

Application of a recently introduced index for acoustic complexity to an avian soundscape with traffic noise

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An altered acoustic environment can have severe consequences for natural communities, especially for species that use acoustic signals to communicate and achieve breeding success. Numerous studies have focused on traffic noise disturbance, but the possible causes of road effects are inter-correlated and the literature on noise qua noise is sometimes contradictory. To provide further empirical data in this regard, the authors investigated the spatio-temporal variability of the singing dynamics of an avian community living in an acoustic context altered by traffic noise. Fieldwork was carried out in a wood of Turkey oaks (central Italy) bordered on one side by a main road. The soundscape was examined by positioning eight digital recorders, distributed in two transects perpendicular to the road, and recording between 6:30 and 8:30 a.m. for 12 continuous sessions. The acoustic complexity index was used to obtain a quantification of singing dynamics, which were positively correlated with traffic noise. This may indicate that birds try to propagate their signals with greater emphasis (e.g., amplified redundancy or loudness of the songs) to override the masking effect of noise. Nevertheless, an ecotonal effect could have influenced the correlation results, with this enhanced dynamic possibly being due to a more densely populated environment.

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I. INTRODUCTION

The ecological effects of roads and the traffic they carry have been well documented over the past two decades. Roads may have no impact on some species and may be of benefit to others, particularly those that are associated with habitat edges, open areas, or human activities (Clark and Karr, 1979; Laursen, 1981). Nevertheless, the deleterious effects of roads on animal populations are extensive and have been well testified by a wide body of research (e.g., Forman and Alexander, 1998; Trombulak and Frissell, 2000; Fahrig and Rytwinski, 2009). The negative impact of roads may include the fragmentation of habitats (and related processes), edge effects, mortalities from animal–vehicle collisions, and increased air, water, and soil pollution. A large number of ecological studies have particularly associated disturbances to wildlife with noise intrusion into the natural environment, since this can result in deficiencies in acoustic communication due to the masking effect of traffic noise (e.g., Forman and Alexander, 1998; Bautista *et al.*, 2004; Dooling and Popper, 2007). However, the possible causes of road effects are usually so inter-correlated that the independent contribution of noise is not yet completely understood (see Summers *et al.*, 2011). The intention of the present paper is to attempt to clarify these doubts and provide and discuss new empirical data about the effective influences of noise disturbance *per se* on the acoustic activity of a bird community observed directly in its living environment.

Masking interference occurs when the distance over which a signal can be heard, also known as the “active space” of communication, is reduced by background noise (see Marten and Marler, 1977). In this sense, the anthropogenic noise generated by cars, planes, and industrial activity is regarded as a crucial constraint that creates a new selection pressure on the wildlife species that use acoustic signals to communicate and achieve breeding success. Many birds and amphibians have modified their vocalizations or calling behaviors to bypass this masking interference (e.g., Rabin *et al.*, 2003; Parris *et al.*, 2009), altering the amplitude, frequency, duration, and timing of their vocalizations (Slabbekoorn and Peet, 2003; Brumm and Slabbekoorn, 2005; Warren *et al.*, 2006).

Recent studies of wildlife responses to noise have also identified variations in animal behavior and spatial distributions. Indeed, an extensive body of literature has shown that bird abundance, occurrence, and species richness are negatively correlated with levels of traffic noise (e.g., Reijnen *et al.*, 1995; Forman *et al.*, 2002; Peris and Pescador, 2004). Accordingly, in order to assess the impact of traffic noise on animals and select the most effective form of mitigation, more in-depth investigations of how it is associated with alterations in wildlife behavior and fitness become essential.

Recently, Pijanowski *et al.* (2011a,b) introduced a new ecological subject area known as soundscape ecology “to describe the relationship between a landscape and the composition of its sound.” This field of research is based upon the study and interpretation of animal (biophony), geophysical (geophony), and human-produced (anthrophony) sounds. Thus, the soundscape is composed of structured energy that is a fundamental proxy for investigating

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landscape features, consequently becoming an essential tool with which to monitor environmental health and its spatial and temporal evolution.

As a result of this awareness, the soundscape approach has recently been used to monitor wildlife populations (Farina *et al.*, 2011a). The simple act of passive listening to animal recordings provides a new way of evaluating differences between diverse communities, monitoring their evolution over time and, possibly, enabling there to be a focus on the relationships between animals and other external elements, such as human intrusion (Pijanowski *et al.*, 2011a; Farina *et al.*, 2011a). Moreover, automated digital recorders enable the simultaneous monitoring of multiple sites, the storage and later analysis of the songs of many singers in a large area, and the consequential capture of inexpensive, long-term, large-scale surveys of ecosystem dynamics (Hobson *et al.*, 2002; Celis-Murillo *et al.*, 2009).

A vast amount of information can be collected from each acoustic environment and, as a result, the study of the animal soundscape requires special software and indices with which to rapidly and efficiently process audio files. Many researchers have used a variety of methods to automate recognition of species' songs (Trifa *et al.*, 2008; Anderson *et al.*, 1996; Kogan *et al.*, 1998), while indices have rarely been calibrated for the monitoring of entire animal communities (e.g., Sueur *et al.*, 2008). In this context, Pieretti *et al.* (2011) introduced the acoustic complexity index (ACI), which is an acoustic information extraction procedure based on the experience that the majority of biotic sounds have an intrinsic complexity that most geophones and human-generated noise do not. This process computes the relative variation of recorded amplitudes of adjacent temporal steps in each selected frequency bin, subsequently enhancing sounds characterized by strong modulations of energy (hereafter known as "intensity"; see the Appendix for explanation) while reducing the influence of other flat-like sounds. In this way, it is possible to both obtain an indirect and rapid measure of the complexity of the soundscape and contemporarily filter out sounds that are composed of constant levels of intensity, like much of the human-generated noise in the environment today (traffic noise, airplanes, background noise generated by geophones, etc.). More recently, Farina *et al.* (2011a) and Farina *et al.* (2011b) proposed the use of the SoundscapeMeter plug-in, powered by the WaveSurfer software (Sjölander and Beskow, 2000), to rapidly process a large amount of sound data with the ACI and other parameters.

In this paper, we present an experimental study in which recording microphones were positioned in a wood of Turkey oaks along a gradient of a progressive distance from a main road to the core of the wooded area. In particular, we investigated the soundscape of the local bird community, since songbirds are considered to be excellent subjects for studying the consequences of traffic noise on biophones. Indeed, they are among the most widespread and familiar animals in urban areas, and acoustic communication is vital in many aspects of their life since they use calls and songs to attract and select mates, defend their territories, and warn against predators (Collins, 2004).

The purpose of this study is to extend the use of the ACI methodology to the monitoring of the dynamics of the biotic soundscape near a busy road. It is also the intention to use this approach as a way of indirectly assessing whether the road environment (and the associated noise) influences wildlife. We further examine how diversity and the distribution of avian species are related to proximity to a road, and if the difference in traffic noise between work days and the week-ends has different effects on the birds' singing activity.

