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Review

The sound of management: Acoustic monitoring for agricultural industries

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ABSTRACT

Global biodiversity is declining rapidly while the human population grows exponentially. This creates pressure for agricultural industries to improve productivity, but also demonstrate that on-farm management actions are minimising impacts on biodiversity. However, the costs and logistical considerations of traditional biodiversity assessment methods are beyond the scope of many agricultural industries and landholders. Our goal was to evaluate the potential for acoustic biodiversity monitoring in agricultural systems. We assessed a range of species-specific and more general acoustic indices using five key criteria (i.e. relevance to industry, diagnostic capability, spatio-temporal scale, logistical feasibility, and utility as a biodiversity surrogate) to determine whether they were suitable for assessing biodiversity outcomes for agricultural industries and individual farmers. Based on these assessment criteria, species-specific or guild-specific acoustic bioindicators that are processed using automatic recognisers are more appropriate for biodiversity monitoring when the goal is to assess industry- or farm-specific impacts on biodiversity. If there is no need to establish a diagnostic link between on-farm management practices and biodiversity, then acoustic indices are more logistically feasible to use and may more accurately reflect overall biodiversity. We also recommend using birds and bats for acoustic monitoring in agricultural systems because they are relatively easy to monitor, exhibit peaks in activity around dusk or dawn, and are not necessarily water dependent. We believe that acoustic monitoring has the potential to deliver consistent, repeatable results at a relatively low cost compared to traditional biodiversity monitoring, which will allow individual farmers and agricultural industries to more easily track their sustainability performance. This becomes even more critical as we consider the increasing role that agricultural regions will have in sustaining the world's rapidly declining biodiversity.

1. Introduction

Over the last 100 years industrialised farming has become widespread, increasing the yield from croplands across the globe (Donald et al., 2001). This increase in production is in response to a rapid increase in global population, which is likely to reach 8.9 billion people by the year 2050 (Cohen, 2003). The intensification of land use has come at a cost, manifested particularly in a decline in biodiversity (Scherr and McNeely, 2008). However, there is mounting evidence that when sustainable land-use practices are used, these two benefits are not mutually exclusive (Graibaldi et al., 2017; Tscharntke et al., 2005) and that on-farm biodiversity can be improved without limiting agricultural production (Perfecto and Vandermeer, 2010; Clough et al., 2011).

On-farm biodiversity has been linked to increased yields and so there is a clear economic benefit to retaining and enhancing biodiversity in many cases (Balvanera et al., 2013). For example, riparian corridors act as reserves for beneficial insects and the animals that feed on them, while insectivores such as bats and birds provide additional benefits such as pest insect suppression (Maas et al., 2013; Tscharntke et al., 2007). The financial benefits of insectivores in North American croplands has been estimated at between US$4.5 to $5.5 billion through reduced pesticide use and crop damages (Losey and Vaughan, 2006; Naranjo et al., 2015). In another case, Mexican free tailed bats (*Tadarida brasiliensis*) in south-central Texas were estimated to save landholders US $741,000 per year, over 10,000 acres of cotton, through the suppression and reduction of cotton crop pests such as the cotton boll worm (*Helicoverpa zea;* Cleveland et al., 2006).

Societal pressure to source products from agricultural industries that undertake sustainable practices is increasing (Gomiero et al., 2011). International non-governmental organisations (NGOs) such as the World Wildlife Fund for Nature (WWF) often lead sustainability initiatives (e.g. the Roundtable on Sustainable Palm Oil), and companies that receive approval may have a marketing advantage over non-compliant alternatives (Laurance et al., 2010; Teegen et al., 2004). This

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puts pressure on agricultural industries to demonstrate that best management practices are resulting in positive biodiversity outcomes aligned with the goals and vision statements found in sustainability initiatives (Roth, 2010). However, biodiversity must be monitored to present evidence of sustainability, and this process can be costly and difficult to undertake. Gardner et al. (2008) predicted the cost of undertaking a comprehensive biodiversity assessment in the Brazilian Amazon to be over US$140,000, even when focusing on a single taxonomic group. Thus, extensive on-ground biodiversity surveys based on traditional monitoring techniques are unlikely to be feasible for many agricultural industries. Instead, a more cost-effective approach is required.

