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Realising the potential for acoustic monitoring to address environmental policy needs

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Summary

Monitoring biodiversity is key to understanding what is changing and why. Recent developments in acoustic monitoring approaches have seen cheaper hardware, more advanced analytical tools, and moves towards standardisation of methods. However, the potential for acoustic monitoring to address key needs of policymakers has not yet been realised.

We discuss key policy needs that are driving the requirements for information on biodiversity. This includes the need for species and habitat information as well as the desire for information on ecosystem ‘health’, ecosystem services and function, impacts of interventions, and how to better engage people with nature.

As acoustic monitoring methods develop, they could help address many of these policy needs. We highlight those methods with the greatest potential to meet these needs, including low-cost sensors, cross-taxa recording, acoustic signals of function, soundscape analysis, artificial intelligence (AI) classification and citizen science.

By supporting solutions-focussed research into acoustic monitoring, driven by policy needs, we can have the greatest benefit to policymakers, conservation practitioners and researchers, enabling better monitoring and protection of the environment. Foundational challenges that must be addressed include the development of standards, building open datasets, and linking acoustic signals to ecosystem function. These challenges are interdisciplinary and require strategic funding to bring together researchers from multiple domains to develop solutions.

Contents

1 Introduction

1.1 The next step in bioacoustic monitoring research should be policy-led

In this period of rapid global biodiversity change, monitoring is key to assess ecological status (Dirzo *et al.* 2014), identify the drivers of change (Proença *et al.* 2017; Vihervaara *et al.* 2017), and evaluate the impact of interventions. Biodiversity monitoring has undergone substantial developments in the 21st century due to technological advances and increased public participation. One of the methods that has particularly advanced over recent years is acoustic monitoring. As discussed in recent reviews (e.g. Berger-Tal *et al.* 2018; Sugai *et al.* 2019; Gibb *et al.* 2019; Mcloughlin *et al.* 2019), it has benefited from developments such as cheaper hardware, improved sound analysis methods, and standardised recording protocols. Acoustic monitoring has tended to be used for academic research, or for applied monitoring of specific animal taxa, particularly bats and cetaceans (Gibb *et al.* 2019). Increasingly though, a wider range of acoustic monitoring approaches are being used in different scientific, practical and cultural contexts. Here we propose that there is great potential to combine these opportunities with the needs of policymakers in order to make the next step, from proof of concept and research development to real-world applications that address environmental challenges.

To explore the key policy drivers, the potential acoustic solutions, and the underpinning activities needed to support research into the future, we convened a workshop in the winter of 2019. Attendees included policymakers, hardware experts, artificial intelligence (AI) experts, naturalists, academics and charity organisations. Participants brainstormed each of these three topics and prioritised the outcomes. This report covers the priorities identified at this workshop.

1.2 What are the policy drivers and how can acoustic monitoring better serve policy needs?

Environmental policy needs are driven by regulation, targets, and goals. These require information on the state of the natural environment (species or ecosystems) and its change, to promote the protection and restoration of nature and, through this, to enhance societal benefits through ecosystem services. Policy needs have traditionally focused on species and habitat monitoring, particularly due to the legislative requirements of reporting against priorities and targets under national or international legislation, such as the Convention on Biological Diversity (e.g. the Aichi targets up to 2020 (SCBD 2010)), or instruments for agriculture, biodiversity and water in the European Union (Geijzendorffer *et al.* 2016).

Achieving policy outcomes requires action through evidence-based management. This implementation can be considered through the 'DPSIR' framework which describes five categories of policy needs: information on <u>d</u>rivers and <u>p</u>ressures of environmental change, the <u>s</u>tate of the environment, the <u>i</u>mpacts on people and the environment, and societal <u>r</u>esponse (European Commission 1999). Management interventions can be developed to affect environmental change, but their effectiveness needs to be properly evaluated. This is particularly challenging for major investments in widespread interventions, such as agri-environmental schemes, where evaluation requires high quality, real-time, consistent data across a range of taxa (Robinson *et al.* 2018).

