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The call of the wild: Investigating the potential for ecoacoustic methods in mapping wilderness areas

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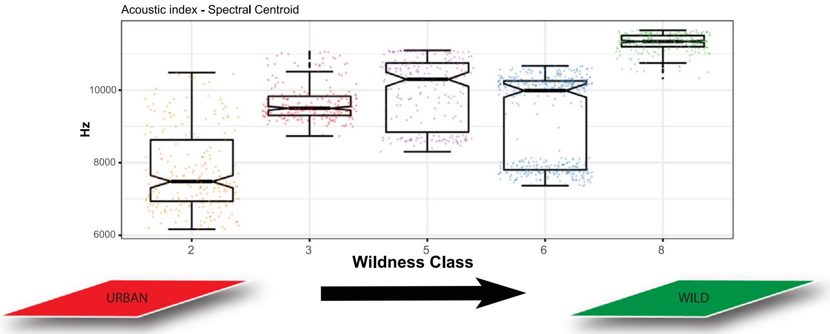
HIGHLIGHTS

- Wilderness mapping methods exclude critical ecological and anthropogenic dimensions.
- Ecoacoustic methods are proposed as a potential means to address this lacuna.
- Acoustic surveys and participatory walks were carried out along urban-wild gradients.
- Acoustic indices predict mapped and perceived wilderness and perceived biodiversity.
- Ecoacoustics should be incorporated into future mapping and new indices developed.

GRAPHICAL ABSTRACT



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ABSTRACT

The critical importance of wilderness areas (WAs) for biodiversity conservation and human well-being is well established yet mapping criteria on which WA management policies are based take neither into account. 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 this paper 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. An important next step is to ascertain the ecological and anthropogenic relevance of these differences, and develop new automated acoustic analysis methods suited to mapping

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the environmental characteristics of WAs. Taken together, our results suggest that future management of WAs could benefit from ecoacoustic methods to take the biosphere and anthroposphere into account.

1. Introduction

Wilderness areas (WA) are critical to sustaining both biodiversity and human well-being (Watson et al., 2016). WAs are considered the "last refuges" for many rare and endangered wild animals and plants (Mittermeier et al., 2003), and have a significant role in ensuring the long-term persistence of biodiversity (Soule and Noss, 1998; Watson et al., 2009; Mittermeier et al., 2015) and they provide a mechanism for coping with the threats of climate change and other impacts of human development. At the same time, the value of WAs for human well-being (Barton et al., 2016; Harper, 2017) and sense of place (Hausmann et al., 2016) is increasingly recognised. Urban expansion and landscape fragmentation have significantly reduced the overall amount, size and connectivity of WAs globally (Ellis et al., 2010) heightening the strategic importance of their systematic identification (Kuiters et al., 2013; Wilson, 2016; Lin et al., 2016) and stimulating urgent calls for new methods to comprehensively and cost-effectively map remaining areas (Carver and Fritz, 2016). In this paper we propose that the emerging field of ecoacoustics (Sueur and Farina, 2015) could serve as a useful complement to extant approaches by firstly providing a unifying framework within which anthropogenic, geophysical and ecological perspectives can be conceptually integrated and secondly providing a cost-effective, scalable method for incorporating biodiversity assessment.

Debate over the best approaches to the protection of wilderness has a long history at both global and European levels (Thoreau, 1862; Wilderness Act, 1964; Soule, 2001; Zunino, 2007). The International Union for the Conservation of Nature (IUCN) describes two main attributes of WAs (Protected Area designation - Category Ib): a relatively high degree of ecological naturalness (the degree to which an ecosystem has deviated from its original state due to human influence), and the absence of human artefacts (e.g. roads, houses, train lines etc.), (Dudley, 2008). Within Europe especially, the term "*wildness*" is now argued to be less politicised than "*wilderness*" and also captures the smaller size of the remaining intact land areas on the continent (Ward, 2019). Wildness quality mapping represents wildness on a relative scale capturing not just areas of high wildness, but the entire continuum from urban to wild. Most examples of wildness quality maps in Europe use satellite data to create maps on a continuum from least wild (e.g. the centre of a large urban conurbation) to most wild (e.g. a remote corner of a mountainous region) (Sanderson et al., 2002; Carver et al., 2012; Müller et al., 2015). Maps usually comprise four key layers: perceived naturalness; absence of modern artefacts; rugged or challenging terrain; and remoteness from roads and ferries. Similar multi-criterion approaches, based on satellite data, have been developed in many regions: Australian national wilderness inventory (Lesslie and Maslen, 1995), the wildness quality index for Europe (EEA, 2010), the human footprint index at the global scale (Sanderson et al., 2002), the map of Denmark (Müller et al., 2015), and the Cairngorm National Park Wildness Quality map (Carver et al., 2008).

This multi-criterion approach is attractive because it can be operationalized at scale using satellite data and Geographical Information Systems (GIS) to create comprehensive maps that support landscape management and decision making such as for renewable energy projects or protected area management (McMorran and Carruthers-Jones, 2015; Ma and Long, 2019, see also Scottish Natural Heritage, 2014). However, overdependence on remotely sensed national scale datasets means that key facets of ecological and human importance are neglected. Human experiences of WAs are intrinsically situated, multisensory and subjective. The value of WAs from a human perspective cannot be mapped remotely, but requires in situ assessments in order to reflect the rich, multi-sensorial and subjective reality of how people understand and value wild places (Ólafsdóttir et al., 2016). Current attempts to develop complementary methods to capture human-level experience repurpose everyday technologies to support terrestrial mapping: e.g. viewshed analysis, an approach adapted from computer gaming, has been explored in order to assess ground-level vistas, rather than aerial land cover (Carver and Washtell, 2012; Sang, 2016); and social media networks have been co-opted to enable crowdsourcing of visitor perceptions of trails in the USA (Carver et al., 2013; See et al., 2016). Such approaches begin to capture human perspectives but focus exclusively on *visual* attributes of the wild landscape, and struggle to capture wider human experience.

The use of "walking" or "mobile" participatory methods to research people's attitudes to place has also grown markedly in recent decades as a key research tool for capturing data relating to people's experience, knowledge and attitudes to surrounding landscapes (Macpherson, 2016; Ingold and Vergunst, 2008). Participatory methods have been used to capture a range of attributes, including cultural and experiential values for WAs and their potential long-term benefits (Holden, 2016; Brown et al., 2017; Dorning et al., 2017). Capturing stakeholder attitudes to landscape may be most accurately performed in the field, despite the challenges this brings (Scott et al., 2009). Walking research offers an intuitive and compelling means of studying human relationships with landscape and place (De Certeau, 1984; Pink, 2015). When walking methods involve walking interviews, they have been found to generate deeper place-based narratives than sedentary research practices, particularly in terms of narrative quantity and spatial specificity to the study area (Evans and Jones, 2011). However most structured approaches to walking methodologies have focused exclusively on urban zones and a key challenge remains as to how this fine-grained local qualitative knowledge can be implemented in a structured way so as to allow comparison between individuals and across different habitat types and landscape gradients. An outstanding methodological challenge is how to design conceptual frameworks for combining the rich qualitative data that comes from these mobile methods with the quantitative data available from remote sensing which forms the bedrock of current wildness mapping approaches.

