PILOT PROJECTS FINAL REPORT		
Call round: 1		
Pilot Project Title: *Toward a Measure of Soundscape Dynamical Acoustic Complexity*		
PI: Alice Eldridge	**Research Organisation:** University of Sussex	
Department: Music	**Start Date:** Oct 2022	**Duration** 5 months
Cost of award (80%): £46,885	**Value of co-investment:** **In kind:** FTE staff time for Prof. Seth **Cash:** £2k – workshop Salary: The School of Engineering and Informatics additionally committed a further month PDRA salary	
Co-I and associated RO: **Co-Is** - Dr Adam Barrett, University of Sussex, Lecturer in Machine Learning and Data Science. - Dr Ivor Simpson University of Sussex, Lecturer in Artificial Intelligence. - Dr Chris Kiefer. University of Sussex, Senior Lecturer in Music Technology - Prof. Anil Seth University of Sussex, Professor of Cognitive and Computational Neuroscience Post-doc - Dr David Kadish	**Acoustic Research themes:** Potential impact is greatest in ARP 4 (Climate Change) and ARP 21 (Soundscape), methodological advances are also relevant to ARP 11 and 16 (Mathematics and Computer science); activities build bridges between wider ARPs and special interest groups (SIGs). • Acoustics for manufacturing and industry • Acoustics for understanding of climate change • AI for making sense of sounds • Computer science for acoustics • Impact of sounds on wildlife • Mathematics for acoustics • Understanding of soundscapes	
Collaborations & Partnerships involved in project: Tell us about bi-lateral or multi-lateral partnerships/participation by the PI or research team in a network, consortium, multi-centre study **PARTNERS – Third Sector, Industry, Government & Policy interface** **National and Global Conservation Organisations** - Dr Jan Dick (Senior Landscape Ecologist), Long-Term Ecosystem Research in Europe, EU. https://elter-ri.eu/, and Centre for Hydrology and Ecology, UK, https://www.ceh.ac.uk/ - Dr Jonathan Carruthers-Jones (Director), Observatoire de la naturalité, FR		

- Dr Paola Moscoso. (Head Scientist and Restoration Manager), Humans for Abundance NGO, Ecuador. https://www.humansforabundance.com/

Policy Actors
- Dr Rosalyn Putland. Centre for Environment, Fisheries, and Aquaculture Science, UK. https://www.cefas.co.uk/
- Dr Carlos Abrahams (Ecological Consultant & DEFRA policy advisor), UK. https://bakerconsultants.co.uk/

Conservation Technology Companies and Organisations
- Stephanie O'Donnell. (Community Manager), Wildlabs, https://www.wildlabs.net/about
- Alex Rogers (Co-Director), Open Acoustic Devices, https://www.openacousticdevices.info/audiomoth

Project Partners

Value and details of in-kind co-investment: - **NA**	**Value and details of cash co-investment:** **NA**

Summary: A summary that can be published on our website (please do consider providing photo/images)

Context: Listening in to ecosystems in recovery. In the face of rapid biodiversity loss and climate change, numerous national and global initiatives aim to foster ecosystem restoration strategies. Current research increasingly calls for restoration of ecosystem *complexity* over specific species targets (Bullock et al 2022, Moreno et al 2020). however, tools for monitoring and measuring ecosystem complexity are underdeveloped. In this project we understand the soundscape as emergent ecosystem property and postulate that information about ecosystem complexity* may be reflected in the soundscape.

So how do we go about measuring the soundscape? Two paradigms dominate contemporary computational ecoacoustics: automated recognisers, for example using deep learning to identify target species; or soundscape indices, which provide statistical (Eldridge et al 2018) or learned (Sethi et al 2020) descriptions of the spectral or temporal structure of the global soundscape. Both show promise as methods for ecological monitoring, however, both approaches currently focus on the analysis and description of short (1-10min), independent samples, obviating analysis of intrinsic higher level spatio-spectro-temporal soundscape dynamics.

