Bioacoustics for Agri-Environment Monitoring

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1 State of the art in acoustic monitoring

1.1 What is acoustic monitoring?

The study of biological and environmental sound is a rapidly developing field of environmental research and practice, with particular relevance to biodiversity monitoring. In the last 20 years, it has significantly developed as a result of digital technology and the increased availability of recording hardware and data storage capacity. The study area is commonly divided into *bioacoustics* - the study of animal communications, and *ecoacoustics* - the more holistic, ecosystem-level, study of biological sounds [biophony] alongside environmental and man-made sounds [geophony and anthrophony] (Pijanowski et al. 2011; Stowell and Sueur 2020; Jérôme Sueur and Farina 2015). However, there are numerous overlaps between these two approaches.

Acoustic sensing has distinct advantages for ecological study, which make it complementary to other sampling methods, and can expand the type of data gathered, as well as its spatial and temporal extent. It can be used on land or under water, in all type of habitats, to sample a wide range of animal species - often simultaneously. An acoustic sensor has the advantage that it can capture a wide spatial range [often 360° and about 100 m in terrestrial habitats], and is much less affected by physical obstructions than visual technologies such as trail cameras (Crunchant et al. 2020). It is 'taxa-agnostic' in that it can collect information on the full assemblage of sound-producing species in the surrounding environment, whether these are mammals, amphibians, birds or invertebrates (Stowell and Sueur 2020). The captured sound recordings can also be permanently archived, and are multi-purpose in that the same recordings can be analysed in different ways depending on project requirements.

Following rapid developments in the capabilities of hardware/software and assessment methods over the last ~20 years, the last 12-24 months have seen the publication of a number of useful 'state of the art' reviews of acoustic survey/monitoring methods. These include general reviews of acoustic monitoring for ecology and conservation (Browning et al. 2017; Gibb et al. 2018; Sugai et al. 2019); together with more targeted reviews on animal communication (Teixeira, Maron, and Rensburg 2019); bird bioacoustics (Darras et al. 2018); freshwater habitats (Greenhalgh et al. 2020); and the use of microphone arrays for localising individual animals (Rhinehart et al. 2020). As part of this trend in consolidating research and developing applications, UK-focused workshop events on acoustic monitoring have recently been organised by two of the authors of this report: Carlos Abrahams [Bird Bioacoustics Workshop - 2017] and Tom August [Acoustic Monitoring Workshop - 2019].

1.1.1 Active vs passive acoustics

Acoustic survey and monitoring can be undertaken either manually, by a surveyor using a hand-held device, or through the use of unattended automated recorders. The former is often used in bat surveys, or by ornithologists making recordings of target bird species using directional microphones.

The alternative practice of deploying automated sensors in remote locations has been termed 'passive acoustic monitoring' [PAM] (Gillespie et al. 2009; Marques et al. 2013; Stowell and Sueur 2020). This method allows sound data to be recorded continuously or at regular intervals over long time periods, without intervention from surveyors. It allows large volumes of data to be gathered with minimal fieldwork resourcing, and using standardised methods, independent of observer biases (Hill et al. 2018; Stowell and Sueur 2020).

1.1.2 Species/group vs indices approaches

There are two broad methodological approaches in the interpretation of biological/environmental sound (Jorge et al. 2018; Stowell and Sueur 2020). The first is a species-based approach that involves detecting, selecting and identifying individual acoustic events within a recording, such as the vocalizations of chosen target species (Dawson and Efford 2009; Digby et al. 2013; Gillespie et al. 2009; Hutto and Stutzman 2009; Mammides et al. 2017; Stowell and Sueur 2020). For such studies, acoustic data are often analysed manually or by using software with single or multi-species recognizers, trained with previously collected data.

The second approach to data analysis is more general and sets out to provide a measure of the diversity of a recorded soundscape through the calculation of acoustic indices (Jérôme Sueur et al. 2014). This method analyses an acoustic recording to produce a numerical score that is related to the quality/character of the sound, based upon frequency, amplitude and time parameters. This analysis method is consistent, relatively easy to implement, and can easily be automated - hence being highly scalable (Stowell and Sueur 2020). This approach is increasingly being used as a reliable method to accurately reflect biodiversity, and a number of studies have demonstrated the value of this approach in a range of different habitat types, to provide information about changes at a site over time, or identify differences between sites (Campos-Cerqueira et al. 2019; Sanchez-Giraldo, 2020a; Depraetere et al., 2012; Gasc et al. 2013; Towsey et al., 2014; Sueur et al. (2008). The interpretation of acoustic indices is based upon the premise that soundscapes are not only spatially heterogeneous, but are also directly related to habitat structure and the characteristic animal communities that are correspondingly present in different habitat types (Bormpoudakis, Sueur, and Pantis 2013).

1.1.3 Hardware trends

Research in ecoacoustic methods has grown massively over the past two decades due to the enabling effects of digital recording technology, and the increasing availability of purpose-built audio recording devices. A range of commercial, research and open-source DIY devices are now available, with both equipment size and costs being reduced (Hill et al. 2018; Beason, Riesch, and Koricheva 2018; Whytock and Christie 2017). These trends are likely to continue, with one of the next steps in development addressing networked arrays of connected sensors so that data can be shared and streamed continuously to a central processor (Blumstein et al. 2011; Roch et al. 2016; Sethi et al. 2018) or - using 'edge computing' principles - signal processing can be integrated directly on board the sensor, so that results, rather than raw sound data are passed through the network (Sheng et al. 2019).

1.1.4 Software trends

Alongside developments in hardware, recent and ongoing research into establishing new and best practice recording and sound processing techniques offers enormous potential for the monitoring of biodiversity, (Bradfer-Lawrence et al. 2019; Burivalova, Game, and Butler 2019; Laiolo 2010). Much of the recent technical progress has been at the level of signal analysis and sound classification, developing methodologies for signal processing, machine learning and visualization (Stowell and Sueur 2020; Sugai et al. 2019). In particular the development of acoustic indices, and the use of machine learning tools for species identification, have seen rapid parallel developments (Stowell et al. 2019; Stowell and Sueur 2020). In recent years there has been considerable growth in the potential scale of data capture and processing, allowing longer-term and larger scale studies than previously possible - for example the 54,000 km^2 covered by Furnas and Callas (2015), or the multi-year recordings of Stuart H. Gage and Axel (2014). The focus of acoustic monitoring can now shift from the recording of individual animals to broad ecosystem-level studies (Stowell and Sueur 2020; Jérôme Sueur and Farina 2015), while still using audio as a prime source of evidence - potentially alongside other remotely-sensed data such as satellite imagery (Abrahams 2020; Carruthers-Jones et al. 2019).