In ecological terms, the current approach to mapping wildness within Europe (using data based primarily on human influence) fails to capture key ecological characteristics, including biodiversity. Contemporary wildness debates highlight how depleted many designated WAs are in terms of their native species as well as their overall levels of biodiversity (Lewis et al., 2016; Monbiot, 2014; Pheasant and Watts, 2015; Guetté et al., 2018). In response, approaches to measuring the *intactness* of natural processes are being explored (Dearden, 1989; Leroux and Rayfield, 2014; Lesslie, 2016). However, operationalising an assessment protocol for use at scale has yet to be achieved. Comprehensive, scalable methods to incorporate biodiversity assessments within WA mapping remain a significant challenge (Pettorelli et al., 2018).

The need for cost-effective biodiversity assessment tools is of course not limited to WA mapping, but is a requisite across all fields of conservation. Situated within the emerging discipline of Ecoacoustics (Sueur and Farina, 2015) there is increasing interest in acoustic methods for biodiversity appraisal from researchers, managers and policymakers alike. Ecoacoustics understands the acoustic environment, or *soundscape* (Pijanowski et al., 2011), as a resource, and therefore as a source of information about ecological status - the soundscape being structured through evolutionary processes, akin to other niche construction processes. Based on the assumption that computational analyses of acoustic recordings therefore provide a biodiversity proxy, an ecological machine listening is emerging, dubbed Rapid Acoustic Survey (Sueur et al., 2008a, 2008b).

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 such as WAs, because it is non-invasive, obviates the need for expert aural identification of individual recordings, is potentially sensitive to multiple taxa and scales cost-effectively (Sueur et al., 2008a, 2008b).

As well as providing cost-effective monitoring methods, ecoacoustics offers a valuable conceptual framework to integrate biospheric and anthropogenic perspectives. Following Odum's (1953) classification of broad ecosystem components, elements of the soundscape are described according to their source: *Geophony* denotes the sounds made by abiotic processes (wind, rain etc.) in the landscape; *biophony* the sounds of animals; and *anthrophony*, the sounds of humans (Pijanowski et al., 2011) We find the term *technophony* (Gage and Axel, 2014) to be more useful in order to refer specifically to the noises of man-made powered machinery, which are distinct in terms of their acoustic signals and resulting impact on soniferous species communication. The soundscape is therefore a site of rich interaction between processes of the lithosphere, biosphere, hydrosphere and anthroposphere: machine listening provides a means to listen to and interpret these interactions. In terms of WA mapping, soundscape components provide descriptors for auditory correlates of existing WA criteria (e.g. distance from road) and a unified framework within which to consider facets of biodiversity and human experience which are currently absent in wildness quality mapping and excluded in decision making.

We propose a new direction for WA mapping and management by investigating the potential for ecoacoustics as both a conceptual framework and a monitoring method to integrate human and ecological perspectives with current geophysical WA mapping schema. We report the first systematic investigation of the relationship between acoustic indices, wildness quality metrics and in situ human subjective perceptions of wildness and biodiversity. Our investigation is structured by the following questions:

Q1) How do AIs differ along a gradient of mapped wildness categories?

Q2) What is the relationship between AIs and a) wildness categories and b) human subjective perceptions of wildness and biodiversity?

Q3) Do AI predict a) wildness quality b) human perceptions of wildness and biodiversity?

We predict that a) overall sound levels and presence of low frequency signals will decrease with increasing wildness as we move away from roads and other human influence; If wildness is associated with higher biodiversity, then b) we would expect an increase in biophonic activity with increasing wildness. If AIs are sensitive to factors which influence human perceptions of WAs other than those captured in wildness quality metrics, then we would expect c) AIs to predict human perceptions more strongly than wildness classes.

2. Methods

2.1. Study sites

Study transects were identified at four sites across the Scottish Highlands and the French Pyrenees, each along comparable gradients from urban to wild. Existing maps of wildness were available for both countries. The four sites were Invereshie & Inshriach National Nature Reserve (I&I) on the Scottish east coast (57° 6′ 45″ N, 3° 50′ 39″ W), Beinn Eighe National Nature Reserve (BEN) on the Scottish west coast (57° 36′ 8″ N, −5° 19′ 0″ W) (Fig. 1) Lesponne, Hautes-Pyrenees (LES) southern France (42° 58′ 51″ N, 0° 8′ 44″ E), and Pouey Trenous, in the centre of the Pyrenees National Park (POT), southern France (42° 50′ 6″ N, −0° 9′ 35″ W). Transects were identified through a combination of desk-based GIS analysis to identify the optimum gradients, supported by discussions with local experts from Scottish Natural Heritage (SNH), the Centre for Mountain Studies and Pyrenees National Park respectively. SNH developed a version of their wildness quality map for Scotland for use in the definition of Wild Land Areas (SNH, 2014) which used a statistical method known as "Jenks" classification, to reclassify all pixels on the map with a similar value for wildness into eight classes, least to most wild. This simplified Jenks version of the wildness map was made available by SNH for this project. The authors used an identical statistical process to reclassify the map of haute-naturalité of the Haute-Pyrenees, produced by IUCN France, into eight Jenks wildness classes (WC) - least wild to most wild (supplementary materials A). This existing remote sensed data on wildness provided a reference condition against which to measure other data types. These simplified Jenks maps of wildness were then used in the GIS to search for a transect that covered a viable continuum of wildness - least wild to most wild - which could be walked in 5 to 6 h.

At all sites, transect gradients spanned a small village (WC2) to a high mountain area (WC8) and the high wild areas feature relatively intact natural areas representative of the Scottish Highlands and French Pyrenees, as defined by the local park authorities. Eight acoustic survey points and participant questionnaire points were selected along the transect at each site, matched across sites to give equivalent representations of WC and habitat. See Table 1 for the description of the subset of sites studied.