Increasingly there is a policy requirement for moving away from a small set of indicator taxa, to consider more holistic measures of biodiversity and the environment, or important ecosystem functions and services (Defra 2018; SCBD 2010). Providing this breadth of biodiversity monitoring is challenging due to the limited availability of taxonomic expertise and the costs involved in contracting staff or supporting volunteers (Robinson *et al.* 2018).

Another important component of environmental policy is the engagement of people. The provision of environmental monitoring through the engagement of volunteers in 'citizen and community science' can provide benefits in cost-efficiency (Gardiner *et al.* 2012), well-being (Jones *et al.* 2013) and empowerment of local stakeholders (Bonney *et al.* 2016). It also supports efforts to 'mainstream biodiversity', a goal of the Convention on Biological Diversity (Convention on Biological Diversity, Decision COP XIII/3). Mainstreaming biodiversity includes conservation and sustainability in every stage of policy and highlights the contribution of biodiversity to socioeconomic development and human well-being.

Acoustic monitoring can help meet existing and future needs for monitoring data, providing larger data volumes, covering wider spatial and temporal scales, and allowing integration of data collection between taxa, or alongside environmental covariates (Gibb *et al.* 2019; Sugai *et al.* 2019). It can also potentially be cheaper and more accurate than many existing monitoring techniques, whilst being complementary to current methods. Acoustic monitoring currently meets a number of policy needs through individual species-level information, but there are many opportunities to use acoustic monitoring to assess progress towards a wider range of policy targets at regional, national and global levels (Figure 1). We discuss below a number of actions needed to realise this potential.

