

Avian soundscapes and cognitive landscapes: theory, application and ecological perspectives

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Abstract The soundscape is proposed as a phenomenological entity with which to investigate environmental complexity. In particular, the avian soundtope, which is defined as a place in which sound is intentionally structured by different bird species, is regarded as an agency acting to achieve several goals. In fact, the soundtope could be viewed as a special case of an eco-field used by birds, not only to establish territorial ownership and patrol an area but also as a means of locating and evaluating the availability of many other material and immaterial resources. The meaning of the multifaceted acoustic pattern produced by bird communities during the breeding season is discussed here under the acoustic niche hypothesis in terms of community coalescence and the permanent establishment of an inter-specific communication network. Furthermore, the spatial and temporal dimensions of a bird soundscape have also been analyzed and discussed in terms of their relationship with environmental proxies. A new Acoustic Complexity Index (ACI), coupled with the implementation (ACI plug-in) of a specific sound editor (WaveSurfer©), is proposed as a way of processing sound data efficiently, thus providing new opportunities to use the bird soundscape signature for

landscape characterization and describing the ecological dynamics of long-term monitoring schemes.

Keywords Bird soundscape · Eco-field · Acoustic niche · Soundtope · Acoustic Complexity Index

Introduction

In recent years, the landscape has been reconceived as a dynamic system composed of matter, structured energy, information and meaning (Cosgrove 2003; Farina 2010), thus expanding upon the more classical, geographical–ecological orientated perspective (Risser et al. 1984; Forman and Godron 1986; Pickett and Cadenasso 1995; Wu and Hobbs 2002; Turner 2005). In fact, a landscape is more than just an area comprised of heterogeneous material to which human intervention may introduce further complexities (Nassauer 1997; Naveh 2000; Barrett et al. 2009). Instead, it becomes a subjective-perceived-context entity (“Umwelt”; sensu Uexküll 1982, 1992), where species, through semiotic and cognitive mechanisms, intercept their resources and adopt spatial configuration carriers of meaning which have been referred to as eco-fields (Farina and Belgrano 2004, 2005; Farina 2008; Farina and Napolitano 2010). The landscape, which is basically perceived by visual cues, is strictly intertwined with a superimposed acoustic layer, the

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soundscape (Schafer 1977), which is created by several types of sounds produced by natural (geophonies, biophonies) and/or human activity (anthrophonies). It is from this relationship that an ecologically relevant complexity emerges (Kull 2010).

The soundscape could be regarded as an important indicator of a physical, energetic and meaningful context in which organisms live. For instance, from the literature on birds emerges a positive relationship between song activity and individual well-being (see the honest signaling theory; e.g. Buchanan et al. 2003), which is in turn an indicator of the abundance of resources (food, shelter, favorable micro-climate, few predators and competitors, etc.) (Laiolo et al. 2008).

At the same time, the soundscape is influenced by environmental conditions such as vegetation structure (see, e.g., Richards and Wiley 1980), while the opportunity to model the acoustic matrix produced, for instance by bird sounds, is the necessary path to take when it comes to approaching the ecology (effects and dynamics) of this structure (Derryberry 2009).

If the soundscape is regarded as an organized, spatial dimension carrier of meaning, in which species in turn receive and produce information with which to locate resources, the study of its structure and related patterns is an inevitable step (see, e.g., Sueur et al. 2008a).

The purpose of this paper is to introduce the reader to the opportunities provided by the avian soundscape approach in order to further investigate the ecology of landscapes. In particular, we intend to highlight the possibility of integrating the concept of the soundscape as a distinct ecological entity (see “[The soundscape](#)”) with the eco-field hypothesis (see “[The eco-field concept](#)”). We will also discuss the acoustic niche hypothesis (see “[The acoustic niche hypothesis](#)”) and soundtope organization (see “[The soundtope](#)”) specifically in relation to bird assemblages. To evaluate the complexity of the soundscape, a new metric measure (the Acoustic Complexity Index, ACI) is briefly described (see “[The Acoustic Complexity Index as a measure of the avian soundscape structure](#)”), while a new plug-in to calculate this using the WaveSurfer 1.8.5 software (Sjolander and Beskow 2000) is also discussed (see “[The WaveSurfer plug-in to calculate the ACI](#)”). Finally, two case studies (see “[Case study 1: Bird acoustic segregation](#)” and “[Case study 2: Spatial patterns of soundscapes](#))

which support the theoretical framework presented in the section “[The theory](#)” are reported in brief.