1.1.5 Survey method trends

Between 1992 and 2018, bioacoustics studies showed a fifteenfold increase in publication and covered three development phases: establishment, expansion, and consolidation (Sugai et al. 2019). Overall, the research in this period was mostly focused on bats [50%], occurred in northern temperate regions [65%], addressed activity patterns [25%], recorded at night [37%], used nonprogrammable recorders [61%], and employed manual acoustic analysis [58%] (Sugai et al. 2019). However, this research landscape is now changing, with programmable recorders and more sophisticated data analysis tools enabling the taxa, geographical regions and research questions being addressed to widen significantly (Chambert et al. 2018; Sugai et al. 2019). This has enabled a shift from earlier work concentrating on bird and fish acoustic communication and auditory mechanics, through a middle period where work on frogs, bats, and crickets was developed, to more recent work consisting of wider studies of biodiversity using an ecoacoustics approach, passive acoustic monitoring, environmental conservation, and the classification of animal calls (Xie et al. 2020).

The research developments in recent years have now reached a sufficient level to allow emerging trends and good practices in the application of ecoacoustics for survey and monitoring to be identified. This includes the testing of acoustic indices in a variety of settings - and comparison of these to matching 'traditional' datasets, e.g. from bird survey (Machado, Aguiar, and Jones 2017; Eldridge et al. 2018). Recent guidelines for the use of acoustic indices have been produced (Bradfer-Lawrence et al. 2020), with recommendations also available for how to use these in landscape ecology (Furumo and Mitchell Aide 2019; Villanueva-Rivera et al. 2011a) and agri-environmental contexts (Doohan et al. 2019).

1.2 Ecoacoustic approaches

As stated above, the data recorded using ecoacoustic methods can be analysed in great depth to identify species, or even individual animals - but this can be time-consuming, and requires significant identification expertise. In contrast, the field of ecoacoustics focuses more on the structural properties and dynamics of biological/environmental sound without requiring any detection or identification of individual sound types, such as species calls (Servick 2014; Sueur and Farina 2015). The field extends bioacoustics by shifting away from identifying species/individuals [e.g. Aide 2013], and instead concentrating on quantifying the overall 'soundscape' - a much more rapid analysis process (Pijanowski et al. 2011). This concept is based on the premise that the character of the soundscape reflects all of the vocalising animals present, as they contribute to the sound of the ecosystem from within the temporal and frequency domains of their own 'acoustic niche' (Krause 1987; Gómez 2020). Due to this partitioning, more diverse ecosystems should exhibit more complex use of acoustic space (Dumyahn and Pijanowski 2011; van der Lee et al. 2020), and this should be detectable within acoustic recordings. As a result, soundscapes are often considered a proxy for other indicators of ecosystem status and condition, such as diversity (Gasc et al. 2013; Harris, Shears, and Radford 2016; Mammides et al. 2017), abundance (Boelman et al. 2007; Buxton et al. 2018; Pieretti, Farina, and Morri 2011), and biomass (Elise et al. 2019). Acoustic indices may also reflect additional dimensions of biodiversity including functional or phylogenetic diversity (Elise et al. 2019; Gasc et al. 2013; Harris, Shears, and Radford 2016; Mammides et al. 2017; Pieretti, Farina, and Morri 2011).

1.2.1 Acoustic indices

A range of indices have been developed for characterising acoustic field recordings, summarising audio data to produce numerical scores that are ecologically meaningful, and that can be used to assess biodiversity, including species richness, community diversity, and functional traits. An acoustic index is a statistic that summarizes some aspect of the distribution of acoustic energy and information within different frequency ranges in a recording - providing an indication of its ecological 'quality' and a link to biodiversity metrics (Towsey et al. 2014; Ross et al. 2020)

Over 60 indices have been developed to classify soundscapes based on their acoustic properties (Bradfer-Lawrence et al. 2019), and Jérôme Sueur et al. (2014) reviewed a range of these for summarising the soundscape. While they all aim to characterise the ecology of a system and provide a metric, in some way, for habitat assessment and monitoring, there is never likely to be a single index that accurately represents all levels of biodiversity at the recorded study sites (Bradfer-Lawrence et al. 2019; Buxton et al. 2018; Ross et al. 2020; Jérôme Sueur et al. 2014; Kasten et al. 2012; Pieretti, Farina, and Morri 2011). Although some acoustic indices may correlate with species richness (Depraetere et al. 2012; Jorge et al. 2018), studies to date have found some inconsistencies in the identified relationships, and so full understanding of their application is still becoming established (Bradfer-Lawrence et al. 2020; Gibb et al. 2019; Mammides et al. 2017; Ross et al. 2020).

Each acoustic index utilises different characteristics of the soundscape - pitch [frequency] and volume [amplitude], and how these vary over time. Often the calculation methods involve contrasting adjacent time steps or frequency bands within a recording, to see how these vary. In effect, acoustic indices reduce the enormous complexity of the soundscape to a single number, greatly simplifying the extraction of summarised information from recordings. Such results can be used to investigate changes in the soundscape, both in time and space. For example, Rodriguez et al. (2014) and Linke et al. (2018) used acoustic indices to describe clear diel cycles in tropical forest soundscapes and freshwater ponds, while seasonal shifts have been examined in both temperate and tropical habitats (Farina, Pieretti, and Piccioli 2011; Pieretti et al. 2015). Clear spatial differences have also been found in the soundscapes of different habitat types (Bormpoudakis, Sueur, and Pantis 2013; Depraetere et al. 2012; Villanueva-Rivera et al., 2011), with habitat change reflected in the soundscape, likely caused by shifts in faunal assemblages (Burivalova et al. 2017; Deichmann et al. 2017; Tucker et al. 2014). In addition, soundscapes have proved useful to study biodiversity along gradients of human disturbance (Tucker et al. 2014; Bobryk et al. 2016; Burivalova et al. 2017; Deichmann et al. 2017).

A key advantage to using acoustic indices is that they are more logistically feasible to implement than species-specific approaches (Doohan et al. 2019). Experts are not required for species identification, indices can be calculated directly without the need for recogniser training [and its reliance on training datasets], and they are simple to calculate with readily available software [A. Gasc et al. (2013); J. Sueur et al. (2008), Villanueva-Rivera et al. (2011b). Another advantage to using acoustic indices is that they are likely to more closely reflect overall changes in biodiversity than indicators that rely on a single taxa (Doohan et al. 2019; J. Sueur et al. 2008).

