Listening to Ecosystems as Complex Adaptive Systems: Toward Acoustic Early Warning Signals

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Abstract

The value of integrating concepts and methods from Complex Adaptive Systems and the interdisciplinary study of soundscape for better understanding, monitoring and managing human-environment interactions is proposed. Through four examples of our recent research the value of soundscape and its interdisciplinary study, the relevance of ecoacoustics to a socially-concerned Alife is illustrated. From this position, the failure of current computational ecoacoustic methods to capture the fundamentally complex, adaptive and *dynamic* nature of ecosystems is noted and the potential for Acoustic Early Warning Signals is outlined. Development of an acoustic dimension to the study of complex adaptive systems promises to spawn valuable conceptual frameworks and cost-effective methods for investigating, understanding, predicting, managing and living in future techno-eco-systems, and better tuning the anthroposphere, technosphere and biosphere such that people and the planet can thrive.

Introduction

Understanding, monitoring and managing human-environment interactions is arguably the most critical challenge of our time (Dietz et al., 2003), scientifically, pragmatically and existentially. For several decades, Complex Adaptive Systems (CAS) have been heralded as providing a unified framework for explaining core ecosystem phenomena, including emergent patterns, critical transitions and cooperative behaviour (Levin, 1998). In recent years, CAS have sharpened from an abstract concept into a set of tools that can be used to solve real-world problems in the management of ecosystems and the public goods they generate (Hagstrom and Levin, 2016) – as well as the social and economic complex systems with which they are irrevocably entangled. The shift from beguiling story to productive tools has been led by new techniques for coupling ecological and evolutionary dynamics, integrating dynamics across multiple scales of organisation, and using data to infer the complex interactions among different components of ecological systems. Despite these advances, historical chasms between population ecology and studies of ecosystem and biosphere continue to hamper advances in understanding the critical question of the relationship between ecosystem structure and function. The theoretical promise has yet to be fully realised (Gordon et al., 2019) and understanding, predicting and managing human-environment interactions remains one of the most important challenges not only for ecosystem science (Hagstrom and Levin, 2016), but for the future of the lives of myriad species which comprise earth's systems.

Two interrelated issues remain critical: Firstly the need for methods to monitor and manage ecosystems under pressure, and more positively, to evidence and guide their restoration; Secondly better and more equitable approaches to governance of the commons. Nearly 20 years ago Dietz et al. (2003) expressed guarded optimism that we could escape the "tragedy of the commons", citing examples of a wide diversity of adaptive governance systems that have been effective stewards of many resources. Yet year on year we are failing to meet the challenge "to develop and deploy understanding of large-scale commons governance quickly enough to avoid the large-scale tragedies that will otherwise ensue." (Dietz et al., 2003) p.1910.

This paper proposes that integrating the interdisciplinary study of the acoustic environment, or *soundscape* with CAS framework and methods holds promise to address these interrelated issues: Firstly because the global soundscape (which can be understood as the set of audible vibrations emanating from the landscape at a particular place and time (Farina et al., 2021) is the *literal* site of interaction of anthropogenic, biological, ecological and geophysical agencies, and therefore provides a valuable global, public, measurable space for their scientific study[1]. Secondly because the soundscape as a concept and everyday, personal experience, coheres an epistemological nexus which provides a means to investigate and articulate personal environmental values and perceptions across cultures, toward harmonious environmental governance.

The next section articulates these differing conceptions of soundscape. Four case studies follow which illustrate the

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[1] see e.g. Silent Cities (https://osf.io/h285u/) for contemporary ecoacoustic investigation of interaction between ecological and industrial processes during the global pandemic

value of soundscape methods in participatory environmental monitoring and governance settings and point to the need for new and dynamical analysis tools. Finally, the potential for integrating acoustic data in early warnings signals is proposed and the value of integrating various facets of ecoacoustics and Artificial Life are speculatively advanced.