The theory

The soundscape

The soundscape (Pijanowski et al. 2011) is an example of structured energy and represents a fundamental component of landscapes. It can be the result of geophonies (wind, water flow), anthrophonies (human-generated mechanical sounds) or biophonies (living organism sounds) (Krause 1987, 1998). In high-fidelity (Hi-Fi) environments “...in which sounds may be heard clearly without crowding and masking” (Schafer 1977), birds are the group of animals which contribute the most, at least in some periods of the year, to the soundscape signature. In fact, birds, like other animals, invest considerable energy in their acoustic activity (song, alarm and social call), especially during the breeding season (e.g., Hopp et al. 1998; Marler and Slabbekoorn 2004; Kroodsma 2005; Catchpole and Slater 2008), differentiating their vocal repertoire according to particular taxonomic groups, individual capacity and social culture (*sensu* Laiolo 2008).

The soundscape, when it is the result of bird activity, is characterized by peaks of intensity and abundance along different frequencies according to several, important controlling factors. These include the hour of day, time of year, weather conditions, climatic dynamics (Truax 2001; Pijanowski et al. 2011), vegetation life form and structure (Brumm and Naguib 2009), human disturbances (Bucur 2006), and landscape structure (Briefer et al. 2010).

The eco-field concept

According to the General Theory of Resources (Farina 2010), resources are heterogeneously distributed in space and time, scarce and cryptic, and require a significant energetic investment to be “captured” and “assimilated” by organisms. When the shortage of a resource is codified by a specific physiological, individual-based need, a genetically or culturally fixed cognitive template, which describes where in the environmental context such a resource can be found, is superimposed. Such comparative

action ends when the cognitive template (the search image) coincides with a spatial configuration carrier of meaning (the eco-field) for that specific resource. In summary, for every individual need that emerges, a specific template is utilized by the organism to identify a specific eco-field. This eco-field is semi-otically the “sign vehicle” with which to ensure that there is access to a specific resource when Peirce’s triadic model of signification (Peirce 1955) is adopted (Farina and Napoletano 2010; Söukand and Kalle 2010).

The significance of the individual acoustic cues of birds has been intensively studied by the bio-acoustic scientific community (e.g., Hutchinson 2002), but the different epistemological approach proposed here enables there to be a more holistic interpretation of bird sound (Burt and Vehrencamp 2005). In fact, individual sounds and collective soundscapes can be interpreted as an organized structure representing a “sound” eco-field that is used to localize resources like food, territory, mates or roosting areas (Farina 2008).

The acoustic niche hypothesis

Birds live in communities, and to avoid or reduce the acoustic overlaps which could create a low fidelity (Lo-Fi) soundscape (sensu Schafer 1977), there should be frequency segregation or a temporal separation of their acoustic performances. In this way, the soundscape of each community should present complex patterns which are able to produce coordinated-emergent signals at any time.

Birds sing at distinct frequencies and intensities over time. The species-specific acoustic repertoire is a dimension of the ecological niche determined by the acoustic competition among species (Krause 1993). Even if the mechanics of the emission of sounds depends upon neurological and other physical constraints (Podos et al. 2004), it is the interrelationship of individuals which determines the timing pattern emissions among them. Indeed, individuals tend to occupy available acoustic niches, thus avoiding acoustic interference/overlap with heterospecific vocalizations. To achieve this goal, individuals can either adjust the timing of their signals (Brumm and Slabbekoorn 2005) or avoid spectral overlap (birds, see Luther 2008; amphibians, see Narins 1995; mammals, see Heller and von Helversen 1989;

insects, see Sueur 2002). Avoiding both temporal and spectral overlap is unnecessarily costly.

