Low cost (audio) recording (LCR) for advancing soundscape ecology towards the conservation of sonic complexity and biodiversity in natural and urban landscapes

A. Farina · P. James · C. Bobryk · N. Pieretti · E. Lattanzi · J. McWilliam

Abstract Low cost (audio) recorders (LCRs) represent a new opportunity to investigate the sonic complexity of both natural and urban ecosystems. LCRs are inexpensive sampling audio recorders which have the external shape of a universal serial bus (USB) flash drive, and are composed of a microphone, an analog-to-digital converter, central processing unit with permanent internal non-volatile memory, rechargeable battery, and a USB connection. The reduced dimensions allow the device to be deployed inconspicuously within any environment, in any configuration and for an extended time period. This investigation tested a specific type of LCR (UR-09) with a spectral range of 8 kHz - sufficient to cover the acoustic range of most western Palearctic songbirds. The reliability of the UR-09, compared with other commercial recorders (Zoom H4 and Song Meter SM1) and based on the quality of recordings quantified by the Acoustic Complexity Index (ACI), was tested and confirmed. An example of the application of LCRs is presented in an evaluation of the audio patterns occurring during dawn and dusk choruses within a forested ecosystem. Results of this investigation are encouraging and a new generation of LCR devices is currently being designed with real-time acoustic data processing capabilities, timer programmability, a larger frequency range and wireless communication compatibility. LCRs are revealed to be ideal instruments to conduct surveys in fragile or protected areas and also in urban environments. Moreover, due to their low cost, they can be used to encourage research in

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soundscape ecology, especially within developing countries, where large areas can be monitored by professionals or incorporating citizen science models of data collection.

Keywords Soundscape ecology · Low cost (audio) recorders · Acoustic complexity index · Acoustic monitoring · Citizen science · Urban ecosystems

Introduction

Wherever there is human activity, sounds are generated. The cracking of twigs when walking, speech, traffic, machinery - all produce sounds that radiate into the surrounding environment. Such human generated sounds - anthrophonies - combine with the sounds of waterfalls, wind and other natural sounds - geophonies - and with sounds produced by animals (bird song, the calls of mammals, and stridulations of insects among others) - biophonies - to form the soundscape or sonic environment (Pijanowski et al. 2011a, b). The soundscape is not constant; it is both spatially and temporally heterogeneous. This variation, prevalent in every ecosystem (natural and urban), can be defined and characterized by specific acoustic signatures (Bormpoudakis et al. 2013).

Soundscape ecology, an emergent field of investigation (Farina 2014) was recently proposed as a new ecological tool applicable to monitoring animal community dynamics (Pijanowski et al. 2011a, b), measuring the level of biodiversity (Gasc et al. 2013), and managing the sources of anthropogenic noises (Botteldooren et al. 2006). This discipline is an innovative approach to investigating the complexity of both human and natural systems, and is less invasive than traditional physical surveys (Davies 2013).

Biologic systems can be investigated in depth by recording and quantifying acoustic energy to infer the complexity of unique areas, such as remote tropical regions or neighborhoods within cities. This technique may also be used to further understand perturbations over the landscape, such as changes in land use, the effects of climatic changes on animal populations or simply the quality of coupled human-natural environments (Liu et al. 2007; Pijanowski et al. 2011a, b). Environmental sounds can be used to assess the degree of biological richness and ecological integrity of the environment (Gasc et al. 2013). Soundscape analysis is a powerful approach in investigating the complexity of the signs and codes - that is to say, the biosemiotic relationships - that vocal animals share to maintain connections with neighboring individuals (Farina and Pieretti 2013). Hence, the soundscape can be interpreted to glean information about the environment for every vocal and non-vocal animal (Farina et al. 2011a; Krause 2012), and the importance of the soundscape was recently extended when Gagliano et al. (2012a, b) reported that plants react morphologically to different sources of sounds (see also Francis et al. (2013) for other effects on vegetation). Moreover, the quality of human life is also affected by the sonic environment where noise pollution levels are commonly accepted as a parameter in environmental quality assessments (Mace et al. 1999).

The sonic heterogeneity that emerges from the overlap of geophonies, biophonies, and anthrophonies creates sonic patterns defined by Farina (2014, p. 17) as 'sonotopes', which can be related to distinct behavior-driven variations in the acoustic activities of individual species (Farina 2014, p.19, Malavasi and Farina 2013). In particular, the sonic quality of fragile and rare habitats seems to be a fundamental parameter of that habitat, but it is underutilized for nature conservation (Barber et al. 2011).

Investigating the soundscape requires collection of information on different acoustic sources - which could be originating from waterfalls, birds, or machinery to give three examples - that are irregularly distributed across the landscape. The passive recording of environmental sounds is a technique that collects a large amount of data with minimal human intrusion

(Hobson et al. 2002), requiring the simultaneous deployment of numerous microphones in arrays or transects to achieve adequate representation of sound sources and to collect statistically relevant data. An array of recorders regularly spaced in a grid format has been shown to be a good experimental design (see Farina and Pieretti 2013, Rodriguez et al. 2013). The line transect method is an established technique in bird census works (Bibby et al. 1992) and it represents the most expeditious investigation. However, various other spatial geometries can be utilized. Applying the same approach in sound-scape investigations, a linear transect of sound recorders dispersed at regular intervals can be used to collect information about the distribution of vocal animals, especially across environmental gradients. The data collected can be analyzed by expert systems at a later time, thus reducing the amount of effort and uncertainty found in field aural identification and signal quantification.

In practice, the costs of most modern audio digital recorders (ranging from US$800 to 1000 for each device), the labour required to setup the equipment in the field, and the requirement for professional bioacousticians to use the equipment and interpret the data means that the realization of a grid or of a transect using numerous acoustic data loggers is often not possible, especially in countries where funding can be very limited, or where citizen science approaches to data collection are adopted.

Recent technological advances have resulted in the availability of low cost audio recorders (LCRs) (approximately 10 US$ per unit) that have interesting performance capabilities that could be comparable with the performance of more expensive devices. They are small devices that can be easily connected to a computer using a USB port, and have a rechargeable internal battery. The disadvantages are the low quality microphone and a reduced spectral sensibility (8 kHz) although this range of frequencies covers the majority of birds, frogs, and terrestrial mammals, but not bats or many insects.

The objectives for this investigation is to test the reliability of the LCR UR-09 and to compare its performance with two other commercial devices: Zoom H4 (Zoom Inc.) and Song Meter SM (Wildlife Acoustic ™), which are used by professionals for soundscape studies both in natural and urban systems. Moreover, in order to evaluate the adequacy of UR-09 to investigate the acoustic dynamics of vocal animals, an example of an application is presented where acoustic patterns of a bird assemblage at dawn chorus is compared to an early morning (Fig. 1). The use of LCRs could open a new realm soundscape research that involves citizen scientists, wildlife managers, rangers, and professional scientists, in natural and urban ecosystems and in both rich and poor countries.
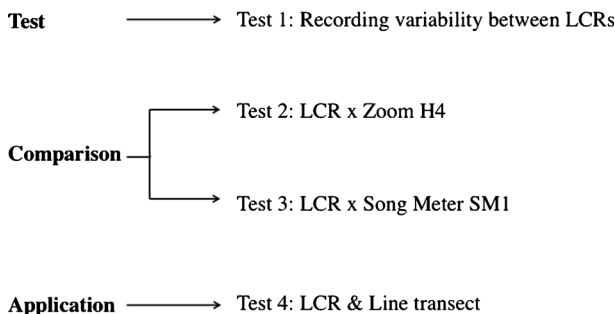

Fig. 1 Schematic representation of the protocol used to test the reliability of the LCR

Materials and methods

The LCR

This investigation involves the use of a commercial LCR digital audio recorder (model UR-09) produced by the ShenZhen HNSAT Industrial Co. Ltd (China). The device is similar in shape to an USB flash drive, has dimensions of 64x22x10 mm, weighs 14 g, and costs around 10 US$ each (Fig. 2). This recorder has a third generation, highly integrated single-chip (ATJ331X, Actions Semiconductor Co., Ltd, China) and records at a sample rate of 16,000Hz in a compressed *.wav* format at 128 bps. Sound is collected by a built-in electret, omni-directional microphone with an output impedance (F=1 kHz 1 Pa) of 2.2 kΩ, a frequency range of 50 Hz to 8 kHz, a sensitivity (F=1 kHz, 0 dB=1 V Pa) of −42±3 dB, and a signal to noise ratio (F= 1 kHz 1 Pa) A-weighted of 60 dB. The recorder has an internal storage capacity of 8 Gb. The device is equipped with an internal Li-Polymer rechargeable battery (NAT 401235, 3.7 V 120 mAh 1212) that can be recharged directly by means of a PC via USB or at a powered hub (Fig. 3). It will record for an average of 16 h and can be extended to 140 h when powered by an external battery. The microphone gain of LCR cannot be modified.

The recorder operates, according the factory's description, with Microsoft Windows 7. The flash memory is formatted according the FAT32 file-system so that generated audio files can also be read by others platforms like Apple OS, Linux and later versions of Windows. Audio files are segmented automatically every four hours.

Acoustic complexity index (ACI)

Performance of the UR-09 recorder and a comparison with other commercial devices was assessed using an Acoustic Complexity Index (ACI), which has been used extensively in the analysis of soundscapes. The ACI is an algorithm created to produce a direct quantification of the complex biotic songs by computing the variability of the intensities registered in spectograms of audio-recordings (Pieretti et al. 2011). The ACI was provided by SoundscapeMeter software (Farina et al. 2012) that is freely available (http://www.disbef.uniurb.it/biomia/soundscapemeter/). This index has been demonstrated to be a good metric to describe acoustic patterns and capable of producing a rapid analysis of acoustic data with a limited investment of time per person (Pieretti et al. 2011).

