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The Australian fish chorus catalogue (2005–2023)

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Biological sources are significant contributors to aquatic soundscapes. Soniferous fish can dominate the soundscape in certain locations, at specific times and frequencies, particularly during the production of choruses. Passive acoustic monitoring of fish choruses can provide important ecological information about soniferous fish populations. This study presents the Australian Fish Chorus Catalogue, an inventory of fish choruses detected from 83 locations in Australian estuarine and marine waters. The Australian Fish Chorus Catalogue contains data on fish chorus occurrence and the spectral and temporal measurements, spectrographic images, and audio examples of 301 fish choruses. This catalogue has been developed to establish the foundations of an ongoing effort to document, quantify, compare, and track Australian fish choruses. We hope this open-access data depository will be used as a reference for future research and will facilitate an increase in understanding of fish choruses, which can then be applied to the monitoring and management of fish populations and their respective ecosystems.

KEYWORDS

fish chorus, unknown fish sounds, passive acoustics, spatiotemporal distribution, soundscape, spectral analysis, data repository

1 Introduction

Fishes are prolific sound producers. Over 1,000 fish species have been documented to produce sound passively or actively (Slabbekoorn et al., 2010; Looby et al., 2022). Active fish sounds are typically produced through the oscillation of the swim bladder by specialised sonic muscles or through the stridulation of bony body parts such as fin rays or pharyngeal teeth (Kaatz, 2002; Kasumyan, 2008; Fine and Parmentier, 2015). Fishes produce sound in support of key life functions, including: feeding, courtship, breeding, aggregation, and territorial aggression (Moulton, 1958; Fish and Mowbray, 1970; Ladich, 2015). Many species produce sound *en masse* during these behavioural functions (Mok and Gilmore, 1983; Connaughton and Taylor, 1995; McCauley, 2012; Borie et al., 2019), which is referred to as a fish chorus.

A standardised definition of a fish chorus has yet to be established. The definition of a biological chorus outlined by Cato (1978) ("when noise from many individuals is continuously above background for an extended period using an equipment averaging time of 1 s") is widely applied in fish chorus literature and, therefore, will be utilised for this study. However, it is important to note that there are variations across the literature regarding the exact parameters (and their quantities) that constitute a fish chorus. This variation is mainly in regards to the number of individuals producing the sound, the duration of the chorus, and the increase in sound levels within the fish chorus characteristic frequency band. Fish choruses can be species-specific (Mok and Gilmore, 1983; Luczkovich et al., 1999; Parsons et al., 2009) and are typically categorised into types based on spectral and temporal characteristics.

A variety of spectral parameters have previously been used to delineate fish chorus types. These include: the characteristic frequency band, peak frequency, and centre frequency of the chorus, as well as the call duration, pulse repetition frequency, and pulse number of the calls of which the chorus was comprised (Parsons et al., 2016; Parsons et al., 2017; McWilliam et al., 2018; Di Iorio et al., 2018). The spectral parameters of a fish chorus can be species-specific (Sprague et al., 1998; Luczkovich et al., 1999; Parsons et al., 2013c) as they can be related, in large part, to the sound-producing mechanisms of the individual fish (Brawn, 1961; Fine et al., 1997; Kaatz, 2002; Lagardère and Mariani, 2006; Parsons et al., 2013a; McCauley and Cato, 2016). For example, the swim bladder and its associated musculature have long been associated with sound production across many fish species (Brawn, 1961; Fine et al., 2001; Fine, 2012; Fine and Parmentier, 2015; Mok et al., 2020). Fish chorus types are also characterised by patterns in the chorusing activity.

Diel, lunar, seasonal, and annual patterns in fish chorus presence and activity have been used to define the temporal characteristics of fish choruses (Wall et al., 2013; Mahanty et al., 2016; Siddagangaiah et al., 2021a). Fish choruses commonly demonstrate characteristic and, in some circumstances, species-specific patterns in the presence or activity across these temporal extents (McCauley, 2012; Parsons et al., 2016; McWilliam et al., 2017; Siddagangaiah et al., 2021a). The nature of these temporal patterns often provides insights into the biological function of the respective chorus. For example, it has been hypothesised that choruses that are present every evening, year-round may be associated with feeding behaviours (McCauley, 2012; McCauley, 2001; McCauley and Cato, 2016; Panicker and Stafford, 2023); however, this has yet to be ground-truthed in the field. Fish choruses that demonstrate seasonality in their presence are more likely to be associated with courtship or breeding behaviours (McCauley, 2001; Van Hoeck et al., 2023; Montie et al., 2015; Connaughton and Taylor, 1995). The temporal distribution of these choruses and the biological functions they are associated with are typically driven by environmental rhythms.

Fish chorus activity has previously been associated with particular environmental cues. Siddagangaiah et al. (2021a), McWilliam et al. (2017), Parsons et al. (2016), McCauley (2012), Locascio and Mann (2011), and Parsons (2009) (just to name a few) have reported significant relationships between fish chorus activity and temperature, lunar phase, and tidal regime. Parsons (2009) identified salinity as one of the drivers of deviations observed in the mean sound pressure levels of a mulloway (*Argyrosomus japonicus*) chorus recorded in the Swan River, Western Australia, and Mann and Grothues (2009) reported a correlation between advection events in the mid-Atlantic Ocean and a significant reduction in fish chorusing. Luczkovich et al. (2024) determined that chorus activity was impacted by hypoxia events, and McWilliam et al. (2017) highlighted a significant negative relationship between wind speed and calling intensity of fish choruses recorded off Lizard Island, Queensland. Variations in fish chorus activity have also been associated with anthropogenic noise (Ceraulo et al., 2021; Siddagangaiah et al., 2021b) and significant natural events such as cyclones (Mahanty et al., 2019; Locascio and Mann, 2005). Identification of the patterns of fish chorus behaviour facilitates the tracking of the response of the chorus source species to these different types of environmental stimuli. Tracking these patterns over time will enable researchers and managers to understand how natural and anthropogenic changes may currently affect these fish populations and predict future impacts. For this to be achieved, the distribution, diversity, drivers, and characteristics of fish choruses need to be better understood.

Over 50 suspected fish chorus types have been identified in Australian waters since 1978 (Cato, 1978; Kelly et al., 1985; McCauley, 2001; McCauley and Cato, 2000; McCauley and Cato, 2016; Parsons et al., 2013b; Parsons et al., 2016; Parsons et al., 2017; McWilliam et al., 2018; Ward et al., 2019; Parsons, 2009; Hawkins et al., 2023). These fish choruses were recorded in aquatic environments ranging from riverine, estuarine, and coastal to coral reefs; islands; the continental shelf; deep offshore waters; and submarine canyons. Some Australian recording sites have demonstrated a high diversity of fish chorus types (Parsons et al., 2017; Parsons et al., 2016; Hawkins et al., 2023), varying across times of the day or during different seasons (Parsons et al., 2017; Parsons et al., 2016; McWilliam et al., 2017; Parsons et al., 2013b). Given the variety, abundance, and dominance of fish choruses in Australian soundscapes, documenting those of known and unknown origins provides valuable information for monitoring and management purposes (Di Iorio et al., 2021; Parsons et al., 2022). Documenting fish choruses can assist in delineating fish distribution (Pagniello et al., 2019; Rountree and Juanes, 2017) and habitat use (Walters et al., 2009; Ricci et al., 2017; Luczkovich et al., 2008), monitoring spawning aggregations (Monczak et al., 2017; Picciulin et al., 2020; Ricci et al., 2017), indicating biodiversity (Hawkins et al., 2023), and in certain circumstances, quantifying the abundance of fish populations (Parsons, 2009; Rowell et al., 2017; Sprague and Luczkovich, 2011). Baselines of fish chorus distribution and spatiotemporal patterns can be utilised for comparisons with future records to assess the impacts of natural and/or anthropogenic change. Future studies may also use fish chorus parameters and descriptions as part of a weight-of-evidence approach to identify chorus source species (McCauley and Cato, 2016). Large-scale mapping of fish choruses is also essential to enhance the scientific understanding of how acoustic communities interact and how they are related. To achieve this, fish choruses need to be identified and baselines of long-term distribution and chorusing patterns documented across significant spatial and temporal extents.

