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VIEWPOINT

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Acoustic restoration: Using soundscapes to benchmark and fast-track recovery of ecological communities

Elizabeth Znidersic | **David M. Watson**

Gulbali Institute, School of Agricultural, Environmental and Veterinary Sciences, Charles Sturt University, Albury, New South Wales, Australia

Correspondence
Elizabeth Znidersic, Gulbali Institute, School of Agricultural, Environmental and Veterinary Sciences, Charles Sturt University, Albury, NSW 2640, Australia.
Email: eznidersic@csu.edu.au

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Abstract

We introduce a new approach—acoustic restoration—focusing on the applied utility of soundscapes for restoration, recognising the rich ecological and social values they encapsulate. Broadcasting soundscapes in disturbed areas can accelerate recolonisation of animals and the microbes and propagules they carry; long duration recordings are also ideal sources of data for benchmarking restoration initiatives and evocative engagement tools.

KEYWORDS
disturbance, ecoacoustics, engagement, microbial ecology, social attraction

As catastrophic wildfires, heatwaves and storms increase in frequency and severity, the world's ecosystems face mounting pressures, pushing relictual populations towards local extinction and compromising ecosystem function. Current restoration approaches were originally developed as site-scale secondary interventions—removing primary stressors and relying on regeneration to do the rest. While these passive methods have largely made way for active interventions (Table 1), most are too effort-intensive to apply beyond individual site scales. Innovation is urgently needed to develop scalable and rapidly deployable methods to arrest further declines, complimenting existing interventions to facilitate recovery.

After a sustained period of development and growth, a critical mass of acoustic ecology research and practice has been attained, evidenced by large-scale government investment in infrastructure (Roe et al., 2021), international data-sharing networks and adoption of standard operating procedures to maximise comparability (Browning et al., 2017). An idea that emerged from our use of sound to survey both species and communities over the past decade is to reimagine this monitoring tool as an active restoration approach. We name this new field 'acoustic restoration', emphasising soundscapes as holistic high resolution digital depictions of ecosystems (Schafer, 1977), recognising the biological, geophysical and socio-cultural values they encapsulate (Parker & Spenneman, 2021; Pijanowski, Villanueva-Rivera, et al., 2011).

Here we introduce the idea and develop four elements of this novel transdisciplinary domain. The first broadens existing use of acoustic lures to attract single species up to entire assemblages, broadcasting soundscapes to fast-track recolonisation of communities from the top down. The second element uses increased animal visitation to augment the rain of seeds, spores, bacteria and fungi re-inoculating aquatic and terrestrial communities, restoring ecosystems from the bottom up. Third, we suggest sound represents an ideal benchmark for restoration, providing an independent and verifiable means of answering the question—are we there yet? Finally, we advocate using soundscapes as evocative engagement tools to remind stakeholders what their river, reef or rainforest sounded like and create new ways to reconnect with places they hold dear.

Acoustic lures are an existing tool in the restorationist's repertoire, used for various vocal animal groups to elicit a response for detection, capture or attracting individuals to specific locations and encourage breeding. To accelerate establishment or recolonisation through social attraction, species-specific acoustic lures have

TABLE 1 The principal techniques presently used for active restoration and remediation after disturbance. Unlike most of these approaches that are best suited to scheduled site-scale initiatives, acoustic restoration is scalable, readily tailored to both aquatic and terrestrial applications and can be rapidly deployed in remote or dangerous landscapes