Ultimately, we interested in methods to measure the *dynamical complexity* of soundscapes and to understand the relationship between soundscape complexity and ecosystem complexity – including integrity, structure and function. As the first step, in this pilot we explored three novel approaches to model, map and measure the soundscape temporal dynamics across scales. These included astronomical histograms (astrograms) of soundscape descriptors to visualise and model soundscape diurnal dynamics (see Fig 3); phase space reconstructions to visualise the attractor dynamics of dawn and dusk choruses; and measurements of the temporal complexity of acoustic features over minutes and hours. Each was calculated for a range acoustic features and soundscape indices. Here we introduce the *Astrogram*. To find out about the others you will have to keep an eye out for our forthcoming paper.

Introducing Astrograms – a method to visualise and model soundscape dynamical signatures

In a recent metareview of acoustic indices as proxies for biodiversity Alcocer et al (2022) reported that 40% of the 35 studies they reviewed relied on spatially and/or temporally pseudoreplicated data. This means that data were collected close together in space and time, and then analysed as independent samples. Issues with pseudoreplication are well documented in biological sciences (Colegrave & Ruxton, 2018) and occur when assumptions of statistical independence are violated. Spatial and temporal pseudoreplication are both common in ecoacoustics. Sound is dynamic in space and time, therefore it is common to sample at regular time intervals across multiple local sites. However, these samples are often then included in analysis as *independent* samples. This causes two issues. Firstly in, statistical terms, failing to account for spatiotemporal autocorrelation can artificially inflate sample sizes, leading to overestimated effect sizes, an increase in type 1 error and incorrect inference. Secondly by treating samples independently we lose information about the spatiotemporal dynamics of the soundscape, that we believe may give key information about ecosystem status. This is true whether we wish to use the data to test a hypothesis using classical statistical methods, or if we wish to build a regression or classification model to test their predictive power.

Alcocer et al (2022) suggest taking an average per day, per site as one means to avoid issues associated with pseudoreplication, and they adopt this approach in their meta-analysis. Whilst this overcomes the statistical issues, it leads to further information loss and a loss of specificity as soundscapes are known to change throughout the day. How else might we represent these data such that we can preserve quintessential soundscape dynamics within clearly interpretable statistical models?

As part of our pilot, we developed and tested the astronomical histogram, or *Astrogram* as rapid, compact yet expressive representation of soundscape diurnal dynamics. This method can be used for any descriptor of feature.

We know that the activity of a healthy acoustic community will vary with astronomical phase of the day (dawn, day, dusk, night). We hypothesised that the pattern of differences between phases – what we might call “diurnal dynamics” may be *more* characteristic of ecological status than an average representation of the soundscape across the same period. We first calculated a range of soundscape indices and acoustic features for one-minute recordings taken from acoustic surveys that were carried out across habitat gradients in temperate and tropical biomes (see Eldridge et al 2018 for details). The data set comprised one minute every 15, around the clock for ten days at 15 sample points in each of three sites across a gradient forested (1), regenerating forest (2) and agricultural land (3)) in Ecuador (EC) and the UK (4 * 24 * 10 * 15 * 3 = 43200 samples in each biome).

We first calculated a set of 9 feature including basic audio descriptors (root-mean-square, zero-crossing-rate, spectral centroid and spectral flux) and five so-called “soundscape indices” (acoustic complexity index, bioacoustics index, acoustic evenness index, spectral entropy and temporal entropy). To test our hypothesis, we built a logistic regression model with habitat status as response and compared the prediction accuracy of astrograms (10 bins at each of 4 phases) with both histograms (10 bins) and summary statistics (mean, variance, skew, kurtosis for each day) for each day at each recorder as predictors.

The value of the approach is evident from a visualisation of each: Figure 1 shows kernel density estimate plots for the distributions of each site. The apparent distinctions are a little clearer in the histograms of figure 2, but if we separate according to astronomical phase (Figure 3) we can clearly see distinct patterns for each site. This approach ameliorates issues of pseudoreplication whilst preserving key ecological information.

