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Discussion

Using ecoacoustic methods to survey the impacts of climate change on biodiversity

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ABSTRACT

Climate change is an important cause of the irreversible transformation of habitats, of the rapid extinction of species, and of the dramatic changes in entire communities, especially for tropical assemblages and for habitat- and range-restricted species, such as mountaintop and polar species.

In particular, climate change effects several aspects of animal sounds (e.g., song amplitude and frequency, song post, and sound phenology). Animal sounds, which are life traits characterized by high plasticity, are able to cope with even modest variations of environmental fundamentals like vegetation cover, land mosaic structure, temperature, humidity, and pH (for aquatic medium). Moreover, the climatic effects on these biophonies can be observed earlier than change in vegetation patterns and visible landscape structures.

Ecoacoustics, the discipline that investigates the role of sound on animal ecology from species to landscapes, offers robust models, such as acoustic adaptation, acoustic niche, acoustic active space, acoustic community, and acoustic phenology to investigate the effect of climate change on species, populations, communities, and landscapes.

From an operational perspective, ecoacoustics procedures can be applied in different contexts, such as locations, weather, species, populations, behavior, physiology, and phenology. In addition, thematic priorities can be selected, such as latitudinal and altitudinal gradients, restricted habitats, stopover areas, extreme environments, weather conditions, short distance migrants, species at high vocal plasticity, sink-source status, active space, social attraction, physiological modifications, dawn and dusk choruses, sound from stressed plants, and time series analysis.

The noninvasiveness of passive acoustic recording, the simultaneous collection of important data, such as community richness and diversity, immigration and extinction events, and singing dynamics as well as the availability of innovative noninvasive technologies operating over a long-term period, establish ecoacoustics as a new and important tool with which it is possible to analyze massive acoustic data sets and quickly predict and/or evaluate the effects of climate change on the environment.

Moreover, passive recording is supported by cheap, user-friendly field sensors and robust data processing and may be part of the citizen science research agenda on climate change.

1. Introduction

The effects of climate change on the environment caused by the accumulation of greenhouse gases of anthropogenic origin in the atmosphere are extensively documented by scientific research (IPCC, 2013). A crude anthropogenic perspective (cost/benefit, energy, trade, and resource control) is blended with a more genuine concern for the state of the Earth in a period during which humanity has reached such a level of ecological intrusion that Nobel prize laureate Paul Crutzen and his colleague Eugene Stoermer applied the term *Anthropocene* to distinguish the current geological epoch (Crutzen and Stoermer, 2000).

The anthropogenic influence on the Earth's climate has complex latitudinal and altitudinal effects on all the scales from individual species that enter into a lottery of winners and losers (e.g., Moss, 1998) to biome shifts (IPCC, 2014), creating great impacts for the speed with which such changes occur, impeding the majority of species to adapt (Parmesan, 2006).

Complex interactions triggered by the extreme events associated with climate change have a strong impact inside trophic chains with cascade effects, like the irreversible transformation of habitats, the rapid extinction of species, and dramatic changes in entire communities where key species are involved (Easterling et al., 2000; Alois and Cheng, 2007).

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A different distribution of meteorological events associated with temperature rise modifies growth rate and reduces the chances of survival of plants and animals, especially for tropical assemblages and for habitat and range-restricted species like mountaintop and polar species.

When possible, animals avoid physiological stress, changing their geographical distribution, but this reduces their chances to have access to necessary resources (sensu Farina, 2012) and populations may easily shift their source status to a sink condition (Pulliam, 1988) with consequences on their survivorship.

Among the most mobile animals, many species of birds are able to adjust their geographical distribution, and a long-term perspective confirms the strict relationship between avifauna and vegetation during the last 180,000 years due to glacial episodes (Holm and Svenning, 2014). Birds with a restricted distribution may have a larger impact compared with ubiquitous species, and the same is expected for long-distance migrants that could face shifts of winter and breeding areas. Changes may also occur along the migratory routes for stopover species (e.g., Huntley et al., 2006; Gordo, 2007) and new studies are necessary to forecast the impacts (e.g., Gregory et al., 2009; La Sorte and Jetz, 2010).

The increase of global temperature is expected to have a major effect in tropical areas for terrestrial ectotherms because they are close to the optimum of temperature and small changes may have a deleterious consequence on a great number of species. For instance, in Ecuador, temperature was found to be a discriminant factor for cricket species in cloud forest ecosystems. In lowland rainforests, a change in temperature could have great consequences regarding the distribution of these groups of species (Nischck and Riede, 2001). Important effects have resulted in species where the gender ratio is driven by environmental temperature. For instance, in the population of marine turtles of the southern United States, a higher number of females is expected because of a warming of only 1 °C (Hawkes et al., 2007). However, species living at higher latitudes have a broader thermal tolerance because they are living in cooler areas than their physiological optimum (Deutsch et al., 2008).

Climate change is continuously monitored due to an extensive application of advanced remote sensing technologies based on the survey of atmospheric physics, aquatic chemistry, and vegetation parameters that are able to cover the entire planet at a common spatial and temporal resolution. The majority of the studies of the effects of climate change on organisms is still based on predictive large-scale models to cope with the abiotic information from satellite sensors, as argued in a recent review by Crick (2004), although some bioclimatic models are quite accurate (Williams et al., 2003).

However, the effects of climate change on the ecological processes, although evident and well documented (Walther et al., 2002), often escape the more thorough enquiries necessary for developing efficient mitigation or remediation policies at medium and small geographic scales. The necessity to develop new approaches and methods is urgent. Among these, sound is an important medium for intra- and interspecific communication among hetero- and homoeothermic groups of animals and produces one of the most interesting candidates.

Unfortunately neglected by ecological investigations for long a time, sounds have an important role in detecting early signs of animal stress connected to climate change from the scale of individual species, populations, communities, and landscapes. The study of sound with an ecological perspective is a focus of ecoacoustics (Sueur and Farina, 2015).

Acoustic communication has proven to be related to animal metabolism, creating an energetic constraint. As a result, this produces a great variety of sounds used to communicate. For this reason, the relationship between climate change that modifies the energetic field in which organisms operate and the results of acoustic emissions are strictly related (Gillooly and Ophir, 2010).