Acoustic monitoring of animals that vocalise (i.e. soniferous animals) is a relatively new method of biological monitoring, which potentially overcomes some of the limitations of traditional biodiversity monitoring. It can be used to estimate the number of species present without requiring the observer to physically see them, creating a catalogue without extensive time in the field (Jones et al., 2012; Wimmer et al., 2013). Acoustic sensors can also be deployed for long periods of time and so this approach is often viewed as a less invasive alternative to *in-situ* field observations, which have the potential to disturb the animals being monitored (Blumstein et al., 2011; Depraetere et al., 2012; Sueur and Farina, 2015). Digital sound recordings are easily stored, making them ideal for long-term monitoring and allows files to be reanalysed in the future as new analytical approaches are developed. While acoustic monitoring has been used to study biodiversity in a wide variety of habitats (Sueur et al., 2008; Villanueva-Rivera et al., 2011), few experimental studies have examined the effectiveness of acoustic monitoring in agricultural industries (but see Villanueva-Rivera et al., 2011), where it is important to capture the causal relationship between land-management practices and biodiversity (Peterson et al., 2017).

Our goal is to evaluate the potential of acoustic monitoring as a cost-effective approach for biodiversity assessment in agricultural systems. We briefly review the role of acoustics in biodiversity monitoring, assess the potential benefits and challenges associated with using acoustics in agricultural settings, and synthesize this information to provide practical recommendations about the most appropriate acoustic metrics for biodiversity monitoring undertaken by agricultural industries.

2. Methods

An online database (Google) was searched for key terms “agriculture”, “biodiversity”, “indicators”, “acoustics” and “ecoacoustics”. A “snowball sampling” technique was then used to broaden the search, with relevant citations taken from initial references, and included in the body of literature reviewed. We continued this process until all of the potential arguments were justified or refuted, or if citations were no longer deemed up-to-date (i.e. approximately 10 years before the review process). References outside of these limits were only included if they were seminal papers, applied to agricultural cropping systems, or presented novel information.

3. Acoustic monitoring for biodiversity assessment

The soundscape of an environment is composed of animal sounds (i.e. biophony), ambient background sounds such as those produced by wind and rain (i.e. geophony) and human-created sound (i.e. technophony) (Mullet et al., 2016; Pijanowski et al., 2011). The soundscape is monitored using microphone-based systems that can be programmed to record continuously or at scheduled time intervals (Brandes, 2008; Gasc et al., 2016). Changes in frequency (i.e. pitch), amplitude (i.e. intensity) and duration of recorded sounds can be analysed to identify particular species and sound sources (Parsons and Szewczak, 2009) and visualised using spectrograms (Fig. 1A; Towsey et al., 2014b). This survey method focuses on vocalisations, which are an integral part of animal orientation and communication with conspecifics (Laiolo, 2010). The number of species present is catalogued by examining species-specific calls (hereafter signals) and because communication vocalisations are often a method to display an individual’s (generally male) reproductive fitness, it is sometimes possible to determine abundance and density of populations (O’Donnell et al., 2013). Thus, these audio recordings can be used to monitor single- or multi-species dynamics, such as changes in abundance and distribution, in addition to biodiversity assessment (Blumstein et al., 2011; Sueur et al., 2008).

Acoustic monitoring in agricultural environments is not a new concept, but few studies have specifically focussed on biodiversity assessment or the use of acoustic bioindicators. Instead, most previous studies have examined pest densities in stored goods (Neethirajan et al., 2007), or in standing crops and trees (Pinhas et al., 2008). Furthermore, studies that do monitor soniferous animals have primarily focussed on their role in providing ecosystems services, such as pest suppression (McCracken et al., 2008) or their response to habitat fragmentation (Frey-Ehrenbold et al., 2013). In the next section, we review and critically assess acoustic bioindicators and their suitability for use in agricultural industries.