II. MATERIALS AND METHODS

A. Study area

The fieldwork was carried out between the 3rd and 14th June 2009 in the "Selva di Castelfidardo," a Turkey oak woodland located in central Italy (altitudinal range: 25–125 m asl) (Fig. 1). In the last two centuries, the large wooded area has been subjected to intensive deforestation, and its remnant extension is now reduced to 30 hectares (Taffetani *et al.*, 2012). From a morphological point of view, the Selva is characterized by hilly and softly descending soil. In the hilly part of the wood, the area is dominated by *Quercus cerris* and *Carpinus orientalis*, changing to *Carpinus betulus*, *Q. cerris*, and Mediterranean species in the brushwood closer to the lower and flatter part of the natural area. The entire locale is indicated as an area with a "high level of naturality" (Tardella *et al.*, 2005; Taffetani *et al.*, 2012).

The Selva is surrounded by rural fields, but, on its northern side, is connected to highway SS16 by a narrow corridor of synanthropic vegetation (Fig. 1). In particular, this vegetated trait is a residual riparian zone that is mainly composed of *Populus alba*, with *Salix Alba*, *Sambucus nigra*, *Ulmus minor*, *Q. cerris*, and *C. betulus* also present (Tardella *et al.*, 2005). An absence of vertical stratification in the vegetation

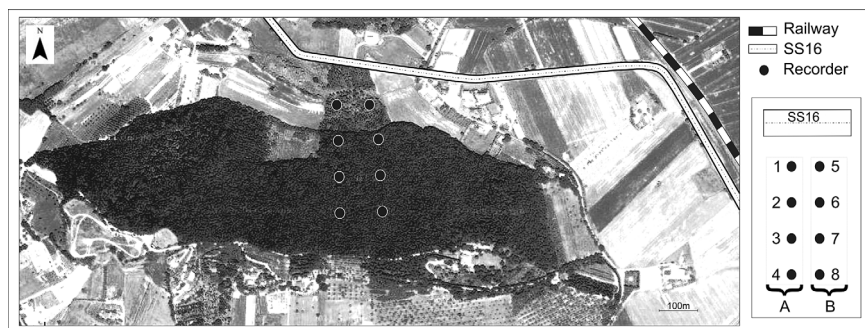


FIG. 1. Location map showing the position of the Selva di Castelfidardo with respect to the main road, the SS16, and the railway line; schematic representation of the distribution of the sampling stations (divided into two transects, A and B).

community characterizes this area, and both the plants and the ground are completely covered by *Hedera helix*. This particular portion of the landscape has been assigned as an area with a “low level of naturalness” by Tardella *et al.* (2005) and Taffetani *et al.* (2012).

The SS16 causes considerable traffic noise intrusion into the natural soundscape. This is particularly the case on weekdays, since this road is a preferred connection between local city centers and the industrial area. A railway line on the eastern side is another significant cause of noise contamination in the local soundscape.

B. Audio file collection and data analyses

The soundscape was investigated by positioning eight digital recorders (Handy Recorder “H4,” Zoom Corporation, Tokyo, Japan) located according to a grid of two parallel lines (transects A and B) perpendicular to the SS16 (Fig. 1). Each transect contained four recording devices (one in the area with a low level of naturalness and three where there was a high level of naturalness), starting at a distance of 100 m from the SS16. With the aim of obtaining a good sampling space in which to capture the soundscape dynamics, each microphone was located approximately 100 m away from the other devices. This distance was chosen to reduce the possibility of the overlapping of sounds between two adjacent recording points, and meant that both a distinct soundscape at each station and good spatial sampling were ensured (A. Farina, personal communication). The H4 recorders were set at 44.1 kHz/16 bit/stereo mode. In order to delete eventual differences in the recording quality of each microphone, or among the different microphones, a sequence of signals of known sound pressure level (tonal notes at different frequencies, white noise—broadband, 0–22 kHz—and four different bird songs) was recorded at a 1 m-distance and used to evaluate eventual calibrations, although it later transpired that this was not necessary.

Twelve recording sessions were conducted at dawn (5:00–9:00 a.m.) only during optimal meteorological conditions (sunny, no wind or rain) to minimize the impact of the weather on both the acoustic performances of the birds in the study area (as suggested by O’Connor and Hicks, 1980) and the soundscape measurements (Pijanowski *et al.*, 2011a). Some recorders failed to produce an audio file on three separate days: number 4 on June 6th, number 4 on June 7th, and number 3 on June 9th.

The audio files (recorded in wav format) were synchronized using the Cool Edit Pro 2.1 software (Syntrillium Software Corp., Phoenix, AZ), with the intention being to both compare the dynamics of the eight stations and capture a contemporary soundscape that was subjected to the same environmental interferences. Two hours of net usable files, from times ranging between 6:30 a.m. and 8:30 a.m., were consequently obtained.

Successively, a database of raw intensity values (corresponding to the power spectral density) was extracted from each 2-h recording using the WaveSurfer software, which was set with a fast Fourier transform (FFT) size of 512 points. The numerical values resulting from this process

provided a quantitative measure of how energy is distributed across the acoustic spectrum.

The soundscape of the investigated area was predominantly characterized by bird vocalizations and traffic-generated noise. Accordingly, and with the aim of analyzing these two sonic components as two different variables and comparing their trends, we split the power spectrum database of every recorded file into two main parts: 0–1.5 kHz and 1.5–22.05 kHz, which were mainly occupied by the traffic noise and bird song, respectively. Then, both parts of the power spectrum database (lower and higher) were processed using the WaveSurfer platform and the SoundscapeMeter plug-in. In order to obtain an immediate measure of the complexity of the biotic soundscape on each audio file, the higher frequencies of each database (over 1.5 kHz) were processed using the ACI (Farina *et al.*, 2011a; Farina *et al.*, 2011b). This enabled us to obtain an estimation of the relative quantity of the vocalizations emitted by the local community (the estimation of the singing dynamics of the living species). Separately, we aggregated the raw and unprocessed power values in the lower frequency bands of the power spectrum (beneath 1.5 kHz) to estimate noise levels consistent with the amount of traffic passing-by on the SS16.

To arrive at the threshold of 1500 Hz, we worked on the basis that most loud traffic noise is below 2 kHz (Warren *et al.*, 2006). Moreover, Summers *et al.* (2011) proved that there was an optimum correlation between traffic noise below and above 2 kHz, indicating that this measure is a good relative index of total noise. Nevertheless, we lowered the threshold from 2 kHz to 1.5 kHz since, in our study site, the birds’ songs ranged from approximately 0.4 (minimum frequency of just one species, the *Streptopelia decaocto*) to 10 kHz, and we wanted to limit the influence of the lower frequency bands of the bird acoustic production on the noise measurements. In contrast, it was less important that a part of the traffic noise was included in the band processed by the ACI, since this algorithm tends to give low values for sounds that present constant intensities, such as from passing cars or plane transits.