Approach	Applications and benefits	Limitations	References
Mechanical and chemical bioremediation	Scalping sites in conjunction with revegetation, chemical dispersers and microbial inoculants for pollutants, typically funded by polluters	Not feasible beyond site scale nor remote areas with no machinery access	Vrba et al., 2003; Brown et al., 2017
Replicate historic disturbance regime	Fire and grazing in terrestrial systems, flooding for freshwater systems; range of historic variation often the goal, integrates well with First Nations knowledge systems	Limited applicability in peri-urban and multifunctional landscapes, historic data often unavailable	Pedroli et al., 2002; Greenberg & Collins, 2015
Revegetation	The default approach for many terrestrial and subtidal biomes, useful way to involve wide range of stakeholder groups, aerial seeding especially beneficial when disturbance and visitation are restricted	Only some plant groups can be propagated and transplanted, long lead time can be challenging for maintaining engagement	Linhart, 1995; Ellison, 2000
Translocation and facilitated dispersal	Routine in freshwater systems, terrestrial applications prioritise ecosystem engineers, equally applicable to widespread species to keep them common	Costly, risky in terms of both low success and tenuous social license (intervention often framed as 'unnatural')	Seddon, 2010; Watson & Watson, 2015
Augmenting natural substrates	Re-snagging and re-meandering rivers, adding coarse woody debris and outcrops to woodlands, returning oyster shells to temperate reefs; topsoil replacement for mine sites, cost effective and well suited to experimental comparisons	Not all structures can be augmented, logistically complex to upscale, environmental alterations may displace early successional taxa	Erskine & Webb, 2003; Woldendorp & Keenan, 2005
Adding engineered structures	Concrete reefs, nest boxes, simulated burrows; all increase heterogeneity of surfaces and boost microclimatic diversity	Costly at scale, can be subverted for commercial gain (e.g. fish attracting devices), not addressing shortage of resources over longer time-scales	Jaap, 2000; Cowan et al., 2021
Eradicating invasive species	Reducing populations of invasive species down to a level where displaced native taxa can re-establish, useful way to engage with local communities	Costly and ongoing, biological control requires significant investment and expertise	Veitch & Clout, 2002; Glen et al., 2013
Acoustic restoration	Broadcasting soundscapes in disturbed terrestrial and aquatic areas can accelerate recolonisation of animals and the microbes and propagules they carry; long duration recordings are also ideal sources of data for benchmarking restoration initiatives and evocative engagement tools	Initial responses restricted to vocal taxa and animal-dispersed propagules, not addressing cause of disturbance, potential for equipment to be vandalised or stolen	Vega-Hidalgo et al., 2021; This paper

been applied successfully to frogs (James et al., 2015), seabirds (Arnold et al., 2011; Herrera-Giraldo et al., 2021), bats (Ruffell et al., 2009), reef fish (Gordon et al., 2019) and whales (Tyack et al., 2011), proving especially effective for long-lived colonial animals that remember using that location prior to disturbance (Jones & Kress, 2012). Putman and Blumstein (2019) flagged the potential for using call playback to recruit animals into newly restored habitats but expanding this approach to community-scale interventions has not been considered. As well as animal vocalisations, sounds from other biological, anthropogenic and geophysical sources can act as individual or collective cues for species (Pijanowski, Farina, et al., 2011). In addition to indicating where to go (e.g. settlement response to reef sounds by crab and oyster larvae; Lillis et al., 2013; Stanley et al., 2009), not go (e.g. avoidance of anthropogenic sounds by cetaceans and fruit bats; Ruffell et al., 2009; Tyack et al., 2011), or how to get there (e.g. encouraging frogs to cross railways via underpasses; Testud et al., 2020), sounds can elicit or modulate behaviours (e.g. rainfall sounds trigger breeding behaviour in frogs; Muñoz et al., 2020).

The same technology used to make popular consumer products for broadcasting music outdoors can readily be repurposed to make autonomous playback devices, matching the soundtrack to the location and substrate, and optimising the duty cycle to the target species and acoustic theatre (e.g. nocturnal playback of flight calls for passage migrant birds, broadcasting frog choruses after significant rainfall). By playing segments of an entire

soundscape or curated compilations of key vocal species ('mix tapes'), concerns over temporary habituation can be minimised noting that, despite oft-shared anecdotes, direct evidence of deleterious impacts of call playback is scant (Watson et al., 2018). Comparing mix tapes with natural or edited soundscapes, mechanistic cues used by various animal groups can be identified, allowing progressively more tailored lures for particular restoration or remediation contexts. Pairing the use of lures with sensor-based surveys (passive acoustic recorders, motion-activated cameras, even controllable web-cams), large-scale restoration initiatives can be conducted and monitored in remote and inhospitable landscapes, control sites restored using conventional practices providing time-matched counterfactuals to quantify any initial or medium-term differences. In addition to minimising demographic and genetic losses from initial disturbance, fast-tracking recolonisation can prevent encroachment of despotic species that aggressively exclude subsequent colonists from the original assemblage (Leseberg et al., 2015).