1.3 Further implementation of ecoacoustics

Ecoacoustic developments in recent years have been taken up rapidly for use in bat and cetacean research and conservation [where other data gathering methods are highly limited], but ecoacoustic methods have not yet become widespread in application with other taxa where existing traditional methods can provide useful data. There is hence great potential, and benefit, for their use more widely as a practical tool for conservation and management (Stowell and Sueur 2020).

Researchers have not yet tapped the potential of ecoacoustics to understand the impacts of different land use activities at larger spatial scales [i.e. regional, national]. However, studies at these scales are underway, e.g. Furnas and Callas (2015), Wood et al. (2019) and https://acousticobservatory.org/. Acoustic sensors should be included in large scale [i.e. national and international] monitoring programmes, in complementary fashion to other standard methods and, in particular, to design acoustic monitoring into long term programs.

1.4 Resourcing benefits of acoustic monitoring

Passive acoustic monitoring, with automated recorders, provides the potential for considerable savings in terms of survey and data processing time [Holmes *et al.* 2014]. For example, Jorge et al. (2018) showed that acoustic methods required just 12.5% of the field time needed for bird point-count surveys, and the time needed to obtain acoustic indices required 13.6% of the time required for processing and analyzing point count data. Similarly, Tegeler, Morrison, and Szewczak (2012) gained >1,100 additional hours of data and recorded more species using automated recorders, with a quarter of the personnel effort needed for traditional surveys.

2 Outputs of acoustic methods for agri-environment monitoring

2.1 Introduction

Acoustic technology is entirely appropriate to fit into existing research and understanding of the effects of individual AES options, or AES agreements (Staley et al., 2016). Deployment of acoustic recorders within farms could highlight spatial or temporal effects of AES management prescriptions (e.g. Blake et al. 2011; Staley et al., 2016), and help determine whether AES interventions are benefitting target taxa - either through direct effects on the land under management, or by providing resources for mobile taxa (Carvell et al. 2015).

The analysis of sound recordings can provide evidence for a wide range of ecological information (Stowell and Sueur 2020). Acoustic data can indicate the simpe presence of particular animals or assemblages, or provide information on the phenology (e.g. Oliver et al. 2018), temporal dynamics (Abrahams 2019; Gottesman et al. 2018; Gómez 2020; Ospina et al. 2013), activity levels (Pérez-Granados, Bota, Giralt, Barrero, Gómez-Catasús, Bustillo-De La Rosa, et al. 2019), or numbers and distribution of vocalising animals (Campos-Cerqueira and Aide 2016; Bradfer-Lawrence et al. 2020). In addition, ecoacoustics has been used to document the health and stability of an ecosystem, providing information about the status of broad species assemblages (Blumstein et al. 2011; Pijanowski et al. 2011; Fuller et al. 2015; Burivalova et al. 2018).

Acoustic recordings can also be rich in wider environmental information (Ross et al. 2020), on landscape or habitat structure (Burivalova, Game, and Butler 2019; Fuller et al. 2015), weather conditions (Sanchez-Giraldo 2020; Metcalf et al. 2020), anthropogenic noise levels (Deichmann et al., 2017; Gill et al. (2017), and atypical sounds such as illegal logging activity and gunshots (Krause 1987; Sethi et al. 2020; Hill et al. 2018). The diversity of uses to which acoustic data can be put are listed below:

- acoustic indices
- species presence/absence or occupancy
- activity levels [e.g. bat passes, or vocal activity rates]
- species assemblage, e.g. species richness
- population density
- population structure
- community structure

- landscape architecture
- animal phenology/periodicity
- reproduction period
- migration period
- species interactions
- ecosystem function

Defra has a framework of outcome indicators to monitor the 25 year Environment Plan - 66 indicators in ten broad themes, with 16 of these being identified under 'headlines' [Defra 2019]. At the present time, 27 indicators have data already available, while some indicators still require further development. AES monitoring will most clearly fit into the 'Wildlife' theme [indicators D1-D7]. It is anticipated that acoustic monitoring of AES could contribute to the following indicators, and headlines:

- D1. Quantity, quality and connectivity of habitats [headline 7]
- D4. Relative abundance and/or distribution of widespread species [headline 7]
- D5. Conservation status of our native species [headline 6]
- D6. Abundance and distribution of priority species in England
- D7. Species supporting ecosystem functions [headline 7]
- Headline 6. Changes in wildlife and wild places that we cherish
- Headline 7. Changes in nature on land and water that support our lives and livelihoods

2.2 Existing species monitoring methods and key outputs

2.2.1 Birds

The principal monitoring data sets for UK birds arise from the BTO/JNCC/RSPB Breeding Bird Survey [BBS] and the BTO Bird Atlas, the last of which was conducted over the period 2007-11 (Balmer 2013). The BBS is an annual monitoring scheme where volunteers cover more than 2000 1km squares spread across England. BBS data are analysed annually to inform bird population trends and have also been used to investigate the impacts of AES options at the national scale. The data are well-suited to this purpose because the survey method has high spatial coverage and replication, but the method is not appropriate for deriving estimates of local abundance, because square-specific annual counts are subject to too much stochastic variation (Staley et al., 2016).

Review of research on birds and AES shows that there has been a clear emphasis on studies relating to winter food supplies [winter bird crops and stubbles etc.], and linear features [field margins, buffer strips and hedgerows] (Staley et al., 2016). There is evidence of large-scale effects on population growth rates in birds in response to AES management.

The critical response variable in bird monitoring is often species-richness or breeding bird numbers, expressed either as counts of individuals or counts of territories [often via numbers of singing males as a proxy]. For AES purposes, winter monitoring is also desirable to assess the performance of options aiming to provide winter food (Staley et al., 2016). For long-term monitoring of AES effects, it is important to use a protocol with consistent, repeatable survey intensity and coverage, which is as independent of surveyor identity as possible. In addition, to compare focal squares with the surrounding landscape, the coverage needs to be similar in intensity per unit area sampled.