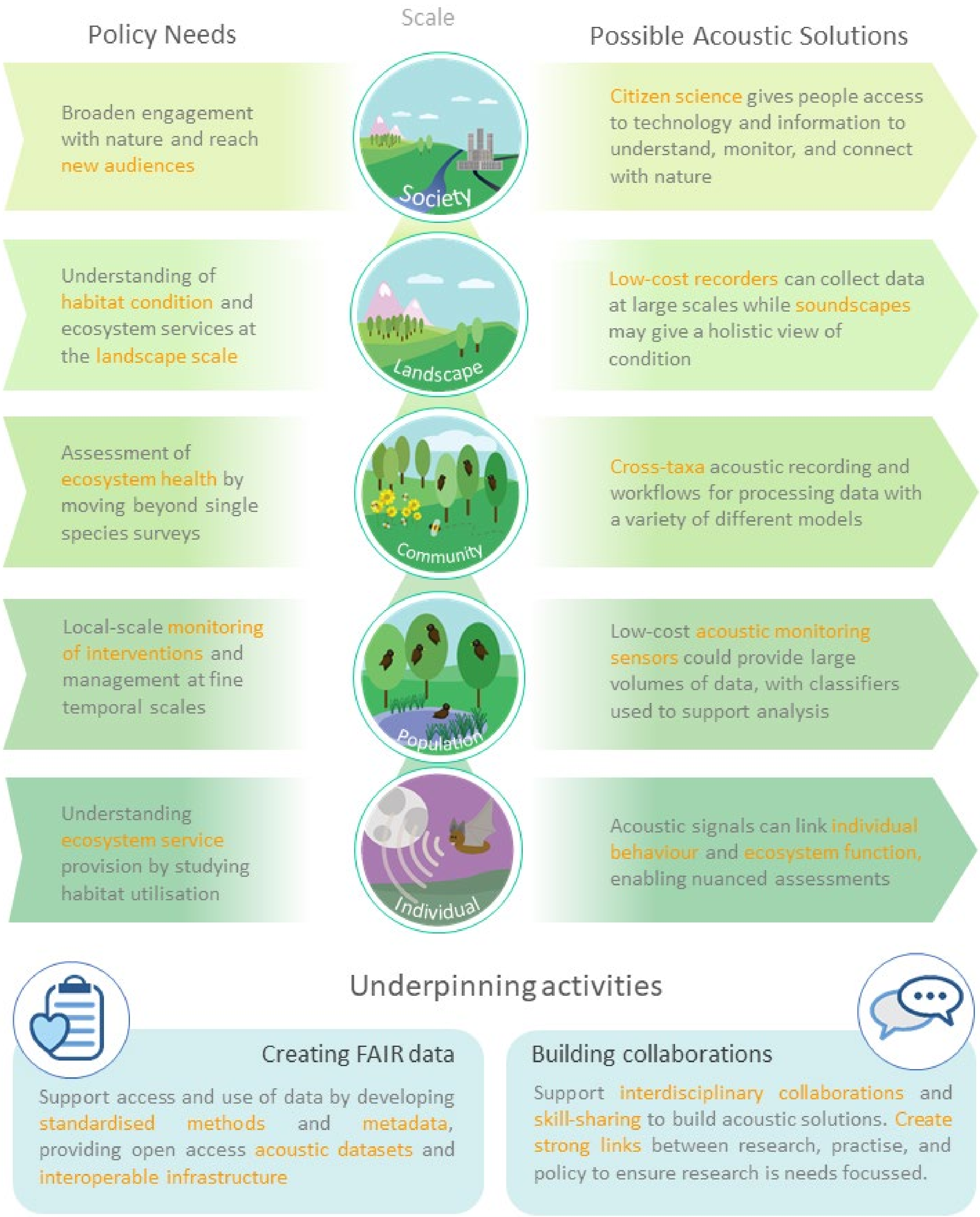

Figure 1: Acoustic monitoring offers possible solutions for existing policy needs. These methods can provide data at a range of scales, depending on the scale of the need. To realise these potential acoustic solutions, we need to undertake underpinning activities to support the creation of Findable, Accessible, Interoperable and Reusable (FAIR) data and collaborations.

2 Acoustic solutions for policy needs

2.1 Providing better assessment of ecosystem health by moving beyond single species surveys, and assessing environmental stressors

Acoustic surveys to date have typically focussed on specific taxa, for example birds or bats. However, for policy makers there is often a desire to quantify ecosystem-service provision (e.g. pollination), habitat condition, or the health of the environment. These require a multi-taxa approach towards monitoring, for example, sounds produced by Orthoptera and small mammals are commonly recorded as 'by-catch' during bat surveys, sometimes far outnumbering the recordings of bats (Middleton 2020). This 'by-catch' is typically noticed and ignored, with some exceptions (Penone *et al.* 2013; Jeliazkova *et al.* 2016; Newson *et al.* 2017). By recording across a broad frequency range, there is the potential to mine recordings for multiple species groups, improving the extent or quality of data (Blumstein *et al.* 2011). However, the best survey and sampling design for one species group may not be the same as for another. This motivates the use of methods for more holistic soundscape analysis (e.g. acoustic indices).

Acoustic indices are methods for summarising the biological sound recorded in acoustic data, alongside anthropogenic and environmental sound (Sueur *et al.* 2014). They are typically easier to implement than species-specific methods (Doohan *et al.* 2019), and in situations where biodiversity or ecosystem health are under investigation, acoustic indices can produce numerical metrics for evaluation. However, acoustic indices can also integrate non-biotic sounds, such as those produced by human activity and rainfall, and so do not always relate directly to ecological parameters (Fairbrass *et al.* 2017). They should therefore be used with caution and may not be appropriate for application in acoustically complex and/or highly disturbed environments. Conversely, non-biotic sounds may provide new insights that add to acoustic indices, such as indices of anthropogenic pressures including illegal hunting and harvesting (Astaras *et al.* 2017; Deichmann *et al.* 2017; Fairbrass *et al.* 2019; Hill *et al.* 2019; Sethi *et al.* 2020b). To realise their potential for addressing policy needs, further empirical testing and development is required. This work should define the metric of policy interest, unpicking terms such as biodiversity and ecosystem health, to understand where, and at what scale, it is appropriate to apply acoustic indices to inform decision-making.