Historically, passive acoustic monitoring (PAM) data have been collected across limited spatial and temporal extents (Ross et al., 2023). However, there is now a movement to prioritise mapping, analysis, and comparison of soundscapes and particular soniferous species at a regional to global scale (Looby et al., 2022; Parsons et al., 2022; Looby et al., 2023a; Darras et al., 2024). The viability of collecting large acoustic datasets has traditionally been restrained by storage and data processing requirements, in addition to the time and effort required to manually analyse all of the data (Napier et al.,

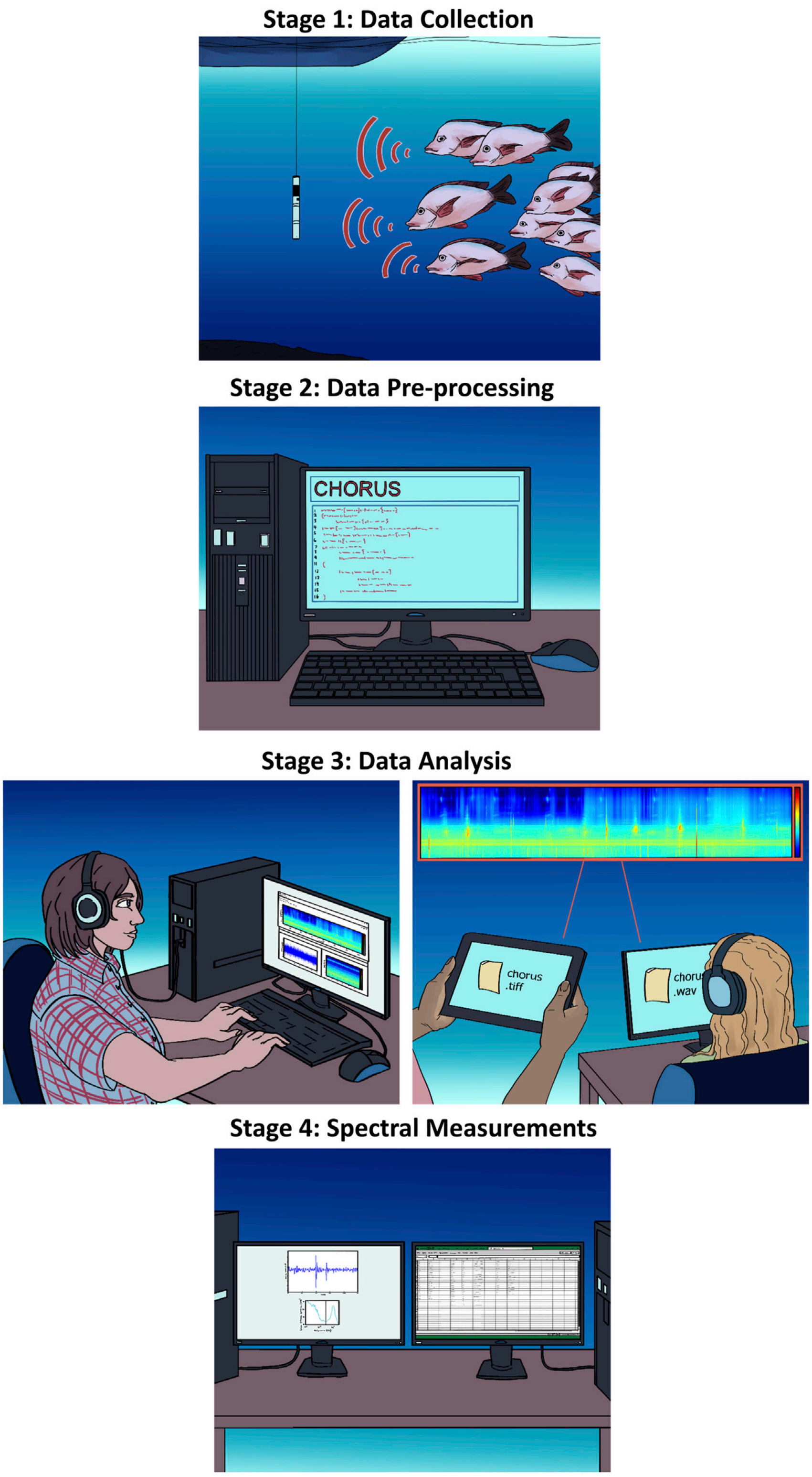

FIGURE 1
Conceptualisation of the four stages of the AFCC development process.

2024). Recent technological advances are starting to tackle these challenges, making PAM more accessible (Gibb et al., 2019). Cloud storage is evolving, facilitating the storage of larger volumes of data and allowing for much faster upload and download speeds (Napier et al., 2024). Additionally, machine learning and signal processing techniques are evolving rapidly, significantly shortening data analysis times, which is allowing large amounts of raw data to be analysed (Napier et al., 2024). Raw acoustic data are increasingly

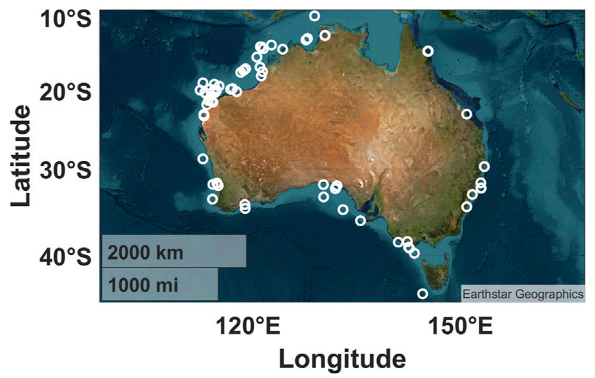

FIGURE 2
Locations of the AFCC recording sites.

being shared with greater accessibility. For instance, federally funded acoustic data in the U.S. have been made available online through NOAA's National Centres for Environmental Information (NCEI) (Wall et al., 2021), and long-term PAM data collected at several locations in Australian waters have been made available on the Australian Ocean Data Network (AODN), collected from a series of passive acoustic observatories as part of Australia's Integrated Marine Observing System (IMOS, 2023). These are just a few examples; for a more comprehensive list of open-access underwater acoustic datasets, please refer to The UK Acoustics Network (2024). Despite this increase in data availability, PAM research is still hindered by the lack of standardisation and transparency in acoustic data collection, processing, and analysis protocols, as well as the limited availability of open-access reference sound libraries (Gibb et al., 2019).