Fig. 2 The UR-09 LCR from ShenZhen HNSAT Industrial Co. Ltd (China). This miniaturized acoustic data logger can be easily deployed in the field with extend sampling times (approximately 16 h)

Fig. 3 Ten LRC units plugged into a USB rechargeable hub. Data contained within each unit can be downloaded and processed using this hub

The ACI was parameterized with a FFT (Fast Fourier Transform) window of 512 points, a noise threshold filter of 3000 amplitude, and "clumping" (the temporal window on which to apply the ACI index along the acoustic file) was set to 1 s intervals. This parameterization was extended to all the tests for field investigation. Two hundred and fifty six classes of frequencies were obtained after applying the FFT to the acoustic files (this transforms the .wav file made by the LCR from a temporal to a frequency domain), each class consisting of a band of 31.25 Hz when the sampling frequency was 16 kHz (LCR, SongMeter SM1), and 86.16 Hz in the case of Zoom H4, when the sampling was 44.1 kHz.

TEST 1: Recording variability between individual LCRs

Fifty UR-09 LCR devices were purchased directly from the producer (ShenZhen HNSAT Industrial Co. Ltd, China) and had been previously tested in their inter-individual variability of recording performances in the Urbino University Scientific Campus Park (43°42'01.18"N 12°38'29.64"E, 321 m a.s.l.) on July 30, 2013 at 6.00 p.m. At that time there were sounds from birds and cicadas to verify the performance and sensitivity of microphone capsules. All recorders were synchronized to record natural, ambient soundscape for 5 min. The ACI index and the energy per unit time falling within a given frequency band (power spectrum) were calculated for every frequency band to evaluate the performance of each audio recorder.

TEST 2: Comparison between the LCR and two commercial-scale acoustic data loggers

TEST 2a comparison with Zoom H4

Zoom H4 is a commercial recorder with good acoustic outdoor reliability and already extensively used in our field research to investigate the sonic structure of a bird community during the breeding period (e.g. Farina and Pieretti 2013). This audio recorder can sample the sound at one of three frequencies (44.1, 48 and 96 kHz), has an input gain mode that ranges from −48 to 0 dB, and additionally offers three recording modes (for musical instruments, low volume musical instruments, and outdoor recordings). This test used a sampling frequency of 44.1 kHz and the microphone was set on the position for outdoor recording mode with a gain of −12 dB. A comparison between four Zoom H4s and four LCRs was carried out on 31 May, 2013 within four different woodland areas of the northern Apennines (M. Tergagliana (44°14'56.19"N, 10°05'33.31"E, 625 m a.s.l.), Virolo (44°13'59.98"N, 10°06'01.29" E,

349 m a.s.l.), Monte Curto (44°14'01.02"N, 10°04'03.69"E, 222 m a.s.l.), Madonna dei Colli (44°12'37.85"N, 10°03'27.12"E, 217 m a.s.l.), by error. These sites form part of an ongoing soundscape research program. The UR-09 recorders were placed in the same container used to protect Zoom H4 from humidity and rain. On the 31 May 2013, 16 files (one from each piece of equipment) each of one hour duration were recorded of the dawn chorus.

Zoom H4 devices have a minimum sampling rate of 44.1 kHz and sound files were re-sampled in the laboratory at16 kHz in order to compare the value of ACI at the same frequency classes of the LCR. The ACI was calculated for one hour of dawn chorus by subdividing the sound files into sections of one minute duration (each one minute division is known as a temporal step). There were 60 temporal steps analyzed for each device.

TEST 2b: comparison between LCR and Song Meter SM 1

The Song Meter SM 1 (Wildlife Acoustics ™) is a very popular device used world-wide to collect acoustic information, especially for long term investigations. Several studies have recently been published using this device (e.g. Sueur et al. 2008, 2012; Farina et al. 2011b; Pekin et al. 2012; Gasc et al. 2013). A comparison was made between the Song Meter SM1 and the LCR by setting the SM1 gain at +40.5 dB (45 dB max available) with a sampling rate of 16 kHz. The comparison was carried out in a beech forest of the Tosco-Emiliano Northern Apennines (Lago Pranda, 44°18'19.99"N, 10°14'39.01"E, 1276 m a.s.l.) from 7.00 to 8.00 a.m. on 24 July 2013. The ACI was calculated for both devices by subsampling one hour sound files in 60 steps of 1 min each.

TEST 3: LCRs used to describe the dynamics of bird communities

This investigation tested the capability of the LCR to collect acoustic information (that is to say biophonic information) in a heterogeneous forested location near "Madonna dei Colli" (44°12'23.87"N, 10°03'38.70"E, 327 m a.s.l.) in the Fivizzano Commune at an average altitude of 200 m a.s.l. This area has an undulating topography and is particularly rich in bird species diversity due to the high heterogeneity of tree species and canopy structure. The forested area is at different successional stages after various logging events and is encompassed by margins of cultivation (e.g. vineyards, olive orchards, and abandoned fields). Plant species and birds are reported in Supplementary Materials #1 and #2, respectively.

Forty UR-09 recorders were placed on the lower branches of trees between 3 and 4 m above the ground at 80 m intervals along a forest path. One device malfunctioned and its data was excluded from the computation. This interval was chosen taking into account the acoustic overlap between adjacent recorders in dense vegetation, which creates a real barrier to sound propagation (Farina and Pieretti 2014). For the morning session, the recorders where placed in the field on July 2nd, 2013, starting at 5.20 am and the data sampling was for one hour starting at 7.20 am. The dawn session was conducted on July 16th, 2013. The recorders were placed along the previous transect and switched on at 17.45 h the day before. The UR-09 LCR lacks a timer to programming a start time. Data sampling was for 60 min starting at 3.30 a.m., which was the start of the dawn chorus at this time of the year. Deployment of the recorders along the 3.2 km transect required 90 min on average for both cases. Canopy cover of each recording site was estimated according to methods of vertical photography proposed Goodenough and Goodenough (2012). The ACI was calculated for both sessions subdividing the one hour period in 60 steps of one minute each.

Results and discussion

TEST 1: Reliability of LCR

From a stock of fifty UR-09 recorders used in this test, eight were discarded for an evident malfunction. The remaining recorders showed similar ACI values (n=42, CV 12.16) along the 256 classes of frequency as indicated from the correlation matrix reported in Table 1. The temporal distribution of ACI for the 5 min intervals has similar values for all the recorders (Table 2). The power spectrum calculated for each recorder for the 5 min interval revealed a CV=20.17.

TEST 2a: LCR & Zoom H4

Positive correlations were found between the ACI values for the different recorders along the 60 temporal steps of 1 min each (Table 3). A correlation $r > 0.80$ was found in 12 of the 16 comparisons. Although the acoustic patterns have a similar distribution between Zoom H4 and the UR-09 LCR, the LCR repeatedly had a higher ACI than that from the Zoom H4. This may be due to a difference in gain levels between Zoom H4 and the LCR.

TEST 2b: LCR & Song Meter sm1

A significant positive correlation ($p < 0.05$) was found between the SM1 and the LCR for ACI along frequencies (256 classes) and for the ACI along the 60, 1 min temporal steps (r=0.98 and 0.96, respectively). The total value of ACI is higher for SM1 probably due to the maximum gain setting. When SM1 is set at +30, similar to a previous investigation (Farina et al. 2011b), the ACI values are found to be always lower than those for the LCR. The excellent correlation between LCR and SM1 (Fig. 4) represents a further contribution to confirm the reliability of LCR.

TEST 3: Line transect survey

A comparison between dawn and morning sessions shows a similar acoustic footprint or signature (Fig. 5) but, as expected, the amount of information at dawn was higher than in the late morning. Also the shape of the acoustic signature appears more complex at dawn with two peaks compared to one in the late morning.

A correlation of r=0.99 was found between dawn chorus and morning ACI values, thus confirming a similar patchy distribution of bird sounds at least during these two periods. From a cluster of recorders the data from the LCRs at dawn was aggregated according to distinct temporal patterns. This result confirms the heterogeneous spatial distribution of birds at dawn: a distribution that is approximately coincident with the roosting places of passerines (Fig. 6a). Cluster analysis applied to the ACI values of the recordings in the early morning produced less clear patterns (Fig. 6b).

No significant correlation was found between vegetation cover and ACI values during the dawn chorus or in the morning (Kruskall-Wallis 7.75 (P=.05), 4.42 (P=0.21) respectively). Of course, further investigations on vegetation structure are required to adequately explain this result.

Perspectives on the application of LCR to urban soundscape evaluation, protection and design

The methods presented in this study provide an example of sampling techniques that are advantageous for remote areas or where human impact may be strong. Due to the dimension of the LCR, it can be easily placed at ground level and attached to shrubby or tree vegetation or

Table 1 Correlation matrix between LCR and ACI values along different frequencies