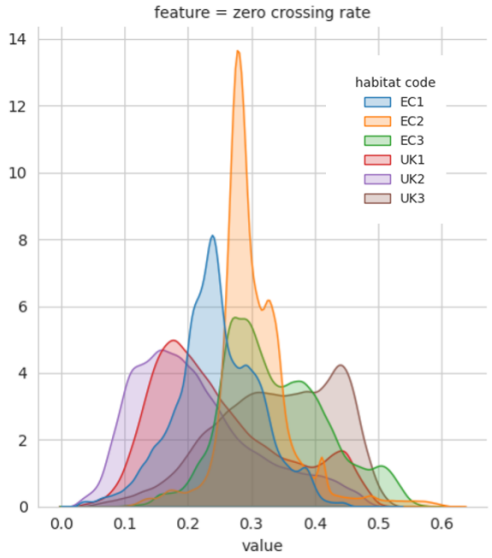

Figure 1. Kernel density estimate plots of a random 5% subset of data demonstrate differences in the distributions between sites. Results for zero-crossing-rate shown for illustration.

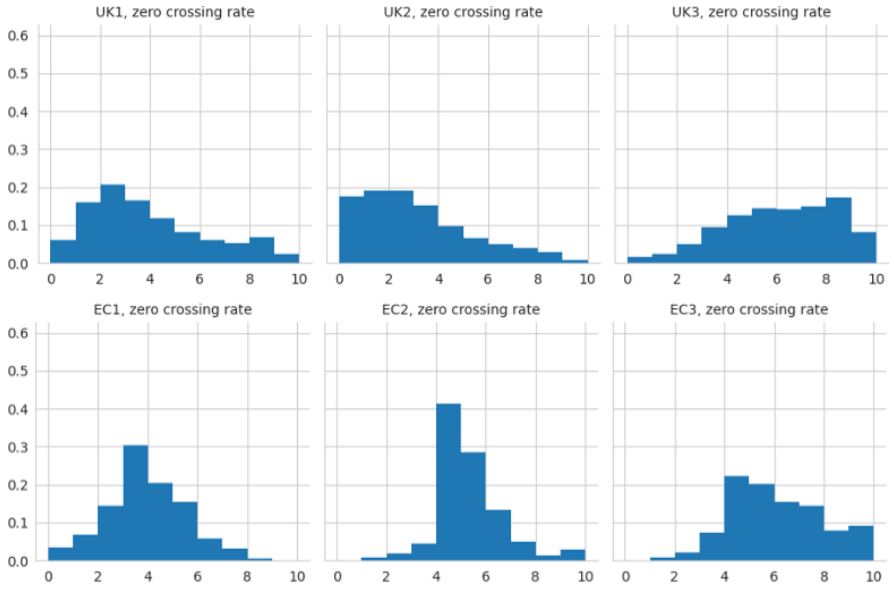

Figure 2. Histograms provide a compact, discrete representation of the data, but obviate visualisation and analysis of soundscape diurnal dynamics. Results for zero-crossing-rate shown for illustration.