Reference libraries are an essential tool for the application of PAM in ecological research. An audio reference library is defined as "a collection of (annotated) audio recordings with known species identities, used as type-specimen references for identifying species in new recordings" (Ross et al., 2023). These annotated collections provide essential baselines for the comparison of known and unknown sounds (Browning et al., 2017; Parsons et al., 2022). Several open-access reference libraries feature recordings of fish calls (Fish and Mowbray, 1970; Vigness-Raposa et al., 2012; Kaschner, 2012; Scholes, 2015; Looby et al., 2023b, Ocean Networks Canada, 2024; Sonothèque, 2024, The British Library, 2024; Tierstimmenarchiv, 2024; FonoZoo, 2024); however, to the authors' knowledge, limited effort has been made to create a library of fish choruses beyond a local-scale extent. In this data paper, we present the Australian Fish Chorus Catalogue (2005–2023) (AFCC, Hawkins et al. (2024)). This catalogue is the first benchmark reference library of 301 described fish choruses, produced by predominantly unknown fish species and recorded at 83 locations in marine and estuarine waters around Australia. Each fish chorus entry includes audio and spectrographic records, seasonal presence data, and measurements of chorus spectral parameters extracted using reproducible methodologies. The catalogue is an open-access data repository available on the AODN. Development of the AFCC is ongoing, and future work will focus on expanding the coverage of Australian soundscapes, undertaking classification of fish chorus types, and identifying source species.

2 Methods

The AFCC has been developed to document previously unreported Australian fish choruses and collate them alongside previously reported Australian fish choruses in a format that allows for comparisons with existing and future fish chorus recordings. The catalogue was created in four stages, and these are conceptualised in Figure 1.

2.1 Stage 1: data collection

The acoustic recordings analysed in this study were collected from 169 underwater acoustic recorder deployments undertaken at 83 locations in Australian marine and estuarine waters from 2005 to 2023 (Supplementary Table S1; Figure 2). Data collection was undertaken by the Centre for Marine Science and Technology (CMST), the Australian Institute of Marine Science (AIMS), the New South Wales Department of Primary Industries (NSW DPI), Parks Australia, and the National Oceanic and Atmospheric Administration (NOAA). Recording lengths ranged from 8 days to over a year in duration, sampling frequencies ranged from 3 to 96 kHz, and sampling schedules varied between locations (Supplementary Table S1). Twenty deployments were undertaken as part of the Australian Integrated Marine Observing System (IMOS (2022)). The IMOS is a nationally coordinated program that consists of a network of oceanographic observing equipment (historically including passive acoustic observatories at selected sites) deployed throughout Australia's coastal areas and open oceans (IMOS, 2022; Lynch et al., 2010). Recordings from the IMOS deployments are freely accessible under a Creative Commons Attribution 4.0 International License (IMOS, 2023). Seven types of acoustic recorders were used to collect the acoustic recordings. The details of these recorder types are outlined in Table 1. These include the Centre for Marine Science and Technology and Defence Science and Technology Organisation underwater sound recorders (CMST-DSTO USRs, McCauley et al. (2017)) and Ocean Instruments SoundTraps. CMST-DSTO USRs were most commonly deployed recorder type (Supplementary Table S1); these included all the IMOS deployments. The remaining acoustic recordings were acquired using SoundTrap ST500, ST300, or ST202s. Data pre-processing and analysis were tailored to the respective recorder type.

2.2 Stage 2: data pre-processing

The acoustic recordings were pre-processed using a MATLAB (The MathWorks Inc., Natick, MA, United States) toolbox, the CHaracterisation Of Recorded Underwater Sound (CHORUS) (Gavrilov and Parsons, 2014). CHORUS and its respective User Guide are available free for download at http://cmst.curtin.edu.

TABLE 1 Information of the hydrophones used for acoustic data collection.

Acoustic recorder type	Hydrophone type	Manufacturer	Calibration	References
CMST-DSTO USR	HTI 90-U	High Tech Inc., Long Beach, MS, United States of America.	Calibrated from 1 Hz to the Nyquist frequency before each independent recording was taken using a white noise generator at −90 dB re 1 V^2/Hz.	McCauley and Cato (2016), McCauley et al. (2017), and Parsons et al. (2017).
	HTI-99-HF	High Tech Inc., Long Beach, MS, United States of America.		
	Massa TR1025C	Massa, Hingham, MA, United States of America.		
	Reson TC4033-1	Teledyne Marine, Thousand Oaks, CA, United States of America.		
SoundTrap	ST500	Ocean Instruments, Auckland, NZ.	Piston phone calibrated at 250 Hz by the manufacturer for both low- and high-gain settings.	Ocean Instruments NZ (2021b) and Ocean Instruments NZ (2021a).
	ST300			
	ST202		Piston phone calibrated at 250 Hz by the manufacturer at 121 dB re 1 μPa.	Ocean Instruments NZ (2021a)

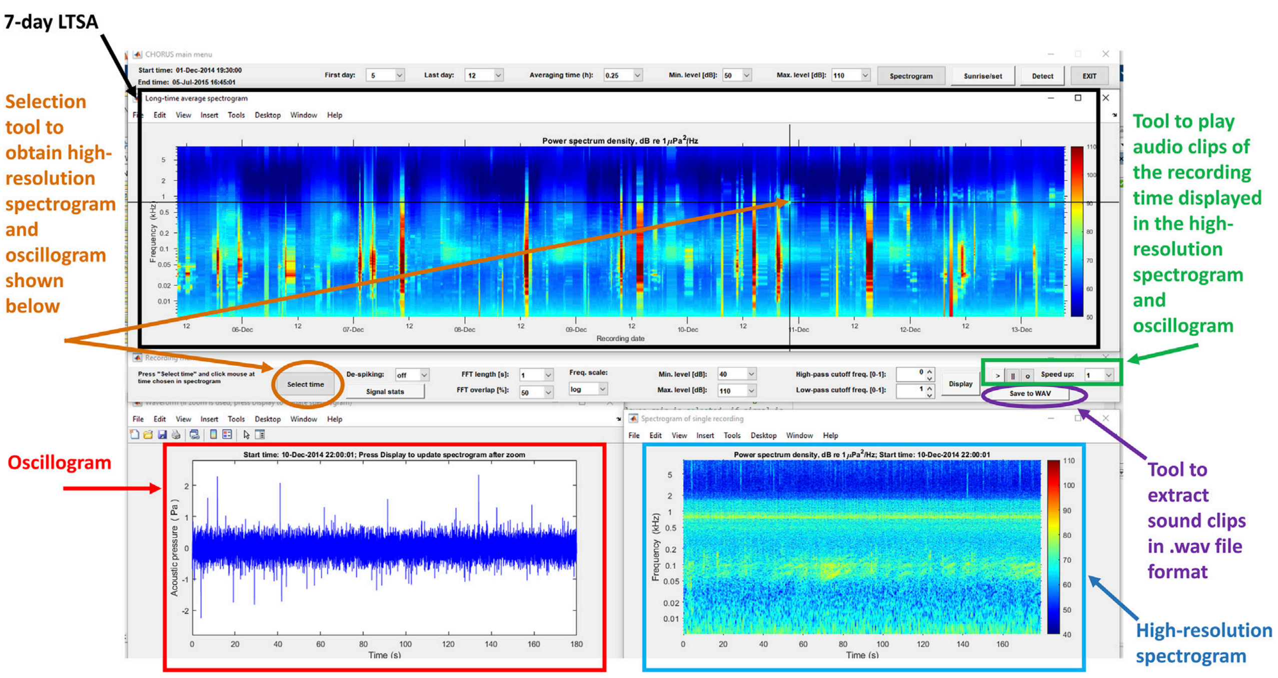

FIGURE 3
Annotated screenshot of the CHORUS_GUI function interface. It displays the tools available in the interface that were used to identify and extract the fish chorus spectrographic and audio records from the AFCC datasets.