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21
1	1.00	0.95	0.98	0.98	0.98	1.00	0.98	0.97	0.98	0.99	0.97	0.98	0.99	0.99	0.98	0.96	0.98	0.99	0.99	0.99	0.99
2	0.95	1.00	0.91	0.99	0.95	0.93	0.89	0.88	0.98	0.96	0.99	0.90	0.96	0.92	0.99	0.99	0.90	0.97	0.92	0.97	0.95
3	0.98	0.91	1.00	0.94	0.99	0.98	0.99	0.99	0.95	0.96	0.95	0.99	0.97	0.96	0.95	0.93	1.00	0.96	0.99	0.96	0.99
4	0.98	0.99	0.94	1.00	0.97	0.96	0.93	0.92	0.99	0.98	0.99	0.94	0.98	0.96	1.00	0.99	0.94	0.99	0.96	0.99	0.98
5	0.98	0.95	0.99	0.97	1.00	0.98	0.97	0.96	0.96	0.97	0.97	0.98	0.98	0.96	0.97	0.96	0.98	0.97	0.98	0.97	0.99
6	1.00	0.93	0.98	0.96	0.98	1.00	0.99	0.98	0.97	0.99	0.96	0.99	0.99	0.99	0.96	0.95	0.99	0.98	0.99	0.98	0.99
7	0.98	0.89	0.99	0.93	0.97	0.99	1.00	1.00	0.94	0.97	0.93	1.00	0.97	0.97	0.93	0.92	1.00	0.96	0.99	0.96	0.98
8	0.97	0.88	0.99	0.92	0.96	0.98	1.00	1.00	0.93	0.96	0.92	1.00	0.95	0.96	0.92	0.90	1.00	0.95	0.99	0.95	0.97
9	0.98	0.98	0.95	0.99	0.96	0.97	0.94	0.93	1.00	0.99	0.99	0.95	0.98	0.97	0.99	0.99	0.95	0.99	0.96	0.99	0.97
10	0.99	0.96	0.96	0.98	0.97	0.99	0.97	0.96	0.99	1.00	0.98	0.97	0.99	0.99	0.98	0.98	0.97	1.00	0.98	0.99	0.98
11	0.97	0.99	0.95	0.99	0.97	0.96	0.93	0.92	0.99	0.98	1.00	0.94	0.98	0.95	1.00	0.99	0.94	0.99	0.96	0.99	0.98
12	0.98	0.90	0.99	0.94	0.98	0.99	1.00	1.00	0.95	0.97	0.94	1.00	0.97	0.97	0.94	0.92	1.00	0.96	0.99	0.96	0.98
13	0.99	0.96	0.97	0.98	0.98	0.99	0.97	0.95	0.98	0.99	0.98	0.97	1.00	0.98	0.98	0.97	0.97	0.99	0.98	0.99	0.99
14	0.99	0.92	0.96	0.96	0.96	0.99	0.97	0.96	0.97	1.00	0.95	0.97	0.98	1.00	0.96	0.94	0.97	0.98	0.98	0.98	0.98
15	0.98	0.99	0.95	1.00	0.97	0.96	0.93	0.92	0.99	0.98	1.00	0.94	0.98	0.96	1.00	0.99	0.94	0.99	0.96	0.99	0.97
16	0.96	0.99	0.93	0.99	0.96	0.95	0.92	0.90	0.99	0.98	0.99	0.92	0.97	0.94	0.99	1.00	0.92	0.99	0.94	0.98	0.97
17	0.98	0.90	1.00	0.94	0.98	0.99	1.00	1.00	0.95	0.97	0.94	1.00	0.97	0.97	0.94	0.92	1.00	0.96	0.99	0.96	0.98
18	0.99	0.97	0.96	0.99	0.97	0.98	0.96	0.95	0.99	1.00	0.99	0.96	0.99	0.98	0.99	0.96	1.00	0.98	0.99	0.98	0.99
19	0.99	0.92	0.99	0.96	0.98	0.99	0.99	0.99	0.96	0.98	0.96	0.99	0.98	0.98	0.96	0.94	0.99	0.98	1.00	0.98	0.98
20	0.99	0.97	0.96	0.99	0.97	0.98	0.96	0.95	0.99	0.99	0.99	0.96	0.99	0.98	0.99	0.96	0.99	0.98	0.99	1.00	0.98
21	0.99	0.95	0.99	0.98	0.99	0.99	0.98	0.97	0.97	0.98	0.98	0.98	0.99	0.98	0.98	0.97	0.98	0.98	0.99	0.98	1.00
22	0.97	0.99	0.94	1.00	0.97	0.96	0.93	0.91	0.99	0.98	0.99	0.93	0.98	0.95	0.99	1.00	0.93	0.99	0.95	0.98	0.98
23	1.00	0.95	0.98	0.98	0.98	1.00	0.98	0.98	0.98	0.99	0.98	0.98	0.99	0.99	0.98	0.96	0.98	0.99	0.99	0.99	0.99
24	0.99	0.94	0.99	0.97	0.99	0.99	0.99	0.98	0.97	0.99	0.97	0.99	0.99	0.98	0.97	0.95	0.99	0.98	1.00	0.99	0.99
25	0.99	0.97	0.97	0.99	0.99	0.98	0.96	0.95	0.99	0.99	0.99	0.97	0.99	0.97	0.99	0.98	0.97	0.99	0.98	0.99	0.99
26	0.99	0.97	0.96	0.99	0.97	0.98	0.96	0.95	0.99	1.00	0.99	0.96	0.99	0.98	0.99	0.98	0.96	1.00	0.98	1.00	0.98

Table 1 (continued)

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21
27	0.98	0.93	0.99	0.96	0.99	0.98	0.98	0.98	0.96	0.97	0.96	0.99	0.98	0.96	0.96	0.94	0.99	0.97	0.99	0.97	0.99
28	0.99	0.92	0.97	0.95	0.96	0.99	0.99	0.98	0.97	0.99	0.96	0.98	0.98	0.99	0.96	0.94	0.98	0.98	0.99	0.98	0.97
29	0.99	0.96	0.97	0.99	0.97	0.99	0.97	0.96	0.99	1.00	0.99	0.97	0.99	0.98	0.99	0.98	0.97	0.99	0.98	1.00	0.98
30	0.99	0.95	0.98	0.97	0.98	0.99	0.98	0.97	0.98	0.99	0.98	0.98	0.99	0.99	0.98	0.96	0.98	0.99	0.99	0.99	0.99
31	0.99	0.91	0.99	0.95	0.98	0.99	1.00	0.99	0.96	0.97	0.95	1.00	0.98	0.98	0.95	0.93	1.00	0.97	0.99	0.97	0.99
32	1.00	0.96	0.98	0.98	0.99	0.99	0.98	0.97	0.99	0.99	0.98	0.98	0.99	0.98	0.99	0.97	0.98	0.99	0.99	0.99	0.99
33	0.99	0.93	0.99	0.96	0.98	1.00	0.99	0.99	0.97	0.99	0.96	0.99	0.99	0.99	0.96	0.95	0.99	0.98	1.00	0.98	0.99
34	0.99	0.91	0.99	0.95	0.98	1.00	1.00	0.99	0.96	0.98	0.95	0.99	0.98	0.98	0.95	0.93	1.00	0.97	1.00	0.97	0.98
35	0.99	0.94	0.95	0.97	0.96	0.99	0.96	0.95	0.98	0.99	0.97	0.96	0.99	0.99	0.97	0.95	0.96	0.98	0.98	0.99	0.97
36	0.99	0.96	0.95	0.98	0.95	0.98	0.95	0.94	0.99	1.00	0.98	0.95	0.98	0.98	0.99	0.98	0.95	0.99	0.97	0.99	0.97
37	1.00	0.96	0.98	0.98	0.99	0.99	0.98	0.97	0.99	0.99	0.98	0.98	0.99	0.99	0.98	0.97	0.98	0.99	0.99	0.99	0.99
38	0.98	0.97	0.93	0.99	0.94	0.96	0.93	0.92	0.99	0.99	0.97	0.93	0.97	0.97	0.98	0.98	0.93	0.99	0.95	0.98	0.96
39	0.99	0.98	0.97	0.99	0.98	0.98	0.96	0.95	0.99	0.99	0.99	0.96	0.99	0.97	0.99	0.99	0.96	0.99	0.98	0.99	0.99
40	0.97	0.97	0.92	0.98	0.93	0.96	0.93	0.92	0.99	0.99	0.98	0.93	0.97	0.96	0.98	0.98	0.93	0.99	0.95	0.99	0.95
41	0.99	0.96	0.98	0.98	0.99	0.99	0.97	0.96	0.98	0.99	0.99	0.98	0.99	0.98	0.99	0.97	0.98	0.99	0.99	0.99	0.99
42	0.97	0.99	0.95	0.99	0.98	0.96	0.93	0.92	0.98	0.97	0.99	0.94	0.98	0.95	0.99	0.99	0.94	0.98	0.96	0.98	0.98

	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42
1	0.97	1.00	0.99	0.99	0.99	0.98	0.99	0.99	0.99	0.99	1.00	0.99	0.99	0.99	0.99	1.00	0.98	0.99	0.97	0.99	0.97
2	0.99	0.95	0.94	0.97	0.97	0.93	0.92	0.96	0.95	0.91	0.96	0.93	0.91	0.94	0.96	0.96	0.97	0.98	0.97	0.96	0.99
3	0.94	0.98	0.99	0.97	0.96	0.99	0.97	0.97	0.98	0.99	0.98	0.99	0.99	0.95	0.95	0.98	0.93	0.97	0.92	0.98	0.95
4	1.00	0.98	0.97	0.99	0.99	0.96	0.95	0.99	0.97	0.95	0.98	0.96	0.95	0.97	0.98	0.98	0.99	0.99	0.98	0.98	0.99
5	0.97	0.98	0.99	0.99	0.97	0.99	0.96	0.97	0.98	0.98	0.99	0.98	0.98	0.96	0.95	0.99	0.94	0.98	0.93	0.99	0.98
6	0.96	1.00	0.99	0.98	0.98	0.98	0.99	0.99	0.99	0.99	0.99	1.00	1.00	0.99	0.98	0.99	0.96	0.98	0.96	0.99	0.96
7	0.93	0.98	0.99	0.96	0.96	0.98	0.99	0.97	0.98	1.00	0.98	0.99	1.00	0.96	0.95	0.98	0.93	0.96	0.93	0.97	0.93

Table 1 (continued)

