73 | (47–115) | 0.003* |
| Centroid frequency (kHz) | 87 | (64–107) | 81 | (57–98) | 0.002* |
| Lower -3 dB frequency (kHz) | 43 | (29–95) | 36 | (27–59) | 0.003* |
| Lower -10 dB frequency (kHz) | 22 | (16–35) | 18 | (13–29) | 0.017* |
| -3 dB bandwidth (kHz) | 81 | (49–107) | 85 | (34–95) | 0.223 |
| -10 dB bandwidth (kHz) | 126 | (103–148) | 130 | (94–146) | 0.445 |
| RMS bandwidth (kHz) | 23 | (18–31) | 25 | (16–35) | 0.365 |

<https://doi.org/10.1371/journal.pone.0230319.t003>

Ethics statement

The research was undertaken with research permits obtained through the Zanzibar Ministry of Agriculture, Natural Resources, Livestock and Fisheries as well as ethical approval from Newcastle University, UK.

Results

The values of the eight acoustic parameters of *S. plumbea* and *T. aduncus* echolocation clicks are summarized in Table 3 and their respective typical waveforms and the power spectra are presented in Fig 2. Although the clicks of *S. plumbea* and *T. aduncus* were similar, the four frequency parameters (peak frequency, centroid frequency, lower -3 dB frequency and lower -10 dB frequency) had significantly higher median values for *S. plumbea* compared to *T. aduncus*

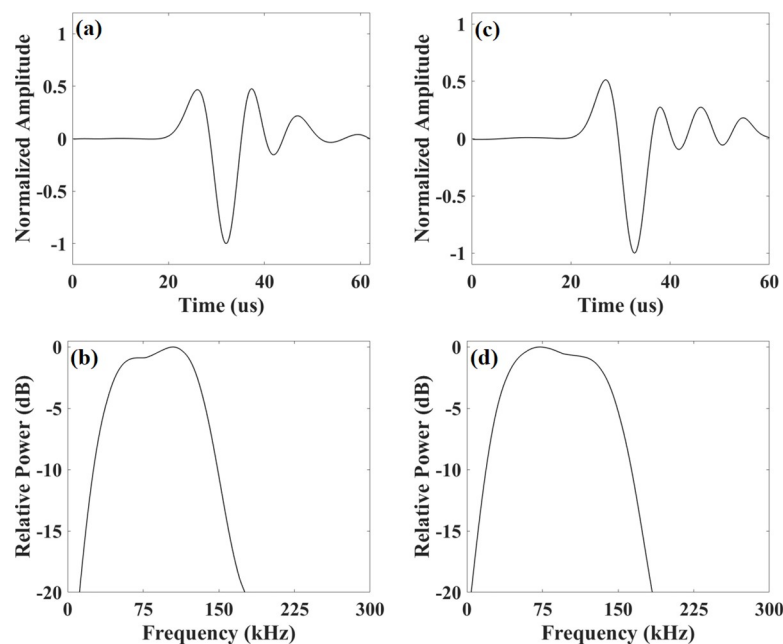


Fig 2. Echolocation click examples for *S. plumbea* and *T. aduncus*. Waveform and power spectrum [Sampling rate: 576 kHz, 32-point rectangular window around the peak of the envelope, and interpolated with a factor of 10 for a spectral resolution of 1.8 kHz] examples of echolocation clicks of *S. plumbea* [(a) and (b)] and *T. aduncus* [(c) and (d)] from Menai Bay, Zanzibar, East Africa.

<https://doi.org/10.1371/journal.pone.0230319.g002>

(Mann-Whitney U Tests, $\alpha = 0.05$, Table 3). Neither -10 dB duration nor the three bandwidth parameters were significantly different between *S. plumbea* and *T. aduncus*.

Overall, the RF model resulted in a 73.2% (5th and 95th quantiles 72.4%-74.0%) correct classification rate for *S. plumbea* and *T. aduncus* echolocation clicks submitted to the model, compared to 50% expected by random chance alone. Similarly, the RF model resulted in a correct classification rate of 28.6% (5th and 95th quantiles 25.7%-31.4%) for *S. plumbea*, compared to an expected rate of 27.6%, and 90.2% (5th and 95th quantiles 90.2%-90.2%) for *T. aduncus*, compared to an expected rate of 72.4%. The RF model demonstrated the following order of importance for the acoustic parameters using mean decreasing accuracy measures for species classification: lower -10 dB frequency, -3 dB bandwidth, -10 dB bandwidth, lower -3 dB frequency, centroid frequency, RMS bandwidth, peak frequency and -10 dB duration.