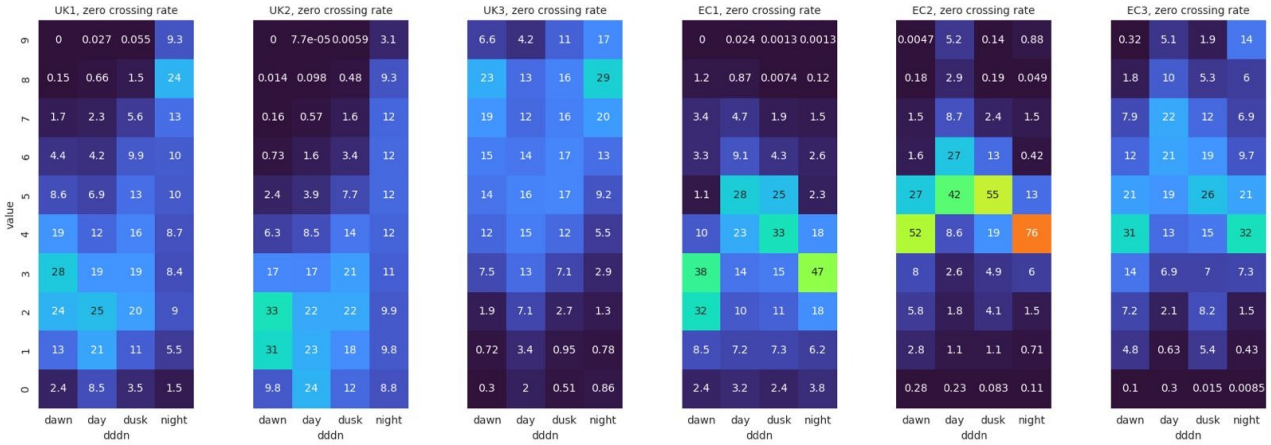

Figure 3. Astronomical histograms (Astrograms) of raw features reveal distinct soundscape diurnal dynamics across sites of differing ecological status. Astrograms represent a three-dimensional normalised histogram of values for a given acoustic feature across four phases of the day. Ten equal intervals are shown on the y-axis, time of day on the x-axis and frequency of each value scaled from dark blue to red. Dawn and dusk are defined as double the length of time between civil dawn and sunrise, beginning at civil dawn, and dusk is double the length of time between sunset and civil dusk, ending at civil dusk**.**

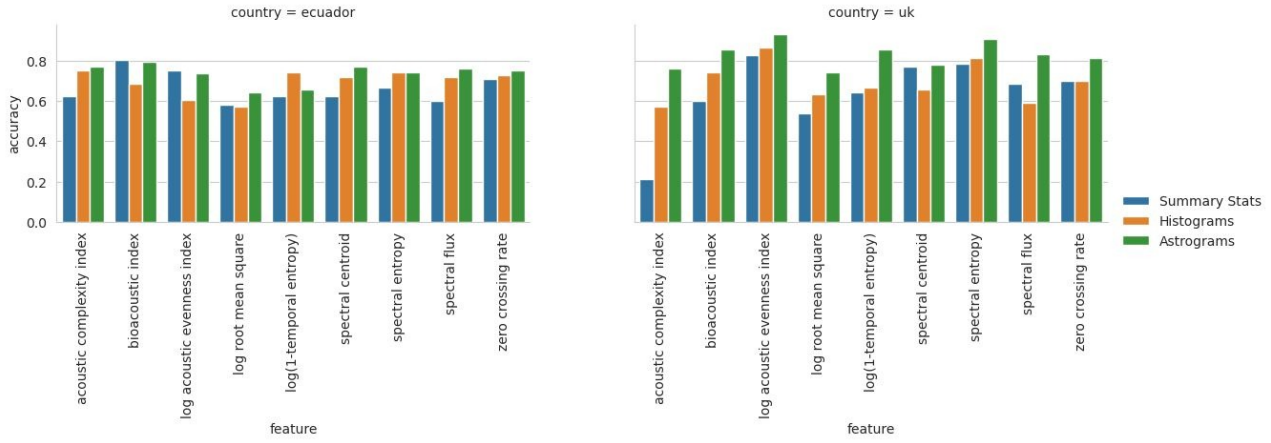

Figure 4. Classification accuracy rates for a logistic regression model with either summary statistics (blue), histograms (orange) or astrograms (green) as predictor and habitat status as response show an overall trend toward highest accuracy for astrograms.

Summary and conclusion. These results suggest that *temporal* dynamics of soundscapes provide valuable information about ecological status over and above independent or averaged analyses of raw features, as is current common practice. Further investigation of soundscape attractor dynamics and feature complexity metrics further bolster this position. Together the results of our pilot inspire future work to develop theory and methods for soundscape *dynamical complexity* and to investigate the relationship between soundscape dynamics and ecosystem complexity to advance basic science and support ecological restoration projects nationally and globally.

References

Alcocer, I., Lima, H., Sugai, L.S.M. and Llusia, D., 2022. Acoustic indices as proxies for biodiversity: a meta-analysis. *Biological Reviews*, *97*(6), pp.2209-2236.

Bullock, J.M., Fuentes-Montemayor, E., McCarthy, B., Park, K., Hails, R.S., Woodcock, B.A., Watts, K.,

Corstanje, R. and Harris, J., 2022. Future restoration should enhance ecological complexity and emergent properties at multiple scales. *Ecography*, *2022*(4).

Colegrave, N. and Ruxton, G.D., 2018. Using biological insight and pragmatism when thinking about pseudoreplication. *Trends in ecology & evolution*, *33*(1), pp.28-35.