2.2. Participant recruitment and perception surveys

Stakeholder participant groups were identified using a strategic iterative snowball process (Dougill et al., 2006; Reed et al., 2009; Colvin et al., 2016) which aimed to: i) avoid imposing a selective stakeholder typology, ii) develop a rounded understanding of who had an interest in the issue, and iii) ensure no social groups were excluded. Participants were recruited through local press, social media, organisational contacts, and member groups such as mountain clubs. Human perception data was collected in situ along the same experimental transects from a total of 73 participants (BEN $n = 11$, I&I $n = 31$, LES n = 31) (see Carruthers-Jones et al., 2019 for details). No human data was collected at POT because extreme weather made the paths impassable during the planned human survey period. Participants were briefed and guided along the transects in groups of eight or less. At each sample point (see for example Fig. 1), participants rated their immediate surrounding landscape in terms of wildness and biodiversity on a scale of 1(least) – to 7 (most) (see Supplementary Material B for questionnaires). To minimise the impact of weather on participant experience, all walks were conducted on days of non-extreme weather conditions (absence of lying snow cover, high winds or heavy rain). Walks at Scottish sites were conducted between April and September 2017; walks at French site LES were conducted during June–September 2018.

2.3. Acoustic surveys

Acoustic surveys were carried out for four days at each of the eight sample points at each site sequentially (I&I and BEN 20th–29th July 2017; LES and POT September 2017). To avoid introduction of additional human sound sources, participatory walks and acoustic surveys were held on different days; surveys were carried out during daylight hours to match the acoustic environment experienced by walkers.

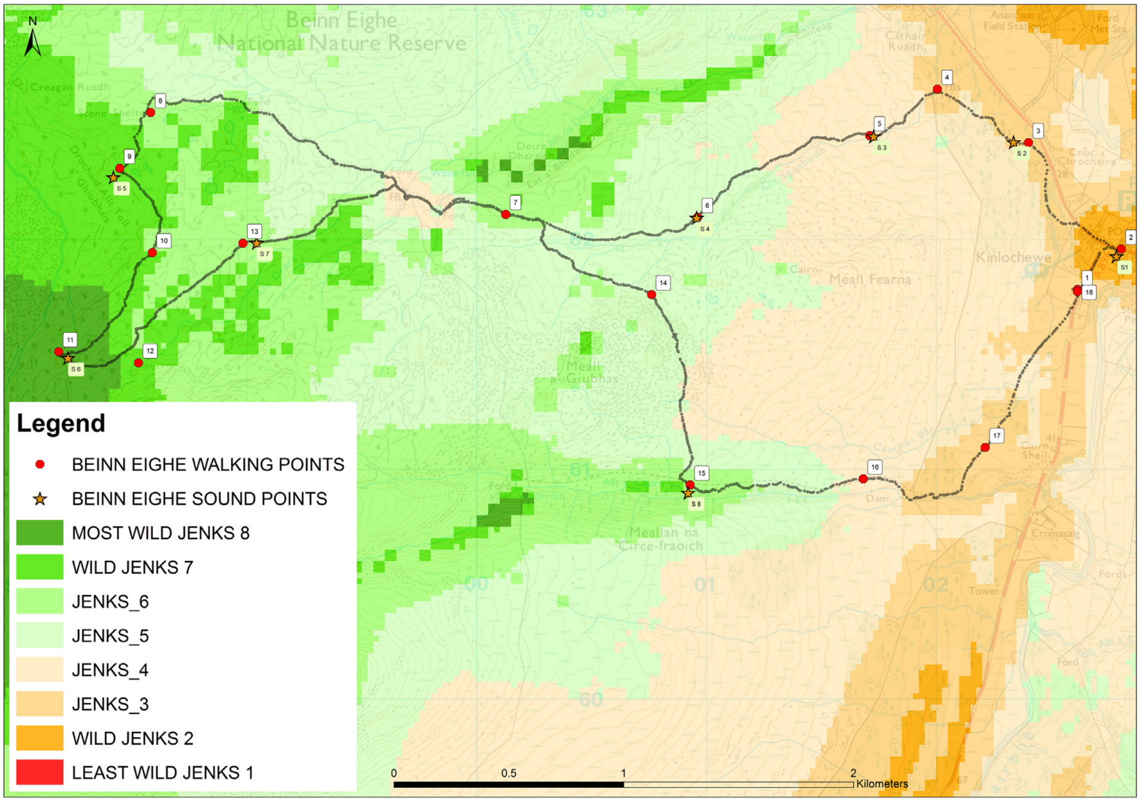

Fig. 1. Example of transect walk along gradient of Jenks wildness classes for Scottish site Beinn Eighe National Nature Reserve (BEN) on the Scottish west coast (57° 36′ 8″ N, −5° 19′ 0″ W) showing human perception and acoustic survey points. See Supplementary Material A for corresponding maps of other sites.

Recordings were made for 5 min in every 15 min between 07:00 and 21:00 using eight Wildlife Acoustics Song Meter SM2+ offline digital recorders at 16 bit amplitude resolution with a 48 kHz sampling rate and a gain of +36 dB, giving a total of 7168 stereo files. The Song Meter is a battery powered, offline, programmable weatherproof recorder, with two channels of omni-directional sound and a flat frequency response between 20 Hz and 20 kHz. Recorders were fixed to trees or posts at 1.5 m above ground level and orientated south to standardise for prevailing weather conditions and wind noise (see Supplementary Materials A and C for details of acoustic survey points).

Manual screening of audio data confirmed that the left (opposite to prevailing weather) channel was consistently less distorted by wind, so the right channel was dropped from the analysis; mono recordings were pre-processed using a high pass filter at 1 kHz to remove remaining artefacts whilst preserving low frequency energy associated with human influence (technophony). Equipment failure and extreme weather rendered 1275 files (17%) unusable; these sites were dropped from the recordings leaving a total of 5893 files (I&I, $N = 1351$; BEN, $N = 1110$; POT, $N = 1715$; LES, $N = 1717$). This left five matched sample points (from the original eight) at each of the four study sites, representing five different wildness classes. See Table 1.

Table 1
Descriptions of habitat at each of the five wildness classes studied.