	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42
8	0.91	0.98	0.98	0.95	0.95	0.98	0.98	0.96	0.97	0.99	0.97	0.99	0.99	0.95	0.94	0.97	0.92	0.95	0.92	0.96	0.92
9	0.99	0.98	0.97	0.99	0.99	0.96	0.97	0.99	0.98	0.96	0.99	0.97	0.96	0.98	0.99	0.99	0.99	0.99	0.99	0.98	0.98
10	0.98	0.99	0.99	0.99	1.00	0.97	0.99	1.00	0.99	0.97	0.99	0.99	0.98	0.99	1.00	0.99	0.99	0.99	0.99	0.99	0.97
11	0.99	0.98	0.97	0.99	0.99	0.96	0.96	0.99	0.98	0.95	0.98	0.96	0.95	0.97	0.98	0.98	0.97	0.99	0.98	0.99	0.99
12	0.93	0.98	0.99	0.97	0.96	0.99	0.98	0.97	0.98	1.00	0.98	0.99	0.99	0.96	0.95	0.98	0.93	0.96	0.93	0.98	0.94
13	0.98	0.99	0.99	0.99	0.99	0.98	0.98	0.99	0.99	0.98	0.99	0.99	0.98	0.99	0.98	0.99	0.97	0.99	0.97	0.99	0.98
14	0.95	0.99	0.98	0.97	0.98	0.96	0.99	0.98	0.99	0.98	0.98	0.99	0.98	0.99	0.98	0.99	0.97	0.97	0.96	0.98	0.95
15	0.99	0.98	0.97	0.99	0.99	0.96	0.96	0.99	0.98	0.95	0.99	0.96	0.95	0.97	0.99	0.98	0.98	0.99	0.98	0.99	0.99
16	1.00	0.96	0.95	0.98	0.98	0.94	0.94	0.98	0.96	0.93	0.97	0.95	0.93	0.95	0.98	0.97	0.98	0.96	0.98	0.97	0.99
17	0.93	0.98	0.99	0.97	0.96	0.99	0.98	0.97	0.98	1.00	0.98	0.99	1.00	0.96	0.95	0.98	0.93	0.96	0.93	0.98	0.94
18	0.99	0.99	0.98	0.99	1.00	0.97	0.98	0.99	0.99	0.97	0.99	0.98	0.97	0.98	0.99	0.99	0.99	0.99	0.99	0.99	0.98
19	0.95	0.99	1.00	0.98	0.98	0.99	0.99	0.98	0.99	0.99	0.99	1.00	1.00	0.98	0.97	0.99	0.95	0.98	0.95	0.99	0.96
20	0.98	0.99	0.99	0.99	1.00	0.97	0.98	1.00	0.99	0.97	0.99	0.98	0.97	0.99	0.99	0.99	0.98	0.99	0.99	0.99	0.98
21	0.98	0.99	0.99	0.99	0.98	0.99	0.97	0.98	0.99	0.99	0.99	0.99	0.98	0.97	0.97	0.99	0.96	0.99	0.95	0.99	0.98
22	1.00	0.97	0.96	0.99	0.98	0.95	0.94	0.98	0.97	0.94	0.98	0.95	0.94	0.96	0.98	0.98	0.98	0.99	0.97	0.98	0.99
23	0.97	1.00	1.00	0.99	0.99	0.98	0.99	0.99	1.00	0.99	0.99	1.00	0.99	0.99	0.99	0.99	0.97	0.99	0.97	0.99	0.97
24	0.96	1.00	1.00	0.99	0.98	0.99	0.99	0.99	1.00	0.99	0.99	1.00	0.99	0.99	0.97	0.99	0.96	0.99	0.96	0.99	0.97
25	0.99	0.99	0.99	1.00	0.99	0.98	0.97	0.99	0.99	0.97	0.99	0.98	0.97	0.98	0.98	0.99	0.97	0.99	0.97	1.00	0.99
26	0.98	0.99	0.98	0.99	1.00	0.97	0.98	1.00	0.99	0.97	0.99	0.98	0.97	0.99	1.00	0.99	0.98	0.99	0.99	0.99	0.98
27	0.95	0.98	0.99	0.98	0.97	1.00	0.97	0.97	0.98	0.99	0.99	0.98	0.99	0.96	0.95	0.99	0.94	0.98	0.93	0.99	0.97
28	0.94	0.99	0.99	0.97	0.98	0.97	1.00	0.99	0.99	0.99	0.98	0.99	0.99	0.99	0.98	0.99	0.96	0.97	0.97	0.98	0.97
29	0.98	0.99	0.99	0.99	1.00	0.97	0.99	1.00	0.99	0.97	0.99	0.99	0.98	0.99	0.99	0.99	0.98	0.99	0.99	0.99	0.97
30	0.97	1.00	1.00	0.99	0.99	0.98	0.99	0.99	1.00	0.99	0.99	1.00	0.99	0.99	0.99	0.99	0.97	0.99	0.97	0.99	0.97
31	0.94	0.99	0.99	0.97	0.97	0.99	0.99	0.97	0.99	1.00	0.98	0.99	1.00	0.97	0.96	0.99	0.95	0.97	0.94	0.98	0.95
32	0.98	1.00	0.99	0.99	0.99	0.99	0.98	0.99	0.99	0.98	1.00	0.99	0.98	0.98	0.98	1.00	0.97	0.99	0.97	1.00	0.98
33	0.95	1.00	1.00	0.98	0.98	0.98	0.99	0.99	1.00	0.99	0.99	1.00	1.00	0.99	0.98	0.99	0.96	0.98	0.96	0.99	0.95

Table 1 (continued)

	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42
34	0.94	0.99	0.99	0.97	0.97	0.99	0.99	0.98	0.99	1.00	0.98	1.00	1.00	0.98	0.96	0.99	0.95	0.97	0.94	0.98	0.94
35	0.96	0.99	0.99	0.98	0.99	0.96	0.99	0.99	0.99	0.97	0.98	0.99	0.98	1.00	0.98	0.99	0.96	0.98	0.97	0.98	0.96
36	0.98	0.99	0.97	0.98	1.00	0.95	0.98	0.99	0.99	0.96	0.98	0.98	0.96	0.98	1.00	0.98	0.99	0.98	0.99	0.98	0.96
37	0.98	1.00	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99	1.00	0.99	0.99	0.99	0.98	1.00	0.97	0.99	0.97	0.99	0.98
38	0.98	0.97	0.96	0.97	0.98	0.94	0.96	0.98	0.97	0.95	0.97	0.96	0.95	0.96	0.99	0.97	1.00	0.98	0.99	0.96	0.97
39	0.99	0.99	0.98	0.99	0.99	0.98	0.97	0.99	0.99	0.97	0.99	0.98	0.97	0.98	0.98	0.99	0.98	1.00	0.98	0.99	0.99
40	0.97	0.97	0.96	0.97	0.99	0.93	0.97	0.99	0.97	0.94	0.97	0.96	0.94	0.97	0.99	0.97	0.99	0.98	1.00	0.97	0.96
41	0.98	0.99	0.99	1.00	0.99	0.99	0.98	0.99	0.99	0.98	1.00	0.99	0.98	0.98	0.98	0.99	0.96	0.99	0.97	1.00	0.98
42	0.99	0.97	0.97	0.99	0.98	0.97	0.94	0.97	0.97	0.95	0.98	0.95	0.94	0.96	0.96	0.98	0.97	0.99	0.96	0.98	1.00

Table 2 Correlation matrix between LCR and ACI values along sampling periods

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21
1	1.00	0.98	0.98	0.99	0.98	0.99	0.97	0.98	0.99	0.98	0.96	0.97	0.97	0.98	0.98	0.96	0.96	0.98	0.96	0.96	0.98
2	0.98	1.00	0.98	0.98	0.98	0.98	0.97	0.99	0.98	0.99	0.97	0.98	0.99	0.98	0.99	0.97	0.96	0.99	0.97	0.97	0.98
3	0.98	0.98	1.00	0.98	0.99	0.99	0.98	0.99	0.99	0.98	0.98	0.99	0.98	0.96	0.98	0.94	0.98	0.98	0.98	0.99	0.96
4	0.99	0.98	0.98	1.00	0.98	0.99	0.97	0.98	0.98	0.98	0.96	0.98	0.97	0.98	0.97	0.95	0.97	0.98	0.97	0.96	0.98
5	0.98	0.98	0.99	0.98	1.00	0.98	0.98	0.99	0.99	0.98	0.98	0.98	0.97	0.97	0.98	0.94	0.98	0.98	0.98	0.98	0.96
6	0.99	0.98	0.99	0.99	0.98	1.00	0.97	0.98	0.99	0.98	0.97	0.98	0.97	0.97	0.97	0.94	0.98	0.97	0.97	0.97	0.97
7	0.97	0.97	0.98	0.97	0.98	0.97	1.00	0.98	0.98	0.97	0.98	0.98	0.97	0.96	0.97	0.93	0.99	0.98	0.98	0.98	0.96
8	0.98	0.99	0.99	0.98	0.99	0.98	0.98	1.00	0.99	0.98	0.97	0.98	0.98	0.98	0.98	0.96	0.97	0.99	0.97	0.97	0.97
9	0.99	0.98	0.99	0.98	0.99	0.99	0.98	0.99	1.00	0.98	0.97	0.98	0.98	0.98	0.98	0.95	0.97	0.98	0.97	0.97	0.97
10	0.98	0.99	0.98	0.98	0.98	0.98	0.97	0.98	0.98	1.00	0.97	0.99	0.99	0.97	0.98	0.96	0.97	0.98	0.98	0.97	0.97
11	0.96	0.97	0.98	0.96	0.98	0.97	0.98	0.97	0.97	0.97	1.00	0.98	0.96	0.97	0.97	0.91	0.99	0.98	0.99	0.99	0.94
12	0.97	0.98	0.99	0.98	0.98	0.98	0.98	0.98	0.98	0.99	0.98	1.00	0.98	0.98	0.98	0.93	0.98	0.98	0.98	0.99	0.96
13	0.97	0.99	0.98	0.97	0.97	0.97	0.97	0.98	0.98	0.99	0.96	0.98	1.00	0.97	0.97	0.98	0.96	0.98	0.97	0.97	0.98
14	0.98	0.98	0.96	0.98	0.97	0.97	0.96	0.98	0.98	0.97	0.94	0.95	0.97	1.00	0.97	0.97	0.94	0.97	0.94	0.94	0.98
15	0.98	0.99	0.98	0.97	0.98	0.97	0.97	0.98	0.98	0.98	0.97	0.98	0.99	0.97	1.00	0.96	0.97	0.98	0.97	0.97	0.97
16	0.96	0.97	0.94	0.95	0.96	0.94	0.93	0.96	0.95	0.96	0.91	0.93	0.98	0.97	0.96	1.00	0.91	0.96	0.92	0.92	0.95
17	0.96	0.96	0.98	0.97	0.98	0.98	0.99	0.97	0.97	0.97	0.99	0.98	0.98	0.97	0.97	0.91	1.00	0.97	0.99	0.99	0.97
18	0.98	0.99	0.98	0.98	0.98	0.97	0.98	0.99	0.98	0.98	0.98	0.98	0.98	0.97	0.98	0.96	0.97	1.00	0.98	0.97	0.95
19	0.96	0.97	0.98	0.97	0.98	0.97	0.98	0.97	0.97	0.98	0.99	0.98	0.97	0.94	0.97	0.92	0.99	0.98	1.00	0.99	0.94
20	0.96	0.97	0.99	0.96	0.98	0.97	0.98	0.97	0.97	0.97	0.99	0.99	0.97	0.94	0.97	0.92	0.99	0.97	0.99	1.00	0.94
21	0.98	0.98	0.96	0.98	0.96	0.97	0.96	0.97	0.97	0.97	0.94	0.96	0.98	0.98	0.97	0.97	0.95	0.97	0.95	0.94	1.00
22	0.98	0.98	0.98	0.99	0.98	0.98	0.97	0.98	0.98	0.97	0.95	0.97	0.97	0.98	0.97	0.96	0.96	0.98	0.96	0.96	0.99
23	0.98	0.99	0.99	0.98	0.98	0.98	0.98	0.99	0.99	0.99	0.98	0.99	0.99	0.97	0.99	0.96	0.97	0.98	0.98	0.98	0.97
24	0.98	0.99	0.99	0.98	0.98	0.98	0.97	0.98	0.98	0.99	0.98	0.99	0.99	0.96	0.99	0.96	0.98	0.98	0.98	0.98	0.97
25	0.08	0.06	0.08	0.08	0.07	0.08	0.07	0.08	0.08	0.08	0.08	0.09	0.07	0.07	0.07	0.04	0.08	0.05	0.08	0.09	0.07
26	0.98	0.99	0.99	0.98	0.98	0.98	0.98	0.99	0.99	0.99	0.98	0.99	0.99	0.97	0.99	0.96	0.98	0.98	0.98	0.98	0.97