Discussion

To our knowledge, this study represents the first report of echolocation click parameters for *T. aduncus* in the Western Indian Ocean and for *S. plumbea* globally. The study found differences in peak, centroid, lower -3 dB and lower -10 dB frequencies of clicks between species. This study further classified the echolocation clicks using a RF model and achieved an overall 73.2% correct species classification rate i.e. a better performance than what was expected by chance alone (50%).

Click source parameters measured in this study differed substantively in some instances from those previously reported for *T. aduncus* and *Sousa* species in other geographic regions (Table 4). Both species had lower peak and centroid frequencies than previously reported in the published literature [23, 41, 55]. These differences may result from morphological species differences [14] and/or optimization of clicks for the specific environmental context of different habitats primarily occupied by the species [17]. Indeed, *S. plumbea* has a relatively longer and narrower skull compared to *S. chinensis* [56]. Additionally, differences among study methodologies may contribute to click parameter differences. The present study used a single hydrophone and selected only the highest amplitude click in each click train for inclusion in the analyses, in order to minimise the likelihood of off-axis click selection. Other studies were able to use hydrophone arrays thus having a higher likelihood of selecting only on-axis clicks [23, 55].

Statistically, all click frequency parameters (peak, centroid, lower -3 dB and lower -10 dB frequencies) measured for *S. plumbea* were higher than those of *T. aduncus*. Differences in

Table 4. Comparisons of the mean \pm standard deviation of source parameters of echolocation clicks of wild *T. aduncus* from different areas and different species of *Sousa*.

| Species | -10 dB duration (μ s) | Peak frequency (kHz) | Centroid frequency (kHz) | -3 dB bandwidth (kHz) | -10 dB bandwidth (kHz) | RMS bandwidth (kHz) | Reference |
|-------------------------------|----------------------------|----------------------|--------------------------|-----------------------|------------------------|---------------------|------------|
| <i>T. aduncus</i> (n = 54) | 14 \pm 2 | 124 \pm 13 | 112 \pm 9 | 62 \pm 17 | 140 \pm 17 | 34 \pm 3 | [23] |
| <i>T. aduncus</i> (n = 89) | 18 \pm 6 | n.a | 91 \pm 13 | n. a. | n. a. | 35 \pm 3 | [41] |
| <i>T. aduncus</i> (n = 92) | 16 \pm 4 | 77 \pm 24 | 80 \pm 13 | 81 \pm 19 | 127 \pm 15 | 24 \pm 4 | This study |
| <i>S. chinensis</i> (n = 77) | 19 \pm 4 | 109 \pm 4 | 95 \pm 6 | 50 \pm 13 | 102 \pm 11 | 29 \pm 3 | [55] |
| <i>S. sahalensis</i> (n = 42) | 15 \pm 2 | 114 \pm 12 | 106 \pm 11 | 59 \pm 18 | 116 \pm 20 | 29 \pm 4 | [23] |
| <i>S. plumbea</i> (n = 35) | 16 \pm 3 | 91 \pm 22 | 87 \pm 12 | 79 \pm 15 | 125 \pm 11 | 24 \pm 3 | This study |

<https://doi.org/10.1371/journal.pone.0230319.t004>

preferred habitat and cranial morphology likely explain the interspecific click differences observed in these parameters. *T. aduncus* and *S. plumbea* in Menai Bay have overlapping distributions. However, *S. plumbea* is only found in shallow waters, close to shore whereas *T. aduncus* occurs across the bay including offshore areas [30]. The significantly lower echolocation click frequencies recorded for *T. aduncus* compared to *S. plumbea* would facilitate longer range echolocation which would be beneficial in the deeper and more open water habitats occupied by *T. aduncus* [57]. Furthermore, differences in skull morphology between species, with *S. plumbea* featuring “a small left posterior branch of the melon”, which may be an adaptation that provide improved directionality when using high frequency sounds [57].