Jenks wild class	Description of Scottish sites	Description of French sites
2	Least wild, urban site	Least wild, urban site
3	Lowland, Plantation native woodland	Lowland, woodland edge
5	Middle mountain, open mountain heath/moorland	Middle mountain, grazing
6	Upland, natural native woodland site	Upland grazing pasture surrounded by native woods
8	Most wild, mountain, upland scrub	Most wild, mountain, ancient woodland

2.3.1. Acoustic indices

AIs were selected and designed based on extensive literature review and our previous validation studies (Eldridge et al., 2018). Six acoustic indices were selected from over 50 initially explored to characterise: a) biophonic activity as an indicator of biodiversity; b) technophonic activity as an indicator of human influence and c) overall sound energy as an indicator of absence of noise. Three *ecological indices* which have been demonstrably linked with biodiversity in temperate biomes were chosen as biodiversity proxies: Acoustic Complexity Index (ACI) which has been reported to correlate significantly with the number of avian vocalisations in an Italian national park (Pieretti et al., 2011); Bioacoustics Index (BAI) (Boelman et al., 2007) which is reported to show significant association with avian species richness (Fuller et al., 2015) and Acoustic Evenness Index (AEI) (Villanueva-Rivera et al., 2011) which has been shown to strongly predict avian species richness (Eldridge et al., 2018); A novel variant of the Normalised Difference Soundscape Index NDSI (Kasten et al., 2012), the Relative Technophony Index (RTI) is introduced as a measure of technophony (see Supplementary Material D for details); and two standard acoustic descriptors used in machine listening tasks to track overall sound energy: Root Mean Square (RMS) and Spectral Centroid (SC), a measure of the overall distribution of sound energy across the frequency spectrum (Peeters, 2004). Median values for RMS and SC were used as they are more robust to outliers. See Supplementary Material D for details of all AIs. All acoustic analyses were carried out using a bespoke Python library (Guyot, 2018) which implements and extends R libraries seewave (Sueur et al., 2008a, 2008b) and sound ecology (Villanueva-Rivera and Pijanowski, 2018).

2.3.2. Auditioning

In order to support interpretation of the acoustic indices, a subset of recordings was selected by taking the median value for RMS at each sample point for each site as indicative of the acoustic activity at that site. These were auditioned by JCJ, AE and PG, noting the dominant sound sources (cars, planes, people, birds, wind, rain). Recordings are available at http://tiny.cc/mdiq6y.

2.4. Statistical analyses

To explore how each AI differs along a wildness gradient (Q1), Wilcoxon signed-rank tests were carried out to test for differences in AI values between pairs of WCs across days. To investigate the relationship between AIs and WCs and human perceptions of wildness and biodiversity (Q2), two-tailed Spearman's rank correlation tests were carried out between each of the six AIs and respective wildness measures and human perceptual judgements. All analyses were carried out for all sites combined, as well as for all sites individually.

Previous ecoacoustic research has demonstrated that compound metrics are more powerful than any single AI in predicting biodiversity metrics such as species richness and/or abundance (Eldridge et al., 2018; Towsey et al., 2014). Therefore, to test whether acoustic analyses predict either WC or human perceptions of wildness (Q3), multivariate random forest regression models (Breiman, 2001) were built using all six AIs as predictors and either WC or human perception of wildness or biodiversity as response. Multivariate random forest regression creates a model based on multiple decision trees to describe a response variable based on one or more predictors, then merges those trees to obtain a more accurate prediction; they are tolerant of deviations from parametric assumptions and skew in the data. The total percentage variance explained and mean squared error (MSE) of the model provide an indication of the predictive strength and accuracy. The relative contribution of predictors was assessed using Variable Importance (VIMP): the difference between prediction error when a given predictor variable is noised up by randomly permuting its values, compared to prediction error under the observed values.

3. Results

3.1. Do AIs differ along urban-wild gradients?

AIs plotted by WC for all sites combined reveal a large degree of scatter for individual AI values (Fig. 2), suggesting a wide range of variation within and between wildness classes across sites. SC shows the strongest increasing trend overall. RMS and BAI show the strongest decreasing trend.

Comparisons among sites (Fig. 3) show significant differences between WCs in five out of six AIs demonstrating strong variation in acoustic environment across the urban-wild gradients studied. In all but one case (AEI at BEN) there are significant differences between extremes of wilderness gradients (WC2 and WC8), but none vary as a simple monotonic function of WC, and considerable variation is observed in the patterns of significant difference between sites, suggesting that there are variations in the soundscape beyond those reflected in current wildness quality maps.

The clearest trend is observed in the SC, which tends to increase, reflecting an overall reduction in low frequency energy as we move along urban-wild gradients; RMS similarly tends to decrease, reflecting an overall reduction in amplitude of all sound signals. Within this general trend, median values for some survey points are significantly above (POT 3) and below (LES 5 and LES 6, BEN 6) values at the ends of the gradient in urban and most wild sites, others show markedly larger variance (BEN 6). RTI largely mirrors SC, showing significant decreases from peri-urban (WC2) to remote sites (WC8) across locations. BEN is the exception here where there is a significant *increase* with increasing wildness. The same sites, LES 5 and LES 6 and POT 3, show marked deviations from otherwise almost linear trends. Biophonic activity, as indicated by the ecological indices (BAI, AEI and ACI) tends to *decrease* from urban to wild sites with significantly greater values between WC2 and WC8 at each site except BEN, which shows an increase. The clearest trend is visible at I&I.

3.2. What is the relationship between AIs and a) wildness categories b) human subjective perceptions of wildness and biodiversity?

Correlation analyses (Fig. 4) suggest that WCs largely reflect human perceptions of wildness and biodiversity, with strong positive correlations in all sites tested. AIs show predominantly moderate, significant correlations with WC, but these vary in magnitude and direction across sites (Fig. 4 top rows).

In line with analyses of AI against wildness class (Fig. 3), acoustic features SC and RMS show the strongest and most consistent relationships. SC shows a moderate, positive relationship with WC and distance from road at sites I&I, LES and POT; relationships with human perceptions of wildness and biodiversity are similar at I&I and LES, however BEN shows no significant relationship between SC and either WC or human perceptions of wildness, but a moderate negative relationship with biodiversity. RMS shows a moderate (I&I, LES) to strong (POT) negative relationship with WC and distance from road.

The relationship between WC and ecological indices ACI, AEI and BAI are significant but vary in magnitude and direction across sites, suggesting variation in levels of biodiversity along the urban-wild gradient between sites. This pattern of relationships seen with WC is the same for distance from road and human perceptions, except at BEN where fewer significant relationships are observed.

Finally, RTI shows significant relationships, but contrary to our predictions, does not show positive relationships with WC or distance from road: moderate negative correlations are observed with all four measures in I&I, small positive relationships in BEN and no significant correlations observed in LES (WC) or POT (WC or Road).

3.3. Do AIs predict mapped and perceived wildness?

Multivariate regression models show that the six AIs tested strongly predict wildness class at each site with low error (Fig. 5). Variance explained for all sites combined is lower than for any individual site apart from BEN, suggesting that variation between sites is stronger than that along the urban-wild gradient. Variable importance varies between sites (Table 2), however RMS and SC are in the top three most important variable at all sites, together explaining over 50% of the variance, in line with the prediction that sound levels will decrease and dominant frequency will increase along urban-wild gradients.