2.2.2 Mammals

Mammal data are collected during bird BBS visits [see above], allowing population trends to be calculated for nine easily detectable and widespread species - hares, rabbits, grey squirrel, deer and red fox (Harris, Shears, and Radford 2016). The potential to monitor AES effects on mammals is limited and complicated by the specificity of the [traditional] survey approaches used for different species (Staley et al., 2016). Many approaches, such as those based on field signs, are likely to be effective for detecting species' presences, but unreliable for changes in abundance.

2.2.3 Bats

There are various bat monitoring schemes, run by the BCT, through the National Bat Monitoring Programme [NBMP]. The scheme covers roosts, waterways and hibernacula, as well as field and woodland surveys. The latter has some relevance to AES (Staley et al., 2016), but is limited due to the use of handheld heterodyne detectors, which do not record sound data, can only cover a very limited frequency range at one time, and require a high level of surveyor experience to interpret the sounds heard.

In contrast to the NBMP, the Norfolk Bat Survey [https://www.batsurvey.org/] and the BCT British Bat Survey [https://www.bats.org.uk/our-work/national-bat-monitoring-programme/passive-acoustic-surveys/british-bat-survey] use full-spectrum static bat detectors and software to improve bat identification and detection [Newson2015]. The method is less biased than traditional survey methods, and requires less effort or skill on the part of the field surveyors. Within these schemes, the collation of data from a number of detectors deployed across the landscape provides data on presence, relative abundance and habitat relationships of bat species, and if used within the AES setting could provide the high-quality, precise, local measures of abundance and species richness required to allow AES effects to be detected - which cannot be provided by extensive volunteer monitoring as is found in the NBMP [and BBS for birds]. The key issue for detecting relative abundance responses to AES at the landscape scale is to have sufficient replication of deployed detectors to gauge the effects of differences in habitats resulting from AES management. This is where some methodological testing and development is needed. Associations with population change in species of conservation interest would then need to be measured (Staley et al., 2016).

At the current time, the monitoring of bats to assess AES effectiveness is being trialled. The recommended survey approach is to use automated full-spectrum bat detectors, that can be deployed to trigger automatically and capture bat calls, with this data being analysed with call identification software (see Newson, Evans, and Gillings 2015). This approach offers great potential for transforming large scale bat monitoring in the UK, and for addressing questions in relation to AES (Staley et al., 2016). Using passive detectors in this way, allows bat species distribution and activity levels to be quantified as a measure of relative abundance at the landscape scale.

2.3 Species-level outputs

Acoustic technology has the potential to complement and advance data gathering methods already commonly used in agri-environment monitoring, providing comparable data for sound-producing animals such as birds, bats, other mammals and invertebrates. It can do this through species-level [or taxon-group] identifications from audio recordings, e.g. identifying bird species from their recorded songs and calls. The clear benefits of using ecoacoustic methods here are in long-term deployments, 24-hour coverage, consistency of data between sites, the large datasets that can be captured, the potential for quality-assurance processes, and the low-levels of resourcing required in comparison to traditional survey methods. These benefits have been repeatedly demonstrated in a large number of studies.

Several studies on bird assemblages have compared point-count data to automated acoustic recording in a variety of habitats such as rainforest (Leach et al. 2016), tropical savanna (Alquezar and Machado 2015), temperate woodlands (Furnas and Callas 2015; Holmes, McIlwrick, and Venier 2014), and temperate meadows (Tegeler, Morrison, and Szewczak 2012). These have shown that the results are comparable in terms of species-richness and assemblage composition when used for equivalent lengths of time in the field. The results from each are not exactly the same, as acoustic recording will miss silent individuals that might be seen by humans, while surveyors can fail to record some species during busy periods, or while their attention is elsewhere. However, automated recording can easily provide larger amounts of data than human surveyors, often with less survey effort (Holmes, McIlwrick, and Venier 2014). For example, Tegeler, Morrison, and Szewczak (2012) gained >1,100 additional hours of data using automated recorders, and recorded more species, with a quarter of the personnel effort.

Survey at difficult to access sites, or with cryptic species, is often improved with ecoacoustics. For example, Zwart et al. (2014) found that acoustic recorders offered a 217% increase in detection for the nocturnal nightjar *Caprimulgus europaeus* over human surveyors, and with 19 detections in 22 survey periods compared to 6 detections by humans.

Although there is potential for some invertebrates to be surveyed using acoustic methods (Görres and Chesmore 2019; Newson 2017), work on birds and bats is far more established, and also able to cover larger spatial areas - due to the vocalizations from these species groups being louder, and consequently offering a greater detection distance.

2.4 Soundscape outputs

Acoustic methods also have the potential to expand agri-environment monitoring into new methods and metrics, through the application of acoustic indices. Such an approach does not provide species-level data [although this can be extracted from the same audio recordings if needed], but provides a quantification of the soundscape character recorded at the site. Acoustic indices could therefore be used to assess habitat quality in different AES areas [e.g. in comparison to non-AES farmed land], or to monitor changes in the environment over time - with the resolution of that data only really constrained by data storage and processing implications.

The use of Acoustic Indices for AES monitoring is potentially very promising, and likely to be the easiest approach to implement for ecoacoustic technology. With repeated recordings through a day, season or year, these metrics can be tracked over time, or compared between locations to look at spatial relatioships. Acoustic indices, can be used as a proxy for biodiversity or environmental quality, and have been linked with measures of species richness, community structure and phenology (Buxton et al. 2016; Fuller et al. 2015; Lellouch et al. 2014; Towsey et al. 2014). The methods of use are hence becoming established, but will require calibrating within an AES setting to understand how indices relate to farm management measures, crop types etc.

2.4.1 Spatial/habitat soundscapes

Consistent differences amongst soundscapes from different land-use types have been found, with some Acoustic Indices [e.g. mean ACI] providing good fine-scale discrimination among a range of habitats (Bradfer-Lawrence et al. 2019; Fuller et al. 2015; Pieretti et al. 2015). This is due to the overall species assemblage present at each location, as well as the influence of wind and rain sound in different vegetation classes such as pasture or forested areas. Distinct patterns in acoustic indices have also been found in urban habitats, as well as farmed or semi-natural areas (Fairbrass et al. 2017; Joo, Gage, and Kasten 2011).

2.4.2 Temporal soundscapes

Soundscapes, and the resulting acoustic indices, vary over time, with clear diel, seasonal and inter-annual patterns. Diel patterns are particularly pronounced in a number of habitats/biomes, with consistent distinctions between day and night being found, for example (Bradfer-Lawrence et al. 2019).