The parameters used for species classification in the present study were similar to those applied in other similar research [11, 14, 23]. Specifically, frequency parameters appear to be powerful for classification of delphinids from clicks. Bandwidth parameters appear, generally, weaker for classification, which is consistent with findings of no or limited differences in these parameters among species [14, 23]. Despite this, bandwidth parameters were found to be relatively important contributors to species classification in this study, suggesting that researchers should continue to consider these parameters in future. Interestingly, whilst none of the bandwidth parameters showed significant differences between the two species, both the -3 and -10 dB bandwidth parameters were important in the RF classifier. This reflects the multivariate nature of click signals and indicates likely interactions among parameters. It re-enforces the importance of retaining parameters for classification despite not showing significant differences across all clicks. Conversely, click duration contributed little to click classification. This is congruent with the limited variability in this parameter for sympatric *Tursiops* and *Sousa* species observed in this study and other studies [23]. However, it is notable that click duration has been identified as a valuable parameter for classification of other delphinid species [12, 58] and thus cannot be assumed irrelevant in future works. Understanding drivers behind the interspecific variability in parameter utility for classification may be an important step in shaping future classifier development and ultimately its field application.

Regarding classification of *T. aduncus* and *S. plumbea* in the current study, both species were classified successfully above the expected rate. However, the improvement above the expected rate for *S. plumbea* was minimal. The sample size for *S. plumbea* was relatively small ($n = 35$) in comparison to *T. aduncus* ($n = 92$) and several of the parameters showed a high level of variability. The relatively small sample size for *S. plumbea* makes it vulnerable to influence from unusual click trains or accidental inclusion of off-axis trains. Therefore, greater sampling effort is required to confirm and improve on the findings in the current study. The relatively high classification rate for *T. aduncus* demonstrates the potential to use PAM of clicks to monitor occurrence of this species. Thus, continued effort to further improve the classifiers and to develop algorithms to be incorporated into PAM monitoring systems for *T. aduncus* is strongly encouraged.

In this study, eight acoustic parameters were considered in the analysis. Future efforts to classify species using clicks may be assisted by expanding the range of parameters considered [59, 60]. For example, measurements of intensity at different frequencies in the spectrum have been shown to facilitate identification of “peak and notch” patterns which have been used to classify both *G. griseus* and *L. obliquidens* [13]. Furthermore, comparing intensity at different frequency bands in the spectrum has improved classification results for *M. densirostris*, *G. macrorhynchus* and *G. griseus* [61, 62]. Previous research have also demonstrated that coefficients in cepstral analysis (inverse Fourier transform of the logarithm of the estimated spectrum of a signal) had good classification performance for some species (e.g. *G. griesus*, *M. densirostris* and *G. macrorhynchus*), with little influence of sound propagation and variation resulting from different recording platforms [15, 63]. Additionally, energy amplitude, off-axis

click distortion and transmission beam-widths may contain some species-specific information. However, these characteristics are dependent on knowing the exact location and orientation of echolocating individuals which requires a multiple hydrophone array which was not available in the present study.

In conclusion, this study presents new information on echolocation click parameters recorded from wild *S. plumbea* and *T. aduncus* resident in Menai Bay, Zanzibar. We further explored whether variation in acoustic parameters of echolocation clicks may be used to identify and classify sympatric living *S. plumbea* and *T. aduncus*. An overall 73.2% species click classification rate was achieved, indicating the potential to separate these two species using PAM. However, the identified classifiers were only at a sufficiently high rate (90.2%) for *T. aduncus* to allow species specific monitoring using PAM based on echolocation clicks. The classification method developed would benefit from further refinement and may be improved by increasing the suite of acoustic parameters considered. It is anticipated that the methods eventually can be incorporated into PAM systems as species-specific classification algorithms, facilitating the use of PAM methodologies to monitor occurrence of specific delphinid species. Such information would provide researchers and managers with the foundational data needed to devise evidence-based species-specific conservation strategies, particularly in areas where species are threatened by anthropogenic activities.

Supporting information

S1 Audio. Echolocation click trains of Indian Ocean humpback dolphin (*Sousa plumbea*).
(ZIP)

S2 Audio. Echolocation click trains of Indo-Pacific bottlenose dolphin (*Tursiops aduncus*).
(ZIP)

S1 Table. Information for each click analyzed. For each click, information is provide indicating species, file name, -10 dB duration (μ s), peak, centroid, lower -3 and lower -10 dB frequencies (kHz), and -3 dB, -10 dB and root-mean-squared bandwidth (kHz).
(XLSX)

Acknowledgments

We thank Juma Kifana, Mwalim Rajab, Foum Ramadhan and Khamis Ramadhan for assistance during the field work. We also thank the academic editor Dr William David Halliday and three reviewers for their constructive feedback that significantly improved this manuscript.