Finally, a comparison of models built for all components shows that for all sites combined, compound AIs predict human subjective judgements of biodiversity (82.22%; MSE 0.25) and wildness (77.29%; MSE 0.64) even more strongly than mapped wildness classes (76.21%; MSE 1.15) and are surprisingly poor predictors of distance from road (69.81%; MSE 599.59).

4. Discussion

We investigated the relationships between AIs, currently designated wildness classes, and human subjective judgements of wildness and biodiversity. A range of statistical analyses were used to investigate how sound levels, frequency content and soundscape components varied along urban-wild gradients at four different sites. Our results demonstrate that i) the soundscape varies

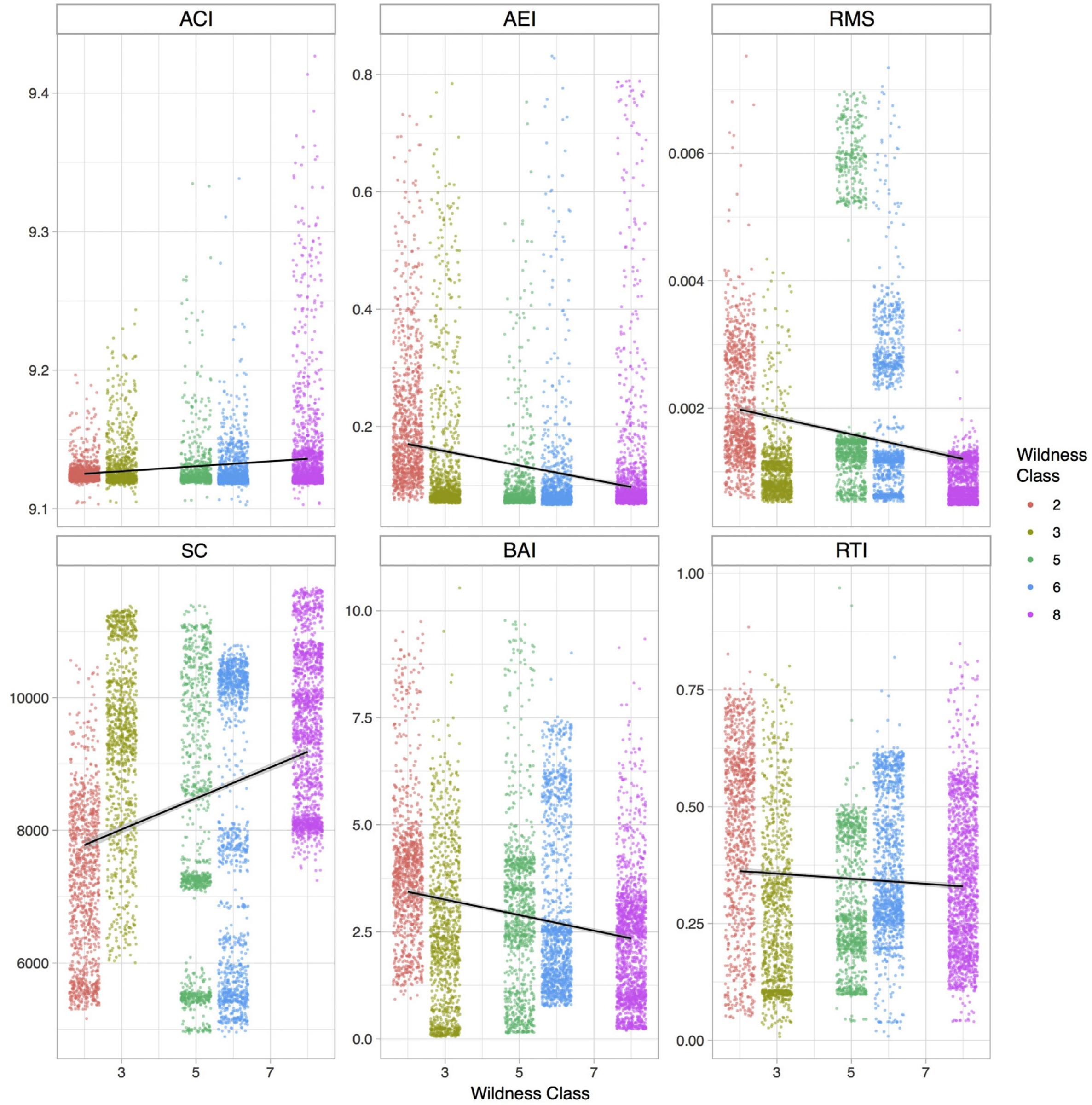

Fig. 2. Scatter plots of AIs (rows) across WCs for all sites combined with linear model fitted (in black).

significantly over wildness class; ii) there are significant variations in soundscape across wild classes between study sites; iii) biophonic activity does not necessarily increase with increasing wildness; and iv) AIs predict human perceptions of wildness more strongly that current wildness classes.

4.1. The soundscape varies significantly over wildness class

The simple acoustic features investigated are in line with the first prediction, that overall sound levels and presence of low frequency signals will decrease with increasing wildness. The increase in SC at all sites (Fig. 3) suggests that peri-urban sites are dominated by lower frequency components than wilder locations. The decrease in RMS across the same gradient suggests that sites generally get quieter as wildness class increases. These results demonstrate that the soundscape varies with human influence and that acoustic metrics recapitulate existing components of wildness mapping.

The RTI was introduced as a measure of the relative dominance of low frequency energy and an explicit proxy for distance from human influence. We predicted that RTI would decrease as we move from urban to wild spaces, mirroring SC, as traffic noise decreases with increasing distance to the road. This trend is observed at I&I (Figs. 3, 4) but is far from consistent across sites. Reviewing the sound recordings reveals that there are high levels of car noise at WC2 and that WC8 is relatively quiet without plane or wind noise, which may explain the clear predicted trend found at this site. Conversely, the opposite trend is evident at BEN and a review of the sound recordings reveals this is driven two factors. Firstly, the low value of RTI at WC2 and WC3 is not due to absence of traffic, but rather the close proximity of cars, and increased noise from wet roads generating high frequency energy (up to 8 kHz), and therefore lower values of RTI. Secondly, at the wilder locations, WC6 & WC8, jet fighter activity (low frequency) is clearly audible in the sound recordings at the higher, more exposed locations leading to higher values for RTI. Derived from the NDSI (Kasten et al., 2012), this band-limited index is