3.1. Key characteristics of acoustic bioindicators

Five key characteristics must be considered when selecting an acoustic bioindicator for the agricultural industries (Peterson et al., 2017). First, 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). Second, a diagnostic link between on-farm management practices and the proposed bioindicator must exist, and the relationship between these two must be validated. Third, novel bioindicators need to be appropriate for the scale of biodiversity assessment being undertaken. This is critical in industries such as cotton where land use practices vary across spatial (i.e. on-farm, regional, national) and temporal (i.e. crop cycle, seasonal, annual) scales. The fourth criterion is that the bioindicator must be logistically feasible to use in terms of cost, technical expertise, and time required to generate and implement it. Finally, 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.

4. An assessment of bioacoustic indicators

Acoustic techniques to monitor bioindicators can generally be categorised into two groups: species recognition and acoustic indices. Next we evaluate different bioindicators within these categories based on the five criteria outlined above (Table 1), drawing on the results of studies in both natural and agricultural systems to help identify which have the most potential for use in agricultural systems.

4.1. Species recognition

Species-specific bioindicators are an intuitive way to link increased biodiversity with land management practices. Species presence/absence and abundance can be measured over space and time, and can be linked to resource availability and the quality of the surrounding environment (Wiegand et al., 2005), such as nesting sites for birds (Fischer et al., 2010). Species-specific bioindicators can also be used to infer the behaviour (e.g. feeding by bats) and activity of some animal groups (Frey-Ehrenbold et al., 2013), which may provide on-farm benefits such as pest control (Jones et al., 2009).

4.1.1. Identification

Recordings can either be manually or automatically processed using species recognisers (Table 1; Brandes, 2008). Manual processing requires extensive expertise and time to filter through each file, which is not ideal for widespread implementation in agricultural systems

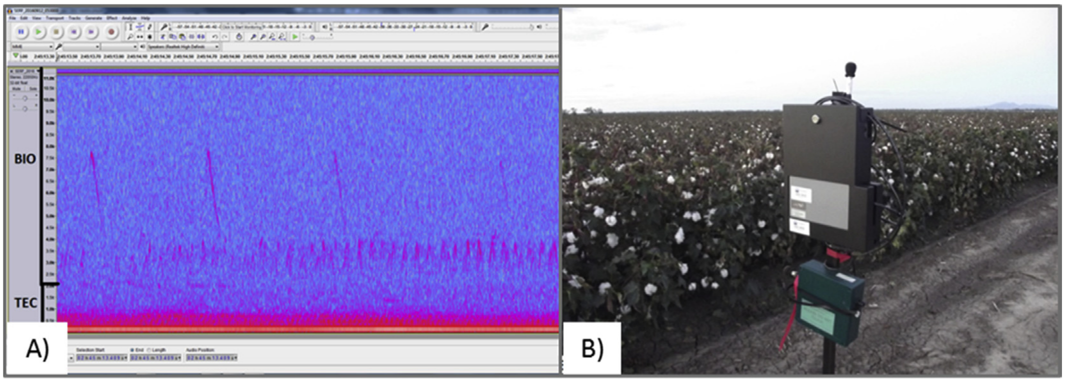

Fig. 1. A) An example of a 1 min spectrogram. The warmer colours represent higher amplitudes. Technophony (TEC) – in this case a car engine – mostly occurs in the lower frequencies (< 2 khz) while Biophony (BIO) is predominately in higher frequency ranges (2–15 khz). B) Acoustic monitoring devices deployed in cotton crop. The top recorder is monitoring ultrasonic frequencies (> 20 kHz), while the bottom is monitoring audible sound (< 20 kHz).

(Brandes, 2008; Wimmer et al., 2013). Automatic recognisers use distinctive features in a signal (e.g. changes in pitch and amplitude, duration) to identify species and offer an attractive alternative to manual processing (Brandes, 2008). Recognisers often rely on machine learning algorithms and exemplar call repositories to match signals to species, and these algorithms become more accurate as source calls are added (Russo and Voigt, 2016; Clement et al., 2014; Klein et al., 2015). Furthermore, the results provided by recognisers are repeatable and quantitative, reducing reliance on human-based subjective approaches (Trifa et al., 2008; Digby et al., 2013). These recognisers are often used in partnership with detection algorithms, which automatically find animal specific calls within large recordings (Mac Aodha et al., 2018; Potamitis et al., 2014; Blumstein et al., 2011). Thus, automatic recognisers simplify the identification process and increases the processing speed compared to manual processing (Brandes, 2008; Swiston and Mennill, 2009), when they are available.