au/products/chorussoftware/ under a single-user license agreement (Gavrilov and Parsons, 2014). This toolbox was designed and built at CMST. Recorder-specific settings were used to pre-process the data. The timing data of each recording were extracted, the calibrated power spectral density (PSD) of each recording file was calculated, and the PSDs were corrected for the frequency response of the respective hydrophone and system. The CHORUS toolbox pre-processing functions that were used in this process included the following: 1) *CMST_LF_data_preprocessing*, 2) *CMST_HF_data_preprocessing*, and 3) *ST_data_preprocessing*. The *CHORUS_GUI* function was then used to manually identify fish choruses.

2.3 Stage 3: data analysis

2.3.1 Manual fish chorus identification

For each dataset, fish choruses were identified via manual scrutiny of 1) long-term spectral averages (LTSA, 7 days in

TABLE 2 Examples of common fish chorus definitions and descriptions reported in scientific literature.

Study	Definition
Cato (1978)	"When the noise from many individuals is continuous above background for an extended period (usually an hour or more) using an equipment averaging time of 1 s."
McCauley (2012)	Fish "call en masse, to form choruses where it becomes difficult if not impossible to discriminate individual calls amongst the cacophony of noise produced by the fish school."
D'Spain et al. (2013)	"Underwater biological choruses occur when a large number of animals, often of a single species, create sound simultaneously over a significant period of time."
McCauley and Cato (2016)	"Choruses typically occur when many individuals of the same species vocalise near-simultaneously in reasonably close proximity to each other (from a sound transmission perspective) to produce a cacophony of sound" and "are characterised by showing daily patterns, predominantly, although not always, occurring at night and usually with some seasonal component."
Parsons et al. (2016)	"vocalizations . . . are often produced en masse, increasing the sound pressure levels (SPLs) significantly before or during the activity."
McWilliam et al. (2017)	"A fish chorus is defined as the continuous sound produced by vocalising fish that significantly raises the background noise level in a characteristic frequency band by > 3 dB for an extended period."
Butler et al. (2021)	When "fishes will aggregate into large groups and call persistently, creating underwater choruses and adding substantial acoustic energy to the marine soundscape."
Siddagangaiah et al. (2021a)	When "fish species vocalize in large numbers and produce sustained choruses that result in a unique sound signature of the marine soundscape."

length at a time), 2) figures of high-resolution relative acoustic amplitude (referred to as oscillograms), and 3) high-resolution spectrograms created using the *CHORUS_GUI* function (Figure 3). LTSAs were visualised in CHORUS with a constant time window of 1,000 s. Spectrograms were plotted on a logarithmic scale ranging from 5 to 48,000 Hz, with a colour scale from 40 to 120 dB re 1 $\mu Pa^2/Hz$. Fish calling events identified in the *CHORUS_GUI* were classified as a fish chorus if they met all of the following criteria:

1. It consisted of overlapping fish calls from many individuals, to the extent that, at times, individual calls within the chorus could not be distinguished.
2. It increased background sound levels within a characteristic frequency band (when using an averaging time of 1 s) to an observable degree in a 7-day LTSA (Hamming window = sampling frequency of respective recording and no overlap).
3. It displayed a prolonged duration (approximately 1 hour or longer).
4. It displayed temporal variation on a diel, lunar, seasonal, or annual scale.

The criteria used for this study were based on a review of fish chorus definitions in the literature; examples of some of these definitions are outlined in Table 2. Fish choruses were distinguished from other biological choruses using characteristic features of fish calls. Fish calls are typically low frequency (<5 kHz), contain repetitive sound elements of short duration, and can often demonstrate multiple frequency harmonics (Amorim et al., 2006; Fish and Mowbray, 1970).

All datasets were reviewed twice. The first round of fish chorus identifications was undertaken by five operators (Authors, L.H., M.J.P., J.M., D.W K., and R.W). M.J.P analysed the Port Hedland and Darwin Harbour datasets; J.M. analysed the Lizard Island sets (except for Lizard Island North Point 2); D.W K analysed the Bonaparte Gulf 2, North West Shelf 1, North West Shelf 3, North West 1, Timor Sea, and Thevenard 1 datasets; R.W analysed the Fowlers Bay 1 and 2 datasets; and L.H analysed all other datasets. The manual chorus identification process outlined above was followed by all operators. To address observer bias and ensure all fish choruses had been identified, all datasets were reviewed a second time, and the above process was repeated for all 169 datasets by L.H.

2.3.2 Fish chorus naming convention

Each fish chorus was assigned a unique identifier. The identifier was associated with the recording location of the specific fish chorus and followed the naming convention "SiteLabel_FishChorusNumber." For example, the first fish chorus identified at the Bremer Bay recording site was named "BB_1." Australian fish choruses described in eight previous studies were also included in the catalogue. These choruses and their corresponding catalogue identifiers are outlined in Table 3. The catalogue also provides descriptions of the fish choruses identified by Hawkins et al. (2023). The recording site, label, and number of each fish chorus reported by Hawkins et al. (2023) correspond to the unique identifier of the respective chorus in the AFCC. Please note that only previous studies where raw data were available could be included; thus, several previously recorded choruses are not included here. These include (but are not limited to) fish choruses reported by Cato (1978), Cato (1980), Kelly et al. (1985), McCauley and Cato (2000), and McCauley (2001).

2.3.3 Recording of presence/absence

Daily fish chorus presence/absence was recorded in Microsoft Excel spreadsheets after the manual inspection of LTSAs of each dataset (one 7-day spectrogram at a time). Each analysed day in every recording was designated one of four classifications: 0 = fish chorus absent, 1 = fish chorus present, 2 = unable to discern presence due to masking from ambient noise, and 3 = unable to discern presence due to lack of available recordings. These daily categorisations provided a record of the seasonal presence/absence for each fish chorus, at every

TABLE 3 Australian fish choruses described in previous studies in relation to the fish choruses reported in the AFCC. Chorus type refers to the type number assigned to the chorus in its respective publication[a].