Therefore, the goals of this paper are as follows:

1) To demonstrate through published material and by personal account examples of how the climate affects the attributes of vocalizing organisms and 2) to provide a framework to use ecoacoustics, a recent extension of bioacoustics into the ecological domain (Sueur and Farina, 2015), to investigate the effects of climate change.

In this narrative, climate change has been considered in terms of direct and indirect effects on ecoacoustic processes described according to acoustic adaptation (hypothesis), acoustic niche (hypothesis), acoustic active space, acoustic community, and acoustic phenology postulates.

In this paper we consider ecoacoustic methods and provide an agenda to promote ecoacoustics approaches. The majority of the examples focus on species like frogs and birds, two groups of animals that extensively use sound to communicate, and partitioning of important traits of their ecological niches.

2. The ecoacoustics competence

There is evidence that the majority of acoustic performances and their patterns are the result of complex interactions between the energetic environment, the animal biomass, and the structure of the social interactions (e.g., Brackenbury, 1979; Wallschager, 1980). The energetic basis of acoustic communication confirms that patterns and individual acoustic performances are both potentially sensitive to environmental conditions (e.g., temperature, humidity, noise, and social organization) (Gillooly and Ophir, 2010). For the extreme plasticity of the acoustic characters, every change in the environment is immediately reflected in the acoustic behavior of organisms. However, research priorities are necessary to quantify the variation in acoustic activity of individuals and assemblages over time within the same habitat (Farina and James, submitted for publication).

Ecoacoustics has been extensively used in biodiversity assessments, such as species of interest (Bardeli et al., 2010), number of species (Towsey et al., 2014a), acoustic diversity (Rodriguez et al., 2014; Desjonquères et al., 2015), habitat evaluation (Bormpoudakis et al., 2013), habitat quality changes (Piercy et al., 2014), and habitat selection (Figueira et al., 2015) and in population ecology, such as distribution and dynamics (Risch et al., 2014), population density (Lucas et al., 2015), viability (Laiolo, 2008), structure (Laiolo and Tella, 2006), and species invasion (Both and Grant, 2012). Similarly, the ecoacoustics approach has been adopted to investigate the ecology of the acoustic communities, such as composition and dynamics (Sueur et al., 2008), acoustic diversity (Gasc et al., 2013), and acoustic interactions (Tobias et al., 2014) as well as the relationship with the landscape (Farina et al., 2011; Joo et al., 2011; Tucker et al., 2014). An important contribution has been offered by ecoacoustics in conservation biology and, in particular, in the analysis of the effects of anthropophonic disturbances (e.g., Barber et al., 2011; Pieretti and Farina, 2013; Azzellino et al., 2011).

2.1. Acoustic adaptation (hypothesis)

The acoustic adaptation (hypothesis) (Morton, 1975; Marten and Marler, 1977; Cosens and Falls, 1984; Ey and Fischer, 2009) assumes that the acoustic properties of habitats such as ground morphology, plant structures, and atmospheric content have a direct effect on the characteristics of animal sounds with the result of maximizing sound propagation. Signal-generating organisms try to reduce attenuation and degradation of the broadcasting acoustic signals in a specific habitat through an adaptation that extends over a long period.

Indirect effects that often drive genetic variation inside populations and alter plasticity capacity or resilience can be linked to small differences in vegetation or landscape (Rubenstein, 1992). Often the indirect effects are not surveyed because too few data are available at microcosm scales.

Habitat structures correlate with the highest frequency song in *Phylloscopus* and *Hippolais* warblers (Badyaev and Leaf, 1997). In closed habitats, these species avoid using rapidly modulated signals and use fewer and longer syllables with larger intervals when compared with species living in open habitats.

Even modest shifts in atmospheric conditions may have a significant impact on vocal animals and may alter the distance at which acoustic signals can be recognized and decoded. Climate change enters into play to justify such variations because climate change means modification of daily atmospheric dynamics including the distribution of rain and wind events within a season, as well as change in a season's duration.

For instance, as reported by Larom et al. (1997) in their study of the African elephant (*Loxodonta africana africana*), the variation of the distance at which their low frequency signal may be detected varies one order of magnitude according to the variation of atmospheric conditions.

Snell-Rood (2012) has observed that North American warblers have a decrease of bandwidth (maximum frequency span within a note) across their geographical range with the increase of atmospheric absorption and a similar effect has been found by the same author in different species of bats from the American Southwest. This means that species have a reduction in signal frequency and an increase in the length of signals with the increase of sound absorption that is coincident with higher air humidity.

Bats use echolocation – short pulses of high frequency, ultrasonic signals – to capture prey. A rise in temperature will affect more bats emitting high frequencies and facilitate species to use low frequency signals because high frequencies are more sensitive to high temperatures with a higher attenuation (Luo et al., 2013).

In frogs from the temperate Iberian Peninsula, Llusia et al. (2013) found a wide thermal breadth during calling behavior, indicating a certain amount of plasticity during calling performance related to environmental temperature. This means that climatic change could be incorporated into the plasticity of the species, although other factors like a reduction of water availability during drought seasons could constrain the physiology of these species, reducing their fitness (Klaus and Lougheed, 2013).

One of the best-known effects of climatic change pertains to the change in sound transmission in marine systems due to acidification (Hester et al., 2008, Miller et al., 2014). This is because half of the CO_2 that is now above 400 ppm resides in water (IPCC, 2013). Water acidification affects low frequency sounds and has implications for marine mammals that use these frequencies to communicate. The decrease in pH reduces the sound absorption, especially at low frequencies, and, in this way, sound travels farther with great impact on marine species like whales that will be obliged to alter the frequency, duration, and intensity of their vocalizations to avoid the masking effect of signals of anthropogenic origin (Brewer and Hester, 2009).