2.2 Permitting continuous, objective, cost-efficient site-based monitoring

Data at fine spatial and high temporal resolutions are needed for planning and assessing conservation action at local scales, while data across large areas and time periods are key to understanding macroecological processes. A common constraint on the spatial and temporal coverage of biodiversity monitoring is the availability of skilled surveyors (Martin *et al.* 2012). Lack of adequate spatial coverage limits our ability to compare across regions or habitat types, while limited sampling across time reduces the power and resolution of estimates of temporal change – a key issue for understanding the threats facing biodiversity (Proença *et al.* 2017). Acoustic monitoring has the potential to overcome these problems, as passive sound recorders can be installed in places that are difficult or dangerous to visit and can be deployed for long periods (Sethi *et al.* 2018), including through periods that are difficult to cover by conventional means, for example at night (Abrahams 2019; Zwart *et al.* 2014). In this way acoustic monitoring compliments other technologies that provide continuous data, such as camera traps (Høye *et al.* 2021; Kays *et al.* 2020).

Long-term continuous deployment may be especially useful for the detection of rare events such as dispersal. Shifts in dispersal dates have been linked to climate change (Furnas *et al.* 2018), and so could track the impacts of past and future policy. Acoustics might also be used to monitor new arrivals, such as invasive alien species, should they be identifiable acoustically. This would help to meet government policy to manage and prevent invasive alien species (The Invasive Alien Species (Enforcement and Permitting) Order 2019). Recording at a high temporal resolution also avoids issues of variability at fine temporal scales. In a recent study comparing manual bat transects undertaken six times through the summer, and continuous recording from an automated sensor at the same location, we found that manual surveys could significantly underestimate abundance and richness when visits coincided with low activity nights. This is even the case when selecting nights for favourable conditions, an issue overcome by using a sensor recording every night (August, Pers. Comm.). In this way continuous monitoring can provide more accurate estimates of bat and bird diversity and abundance, important for planning and conservation policy.

To realise this potential for site-based monitoring we need to continue to improve hardware and develop deployment strategies that allow for large networks of sensors to be placed in the field (e.g. Australian Acoustic Observatory: Roe *et al.* 2021), or for individual contributions of acoustic recordings to a central repository (e.g. Xeno-Canto.org: Vellinga *et al.* 2015). Citizen science may offer a mechanism to realise this need for increased coverage and is worthy of further exploration.

2.3 Providing opportunities to broaden engagement with nature and reach new audiences using citizen science

Many governments have introduced policies that encourage the public to engage with nature, in recognition of the benefits to health and well-being, and as guided by the principle of ‘mainstreaming biodiversity’ in the Aichi targets (Defra 2018; Bonney *et al.* 2009; Miller-Rushing *et al.* 2012; World Health Organisation Regional Office for Europe 2013).

Citizen science approaches are an effective way of engaging the public with research and nature, while generating data at policy-relevant scales (Theobald *et al.* 2015; Hayhow *et al.* 2019). Acoustic monitoring is a natural choice for citizen science as, unlike more traditional survey methods, it requires little time investment, experience, or identification skills – if automated analyses are used (Newson *et al.* 2015). Furthermore, it does not require the capture or collection of specimens. Access to sensors is a barrier that can be addressed by making use of mobile-phone technology (August *et al.* 2015) or by developing schemes where sensors are shared (Newson *et al.* 2015), while automated identification helps to lower the identification skills required to participate (McClure *et al.* 2020).

A citizen science approach brings challenges too. While there is great variability in the design of citizen science projects, a typical project would give participants the flexibility to record where and when they choose, and would not seek to control or document, survey effort (Isaac *et al.* 2015). These properties of citizen science surveys require that consideration is given to the ability of data created to be able to address each policy question, and that appropriate methods are used when drawing inference from these data (Isaac *et al.* 2015; Isaac *et al.* 2014).

Volunteers' motivation must be considered in the design of any survey in order to give the best chance of good quality data, high uptake and long-term engagement (Nov *et al.* 2014). Given the often passive nature of acoustic monitoring, efforts must be made to understand the motivation for long-term engagement. Examples of successful citizen engagement in long-term passive monitoring includes the amateur weather station network used by the Met Office to support short-term forecasting. The ‘Weather Observations Website’ is testament to the appetite for this type of citizen science, and its potential utility (Kirk *et al.* 2021). Forms of engagement to consider include opportunities to interact with other participants, helping them to develop skills through simple to more complex survey activities, and gaining new insight from the data collected. The results of acoustic recording can reveal ‘hidden’ biodiversity, such as bats or freshwater fauna that may be new to many (Greenhalgh *et al.* 2020). Furthermore, this could support greater engagement with people's immediate neighbourhood, empowering them with knowledge to play a greater role in the management of their area.