In order to verify if the differences in the singing dynamics were related to the presence of different birds, the species richness for each station was also calculated by the aural identification of the bird song recorded in each site. So, five randomly selected recording sessions (including one Saturday and one Sunday) were chosen for each recording and successively sampled in four 1-min long samples which were equally distributed over the recording interval (respectively at 6:45, 7:17, 7:45, and 8:15 a.m.). We then calculated species richness (the total number of species identified per station) and species occurrence (presence of a species at least once in each audio sample). We were unable to use abundance as a measure since the dawn chorus spectrogram was so full of vocalizations that it was only possible to classify the sounds in the foreground, with all of the others in the background being disregarded. Furthermore, traffic noise influenced the perfect detectability of the species in the background, especially for the stations that were closest to the road.

It is important to note that masking from both birds and noise did not negatively influence the output of the automatic processing phase and the aim of the analyses. This is due to the fact that the ACI registers the intrinsic variability of sounds, thus giving very different outputs for traffic noise and bird vocalizations that are present in both the foreground and background. The fine resolution at which the algorithm operates (0.0116 s, with an FFT size of 512 points) permitted us to both filter the masking effect caused by the traffic-generated noise falling over 1.500 Hz (characterized by constant levels of intensities even at that small resolution), and to contemporarily enhance the bird singing activity of the dawn chorus. Indeed, if the dense distribution of the vocalizations along the spectrogram may seem to be very homogeneous and quite constant at first sight, it instead has a discontinuous rhythm at a micro-scale that is well-highlighted by the ACI. Consequently, this peculiar property of the ACI algorithm allowed us to measure the complexity of the biophonies effectively.

In order to provide a dB measure of the importance of the noise intrusion in the soundscape, and to also have a control assessment of the indirect estimations obtained from the recordings, noise amplitude measurements of all of the recording sites were taken for 1 min with HD2010 certified sound pressure meters (DELTA OHM, Padova, Italy), five samples for each station. We then noted the minimum (L_{\min}) and maximum (L_{\max}) values of the sound pressure level (SPL) for each lapse of time, and calculated the mean value for both the maximum and minimum measurements at each site. The A-weighted decibel [db(A)] values were utilized because A-weighting filters of acoustic energy below 1.0 kHz are used and heard less by most bird species (Dooling and Popper, 2007). This assessment was performed on a Sunday afternoon in October 2011 to avoid the inclusion of singing birds and to record light traffic. Measurements were discarded and retaken when birds were vocalizing within ~30 m.

C. Statistical and analyses

In order to analyze the data from different perspectives, diverse statistical tests were applied. We opted for a non-parametric analysis when the values of the selected variables did not display a normal distribution. A Wilcoxon signed-ranks test was used for comparisons among the ACI values of the eight stations on different recording days, with the aim being to investigate the differences in avian singing dynamics over the recording period. This process was then repeated for the noise values.

The variability of the ACI and noise values over the time of day was analyzed using a one-way analysis of variance (ANOVA), with the ACI values of each recording as the dependent variable and four time slots (6:30–7:00, 7:00–7:30, 7:30–8:00, 8:00–8:30 a.m.) as the categorical predictor.

Since the audio files were collected on both weekdays and on the weekend, we decided to perform a Mann-Whitney U test to compare weekday, Saturday, and Sunday soundscape patterns. This test was also used to assess

whether there was a significant variability in terms of both noise and ACI values between the four microphones closest to the road and the four that were furthest away.

Finally, in order to investigate if the noise had an impact on the birds' singing dynamics, a Spearman's Rho correlation analysis was used to investigate the relationship between the two main variables of noise disturbance and the ACI. All of the analyses were conducted using the Statistica v.8.0 software (StatSoft, Inc., Tulsa, OK).

III. RESULTS

A. Characterization of the avian community and noise levels (SPL)

The acoustic environment of the investigated area was predominantly composed of bird vocalizations and traffic-generated noise.

The avian community was very active on all of the investigation days, with a total of 18 species revealed by the acoustic census of the recorded files. Stations 1 and 5, which were nearer to the road and characterized by poorer vegetation, revealed a community that was composed of fewer singing species (only 10), while the other inner stations were more varied in terms of their bird composition as they contained between 12 and 15 different species (Table I). In general, the species richness among the six inner stations did not substantially differ, and transect A was richer in terms of species diversity than transect B.

The examined sites differed noticeably in terms of the SPL of the environmental noise, and Table II sets out the SPLs recorded for each recording point. Mean values ranged between 40.8 and 54.83 dB(A). Station 3 registered both the

TABLE I. List of species classified at each recording point.

	Transect A				Transect B			
	1	2	3	4	5	6	7	8
<i>Streptopelia decaocto</i>	x	x			x			
<i>Dendrocopos minor</i>				x				
<i>Troglodytes troglodytes</i>	x	x	x	x	x	x	x	x
<i>Erithacus rubecula</i>	x	x	x	x		x	x	x
<i>Luscinia megarhynchos</i>	x	x	x		x	x		x
<i>Parus major</i>		x	x	x	x	x	x	x
<i>Parus sp</i>	x		x		x	x		x
<i>Turdus philomelos</i>		x	x	x				x
<i>Sylvia atricapilla</i>	x	x	x	x	x	x	x	x
<i>Phylloscopus collybita</i>							x	
<i>Aegithalos caudatus</i>			x			x	x	x
<i>Parus caeruleus</i>	x	x	x	x	x	x	x	
<i>Certhia familiaris</i>			x	x		x		
<i>Oriolus oriolus</i>		x	x				x	x
<i>Fringilla coelebs</i>	x	x	x	x	x	x	x	x
<i>Serinus serinus</i>	x	x	x	x	x	x	x	x
<i>Carduelis chloris</i>	x	x	x	x	x	x	x	x
<i>Carduelis carduelis</i>		x	x	x			x	
Species richness (S)	10	14	15	13	10	12	13	12
Species occurrence (in 1-min samples)	4.65	5.85	6.40	5.20	5.40	5.10	4.75	5.15
Distance from the road (meters)	100	200	300	400	100	200	300	400

TABLE II. Results from the SPL measurements at each recording site.

	1	2	3	4
Max SPL (mean)	52.33	52.63	47.03	51.47
Min SPL (mean)	44.78	44.83	40.80	41.03
	5	6	7	8
Max SPL (mean)	51.67	54.83	49.10	49.80
Min SPL (mean)	44.43	45.27	41.45	41.53

lowest minimum and maximum SPLs of the eight recording points, while station 6 had the highest noise levels. As expected, both the maximum and minimum SPLs were lower for the four sites furthest from the road.