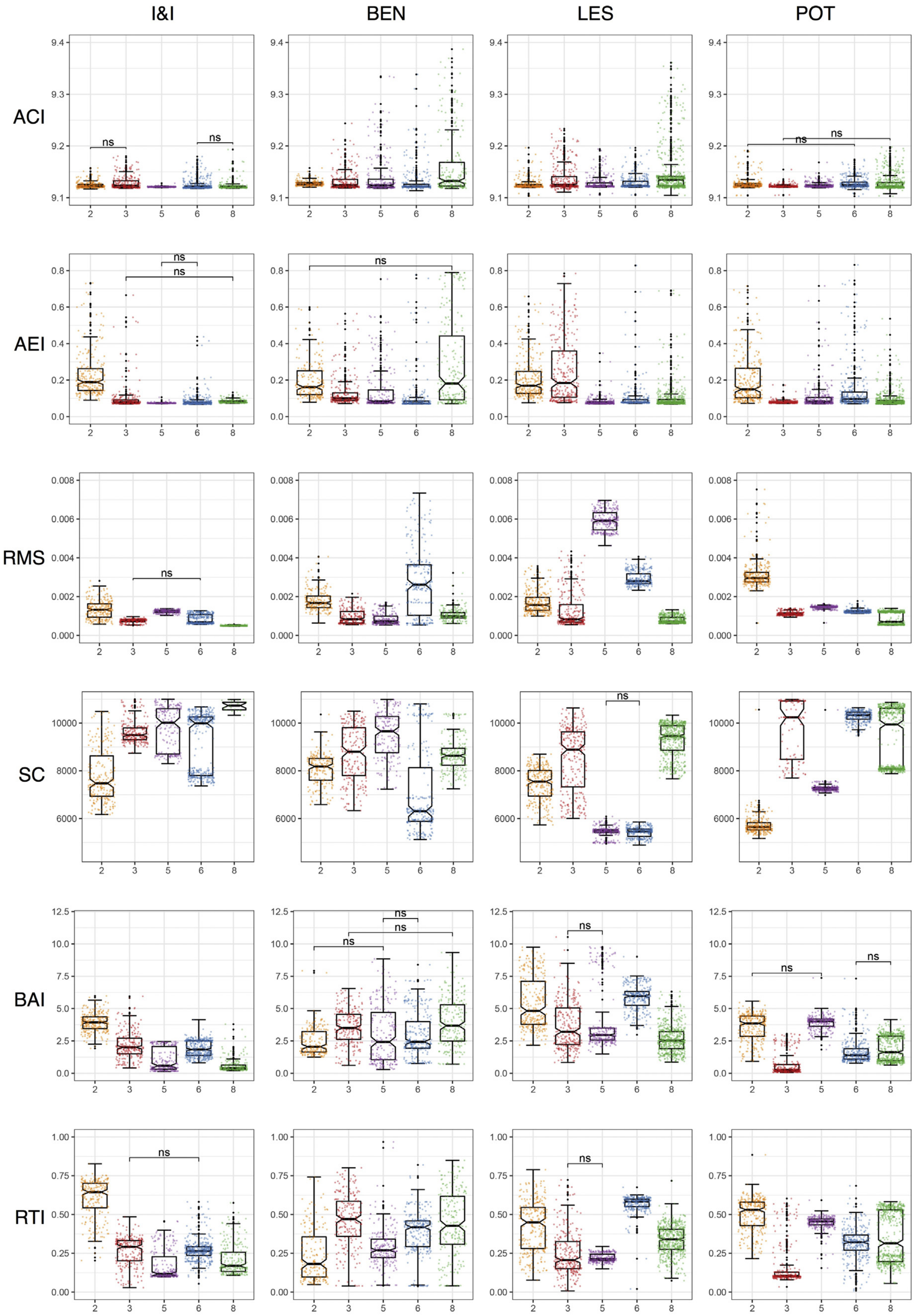

Fig. 3. Tukey's box and whisker plots for AIs values (rows) across days for each WC for each study site (columns). Horizontal lines represent medians; the box represents the interquartile range; whiskers represent min and max values within 1.5 IQR. Non-significant differences ($p < 0.05$) between sites are denoted by bars ns. Individual AI values shown as points.