The soundtope

In landscape ecology, the concept of the ecotope is quite popular (Zonneveld 1995). It can be defined as an area of uniform environmental conditions, such as slope exposure, breeze regime, soil humidity and fertility (physiotope), which provides a living place for a specific assemblage of plants and/or animals (biotope). In transferring and adapting the ecotope concept to the soundscape domain, a “soundtope” is defined as the area in which acoustic conditions allow the presence of intentional, interacting species, as illustrated in Case study 1 in the section “Case studies”. The sensitivity of animals to the acoustic environment is well documented, especially in birds. For instance, the effect of environmental noise on song quality has been investigated in nightingales (*Luscinia megarhynchos*) by Brumm (2004) and in great tits (*Parus major*) by Slabbekoorn and den Boer-Visser (2006). Birds select areas of acoustic suitability, and among these then choose the most favorable. The soundtope is a Hi-Fi location (sensu Schafer 1977) and an essential proxy if we assume that song activity is not merely a signal of individual well-being (but see Reid et al. 2005), but also an important sign of intra- and inter-specific permanent communication (Mathevon et al. 2008).

The methodology

The Acoustic Complexity Index as a measure of the avian soundscape structure

The ACI is a metric which has recently been applied to the numerical analysis of bird sound files after their FFT transformation (Farina and Morri 2008; Pieretti et al. 2010).

The ACI measures the absolute difference (d_k) between two adjacent values of intensity $d_k = (I_k - I_{k+1})$ in a single frequency interval (e.g., 86.13 Hz bandwidth when a FFT window length of 512 is applied to a file sampled at 44,100 Hz). It is calculated as the ratio between the summation of d_k along prefixed temporal intervals j and the total amount of sound intensity I_k : in j th temporal intervals

Fig. 1 Example of the application of the ACI metric to the analysis of an avian soundscape in three recording locations (RP 1, 2, 3) in a Mediterranean shrubland (7 April 2010, 0600–0700 hours, Deiva, Liguria Region, Italy, 44°13'31"N, 9°30'24"E, 280 m a.s.l.; Handy Recorder H4, Zoom, sampling rate at 44,100 Hz, 16 bit, FFT 512). The ACI has been calculated every second for 86 pieces of data, totaling 3,600 ACI measures on a power matrix composed of 309,600 elements, along 241 classes of frequency. A low pass filter of 1,400 Hz was utilized to eliminate background noise. The RP 1 is dominated by *Leiothrix lutea* and *Turdus merula* ($ACI_{tot} = 1,380$), the RP 2 by *Turdus merula* (first peak) and *Regulus ignicapillus* (second peak) ($ACI_{tot} = 1,997$), while the RP 3 had very few calls and distant songs (*Sylvia melanocephala* call) produce a very poor ACI signature ($ACI_{tot} = 578$)

(e.g. $j = 30$ s in Case study 2 in the section “Case studies”)