4.1.2. *Target species*

When selecting soniferous species in agricultural environments, two taxonomic groups display the most potential: birds and bats. Birds and bats are relatively easy to monitor acoustically and they exhibit peaks in activity around dawn and/or dusk (Kati et al., 2004; Scanlon and Petit, 2009; Wimmer et al., 2013). There is currently a wide range of specialist equipment available to undertake real-time presence studies or to undertake *post hoc* analysis (e.g. long-term acoustic monitoring devices; Stahlschmidt and Brühl, 2012). Automatic recognisers are already widely used, and many are available depending on the target species and the study location (Adams et al., 2010; Obrist et al, 2004; Walters et al., 2012). However, these may be limited by variation in calls (including regional dialects) and also the tendency of some birds to mimic the calls of others (Brandes, 2008; Towsey et al., 2014a).

Birds and bats may be useful bioindicators in agricultural landscapes because of their sensitivity to habitat change such as land clearing and habitat fragmentation (Blumstein et al., 2011, Davy et al., 2007; Donald et al., 2001; Firbank et al., 2008; Hendrickx et al., 2007). Remnant vegetation supports a disproportionally large amount of biodiversity in farming landscapes (Fischer et al., 2006). Previous studies have found that habitat patch size, type and condition, the intensity of surrounding land use, and landscape context significantly influence bird diversity in agricultural landscapes in eastern Australia (Mac Nally 1994; Fischer et al., 2006; Jansen and Robertson 2001; Major et al., 2001; Martin et al., 2006; Haslem et al., 2015). These areas often support small woodland bird species, which are reliant on dense tree cover and prefer structurally complex habitat, including a mixture of trees, shrubs, hollow trees, and downed woody debris for protection, foraging, roosting, and nesting (Robinson and Traill 1996; Reid 1999; Ford et al., 2001; Ford 2011). However, the biodiversity that a remnant habitat patch supports also depends on how well-connected it is to other patches. For example, bat activity has been shown to be higher in remnant vegetation compared with adjacent fields, likely due to the presence of linear corridors such as tree lines, which provide roosting opportunities (Lentini et al., 2011; Murray and Kurta, 2004). Thus, farmers can implement vegetation management strategies that include a combination of landscape corridors, stepping stones (e.g. smaller habitat patches or trees), and areas containing structurally complex habitats to improve biodiversity outcomes on the farm (Fischer et al., 2006; Kindlmann and Burel, 2008), as well as other off-farm natural areas (Perfecto and Vandermeer, 2010).

Table 1
Numerous bioindicators are available, which meet the key criteria for an indicator to varying degrees. The methods fall into three general categories and their ability to meet the criteria is classified as high (check mark), medium (circle) and low (X).

Category	Method	Relevance to program proponent	Diagnostic	Spatio-temporal scale	Logistical feasibility	Biodiversity Surrogate
Species specific	Manual processing	✓	✓	✓	✗	●
Species specific	Automatic species recogniser	✓	✓	✓	●	●
Acoustic index – Alpha	Acoustic entropy index (H)	✗	✗	✗	✓	✓
Acoustic index – Alpha	Acoustic Complexity (ACI)	✗	✗	✗	✓	●
Acoustic index – Alpha	Acoustic richness (AR)	✗	✗	✗	●	✓
Acoustic index – Alpha	Acoustic evenness (AEI)	✗	✗	✗	✓	✓
Acoustic index – Alpha	Normalized difference soundscape index (NDSI)	✗	✗	✗	✓	●
Acoustic index – Beta	Dissimilarity index (D)	✗	✗	✗	✓	✗