Author Contributions

Conceptualization: Liangliang Yang, Per Berggren.

Data curation: Liangliang Yang, Matt Sharpe, Andrew J. Temple, Per Berggren.

Formal analysis: Liangliang Yang, Andrew J. Temple.

Funding acquisition: Xiaomei Xu, Per Berggren.

Investigation: Matt Sharpe, Andrew J. Temple, Narriman Jiddawi.

Methodology: Liangliang Yang, Andrew J. Temple, Per Berggren.

Resources: Narriman Jiddawi, Per Berggren.

Software: Liangliang Yang.

Supervision: Xiaomei Xu, Per Berggren.

Writing – original draft: Liangliang Yang, Per Berggren.

Writing – review & editing: Liangliang Yang, Matt Sharpe, Andrew J. Temple, Xiaomei Xu, Per Berggren.

References

1. Mellinger DK, Stafford KM, Moore SE, Dziak RP, Matsumoto H. An overview of fixed passive acoustic observation methods for cetaceans. *Oceanography*. 2007; 20(4):36–45.
2. Soldevilla MS, Wiggins SM, Hildebrand JA, Oleson EM, Ferguson MC. Risso's and Pacific white-sided dolphin habitat modeling from passive acoustic monitoring. *Mar Ecol Prog Ser*. 2011; 423:247–60.
3. Stimpert AK, Au WW, Parks SE, Hurst T, Wiley DN. Common humpback whale (*Megaptera novaeangliae*) sound types for passive acoustic monitoring. *The Journal of the Acoustical Society of America*. 2011; 129(1):476–82. <https://doi.org/10.1121/1.3504708> PMID: 21303027
4. Giorli G, Au WW, Neuheimer A. Differences in foraging activity of deep sea diving odontocetes in the Ligurian Sea as determined by passive acoustic recorders. *Deep Sea Research Part I: Oceanographic Research Papers*. 2016; 107:1–8.
5. Sousa-Lima RS, Norris TF, Oswald JN, Fernandes DP. A review and inventory of fixed autonomous recorders for passive acoustic monitoring of marine mammals. *Aquat Mamm*. 2013; 39(1):23.
6. Tyack P. Population biology, social behavior and communication in whales and dolphins. *Trends in ecology & evolution*. 1986; 1(6):144–50.
7. Au WW. *The sonar of dolphins*. New York: Springer-Verlag; 2012. p. 115–23.
8. Lammers M, Au W, Aubauer R, Nachtigall P. A comparative analysis of the pulsed emissions of free-ranging Hawaiian spinner dolphins (*Stenella longirostris*). *Echolocation in bats and dolphins*. 2004: 414–9.
9. Caldwell MC, Caldwell DK, Tyack PL. Review of the signature-whistle hypothesis for the Atlantic bottlenose dolphin. *The bottlenose dolphin*. 1990:199–234.