Eldridge, A., Guyot, P., Moscoso, P., Johnston, A., Eyre-Walker, Y. and Peck, M., 2018. Sounding out ecoacoustic metrics: Avian species richness is predicted by acoustic indices in temperate but not tropical habitats. *Ecological Indicators*, *95*, pp.939-952.

Moreno-Mateos, D., Alberdi, A., Morriën, E., van der Putten, W.H., Rodríguez-Uña, A. and Montoya, D., 2020. The long-term restoration of ecosystem complexity. *Nature Ecology & Evolution*, *4*(5), pp.676-685.

Sethi, S.S., Jones, N.S., Fulcher, B.D., Picinali, L., Clink, D.J., Klinck, H., Orme, C.D.L., Wrege, P.H. and Ewers, R.M., 2020. Characterizing soundscapes across diverse ecosystems using a universal acoustic feature set. *Proceedings of the National Academy of Sciences*, *117*(29), pp.17049-17055.

Objectives: As stated in the original case for support

The project aimed to build evidence and partnerships for a large-scale grant to investigate measures of the emergent complexity of soundscapes through four objectives:

O1) Partnerships. To establish partnerships with 1) ecological restoration programmes 2) policy actors and 3) conservation technology organisations through a series of workshops
O2) Pilot. To establish the potential value of this approach by carrying out exploratory analyses on existing terrestrial, marine and freshwater data sets.
O3) Publish. To publish a peer-reviewed position paper and a technical report.
O4) Grant. To write at least one large grant to validate the approach.

Outcomes/Impact*: Please refer to stated objectives. What impact has this had on the Acoustics Sector? How are the results being applied? Please provide specific examples/evidence to support the provided statements.

We ran a successful workshop at the start of the project to build partnerships **(O1)**; PI and Co-I Simpson were invited to share findings at a small R&D workshop[1] at Kilpisjarvi Research Station[2], Finland (funded by Oulu University, Biodiverse Anthropocenes programme[3]). This cemented partnerships with Dr Dick at CEH and Dr Caruthers-Jones and built consortia for future Horizon bids and means that we still have budget for a third workshop to finalise bid plans (see O4).

O2) Pilot was successful in a) bolstering support for the potential application of information theoretic metrics b) evidencing the value of further investigation into soundscape temporal dynamics and complexity measures.

The pilot proceeded in two phases. In phase one we carried out exploratory correlation analyses and took a first look at Grainger Causality (see interim report). Whilst results were promising we realised that there was insufficient time to carry out a sufficiently rigorous

analysis to enable interpretable results during the pilot project. We took the decision to invest the remaining time in systematic exploration of temporal structures and dynamics, a necessary foundation for more sophisticated analyses. In the process we made a methodological innovation which overcomes issues of temporal pseudoreplication and facilitates visualisation and analysis of soundscape diurnal dynamics. To the best of our knowledge, we have carried out the first state space reconstruction analysis of dawn chorus dynamics. Finally, we developed and tested a means to measure feature complexity, as a means to assess soundscape temporal complexity across scales and demonstrated an increase in conditional mutual information for temporal complexity and habitat, conditioned on raw features.

O3) Publication is in draft for submission to *Methods in Ecology and Evolution*.
In addition, Co-I Kiefer has published the following peer reviewed conference paper, based on ideas generated during the proiect:

- Kiefer, C. Dynamical Complexity Measurement with Random Projection: A Metric Optimised for Realtime Signal Processing. Sound and Music Computing, Stockholm, 2023

O4) To date we have submitted four **further grants** (two awarded), one awaiting review; the main large-scale grant is in preparation.

Submitted and rejected

1. EPSRC New Horizons (£250k): *Investigating Soundscape Dynamical Acoustic Complexity as a proxy for Ecological Integrity*. PI: Eldridge. Status: reject

Awaiting review

2. EPSRC New Investigators Award. PI Barrett

Submitted and awarded

3. NERC Discipline Hopping (£19k). Listening Below: Investigating Complexity Metrics for Ecoacoustics in Reef and Soil Ecosystems. PI: Eldridge. Status**: awarded.**

4. Engineering and Informatics (£8k) HEIF *Ecoacoustic Monitoring Dashboard for Sussex Sustainable Woodlands.* PI Simpson, Co-I Eldridge, Kiefer. PDRA Kadish. Status: **awarded**