Anurans (e.g. frogs and toads) and insect species have long been used as bioindicators of ecosystem health and for biodiversity assessment (Moreira and Maltchik, 2014; Blair, 1999). However, their effectiveness may be limited for agricultural industries. Anurans are highly reliant on water for reproduction and survival, and as such are more likely to reflect environmental climatic conditions rather than biodiversity (Hazell et al., 2001). Anuran diversity naturally decreases away from water, and so the utility of these species also diminishes. Insects are also commonly used as bioindicators, but the taxa most commonly used to reflect biodiversity (i.e. butterflies; Blair, 1999) are generally non-soniferous, making them inappropriate for use in acoustic monitoring. However, acoustic monitoring of insects is a rapidly growing area of research (Schmidt and Balakrishnan, 2014). For example, Aide et al. (2017) found that insect richness was positively related to acoustic space use in tropical forests, while data from automatic recognisers have been used to quantify trends in Orthoptera species abundance (*Tettigonia viridissima and Ruspolia nitidula*; Jeliazkov et al., 2016). While this research appears promising, insect assemblages are extremely diverse. As a result, acoustic libraries tend to be less developed for insects compared to other species (Schmidt and Balakrishnan, 2014). In addition, the current lack of information on soniferous insect assemblages as a proxy for biodiversity assessment in agricultural systems makes these species less attractive as bioindicators at the present time.

4.1.3. Advantages and disadvantages

The use of one bioindicator species or a suite of species for biodiversity monitoring has always been contentious because there is an implicit assumption that the species selected is related to the abundance and diversity of other species in the ecosystem (Carignan and Villard, 2002). Nevertheless, bioindicator species are often used in practice because they provide a pragmatic way to assess land management impacts on an ecosystem. Thus, the choice of the bioindicator is extremely important. Sensitive species may be selected if an early warning of land management impact is needed (e.g. pesticide drift); dispersal-limited species can be used to assess habitat connectivity or localised habitat conditions (e.g. the presence of structurally complex vegetation); and a suite of resource-limited species can be used to ensure that various habitat types are available for activities such as foraging or nesting (Carignan and Villard, 2002). In addition, flagship species may be used to engage the public and increase awareness about sustainability efforts within the industry. Thus, a group of bioindicator species that reflect different ecological guilds is often used as a proxy for biodiversity and ecosystem integrity.

One advantage of species-specific acoustic bioindicators is that they can be intuitively linked to land management practices (Padoa-Schioppa et al., 2006). As such, species-specific bioindicators can be selected based on their relevance to industry and landholders, as well as their diagnostic relationship with on-farm land management practices (Table 1); noting that the ecology and behaviour of potential target species makes them more or less suitable at different scales. While we have highlighted the usefulness of two taxonomic groups (i.e. bats and birds) as the most appropriate for use as acoustic bioindicators, the behaviours of these taxa are diverse, with some species having complex migratory patterns and others strict home territories (Glass, 1982; Law and Anderson, 2000; Price et al., 1999). For example, if a single farm is the focus of a biodiversity assessment then selecting a species that is highly nomadic or exhibits structured migration patterns may not effectively represent the landholder's actions to improve biodiversity. Rather, the bioindicator may be reflecting changes in land-management practices at a broader landscape scale undertaken by multiple landholders. Furthermore, the program proponents must consider the migration patterns of a species at certain times of the year when selecting a bioindicator (Glass, 1982) because these natural fluctuations in presence will greatly influence the results.

Logistically, there are a number of considerations that need to be addressed before species-specific bioindicators can be used for biodiversity monitoring in agricultural systems. First, automatic recognisers must be developed to identify the target species from background noise. This can be a complex and time consuming process in the initial stages as libraries of sounds and algorithms need to be created (Obrist et al., 2004; Parsons and Jones, 2000; Towsey et al., 2014a). Automatic recognisers can also lead to over- or under-estimation of the presence of bioindicators through false positives and negatives which must be assessed in *post hoc* analysis (Wimmer et al., 2013; Nicholls and Goldizen, 2006). Furthermore, the recogniser may need to be periodically reviewed and adjusted, particularly if the target species has a complex call repertoire (Towsey et al., 2014a).