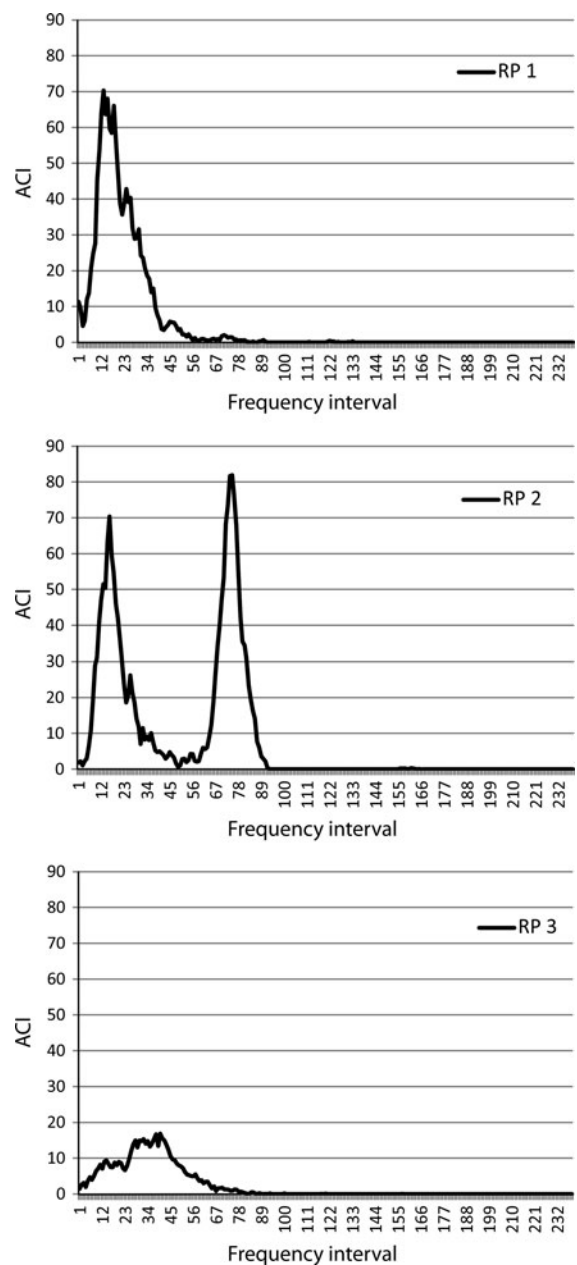
$$ACI = \sum d_k / \sum I_k$$

where k is the number of the intensity values present in each j interval. The ACI is particularly efficient in filtering out geophonies (e.g., wind) and anthrophonies (e.g., road traffic) and distinguishing between patterns inside a threshold of sound degradation. It can also be used to represent the acoustic signature of a soundscape produced by a community at a specific place (Fig. 1), time of day, or between seasons (Fig. 2). The ACI values can be the basis for further computations such as the Shannon entropy that is applied to the frequency classes, the acoustic niche breadth and overlap, or the dissimilarities between different temporal intervals, using, for instance, the Levenshtein distance (Levenshtein 1966).

The WaveSurfer plug-in to calculate the ACI

A new processing plug-in (ACI plug-in), along with a dedicated graphical interface, has been developed by our group (E.L. and L.P.) for use with WaveSurfer® 1.8.5 to automatically calculate the ACI, the Shannon entropy, the acoustic niche breadth and overlap, and the Levenshtein distance (Levenshtein 1966; Tougaard and Eriksen 2006).

WaveSurfer® 1.8.5 (<http://sourceforge.net/projects/wavesurfer>) is an open source audio editor for sound visualization and manipulation (Sjolander and Beskow 2000). It provides a graphical interface which enables the user to analyze and manipulate sounds in an easy and intuitive way. It can be used as a stand-alone tool or as a platform wherein users can develop specialized applications.



The ACI plug-in enables the user to analyze a single sound file or a multiple selection thereof. For each file, it is also possible to drive the analysis of the entire file or a subset of it as defined by a bounding-box.

Finally, a batch-mode routine to drive the analysis of very large sound files has also been developed. When conducting a batch-mode analysis, the user should specify the size of a time window upon which