Regardless of whether visiting animals stay, simply attracting passing animals to target sites will augment recolonisation of the bacteria, fungi, protists and plankton that perform foundational roles in food webs. Mycorrhizal fungi can take decades to return after wildfire (Dove & Hart, 2017), while the microbial films that underly energy flux in freshwater systems can take over a century to recover from industrial pollution (Vrba et al., 2003). The simplified microbial communities that characterise disturbed systems diminish their resilience, increasing sensitivity to additional disturbance events. The idea of using visiting animals to fast-track restoration has been trialled before (Sengupta et al., 2022), primarily in reforesting agricultural land where the addition of artificial perches to cleared areas facilitates dispersal of large-seeded plants by visiting birds (Athiê & Dias, 2016; Wunderle, 1997), which can be expanded to smaller-seeded groups via the related concept of induced seed dispersal (Silva et al., 2020) or scaled up by integrating revegetation of small patches of trees to facilitate colonisation of animal-dispersed trees (applied nucleation; Zahawi et al., 2013). Although more relevant in terrestrial systems, the potential for wide-ranging aquatic organisms to seed microbial recovery has been noted by researchers working on both marine reefs (e.g. fish accelerating recovery of coral endosymbionts after bleaching events; Grupstra et al., 2021) and freshwater wetlands (e.g. the microbiome of fish homogenising river bacterial communities; Zha et al., 2020). In addition to fungi and bacteria, seeds and small animals are transported by birds (Fontaneto, 2019; González-Varo et al., 2019) and fish (Goulding et al., 1990; Schofield et al., 2018) effecting long-distance dispersal across inhospitable intervening areas.

A frequently recognised failing of restoration initiatives is brokering agreement on the answer to the question: 'What does success look like?' (after Prach et al., 2019). Acoustic restoration recasts this question as 'What does success sound like?'. For mining and other commercial infrastructure development, pre-disturbance recordings from impacted sites offer a quantifiable benchmark for future restoration practitioners to work towards. For already disturbed sites, soundscapes from adjacent areas or ecologically similar reference sites can provide high resolution data about both species assemblages and structural characteristics that can be logistically complex to estimate at the whole-of-system scale (e.g. Butler et al., 2016). Current ecoacoustics allows a suite of metrics to be extracted from recordings (Figure 1), including species richness (Towsey et al., 2014) and identification of dominant taxa (Vega-Hidalgo et al., 2021), but also seasonal dynamics, changes in flow (Linke & Deretic, 2020), breeding events, even estimating canopy complexity by quantifying how sound from storms dissipates (Haskell, 2020). Progressive monitoring of restored sites will reveal which targets are met and which are yet to be attained, prioritising on-ground actions to optimise recovery. Noting recent advances in estimating abundances, identifying individuals, detecting reproductive events, mass flowering and even predation success with current analysis and visualisation techniques (Browning et al., 2017 and references therein), burgeoning ecoacoustics research will enable future practitioners to extract progressively more historic information from archived recordings, giving restoration practitioners a trove of pre-disturbance metrics to gauge the functional success of their work.

Finally acoustic restoration offers unparalleled opportunities for meaningful engagement. Just as a green flush of new growth tells an experienced observer about recent rain, so a chorus of frogs or flight calls of ducks tells an experienced listener that the recent rain has had population-scale effects. Sounds are evocative and every place has its own soundscape (Pijanowski, Farina, et al., 2011; Schafer, 1977). Farmers remember curlews calling on moonlit nights when they were children (Robb et al., 2012), chorusing cicadas alert rainforest people to heat waves in the treetops (Feld et al., 2020). The sounds of animals and particular winds or waves feature strongly in First Nation accounts of places of cultural significance (Parker & Spenneman, 2021). In addition to rallying communities to restore connections with what places once sounded like, natural sounds have a range of health benefits (Buxton et al., 2021), tangible reminders of the value of immersive outdoor experiences. Natural sounds transcend human language, online and mobile platforms defining new ways for the environment to project its own voice into the boardrooms, studios and chambers where critical decisions are made. More soberingly, as development escalates and entire biomes make way for production agriculture and aquaculture, archived soundscape recordings and the whole-of-assemblage permanent