While the presence of a target species can be detected relatively easily, estimating abundance is more difficult; although a number of researchers have been able to accurately estimate target species density (Dawson and Efford, 2009; O'Donnell et al., 2013). First, there are a number of issues which make this approach difficult for agricultural industries. Evenly spaced arrays of recording devices need to be deployed and synchronised. Then *post hoc* analysis of the triangulation of recordings must be used to estimate the density of calling individuals at each time step (e.g. per minute; Dawson and Efford, 2009) and this can quickly become expensive. Furthermore, in the case of highly mobile taxa such as birds and bats, it is possible that the same individual could be counted numerous times. Consequently, an estimate of activity (e.g. bat echolocation call passes per hour; a pass is a series of calls separated from other calls by at least 1 s) may be more appropriate for agricultural industries. Such an estimate is likely to provide a more realistic representation of changes in activity over time, and it may be more biologically appropriate benchmark for pest suppression than abundance alone (Miller, 2001).

4.2. Acoustic indices

Acoustic indices are mathematical metrics which are used to quantify differences in amplitude and frequencies in sound files as a whole, rather than a specific species. This approach is increasingly being used as a reliable method for understanding changes in biodiversity (Depraetere et al., 2012; Gasc et al., 2013; Towsey et al., 2014a). By using the sum of all acoustic features from a sound file, acoustic indices also provide information about changes at a site over time, as well as differences between sites (Towsey et al., 2014a).

Acoustic diversity can potentially be used as a surrogate for biodiversity assessment (Sueur et al., 2008), without the need to identify every species present. Recordings capture sounds from the surrounding soundscape, but a large quantity of data are often left unused (Ma et al., 2006). More recently, interest has increased in using these "non-target" recordings for biodiversity assessment (Depraetere et al., 2012; Gasc et al., 2013). A number of studies have shown that complex habitats contain a higher diversity of vocalising species, which produce more acoustic signals (Darras et al., 2016; Depraetere et al., 2012; Gasc et al., 2013; Grant and Samways, 2016; Sueur et al., 2008). For example, Gasc et al. (2013) found that the acoustic diversity of a tropical forest was positively related to the number of bird species. Acoustic data can also be analysed to examine the composition and diversity of all recorded vocalising organisms, as well as other acoustic features of the soundscape, such as human mediated sounds (e.g. engines and machinery) (Farina et al., 2016; Gasc et al., 2016; Sueur and Farina, 2015; Towsey et al., 2014). Acoustic diversity indices currently in use can be categorised into one of two groups: alpha (within) or beta (between) diversity. In the following sections, we compare six acoustic indices and assess their merit as biodiversity surrogates for agricultural industries (Table 1).

4.2.1. Alpha indices

The Acoustic Entropy (H) index (Sueur et al., 2008) measures the overall randomness (i.e. entropy) of noise within a recording and is the most frequently used for biodiversity assessment. While the *H* index is not a direct measure of biodiversity *per se*, studies in eastern Australian woodlands and African tropical rainforests have found it to be highly correlated with bird species diversity (Fuller et al., 2015; Sueur et al., 2008). In contrast, the Acoustic Complexity Index (*ACI*) removes sources of underlying noise before quantifying the number of unique signals in the sound (Pieretti et al., 2011). This is particularly advantageous in environments where broadband sounds, such as those produced by insects, are more prevalent (Pieretti et al., 2011). The ACI value is indicative of the complexity of the sound, with more complex recordings receiving higher ACI scores. More complex sounds can be conceptually linked to more animal sounds and higher biodiversity (Pieretti et al., 2011; Farina et al., 2016). While most studies rely on this assumption, a correlation between *ACI* and bird activity (i.e. number of calls) was found in Mediterranean Europe (Farina et al., 2011; Pieretti et al., 2011).

The Acoustic Richness (*AR*) index uses both temporal entropy and the median envelope (i.e. the top and bottom of the sound's waveform) to determine the number of different sounds within a recording (Depraetere et al., 2012). It has been used successfully in areas with low acoustic diversity, such as temperate zones (Depraetere et al., 2012), and when tested across three different habitat types with varying levels of disturbance in Europe, *AR* was found to be correlated with bird species richness.