Study	Chorus type	Recording location	Fish chorus ID
McCauley (2012)	1	Maret Island	MI_1
	2	Maret Island	MI_4
Parsons et al. (2013b)	1	Cowaramup 1	CW1_3
	2	Cowaramup 1	CW1_2
	3	Cowaramup 1	CW1_1
McCauley and Cato (2016)	1	Perth Canyon	PC_1
Parsons et al. (2016)	1	Darwin Harbour 1	DH1_1
	2	Darwin Harbour 1	DH1_2
	3	Darwin Harbour 1	DH1_3
	4	Darwin Harbour 1	DH1_4
	5	Darwin Harbour 1	DH1_5
	6	Darwin Harbour 3	DH3_6
	7	Darwin Harbour 1	DH1_6
	8	Darwin Harbour 1	DH1_7
	9	Darwin Harbour 1	DH1_8
Parsons et al. (2017)	1	Swan River	SW_1
Parsons et al. (2017)	1	Port Hedland	PH_1
	2	Port Hedland	PH_2
	3	Port Hedland	PH_3
	4	Port Hedland	PH_4
	5	Port Hedland	PH_5
	6	Port Hedland	PH_6
	7	Port Hedland	PH_7
McWilliam et al. (2018)	1	Lizard Island North Point	LNP_1
	2	Lizard Island Offshore	LIO_6
	3	Lizard Island North Point	LNP_2
	4	Lizard Island Offshore	LIO_1
	5	Lizard Island Offshore	LIO_3
	6	Lizard Island Offshore	LIO_4
Ward et al. (2019)	3	Fowlers Bay 1	FB1_3

[a]Several fish choruses outlined here were included in the study by Hawkins et al. (2023). These included the fish choruses reported by McCauley (2012), McCauley and Cato (2016), Parsons et al. (2016), and Parsons et al. (2017).

location, and were subsequently collated to provide a monthly presence/absence measure. If the respective fish chorus was detected on any day of a particular month, it was marked as present (1), and if the fish chorus was not detected across any days of the respective month, it was marked as absent (0). Fish chorus monthly presence/absence has been made available as part of the catalogue.

2.3.4 Extraction of spectrographic and audio records

Each fish chorus entry in the AFCC includes spectrographic and audio records. The spectrographic records for each chorus include the following: 1) a soundscape spectrogram, 2) a high-resolution chorus spectrogram, 3) a composition of a spectrogram and oscillogram of the individual call/s making up the specific chorus, and 4) a mean power spectrum plot. The spectrograms and oscillograms were extracted manually from LTSAs created in the *CHORUS_GUI* (Figure 3) during the fish chorus identification process. The mean power spectrum plots were created using a custom-written MATLAB function to illustrate the frequency content of the respective fish chorus. Two audio records for each fish chorus were included in the catalogue. The first was an audio recording featuring the chorus, and the second was a shorter recording, featuring the individual call/s of the respective fish chorus. Both audio record types were also extracted manually using the *CHORUS_GUI* function (Figure 3) and saved as .wav files.

2.4 Stage 4: spectral measurements

2.4.1 Spectral characteristic extraction

A series of parameters were measured for each fish chorus to describe the spectral characteristics of the chorus. These parameters included the following: minimum frequency, maximum frequency, peak frequency, 3 dB bandwidth, 3 dB bandwidth low frequency, 3 dB bandwidth high frequency, 10 dB bandwidth, 10 dB bandwidth low frequency, 10 dB bandwidth high frequency, 20 dB bandwidth, 20 dB bandwidth low frequency, 20 dB bandwidth high frequency, centre frequency, root-mean-square (RMS) bandwidth, RMS bandwidth low frequency, RMS bandwidth high frequency, 90% energy bandwidth, 90% energy signal duration, peak chorus band level, ambient level, and chorus band level increase over ambient level (SNR). Descriptions and definitions of each spectral parameter are outlined in Supplementary Table S2. The start time, end time, minimum frequency, and maximum frequency of each fish chorus were manually selected from spectrograms in a conservative manner (i.e., by over-predicting the boundary box and thus over-predicting duration and bandwidth) by operator L.H. The more robust and exact measurements (such as 90% energy duration and 90% energy bandwidth) were automatically computed within the boundary boxes using custom software in MATLAB (this software can be accessed in the AFCC data repository, titled "AFCC_Mcode.m" (Hawkins et al., 2024)). Centre frequency was calculated using the equation provided by Au (1993) (page 217, Equation 10.3). RMS bandwidth low and high frequencies, 90% energy duration, and 90% energy bandwidth were calculated using their respective equations taken from Erbe et al. (2022). It is important to note that if the fish chorus signal-to-noise ratio (SNR) was low (i.e., below 3, 10, or 20 dB), the spectral variables 3 dB bandwidth, 3 dB bandwidth low frequency, 3 dB bandwidth high frequency, 10 dB bandwidth, 10 dB bandwidth low frequency, 10 dB bandwidth high frequency, 20 dB bandwidth, 20 dB bandwidth low frequency, and 20 dB bandwidth high frequency could not be measured; this occurrence is noted in the spectral measurement spreadsheet as NA.

Measurements of each parameter were taken over the course of one chorusing event per fish chorus (generally within a 24-h period) and, therefore, are not representative of the fish chorus over the entire recording period of the specific recorder deployment. The extent of these calling events is defined in the spectral measurement spreadsheet (see Section 3.3). The chorusing events used for these measurements typically occurred during a period of high chorusing activity with minimal masking from ambient noise sources. On occasion, full spectral analysis of fish choruses was impossible due to masking from ambient noise or if the fish chorus exceeded the Nyquist frequency of the sampling regime. In the case of the former, fish choruses were partially analysed during periods of minimal or no masking. Where ambient noise masked the chorus to an extent that spectral characteristics could not be accurately determined at any point in the recording or when a fish chorus exceeded the frequency cut-off, the maximum and minimum frequency of the chorus were estimated from the scrutiny of the LTSAs, and all other spectral characteristics were omitted as the entire chorus energy could not be sampled.

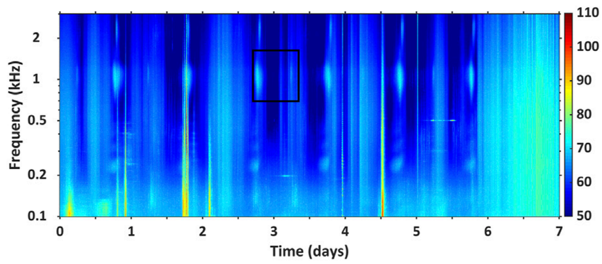

FIGURE 4
Example of the 7-day LTSA record provided for each fish chorus in the AFCC. This figure displays the PSD (dB re 1 μPa^2/Hz) and diel presence of fish chorus BB_1 (highlighted in the black box) over 7 days at local time. This spectrogram was produced with an averaging time of 0.25 h and a FFT window length of 300 s. The acoustic data at this location were collected at a 6 kHz sampling frequency.

2.5 Technical validation

The analyses undertaken in this study followed previously reported protocols that have been adapted in this study where appropriate. The technical quality of the catalogue data is assured by the use of these protocols, which have been validated through the peer-review process. Such protocols include the pre-processing techniques outlined by McCauley and Cato (2016) and McCauley et al. (2017) for data recorded by the CMST-DSTO USRs, McWilliam et al. (2018) and Marley et al. (2017) for data recorded by SoundTraps (ST500 and ST300 STD), and Gavrilov and Parsons (2014) for the use of the CHORUS toolbox in the data pre-processing and fish chorus identification stages of the analysis. The fish chorus identification process followed protocols established by Parsons et al. (2016), Parsons et al. (2017), and McWilliam et al. (2018). During the identification process, each acoustic dataset was reviewed twice to ensure all fish choruses present in the soundscape were identified. The spectral measurements of each fish chorus were validated manually. Validation was undertaken through the scrutiny of a series of spectrograms, and PSD and mean spectrum figures were created during the spectral measurement process.