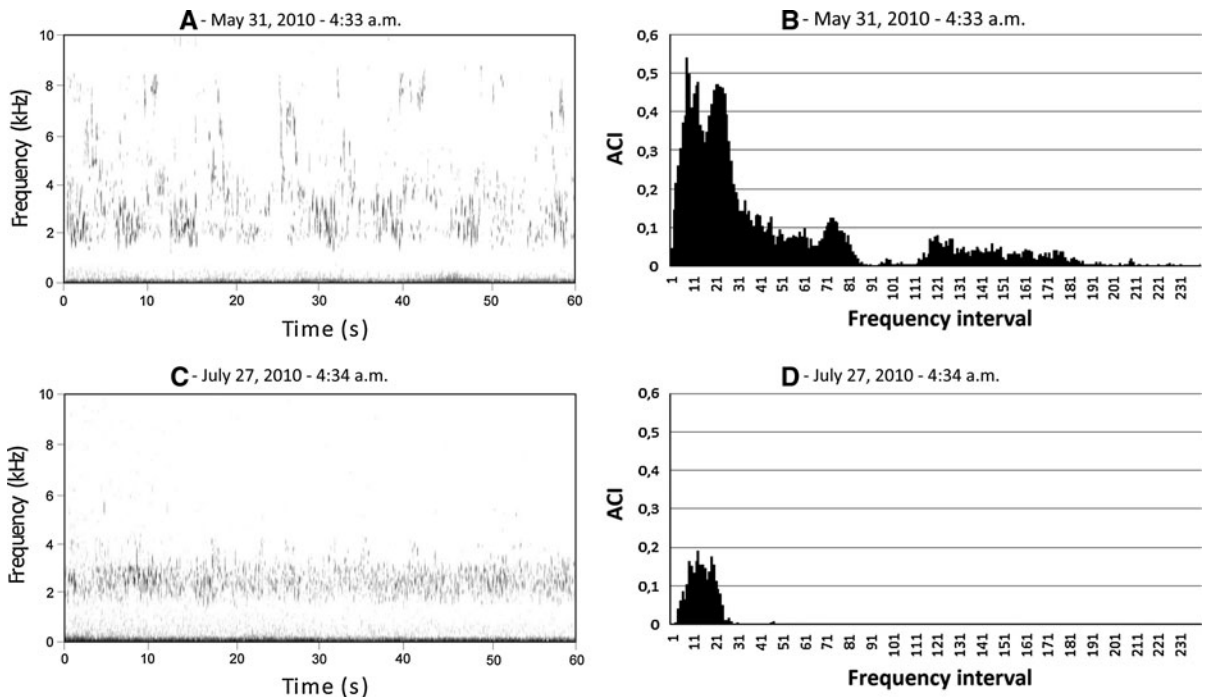


Fig. 2 Example of a dawn chorus spectrogram and ACI signature at two distinct periods of the breeding season (60 s of recording, SongMeter, Wildlife Acoustic, sampled at 44,100 Hz, 16 bit, stereo, FFT 512) in a Mediterranean shrubland (Deiva, Liguria Region, Italy, 44°13'31"N, 9°30'24"E, 280 m a.s.l.): **a** Spectrogram in the middle of the breeding season (31 May 2010) and **b** the acoustic signature

provided by the ACI, where a maximum of seven species (*Turdus merula*, *Erithacus rubecula*, *Sylvia undata*, *S. cantillans*, *S. melanocephala*, *Regulus ignicapillus*, *Leiothrix lutea*) were contemporarily singing. **c** Spectrogram at the end of the breeding season (27 July 2010) and **d** the acoustic signature of the *Leiothrix lutea*, the only singing bird present at that time

to drive the analysis. In this circumstance, and by segmenting the entire file, the ACI plug-in automatically iterates the analysis over each window obtained. Moreover, it is also possible to define the time distance between each window, both manually and randomly.

The importance of frequency categories and the intensity of songs along selected categories of frequency are the other metrics used.

Case studies

Case study 1: Bird acoustic segregation

To test the acoustic niche hypothesis, a field study was conducted during the 2009 breeding season in a mixed turkey oak wood, namely the “Macchia Grande di Manziana” (Rome Province, Italy) (see

the extended work in Malavasi 2010) This natural area is about 530 ha wide, has been un-logged for almost 100 years, and is surrounded by moderately grazed fields. Recordings were taken in the wood's core area (800 m from perimeter) in May, once a week, in favorable weather conditions during dusk choruses (between 1750 and 2030 hours). We used the H4 Handy Recorder (Zoom), and sampled sound at 44,100 Hz and 16 bits with the Songscope[®] 2.4 software (Wildlife Acoustics). The species were recognized aurally.

The Songscope software's features permit the drawing of squares (i.e. annotations) around vocalizations, or a part thereof, and the extraction of time (x) and frequency (y) coordinates for each annotation. Accordingly, we can consider vocalizations in a spectrogram, like squares in a bi-dimensional space. Annotations were drawn following the shape of the vocalizations as closely as possible. As it was