B. ACI and noise dynamics

A general view of the noise levels during the 12 recording sessions revealed an expected minimum on 7th and 14th June (Sundays), followed by 6th and 13th June (Saturdays). The Wilcoxon analysis revealed great variability in the noise levels, particularly on three days where the results were significantly different from all of the others: 3rd June (a Wednesday, with a very high level of noise), and 7th and 14th June (both Sundays, characterized by a low level of traffic noise; see Fig. 2).

A corresponding trend was not recorded for the ACI values since there was only a significant difference in the avian song results between the 3rd and 14th June (Wilcoxon test: $Z = 2.197$; $p = 0.28$). On the other days, the ACI values were similar (Fig. 2).

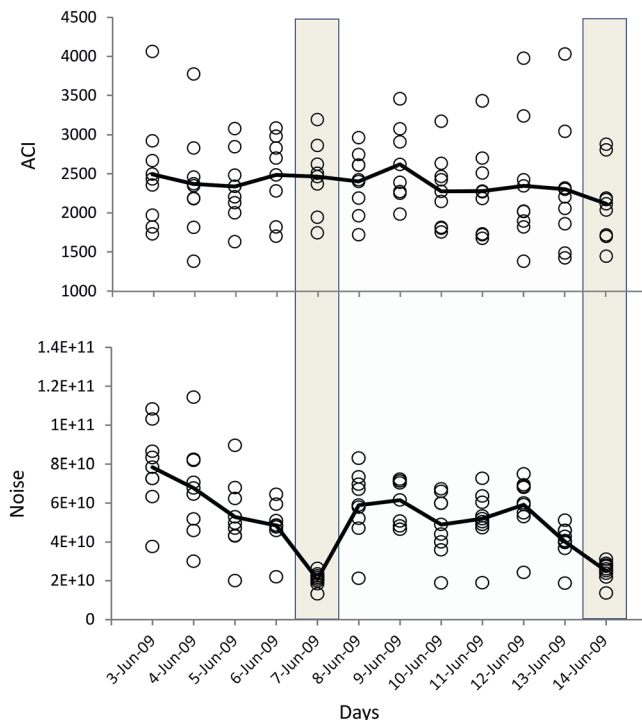


FIG. 2. (Color online) Distributions of the ACI and noise values registered at each recording session. The black line connects the mean values of the sessions; Sundays are represented with a gray background.

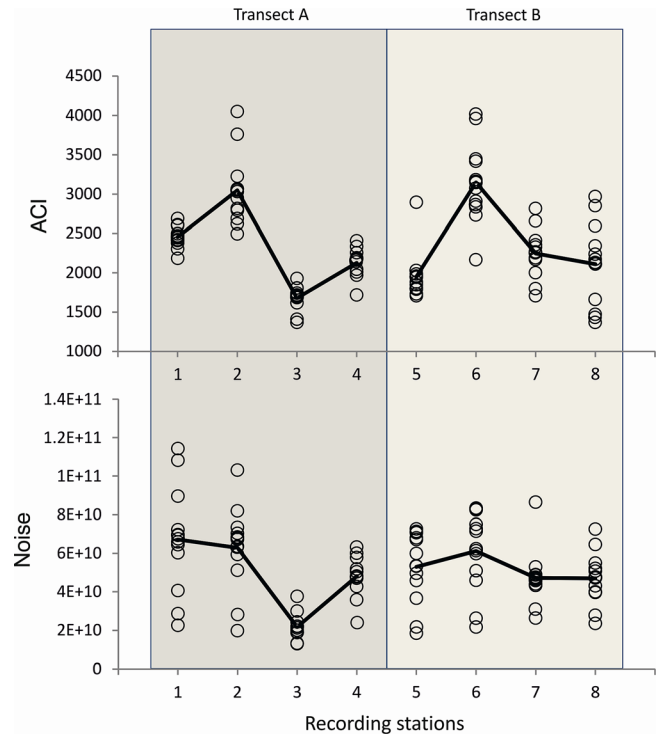


FIG. 3. (Color online) Distributions of the ACI and noise values registered at each recording point. The black line connects the mean values of the recording sites.

Confirmed by the SPL measurements (Table II), traffic noise declined with distance from the road since the four closest stations (1, 2, 5, and 6) were the noisiest over the 12 recording days (Fig. 3). More precisely, stations 1 and 6 were the noisiest sites, while station 3 always recorded low noise levels. Station 6 had more acoustic disturbance than station 5, which was nearer to the road. This was probably due to the fact that the latter was more elevated and exposed on the eastern side of our investigated area, where there was a railway line influencing the soundscape patterns (Fig. 1). The ACI results varied greatly along the recording points, with a wide degree of intensification of bird acoustic dynamics at sites 2 and 6 and limited singing activity at station 3 (Fig. 3). Accordingly, the Mann-Whitney U test revealed a significant difference among the stations in relation to distance from the road for both the ACI and noise values when divided into two groups of four sites (ACI: $U = 375.0$, $Z = 5.49$, $p < 0.001$; noise: $U = 555.0$, $Z = 4.036$, $p < 0.001$).

When performed in relation to a different form of bird behavior on weekdays, Saturdays, and Sundays, the same statistical analysis revealed a clear discrepancy between the ACI and the noise results. The bird singing dynamics did not show any significant differences on these days ($U = 899.0$, $Z = 0.38$, $p = 0.70$), while, as expected, the noise disturbance was extremely diverse on working days and weekends ($U = 270.0$, $Z = 5.54$, $p < 0.001$), with a further difference registered between Saturdays and Sundays ($U = 21.0$, $Z = 3.79$, $p < 0.001$).

The Spearman's Rho correlation matrix between the ACI and noise values revealed a significant correlation ($r = 0.48$, $p < 0.05$, $N = 93$; Table III) for the entire period. If

TABLE III. Spearman's Rho correlation matrix of the ACI values and intensities below 1500 Hz for all of the audio recordings.

	<i>r</i>	<i>p</i>	<i>n</i>
All sessions	0.477291	<0.001	93
Weekdays	0.606375	<0.001	63
Weekend	0.413571	<0.03	30

we only consider the weekends, there is a weaker but nevertheless significant correlation ($r=0.41$, $p<0.05$, $N=30$), while the correlation increases if we only count working days ($r=0.61$, $p<0.05$, $N=63$). When the first line of recording points (station 1 and 5) are deleted from the analysis because of their very different vegetation, an emphasized effect is obtained, with a correlation coefficient of 0.54 (0.70 for weekdays against 0.42 for weekends; Table IV).

Finally, the one-way ANOVA revealed that the ACI values were not particularly dissimilar along the four time slots. In contrast, there was a significant variation in noise values ($F=5.37$, $p<0.022$) between 6:30–7:00 a.m. and 8:00–8:30 a.m., which corresponded to the interval of the lightest traffic and the peak of the noise, respectively (Fig. 4).