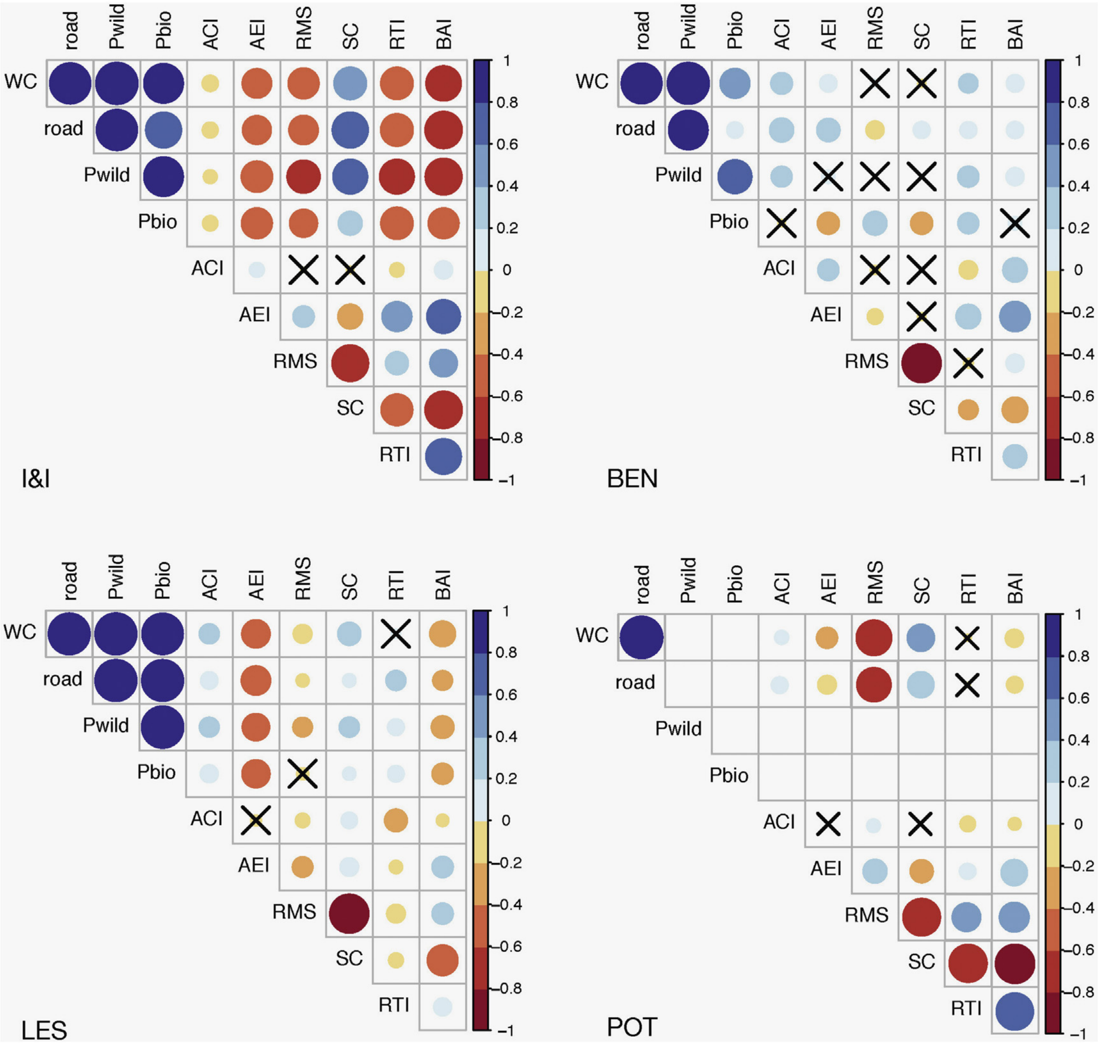

Fig. 4. Correlation matrices of Spearman's rank coefficients for correlations between Wild Class (WC), distance from road (road), human perceptions of wildness (PWild), human perceptions of biodiversity (Pbio) and acoustic indices for all sites (I&I top left, BEN top right and LES bottom left and POT bottom right). Crosses denote non-significant correlations (95% confidence intervals). Note that no human data is available for POT.

based on the assumption that the sound of human industry (technophony) contains predominantly low frequency components. This is true at landscape scales or where sample sites may be surrounded by vegetation cover which attenuates high frequency components of signals. In urban settings, where traffic is in close proximity to sample points, these assumptions of band-limited sound signals break down, and so new approaches to acoustic monitoring may be needed across urban-wild gradients.

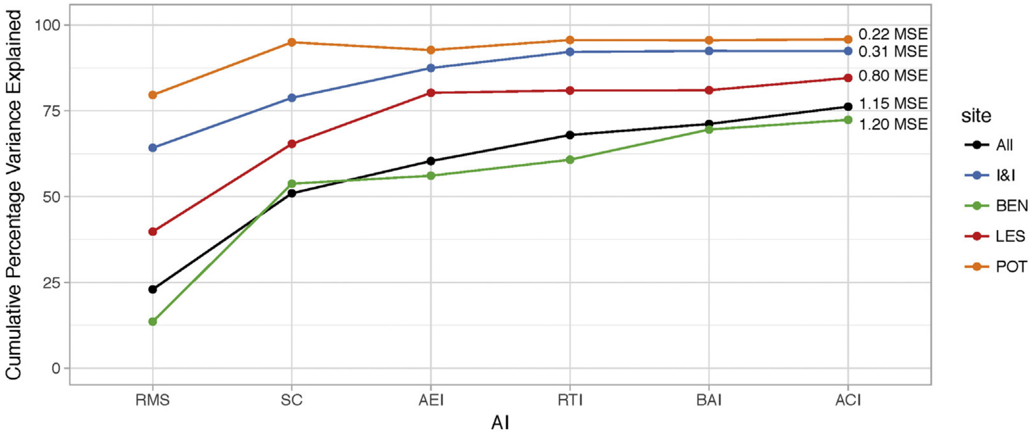

Fig. 5. Cumulative percentage variance explained by multivariate random forest regression models with 6 AIs as predictors and wildness class as response for all sites combined (76.21% MSE 1.15) each site (I&I 92.44% MSE 0.31, BEN 72.37% 1.2 MSE, LES 84.56% 0.8 MSE, POT 95.81% 0.22 MSE). Out of bag error rates for the six AI model are detailed at the right of each curve. AIs were added to each model in the order of variable importance for all sites combined (x axis).

Table 2
Relative variable importance for AIs as predictors of wildness classes at each site and all sites combined.

AI	Relative variable importance				
	ALL	I&I	BEN	LES	POT
RMS	1.00	0.96	1.00	0.88	0.89
SC	0.66	1.00	0.62	1.00	1.00
AEI	0.56	0.41	0.74	0.95	0.04
RTI	0.50	0.37	0.58	0.27	0.29
BAI	0.48	0.54	0.50	0.23	0.36
ACI	0.43	0.11	0.61	0.45	0.09

4.2. There are significant variations in soundscape across urban-wild gradients and between sites

Within these overall trends there are significant differences in soundscape along gradients and differences in the magnitude and direction of correlations, suggesting there is wider environmental variation than that captured in current wildness quality mapping methods. The ecological relevance of these variations requires further study. Auditioning the recordings reveals that the anomalous trends in BEN are due primarily to gusting winds in the WC6 and WC8, which generates broadband energy, resulting in the large variance in both SC and RMS at WC6. The anomalous patterns observed at LES 5 and LES 6 (high RMS, low SC) are due to river and running water near the site which generates acoustic energy in the low frequency band.

The need for high quality biophysical naturalness metrics linked to land use and management, as well as broader ecological approaches to measuring the intensity and biophysical impact of anthropogenic activities, have been cited as key future challenges for the mapping of wildness (Lesslie, 2016). The considerable variation observed in the patterns of significant difference between sites (Fig. 3) suggests that AIs are sensitive to differences between recorder locations not captured by current wildness class mapping schema. Systematic interpretation of these differences requires more detailed ecological data sets as a baseline.

4.3. Biophonic activity does not necessarily increase with increasing wildness

Values for ecological indices BAI, ACI and AEI do not show either strong positive correlations, or significant increases across gradients as predicted under the assumption that biodiversity increases along urban-wild gradients. This could be due to absence of biophonic activity or inadequacy of the indices. Auditioning of the recordings for site BEN suggests that the trend from other sites is confounded here by high wind noise (gusts) and rain (drops) creating acoustic energy within a range that is commonly associated with bird vocalisation, especially at sites WC6 and WC8. BAI fell from WC2 to WC8 at all sites except BEN, suggesting lower levels of biophonic activity at the wild end of the urban to wild gradients measured. Auditioning for site I&I revealed much higher levels of biophonic activity (abundance and species richness) at WC2 compared with all other sites at I&I, and WC8 was effectively silent.