10. Kyhn LA, Jensen FH, Beedholm K, Tougaard J, Hansen M, Madsen PT. Echolocation in sympatric Peale's dolphins (*Lagenorhynchus australis*) and Commerson's dolphins (*Cephalorhynchus commersonii*) producing narrow-band high-frequency clicks. *J Exp Biol*. 2010; 213(11):1940–9. <https://doi.org/10.1242/jeb.042440> PMID: 20472781
11. Jensen FH, Rocco A, Mansur RM, Smith BD, Janik VM, Madsen PT. Clicking in Shallow Rivers: Short-Range Echolocation of Irrawaddy and Ganges River Dolphins in a Shallow, Acoustically Complex Habitat. *Plos One*. 2013; 8(4):e59284. <https://doi.org/10.1371/journal.pone.0059284> PMID: 23573197
12. Rankin S, Archer F, Keating JL, Oswald JN, Oswald M, Curtis A, et al. Acoustic classification of dolphins in the California Current using whistles, echolocation clicks, and burst pulses. *Mar Mamm Sci*. 2017;(33):520–40.
13. Soldevilla MS, Henderson EE, Campbell GS, Wiggins SM, Hildebrand JA, Roch MA. Classification of Risso's and Pacific white-sided dolphins using spectral properties of echolocation clicks. *The Journal of the Acoustical Society of America*. 2008; 124(1):609–24. <https://doi.org/10.1121/1.2932059> PMID: 18647003
14. Baumann-Pickering S, Wiggins SM, Hildebrand JA, Roch MA, Schnitzler H-U. Discriminating features of echolocation clicks of melon-headed whales (*Peponocephala electra*), bottlenose dolphins (*Tursiops truncatus*), and Gray's spinner dolphins (*Stenella longirostris longirostris*). *The Journal of the Acoustical Society of America*. 2010; 128(4):2212–24. <https://doi.org/10.1121/1.3479549> PMID: 20968391
15. Soldevilla MS, Baumann-Pickering S, Cholewiak D, Hodge LEW, Oleson EM, Rankin S. Geographic variation in Risso's dolphin echolocation click spectra. *The Journal of the Acoustical Society of America*. 2017; 142(2):599–617. <https://doi.org/10.1121/1.4996002> PMID: 28863585
16. Götz T, Antunes R, Heinrich S. Echolocation clicks of free-ranging Chilean dolphins (*Cephalorhynchus eutropia*). *The Journal of the Acoustical Society of America*. 2010; 128(2):563–6. <https://doi.org/10.1121/1.3353078> PMID: 20707424
17. Kyhn LA, Tougaard J, Beedholm K, Jensen FH, Ashe E, Williams R, et al. Clicking in a Killer Whale habitat: Narrow-band, high-frequency biosonar clicks of harbour porpoise (*Phocoena phocoena*) and Dall's porpoise (*Phocoenoides dalli*). *Plos One*. 2013; 8(5):e63763. <https://doi.org/10.1371/journal.pone.0063763> PMID: 23723996