IV. DISCUSSION

Anthropogenic noise is becoming one of the most common threats to landscapes all over the world. Altered acoustic conditions can have severe consequences for natural communities, and the study of soundscapes in terms of various spatial and temporal scales can contribute to our understanding of how humans affect animal ecosystems (Joo *et al.*, 2011; Pijanowski *et al.*, 2011a,b).

This study is an attempt to investigate the spatio-temporal variability of the singing dynamics of an avian community dealing with a main road that is particularly busy on weekdays. Of all of the related negative effects on wildlife that such a road may produce, we chose to focus on the impact of traffic noise in relation to the bird biophony. Acoustic dynamics have recently been regarded as a proxy for biodiversity (Krause, 1987; Sueur *et al.*, 2008), but they can also carry other important information, such as that related to the well-being and fitness of a singing community (Farina *et al.*, 2011a).

Several studies of the impact of road effects on birds and other animals indicate that there is a clear, negative relationship between traffic intensity and species richness, with

TABLE IV. Spearman's Rho correlation matrix of the ACI values and intensities below 1500 Hz for all of the audio recordings without counting the first line of stations (1 and 5).

	<i>r</i>	<i>p</i>	<i>n</i>
All sessions	0.546218	<0.001	69
Weekdays	0.700509	<0.001	47
Weekend	0.427442	<0.05	22

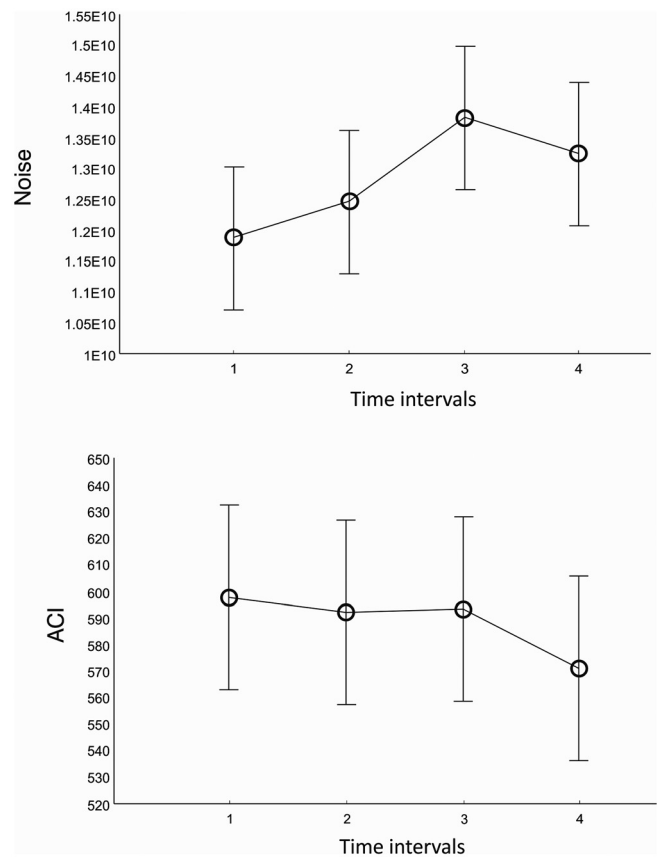


FIG. 4. ACI and noise evolution along time intervals of the day: (1) 6:30–7:00 a.m.; (2) 7:00–7:30 a.m.; (3) 7:30–8:00 a.m.; and (4) 8:00–8:30 a.m.

changes in species composition and population sizes (e.g., Trombulak and Frissell, 2000; Forman *et al.*, 2002). Furthermore, recent research on songbird behavior and ecology near to oil and gas facilities found that noise led to a significant reduction in pairing success, bird density, and species diversity (Habib *et al.*, 2007; Bayne *et al.*, 2008; Francis *et al.*, 2009; Francis *et al.*, 2011).

In our study sites, the singing species did not substantially differ among the six inner stations, but we registered a slightly greater number of species in station 3, which had a much lower degree of noise protrusion in comparison to the other sites. Transect A generally had a higher level of species diversity than B, probably due to the distance from the railway line which, even if only occasionally, caused very intense and masking interference. Furthermore, the species richness of the two sites closest to the road was lower ($S=10$) than in the other sites, and was characterized by the presence of species that are very common in urban environments, such as *Turdus merula*, *Sylvia atricapilla*, *Fringilla coelebs*, and *Streptopelia decaocto* (Table I). This may be due to the effect of traffic noise, which can cause the movement of sensitive species to more distant and quieter sites, but it could also be related to other negative effects of the road (e.g., fragmentation of habitat, road casualties and increased air, water and soil pollution) (Forman and Alexander, 1998). Nevertheless, it may be possible to link this reduced species richness to the different vegetation characterizing stations 1 and 5; the less diversified and stratified

plant composition here may not guarantee the resources for the sustainability of a superior number of species (MacArthur *et al.*, 1962).

On the other hand, the Mann-Whitney U test revealed that both bird and noise values were significantly higher with greater proximity to the road, indicating a more active singing performance where the noise was more intense. This is mainly due to the abundant expression of the biophony at stations 2 and 6, which were 200 m from the road and were characterized by approximately the same level of traffic noise as at stations 1 and 5. One possible explanation for this high acoustic activity could be related to the stations' position in an ecotonal environment. Indeed, these sites were characterized by a peculiar location at the edge of the highly natural wooded area, bordering rural fields and other vegetated small terrains attached to the main road. An ecotone is defined as a transitional area between two different systems (Holland *et al.*, 1991), and contains elements of bordering communities, plants, and organisms. For definition, ecotones often have a superior number of species and greater population densities than the communities on either side of them. This tendency toward increased biodiversity within the ecotone is defined as the "edge effect," which is accompanied by the "edge" species, which occur primarily or most abundantly in ecotones (Leopold, 1933; Hansen and di Castri, 1992).

Nevertheless, recent research, such as that by Baker *et al.* (2002), noted that there is not a large body of evidence from studies of avian communities to support there being an edge effect of increased density and species richness, and there is no evidence of entirely ecotonal species. Accordingly, on the basis of the outcomes of our acoustic census, we did not find a higher level of species diversity to justify this very diverse ACI measure. On the contrary, a comparatively higher richness of singing species in the two transects occurred at stations 3 and 7, which were both characterized by a low level of noise disturbance and low ACI values. It may be that the greater density of individuals caused the major acoustic activity recorded at stations 2 and 6, even though we cannot confirm this hypothesis with the data at our disposal. Moreover, as suggested by Nemeth and Brumm (2009), the birds may have enhanced their vocal expressions simply to better defend their territory in a more densely populated environment. An increase in the density of individuals could bring about an intensification of social interactions with neighbors, thus leading to an emphasized singing dynamic in the entire community.