Increased acidification also seems to reduce the capacity of young clownfish during their pelagic life to distinguish noisy sites (reef sites) that are more potentially rich in predators, when tested in an experimental arena by Simpson et al. (2011). Moreover, differences in water temperature may be a factor for improving the hearing capacity in fish species as well as their acoustic output. Wysocki et al. (2009) have proven that the auditory sensitivity increases at higher temperatures in stenotherm species (*Ictalurus punctatus*) and eurytherm species (*Pimelodus pictus*). However, in *I. punctatus*, there was a gain of 36 dB between 10 °C and 26 °C, and in *P. pictus*, this increase was more modest.

2.2. Acoustic niche (hypothesis)

The acoustic niche (hypothesis) is based on the ecological niche concept (Hutchinson, 1957; Hutchinson, 1978) and on the empirical observations in which only a few parts of species-specific sounds overlap each other, avoiding cacophonic effects (Krause, 1987; Krause, 1993). The acoustic niche hypothesis represents an important model used to understand better how species enter into competition or avoid competition during their acoustic performances. There is a growing accumulation of evidence that acoustic communities organize their acoustic performances with criteria that:

a) Reduce the frequency overlap between species (through long-term adaptation),
b) Reduce temporal overlap between species with similar frequencies through plasticity mechanisms.

In this way, species occupy a temporal and frequency bandwidth that results in the Krause concept of "the animal orchestra" (Krause, 2012). The premise being that the voice of each organism in a given habitat strives for its own bandwidth – a clear channel of transmission and reception – to avoid masking, much like instruments in an orchestra are organized.

The patterns of biophonic organization and discrimination are more prominent closer to equatorial biomes. However, in temperate habitats, biophonic organization may not be as obvious given the competition for bandwidth from certain birds, disallowing enough time to establish clear partitioning. For example, with black-capped chickadees (*Poecile atricapillus*) of the American southeast, it was observed that they detect the biophony in much the same way that humans receive the signals in real time. However, the receiving mechanism of the bird instantaneously processes and pitch-shifts the signal so that it internally creates its own clear bandwidth (Freeberg et al., 2012).

Climatic variability may produce an increase of vocal repertoire in vertebrates, as is the case with mockingbirds, a group of species distributed in a variety of habitats of the New World (Botero et al., 2009). Species living in more variable and unpredictable environments (as expected under a climate change scenario) should be able to learn and invent new syllables, as argued Botero et al. (2009), or modify their repertoire (Laiolo, 2008; Laiolo and Tella, 2006), remodulating their acoustic niche with important consequences to interspecific competition. Particularly, when sound-generating organisms add signals into an assemblage for the first time, frequency partitioning can rarely be achieved, and this can create masking effects and confused messages. For instance, when the playback song of the Red-billed leiothrix (*Leiothrix lutea*) was applied inside an area at high density of blackcaps (*Sylvia atricapilla*), which had probably not previously heard such exotic species, the latter species suspended their song, singing again only during the Red-billed leiothrix' singing pauses (Farina, submitted for publication). In this way, the playback of this new species acts as an intruder preventing blackcaps from maintaining an intense net of vocal interactions necessary for mating and territory defense. Red-billed leiothrix, encouraged by an increase of temperature in summer time and by a mild climate in winter, is expanding its range across the northern and central Mediterranean (Dubois, 2007; Puglisi et al., 2009; Herrando et al., 2010; Farina et al., 2013) and can be expected to have a great impact on blackcap populations as well as on other songbirds at regional scales.

In conclusion, climate change can operate at the level of the acoustic niche, disrupting co-evolutive processes that have avoided a deleterious competition.

2.3. Acoustic active space

The acoustic active space is defined as the distance from the source over which the signal amplitude remains above the detection threshold of a potential receiver (e.g., Brenowitz, 1982; Brown, 1989). The selection of adapted frequencies, intensities, and sound structures are chosen for the best intraspecific communication, and this does not necessarily mean the farthest distance at which the signal is received. Often antipredatory behavior could be consistent with the hypothesis to transmit at a distance no larger than the distance preferred to maintain intraspecific contact (Richards and Wiley 1980).

In order to maintain an effective signal, some birds have been observed changing position in song post on trees (Krams, 2001) as consequence of change in temperature and precipitation. For instance, Moller (2010) found an increase of the song post height of 18%

(1.2 m) when temperature increased by 20% and precipitation by 30% between spring 1986 to 1989 and in 2010. This has severe implications in terms of the optimal design of songs, variance in mating success, and predatory–prey interactions.

On rainy days, Lengagne and Slater (2002) have found a decrease of acoustic activity of the tawny owl (*Strix aluco*). Rain has a frequency band of 0 kHz to 5 kHz and a mean amplitude of 55.8 dB. Tawny owls, in order to maintain the active space in the same condition, could increase the signal amplitude to 115.5 dB, which is "an amplitude close to that of an aircraft taking off" as reported by Lengagne and Slater (2002, p. 2124). Changing the number of days of rain or of strong wind may have serious consequences in several communication mechanisms that include mating formation, territory defense, and predatory avoidance. Lengagne et al. (1999) have found that, in windy conditions, in order to maintain contacts between individuals, king penguins (*Aptenodytes patagonicus*) increase the number of calls and the number of syllables per call. This is in accordance with the signal redundancy expected by the mathematical theory of communications by Shannon and Weaver (1949) in the presence of noise in the transmission channel.

2.4. Acoustic community

An acoustic community has been defined by Farina and James (submitted for publication) as an aggregation of species that produces sound by using internal or extra-body sound-producing tools, with such communities occurring in aquatic (freshwater and marine) and terrestrial environments. Rarely is an acoustic community coincident with other types of ecological communities (e.g., patch community described by Forman and Godron (1981)), but it represents a functional unit rich in acoustic information. Easily surveyed using a non-intrusive, passive audio recording technology, the analysis of acoustic communities may open new ways to investigate the physical and biological changes that occur in the environment. The investigation of acoustic communities located at different latitudes or altitudes could be used to track climate change, especially in endangered habitats or biomes (Hughes, 2000; McCarty, 2001).

The sonic performance of acoustic communities reaches its maximum at dawn and dusk when species are contemporarily singing, producing choruses that are one of the most spectacular acoustic events of nature (Burt and Vehrencamp, 2005; Farina et al., 2015). Choruses have been observed in aquatic (e.g., shrimps, fishes, and whales) and in terrestrial animals (e.g., frogs, insects, birds, and mammals).