The Acoustic Evenness (*AEI*) index describes the number and evenness of bins within a frequency range using the Gini coefficient (Villanueva-Rivera et al., 2011) and thus describes the balance of sound in the soundscape. It is based on the premise that natural landscapes are likely to produce more even soundscapes as animals vocalise across a wide range of frequencies; while altered landscapes are expected to have reduced evenness as the soundscape is dominated by technophony and geophony in fewer frequency bands (Fig. 1A; Villanueva-Rivera et al., 2011); Evidence suggests that *AEI* may be a reliable proxy for biodiversity, after being tested in subtropical forests in eastern Australia (Fuller et al., 2015) and a variety of habitats (including crop lands) in the United States of America (Villanueva-Rivera et al., 2011).

The Normalized Difference Soundscape Index (*NDSI*) is the ratio of technophony to biophony in the soundscape (Kasten et al., 2012) and has been used in subtropical woodlands (Fuller et al., 2015), temperate forests (Gage and Axel, 2014), and monoculture crops (Gage et al., 2015). While this index does not measure acoustic diversity *per se*, it has been shown to be correlated with bird species richness and ecological condition in fragmented landscapes (Fuller et al., 2015). Gage et al. (2015) also used NDSI to explore how biophony-dominated soundscapes change 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 in general, with the lowest values found in agricultural dominated landscapes and highest in Popular dominated forest.

4.2.2. Beta indices

The Dissimilarity (*D*) index (Sueur et al., 2008) compares differences in temporal and spectral envelopes of sound between sites, providing a measure of community diversity similar to the dissimilarity indices used in traditional ecological studies (Gorelick, 2006; Sueur et al., 2008). While *D* does not directly measure biodiversity, this index can be used to compare differences in two acoustic communities under different conditions, as well as across temporal and spatial scales (Sueur et al., 2008).

4.2.3. Advantages and disadvantages

The greatest advantage to using acoustic indices for biodiversity assessment is that they are generally more logistically feasible to implement than species-specific recognisers (Table 1). Experts are not required for species identification, indices can be calculated directly (i.e. there is no need for recogniser training as species are not identified), and they are computationally easy to calculate (Gasc et al., 2013; Sueur et al., 2008, Villanueva-Rivera et al., 2011). False colour spectrums have also been developed to link biotic communities and acoustic indices in a visual medium (Towsey et al., 2014b). Indices are visually displayed in colour and provide biotic information over temporal scales (from 24 h datasets to a year scale). This approach can reduce reliance on filtering in long term monitoring, as the influence of geophony and technophony are reduced and can be used to show trends in individual species behaviour. Nevertheless, each index has unique limitations that must be considered.

The most common issue with acoustic indices is sensitivity to broadband noises, such as geophony (i.e. wind and rain) and insect choruses. These can influence the sensitivity of *H, ACI, AR, AEI* through masking sounds or exaggerating noises in certain frequency bands (Eldridge et al., 2016; Villanueva-Rivera et al., 2011). Technophony can also artificially increase *ACI*, particularly if it is above 2 kHz, which leads to the conclusion that there is higher biotic diversity than is actually present (Pieretti et al., 2011). In addition, other indices such as *NDSI* are based on the assumption that soniferous species are vocalising above the technophony threshold (Kasten et al., 2012), despite this being highly unlikely for some species (e.g. owls). Finally, some acoustic indices such as *AR* require pre-processing of recordings, such as the application of filters to audio files before analysis (Depraetere et al., 2012). This increases processing time and may not remove all unwanted noise.

Another advantage to using acoustic indices is that they likely represent overall changes in biodiversity more accurately than species-specific bioindicators (Sueur et al., 2008). However, some indices (e.g. *ACI*) represent changes in acoustic activity (i.e. call rates), not biodiversity *per se* (Fuller et al., 2015), and may be less sensitive in areas of low biotic activity, or under-sample species that avoid human activity or presence (*H*) (Depraetere et al., 2012).

Mismatches in spatio-temporal scaling may also be a more significant issue for acoustic indices than species-specific bioindicators because acoustic indices describe sounds made by multiple species (Table 1), with different home ranges, habitat needs, and migratory patterns. Consequently, species that are resource-dependent at a local scale may respond to on-farm land management actions, while other species may be more dependent on habitat connectivity at broader scales or migratory patterns affected by climate variability. As such, acoustic indices have less diagnostic capability than species-specific bioindicators (Table 1) and as such, there is no guarantee that increases or decreases in an acoustic index reflect on-farm management actions. Instead, changes in acoustic indices could be driven by regional efforts to increase biodiversity, or related to migration patterns of a few species (Glass, 1982; Price et al., 1999).