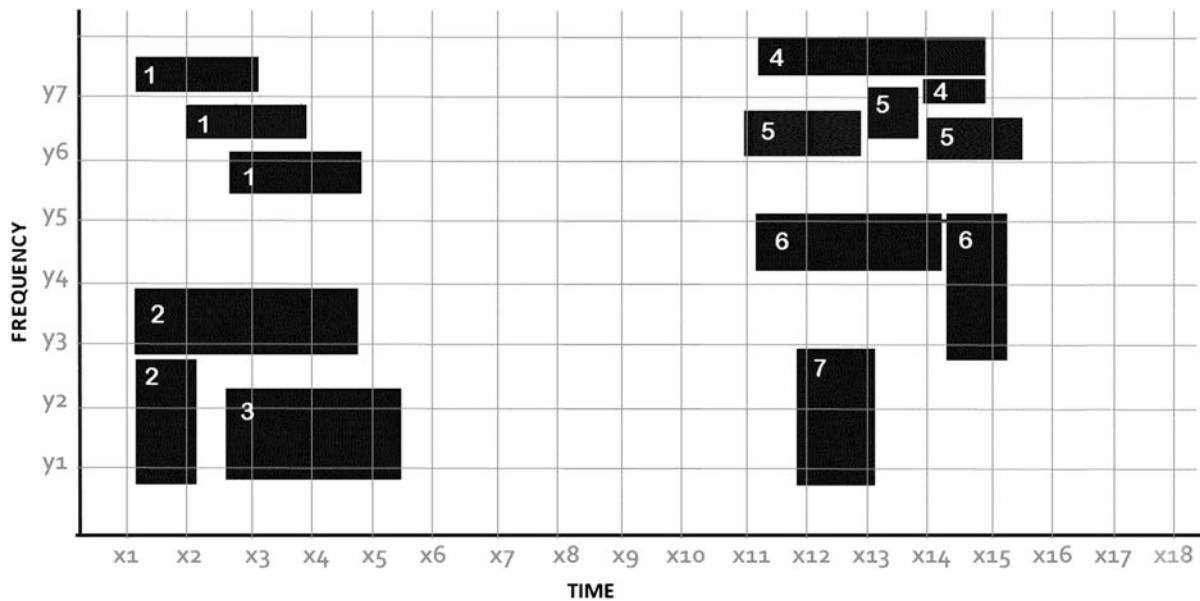


Fig. 3 Songs were split up in one to several squares to obtain data as precise as possible on the frequencies occupied through time. Squares belonging to the same song are indicated with the same number

impossible to draw annotations other than squares, every vocalization was de-composed of several squares in order to avoid empty spaces (Fig. 3).

Using this technique, we analyzed 15 min of recordings, obtaining the details of 15 species and 749 songs that we have decomposed into 2,966 squares. To verify the time overlap, we calculated the amount of time that each species spent singing, both with other species and alone. The niche overlap analysis was performed with the Monte Carlo simulation software (EcoSim, 30,000 iterations, Pianka index, RA2 and RA3 algorithm). The results confirmed the time overlap between species within the community (RA2, Standardized effect size = 3.778, $P < 0.001$; RA3, Standardized effect size = 3.527, $P < 0.001$). Even if the species tended to sing at the same time, only 20% of their songs overlapped in frequency. The average percentage of species able to overlap their songs in terms of frequency is 61.5% (obtained from a weighted mean of each species' overlap potential). A Chi square test (3.939; df 1; $P < 0.05$) confirms a significant difference between the two percentages. Accordingly, vocalizations must be strictly coordinated to avoid spectral overlap during temporal overlapping.

This complex behavior is, apparently, not functional; most of the studies of the acoustic niche of birds have found that there was temporal avoidance (Brumm and Slabbekoorn 2005), while in the analyzed community it would seemingly be much easier to do the same. What does, however, appear not to be functional is to sing at the same time without ending with masking reciprocal signals (see the review by Naguib and Mennill 2010).

Apes, social carnivores and many birds are known to use coordinated vocalizations with individuals of the same species in order to threaten potential intruders (Hagen and Bryant 2003). In such an association, birds could communicate information about group capabilities to non-group members taking on the role of eavesdroppers (McGregor and Dabelsteen 1996). Indeed, following the principles of hetero-specific attraction or avoidance (Mönkkönen et al. 1990), acoustic information in such a case would deter intruders and attract allies. In birds, highly-coordinated duets can signal coalition strength and are perceived as more threatening than solo vocalizations (Hall and Magrath 2007). Brumm and Slater (2007) maintain that the coordinated duets of individuals in a pair may also act as a new signal in

itself, and that this sort of meta-parameter could be formed by temporal patterning between individual contributions to the collective signal. More than two individuals can coordinate their songs strictly; Mann et al. (2006) found coordinated choruses between four to five conspecifics. Different species could never achieve this kind of coordination, since an individual can only sing his own peculiar species' song. Nevertheless, we found that they can perform in strict coordination, with an emergent pattern which may well also act as a new signal.

The community's coordinated vocalizations may act as a joint resource defense, as is thought to be the case for duets (Seibt and Wickler 1977). Indeed, mixed-species' associations are often argued to have a function in the defense of a shared territory (Murray 1971; Burger 1981), and in birds, cases are known where mutual responses to aerial alarm calls between species have been produced (Magrath et al. 2009), proving that they can recognize other species' vocalizations.