Table 2 (continued)

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21
27	0.97	0.99	0.97	0.97	0.97	0.97	0.96	0.98	0.97	0.98	0.95	0.97	0.99	0.97	0.98	0.97	0.95	0.97	0.96	0.95	0.97
28	0.98	0.99	0.99	0.98	0.98	0.98	0.98	0.99	0.99	0.99	0.98	0.99	0.99	0.97	0.99	0.96	0.97	0.98	0.98	0.98	0.97
29	0.98	0.99	0.98	0.98	0.98	0.98	0.97	0.98	0.98	0.99	0.97	0.98	0.99	0.97	0.98	0.96	0.97	0.98	0.98	0.97	0.97
30	0.99	0.98	0.99	0.99	0.98	0.99	0.98	0.98	0.99	0.98	0.97	0.98	0.97	0.97	0.97	0.94	0.98	0.97	0.97	0.97	0.97
31	0.98	0.99	0.99	0.99	0.99	0.98	0.98	0.99	0.99	0.99	0.97	0.99	0.98	0.97	0.98	0.95	0.97	0.99	0.98	0.98	0.97
32	0.98	0.98	0.99	0.97	0.98	0.98	0.97	0.98	0.98	0.99	0.98	0.99	0.98	0.95	0.98	0.93	0.97	0.98	0.98	0.99	0.95
33	0.98	0.97	0.99	0.98	0.98	0.99	0.98	0.98	0.98	0.97	0.97	0.98	0.96	0.96	0.97	0.93	0.97	0.97	0.97	0.97	0.96
34	0.98	0.98	0.99	0.97	0.98	0.98	0.98	0.98	0.99	0.99	0.98	0.99	0.98	0.96	0.98	0.94	0.98	0.98	0.98	0.99	0.96
35	0.97	0.98	0.95	0.96	0.95	0.95	0.95	0.97	0.96	0.97	0.94	0.95	0.99	0.97	0.98	0.99	0.93	0.97	0.95	0.94	0.98
36	0.98	0.97	0.98	0.98	0.99	0.98	0.98	0.98	0.99	0.97	0.97	0.98	0.96	0.97	0.97	0.93	0.97	0.98	0.97	0.97	0.96
37	0.98	0.98	0.97	0.98	0.97	0.97	0.96	0.98	0.98	0.97	0.94	0.96	0.96	0.98	0.97	0.96	0.95	0.97	0.95	0.94	0.97
38	0.97	0.98	0.96	0.97	0.96	0.96	0.96	0.98	0.97	0.98	0.94	0.96	0.98	0.98	0.98	0.98	0.94	0.98	0.95	0.94	0.97
39	0.97	0.98	0.96	0.97	0.96	0.96	0.96	0.98	0.97	0.98	0.94	0.96	0.98	0.98	0.98	0.98	0.94	0.98	0.95	0.94	0.97
40	0.97	0.98	0.99	0.98	0.98	0.98	0.98	0.98	0.98	0.99	0.98	1.00	0.98	0.95	0.98	0.94	0.98	0.98	0.99	0.99	0.96
41	0.98	0.99	0.99	0.98	0.99	0.98	0.98	0.99	0.99	0.99	0.97	0.98	0.99	0.98	0.99	0.96	0.97	0.98	0.97	0.97	0.98
42	0.98	0.99	0.99	0.98	0.99	0.98	0.98	0.99	0.99	0.99	0.97	0.98	0.99	0.98	0.99	0.96	0.97	0.98	0.97	0.97	0.98

	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42
1	0.98	0.98	0.98	0.08	0.98	0.97	0.98	0.98	0.99	0.98	0.98	0.98	0.98	0.97	0.98	0.98	0.97	0.97	0.97	0.98	0.98
2	0.98	0.99	0.99	0.06	0.99	0.99	0.99	0.99	0.98	0.99	0.98	0.97	0.98	0.98	0.97	0.98	0.98	0.98	0.98	0.99	0.99
3	0.98	0.99	0.99	0.08	0.99	0.97	0.99	0.98	0.99	0.99	0.99	0.99	0.99	0.95	0.98	0.97	0.96	0.99	0.99	0.99	0.99
4	0.99	0.98	0.98	0.08	0.98	0.97	0.98	0.98	0.99	0.99	0.97	0.98	0.97	0.96	0.98	0.98	0.97	0.98	0.98	0.98	0.98
5	0.98	0.98	0.98	0.07	0.98	0.97	0.98	0.98	0.98	0.99	0.98	0.98	0.98	0.95	0.99	0.97	0.96	0.98	0.98	0.99	0.99
6	0.98	0.98	0.98	0.08	0.98	0.97	0.98	0.98	0.99	0.98	0.98	0.99	0.98	0.95	0.98	0.97	0.96	0.98	0.98	0.98	0.98
7	0.97	0.98	0.97	0.07	0.98	0.96	0.98	0.97	0.98	0.98	0.97	0.98	0.98	0.95	0.98	0.96	0.96	0.96	0.98	0.98	0.98

Table 2 (continued)

	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42
8	0.98	0.99	0.98	0.08	0.99	0.98	0.99	0.98	0.98	0.99	0.98	0.98	0.98	0.97	0.98	0.98	0.98	0.98	0.98	0.99	0.99
9	0.98	0.99	0.98	0.08	0.99	0.97	0.99	0.98	0.99	0.99	0.98	0.98	0.99	0.96	0.99	0.98	0.97	0.97	0.98	0.99	0.99
10	0.97	0.99	0.99	0.08	0.99	0.98	0.99	0.99	0.98	0.99	0.99	0.97	0.99	0.97	0.97	0.97	0.98	0.98	0.99	0.99	0.99
11	0.95	0.98	0.98	0.08	0.98	0.95	0.98	0.97	0.97	0.97	0.98	0.97	0.98	0.94	0.97	0.94	0.94	0.94	0.98	0.97	0.97
12	0.97	0.99	0.99	0.09	0.99	0.97	0.99	0.98	0.98	0.99	0.99	0.98	0.99	0.95	0.98	0.96	0.96	0.96	1.00	0.98	0.98
13	0.97	0.99	0.99	0.07	0.99	0.99	0.99	0.99	0.97	0.98	0.98	0.96	0.98	0.99	0.96	0.98	0.98	0.98	0.98	0.99	0.99
14	0.98	0.97	0.96	0.07	0.97	0.97	0.97	0.97	0.97	0.97	0.95	0.96	0.96	0.97	0.97	0.97	0.98	0.98	0.95	0.98	0.98
15	0.97	0.99	0.99	0.07	0.99	0.98	0.99	0.98	0.97	0.98	0.98	0.97	0.98	0.98	0.97	0.98	0.98	0.98	0.98	0.99	0.99
16	0.96	0.96	0.96	0.04	0.96	0.97	0.96	0.96	0.94	0.95	0.93	0.93	0.94	0.99	0.93	0.96	0.98	0.98	0.94	0.96	0.96
17	0.96	0.97	0.98	0.08	0.98	0.95	0.97	0.97	0.98	0.97	0.97	0.97	0.98	0.93	0.97	0.95	0.94	0.94	0.98	0.97	0.97
18	0.98	0.98	0.98	0.05	0.98	0.97	0.98	0.98	0.97	0.99	0.98	0.97	0.98	0.97	0.98	0.97	0.98	0.98	0.98	0.98	0.98
19	0.96	0.98	0.98	0.08	0.98	0.96	0.98	0.98	0.97	0.97	0.98	0.97	0.98	0.95	0.97	0.95	0.95	0.95	0.99	0.97	0.97
20	0.96	0.98	0.98	0.09	0.98	0.95	0.98	0.97	0.97	0.98	0.99	0.97	0.99	0.94	0.97	0.94	0.94	0.94	0.99	0.97	0.97
21	0.99	0.97	0.97	0.07	0.97	0.97	0.97	0.97	0.97	0.97	0.95	0.96	0.96	0.98	0.96	0.97	0.97	0.97	0.96	0.98	0.98
22	1.00	0.98	0.98	0.07	0.98	0.98	0.98	0.98	0.98	0.98	0.97	0.98	0.97	0.97	0.97	0.98	0.98	0.98	0.97	0.98	0.98
23	0.98	1.00	0.99	0.08	0.99	0.98	0.99	0.99	0.98	0.99	0.99	0.98	0.99	0.98	0.98	0.97	0.98	0.98	0.99	0.99	0.99
24	0.98	0.99	1.00	0.08	0.99	0.98	0.99	0.99	0.98	0.99	0.99	0.97	0.99	0.97	0.96	0.96	0.98	0.98	0.99	0.99	0.99
25	0.07	0.08	0.08	1.00	0.08	0.08	0.08	0.08	0.09	0.08	0.08	0.09	0.09	0.06	0.07	0.07	0.07	0.07	0.09	0.07	0.07
26	0.98	0.99	0.99	0.08	1.00	0.98	0.99	0.99	0.98	0.99	0.99	0.98	0.99	0.97	0.98	0.97	0.98	0.98	0.99	0.99	0.99
27	0.98	0.98	0.98	0.08	0.98	1.00	0.98	0.99	0.97	0.97	0.97	0.96	0.97	0.98	0.96	0.97	0.99	0.99	0.97	0.98	0.98
28	0.98	0.99	0.99	0.08	0.99	0.98	1.00	0.99	0.98	0.99	0.99	0.97	0.99	0.97	0.98	0.96	0.98	0.98	0.99	0.99	0.99
29	0.98	0.99	0.99	0.08	0.99	0.99	0.99	1.00	0.98	0.99	0.99	0.97	0.99	0.98	0.97	0.97	0.99	0.99	0.99	0.99	0.99
30	0.98	0.98	0.98	0.09	0.98	0.97	0.98	0.98	1.00	0.98	0.98	0.99	0.98	0.96	0.98	0.97	0.96	0.96	0.98	0.98	0.98
31	0.98	0.99	0.99	0.08	0.99	0.97	0.99	0.99	0.98	1.00	0.99	0.98	0.99	0.96	0.99	0.98	0.97	0.97	0.98	0.99	0.99
32	0.97	0.99	0.99	0.08	0.99	0.97	0.99	0.99	0.98	0.99	1.00	0.98	0.99	0.95	0.98	0.96	0.96	0.96	0.99	0.98	0.98
33	0.98	0.98	0.97	0.09	0.98	0.96	0.97	0.97	0.99	0.98	0.98	1.00	0.98	0.94	0.99	0.97	0.95	0.95	0.98	0.97	0.97