3 The use of acoustic methods for agri-environment monitoring

3.1 How the technology is, or could be, used in agri-environment monitoring

Acoustic monitoring has great promise for the monitoring in agri-environment schemes, with the potential to serve as a powerful tool for measuring the influence of different scheme options on a range of wildlife. It can be used to assess management actions, landscape structure, and overall ecological condition – and is relatively inexpensive and simple to implement and undertake when compared to traditional methods, requiring less training, staff, time, and operational costs (Doohan et al. 2019; Fuller et al. 2015; Sueur et al. 2012; Zwart et al. 2014).

One of the key benefits of an acoustic approach is that it is relatively taxa-agnostic – sound recordings made in the field will simultaneously capture all sound-producing animals within the detection and frequency range of the recorder unit (Campos-Cerqueira et al. 2019; Kalan et al. 2015; Marques et al. 2013; Deichmann et al. 2017, 2017). A single recorder can therefore potentially record bats, other mammals, birds, and invertebrates at the same time. This 'soundscape' can be interrogated for the presence and call activity levels of particular species or be evaluated as a composite of the combined sounds, using acoustic indices. The recording acts as a permanent sample from the site, and can be archived for long-term storage and reanalysis in future, as necessary (Aide et al. 2013). Acoustic recording with automated 'passive' recorders can also be conducted simultaneously at a number of sampling locations (Digby et al. 2013; A. Gasc et al. 2013; Jorge et al. 2018), and at large spatial and temporal scales, providing benefits for regional or national monitoring schemes (Furnas and Callas 2015; Towsey et al. 2018).

While acoustic monitoring has been used to study biodiversity in a wide variety of habitats, few experimental studies have examined the effectiveness of acoustic monitoring in the agricultural context (Doohan et al. 2019). There are, to our knowledge, no acoustic monitoring projects [beyond the LM0456 project mentioned below] that have focussed on the UK farmed landscape. Acoustic monitoring in agricultural environments is not an entirely new concept, but previous studies have examined issues such as animal welfare (Ginovart-Panisello et al. 2020; Manteuffel, Puppe, and Schön 2004; Mcloughlin, Stewart, and McElligott 2019); pest densities in crops or stored goods (Neethirajan et al. 2007; Pinhas et al. 2008), or have focussed on the role of target animals in providing ecosystem services, such as pest suppression by bats (McCracken et al. 2008). In constrast to these applications, there has been less work focussed on the biodiversity assessment of different land management options and the use of acoustic bioindicators within an AES context.

To enable the development of acoustic monitoring for agricultural purposes, Doohan et al. (2019) set out five key characteristics that need to be considered when selecting an appropriate indicator:

1. The bioindicator must be relevant to the industry; it must meet the requirements and goals of the program proponent [i.e. the stakeholder who is undertaking the biodiversity monitoring program]
2. A diagnostic link between on-farm management practices and the proposed bioindicator must exist, and the relationship between these two must be validated.
3. Novel bioindicators need to be appropriate for the scale of biodiversity assessment being undertaken. This is critical for crop or farm types where land use practices vary across spatial [i.e. on-farm, regional, national] and temporal [i.e. crop cycle, seasonal, annual] scales.
4. The bioindicator must be logistically feasible to use in terms of cost, technical expertise, and time required to generate and implement it.
5. The bioindicator must be a surrogate for changes in biodiversity. If it is not, then it is important to state that a component of on-farm biota is being monitored, rather than biodiversity as a whole.

Previous studies have identified bats and birds as suitable indicators for AES monitoring, due to their general ubiquity, known habitat preferences, recognised survey methods, and existing data context. Both of these species groups can be monitored very well using an acoustic approach, and the information gained from acoustic data can be interpreted in much the same way as that from traditonal survey methods, e.g. the presence/absence of a species in a farm plot can be determined, and species-richness for the overall assemblage can be calculated

Acoustic indices offer a new approach to AES monitoring, which has considerable potential in terms of providing new and broader-based information than species-based methods, and with a simpler data analysis workflow. In terms of the five characteristics set out above, the scale of acoustic detection spaces [commonly c.50-100m radius] fits well with a field-plot approach, the approach is logistically feasible for regional data-gathering, and acoustic indices have proven to be surrogates for changes in biodiversity. However, further development is likely to be needed in how best to interpret the outputs from indices, as there is only limited understanding currently of the relationship between acoustic indices and different land managment options.

Both of these approaches, the species-based and index-based, therefore have value within an AES context, and are discussed further below.

3.1.1 Species approach

The use of species indicators is an intuitive way to understand the link between increased biodiversity and land management practices. Species occupancy and abundance can be measured over space and time, and can be linked to resource availability and the quality of the surrounding environment, such as breeding sites for birds (Abrahams and Geary 2020; Campos-Cerqueira and Aide 2016; Chambert et al. 2018; Furnas and Callas 2015; Furnas and McGrann 2018; Grava et al. 2008). Audio data can also be used to infer the behaviour and activity of some animal groups, such as bird breding displays (Abrahams 2019), and bat foraging] (Frey-Ehrenbold et al. 2013), which may provide on-farm benefits such as pest control (Jones et al. 2009).

When selecting target species for monitoring in agricultural environments, birds and bats are regarded as displaying the most potential (Doohan et al. 2019). Both are relatively easy to monitor acoustically, their habitat needs are reasonably well understood, and they exhibit clear peaks in activity that allow monitoring periods to be defined [Doohan et al. (2019); Wimmer et al. (2013);]. These taxa are also useful bioindicators because of their sensitivity to habitat change, and preferences in terms of habitat corridors, structurally complex vegetation, patch size and the intensity of the surrounding land-use (Doohan et al. 2019; Blumstein et al. 2011; Donald, Green, and Heath 2001; Firbank et al. 2008; Wordley et al. 2017). With this understanding, species-specific acoustic indicators can be intuitively linked to land management practices, and the structural characteristics of the landscape elements they create (Padoa-Schioppa et al. 2006). As such, species-specific bioindicators can be selected based on their relevance to regulators and farmers, as well as their relationships with agricultural management practices.

As one example, Grant and Samways (2016) acoustically assessed the species richness of various habitats with both non-native and indigenous vegetation. They identified 65 soniferous species, including birds, frogs, crickets, and katydids. Large, natural grassland sites had the highest mean species richness, while areas covered in non-native timber or grass species were devoid of acoustic species. Sites grazed by native and domestic herbivores were richer in acoustic species than in intensively managed grasslands. Natural vegetation patches, especially wetland areas, supported high mean acoustic diversity, which increased as plant heterogeneity and patch size increased. Native forest patches contained a highly characteristic acoustic assemblage, emphasizing their complementary contribution to local biodiversity. Overall, acoustic signals accurately reflected spatial biodiversity patterns, and were a good indicator for habitat conservation value.