There is a further reasonable explanation for this enhanced bird acoustic behavior, namely the possible activation of peculiar adaptations to a noisy environment, such as changes to songs. Birds, like many other animals, react with a behavior known as the Lombard effect, which is an increase in the amplitude of their vocalizations upon a rise in environmental noise levels (Brumm and Slabbekoorn, 2005; Zoellinger and Brumm, 2011). Laboratory experiments under controlled conditions suggest that males of several species of bird weigh the signal-to-noise ratio between their vocalizations and noise, adjusting their vocal amplitude accordingly (e.g., Brumm and Todt, 2002; Brumm, 2004).

Additionally, studies have shown that many bird species are capable of activating changes in the rate and duration of strophes (Brumm and Slater, 2006; Slabbekoorn and den Boer-Visser, 2006), increasing the serial redundancy or changing the duration of syllables (Lengagne *et al.*, 1999) to maintain the efficiency of the communication. All of these findings suggest that birds are able to lessen acoustic masking by adjusting their vocal performance or signal structure. Certainly, such mitigations are limited, but they are likely to endure through natural selection because animals that communicate efficiently will improve their chances of reproductive success (Brumm, 2004).

The intensified loudness of the syllables emitted, as well as the amplified redundancy of song strophes, could lead to an increase in ACI outcomes. Sustaining this thought, we found that there was a surprisingly significant and positive correlation between noise and ACI measures over the 12 recordings days (Spearman Rho: $r = 0.477$, $p > 0.001$). When we deleted the first line of those stations characterized by different vegetation (stations 1 and 5), the results were even neater and displayed a significant correlation of 0.546 for all sessions. It could be speculated that these outcomes might be related to increased acoustic expression on the part of individuals trying to propagate their signals with greater emphasis to override the masking effect of noise. The song-adjustment hypothesis could also be confirmed by the fact that the quietest sites (stations 3, 4, 7, 8) along each perpendicular transect had a relatively high number of singing species but low ACI results. Thus, in the recording sites where we expected there to be a major diversity of sounds, and, as a consequence, a greater acoustic complexity, we instead registered lower values. These species may transmit their signals better, without the need to enforce their loudness or sing with a major number of repetitions because their acoustic environment is less disturbed, as recently found in several bio-acoustical studies (Brumm, 2004; Brumm and Slabbekoorn, 2005). The noise levels were not constant, but instead varied over the recording sessions and time of day, while the bird community did not react to these changes with a statistically significant, consistent variation of its acoustic expression (Figs. 2 and 4). As expected, on Saturdays and Sundays there was a clear reduction in traffic noise intrusion, which was almost absent or at least comparatively more attenuated than on weekdays (Fig. 2). In the same way, a significant difference between the quietest traffic period of the day (6:30–7:00 a.m.) and the peak of car and truck transits (7:30–8:00 a.m.) was also recorded (Fig. 4). Conversely, in these analyses the ACI does not produce a statistically significant modification of bird acoustic dynamics, since the community did not greatly modify its total vocal expression on the weekends, instead singing every morning with a gradient that was typical of the bird dawn chorus (very high in the early hours and gradually descending with the passage of time; Fig. 4). Interestingly, this decreasing gradient was not absolutely continuous as expected, but presented a slight increase in the time interval associated with the pitch of traffic, although this outcome was not significantly different from the other time intervals in the ANOVA test. The tendency of the bird community to not really change its vocal

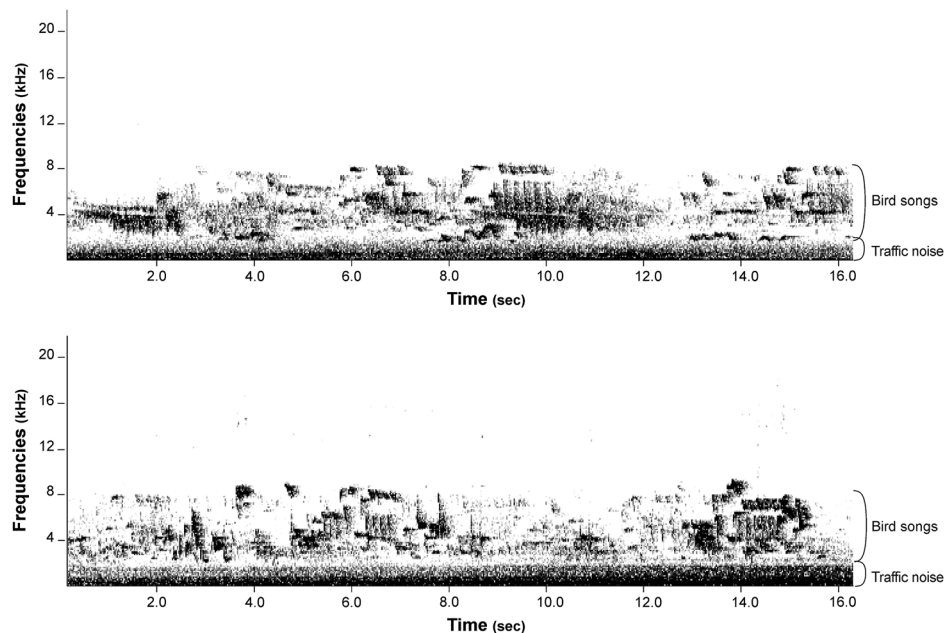


FIG. 5. Examples of typical spectrograms recorded in the Selva.

expression, even in the presence of attenuated noise levels, was confirmed by the Spearman's Rho correlation results for weekdays and the weekends, which had stronger coefficients on the noisy days than on the quieter ones (Tables III and IV). Clearly, the reduced noise disturbance at the weekends is less correlated with a singing community dynamic that continues to be almost constant across the days.

Adding up all of the statistical outcomes, it is noteworthy that bird acoustic activity seems to be more intense in sites where environmental noise levels are higher. This behavior is confirmed by the correlation analyses, which were all significantly positive. On the other hand, we found that the differences in singing behavior at the weekend, or depending on the time of day, were not important enough to be significant in the ANOVA test. It may be that birds have adapted their singing dynamics to the modified environmental noise levels and continue with their "adjusted" singing performances even in the absence of noise intrusion. This would be in contrast to certain other studies which suggest that louder songs are more costly to produce (Zoellinger *et al.*, 2011), meaning that enhanced vocal activity is likely to stop as soon as noise disturbance ceases, thus avoiding the waste of useful energy (Brumm and Todt, 2002).

Other possibilities can also be considered, such as the fact that birds are segregated between noisy and non-noisy sites on the basis of their vocal plasticity and ability to enhance their song production; individuals inclined or genetically predisposed to produce intense singing behavior may tolerate anthropogenic noise and live in disturbed sites, while other sensitive or less adaptable individuals may prefer to live in quieter areas. Another possible explanation may relate to the fact that the major availability of resources assumed in the ecotonal sites could correspond to an increased availability of energy to expend on communication. It is also important to note that the correlation coefficient may in part be influenced by the very elevated singing

dynamics registered at the ecotonal sites, which, as previously observed, could be associated with both a larger number of individuals than the ecotone can sustain and the consequential enhanced vocal expressions related to the denser community.