Table 2 (continued)

	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42
34	0.97	0.99	0.99	0.09	0.99	0.97	0.99	0.99	0.98	0.99	0.99	0.98	1.00	0.96	0.98	0.96	0.97	0.97	0.99	0.98	0.98
35	0.97	0.98	0.97	0.06	0.97	0.98	0.97	0.98	0.96	0.96	0.95	0.94	0.96	1.00	0.94	0.96	0.98	0.98	0.96	0.98	0.98
36	0.97	0.98	0.97	0.07	0.98	0.96	0.98	0.97	0.98	0.99	0.98	0.99	0.98	0.94	1.00	0.97	0.96	0.96	0.97	0.98	0.98
37	0.98	0.97	0.96	0.07	0.97	0.97	0.96	0.97	0.97	0.98	0.96	0.97	0.96	0.96	0.97	1.00	0.97	0.97	0.96	0.98	0.98
38	0.98	0.98	0.98	0.07	0.99	0.99	0.98	0.99	0.96	0.97	0.96	0.95	0.97	0.98	0.96	0.97	1.00	1.00	0.97	0.98	0.98
39	0.98	0.98	0.98	0.07	0.99	0.99	0.98	0.99	0.96	0.97	0.96	0.95	0.97	0.98	0.96	0.97	1.00	1.00	0.97	0.98	0.98
40	0.97	0.99	0.99	0.09	0.99	0.97	0.99	0.99	0.98	0.98	0.99	0.98	0.99	0.96	0.97	0.96	0.97	0.97	1.00	0.98	0.98
41	0.98	0.99	0.99	0.07	0.99	0.98	0.99	0.99	0.99	0.99	0.98	0.97	0.98	0.98	0.98	0.98	0.98	0.98	0.98	1.00	1.00
42	0.98	0.99	0.99	0.07	0.99	0.98	0.99	0.99	0.98	0.99	0.98	0.97	0.98	0.98	0.98	0.98	0.98	0.98	0.98	1.00	1.00

	Time	Freq
Table 3 Correlation matrix between Zoom H4 (161 to 589: number of identification of every recorder) and LCR based on the values of ACI according to frequency and time		
161×LCR	0.91	0.88
162×LCR	0.97	0.97
163×LCR	0.78	0.85
165×LCR	0.89	0.73
167×LCR	0.91	0.74
168×LCR	0.77	0.68
169×LCR	0.97	0.89
170×LCR	0.95	0.94
581×LCR	0.87	0.72
583×LCR	0.91	0.89
584×LCR	0.95	0.83
585×LCR	0.83	0.97
586×LCR	0.37	0.85
587×LCR	0.86	0.71
588×LCR	0.85	0.45
589×LCR	0.68	0.64

buildings using very simple solutions. The use of low cost recorders can create a new perspective in nature monitoring with enormous potential benefits for habitat conservation, rare species detections, and landscape assessment, planning and management. The more LCRs used in a study, the greater the sensitivity and/or spatial scale that can be covered. The variability in LCR microphone capsules has minor consequences on ACI calculation because this index is a normalized measure of the information.

The results obtained by our sampling efforts are very encouraging and there is no doubt that ecological acoustics has entered into a new area of field research and acoustic monitoring. The LCR has the potential to be used by a greater number of professional researchers and by citizen scientists. This applicability provides an opportunity for increasing the area over which LCRs are used and it is likely that important data sets will be produced and made available for the scientific community. Nation-wide census schemes could be reshaped and the contribution of non-professional individuals could be more important than in the past. For instance, the application of LCRs may be a useful tool to estimate population changes of bird communities along roadsides or for direct bird censuses with real time acoustic data processing. This method could be applied for instance to the North America Breeding Bird Survey (http://www.mbr-pwrc.usgs.gov/bbs/intro10.html). The use of LCRs could provide a direct comparison between bird richness and individual abundance and environmental sounds could be obtained from using small arrays of LCRs.

Some technical improvements are possible, for example equipping LCRs with a very inexpensive photocell that can switch on the recording only in the presence of light excluding, for instance, the night time. This application is under experimentation and seems to work very well. Supplementing the LCR's power supply with an external battery allows for over five, 24 h days of continuous registration saturating the internal memory of 8 Gb. The LCR could record for 10 consecutive days if equipped with a photocell.