Within the UK, ongoing research projects have implemented a species-based approach to AES acoustic monitoring. The LM0457 (Staley et al., 2016) study developed the scope for monitoring landscape-scale biodiversity impacts of AES in England. It included bioacoustic monitoring for bats as part of the recommended approach. The specific field protocol put forward involved three bat detectors deployed simultaneously within a 3 × 3km square [i.e., a core 1 km square, plus an outer spill-over area]. The detectors would be deployed for at least three consecutive survey nights in one location, before being moved to new sampling locations within the same 3 × 3 km square. After this 6-day deployment, they would be moved to a new 3 × 3km square, and thus, the three detectors would be rotated between four 3 × 3 squares per month. The multi-night deployment per location is important in order to help to average out variation in bat activity due to weather, and moving the detectors within a 3 × 3 square will help to control for habitat heterogeneity. Sampling would take place between May and the end of September to cover the bat active season.

The survey design and sampling methodology recommended in the LM0457 report have since been successfully applied in the ongoing LM0465 'Landscape-scale species monitoring of AES effects' project, in which species-resolution data are collected for a range of mobile taxa, habitats and plant communities within 54 1x1km squares, selected along local and landscape-scale AES gradients. This project specifically considers impacts beyond farm or agreement boundaries and surveys pollinating invertebrates [bees and hoverflies], butterflies, moths, birds and bats. Three years of field data have been successfully collected and reported on, with a fourth year scheduled in 2021.

3.1.2 Indices approach

Audio recordings can be analysed with acoustic indices to examine the composition and diversity of all recorded vocalising organisms, as well as other acoustic features of the soundscape, such as environmental and human sounds [e.g. engines and machinery] (Farina and James 2016; Pijanowski et al. 2011; Jérôme Sueur and Farina 2015; Towsey et al. 2014). It is generally regarded that complex habitats contain a higher diversity of vocalising species, which produce more, and varied, acoustic signals (Darras et al. 2016; Depraetere et al., 2012; Gasc et al. 2013; Sueur et al. 2008).

There are a few acoustic index studies conducted with acoustic indices that are relevant to the agri-environment context:

6. Villanueva-Rivera et al. (2011b) used the Acoustic Evenness [AEI] index across a variety of habitats [including crop lands] in the USA, finding that it may be a reliable proxy for biodiversity.
7. Depraetere et al. (2012) tested Acoustic Richness [AR] across three different habitat types with varying levels of disturbance in Europe, finding a correlation with bird species richness.
8. Tucker et al. (2014) investigated soundscapes in fragmented forest remnants. This indicated that the measurement of relative soundscape power reflects ecological condition and bird species richness, and is dependent on the extent of landscape fragmentation, and the consequent size and connectedness of forest patches.
9. Bobryk et al. (2015) compared different agricultural systems – soybean monoculture, pecan alley crop, silvopasture and natural forest. This indicated significant relationships between Acoustic Complexity Index and the overall structural complexity of the habitats [measured using vegetation height], and with the overall species richness identified by manual review of the audio recordings.
10. Gage et al. (2015) applied the Normalized Difference Soundscape Index [NDSI] across different vegetation types in agricultural environments, including winter wheat, successional forest and Poplar dominated forest. The results showed that NDSI had a positive relationship with biotic activity, with the lowest values found in agricultural dominated landscapes and highest in Poplar dominated forest.
11. Eldridge et al. (2018) compared a range of acoustic indices from recordings in ancient woodland, regenerating farmland with patches of woodland, and a downland barley farm. Species richness and acoustic indices were highest in the semi-natural habitats, and lowest in the arable farmland.
12. Turner, Fischer, and Tzanopoulos (2018) investigated the effects of stand-age [0–85 years] and structure on the acoustic properties of plantations in Thetford Forest. Moderate relationships were observed between acoustic diversity and forest stand-age and vegetation characteristics [canopy height; canopy cover]. A strong linear relationship was observed between distance to the nearest road and the ratio of anthropogenic noise to biological sounds within the soundscape.
13. Myers, Berg, and Maneas (2019) used acoustic indices to compare the soundscapes of organic and conventional olive groves in Greece, using Acoustic Complexity Index [ACI], the Acoustic Diversity Index [ADI] and the Bioacoustic Index [BIO]. Olive groves under organic farming had significantly higher values for the ACI and BIO indices, and higher, but not significant, values for the ADI index. Site level variables, especially underlying vegetation height, had a significant influence on the ACI and BIO indices.

14. Furumo and Mitchell Aide (2019) compared the acoustic features of different land cover types in and around neotropical oil palm plantations, finding that soundscape analysis was effective in differentiating land uses. Their forest soundscapes were significantly different from the soundscapes of oil palm production sites, demonstrating the potential of acoustic monitoring to rapidly evaluate the effects of landscape-level changes on biodiversity.
15. Campos-Cerqueira et al. (2019) evaluated the impact of Forest Stewardship Council certification at certified forestry sites and non-FSC forestry sites, and unmanaged reference sites. Soundscape variation was best explained by the management type, with FSC sites having higher values than the reference and non-FSC sites especially.
16. Müller et al. (2020) investigated the effects of habitat patch size on acoustic diversity, using forest 'island' patches within an agricultural landscape. They found that Acoustic Diversity Index values were positively related to habitat size, vegetation structural diversity and bird species richness.
17. Dixon, Baker, and Ellis (2020) explored the potential to monitor biodiversity in agricultural landscapes by linking high-resolution remote sensing by drone with passive acoustic monitoring. Analysis revealed a significant direct association between vocalizing bird species richness and percent non-crop vegetation cover.

These studies, although mostly taking place in different countries and habitat types than in the UK, all indicate that acoustic indices can effectively detect differences in land management practices. They show that 'environmentally-friendly' farming and forestry practices, such as organic production and FSC certification, result in a more diverse soundscape and higher value acoustic index scores. The same pattern is likely to be found in comparison between standard farming practices and AES within the UK - although this still remains to be demonstrated.