3 Data records

The AFCC has been deposited at the AODN repository (https://doi.org/10.26198/qfj2-jj93, Hawkins et al. (2024)). This is a full copy of all data at the date of submission of this publication. The catalogue holds an inventory of fish chorus records and online spreadsheets, including a file for each fish chorus, which contains the respective

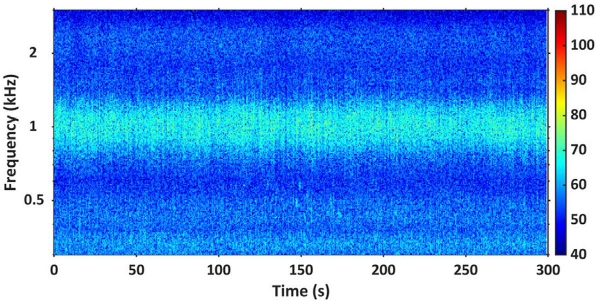

FIGURE 5
Example of the high-resolution spectrogram record provided for each fish chorus in the AFCC. It displays the PSD (dB re 1 μPa^2/Hz) of fish chorus BB_1 over a 300 s resolution. This spectrogram was produced with an FFT window length of 0.5 s and 60% overlap. The acoustic data shown here were collected at a 6 kHz sampling frequency.

spectrographic records and audio files. Three online spreadsheets have been made available; these provide deployment information and the seasonal presence, duration, and spectral measurements of each fish chorus.

3.1 Spectrographic records

Each fish chorus file presented in the catalogue includes four spectrographic records. These records provide a range of graphical representations of each fish chorus. The first spectrographic record is a 7-day LTSA, and it displays the PSD (dB re 1 μPa^2/Hz) of the fish chorus across time in days (*x*-axis) and frequency in kHz (*y*-axis). These records are created using a Hamming fast-Fourier transform (FFT) window equal to the sampling frequency of the respective recording (so that the frequency resolution equaled 1 Hz) with no overlap (Gavrilov and Parsons, 2014). The recording-specific sampling frequency can be found in Supplementary Table S1. This record demonstrates the diel pattern of a respective fish chorus over 1 week, at local time. If there were multiple sound sources visible in the 7-day LTSA, the respective fish chorus was highlighted using a black or white box as demonstrated in the example record, shown in Figure 4. Please note that the time scale of the LTSA may be slightly shorter for some fish choruses due to limitations of the respective recording schedules.

The second spectrographic record features a high-resolution spectrogram of a respective fish chorus, displaying the PSD (dB re 1 μPa^2/Hz) of the fish chorus across frequency (kHz) and time over a time scale ranging 100–600 s. These spectrograms are produced with an FFT window length of 0.5 s and an overlap of 50 or 60%. An example of this record is shown in Figure 5. The third record is a composition of a high-resolution spectrogram again depicting PSD (dB re 1 μPa^2/Hz) across time and frequency (with time scales ranging from 1 to 100 s) and a corresponding oscillogram to display the energy and relative amplitude of the individual call/s making up the respective fish chorus (if possible). The spectrograms of these figures were produced with an FFT length of 0.05 or 0.1 s and an overlap of 80 or 90%. The FFT window length and overlap combination were dependent on the peak frequency of the fish chorus calls. An example of this composition figure is demonstrated in Figure 6. It is important to note that it is often difficult to distinguish single calls within a chorus. Therefore, for some fish chorus records, the call composition figures have yet to be included in the catalogue.

The final spectrographic record is a mean power spectrum plot of a respective fish chorus. It displays the mean (i.e., averaged over the duration of the chorus) frequency content of the fish chorus over one chorusing event per fish chorus (generally within a 24-h period). The two black lines on each mean power spectrum plot show the maximum and minimum frequencies of the respective fish chorus (Figure 7). The timing and extent of each chorusing event were chosen to exclude (as much as possible) the contribution of ambient sound to the chorus frequency band. On the occasion that a fish chorus was significantly masked by ambient sounds, a mean spectrum plot was not produced for that particular chorus. This was also the case for fish choruses with a frequency that exceeded the Nyquist frequency of the respective USR. As the mean power spectrum plot was produced from one chorusing event only, it is important to note that it is not representative of the frequency content of the respective fish chorus over the entire recording period. The extent of each calling event is defined in the spectral measurement spreadsheet (see Section 3.3).

Each spectrographic record is available in the .tif file format. The records are named using the following conventions:

1. ChorusIdentifier_soundscape_spectrogram.tif.
2. ChorusIdentifier_chorus_spectrogram.tif.
3. ChorusIdentifier_call_composition.tif.
4. ChorusIdentifier_meanspectrum.tif.

3.2 Audio records

A 100–600 s .wav audio file of each fish chorus is featured in the AFCC. Each chorus audio record is named using the convention “ChorusIdentifier_chorus_audiofile.wav.” This audio file aligns with the sounds shown in the respective chorus spectrogram figure. If possible, an additional, shorter .wav audio file of the individual calls making up the chorus is also provided. These audio records were named using the convention “ChorusIdentifier_call_audiofile.wav.” The shorter audio file aligns with the sounds shown in the respective call composition figure.

3.3 Online spreadsheets

Three online spreadsheets are featured in the AFCC. They include 1) deployment information, 2) fish chorus seasonal presence/absence, and 3) fish chorus duration and spectral measurements. The online deployment information table contains the latitude, longitude, start time, and end time of each deployment. This table has been made available in the .pdf file format. The file is named “AFCC_deployment_information.pdf.” The seasonal presence/absence spreadsheet has been made available as a Microsoft Excel spreadsheet in the .csv file format. The columns of the spreadsheet are as follows:

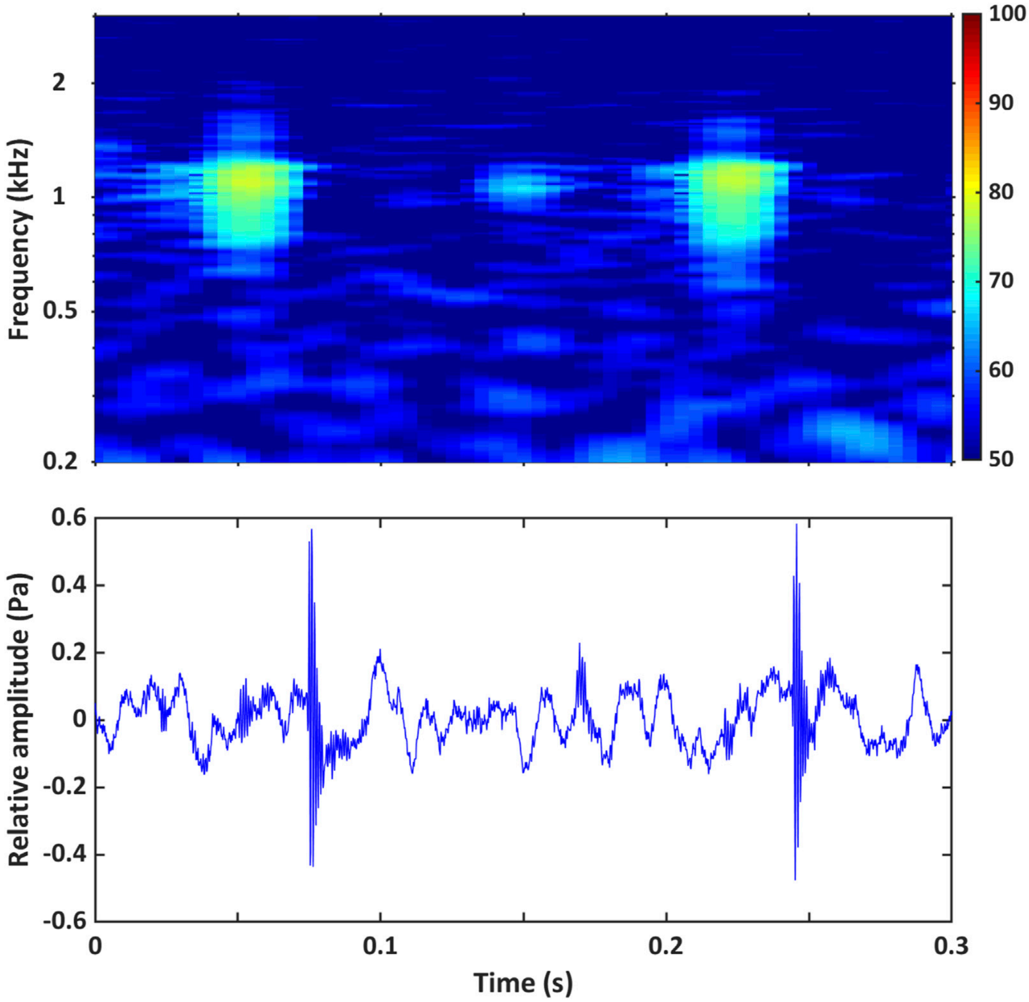

FIGURE 6
Example of the call composition record provided for each fish chorus in the AFCC. It comprises a high-resolution spectrogram and oscillogram, displaying the PSD (dB re 1 μPa^2/Hz) of the fish chorus calls (collected over 0.3 s) and the relative amplitude of the fish chorus calls of chorus BB_1, respectively. The spectrogram component of the figure was produced with an FFT window length of 0.01 s and 90% overlap. The acoustic data shown here were collected at a 6 kHz sampling frequency.

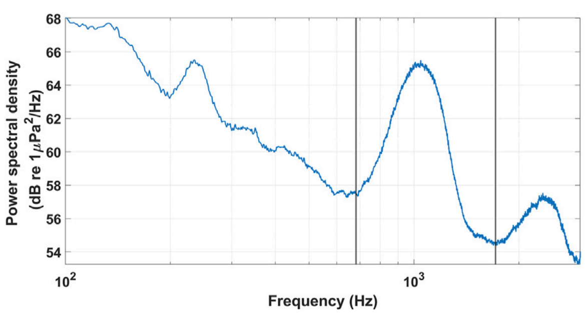

FIGURE 7
Example of the mean power spectrum record that is provided for each fish chorus in the AFCC. It displays the spectral content of the BB_1 fish chorus. The black lines denote the minimum and maximum frequency of the fish chorus, respectively. The acoustic data shown here were collected at a 6 kHz sampling frequency.

- "Loc": location (the name of the location where the recording of the fish chorus was taken).
- "Label": a shortened version of the location name to help with the fish chorus naming conventions.
- "ID": chorus identifier (the unique name for each fish chorus).
- "Seasonal presence": the seasonal presence or absence of each fish chorus at the recording location. Each letter corresponds to the months of the year in order from January to December, 0 indicates fish chorus absence, 1 indicates fish chorus presence, 2 indicates that the presence of the fish chorus could not be discerned due to masking by ambient sound sources, and 3 indicates that the presence of the fish chorus could not be discerned due to the lack of acoustic recordings available for that respective period.

The spreadsheet file is named "AFCC_seasonal_presence.csv." A snapshot of this spreadsheet is displayed in Table 4.

TABLE 4 Snapshot of the seasonal presence spreadsheet made available in the AFCC. This snapshot displays the seasonal presence of the fish choruses identified at the Bremer Bay recording location from January (J) to December (D). 0 = fish chorus absent and 1 = fish chorus present.

Location	Label	Chorus ID	J	F	M	A	M	J	J	A	S	O	N	D
Bremer Bay	BB	BB_1	1	1	1	1	1	1	1	1	1	1	1	1
Bremer Bay	BB	BB_2	1	1	1	1	1	0	1	1	1	1	1	1
Bremer Bay	BB	BB_3	0	0	0	0	0	1	1	1	1	1	1	0

The fish chorus spectral measurement spreadsheet has been made available in a Microsoft Excel spreadsheet in the .csv file format. The file is named "AFCC_measurement_spreadsheet.csv." The definitions of each measurement variable are outlined in Supplementary Table S2. In addition to the variables shown in Supplementary Table S2, the following columns are also included in the online spreadsheet:

- "SD": extraction start date and time (start date and time of fish chorus recording used for spectral measurements in Universal Coordinated Time (UTC)).
- "ED": extraction end date and time (end date and time of fish chorus recording used for spectral measurements in UTC).
- "HRS": the number of hours ahead (+) or behind (−) the UTC of the recording location of the respective fish chorus.
- "ANLS": analysis type was designated with one of four classifications: 1) full analysis, 2) partial analysis due to ambient noise masking, 3) no analysis undertaken due to the chorus frequency exceeding the Nyquist frequency of the sampling regime, where the minimum frequency was estimated from the scrutiny of spectrograms, and 4) no analysis undertaken due to ambient noise masking, where the minimum and maximum frequency were estimated from the scrutiny of spectrograms.

4 Discussion and future work

The AFCC is the first open-access data repository of fish chorus data at a national scale. It holds spectral, spatial, and temporal distribution records of 301 fish choruses recorded across 83 locations in Australian estuarine and marine waters. The majority of these 83 locations are spread across marine waters all around the continent; however, few or no acoustic recordings could be sourced for several key marine areas. These include the Gulf of Carpentaria, the Great Barrier Reef, waters around Tasmania, and waters off the western side of the Great Australian Bight. Studies have shown that Australian recording sites with similar environments exhibit high fish chorus diversity (Parsons et al., 2017; McWilliam et al., 2018; Ward et al., 2019; Hawkins et al., 2023). This suggests a significant potential for identifying new types of fish choruses in these areas. The same can be said for Australian estuarine and freshwater environments. The AFCC contains very few fish choruses recorded in estuarine environments and none from freshwater environments. This is also due to a lack of available acoustic recordings. However, fish choruses have been extensively documented in estuarine environments globally (Lagardère and Mariani, 2006; Luczkovich et al., 2008; Montie et al., 2015; Zhi-Tao et al., 2017), and acoustic recordings in an Australian estuary have demonstrated a particularly high fish chorus diversity (Parsons et al., 2016). Little is known regarding fish chorus contributions to freshwater soundscapes. Only a few freshwater fish choruses have been described (Borie et al., 2014; Linke et al., 2018; Borie et al., 2019), including a fish chorus recorded in the Einasleigh River in Northern Australia (Linke et al., 2018). Many more fish choruses likely exist in these yet-to-be-recorded marine, estuarine, and freshwater environments. Consequently, the authors recommend prioritising future acoustic data collection in these under-represented areas. Fish choruses will continue to be added to the AFCC using a standardised methodology as more acoustic recordings become available.