Some alternative solutions to LCR include smart phones applications suggested by Zhang et al. (2010), but at the moment it remains an interesting stratagem with high costs of the hardware and there are issues around leaving such devices outside for a long period of time. A more sophisticated and *ad hoc* designed digital recorder with many additional performances like time setting, data processing in real time and remote capacities by using a Wi-Fi, spatial
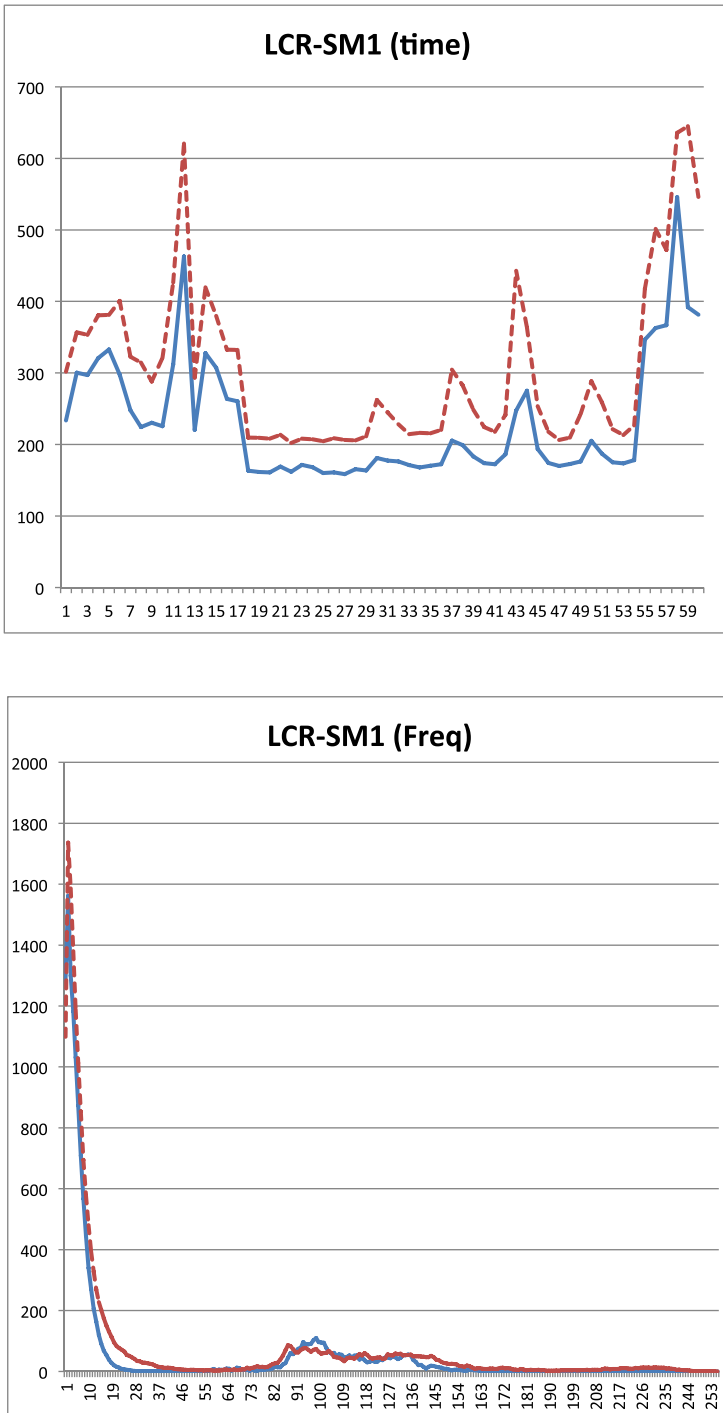
Fig. 4 A comparison of ACI values between LCR (continuous line) and SM1 (dashed line) **a** along a 60 min time lag (x axis) and **b** along frequency bins (x axis)
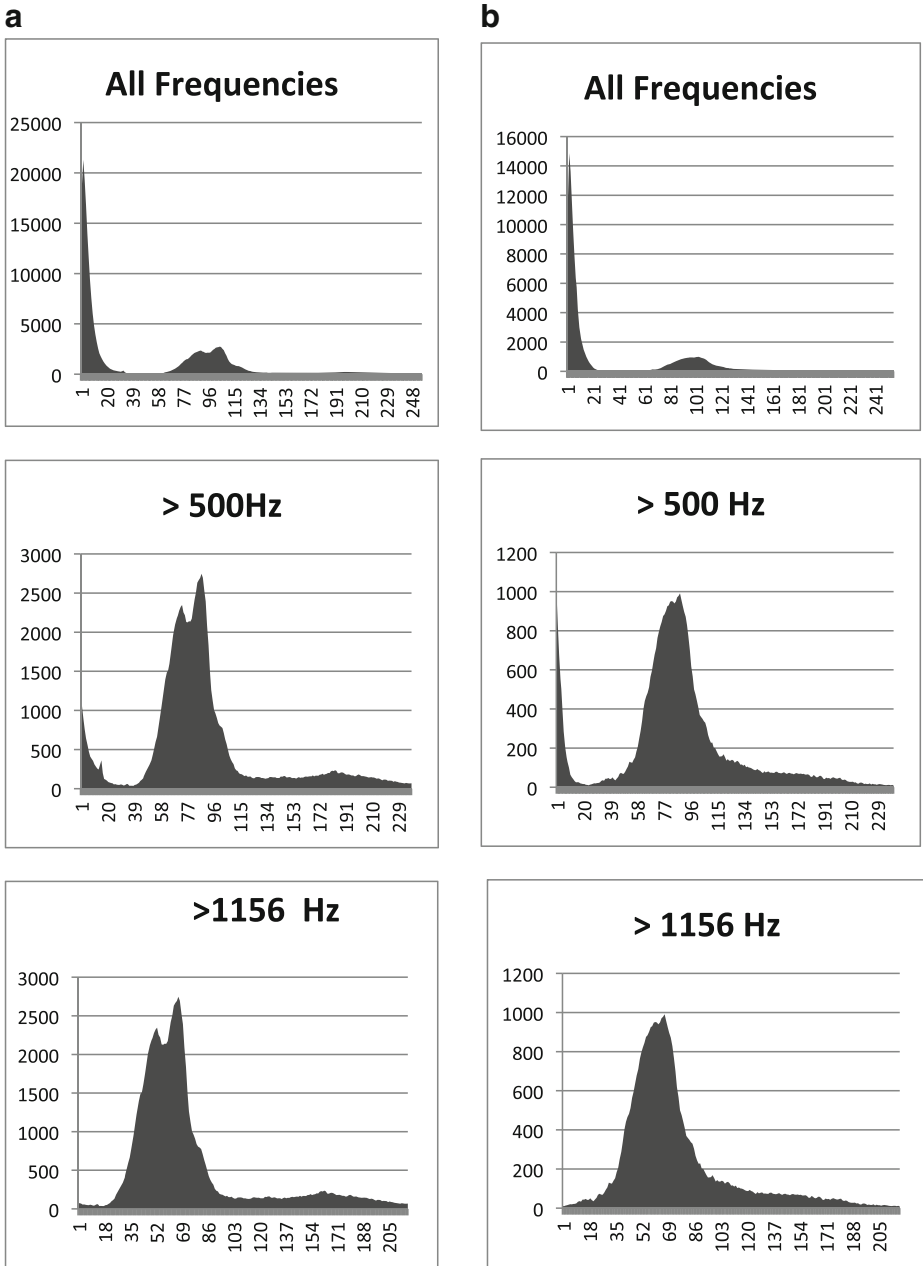
a

All Frequencies

b

All Frequencies

> 500Hz

> 500 Hz

>1156 Hz

> 1156 Hz

Fig. 5 Acoustic signature (ACI metric) **a** at dawn chorus between 0330 and 0430, and **b** During the morning activity from 07200 to 08200 at different frequency thresholds (all frequencies >500 Hz and>1,156 Hz). The dawn chorus shows the more complex signature with two peaks at different frequency bands. Every frequency step represents a frequency band of 31.25 Hz
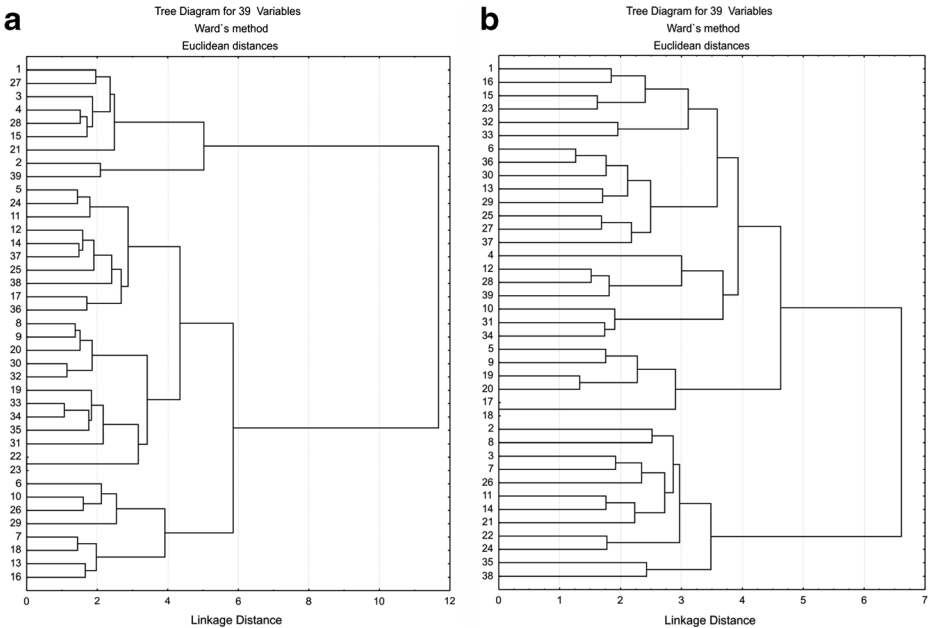
Fig. 6 Aggregation of sampling stations according to different ACI values **a** along the frequencies observed during the dawn period between 0330 and 0430, and **b** along the frequencies observed during the early morning from 07200 to 08200. The aggregation was performed using the cluster analysis (Ward's method and Euclidean distance on a matrix of normalized (0–1) data)

localization, low power consumption and a high storage capacity is under experimentation (Lattanzi and Bogliolo 2012).

The same methodology can also be used to investigate the acoustic events of amphibians, insects, and mammals. Further, the low cost approach can be extended to freshwater and marine systems. Costs may be reduced significantly in comparison with the traditional marine recording methods (submerged data loggers equipped with professional hydrophones). However, a LCR that can be submerged remains quite expensive when compared with the terrestrial LCR.

The use of low cost recorders can create a new perspective in nature monitoring with enormous potential benefits for habitat conservation, rare species detections, and landscape management. The possibility to deploy a great number of recorders in an easy way and with very low costs provides new opportunities to sample environmental heterogeneity with great accuracy and, hence obtain a realistic correlation between acoustic activity of vocal animals, human activity and various characteristics of the environment. With this approach it will be possible, as in the case of birds, to investigate acoustic activity outside the breeding period when this activity is scarce but no less significant than during the breeding season. For instance, this method could be used to investigate the specific composition and dimension of mixed flocks of vagrant birds and their spatial distribution.

The urban environment, a real challenge in the integration between humans and nature (Katti and Warren 2004; McDonald et al. 2008; Gordon et al. 2009) were green belts, parks and physical refuges like roofs host a great variety of animals (Goddard et al. 2010) with beneficial effects on biodiversity conservation, is spreading dramatically at the global level (UNFPA 2007).

In urban areas unwanted sounds are the major cause of sonic pollution, a direct concern for human health and an important source of citizen dissatisfaction (Skanberg and Ohstrom 2002; Ohrstrom et al. 2006. In particular due to broad valence (the emotional value) that sounds have in the urban social context, recording and categorizing sound perception is a complicated exercise for researchers and policymakers (Kang and Zhang 2010).

Contemporary noise pollution has important effects on biodiversity and directly on vocal animals (Brumm and Slabbekoorn 2005; Warren et al. 2006; Dowling et al. 2011; Proppe et al. 2013) producing a differentiate distribution of species (Joo et al. 2011) and changes in local dialects (Luther and Baptista 2010).

Improving the quality of urban soundscape means designing "soundmarks", like fountains or sonic sculptures, and also increasing the quiet in urban green spaces and parks. In particular the preservation or enhancement of the quality of sonic environment of urban parks may have a double benefit acting on the human well-being (from one side) and on the presence and abundance of vocal animals. Bird song and water are two sounds preferred by park visitors identified in a recent study carried out by Yang and Kang (2005) but green belts and tree lines along the avenues may also represent important source of sonic quality.

The decrease of urban noise and more in general the increase of the quality of the soundscapes have been proven to have important effects on many species of birds (Slabbekoorn and Ripmeester 2008). The reduction of noise in an urban park allows the presence of rare species as recently found by Paton et al. (2012) in Spain and Portugal.

The sonic approach to solve, at least some of the numerous problems that the high energy consumption, the concentration of technologies, services and people pose in urban environments seems a promising strategy. Urban areas require constant environmental monitoring due the rapid changes in human fluxes around the urban spaces. The use of cheap, small low cost audio recorders seems extremely important as a technique for recording and analyzing sounds in the urban environment. LCRs can be easily distributed and the information collected by such devices can be coupled with social psychological studies on the perception of the individual surroundings.