It is proposed that this pattern is driven by a number of factors. Firstly, as a general trend, all high wildness sites were also higher in terms of altitude than low wildness sites. Biodiversity is known to fall with altitude and the resultant lower temperatures, as is evidenced by the importance to avian richness of summer temperature (Lennon et al., 2000; Marzluff et al., 2012). Other studies have shown that avian richness is higher in urban areas with diverse habitats than in upland areas (Rosenfeld, 2013); and more widely that biodiversity can be higher in urban gardens than in semi-natural landscapes (Thompson et al., 2003). Furthermore, the high wildness sites of the type found at WC8 in I&I and BEN for example, are recognised as being ecologically impoverished compared to their original post-glacial state (Hobbs, 2009; Fisher et al., 2010).

A second key factor is the deployment period for the recorders which for practical reasons did not coincide with peak annual avian activity. This was compounded by unseasonably bad weather at both the Pyrenees study sites. Auditioning revealed that bird vocalisation across these two sites was much lower than would be expected based on expert knowledge of the sites.

The results for the AIs designed to capture biophonic activity were also confounded by the high frequency components of noise from cars, wind and rain, as outlined above. AIs such as BAI for example were originally designed for monitoring use in more remote, tropical areas, low in technophony. In the current study, the higher frequencies resulting from technophony are also detected by the sound recorders at the low wildness peri-urban sites (WC2 & WC3).

4.4. AIs predict human perceptions of biodiversity more strongly than wildness classes

AIs strongly predicted wildness class, but human perceptions of wildness and biodiversity are even more strongly predicted. As discussed above, further work is needed to validate the use of acoustic methods for biodiversity monitoring in wilderness mountain areas, but these results suggest that acoustic methods are sensitive to the same factors which influence human experiences of wilderness, which current mapping methods are insensitive to.

4.5. Recommendations

The complexity and dynamically evolving nature of the relationship between humans and their landscape requires us to change our perspectives and seek new ways of understanding these complex spaces that are also better suited and more robust for use in planning, nature conservation and policy making (Hennig and Künzl, 2016). Our results stimulate further work in the application of ecoacoustic methods in wildness mapping methodologies in order to ensure that they better reflect ecological and human processes and values. The next important steps are, firstly, the development of new AIs better suited to assessing the components of soundscape relevant to measuring wilderness across urban-wild interfaces; secondly, validation of these acoustic methods with baseline data from biodiversity and local habitat assessment in order to establish the ecological significance of the variations across sites observed here. This will require repeated local spatial replications, as well as replications across different biomes. The transects selected for this study spanned a continuum of low to high wildness across a relatively short distance of around 10 km. Whilst this was necessary in order to enable human participants to walk the transects in a single day, future iterations of the methodology may benefit from using a protocol, with short, medium and long transects across a more diverse range of habitats/ecotones. At some study sites the issue of scale could be further explored by using a nested protocol so the long transect would contain a short and a medium transect. Using longer transects would allow spatial replication of acoustic surveys within a given wildness class, and thus provide better understanding of the characteristics of these areas, how acoustic events relate to local environmental data, as well as highlighting any possible edge effects. More specifically, the use of precisely positioned and configured arrays of sound recorders inside a particular wildness class would also add greater resolution to the analyses, capturing the “near field” ecoacoustic events which may better reflect the detail of the localised variation in the perceptual experience of a wilderness soundscape for both humans and other resident vocal species (Farina, 2019). Combining this multi-scalar approach with longer term deployment of the recorders over the period of a full year is also recommended to capture seasonal variation in acoustic events, and would also reduce sensitivity to extreme weather or other ephemeral events.

New acoustic analyses for wilderness mapping are also needed to deal with geophonies associated with extreme weather and water in mountainous wilderness areas. Our results show that simple acoustic features (RMS and SC) are more strongly correlated with changes in the soundscape across urban-wild gradients than ecological indices. This is in line with previous work in which these simple descriptors were also stronger predictors of avian species richness (Eldridge et al., 2018). Results also suggest that technophony (e.g. cars passing) contains high frequency components and that geophonic components (e.g. wind, rain and rivers) are similarly broad spectrum, rendering band-limited indices unsuitable.

Two distinct approaches to automated acoustic analyses have been deployed to date: ecoacoustic indices such as those tested here which have been designed by hand, based on assumptions about the statistical structures of particular soundscape components (biophonies and technophonies). In contrast, automated identification of individual species calls (Stowell and Plumbley, 2014) has tended to use supervised clustering or neural network style models trained with pre-selected canonical examples of specific species calls. Both approaches may be problematic for WA assessment due to wide variation of acoustic signatures across different biomes of the same wildness designation. An alternative approach, which warrants further investigation, is to repurpose the internal representations of neural networks to serve as machine-generated acoustic indices. When neural networks are trained, they create internal models of the data on which they are trained. These “latent spaces” are representations of the original audio signals which could be used to cluster or classify similar acoustic events in an unsupervised manner. In the context of wilderness mapping, this has the advantage of providing a means to machine-generate acoustic features without recourse to spurious assumptions over the spectral characteristics of particular acoustic events, or the need for extensive training data. Moreover, once trained on a known urban-wild gradient, the model could be used for monitoring or mapping extant or newly designated wilderness areas in similar ecotones.

5. Conclusion

The critical ecological and societal importance of WAs is well recognised, yet the metrics and maps which subserve current wilderness management policies take neither directly into account. We report the first investigation into the potential for ecoacoustics to provide a cost-effective, scalable method for biodiversity assessment and a framework for integrating anthropogenic and ecological perspectives within existing geophysical frameworks. Our results demonstrate that a small suite of AIs strongly predict wilderness gradients, but also reveal considerable environmental variation within areas of equal wildness as designated under current metrics. The potential ecological relevance of this variation requires further investigation which we propose is best addressed by adding full habitat and bird surveys to the data collection methods reported here, as well as detailed transcription of soundscape components from site recordings. We further demonstrate that AIs predict human perceptions of biodiversity and wildness, suggesting that acoustic methods capture important facets of the human experience of wildness. We argue that in recognising the acoustic environment as the nexus of atmospheric, biospheric and anthropogenic processes, ecoacoustics also provides a framework within which to integrate ecological and anthropogenic perspectives on wilderness, answering calls for new approaches to conceptualising and measuring wild spaces as the site of complex and dynamic human-environment relations (Lesslie, 2016; Hennig and Künzl, 2016). We recommend that ecoacoustics should be incorporated into future WA mapping and management, and suggest new research directions to develop and validate acoustic methods suited to the unique conditions of wilderness areas, across a range of biomes.

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Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Author contributions

JCJ, AE, CH and GH designed the study; AE supervised the acoustic surveys; JCJ identified the transects and carried out human and acoustic surveys; PG, AE, JCJ and CH conducted the analyses and interpreted the results; JCJ and AE prepared and finalised the manuscript.

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