Ecological and semiotic soundscapes

Whilst bioacoustics has studied the anatomy of sound as a biological signal that transfers information between individuals (Fletcher, 2007), the ecological study of the global soundscape as an emergent property of ecosystems is in its infancy. Originally coined in the context of urban design (Southworth, 1967), the term *soundscape* was popularised by a group of environmentally-aware composers, sound artists and sonic sociologists to describe 'the acoustical characteristics of an area that reflect natural processes' (Murray Schafer, 1977); along with other nomenclature – acoustic horizon, sound marks, sound maps – the term focused attention on acoustic components of the landscape. The associated field of Acoustic Ecology set out to study sonically-mediated human-environment interactions. Soundscape in this domain therefore refers to the acoustic environment, as perceived by humans, in context. Increasing interdisciplinarity in contemporary researchers, including myself, mean that Acoustic Ecology is no longer the reserve of humanists, but is productively reframed as a transdisciplinary domain encompassing art, science and indigenous perspectives (Barclay, 2019)

Decades later, the scientific discipline of soundscape ecology advanced a framework to investigate soundscape in terms of the causes and consequences of the biological (biophony), geophysical (geophony), and human-produced (anthrophony) sounds that emanate from a landscape (Pijanowski et al., 2011). Soundscape ecology highlights the soundscape as the site of interaction of biological, ecological, industrial and geophysical processes, creating a space to study socio-ecological interactions. The emerging interdisciplinary science of ecoacoustics (Sueur and Farina, 2015) subsumes both soundscape ecology and bioacoustics to study the ecological role of sound across species and scales, from individual, through community, population to landscape and brings attention to the role of the soundscape in evolutionary processes.

An evolutionary perspective highlights four productive ideas. Firstly, that sound is a core dimension in the evolutionary ecosphere, like food, water, and habitat. The acoustic component of CAS study has been neglected to date. Secondly, beyond basic survival, sound is a significant component in the Umwelt (Von Uexküll and Mackinnon, 1926) of many species, including human. From an ecosemiotic perspective (Maran et al., 2007), the soundscape is a cognitive medium, therefore can only sensibly be considered from an organismic perspective (Farina et al., 2021). Just as 'there are as many worlds as there are subjects' (Von Uexküll and Mackinnon, 1926) p.70, each organism experiences a unique soundscape shaped by the specificity of its biological receptors and semiotic sensitivities. This organism-centered perspective follows Uexkúllian Umwelt in recognizing the meaning-making subjectivity of each organism in its interaction with the environment (Tønnessen, 2009). Thirdly, therefore, the acoustic environment mediates the interactions between all soniferous and sonically sensitive species dwelling at a given place and time: like a global feedback delay buffer, the global soundscape is shaped by the past and shapes the future voices in a given biome. Finally, it follows that the global soundscape is a source of information about the ecological status of an acoustic community. Just as the fossil record tells us something about hard bodied things of the past, a global soundscape tells us something about the lives of soniferous species in the present.

Ecoacoustics approaches the soundscape, as an ecological, and semiotic, resource, and therefore as a source of information about ecological status - the soundscape being structured through evolutionary processes, akin to other niche construction (Hutchinson, 1957) processes. Based on the assumption that computational analyses of acoustic recordings therefore provide a proxy for ecosystem status, an ecological machine listening is emerging, dubbed Rapid Acoustic Survey (Sueur et al., 2008). Over 60 computational acoustic indices have been proposed and evaluated to date (Buxton et al., 2018), and have been variously shown to map spatial heterogeneity (Bormpoudakis et al., 2013), reflect observed changes in habitat status (Kasten et al., 2012) and, biocondition (Eyre et al., 2015), and to strongly predict species richness across a wide range of terrestrial (Eldridge et al., 2018; Boelman et al., 2007) and aquatic habitats (Bertucci et al., 2016; Harris et al., 2016). The increasing power and decreasing cost of hardware makes acoustic survey comparable to satellite monitoring in terms of scalability in space and time, but it has the benefit of providing high-resolution data which intimately reflect the real-time dynamics of populations in situ. Acoustic survey is a highly attractive solution for large scale ecological monitoring, especially in remote locations, because it is: non-invasive; obviates the need for expert aural identification of individual recordings; sensitive to multiple taxa; effective across terrestrial, freshwater and marine habitats; and importantly for CAS study, scales cost-effectively (Sueur et al., 2008).