One interesting finding from Eldridge et al. (2018) is worth highlighting here. Their analysis suggested that between-habitat differences in acoustic indices were greater than differences in bird species lists. This indicates that acoustic assessments could potentially provide a more complete measure of biodiversity than traditional avian surveys. Potential explanations for this are: [i] differences in vocalization characteristics of registered species, such as skylarks in agricultural land and pheasants in forest, both species having very distinct calls which strongly impact many of the indices values; [ii] prevalence of non-avian taxa; [iii] site-specific differences in anthrophony, such as airplanes, generators or human voice; [iv] site-specific differences in geophony [wind, rain], potentially augmented by the impact of habitat structural variation on propagation of acoustic signals. Importantly, for application in the UK, this study also observed stronger relationships between indices and species richness in UK habitats than have been reported in other recent studies, many of which have been carried out in tropical environments, where results may have been confounded by other vocalizing taxa, – such as large insect choruses.

3.2 Limitations and development needs for acoustic monitoring

The practical use of acoustic monitoring for bats is well-established, with standard good practice documentation available (Collins 2016). Significant use with this taxa, and increasingly wide-ranging scientific work covering birds, means that the limitations and benefits of the acoustic approach are well understood. Its use for other taxa, or soundscapes, however, has not yet been formalised into guidance, with a few notable exceptions (e.g. Abrahams and Denny 2018). In particular, we are aware that attempts to date to apply ecoacoustics to agri-environment monitoring are very rare (Doohan et al., 2019), despite clear potential benefits offered in terms of data consistency, scale, etc. It is recognised that a lack of consensus on best practices for acoustic monitoring has, so far, hindered its application in conservation and land-use management contexts [Metcalf2020]. but there is growing interest in establishing acoustic recording protocols to monitor changes in the soundscape through time and space (Ross et al. 2018; Ross et al. 2020; Sethi et al. 2020).

Recent research has set out principles and processes for advancing the practical use of ecoacoustics in environmental assessment. Linke, Gifford, and Desjonquères (2020) described six steps that need to be undertaken to improve the utility of acoustic approaches for ecological monitoring and assessment, reflecting issues also highlighted by other authors such as Gibb et al. (2018). The six steps were put forward in relation to freshwater acoustics, but are equally relevant to the agricultural context:

1. Characterising sounds and linking occurrences to organisms and ecosystem processes
2. Improving automatic detection and analysis methods
3. Making data and science accessible
4. Quantifying spatial heterogeneity and modelling spatial sound propagation
5. Considering multi-scale temporal variation
6. Deriving links between ecological condition and sounds

3.3 Development required for species approach

A fundamental requirement for the efficient automated processing of species-level analyses is a recogniser that can detect and identify sounds from the target species (Brandes 2008; Digby et al. 2013). Such a classifier can be built using machine-learning methods, but needs an established training set of sounds from the target species that have already been identified through a manual process (Gibb et al. 2018; Towsey et al. 2014). Although such training sets and recognisers are being developed [e.g. https://birdnet.cornell.edu/ and https://www.bto.org/our-science/projects/bto-acoustic-pipeline], further work is required to widen the scope of these, and ensure that they serve the needs of AES monitoring. There are commercially available recognisers available to allow fast and accurate processing of bat calls [SonoChiro, Kaleidoscope Pro, and Anabat Insight], but these still require some care and expetrise in use (Rydell et al. 2017). Similarly complete systems for birds and other taxa are not yet freely available.

3.4 Development required for indices approach

In comparison to species approaches, the processing of sound recordings into acoustic indices is relatively simple. This is a direct computational procedure, that does not require training data or the development of a classifier. The development need for the indices approach is, instead, a greater understanding of which combination of indices to use and how to interpret the derived scores. The relative novelty of this field and the pace of innovation mean there are currently no accepted standards or guidance on how such data can be used for effective monitoring (Bradfer-Lawrence et al. 2019; Gibb et al. 2018), and existing guidance has focussed on assessing faunal presence rather than soundscape analysis (Browning et al. 2017).

Despite many promising research results, acoustic index studies to date have reported contradictory patterns, even when using the same acoustic indices (Browning et al. 2017; Eldridge et al. 2016). However, these disparities are possibly due to inconsistencies and wide variation in data collection methods, and choices around the indices employed, rather than fundamental problems with the approach itself (Bradfer-Lawrence et al. 2019).

Across the board though, one common issue with acoustic indices [and some species-level approaches] is sensitivity to broadband and background noises, such as geophony [i.e. wind and rain] and anthrophony/technophony, such as traffic, aeroplanes and machinery. Insect choruses are also an issue in the tropics, but are not an issue within the UK, where urban noise is likely to be one of the main confounding factors (Fairbrass et al. 2017). These interferences mask target sounds and produce erroneous scores for acoustic indices (Eldridge et al. 2016; Metcalf et al. 2020; Pieretti, Farina, and Morri 2011; Villanueva-Rivera et al. 2011b; Ross et al. 2020). This is an issue that can often be dealt with through appropriate survey design, equipment choice and data management - important procedures within any survey approach. However, it needs to be borne in mind that acoustic indices are not purely an ecological measure, but are more indicative of more general environmental qualities (Gibb et al. 2018). This may be a benefit, or a disadvantage, depending upon the aims of the monitoring project.

In relation to survey design, the detection/recording radius around an acoustic recorder is an important criteria in interpreting survey results. When targeting a single-species, this distance can often be determined to some level of accuracy, but acoustic indices combine the sounds from a wide range of sources, each with their own frequency and amplitude characteristics - and hence detection ranges (Gibb et al. 2018). For example, high-frequency low-amplitude sounds from small mammals are likely to be only very local to the recording unit, while low-frequency high-amplitude sounds, e.g. bittern calls, will carry a long distance. The interplay of these mismatches in scaling will determine the outputs of acoustic indices and mean that the spatial region covered by each recorder is inherently variable. Consequently, the sound being interpreted may respond to both on-farm land management actions, and wider habitat/landscape influences, including regional efforts to increase biodiversity, or the migration patterns of a few species (Doohan et al. 2019).

If the practical and theoretical problems identified above can be sufficiently resolved in scientific studies and real-world case-studies, then acoustic indices offer a potentially important and unique source of information for application within environmental monitoring (Gibb et al. 2018).

3.5 Detecting temporal change with acoustic monitoring

The long-term and repeatable deployments that can be accommodated with passive acoustic monitoring enable the detection of changes in soundscapes over time. This can investigate diurnal variation in bird song or insect activity, for example (Abrahams 2019; Bradfer-Lawrence et al. 2019; Linke, Gifford, and Desjonquères 2020; Ross et al. 2020), or show soundscape dynamics over seasonal and multi-year timescales (Farina, Pieretti, and Piccioli., 2011; Frommolt, 2017; Phillips, Towsey, and Roe, 2018; Pijanowski 2011).