18. Møhl B, Wahlberg M, Madsen PT, Heerfordt A, Lund A. The monopulsed nature of sperm whale clicks. *The Journal of the Acoustical Society of America*. 2003; 114(2):1143–54. <https://doi.org/10.1121/1.1586258> PMID: 12942991
19. Madsen PT, Carder DA, Bedholm K, Ridgway SH. Porpoise clicks from a sperm whale nose—Convergent evolution of 130 kHz pulses in toothed whale sonars? *Bioacoustics*. 2005; 15(2):195–206.
20. Zimmer WMX, Johnson MP, Madsen PT, Tyack PL. Echolocation clicks of free-ranging Cuvier's beaked whales (*Ziphius cavirostris*). *The Journal of the Acoustical Society of America*. 2005; 117(6):3919–27. <https://doi.org/10.1121/1.1910225> PMID: 16018493
21. Madsen P, Johnson M, de Soto NA, Zimmer W, Tyack P. Biosonar performance of foraging beaked whales (*Mesoplodon densirostris*). *J Exp Biol*. 2005; 208(2):181–94.
22. Melcón ML, Failla M, Iñíguez MA. Echolocation behavior of franciscana dolphins (*Pontoporia blainvillei*) in the wild. *The Journal of the Acoustical Society of America*. 2012; 131(6):EL448–EL53. <https://doi.org/10.1121/1.4710837> PMID: 22713020
23. de Freitas M, Jensen FH, Tyne J, Bejder L, Madsen PT. Echolocation parameters of Australian humpback dolphins (*Sousa sahulensis*) and Indo-Pacific bottlenose dolphins (*Tursiops aduncus*) in the wild. *The Journal of the Acoustical Society of America*. 2015; 137(6):3033–41. <https://doi.org/10.1121/1.4921277> PMID: 26093395
24. Palmer KJ, Brookes K, Rendell L. Categorizing click trains to increase taxonomic precision in echolocation click loggers. *The Journal of the Acoustical Society of America*. 2017; 142(2):863–77. <https://doi.org/10.1121/1.4996000> PMID: 28863550
25. Kotsiantis SB, Zaharakis I, Pintelas P. Supervised machine learning: A review of classification techniques. *Emerging artificial intelligence applications in computer engineering*. 2007; 160:3–24.
26. Bittle M, Duncan A, editors. A review of current marine mammal detection and classification algorithms for use in automated passive acoustic monitoring. *Annual Conference of the Australian Acoustical Society, Science, Technology and Amenity*; 2013.
27. Valletta JJ, Torney C, Kings M, Thornton A, Madden J. Applications of machine learning in animal behaviour studies. *Anim Behav*. 2017; 124:203–20.
28. Berggren P. *Whales and dolphins: a field guide to marine mammals of East Africa: WIOMSA/East Publishing*; 2009.
29. Amir OA, Berggren P, Jiddawi NS. Recent records of marine mammals in Tanzanian waters. *J Cetacean Res Manage*. 2012; 12(2):249–53.
30. Stensland E, Carlen I, Särnblad A, Bignert A, Berggren P. Population size, distribution, and behavior of Indo-Pacific bottlenose (*Tursiops aduncus*) and humpback (*Sousa chinensis*) dolphins off the south coast of Zanzibar. *Mar Mamm Sci*. 2006; 22(3):667–82.
31. Sharpe M, Berggren P. Indian Ocean humpback dolphin in the Menai Bay off the south coast of Zanzibar, East Africa is Critically Endangered. *Aquat Conserv: Mar Freshwat Ecosyst*. 2019; 29(12):2133–46.
32. Parra GJ, Corkeron PJ, Marsh H. The Indo-Pacific humpback dolphin, *Sousa chinensis* (Osbeck, 1765), in Australian waters: a summary of current knowledge. *Aquat Mamm*. 2004; 30(1):197–206.
33. Amir OA, Berggren P, Narriman SJ. The incidental catch of dolphins in gillnet fisheries in Zanzibar, Tanzania. 2002.
34. Amir OA, Jiddawi NS, Berggren P. The occurrence and distribution of dolphins in Zanzibar, Tanzania, with comments on the differences between two species of *Tursiops*. *Western Indian Ocean journal of marine science*. 2005; 4(1):85–94.
35. Christiansen F, Lusseau D, Stensland E, Berggren P. Effects of tourist boats on the behaviour of Indo-Pacific bottlenose dolphins off the south coast of Zanzibar. *Endanger Species Res*. 2010; 11(1):91–9.
36. Stensland E, Berggren P. Behavioural changes in female Indo-Pacific bottlenose dolphins in response to boat-based tourism. *Mar Ecol Prog Ser*. 2007; 332:225–34.
37. Berggren P, Amir OA. Sustainable dolphin tourism in East Africa. Zanzibar: WIOMSA Technical Report; 2007. p. 72.
38. Gridley T, Berggren P, Cockcroft VG, Janik VM. Whistle vocalizations of Indo-Pacific bottlenose dolphins (*Tursiops aduncus*) inhabiting the south-west Indian Ocean. *The Journal of the Acoustical Society of America*. 2012; 132(6):4032–40. <https://doi.org/10.1121/1.4763990> PMID: 23231132
39. Temple AJ, Tregenza N, Amir OA, Jiddawi N, Berggren P. Spatial and Temporal Variations in the Occurrence and Foraging Activity of Coastal Dolphins in Menai Bay, Zanzibar, Tanzania. *Plos One*. 2016; 11(3):e0148995. <https://doi.org/10.1371/journal.pone.0148995> PMID: 26934473