5. Recommendations for agricultural industries

We believe that species-specific or guild-specific bioindicators are most appropriate because they meet four of the five criteria for a successful indicator (Table 1). When chosen carefully, they are highly relevant to the program proponent (i.e. growers within the agricultural industry); are appropriate for the spatial and temporal scale of the program (e.g. farm and industry specific) and thus, are diagnostic to changes in land management practices; and are logistically feasible if agricultural industries invest in the development of automatic recognisers. In addition, a suite of species-specific bioindicators representing ecological guilds may be used as a surrogate for overall biodiversity.

If the monitoring goal is to measure broader biodiversity within a region, independent of industry or land management practices, acoustic indices will likely provide a more accurate estimate of overall biodiversity (Gasc et al., 2013). While acoustic indices are cost effective alternatives to species-specific identification, they are less readily linked to changes in land management practices and may not reflect the response of biodiversity to on-farm management. This makes acoustic indices much less suitable for use in on-farm biodiversity assessments or industry-specific assessments.

Birds and bats have the most potential for use as species-specific or guild-specific bioindicators in most irrigated and dryland agricultural systems (Bowen-Jones and Entwistle, 2002). However, farms are found in diverse geographic locations, and as such different species or guild bioindicators may be needed if a single species is not present across regions (Duelli and Obrist, 2003). It is also important to understand the ecology of the target species because this will determine whether it is interacting with the environment at a suitable spatial and temporal scale and whether it is likely to have the desired diagnostic capability. Ecological traits that are important to consider are: the geographic distribution of a species, whether it is a resident rather than transient visitor and maintains a restricted home range, whether it is migratory, and its feeding behaviour. If an acoustic bioindicator meets all five criteria (Table 1), it is also advantageous if the species provides additional benefits to the grower (e.g. pest suppression) or can be used to promote sustainability efforts in the agricultural industry. These recommendations are based on our best scientific knowledge to date and are intended to guide future acoustic monitoring programs in agricultural systems. However, to our knowledge acoustic monitoring has not been operationalised by a private agricultural industry to date. Thus pilot studies should be implemented in the field to validate the effectiveness of acoustic biodiversity monitoring before a broad-scale program is implemented within a private agricultural industry.

6. Conclusions

Acoustic monitoring shows great promise for biodiversity monitoring in agricultural systems because it is relatively inexpensive to implement and undertake when compared to traditional methods. Species-specific bioindicators detected using automated recognisers hold the most promise when the aim of the program is to assess the industry-specific or farm-specific impact on biodiversity; they can be conceptually linked to management practices at scales relevant to farmers and validated. They should also be chosen carefully to ensure that they are relevant to the program proponent. Although automatic recognisers do not currently exist for all species, species-specific indicators become logistically feasible if the industry invests in the development of the algorithms. Unlike some acoustic indices, species-specific bioindicators are unlikely to reflect changes in on-farm biodiversity as-a-whole. However, these measures may be sufficient for the sustainability reporting needs of an agricultural industry, as long as this assumption is transparently communicated in sustainability reports. An alternative would be to report on a suite of species-specific bioindicators that represent guilds dependent on a more diverse set of habitats. However, if the goal is a more general assessment of biodiversity within agricultural and mixed landscapes, acoustic indices offer a more logistically feasible approach for industry reporting (Sueur et al., 2008).

The acoustic analysis methods discussed in this paper are rapidly evolving, with recent technological advancements in both species recognisers and the visualisation of acoustic recordings. While future research clearly needs to be undertaken to develop, improve, and validate automatic species-recognition methods, acoustic monitoring has the potential to deliver consistent and repeatable results, allowing individual farmers and agricultural industries to more easily track their sustainability performance. This becomes even more critical as we consider the increasing role that agricultural regions will have in sustaining the world's rapidly declining biodiversity.

7. Declarations of interest

None.

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