Choruses have been found related to the circadian cycles of testosterone and to the physiological needs of individuals (Thomas, 1999; Thomas and Cuthill, 2002; Thomas et al., 2002; Barnett and Briskie, 2007; Cuthill and MacDonald, 1990). Choruses are influenced by light intensity (Kacelnik, 1979; Berg et al., 2006), air motion (Wiley and Richards, 1978; Henwood and Fabrick, 1979; Wiley, 1991; Dabelsteen and Mathevon, 2002) and by social factors like mate attraction, territory defense, and the resolution of social dynamics (e.g., Morse, 1989; Greenfield, 1994; Hoi-Leitner et al., 1995; Burt and Vehrencamp, 2005; Tobias et al., 2014).

With the increase of temperature, we expect changes in the physiology of organisms. For instance, in birds, there could appear to be an extra expense of energy saved during less cold nights that could be utilized to sing more loudly or longer at dawn (Staicer et al., 1996). The availability of extra energy could be verified by measuring the length and the total information of the dawn choruses.

The short period of chorus (e.g., in birds at temperate latitudes) during the breeding season last approximately 50 min (Farina et al., 2015), and the contemporary acoustic emission of the majority of vocal animals creates a very special moment, highly favorable to the discovery of changes in species composition and in physiological constraint.

In birds, the acoustic signatures (distribution of acoustic information along frequencies) that characterize the complexity of the acoustic community and the chorus ratio (CR) after the lull observed at sunrise (Farina et al., 2015) allow a clear indication of details within chorus features. Chorus ratio measures the ratio between the acoustic information in choruses and the information collected at two periods of the same length of the chorus (post Chorus 1 and 2). A high value of CR indicates prevalent activity in the dawn chorus and modest acoustic activity after that period. There is evidence (Farina et al., 2015) that a high value of CR characterizes habitats poor in resources where birds that have to spend energy singing at dawn require some time to recover the lost energy by reducing their singing activity.

A major change in the acoustic signature due to community turnover is expected during longer periods, while during small and medium periods, the CR probably indicates variations in resource availability as per the effect of seasonality (more wet, more dry, too hot, too cold, etc.). However, advantages due to the increase of temperature could be annulled by the negligible availability of food.

Dawn and dusk choruses are important phenomena during which to collect acoustic information across a range of temporal scales. A long-term study on a specific site (Sugarloaf State Park, California) since 2000 (Fig. 1). and methods and results are detailed in the supplementary material. From this pioneering study, the results indicate a sharp decrease of acoustic complexity of biophonies associated with a decrease of geophonies from a stream since 2011 due to a persistence of drought periods (Fig. 1). The Sugarloaf study confirms how birds are sensitive to the variation of climate conditions, anticipating changes that will appear in plant community composition.

In conclusion, the duration of the chorus before sunrise, the complexity of acoustic signature, and the CR are important descriptors of the chorus patterns in the scenario of climate change. These variables can be processed in relationship with temperature and other climatic and meteorological parameters with the possibility of shifting from daily to seasonal and annual scales (Farina et al., 2015).

2.5. The acoustic phenology

Phenology has been defined by Lieth (1974, p. 4) as "the study of the timing of recurrent biological events, the causes of their timing with regard to biotic and abiotic forces, and the interrelation among phases of the same or different species". This approach allows us to track the changes of the physiological rhythm and the interspecific relationships occurring in organisms because of environmental constraints. The study of the phenology is used by botanists to assess climate change (Chmielewski and Rötzer, 2001; Walther et al., 2002; Badeck et al., 2004; Cleland et al., 2007).

A recent report from Menzel et al. (2006) has demonstrated that the increase of temperature in the period from 1971 to 2000 significantly affected 30% of plants with an advance in leafing, flowering, and fruiting and only 3% of the vegetation delayed. Spring and summer advances were 2.5 days per decade. This has a large impact on animals that are intimately connected to plants for food, breeding, and refuge. Frogs and birds are the preferred subject for investigation by zoologists of changes in phenology. Frogs have a biphasic life history and restricted reproductive habitats. These animals have periods of intense vocal activity and are easily recognized using automatic algorithms (e.g., Jaafar et al., 2013). Because of their extreme sensitivity to environmental conditions, they are ideal organisms to investigate vis à vis climate change. However, for the ephemeral conditions in which amphibians are adapted, long-term studies are necessary to establish trends and to evaluate the effects on populations.

Evidence of climatic change on frogs is often limited to a modeling stage, but Narins and Meenderink (2015) have found indications of the increase of call pitch and the shortening of call duration as a consequence of temperature increase over a period of 23 years in Puerto Rico along an altitudinal gradient. Parallel to the rise of temperature is also a reduction in body size, and this has consequences on the entire food web in the rainforest. Using passive recording, Ospina et al. (2013) have investigated frog assemblage and, from the analysis of four months