The following section provides examples of our own research which investigate the potential for soundscape methods in environmental monitoring and management contexts.

Listening to Ecosystems

Example 1: Machine Listening to Biodiversity

The first example (Eldridge et al., 2018) illustrates the value of computational soundscape methods as a cost-effective biodiversity monitoring method in terrestrial habitats. We conducted the most comprehensive comparative evaluation to date of the relationship between avian species diversity and a suite of acoustic indices. Acoustic surveys were carried out across habitat gradients in temperate and tropical biomes. Baseline avian species richness and subjective multi-taxa biophonic density estimates were established through aural identification by expert ornithologists. Twenty-six acoustic indices were calculated and compared to observed variations in species diversity. Highly significant correlations, of up to 65%, between acoustic indices and avian species richness were observed across temperate habitats, supporting the use of automated acoustic indices in biodiversity monitoring where a single vocal taxon dominates. Multivariate classification analyses demonstrated that AIs actually predicted habitats more strongly than the human-labelled avian species community composition in temperate habitats. That said, issues with interpretability and differential response to species assemblages in temperate vs tropical habitats highlighted the need for alternative approaches for computational ecoacoustics.

Example 2: Culturally Aligned Conservation Technology for Community Reef Restoration

The second example further bolsters the potential of rapid acoustic survey, this time in marine environments, and speaks to the value of nested, institutional variety in adaptive environmental governance, highlighted by Dietz et al (Dietz et al., 2003). The work addresses the need to support community reef conservation in Indonesia. Identifying coral reef systems with the greatest chance of survival requires effective assessment and monitoring to guide management at a range of scales from community to government. The development of rapid monitoring approaches amenable to collection at community level, yet recognised by policymakers, remains a challenge. The coral reef environment has a unique soundscape (Lobel et al., 2010) generated by marine organisms relying on sound for a range of activities including navigation, spawning, feeding, mating, and avoiding predators (Amorim, 2006; Tricas and Boyle, 2014). This includes low frequency calls and grunts of fish and higher frequency crackles of invertebrates, thought to be generated through cavitation by snapping shrimp (Versluis et al., 2000). This distinctive sound, that peaks between 4 kHz and 6 kHz (Au and Banks, 1998), is put to use by Indonesian fishers to identify good fishing grounds above coral reef by placing their ear to a wooden oar lowered into the sea to listen for the 'crackling' sound (Y. Yahya, 2020, personal communications).

The use of affordable acoustic recorders to assess reef health therefore not only provides an accessible, affordable methodology that can be carried out practically by local fishers, but one which aligns with existing everyday practices and knowledge sytems. Using the audio from GoPro video cameras, 34 reef samples were collected across West Papua. Analysis reveals a strong, positive relationship between acoustic evenness (Villanueva-Rivera et al., 2011) and fish abundance, species richness and family level indicators of ecosystem status. The results promote the potential for acoustic methods in rapid bioassessment toolkits (Peck et al., 2021) but again, highlight the need for more refined computational ecoacoustic methods.

Example 3: Inclusive Wilderness Mapping

The third example illustrates the value of the soundscape as an epistemological nexus for integrating ecological monitoring with assessment of stakeholder landscape values in wilderness mapping. Conservation of wilderness areas (WAs) is critical to the future of our biosphere, on ecological, cultural and social levels. Scholars across disciplines have established the importance of wilderness as a key site for endangered species (Soulé, 2014), human recreation and well-being (Milner-Guilland et al., 2014), as well as the wider network of ecological processes on which all life depends (Chan et al., 2006). Recognition of the value of wilderness across cultural, socio-economic, and ecological perspectives bolsters the conservation imperative, but the respective associated land uses rarely align. As Dietz et al identify, resolution of the conflicting needs of human stakeholders, ecological and economic imperatives poses a significant challenge globally (Vucetich et al., 2018; Redpath et al., 2013).