New volunteer audiences should also be considered. For example, the requirement for better hardware technology could engage active ‘maker’ communities (Hill *et al.* 2019), and the need for large training datasets for AI could engage volunteers in tagging audio data online (Cartwright *et al.* 2019).

2.4 Providing nuanced biodiversity assessments by linking behaviour and ecosystem function

Assessing habitat quality and ecosystem services requires data that goes beyond the presence or absence of a species. The behaviour of a species (e.g. feeding or commuting) is important for understanding the utility of the landscape to the individual, as well as the service provision of the individual, through its behaviour (e.g. pest control).

Acoustic signals can provide information on the abundance of a given species, its behaviour (Teixeira *et al.* 2019), the quality of a given habitat (Elise *et al.* 2019; Goretskaia *et al.* 2017), and service provision, all of which support key policy needs. Examples of acoustic behavioural measurements principally come from bird (Keen *et al.* 2020), bat (Greif *et al.* 2019), and marine mammal research (Rojano-Doñate *et al.* 2018), where species-specific signals are often used to infer physiological or life-history processes, such as reproductive success (e.g. Keen *et al.* 2020). Passively generated sounds, such as insects' wingbeats, can also be used to measure individual behaviour; providing a non-invasive route to monitoring ecological function and ecosystem service provision (Miller-Struttmann *et al.* 2017).

Establishing the link between individual behaviour of animals, measures of these behaviours, and ecological function is a key challenge. Function is often inferred through the presence of functionally important taxa, however abundance is important where functional capacity is the aggregate effect of a group of individuals (Kleijn *et al.* 2015). We must work to better establish the links between acoustic signals of individual behaviour, measures of abundance, and the provision of ecosystem services, in order to allow accurate assessment of habitat quality. For example, bumblebees’ buzz pollination (sonication) can be directly linked to pollination service provision (De Luca *et al.* 2013; Gradisek *et al.* 2017), but using flight sounds of insects to estimate the same function is more challenging (Miller-Struttmann *et al.* 2017).

Policies that drive the creation or management of habitats to support ecosystem services and biodiversity could benefit from advances made to monitor animal behaviour through acoustic signals. For example, recording buzz pollination in wildflower field margins planted to support pollinators, bats commuting along hedgerows planted to support connectivity, or breeding birds in agricultural land.

It is necessary to cross-validate proposed acoustic measures of function with measures gained through conventional survey techniques, noting that these may have their own biases (O’Connor *et al.* 2019). For example, video recordings could be made alongside acoustic surveys to ground-truth measures of activity or behaviour (Buxton *et al.* 2018; Steen 2017).

3 Underpinning activities to support acoustic solutions

3.1 Creating interoperable data by developing standardised methods and metadata

At present, with few exceptions, there is a lack of consistency and comparability in approaches to acoustic monitoring, including survey and metadata standards. Standards for data collection and analysis are needed to allow datasets to be combined to address macro-scale questions, and to expand research and practical applications (Darras *et al.* 2018; Sugai *et al.* 2019). We are missing evidence-based good practice guidelines, synthesising the crucial aspects of survey design and analysis workflows for most taxa (Browning *et al.* 2017). Even for birds, the taxon with the most research effort, only a few methods have been produced, covering different biomes (e.g. Abrahams 2018). Sugai *et al* (2019) give an excellent overview of the key parameters to consider when designing an acoustic survey, with reference to previous field-studies and the pros and cons of each approach. This is a good starting point from which to build good practice guides and standards. Performance standards for recording hardware are also required; there is a diversity of devices, some commercial, some open hardware (e.g. Hill *et al.* 2019; Sethi *et al.* 2018; Sugai *et al.* 2019). This requires transparent reporting of hardware performance and sensitivity characteristics for data from different devices to be compared, including to – as yet unknown – future recording devices. With machine learning methods increasingly being used for species identification, biological recording standards should be updated to ensure appropriate metadata are collected regarding the method of identification, such as a unique identifier of the machine learning model used for the classification.