V. CONCLUSIONS

Many studies have reported reduced species diversity and densities of birds along highways, and traffic is today regarded as the main source of anthropogenic noise, particularly in urban areas. Other features of roads can also have a negative impact on bird dynamics and behavior. In the present study, it was found that avian sounds were positively correlated with traffic noise, which may indicate that birds are prone to communicate with greater emphasis when there is noise disturbance. Nevertheless, an ecotonal effect could have contributed to this result, and this enhanced dynamic may be due to a more densely populated environment. More investigations measuring the effect of anthropogenic noise on population singing dynamics are required, as we believe that examinations of bird soundscapes in human-influenced systems can enhance our understanding of fauna in complex urban systems. Moreover, these studies may be a crucial and immediate proxy when it comes to identifying the actions needed for species conservation and enabling advances to be made in urban planning and policy.

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APPENDIX

In this appendix, we provide a detailed definition of the ACI ideated for the first time by Farina and Morri (2008) and then edited and published by Pieretti *et al.* (2011).

The ACI is a simple procedure created to provide a measure of the degree of complexity of the acoustic emissions present in the environment. It is calculated on a matrix extrapolated from the spectrogram as a result of an FFT; this matrix is divided into temporal steps and frequency bins, and represents the numerical translation of the sounds registered in the acoustic recording.

The ACI formula is as follows:

$$ACI_{ij} = \frac{\sum_{k=1}^n |I_k - I_{k+1}|}{\sum_{k=1}^n I_k},$$

where I_k represents a value of intensity (we have named it “intensity” for the sake of simplicity, but it is the equivalent of the magnitude) resulting from a selected frequency bin (i) and a selected temporal step (k), and I_{k+1} represents the adjacent value of intensity in the next temporal step in the same frequency bin. The interval of time in which the calculation is made is indicated by j (for example, 1 s, 5 s, etc.), while n represents the total number of temporal steps (k) contained in every j . After the application of this formula, the sum of the results for all of the frequency bins (i) and temporal intervals (j) is calculated.

On this basis, it is possible to say that the ACI computes the absolute difference between two adjacent intensity values which outputs in high values for modulated sounds, and small values for constant sounds. In Fig. 5, we show two spectrograms from the Selva of Castelfidardo, in which it is possible to note the difference between the complexity of bird songs (modulated sounds) and traffic noise (with “flat-like” behavior; Fig. 5).

Anderson, S. E., Dave, A. S., and Margoliash, D. (1996). “Template-based automatic recognition of birdsong syllables from continuous recordings,” *J. Acoust. Soc. Am.* **100**, 1209–1219.

Baker, J., French, K., and Whelan, R. J. (2002). “The edge effect and ecotonal species: Bird communities across a natural edge in southeastern Australia,” *Ecology* **83**, 3048–3059.

Bautista, L. M., Garcia, J. T., Calmaestra, R. G., Palacin, C., Martin, C. A., Morales, M. A., Bonal, R., and Vinuela, R. (2004). “Effect of weekend road traffic on the use of space by raptors,” *Conserv. Biol.* **18**, 726–732.

Bayne, E. M., Habib, L., and Boutin, S. (2008). “Impacts of chronic anthropogenic noise from energy-sector activity on abundance of songbirds in the Boreal Forest,” *Conserv. Biol.* **22**, 1186–1193.

Brumm, H. (2004). “The impact of environmental noise on song amplitude in a territorial bird,” *J. Anim. Ecol.* **73**, 434–440.

Brumm, H., and Slabbekorn, H. (2005). “Acoustic communication in noise,” *Adv. Study Behav.* **35**, 151–209.

Brumm, H., and Slater, J. B. (2006). “Ambient noise, motor fatigue, serial redundancy in chaffinch song,” *Behav. Ecol. Sociobiol.* **60**, 475–481.

Brumm, H., and Todt, D. (2002). “Noise-dependent song amplitude regulation in a territorial songbird,” *Anim. Behav.* **63**, 891–897.

Celis-Murillo, A., Deppe, J. L., and Allen, M. F. (2009). “Using soundscape recordings to estimate bird species abundance, richness, and composition,” *J. Field Orn.* **80**, 64–78.

Clark, W. D., and Karr, J. R. (1979). “Effects of highways on Redwinged Blackbird and Horned Lark populations,” *Wilson Bull.* **91**, 143–145.

Collins, S. (2004). “Vocal fighting and flirting: The functions of birdsong,” in *Nature's Music: The Science of Birdsong*, edited by P. Marler and H. Slabbekorn (Academic, San Diego, CA), pp. 39–79.

Dooling, R. J., and Popper, A. N. (2007). *The Effects of Highway Noise on Birds*, The California Department of Transportation, Division of Environmental Analysis (Environmental BioAcoustics LLC, Rockville, MD), pp. 1–74.

Fahrig, L., and Rytwinski, T. (2009). “Effects of roads on animal abundance: An empirical review and synthesis,” *Ecol. Soc.* **14**, 21, <http://www.ecologyandsociety.org/vol14/iss1/art21/>.

Farina, A., Lattanzi, E., Malavasi, R., Pieretti, N., and Piccioli, L. (2011a). “Bird soundscape and the cognitive landscape approach: Theory, methods and perspectives,” *Landscape Ecol.* **26**, 1257–1267.

Farina, A., and Morri, D. (2008). “Source-sink e eco-field: ipotesi ed evidenze sperimentali. Atti del X congresso nazionale della SIEP-IALE. Ecologia e governance del paesaggio: esperienze e prospettive” (“Source-sink and eco-field: hypothesis and experimental evidences,” *Proceedings of the X National Congress of the SIEP-IALE. Ecology and Landscape Governance: Experiences and Perspectives*) Bari, pp. 365–372.

Farina, A., Pieretti, N., and Piccioli, L. (2011b). “The soundscape methodology for long-term bird monitoring: A Mediterranean Europe case-study,” *Ecol. Inf.* **6**, 354–363.

Forman, R. T. T., and Alexander, L. E. (1998). “Roads and their major ecological effects,” *Ann. Rev. Ecol. Syst.* **29**, 207–231.

Forman, R. T. T., Reineking, B., and Hersperger, A. M. (2002). “Road traffic and nearby grassland bird patterns in a suburbanizing landscape,” *Environ. Manage. (N.Y.)* **29**, 782–800.

Francis, C. D., Ortega, C. P., and Cruz, A. (2009). “Noise pollution changes avian communities and species interactions,” *Curr. Biol.* **19**, 1415–1419.

Francis, C. D., Paritsis, J., Ortega, C. P., and Cruz, A. (2011). “Landscape patterns of avian habitat use and nest success are affected by chronic gas well compressor noise,” *Landscape Ecol.* **26**, 1269–1280.