Current WA mapping methods are framed in terms of absence of anthropogenic influence, and created using visual satellite data, obviating consideration of the ecological or anthropogenic value of WAs. In Carruthers-Jones et al. (2019) we suggest that taking the acoustic environment into account could address this lacuna. We report the first investigation into the potential for ecoacoustic methods to complement existing geophysical approaches. Participatory walks, including in situ questionnaires and ecoacoustic surveys were carried out at points along transects traversing urban- wilderness gradients at four study sites in the Scottish Highlands and French Pyrenees. The relationships between a suite of six acoustic indices (AIs), wilderness classifications and human subjective ratings were examined. We observed significant differences between five out of six AIs tested across wilderness classes, demonstrating significant differences in the soundscape across urban-wild gradients. Strong, significant correlations between AIs, wilderness classes and human perceptions of wildness were observed, although magnitude and direction of correlations varied across sites. Finally, a compound acoustic index is shown to strongly predict mapped wildness classes (up to 95% variance explained (MSE 0.22)); perceived wilderness and biodiversity are even more strongly predicted. Together these results demonstrate that the acoustic environment varies significantly along urban-wild gradients; AIs reveal details of environmental variation excluded under current methods, and capture key facets of the human experience of wildness.

In a subsequent study in Abisko National Park, we trialled the possibility of integrating richer ethnographic data, by carrying out in situ semi-structured, multisensory interviews that access stakeholder perceptions, values, affect and vision into the map (Eldridge 2020). By figuring soundscapes as the locus of interaction between diverse actors, species, and disciplines we are investigating relationships with and responses to wildness through different forms of listening. Through this work we are developing a concept of soundscape as an epistemological nexus and in doing so, move towards the integration of hard data necessary for ecosystem monitoring and 'soft' data sensitive to stakeholder values that is necessary for engaged, inclusive and just governance.

Example 4: Supporting Indigenous-led Conservation through Sonic Ethnography

Understanding environmental values of local stakeholders is not only important for environmental governance, but local knowledge has the potential to feedback into approaches to environmental management and decision making through giving insight into sustainable land use practices. Traditional Indigenous Knowledge (TIK) is increasingly recognised as not only legitimate but critical in academia in general (Snively et al., 2018) and in environmental research and policy in particular (Menzies, 2006). However, articulating TIK in ways commensurate with the bureaucratic processes that must be engaged with in order to protect them is challenging. Our recent research highlighted the importance of the acoustic environment, or soundscape, for the wellbeing and culture of indigenous Waorani peoples of Ecuador (Moscoso et al., 2018). In a current action research project, we are working with the the Ancestral Kichwa Population of Kawsak Sacha (PAKKS), a group of seven communities in eastern Ecuador to support their application for National Heritage status.

Contemporary ecoacoustics research establishes the role of soundscapes in ecosystem function as well as human and animal wellbeing, but for these Kichwa populations, soundscape is the interface not only between cultural and ecological processes, but spiritual dimensions:

We use the songs to communicate with the jungle and its guardian spirits, to call the animals of the forest or the fish of the river, to invoke or promote the fertility of the crops, to cure evils and diseases, remembering and transmitting the teachings left by our ancestors, to live well together. They are like roads and bridges that reconnect us with our history and with our origins. The living beings of the jungle also have their own way of expressing the life that manifests through them. The set of songs heard is like a symphony, which took millions of years to write. It is a unique and priceless creation, which we cannot let be destroyed or disappear. Didier Lacaze - Sacha Warmi

Integrating approaches from TIK, anthropology, soundscape ecology and conservation we are working to innovate and evaluate bespoke, transdisciplinary, participatory soundscape methods as a vehicle for registering indigenous cosmology: a vessel for cultural heritage, a vector for articulating conservation imperatives and a voice for earth jurisprudence. Through this participatory action research, we hope to generate new knowledge on the role of soundscape in the life and cosmology of indigenous peoples that can be applied as a tool for safeguarding both TIK and Amazonic ecosystems as a coupled cultural-ecosystem.