A standardised methodology for the extraction of these records has been outlined here to ensure reproducibility to facilitate analysis of new recordings and comparisons with new fish chorus data. The spectral and temporal measurements included in the repository are indicative characterisations of the respective fish choruses; however, it is important to note that while these measurements represent the spectral characteristics of these fish choruses in acoustic conditions as close to ideal as possible, the authors acknowledge that the spectral measurements of these fish choruses may vary with time. This may be associated with alterations in the behaviour of the source species or may be due to changes in the acoustic habitat at the respective recording location. As such, this potential for variation needs to be taken into account when using the AFCC records for comparison. The spectral and temporal measurements have been used to differentiate fish chorus types per recording location within the AFCC, but they can also be used in combination with the spectrographic and audible records for fish chorus identification. The AFCC records can be compared with ground-truthed fish vocalisations in established sound libraries, such as the Audio Gallery (Discovery of Sound in the Sea) (Vigness-Raposa et al., 2012), Fish Sounds (Fish and Mowbray, 1970), The SOUND Table (Kaschner, 2012), the Macaulay Library (Scholes, 2015), Ocean Networks Canada (Ocean Networks Canada, 2024), Sonothèque (Sonothèque, 2024), the British Library Sound Archive (The British Library, 2024), FishSounds (Looby et al., 2023b), the Animal Sound Archive (Tierstimmenarchiv, 2024), and FonoZoo (FonoZoo, 2024), to assist with the identification of fish chorus source species and delineation of their distribution. Identification of fish chorus source species enhances the effectiveness of using ecological information from the AFCC records to monitor and manage these species.

The AFCC has contributed to the development of PAM of fish choruses to be applied to the monitoring and management of fish populations in Australian waters. The presence, distribution, and diversity of Australian fish choruses have been mapped and made accessible for managers and researchers, not only as a reference library but also as a source of ecological data. If the source species and biological function of the AFCC choruses are discerned, the AFCC can provide information on the distribution, behaviour, habitat use, and spawning dynamics of specific fish species. The value of PAM of ground-truthed fish choruses has been demonstrated in several monitoring applications, including the delineation of spawning seasons (Connaughton and Taylor, 1995; Barrios, 2004; Tellechea et al., 2011; Ricci et al., 2017; Monczak et al., 2017), identification of important spawning habitats (Saucier and Baltz, 1993; Luczkovich et al., 1999; Luczkovich et al., 2008; Ricci et al., 2017), and the tracking of invasive species (Rountree and Juanes, 2017). This would be particularly valuable for important commercial fish species (Stratoudakis et al., 2024) or for endangered or cryptic species (Mann and Grothues, 2009; Parsons et al., 2017; Rowell et al., 2015). Even if the AFCC fish choruses are not ground-truthed to species, the records of these choruses still provide important ecological information.

The value of identifying and documenting unknown underwater biological sounds has recently been brought to attention (Parsons et al., 2022). Unidentified sounds not only assist in the process of source species elucidation but can also be used to measure biodiversity and indicate habitat conditions (Rountree et al., 2012; Krause and Farina, 2016; Di Iorio et al., 2018; Lin et al., 2019; Parsons et al., 2022). The AFCC provides valuable baselines of the distribution, diversity, seasonal presence, and spectral and temporal characteristics of Australian fish choruses, which can be applied to a variety of research or monitoring efforts. The potential application of the AFCC is demonstrated in the study by Hawkins et al. (2023). The study counted the number of fish choruses recorded at 29 locations that are also included within the AFCC. This measure of fish chorus diversity was used to highlight potentially important foraging and spawning habitats for fish aggregations and to identify spatial drivers of fish chorus diversity (Hawkins et al., 2023). The AFCC records can also be used as a baseline to monitor fish chorus contributions to a specific location over time. Fish can be used as effective indicators of ecosystem conditions (Harris, 1995; Schiemer, 2000; Whitfield and Elliott, 2002; Dulvy et al., 2008). Long-term monitoring of fish choruses has the potential to reveal impacts of environmental and anthropogenic change on soniferous fish populations and their respective habitats (Locascio and Mann, 2005; Indeck et al., 2015; Luczkovich et al., 2024) and be used to predict the response of vulnerable species to climate change (Monczak et al., 2019; Vieira et al., 2022). The AFCC aims to not only support future research, monitoring, and management efforts in Australian waters but also to inspire similar studies on fish choruses and their contributions to underwater soundscapes worldwide, even when the source species are yet to be confirmed.

Moving forward, the creation and development of fish chorus reference libraries will need to address several issues. Standardisation in acoustic data collection, processing, and analysis methods needs to be prioritised, facilitating comparisons and ensuring consistency and reliability across various studies (Browning et al., 2017; Gibb et al., 2019; Parsons et al., 2022). Enhanced collaboration among researchers and institutions needs to be encouraged to pool resources and share data and knowledge, thereby expanding the availability, diversity, and volume of raw acoustic data and of ground-truthed fish sounds. For example, the spatial scope of the AFCC would not have been possible without raw data contributions from CMST, AIMS, NSW DPI, Parks Australia, and NOAA. Advanced technologies, such as machine learning, signal processing, and artificial intelligence, need to be integrated into reference library development and maintenance. This will facilitate automated analysis and classification of sounds, making it easier and less time-consuming to identify and catalogue fish species (Napier et al., 2024). A strong emphasis needs to be placed on metadata quality to enhance the usability of the libraries for comparative research purposes and for monitoring efforts (Bradbury et al., 1999; Parsons et al., 2022). Additionally, data continuity needs to be safeguarded. Long-term financial security is needed to ensure the maintenance of these libraries (Parsons et al., 2022), such as the support provided for the NOAA NCEI passive acoustic data archive (Wall et al., 2021). Finally, the promotion of open-access needs to be prioritised to facilitate acoustic data availability to a wider audience, fostering greater innovation, continued development of data analysis techniques, and knowledge sharing in this field (Parsons et al., 2022).

Data availability statement

The datasets presented in this study can be found in online repositories. The names of the repository/repositories and accession number(s) can be found in the article/Supplementary Material.

Ethics statement

The animal study was approved by the Curtin University Animal Ethics Committee, the New South Wales Department of Primary Industries, Parks Australia, and the Great Barrier Reef Marine Park Authority. The study was conducted in accordance with the local legislation and institutional requirements.

Author contributions

LH: conceptualization, data curation, formal analysis, investigation, methodology, project administration, software, validation, visualization, writing–original draft, and writing–review and editing. CE: conceptualization, methodology, software, supervision, writing–review and editing, and resources. AB: resources and writing–review and editing. CB: resources and writing–review and editing. JeM: writing–review and editing and resources. JaM: writing–review and editing and formal analysis. IP: writing–review and editing and supervision. MP: resources, writing–review and editing, conceptualization, data curation, and formal analysis. NR: resources and writing–review and editing. RW: resources and writing–review and editing. DW-K: formal analysis and writing–review and editing. RM: methodology, resources, supervision, and writing–review and editing.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/frsen.2024.1473168/full#supplementary-material

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