While standardised methods for recording and sharing acoustic metadata are not yet mature, there is work underway to develop good practice (e.g. GUANO standard; Roch *et al.* 2016) and to adapt existing standards, such as AudubonCore (Morris *et al.* 2013), to meet the needs of audio recordings. Working together, as members of the acoustic monitoring community, to adopt these standards will improve the outcomes from research and allow cross-scale and comparative investigations for better understanding biodiversity trends.

3.2 Supporting the development of automated audio analysis by providing open access to training data

Progress in the related domain of visual classification has been driven by large and taxonomically diverse datasets of images (e.g. Van Horn *et al.* 2018). These datasets are important for training and evaluating machine learning models. In contrast, current audio datasets are either limited to one taxonomic group (e.g. birds (Vellinga *et al.* 2015; Stowell *et al.* 2019)), or do not contain species-level annotations (Gemmeke *et al.* 2017). We need training and evaluation datasets that cover a broad range of species, behaviours, geographic locations, weather conditions, background noises, and recording equipment (Gibb *et al.* 2019; Mcloughlin *et al.* 2019). Where possible, this should use a unified taxonomy with standardised metadata. Creating these datasets will require collaborations, across individuals and institutions, to collect and annotate the data. Permissive open-source licensing should be adopted where possible to ensure the audio data can be used for research. We should also consider creating ‘hidden’ evaluation datasets that can be used to benchmark models, allowing for objective comparisons to be made. This is particularly important if the results of machine-learning analyses are to be trusted, and so that confidence in automated species identifications on biological recording platforms is not eroded. Finally, building these datasets with FAIR data principles at their heart will ensure the greatest return on investment for academia, conservation, and policymakers (Wilkinson *et al.* 2016).

3.3 Scaling up acoustic monitoring by building an interoperable infrastructure

A digital infrastructure, whose components are interoperable, is fundamental to the widespread adoption and success of acoustic monitoring. This infrastructure must support workflows ranging from data collection, data storage, analysis, through to interpretation (Browning *et al.* 2017). While we do not suggest this infrastructure is 'owned' or built by a single organisation, it is key that data should be able to flow easily from one component to another. This infrastructure should include:

1) a distributed network of acoustic sensors;

2) cloud-based storage for hosting datasets and data collected and generated by the acoustic sensors;

3) cloud-based computational resources for running machine learning models, as well as software tools, to enable efficient data annotation and training of the machine learning models; and

4) data access and governance controls to address privacy and security concerns such as people speaking in proximity to the audio sensors.

Additionally, it would be beneficial if the infrastructure had:

5) acoustic sensors that are connected to the internet;

6) effective audio analysis protocols, such as machine learning classification models, embedded on audio sensors;

7) complementary sensors, such as weather sensors, to record auxiliary data which will aid in the analysis of audio.

Efforts to build and connect this digital infrastructure for acoustic monitoring are underway. Examples include urban sensor networks for bats with edge computing (Mac Aodha 2018), cloud pipelines for cross-taxa machine learning classification (bto.org/our-science/projects/bto-acoustic-pipeline, see Box 1), and acoustic sensor networks that transmit data to a central data store for real-time display online (Sethi 2020a).

Coherent practice amongst these and future developments could be ensured through incentives provided by funders, and closer liaison between scientists, technologists and data specialists. Significant funding will be required to create and maintain sensor networks, host vast datasets generated, and to develop and host classification models. A resilient acoustic monitoring system is likely to rely on multiple funding sources, including income from commercial use. A scoping exercise is needed to identify the potential funding models for the elements of a sustainable acoustic monitoring infrastructure.

Box 1 – BTO Acoustic pipeline

The British Trust of Ornithology (BTO) Acoustic Pipeline (http://bto.org/pipeline) is a workflow for analysing acoustic data using artificial intelligence (AI) classifiers. The workflow consists of a desktop application for managing the upload of audio files and a cloud platform for analysis of the recordings using AI. Results of the analyses are made available through a web-platform and can be downloaded as .csv files.