Promises and pitfalls

These case studies illustrate the potential for soundscape methodologies in real world conservation settings. Enabled by affordable recording technologies, Rapid Acoustic Survey enables cost-effective, accessible tools for communities to take ownership of evidencing their own conservation initiatives in ways that are meaningful at the community level, and can produced data that are recognised by governmental schemes. The integration of ethnographic and computational approaches to soundscape study provides the potential for stakeholder values to be integrated with hard data, toward more inclusive mapping, monitoring and management, providing a means to develop nested environmental governance institutions.

First generation acoustic indices described here have created a step change in environmental monitoring, but the use of these hand crafted statistical summaries do not generalise across habitats. Advances in machine learning provide more powerful possibilities to automatically generate audio features using convolutional neural networks to embed soundscapes into a common acoustic space (Sethi et al., 2020). The results are impressive, but even this highly generaliseable method fails to capture the fundamentally *dynamic* nature of ecosystems and their interaction with anthropogenic processes. The final section of this paper points to a promising integration of CAS and acoustic perspectives.

Listening to Ecosystems as Complex Adaptive Systems: Toward Acoustic Early Warning Signals

One of the key promises of CAS in environmental monitoring is in recognising critical transitions, or tipping points. Where emergent structures persist through self organisation, systems may exhibit alternative stable states, the ecological 'value' of which may differ; the transition from one basin of attraction to another (Scheffer et al., 2009). Classic examples include freshwater lakes, characterised by states with either clear-water and macrophytes, or turbid water and plankton (Scheffer et al., 1993), or coral bleaching events from which reefs can die or recover. The attractor landscape characteristically exhibits hysteresis meaning that reverting a system from a turbid to clear-water state or recolonising a reef is demonstrably difficult (Jeppesen et al., 2007). As noted by Hagstrom and Levin (2016) a major challenge here is that these dynamics play out on multiple scales of space, time and organisational complexity, which presents a fundamental modelling challenge and difficulty in collecting data at the appropriate temporal resolution, which may not be known in advance.

The first generation of EWSs were predominantly derived from the theory of critical slowing down (CSD), which refers to the fact that as a system approaches a tipping point, it's resilience (ability to withstand external forcing) decreases, leading to a concomitant decrease in stability (ability to return to its previous state after a perturbation) (Scheffer et al., 2009). Drawing from Dynamical Systems Theory, tipping points can be theoretically characterised by the dominant eigenvalue approaching zero (Boettiger et al., 2013); the corollary is that when a system is far from equilibrium its dynamics are random fluctuations (white noise) and as it approaches the attractor, the noise reddens (Dakos and Soler-Toscano, 2017). In practical terms, slowing down of systems' ability to return manifests in observable behavioural changes in ecosystem inhabitants. Dakos et al have demonstrated that a suite of readily calculable abundance based statistics alter predictably as a bifurcation point is approached. Variance, autocorrelation, density ratio and skewness all increase; return rate decreases (Dakos et al., 2012). EWS can be thought of in simple terms as a significant temporal trend in these statistical moments.

One key advantage of CSD derived ESWs is that they require few assumptions, meaning that they are readily applicable to a range of systems. These generic indicators have been shown to be present prior to the transitions biological and non-biological systems across scales, from squid giant axons (Matsumoto and Kunisawa, 1978) to abrupt changes in global climate change (Dakos et al., 2008), including whale stocks (Clements et al., 2017). However, ecological data are notoriously noisy and distinguishing trends in summary statistics is challenging. One issue with classical EWS based on CSD is that various types of bifurcations that cause large-scale transitions are *not* preceded by CSD, undermining their widespread applicability. Another issue is that they require high quality, reliable, long term abundance data (Hefley et al., 2013; Clements et al., 2015). It should also be noted that the majority of studies have focused on theoretical expectation of their presence, without control.