Habib, L., Bayne, E. M., and Boutin, S. (2007). “Chronic industrial noise affects pairing success and age structure of ovenbirds *Seiurus aurocapilla*,” *J. Appl. Ecol.* **44**, 176–184.

Hansen, A. J., and di Castri, F. (1992). *Landscape Boundaries. Consequences for Biotic Diversity and Ecological Flows* (Springer, New York), pp. 1–432.

Hobson, K. A., Rempel, R. S., Greenwood, H., Turnbull, B., and Van Wilgenburg, S. (2002). “Acoustic surveys of birds using electronic recordings: New potential from an omni-directional microphone system,” *Wild. Soc. Bull.* **30**, 709–720.

Holland, M. M., Risser, P. G., and Naiman, R. J. (1991). *Ecotone. The Role of Landscape Boundaries in the Management and Restoration of Changing Environment* (Chapman and Hall, London, UK), pp. 1–145.

Joo, W., Gage, S. H., and Kastenc, E. P. (2011). “Analysis and interpretation of variability in soundscapes along an urban-rural gradient,” *Landsc. Urban Plann.* **103**, 259–276.

Kogan, J. A., and Margoliash, D. (1998). “Automated recognition of bird song elements from continuous recordings using dynamic time warping and hidden Markov models: A comparative study,” *J. Acoust. Soc. Am.* **103**, 2185–2196.

Krause, B. (1987). “Bioacoustics, habitat ambience in ecological balance,” *Wh. Earth Rev.* **57**, 14–18.

Laursen, K. (1981). “Birds on roadside verges and the effect of mowing on frequency and distribution,” *Biol. Conserv.* **20**, 59–68.

Lengagne, T., Aubin, T., Lauga, J., and Jouventin, P. (1999). “How do king penguins (*Aptenodytes patagonicus*) apply the mathematical theory of information to communicate in windy conditions?,” *Proc. R. Soc., London, Ser. B* **266**, 1623–1628.

Leopold, A. (1933). *Game Management* (Scriber, New York), pp. 1–481.

MacArthur, R. H., MacArthur, J. W., and Preer, J. (1962). “On bird species diversity II. Prediction of bird census from habitat measurements,” *Am. Nat.* **96**, 167–174.

Marten, K., and Marler, P. (1977). “Sound transmission and its significance for animal vocalization I. Temperate habitats,” *Behav. Ecol. Sociobiol.* **2**, 271–290.

Nemeth, E., and Brumm, H. (2009). “Blackbirds sing higher-pitched songs in cities: Adaptation to habitat acoustics or side-effect of urbanization?,” *Anim. Behav.* **78**, 637–664.

O'Connor, R. J., and Hicks, R. K. (1980). “The influence of weather conditions on the detection of birds during Common Birds Census fieldwork,” *Bird St.* **27**, 137–151.

- Parris, K. M., Velik-Lord, M., and North, J. M. A. (2009). "Frogs call at a higher pitch in traffic noise," *Eco. Soc.* **14**, 25, <http://www.ecologyandsociety.org/vol14/iss1/art29/>.
- Peris, S. J., and Pescador, M. (2004). "Effects of traffic noise on passerine populations in Mediterranean wooded pastures," *Appl. Acoust.* **65**, 357–366.
- Pieretti, N., Farina, A., and Morri, D. (2011). "A new methodology to infer the singing activity of an avian community: The acoustic complexity index (ACI)," *Eco. Ind.* **11**, 868–873.
- Pijanowski, B. C., Farina, A., Gage, S., Dumyahn, S., and Krause, B. (2011b). "What is soundscape ecology? An introduction and overview of an emerging new science," *Landscape Ecol.* **26**, 1213–1232.
- Pijanowski, B. C., Villanueva-Rivera, L. J., Dumyahn, S., Farina, A., Krause, B., Napoletano, B., Gage, S., and Pieretti, N. (2011a). "Soundscape ecology: The science of sound in landscapes," *BioScience* **61**, 203–216.
- Rabin, L. A., McCowan, B., Hooper, S. L., and Owings, D. H. (2003). "Anthropogenic noise and its effect on animal communication: An interface between comparative psychology and conservation biology," *Int. J. Com. Psy.* **16**, 172–192.
- Reijnen, R., Foppen, R., Braak, C. T., and Thissen, J. (1995). "The effects of car traffic on breeding bird populations in woodland. III. Reduction of density in relation to the proximity of main roads," *J. Appl. Ecol.* **32**, 187–202.
- Sjölander, K., and Beskow, J. (2000). "WaveSurfer—An open source speech tool," in *Proceedings of the ICSLP 2000*, Vol. 4, pp. 464–467.
- Slabbekoorn, H., and den Boer-Visser, A. (2006). "Cities change the songs of birds," *Curr. Biol.* **16**, 2326–2331.
- Slabbekoorn, H., and Peet, M. (2003). "Birds sing at a higher pitch in urban noise," *Nature* **424**, 267.
- Sueur, J., Pavoine, S., Hamerlynck, O., and Duvail, S. (2008). "Rapid acoustic survey for biodiversity appraisal," *PLoS One* **3**, e4065.
- Summers, P. D., Cunningham, G. M., and Fahrig, L. (2011). "Are the negative effects of roads on breeding birds caused by traffic noise?," *J. Appl. Ecol.* **48**, 1527–1534.
- Taffetani, F., Catorci, A., Ciaschetti, G., Cutini, M., Di Martino, L., Frattaroli, A. R., Paura, B., Pirone, G., Rismondo, M., and Zitti, S. (2012). "The *Quercus cerris* woods of the alliance *Carpinion orientalis* Horvat 1958 in Italy," *Plant Biosystems* **146**, 1–36.
- Tardella, F. M., Paolini, C., Salvucci, G., Raponi, M., and Orsomando, E. (2005). *Carta della vegetazione della Selva di Castelfidardo e del territorio circostante con itinerari naturalistici* ("Vegetational map of the Selva of Castelfidardo and the surrounding landscape with naturalistic itineraries") (S.EL.CA., Firenze), pp. 1–12.
- Trifa, V. M., Kirschel, A. N. G., Taylor, C. E., and Vallejo, E. (2008). "Automated species recognition of antbirds in a Mexican rainforest using hidden Markov models," *J. Acoust. Soc. Am.* **123**, 2424–2431.
- Trombulak, S. C., and Frissell, C. A. (2000). "Review of ecological effects of roads on terrestrial and aquatic communities," *Conserv. Biol.* **14**, 18–30.
- Warren, P., Katti, M., Ermann, M., and Brazel, A. (2006). "Urban bioacoustics: It's not just noise," *Anim. Behav.* **71**, 491–502.
- Zoellinger, S. A., and Brumm, H. (2011). "The Lombard effect," *Curr. Biol.* **21**, R614–R615.
- Zoellinger, S. A., Goller, F., and Brumm, H. (2011). "Metabolic and respiratory costs of increasing song amplitude in Zebra Finches," *PLoS One* **6**, e23198.