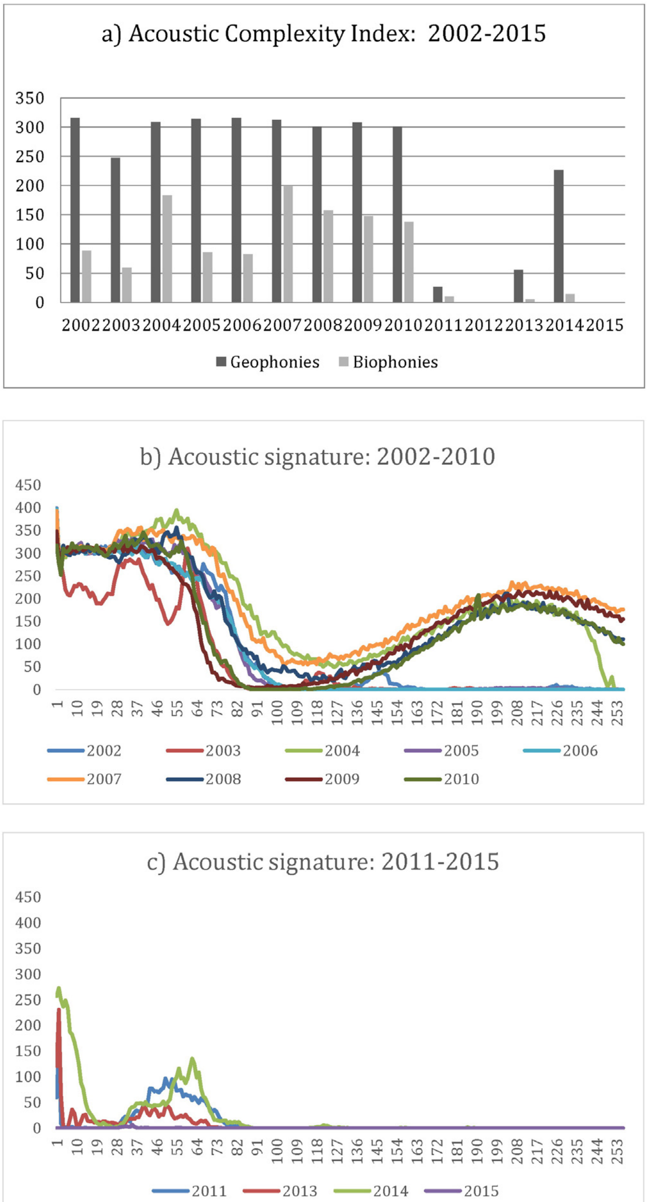

Fig. 1. a) Acoustic Complexity Index (ACI) (y axis) of geophonies and biophonies at the Sugarloaf site (California, 38° 26′ 20.64″ N/122° 29′ 56.1″ W) during 30 s of dawn chorus (2002–2015). b) The ACI value (y axis) along 256 frequency bins (x axis) (acoustic signature) during the periods 2002–2010. c) The ACI value (y axis) along 256 frequency bins (x axis) (acoustic signature) during the periods 2011–2015. No data are available for 2012. From the data, the dramatic decrease of ACI since 2011 is evident. The geophonies are the result of the running water of a nearby stream. The great drought since 2011 has reduced this acoustic source. In 2015, no water sound has been recorded. The same condition is reflected in the acoustic signature that since 2011 appears drastically reduced and practically absent in the 2015 survey. ACI has been calculated according to Pieretti et al. (2011). For more details, see supplementary material.

of recording, found a clear decline of four *Eleutherodactylus* species (*E. brittoni*, *E. juanariveroi*, *E. coqui*, and *E. cochranae*) during the period of survey. *Eleutherodactylus coqui* and *E. cochranae* were positively correlated with temperature, while *E. brittoni* and *E. juanariveroi* were negatively correlated with vegetation and precipitation. This different response to environmental factors has been explained due to the different behaviors of these frogs. The *E. brittoni* and *E. juanariveroi* are small species that move up on top of vegetation to sing and are therefore more exposed to adverse weather conditions. *Eleutherodactylus coqui* and *E. cochranae* call in lower vegetation at a shelter position and are less exposed to climate.

Other examples of a change in frog phenology have been found near Ithaca, NY over a long period from 1900 to present (Gibbs and Breisch, 2001). Four species of frogs are now calling 10 to 13 days earlier, two are unchanged, and none is calling later. The data suggest that climate has warmed in central New York during this century and has resulted in earlier breeding in some amphibians, which is a possible first indication of biotic response to climate change in eastern North America.

Weather forecasting applied to the influence of environment on calling was discussed by Steelman and Dorcas (2010) as an efficient method to interpret time series data. However, simultaneously, there is evidence that the social environment may be important in influencing the signal content because temperature, at least in the Common eastern froglet, *Crinia signifier*, seems subordinated to social calling (Wong et al., 2004). This means that water temperature has an effect only for individuals that were calling continuously on their own for this species, but it occurs without effect for individuals calling in duet or groups.

Animals are more mobile than plants and thus can react more quickly to climate change (e.g., variation in temperature and/or raining regime). In the past, birds have probably faced changes in physical conditions after the glacial period. Climate change creates a mismatch between local resources, migration, and breeding time. This is particularly important for migratory birds that use an internal clock, which determines the date of migration. However, such mechanisms may be deceived by environmental conditions in the breeding areas that can result in hostile repercussions (Carey, 2009).

Martin (2001) has found such independence for four species of ground-nesting birds (Virginia's Warbler (*Oreothlypis virginiae*), Dark-eyed Junco (*Junco hyemalis*), Red-faced Warbler (*Cardellina rubrifrons*), and Orange-crowned Warbler (*Oreothlypis celata*) in central Arizona. The birds shifted their breeding habitat as a direct response to the change of weather conditions.

Birds obliged to move outside the preferred habitat are exposed to a higher level of predation with an increase of biotic costs. Moreover, the shifting of species from one assemblage to another exposes species to unknown costs of competition and predation. Finally, the combination of abiotic and biotic costs may have severe consequences on populations.

A recent investigation carried out by Bruni et al. (2014) on some North American birds confirmed the great sensitivity to abiotic conditions like ambient temperature, precipitation, cloud cover, and lunar phase. Similar results have been shown after a review of the effects of climate change on Australian birds by Chambers et al. (2005).

Birds in tropical regions have been found to be extremely sensitive to photoperiods. In spotted antbirds (*Hylophilax n. naeviodes*), for example, Hau et al. (1998) observed the capacity to change gonadal development by the simple alteration of a quarter of an hour in the duration of day under experimental conditions. Moreover, the situation for birds living in extreme environments (deserts, high altitudes, and high latitudes) is problematic. For these species, already living at the limits of their physiological tolerance, small changes in climate may represent an irreversible change (Carey, 2002). Change in phenology has been proven to occur, especially at low altitudes, while at high altitudes there are fewer differences due to snowmelt. This has been reported by Inouye et al. (2000) for the Rocky Mountains where, from 1975 to the present, there were no evident changes in temperature and where the plant phenology is linked to snowmelt. In this case, birds are occupying territories covered by snow quite early. This situation has been documented for American robins (*Turdus migratorius*), a species that was observed to arrive 14 days earlier than they did in 1981 due to higher temperatures in low land wintering areas. Accordingly, high altitude spots may be important sites to monitor the acoustic activity of migratory birds as good indicators of what might occur in lowland habitats.