An emerging alternative is the use of trait information; fitness-related phenotypic traits such as body size in particular. Trait based approaches offer several advantages: Body size is known to determine the fate of an individual (Ozgul et al., 2009) and dynamics of the population (Ozgul et al., 2014); Environmental experience of a population can be inferred from the distribution of plastic phenotypic traits, providing an indication of likely demographic response to future environmental perturbation (Ellner and Rees, 2006) and changes in plastic phenotypic traits are likely to precede changes in abundance (Ozgul et al., 2014). This potential has been demonstrated in microcosm experiments where declines in mean body size of stressed populations, significantly preceded their collapse, and are also linked to generic abundance-based signals. However, this approach still suffers from paucity of data and whilst theoretically convincing, it has yet to be demonstrated that trait based EWS are *early enough*, i.e. in time to make interventions before a tipping point is reached.

An exciting possibility that has yet to be explored is the development of *Acoustic* Early Warning Signals. Just as phenotypic changes such as body size precede population changes, so we might expect that individual *behavioural* changes in response to changing environmental conditions will be affected well before they register in phenotypic change. Behavioural changes may manifest in changes in vocalisation patterns of some organisms and even register in movement of others (as in soil bioacoustics) (Maeder et al., 2019). Affordable, robust, programmable acoustic recorders enable collection of acoustic time-series data which is readily scaleable across space and time from seconds to days to months to years. Automated features can be calculated on the time-scale of interest and retrospectively sampled to fit the phenomena of interest. The potential for Acoustic Early Warning Signals - for ecosystem recovery as well as collapse holds great promise and warrants investigation.

Summary and Future Work

Effective strategies for monitoring and managing systems at human-environment interfaces have never been more critical to the future of life on earth. Cost-effective tools for ecosystem monitoring are a critical component. However, it has long been recognised that time-honoured simple species counts are neither viable (manually, they don't scale), nor instructive: the essential dimensions of diversity extend above and below species level (Levin, 1998). The potential for soundscape methodologies to complement CAS frameworks for the monitoring and management of human-environment interfaces has been outlined. Approaching the soundscape as an ecological resource, and source of information points to the potential for *listening* not only to ecosystem status, but to the soundscape as the site of interaction of ecological and anthropogenic processes. At the same time the paucity of both theory and computational methods in Ecoacoustics could benefit Artificial Life approaches in general and concepts and tools from the study of CAS in particular. Framing the soundscape as an epistemological nexus affords integration of ethnographic, ecological and computational methods, providing a means to integrate human perspectives and values into environmental monitoring and inspiring new directions in computational analysis. Acoustic Early warning signals are just one potentially rich avenue for research. Other valuable research possibilities at the interstices of ecoacoustics and Alife include:

- *Acoustic Alife and ecoacoustic simulation studies.* Observing firstly that the acoustic component of CAS has traditionally been neglected, and secondly that ecoacoustics suffers a theoretical paucity (Farina et al., 2021), we recently introduced Synthetic Acoustic Ecology (Eldridge and Kiefer, 2018); this sonically situated flavour of Alife evolutionary agent-based model has spawned further research in acoustic niche differentiation (Kadish et al., 2019; Masumori et al., 2020) developing a new acoustic theme in Alife and a new branch of ecoacoustic simulation studies which hold promise for advancing both fields.

- *Ethnographically-informed computational ecoacoustics.* The value of data collection methods that align with local epistemologies enables *nesting* and *institutional variety* through the interaction of local, regional and global institutions; these are identified as key factors in adaptive governance of complex systems and empower local governance. The need for dynamical approaches has also been stressed. Simply deploying acoustic features in EWS measures is one approach; another is to combine ethnography and participatory design to draw inspiration from TIK: How might the deep tacit knowledge of hunters, forest societies, fishers, foresters be used to inform algorithm design for next generation conservation technology? How might such approaches be integrated with increasingly common participatory mapping and modelling methods to enrich our view of socio-cultural-ecological CASs through multiple perspectives?

As the human population continues to expand, and with it the anthroposphere, the ability to monitor the interaction of ecological, socio-cultural and technological agencies becomes ever more critical; research at the interstices of ecoacoustics and Artificial Life is well placed to make a positive contribution to ensuring a harmonious future for people and planet.

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