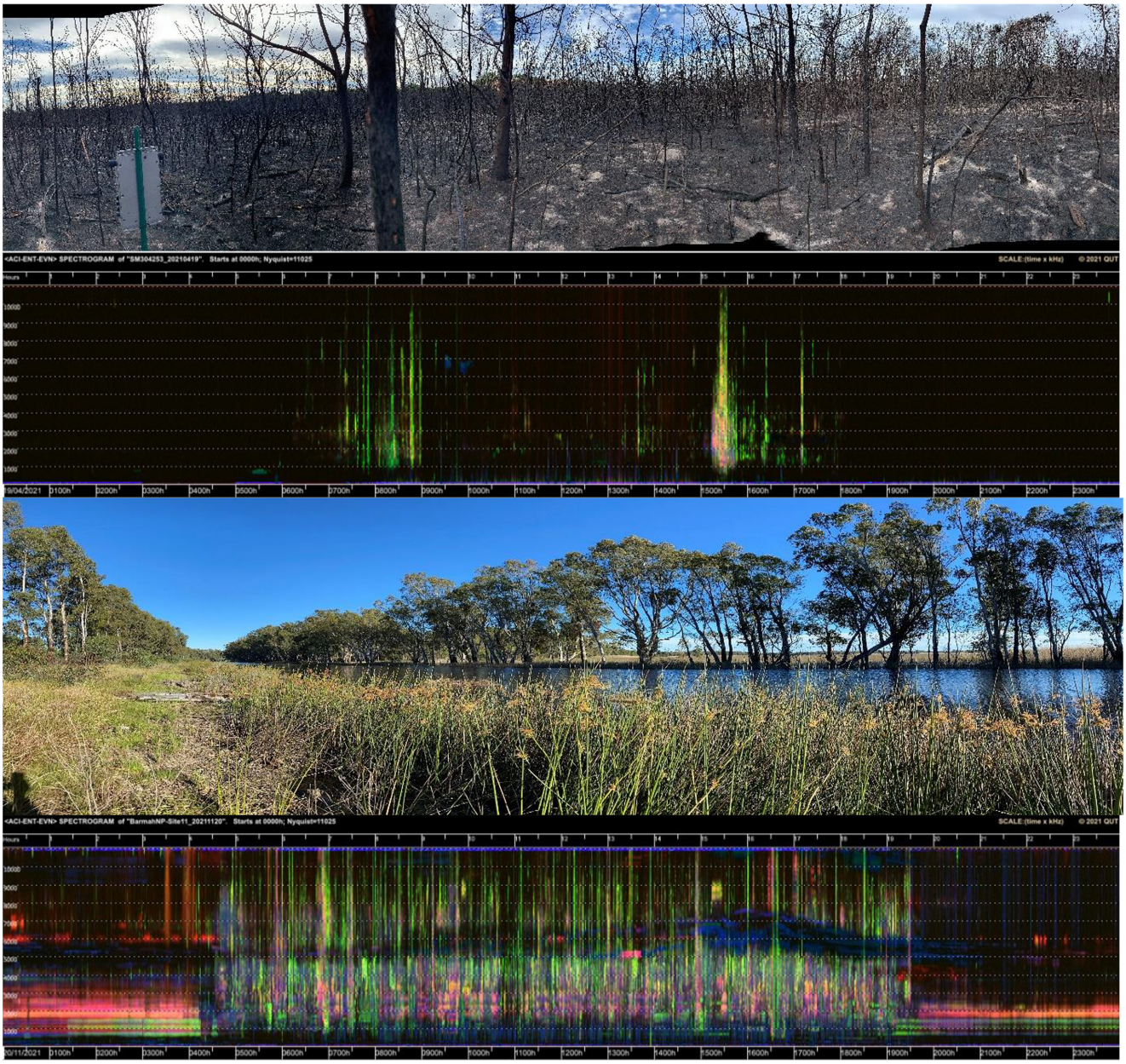

FIGURE 1 The top two images depict a recently burnt area on French Island, Australia. Beneath the photograph is a 24-h sound recording from the same site, processed into a visual interpretation of the soundscape (long-duration false-colour spectrogram). The *x*-axis is 24 h (midnight to midnight), *y*-axis 0–11,000 Hz generated by three acoustic indices (ACI acoustic complexity index, ENT spectral entropy and EVN event count index). The bottom pair of images depict a wetland recently filled by environmental flows at Barmah National Park, Australia. The long-duration false-colour spectrogram shows an acoustically full site of species (insects, frogs, birds) vocalising during the 24-h period across most frequency bands, unlike the silent soundscape of the burnt site punctuated by passing songbirds. Both examples demonstrate how acoustic recordings can quantify ecosystem attributes (restoration required or intact and functional), species diversity (groups of taxa calling) akin to the corresponding photograph. By measuring whole-of-system biological activity, acoustic data offer high resolution samples of biological activity to benchmark ecological comparisons and a trove of archivable site-specific sounds to engage stakeholders

records they represent will remind people what wild places were once like.