3. Methods and application of ecoacoustics

To survey vertebrates like frogs and birds, there are well-tested methodologies mostly based on song, call, and visual count along transects (Bystrak, 1981; Crump and Scott, 1994) or in spot counts (e.g., Parker, 1991) see also (Ralph and Scott, 1981; Verner, 1985; Bibby et al., 1992; Ralph et al., 1993). However, these methods require a lot of time and several experts, and they are rarely applied in long-term monitoring schemes (Gage and Miller, 1978).

The alternative methodology of a passive acoustic survey is a very efficient system offering several opportunities to identify some groups and to investigate biology, ecology, and the temporal dynamics of species (Brandes, 2008) and their biogeography (Lomolino et al., 2015). This methodology is adapted to identify some groups of species like baleen whales (Mellinger and Clark, 1997) or bats (Henriquez et al., 2014), to monitor acoustic habitats at large spatio-temporal scales in terrestrial and marine environments (Boebel et al., 2006; Mason et al., 2008; Qi et al., 2008; André et al., 2011; Gage et al., 2015; Merchant et al., 2015), and to be a part of the species and habitat conservation strategies. For instance, passive acoustic recording has been used in South Carolina by Moskwik et al. (2013) to search for the ivory-billed woodpeckers (*Campephilus principalis*), which is considered critically endangered or possibly extinct, and is a species living in old growth forests of the southeastern United States (Fitzpatrick et al., 2005; Bird Life International, 2013). A real-time bioacoustics-monitoring project with automated species identification has been proposed by Aide et al. (2013) with the use of cellphone technologies to transmit and successively identify species.

The ecoacoustics methodology is achieved using a multistep workflow comprising recording, database management, signal analysis, quantification, and statistics, as recently argued by Sueur and Farina (2015). Several different strategies can be applied to capture sound from species or from physical phenomena (e.g., Pijanowski et al., 2011a,b; Kasten et al., 2012). For instance, sound data can be collected using sophisticated microphone capsules (Monacchi, 2014) that are able to collect acoustic information from different directions and in separate channels or by placing arrays of cheap microphones that capture the acoustic information at close distance, facilitating the link of acoustic cues with environmental conditions (Farina et al., 2014). Due to the high variability of the acoustic phenomena, self-replication in space and time of recordings is always recommended.

The field of ecoacoustics promotes the application of inferential methods for the evaluation of acoustic information. Recently, new metrics allow researchers to process large amounts of acoustic data and to extract functional patterns to interpret the dynamics of acoustic communities (Kasten et al., 2010; Sueur et al., 2014; Gage and Axel, 2014; Towsey et al., 2014b). For instance, new low cost recorder (LCR) prototypes (Soundscape Explorer™ (T: terrestrial; A: Aquatic), Lunilettronik, Fivizzano, Italy) offer the opportunity to collect data in real time along with some meteorological parameters (humidity, atmospheric pressure, temperature, and light) and to process the acoustic complexity index (ACI) coincidentally and internally (Farina and Morri, 2008; Pieretti et al., 2011; Farina et al., 2015). This index computes the acoustic amplitude along distinct frequency bins (ACIt metric) and along temporal steps (ACIf metric). The innovation of this methodology is the direct friendly handling of a great amount of acoustic data, using a new procedure of data mining that extracts and identifies acoustic events (Farina et al., submitted for publication). This method has the advantage of selecting acoustic events where there is interest in closely observing acoustic sources like geophonies (e.g., wind, rain, and thunder), technophonies (e.g., airplanes, trains, cars, and horns) or biophonies (e.g., invading species, endangered species, choruses, etc.). This technique saves a lot of processing time and does not require a high specialization of the operators. At the same time, it offers a broad range of possible applications, like conservation of endangered species, validation of habitat restoration policies, assessment of the seasonal diversity, and monitoring the effects of climate change.

4. Agenda to assess and monitor climate change using acoustics

The sensitivity of sonic performances of animals even under modest modification of the physical parameters of the environment (like temperature, humidity, and pH for the aquatic medium) allows efficient investigation at multiple scales to demonstrate the effects of climate change on animal assemblages. Coupled with biogeography (Lomolino et al., 2015), the ecoacoustics approach can better depict the effect of the impoverishment of species richness due to climate stress in terms of realized acoustic niche expansion after the presence of empty niches.

Moreover, the ecoacoustics approach offers great advantages because it excludes or reduces human intrusion in the surveyed area, uses automated recording and real-time processing, and it adopts metrics to evaluate complexity, diversity, and dynamics of acoustic communities (Table 1).

The active role of the acoustic performance of some organisms is responsible for the magnification of the effects of climate change, an interesting thesis on which very few data are available. Drought produces stress on trees and hence an increased vulnerability to insect attack. Insects are drawn to stressed trees using chemical signals but also (probably) are attracted by the sounds emitted by cells. These sounds, which are produced by forest trees when under drought stress, are known as cavitation, which is the result of cells collapsing by gradual dehydration and water stress. The majority of sounds emitted are within a frequency range of 20 kHz to 200 kHz and may represent an important signal for insects. For instance, bark beetles are the perfect candidates to hear such sounds because there is increasing evidence that they emit signals in the ultrasound range (Dumm and Crutchfield, 2013). Considering that the increase of temperature favors the activity of defoliating insects that exacerbates the amount of CO_2 in the atmosphere through their high metabolism, it seems probable that a positive feedback between insects can spread, signaling favor by cavitation, defoliation, forest decline, and CO_2 increase. This process appears to be a difficult approach in land management due to the impossibility to control insect pests or other effects like fires that contribute to

Table 1
Major advantages to adopt an ecoacoustics approach to study and monitor climate change.