40. Oswald JN, Rankin S, Barlow J. The effect of recording and analysis bandwidth on acoustic identification of delphinid species. *The Journal of the Acoustical Society of America*. 2004; 116(5):3178–85. <https://doi.org/10.1121/1.1804635> PMID: 15603163
41. Wahlberg M, Jensen FH, Soto NA, Beedholm K, Bejder L, Oliveira C, et al. Source parameters of echolocation clicks from wild bottlenose dolphins (*Tursiops aduncus* and *Tursiops truncatus*). *The Journal of the Acoustical Society of America*. 2011; 130(4):2263–74. <https://doi.org/10.1121/1.3624822> PMID: 21973382
42. Lammers MO, Au WW, Herzing DL. The broadband social acoustic signaling behavior of spinner and spotted dolphins. *The Journal of the Acoustical Society of America*. 2003; 114(3):1629–39. <https://doi.org/10.1121/1.1596173> PMID: 14514216
43. Frasier KE, Roch MA, Soldevilla MS, Wiggins SM, Garrison LP, Hildebrand JA. Automated classification of dolphin echolocation click types from the Gulf of Mexico. *PLoS Comp Biol*. 2017; 13(12): e1005823.
44. Roch MA, Klinck H, Baumann-Pickering S, Mellinger DK, Qui S, Soldevilla MS, et al. Classification of echolocation clicks from odontocetes in the Southern California Bight. *The Journal of the Acoustical Society of America*. 2011; 129(1):467–75. <https://doi.org/10.1121/1.3514383> PMID: 21303026
45. Rasmussen MH, Wahlberg M, Miller LA. Estimated transmission beam pattern of clicks recorded from free-ranging white-beaked dolphins (*Lagenorhynchus albirostris*). *The Journal of the Acoustical Society of America*. 2004; 116(3):1826–31. <https://doi.org/10.1121/1.1775274> PMID: 15478450
46. Madsen PT, Wahlberg M. Recording and quantification of ultrasonic echolocation clicks from free-ranging toothed whales. *Deep sea research part I: oceanographic research papers*. 2007; 54(8):1421–44.
47. Rahi PK, Mehra R. Analysis of power spectrum estimation using Welch method for various window techniques. *International Journal of Emerging Technologies and Engineering*. 2014; 2(6):106–9.
48. Zimmer WM. *Passive acoustic monitoring of cetaceans*: Cambridge University Press; 2011.
49. Fernández-Delgado M, Cernadas E, Barro S, Amorim D. Do we need hundreds of classifiers to solve real world classification problems? *The Journal of Machine Learning Research*. 2014; 15(1):3133–81.
50. Breiman L. Random forests. *Machine learning*. 2001; 45(1):5–32.
51. Breiman L, Friedman J, Olshen R, Stone C. *Classification and Regression Trees* (Monterey, California: Wadsworth). Inc; 1984.
52. Breiman L. Bagging predictors. *Machine Learning*. 1996; 24(2):123–40.
53. Breiman L. *Manual on setting up, using, and understanding random forests v3. 1*. Statistics Department University of California Berkeley, CA, USA. 2002; 1:58.
54. Arumugam J, Bukkapatnam STS, Narayanan KR, Srinivasa AR. Random forests are able to identify differences in clotting dynamics from kinetic models of thrombin generation. *Plos One*. 2016; 11(5): e0153776. <https://doi.org/10.1371/journal.pone.0153776> PMID: 27171403
55. Fang L, Li S, Wang K, Wang Z, Shi W, Wang D. Echolocation signals of free-ranging Indo-Pacific humpback dolphins (*Sousa chinensis*) in Sanniang Bay, China. *The Journal of the Acoustical Society of America*. 2015; 138(3):1346–52. <https://doi.org/10.1121/1.4929492> PMID: 26428773
56. Jefferson TA, Van Waerebeek K. Geographic variation in skull morphology of humpback dolphins (*Sousa* spp.). *AQUATIC MAMMALS*. 2004; 30:3–17.
57. Au WW, Hastings MC. *Principles of marine bioacoustics*: Springer; 2008. 679 p.
58. Baumann-Pickering S, Simonis AE, Oleson EM, Baird RW, Roch MA, Wiggins SM. False killer whale and short-finned pilot whale acoustic identification. *Endanger Species Res*. 2015; 28(2):97–108.
59. Yin S, McCowan B. Barking in domestic dogs: context specificity and individual identification. *Anim Behav*. 2004; 68(2):343–55.
60. Hammerschmidt K, Todt D. Individual differences in vocalisations of young barbary macaques (*Macaca sylvanus*): a multi-parametric analysis to identify critical cues in acoustic signalling. *Behaviour*. 1995; 132(5):381–99.
61. Gillespie D, Caillat M. Statistical classification of odontocete clicks. *Canadian Acoustics—Acoustique Canadienne*. 2008; 36(1):20–6.
62. Gillespie D, Chappell O. An automatic system for detecting and classifying the vocalisations of harbour porpoises. *Bioacoustics*. 2002; 13(1):37–61.
63. Roch MA, Soldevilla MS, Hoenigman R, Wiggins SM, Hildebrand JA. Comparison of machine learning techniques for the classification of echolocation clicks from three species of odontocetes. *Canadian Acoustics*. 2008; 36(1):41–7.