Acoustic ecology has surged in popularity as a compliment to existing ecological techniques, due primarily to the rich resolution and archival stability of acoustic data. As the 'hype' recedes and our transdisciplinary field matures, we see great benefits of applying acoustic ecology to the practice of ecological restoration. As well as cost-effective and nimble (deployable within hours of disturbance events), acoustic restoration minimises the need for ongoing visits by teams of people, reducing risks of site disturbance and inadvertent introduction of invasive species and pathogens. In addition to accelerating recovery from wildfire, coral bleaching, blackwater events and catastrophic storms, acoustic restoration could be used proactively to push range shifts toward

unoccupied but otherwise suitable future habitats to minimise climate impacts, for both resident and migratory assemblages in insular and extensive systems. Advances in eDNA sequencing and semi-automated identification using DNA-barcoding entrain reliable means of quantifying change in microbial communities—both occurrence and genetic interchange—with parallel work on seedling emergence, soil and water properties enabling quantification of changes to plant populations and ecosystem health. Rather than chasing shifting baselines or arguing about the unreliability of indicator taxa or space-for-time substitutions, archived open access soundscapes can guide diverse stakeholder groups towards a common purpose, defining on-ground work towards agreed targets representing the true complexity of ecosystems.

To realise these benefits and maximise the utility of acoustic restoration, we suggest four priority actions. First, we urge empirical ecologists to collect long duration recordings as part of their fieldwork. With equipment now readily available, recording soundscapes and associated metadata should be as routine as taking photographs of your study area. As large distributed arrays of acoustic sensors are being established to track environmental change at continental scales (Roe et al., 2021), investment will be increasingly directed towards platforms to curate, share and visualise these data. Second, we encourage researchers and practitioners alike to listen to their systems. The simple observation that "higher quality woodlands rustle underfoot" (Freudenberger, in litt.) presaged the importance of productivity, litterfall and litter-dwelling invertebrates in driving woodland foodwebs (Watson, 2011). The very act of recording sounds increases one's awareness of the surrounding landscape (Feld et al., 2020) and helps tune one's understanding of the underlying variability and constitutive complexity. Third, think beyond species. While species recognition is increasingly achievable for many animal groups, using ecoacoustics to quantify species richness is akin to using satellite photography to identify vegetation types. It's not the best tool for the job. False colour spectrograms and other applications of acoustic indices are readily able to extract a variety of metrics from recordings, many of which are likely influenced by the same underlying mechanisms that determine species occurrence and community composition. Looking past species to these biotic and abiotic gradients will reveal new variables that ecoacoustics is far better suited to quantify—bioacoustic signatures that distinguish changes in productivity, seasonality, resilience, and energy flux. Finally, collaborate: with acoustics specialists that can test microphones, calibrate equipment and ensure metadata are associated and complete; with environmental DNA specialists that can take a vial of water or bag of soil and tell you how many species of salamander live in that forest; with microbial ecologists that can take those samples and quantify how many taxa have recovered in that site since the last samples were taken. Restoring our streams and grasslands, our mangroves and estuaries, wetlands and saltmarshes is a top priority, remediating past damage and responding rapidly to future disturbance. Grounded in collaboration and facilitated by digital technology, acoustic restoration compliments existing on-ground approaches using the unique properties of sound to accelerate, augment, benchmark and engage.

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AUTHORSHIP

EZ responsible for the original concept of acoustic restoration, wrote the sections on acoustic lures and soundscape ecology. DMW responsible for the idea of microbial augmentation and aquatic applications, wrote majority of the first draft. EZ and DMW equally responsible for concept of acoustic benchmarking, both authors contributed to revisions.

PEER REVIEW

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DATA AVAILABILITY STATEMENT

No new data are presented in this manuscript, the long duration acoustic data summarised in Figure 1 are derived from the open access Ecosounds, https://www.ecosounds.org/projects/1131/regions/1/points/3212/audio_recordings

ORCID

Elizabeth Znidersic https://orcid.org/0000-0002-2804-1731
David M. Watson https://orcid.org/0000-0003-1821-4632

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