Context	Advantages	Comments
Biological	High reaction of acoustic performance to modest modification of the atmosphere	Due to the energetic basis of acoustic communication, every event that changes the energy in the environment is immediately reflected in different acoustic performances. The distance at which a signal may be decoded and recognized will alter the result.
	High acoustic plasticity of acoustic species that reflects the heterogeneity of the environment	The increase of variability in the song repertoire of some species may be a good indicator of the increased heterogeneity of the environment subjected to extreme events.
	Low invasiveness of passive recording	Little or no human intrusion in the wild during data collection. Passive recording is a non-invasive and extremely efficient system for the collection of environmental data related to the complex phenomenology of climate change.
Methodological	Automated processing of acoustic data	A new generation of low cost recorders has an onboard routine to process the acoustic files in real time (e.g., Soundscape Explorer Terrestrial (Lunilettronik, Fivizzano, I).
	Real-time output of data	Wi-Fi or GSM systems can connect different recorders and transfer data in real time to a remote station.

the intake of CO_2 in the atmosphere but can be monitored using an ecoacoustics approach.

There is a great expectation in the application of ecoacoustics metrics of measuring the diversity of species. However, it is necessary to point out that a direct correlation between acoustic diversity and biological diversity exists only in tropical biomes in which the acoustic niche of species is narrow and the complexity of a spectrogram is highly related to the diversity of animal assemblages.

For instance, in temperate biomes, we have to consider carefully the relationship between the complexity of spectrograms and species diversity because individual species like song thrushes (*Turdus philomelos*) often utilize a broad range of frequencies during their acoustic performances. Nonetheless, the evenness of the temporal distribution of acoustic information (Farina et al. in prep) represents a good proxy of species diversity. The high value of evenness indicates a rich community because, from empirical observations, it is more likely that those close to a microphone are singing individuals of different species than that they are more individuals of the same species.

The ecoacoustics represents a powerful tool to evaluate the effect of climate change because it can document changes of biophonic phenology and species behavior and the entrance/departure of a species in an acoustic community with consequences to the acoustic signature.

Due to advanced technology, today it is easy to collect acoustic data for long periods. The extended life of batteries coupled with a continuous solar power supply, great storage capacity of cards, and flexible time settings of acoustic sensors allow for the collection of great quantities of data, which was impossible until the mid-2000s.

Onboard-processed acoustic data transformed by metrics into meaningful information, especially when coupled with abiotic variables (e.g., light, humidity, temperature, pressure, and wind) and vegetation parameters (e.g., using the LiDAR technique (Pekin et al., 2012)), may efficiently elucidate and describe the effects of climate change. For this, the application of the ecoacoustics tool requires a deep understanding of the life history of the species, a precise agenda, robust models, and well-framed questions. Individual life traits, habitat characteristics, and species assemblage are some of the objectives to be attained.

Quality acoustic observations require standard methods and calibrated recorders. Significant findings using ecoacoustics will require multiple sampling stations around the world recording at the same time, using the same settings combined with rapid information processing facilities.

In a scenario of accelerated climate change conditions, the reaction of species is complex and largely depends on where the species are, their dimensions and size of the populations, level of heterogeneity of their genes, etc. (e.g., Bradshaw and Holzapfel, 2006). It is important to focus on primary goals like fragile systems, representative ecosystems, and hotspots for biodiversity or endemic species. In addition, recording the time of occurrence of the dawn and dusk choruses, when the majority of species is singing all together is a moment when important information about animal assemblages and their relationship to climate change is conveyed. Acoustic monitoring and analysis should also be conducted outside the breeding season by collecting soundscape examples, such as every type of frequency that could be associated with weather conditions (wind, rain, etc.) and that posits important indicators of seasonal trends.

Bioregions, such as the Australia wet tropics that are facing a compression of the climatic zone should represent a good candidate for key studies (Williams et al., 2003). Table 2 lists contests in which to carry out the investigations, a number of priorities in which operate and recommendations and explanations how to apply the ecoacoustics models.

Although several empirical studies have described the ecoacoustic characteristics of species in terrestrial and aquatic environments, very few investigations have been made that directly connect climate change with acoustic patterns (e.g., Llusia et al., 2013; Sueur and Sanborn, 2003) and this indicates that specific research objectives using acoustics to assess climate change be adopted.

Newly devised educational programs are essential tools to learn about and appreciate natural world soundscapes. These would set the standards and protocols and be easy and inexpensive ways to use soundscapes to identify problems in fragile areas like the national parks and wildlife preserves (Krause, 2002).

Table 2
Priorities, recommendations, and explanations for applying an ecoacoustics model to study and monitor climate change.

Contest	Priorities	Recommendations and explanations
Locations	Latitudinal and altitudinal gradient	Investigate species or acoustic communities utilizing a comparative protocol along a latitudinal or an altitudinal gradient.
	Restricted habitats	Concentrate the research on species or acoustic communities living in restricted habitats.
	Stopover areas	Develop the research in stopover areas that are considered important for migrants. The temporary appearance of migratory species in an acoustic community may represent a good indicator of the dimension and/or persistence of the migratory phenomenon.
	Extreme environments	Concentrate research on species living in extreme environments; a small change in environmental conditions could create survival problems that could be detected in advance using an ecoacoustics approach.
Weather	Weather conditions	Concentrate research on the variation of species' vocal performance or acoustic community patterns under different weather conditions.
Species	Short-distance migrants	Investigate the acoustic performance of species that migrate for short distances (e.g., from lowland to mountain tops during the breeding season).
	Species at high vocal plasticity	Concentrate research resources on species that modulate their vocal repertoire according to the structure of the vegetation (e.g., bats have a plastic behavior that modifies the frequency of emission of a call according to the physical character of the atmosphere and are extremely sensitive to changes in air humidity).
Population	Sink-source populations	Investigate the differences, if any, in the acoustic performances between sink and source populations using metrics like the chorus ratio.
Behavior	Life traits	Verify the change of some behavioral expressions like the height of song post (e.g., frogs and birds) in relation to acoustic performance and climate.
	Active space	Investigate the change in the active space of species that have territorial behavior as indicators of the modification of acoustic diffusion of signals.
	Social attraction	Evaluate the impact on social attraction (e.g., in colonial birds) in different environmental conditions in combination with acoustic performance.
Physiology	Physiological modification	Pursue research on the physiological changes (e.g., gonadal development) of species and their effects on acoustic performances.
	Dawn and dusk chorus	Concentrate the studies during dawn and dusk choruses. These periods are strategic for analyzing important energetic performances of the acoustic communities and its complexity in a short time interval.
	Sounds from stressed plants	Investigate the role of ecoacoustic activity of stressed plants as attractors of insect pests and assess the capacity of some defoliating insects to copy these signals.
Phenology	Time series analysis	Create a connection (common database) between historical time series (e.g., data on the arrival and departure of long-distance migratory species and ecoacoustic monitoring schemes).