This workflow successfully meets a number of the challenges we have identified. The taxonomic and geographic scope of the Pipeline is continually updated, currently the the Pipeline classifies bats, bush-crickets and small mammals. Additionally, the Pipeline will classify two species of moth that produce ultrasound, and a single class that captures birds, and another for frogs. This cross-taxa processing allows for a more holistic assessment of biodiversity as outlined in section 2.1.

The BTO Pipeline operates a freemium pay model at the time of writing, where access and use is free below 100 GB of data per year (equivalent to approximately 50 nights of triggered bat recording), after which charges apply. The Pipeline enables users to manage and share their recordings and provides functionality for project management, for example enabling multiple volunteers to submit recordings that will come together for a particular project. The Pipeline encourages users to share their data so that it can be used to improve the Pipeline and verified data can be shared with third parties; it does this through a discounted payment structure. Where data cannot be shared for commercial reasons, users can opt for confidential processing and storage at a higher cost. By using a freemium pay model, the Pipeline is able to cover its costs in cloud processing and storage, provide staff time to support users, and allow ongoing development. The revenue ensures the long-term viability of the Pipeline. Since the Pipeline was launched in March 2021, 810 users have uploaded over 30.2 million recordings, resulting in 19.3 million species identifications.

Through the creation of the Acoustic Pipeline the BTO have put in place some of the underpinning infrastructure highlighted in section 3.3. This includes cloud data storage and processing using AI. Metadata including the model used and its version are also shared with the results. However, acknowledging that the Pipeline is under continued development, some challenges remain. Data are exported in a custom format rather than using an established standard such as Darwin Core reducing its interoperability. Neither model nor training data are shared making it difficult to assess the accuracy of the model without access to a reference library of audio files to test the Pipeline. A peer-reviewed publication is available for the bush-cricket classifier (Newson, 2017) and will shortly be available for bats (Border, 2022 - in press), and supplementary data on model performance is available on the BTO website.

Regardless of the challenges that remain, the BTO Acoustic pipeline represents a realisation of the potential for AI classifiers to be made widely accessible to undertake cross-taxa recording. This has a positive impact on the scale of analyses possible and the questions we are now able to address.

3.4 Sharing knowledge between researchers and across domains by building a community of practice

Outlining these underlying activities, a common theme of multi-disciplinary working emerges. Multi-disciplinarity should be supported by continuing to build skill-sharing and sustainable models of collaboration into our standard practice.

It is equally important to build strong links between academics, practitioners, and policy makers. This will focus research efforts on important knowledge gaps, facilitate the collection of data where deficiencies are identified, and ensure the rapid transition of existing knowledge and new innovations into standard practice.

4 Conclusions

Acoustic monitoring methods show considerable promise and are well placed, alongside existing monitoring methods, to address a number of knowledge and data gaps that are currently limiting our ability to monitor the environment, evaluate interventions, positively impact nature, and assess ecosystem services. From monitoring ecosystem health and function, to the engagement of the public in data collection, acoustic monitoring offers a range of possible solutions for policy makers. We are on the verge of realising this potential.

To make the final step to realising this potential, a few key research questions remain:

- What metrics from acoustic sampling best measure ecosystem health and ecosystem function? This in turn requires clear definitions of these terms and the underlying policy interest.

- How can citizen scientists be engaged long-term in passive acoustic monitoring? This is not yet well understood, however, lessons could be learnt from the weather watching community.

- How do we design cross-taxa surveys? Passive surveys that aim to record across taxa must make a compromise between the optimal designs for each taxonomic group.

- How can acoustic measures be linked to more traditional measures of abundance and activity?

To fully operationalise the potential of acoustic monitoring to address environmental policy needs and to address these outstanding research gaps, it will require the acoustic monitoring community to work together, across roles and multiple disciplines. Developing standards and building open datasets and linking acoustic signals to ecosystem function can only be achieved by open collaboration at both the national and international scale. In turn, funding will need to be found, and targeted strategically at these foundational challenges, enabling the community to solve these problems together. This could be addressed partly through field-based, enhanced pilot studies for adaptively addressing the knowledge gaps and implementation challenges simultaneously while beginning to operationalise acoustic monitoring schemes. We believe that moving forward in this way will bring the greatest benefit to policymakers, conservation practitioners and researchers, enabling better monitoring and protection of the environment.

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