A number of research studies have highlighted the statistical power that can be provided by acoustic methods to detect long-term trends in the populations of target species:

7. Furnas and Callas (2015) assessed the use of automated recorders and occupancy models to monitor common forest birds across a 5.4-million-ha region of northern California. Using a survey protocol of 5-minute recordings at 3 times of the morning repeated over 3 consecutive days at 453 sites, they detected 32 species at >10% of sites. Given a sampling effort of 100 new sites per year, they demonstrated 80% power to

detect occupancy declines as small as 2.5% per year over 20 years for the 32 most common species.

8. Law et al. (2015) conducted a study on bats that concluded that a sampling design using two detectors per monitoring point for two nights could detect a 30% decline within 10 years with 90% power 11 out of 12 species, using either changes in activity levels or occupancy.
9. Newson (2017) simulated sampling strategies that would successfully detect a 25% decline in occurrence with 80% power for the main bat species in the UK. This showed that 3 nights of recording at 100 sites would be sufficient for the commonest pipistrelle species, but that for rarer and less detectable species, 1000-1500 sampling sites would be required.
10. Furnas and McGrann (2018) investigated the dates of peak vocal activity for passerines at 553 sites in California, and the potential impacts of climate change on these. For an 80% power standard, they found that repeating their level of survey effort on an annual basis would allow detection of an advancement of average peak vocal activity by as small as 2.2 days over 10 yr for some priority species. They could detect smaller average shifts of 0.8 day decade–1 for this group or 1.6 days decade–1 for all passerines over 20 yr.
11. Wood et al. (2019) assessed sampling levels and detection probabilities needed to detect small changes in site occupancy of two owl species: the common but declining spotted owl and the rare but increasing invasive barred owl. Simulation-based power analyses indicated that detection/non-detection data collected at large numbers of sites (500–1500) can yield high statistical power (> 80%) to detect ≥2% annual declines in site occupancy within 10 years, but depended on the number of visits per site, initial occupancy rates, and detection probabilities. Statistical power to detect ≥30% declines in local survival rates in 10 years was also high. Based on ~6-night passive-acoustic surveys, simulations indicated that 2% annual declines in spotted owl site occupancy could be detected with high statistical power in 10 years with 1,000 sites surveyed three times per season (year) or 1500 sites surveyed two times per season. Statistical power to detect 4% annual increases in site occupancy for expanding barred owl populations with this sampling scheme was also high.

4 How acoustic monitoring could support AES delivery

As shown in the research highlighted above, acoustic monitoring methods can be applied at field, farm, regional and national scales to inform the management of agri-environment schemes. They could also potentially be used to monitor a range of options within the scheme, and assess the biodiversity benefits that result from their implementation. To illustrate this point, a selection of Countryside Stewardship options are highlighted below in Table 1, with commentary provided on species-level or acoustic index approaches that might be employed to gather data on the effectiveness of each option.

Table 1. Potential applications for acoustic monitoring of Countryside Stewardship Options

Code	Option Name	Examples of potential acoustic monitoring approaches
AB1	Nectar flower mix	Pollinating species, e.g. bees, can be detected using acoustic monitoring. The detection radius is small, and species can not often be distinguished, but acoustic activity levels can be discerned and compared between sampling locations (Galen et al. 2019). Acoustic activity (number of buzzes) is highly correlated with visual estimates of bumble bee density, and predicted seed set of pollinated plants - allowing estimation of pollination services (Miller-Struttmann et al. 2017).
AB4	Skylark plots	A range of studies have shown that skylark song behaviour can be recorded easily using acoustic methods (Eldridge et al. 2018; Linossier et al. 2013; Szymański et al. 2017), and that vocal activity rates in birds can be related to the number of individuals present Pérez-Granados, Bota, Giralt, Barrero, Gómez-Catasús, Rosa, et al. (2019).
BE3	Management of hedgerows	Bat and insect activity along hedgerows is affected by their management. Froidevaux et al. (2019) found that hedgerow management as prescribed by targeted AESs had a positive effect. Bat species richness significantly increased with time since last trimming, and hence hedgerow height, with particular benefits for rare horseshoe bats. Another study, by Lacoeuilhe et al. (2016), also showed that acoustic methods

		could indicate the importance of hedgerow quality for the ecology of bat and bush cricket communities.
LH1	Management of lowland heathland	Abrahams (2020) has shown the benefits of acoustic monitoring for assessing the distribution and populations of breeding birds on lowland heathland, and Docker, Lowe, and Abrahams (2020) and Raymond et al. (2020) have shown that individual nightjar males can be recognised from their songs. Fischer et al. (1997) investigated the grasshopper populations of grass heath areas, identifying them to species by their song types and assessing habitat condition in relation to eutrophication effects.
OT2	Organic land management - unimproved permanent grassland	Dodgin (2018) employed acoustic indices to study grassland carrion beetle food webs and to capture the phenology of a grassland soundscape following a prescribed burn. Shamon et al. (2021) studied grassland birds, and found that the Bioacoustic Index aligned with known relationships between grassland birds and spatial covariates.
WD2	Woodland improvement	The effects of woodland management on resident fauna and the consuequent soundscape have been demonstrated with the use of acoustic indices by Depraetere et al. (2012), Tucker et al. (2014) and Turner, Fischer, and Tzanopoulos (2018). Others studies by Eldridge et al. (2018), Fuentes-Montemayor et al. (2013), Lintott et al. (2014),have shown that acoustic methods can be also used at the species-level for recording birds and bats in woods within agricultural landscapes.
WT3	Management of ditches of high enviromental value	van der Lee et al. (2020) used acoustic indices to assess drainage ditches impacted to varying degrees by agricultural activities and wastewater discharges. They showed that the recorded acoustic patterns were primarily associated with the fluctuation in dissolved oxygen saturation, while specific frequency bands could be related to the sound-producing invertebrate community.
WT6	Management of reedbed	Acoustic monitoring has been used for a number of studies of reedbed birds, including bittern and water rails, both in the breeding season and during winter (e.g. Bardeli et al. (2010);

Stiffler, Anderson, and Katzner (2018)). These have shown the clear benefits of acoustic methods in detection these cryptic species in this difficult to survey habitat.

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