In preparation

5. NERC Pushing Frontiers (£1M) deadline July 2023: *Complexity, Causality and Meaning: Advancing Computational Ecoacoustics for Long Term Ecosystem Restoration*. PI Eldridge

Impact
The astrogram methodology developed during this pilot will be applied in a HEIF funded *Ecoacoustic Monitoring Dashboard*. This is a collaboration with Lewes and Eastbourne District Council and local Woodland Enterprise Centre[4]. Funded by the Forestry Commission, the project explores the potential for sustainable, commercial timber from small scale woodlands of Sussex and Kent. We are supporting them in developing an acoustic monitoring protocol to evidence the impact of timber extraction on woodland biodiversity.

Notes

1) https://www.oulu.fi/en/projects/extending-realities-pioneering-visual-acoustic-and-sensory-technologies-transdisciplinary-research

2) https://www.helsinki.fi/en/research-stations/kilpisjarvi-biological-station

3) https://www.oulu.fi/en/research/arctic-interactions-resilience-and-global-change/biodiverse-anthropocenes

4) https://www.woodnet.org.uk/

***What activities have you undertaken to engage with research users, special interest groups and the general public to inform them about the research?**

1. Academic and stakeholder: Conceptual outline of research presented as part of keynote at UKAN annual talk. (https://acoustics.ac.uk/ukan-annual-meeting/
2. Academic and stakeholder: Interim results presented at research workshop in Finland (see footnote 1) above)
3. Research users: Currently collaborating with Forestry Commission funded local council project to support sustainable forest products.
4. General public: invited to lead Ecoacoustics work in france: https://www.campfr.com/course/onsite/77/ecoacoustics-listening-transmitting-and-curating-soundscapes-with-alice-eldridge-raquel-castro-grant-smith-leah-barclay-annea-lockwood-and-hildegard-westerkamp

In preparation:

5. Once we have published a pre-print we will post a blog at international conservation technology project wildlabs.net/

***Have any new research tools or methods been created or commissioned, if so, provide details: -**

We have innovated a simple new method for visualising and analysing soundscape diurnal dynamics.

***What activities have you undertaken to engage with research users, special interest groups and the general public to inform them about the research?**

Replicate question?

***Have any new research datasets, databases and models making, or potential to make, significant difference to your research (or that of others), been created, if so, provide details: -**

Previously unpublished data from Leverhulme grant RPG2014 will be published on Zenodo.

Conclusion: What is the primary outcome of this research? This pilot enabled us to build a strong interdisciplinary team, carry out pilot research and build a consortium to develop a new paradigm for computational ecoacoustics based on soundscape emergent complexity.	
Plans for follow-on activities/grants: How are these results being used to further the area of research or its application in an industrial setting? We are currently working with local authority and local organisations to develop acoustic monitoring in support of sustainable forestry products. We are currently preparing at £1M bid for the NERC Pushing Frontiers call to continue the research.	
Weblink: (to the outcome of the project, the Open Access repository for the data[1], or press releases): New library and python notebooks for all plots will be available at https://gitlab.com/groups/ecolistening/	
List of publications: in peer reviewed or non-peer reviewed literature. If no publications are available, what are the plans to publish? Please follow UKRI guidelines for Open Access **https://www.ukri.org/manage-your-award/publishing-your-research-findings/** We achieved more robust analyses than we anticipated, therefore we are preparing a full journal article, rather than position paper plus technical paper. - The main article is in preparation for submission to Methods in Ecology and Environment. - As above, we have already had success in follow on funding (albeit small). The results from this study of temporal complexity in reef chorusing are in preparation for a technical report/ pre-print in bioarxiv. As above, one peer reviewed conference paper has already been authored. This is not a direct outcome, but was inspired by the work of the team and is attributable to the grant for the sake of reporting (research fish etc.) Kiefer, C. Dynamical Complexity Measurement with Random Projection: A Metric Optimised for Realtime Signal Processing. Sound and Music Computing, Stockholm, 2023 (in press).	

[1] As a UKRI award holder you must follow their research data policies- https://www.ukri.org/manage-your-award/publishing-your-research-findings/making-your-research-data-open