The longer that individuals share resources in the same environment, the more their fitness interests overlap to a considerable degree (Tooby and Cosmides 1996). The woods in which we chose to make our recordings have not been logged for almost 100 years, and maintain a core area that is suitable for a complex and stable bird community. So, if species have had the time to coordinate and gain benefits from their association, they will probably continue to act as a coalition against intruders (Hagen and Bryant 2003). In such a cooperative association, birds could communicate information about group capabilities to non-group members. As a consequence, we could affirm that patterns of vocalizations within a

community could contribute to defining the species' composition of the community itself.

Case study 2: Spatial patterns of soundscapes

In order to correctly comprehend the cognitive landscape of animals, we need to incorporate many layers of environmental signs, such as the acoustic cues that organisms are known to both understand and respond to (Farina and Belgrano 2005). In this sense, the analysis of soundscapes through space and time could provide an additional layer of information on species behavior and their interactive communication networks (Burt and Vehrencamp 2005).

The volatility of soundscapes makes them difficult to quantify, and the impossibility of contemporarily being in different places precludes the procurement of a clear vision of the acoustic pattern. For this reason, and to cover a relatively broad area, 20 digital recorders (H4 Handy Recorder; Zoom) were placed along a regular grid of 100 × 100 m in a beech wood in Tuscany (Italy). The bird acoustic activity was recorded for 2 h of sampling at 44,100 Hz and in 16-bit stereo for 10 sessions in the early morning during the breeding season in June–July 2008.

The ACI was calculated at each location to provide a measure of the birds' singing activity. To study the spatio-temporal evolution of the bird soundscape, a cartographic representation of the ACI values was produced for each recording session using a spatial interpolation technique (Surfer® v.9.0, Golden Software).

As shown in Fig. 4, where bright colors indicate higher ACI values, the great variability found across

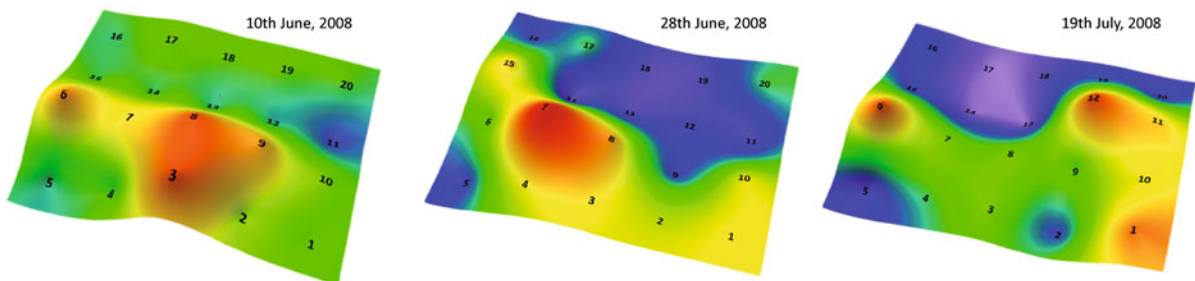


Fig. 4 Spatial representation of the soundscape produced during 2 h of recording (0700–0900 hours) by the spatial interpolation of ACI values (at growing values from blue to red) produced from 20 recording locations and reflecting the

singing dynamics of a bird community in a beech wood (Appennino Tosco-Emiliano National Park, 44°17'49.18"N, 10°15'25.80"E, 1,350 m a.s.l.) on three dates during the breeding season (10 and 28 June and 19 July 2008)

the season demonstrates that song activity probably is linked to several factors (different breeding times, the temporary availability of specific resources, the structure complexity of the habitats, etc.).

Contemporarily, singing activity may also depend on many endogenous and external influences, as well as on human disturbance which often severely modifies the harmony and dynamics of natural sounds. In fact, many studies have focused on the effect on wildlife of the noise caused by traffic and cities, demonstrating altered behavior in different species (Rheindt 2003; Slabbekoorn and Peet 2003; Dooling and Popper 2007; Nemeth and Brumm 2009). Specifically, Krause (1999) found that an infrequent fly-over of a military jet in the Amazon Basin caused a reduction in the number of animal vocalizations. In contrast, in our investigated area, we found evidence that the vocalizing birds were not apparently influenced by the daily intrusion of airplanes; there was a significantly weak correlation between the different grades of disturbance and the birds' singing activities (Spearman's rho correlation: $r = 0.36$; $n = 196$; $P < 0.001$). Moreover, we observed that the bird community did not stop its singing activities during airplane transits (Pieretti, personal communication).