Due to their cheap cost, large numbers of LCRs can be placed across urban settlements according and even at different heights to collect information about the multilayer sound sources. The new generation of LCR, that incorporate Wi-Fi facilities will be more efficient for long-term studies reducing further the cost of manpower necessary to transfer acoustic information in permanent acoustic database.

Environmental sounds can be used to describe the complexity of several human disturbed environments in which the complexity of the topography and the heterogeneity of vegetation prevent the application of standard environmental sampling methodologies. Environmental sounds can be used as indicators of environmental complexity when other traditional systems are too expensive or too time consuming. A relatively low technology can solve problems that would require complex remote sensing technologies. Hence, the application of LCR with multiple recorders spatially deployed across a (natural or urban) landscape opens the way to new studies in animal behaviour and ecology, coupling resource availability and real distribution of vocal organisms.

The use of LCRs is a good very low-cost solution when the principal aim is to investigate the information associated with environmental sounds. This investigation suggests that expensive acoustic recorders can be substituted by low-cost devices with a greater number of devices in the field. The use of LCRs opens new opportunities to create a sustainable research program allowing a greater number of people to benefit from this innovative micro-technology. Using LCR may also allow researchers with limited and low resources to operate. This is especially the case in developing countries where conservation programs are limited or non-existent. This

emerging technology now offers an opportunity to deepen our understanding of environmental systems. This is an essential step in designing and implementing effective conservation management programs.

References

Barber JR, Burdett CL, Reed SE, Warner KA, Formichella C, Crooks KR, Theobald DM, Fristrup K (2011) Anthropogenic noise exposure in protected natural areas: estimating the scale of ecological consequences. Landsc Ecol 26:1281–1295

Bibby CJ, Burgess ND, Hill DA (1992) Bird census techniques. Academic Press Limited, London

Bormpoudakis D, Sueur J, Pantis JD (2013) Spatial heterogeneity of ambient sound at the habitat type level: ecological implications and applications. Landsc Ecol 28:495–506

Botteldooren D, De Coensel B, De Muer T (2006) The temporal structure of urban soundscapes. J Sound Vib 292:105–123

Brumm H, Slabbekoorn H (2005) Acoustic communication in noise. In: Slater PJB, Snowdon CT, Roper TJ, Brockmann HJ, Naguib M (eds) Advance in the study of behavior, Elsevier, vol. 35th edn., pp 151–209

Davies WJ (2013) Editorial. Special issue: Applied soundscape. Appl Acoust 74:223

Dowling JL, Luther DA, Marra PP (2011) Comparative effects of urban development and anthropogenic noise on bird songs. Behav Ecol 23:201–209

Farina A (2014) Soundscape Ecology: Principles, Patterns. Methods and Applications. Springer, Dordrecht, NL

Farina A, Lattanzi E, Malavasi R, Pieretti N, Piccioli L (2011a) Avian soundscapes and cognitive landscapes: theory, application and ecological perspectives. Landsc Ecol 26:1257–1267

Farina A, Lattanzi E, Piccioli L, Pieretti N (2012) The SoundscapeMeter User Manual. www.disbef.uniurb.it

Farina A, Pieretti N (2014) Sonic environment and vegetation structure: a methodological approach for a soundscape analysis of a Mediterranean maqui. Ecol Informat. doi:10.1016/j.ecoinf.2013.10.008

Farina A, Pieretti N (2013) From Umwelt to Soundtope: An Epistemological Essay. Biosemiotics. doi:10.1007/s12304–013–9191–7

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

Francis CD, Kleist NJ, Ortega CP, Cruz A (2013) Noise pollution alters ecological services: enhanced pollination and disrupted seed dispersal. Proc R Soc B. doi:10.1098/rspb.2012.0230

Gagliano M, Manuco S, Robert D (2012a) Towards understanding plant bioacoustics. Trends Plants Sci 17(6):323–325

Gagliano M, Renton M, Duvdevani N, Timmins M, Mancuso S (2012b) Out of sight but not out of mind: alternative means of communication in plants. PLoS ONE 7(5):e37382

Gasc A, Sueur J, Jiguet F, Devictor F, Grandcolas V, Burrow P, Depratere M, Pavoine S (2013) Assessing biodiversity with sound: Do acoustic diversity indices reflect phylogenetic and functional diversities of bird communities? Ecol Indic 25:279–287

Goddard MA, Dougill AJ, Benton TG (2010) Scaling up from gardens: biodiversity conservation in urban environments. Trends Ecol Evol 25(2):90–98

Goodenough AE, Goodenough AS (2012) Development of a rapid and precise method of digital image analysis to quantify canopy density and structural complexity. Int Sch Res Netw ISRN Ecol. doi:10.5402/2012/619842

Gordon A, Simondson D, White M, Moilanen A, Bekessy SA (2009) Integrating conservation planning and landuse planning in urban landscapes. Landsc Urban Plan 91:183–194

Hobson KA, Rempel RS, Greenwood H, Turnbull B, Van Wilgenburg S (2002) Acoustic surveys of birds using electronic recordings: new potential from an omni-directional microphone system. Wildl Soc Bull 30(3):709–720

Joo W, Gage SH, Kasten EP (2011) Analysis and interpretation of variability in soundscapes along an urban–rural gradient. Landsc Urban Plan 103:259–276

Kang J, Zhang M (2010) Semantic differential analysis of the soundscape in urban open public spaces. Build Environ 45:150–157

Katti M, Warren PS (2004) Tit, noise and urban bioacoustics. Trends Ecol Evol 19(3):109–110

Krause B (2012) The great animal orchestra.Little. Brown and Company, New York

Lattanzi E, Bogliolo A (2012) VirtualSense: A Java-based open platform for ultra-low-power wireless sensor nodes. International Journal of Distributed Sensor Networks, ID 154737. doi:10.1155/2012/154737

Liu J, Dietz T, Carpenter SR, Folke C, Alberti M, Redman CL, Schneider SH, Ostrom E, Pell AN, Lubchenco J, Taylor WW, Ouyang Z, Deadman P, Kratz T, Provencher W (2007) Coupled human and natural systems. AMBIO: J Hum Environ 36:639–649

Luther D, Baptista L (2010) Urban noise and the cultural evolution of bird songs. Proc R Soc B 277:469–473

Mace BL, Bell PA, Loomis RJ (1999) Aesthetic, affective and cognitive effects of noise on natural landscape assessment. Soc Nat Resour 12:225–242

Malavasi R, Farina A (2013) Neighbour's talk: interspecific choruses among songbirds. Bioacoustics 22(1):33–48

McDonald RI, Kareiva P, Forman RTT (2008) The implications of current and future urbanization for global protected areas and biodiversity conservation. Biol Conserv 141:1695–1703

Ohrstrom E, Skanberg A, Svensson H, Gidlof-Gunnarsson A (2006) Effects of road traffic noise and the benefit of access to quietness. J Sound Vib 295:40–59

Paton L, Romero F, Cuenca J, Escudero JC (2012) Tolerance to noise in 91 bird species from 27 urban gardens of Iberian peninsula. Landsc Urban Plan 104:1–8

Pekin BK, Jung J, Villanueva-Rivera LJ, Pijanowski BC, Ahumada JA (2012) Modeling acoustic diversity using soundscape recordings and LIDAR-derived metrics of vertical forest structure in a neotropical rainforest. Landsc Ecol 27:1513–1522

Pieretti N, Farina A, Morri D (2011) A new methodology to infer the singing activity of an avian community: The Acoustic Complexity Index (ACI). Ecol Indic 11(3):868–873

Pijanowski BC, Farina A, Dumyahn SL, Krause BL, Gage SH (2011a) What is soundscape ecology? Landsc Ecol 26(9):1213–1232

Pijanowski BC, Villanueva-Rivera LJ, Dumyahn SL, Farina A, Krause B, Napoletano BM, Gage SH, Pieretti N (2011b) Soundscape ecology: the science of sound in the landscape. BioScience 61(3):203–216

Proppe DS, Sturdy CB, St. Clair CC (2013) Anthropogenic noise decreases urban songbird diversity and may contribute to homogenization. Glob Chang Biol 19:1075–1084

Rodriguez A, Gasc A, Pavoine S, Grandcolas P, Gaucher P, Sueur J (2013) Temporal and spatial variability of animal sound within a neotropical forest. Ecol Informat. doi:10.1016/j.ecoinf.2013.12.006

Skanberg A, Ohstrom E (2002) Adverse health effects in relation to urban residential soundscapes. J Sound Vib 250(1):151–155

Slabbekoorn H, Ripmeester EAP (2008) Birdsong and anthropogenic noise: implications and application for conservation. Mol Ecol 17:72–83

Sueur J, Pavoine S, Amerlynck O, Duvail S (2008) Rapid acoustic survey for biodiversity appraisal. PLOS ONE 3(12):e4065

Sueur J, Gasc A, Grandcolas P, Pavoine S (2012) Global estimation of animal diversity using automatic acoustic sensor. In: Le Galliard JF, Guarini JM, Gaill F (eds) Sensors for ecology: towards integrated knowledge of ecosystems, CNRS Editions pp 101–119

UNFPA (2007) State of the world population 2007: Unleashing the potential of urban growth. United Nations Population Funds

Warren PS, Katti M, Ermann M, Brazel A (2006) Urban bioacoustics: it's not just noise. Anim Behav 71:491–502

Yang W, Kang J (2005) Acoustic comfort evaluation in urban open public spaces. Appl Acoust 66:211–229

Zhang J, Roe P, Pham B, Mason R, Towsey M, Sumitomo J (2010) Archiving nature's heartbeat using smart phones. In: Wachowicz M (ed) Movement-Aware Applications for Sustainable Mobility. Technologies and Approaches, IGI Global, p 19. doi:10.4018/978–1–61520–769–5.ch008