The considerable variations in the spatial configurations of the ACI patterns in the different recording sessions, even though they are not seemingly linked to the intrusion of anthropogenic noise, highlight the need to study further the variability of bird sounds across the landscape. This is particularly the case if we are to properly consider the spatio-temporal patterns of the sounds which drive bird behavior and ecology as a kind of cognitive element that the organisms perceive through many scales at the same time (see "The eco-field concept"). Accordingly, it is necessary to further test the singing fluctuations during the daily cycles across the landscape, since the temporal changes in birds' vocalizations, or their movement to different parts of the territory, might act as environmental cues to the organisms to define their behavior, e.g., to delimit the border of their territories and interact with the neighborhood.

Discussion: ecological perspectives

According to the acoustic niche hypothesis, the bird soundtope that is regarded in our hypothesis as a

distinct type of collective "acoustic" eco-field, although changing in time and space as demonstrated in Case study 2, seems to be an informative subdivision of the soundscape, which could operate as an agency to alert individual species about the composition of the local community. Moreover, this acoustic structure could inform the members of the community about the amount of available resources, predatory pressures and any opportunity to incorporate new individuals (see Case study 1), although further evidence is needed to support this proposition.

The relationship between the structure of vegetation and type of bird sounds has long been known and proved experimentally (e.g., Blumenrath and Dabelsteen 2004), but few investigations have considered bird soundscape turnover in terms of changes of vegetation along the succession or changes of land use. The evolution of the bird soundscape along these proxies seems to be one of the most promising aspects for future consideration if we accept the plasticity of acoustic signaling (Laiolo and Tella 2005).

Similar effects are expected for invasive species which can suddenly occupy a new position in a stable community. In fact, there is growing evidence that the arrival of a new species into a community can have some consequences in terms of the impact on the soundscape. This is probably the case with the Red-billed Leiothrix (*Leiothrix lutea*), a medium-sized babbler that is native to Southeast Asia, southern China and the Himalayan regions of India. This species is regarded as invasive in many regions, such as Hawaii (Ralph et al. 1998) and Japan (Amano and Eguchi 2002a, b; Eguchi and Amano 2004; Dubois 2007).

Meanwhile, in Italy, this bird is reported to be one of the few exotic species which could represent a threat to native birds (Pautasso and Dinetti 2009); it has spread across the eastern Liguria in recent times (Nardelli, personal communication), quickly becoming one of the most common species in the Mediterranean shrubland (maqui) in that area. There is good evidence that the song of the Red-billed Leiothrix partially overlaps in frequency and time with that of the Blackbird (*Turdus merula*), thus supporting the hypothesis that its vocal repertoire has not yet been incorporated into the community and the loudness of this invasive species could modify the acoustic performance of the entire bird community.

The soundscape approach opens up new perspectives for investigations in the field of landscape ecology, but the implementation of automatic routines to quickly process several large sound files is required and appears to be urgent. Today, new hardware which enables the collection of sounds from nature at programmable times and for variable periods is available at reasonable prices (e.g., Songmeter™; Wildlife Acoustic). This technology, coupled with dedicated software (e.g., Seewave; Sueur et al. 2008b) and a robust metric like the ACI (Pieretti et al. 2011) and other derivative indexes like the Niche Acoustic Breadth and Overlap and the Shannon entropy, is the essential premise for a long-term plan of investigation into animal sounds in general and bird sound surveys in particular, as argued by Gage et al. (2011).

The inclusion of the soundscape in landscape ecology seems to be a very promising approach, especially to the study of birds and the processes that this group of animals activates. It is also important for people (e.g., Hedfords and Berg 2003). In fact, the Hi-Fi landscape is preferred when a selection of sounds is proffered to people for environmental evaluation (Carles et al. 1999).

Finally, when extended to the entire biophonic spectrum and to monitoring under the scenario of climate change (see, e.g., Gibbs and Breisch 2000; Botero et al. 2009), the soundscape represents a formidable and innovative tool to be developed in the future.

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