In 2014, the International Society of Ecoacoustics (ISE) was created (https://sites.google.com/site/ecoacousticssociety/), which is evidence of the burgeoning bioacoustics interest among ecologists. An ecoacoustics society represents an important reference for scientists, technicians, and policy makers. The ISE promotes a scientific approach to the study of ecoacoustics, creates a network of scholars and students, disseminates ideas and research, conserves soundscapes, and is a central source that will address, guide, and support transnational programs of research in the future.

Possible programs that can be activated to reduce or stop the processes responsible for climate change would engage the help of non-professional scientists. Citizen science is indispensable to achieving the coverage of territories and the knowledge necessary to investigate climate change and its consequences. With short learning curves, it is able to cover some vertebrata and invertebrate community compositions and spatial distribution, although some formal limitations and models must be respected, such as the collection methodologies and validation of data. Methods of data collection must be well designed and standardized. The goal must be a clear exposition of simple questions. Finally, citizens must receive feedback for their contributions as recommended by Silvertwon (2009). The use of LCRs with onboard automated metric processing is a powerful tool in the hands of citizens that could be operated easily within their surrounding communities. For example, the LCR can be placed in urban parks and recreational areas to collect important information that simultaneously describes the direct human impact and the indirect consequences of long-term anthropogenic climate change.

In conclusion, ecoacoustics and related sub-disciplines, are important fields of investigation and application to the complex issues of climate change. The diffusion of ecoacoustic methodologies when coupled with other remote sensing methods represents a powerful new method of exposing behavior in species and environmental systems under a climate change regime.

Appendix A. Supplementary data

Supplementary data to this article can be found online at http://dx.doi.org/10.1016/j.biocon.2016.01.013.

References

Aide, T.M., Corrada-Bravo, C., Campos-Cerqueira, M., Milan, C., Vega, G., Alvarez, R., 2013. Real-time bioacoustics monitoring and automated species identification. PeerJ http://dx.doi.org/10.7717/peerj.103.

Alois, P., Cheng, V., 2007. Key stone species extinction overview. http://www.arlingtoninstitute.org/wbp/species-extinction/443.

André, M., der Schaar, M., Zaugg, S., Houégnigan, L., Sànchez, A.M., Castell, J.V., 2011. Listening to the deep: live monitoring of ocean noise and cetacean acoustic signals. Mar. Pollut. Bull. 63, 18–26.

Azzellino, A., Lanfredi, C., D'Amico, A., Pavan, G., Podestà, M., Haun, J., 2011. Risk mapping for sensitive species to underwater anthropogenic sound emissions: model development and validation in two Mediterranean areas. Mar. Pollut. Bull. 63, 56–70.

Badeck, F.W., Bondeau, A., Böttcher, K., Doktor, D., Lucht, W., Schber, J., Sitch, S., 2004. Reponses of spring phenology to climate change. New Phytol. 162, 295–309.

Badyaev, A.V., Leaf, E.S., 1997. Habitat associations of song characteristics in *Phylloscopus* and *Hippolais* warblers. Auk 114, 40–46.

Barber, J., Burdett, C., Reed, S., Warner, K., Formichella, C., Crooks, K., Theobald, D., Fristrup, K., 2011. Anthropogenic noise exposure in protected natural areas: estimating the scale of ecological consequences. Landsc. Ecol. 26, 1281–1295.

Bardeli, R., Wolff, D., Kurth, F., Koch, M., Frommolt, K.H., 2010. Detecting bird sounds in a complex acoustic environment and application to bioacoustic monitoring. Pattern Recogn. Lett. 31, 1524–1534.

Barnett, C.A., Briskie, J.W., 2007. Energetic state and performance of dawn chorus in silvereyes (*Zosterops lateralis*). Behav. Ecol. Sociobiol. 61, 579–587.

Berg, K.S., Brumfield, R.T., Apanius, V., 2006. Phylogenetic and ecological determinants of the neotrpical dawn chorus. Proc. R. Soc. B 273, 999–1005.

Bibby, C.J., Burgess, N.D., Hill, D.A., 1992. Bird Census Techniques. Academic Press, London.

Boebel, O., Kindermann, L., Klinck, H., Bornemann, H., Plotz, J., Steinhage, D., Riedel, S., Burkhardt, E., 2006. Real-time underwater sounds from the southern ocean. *Eos* 87 (36), 361–372.

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

Botero, C.A., Boogert, N.J., Vehrencamp, S.L., Lovette, I.J., 2009. Climatic patterns predict the elaboration of song displays in mockingbirds. Curr. Biol. 19, 1151–1155.

Both, C., Grant, T., 2012. Biological invasions and the acoustic niche: the effect of bullfrog calls on the acoustic signals of white-banded tree frogs. Biol. Lett. 8, 714–716.

Brackenbury, J.H., 1979. Power capabilities of the avian sound-producing system. J. Exp. Biol. 78, 163–166.

Bradshaw, W.E., Holzapfel, C.M., 2006. Evolutionary response to rapid climate change. Science 312, 1477–1478.

Brandes, T.S., 2008. Automated sound recording and analysis techniques for bird surveys and conservation. Bird Conserv. Int. 18, S163–S173.

Brenowitz, E.A., 1982. The active space of red winged blackbird song. J. Comp. Physiol. 147, 511–522.

Brewer, P.G., Hester, K., 2009. Ocean acidification and the increasing transparaency of the ocean to low-frequency sound. Oceanography 2 (4), 87–93.

Brown, C.H., 1989. The active space of monkey and grey cheeked mangabey vocalizations. Anim. Behav. 37, 1023–1034.

Bruni, A., Mennill, D.J., Foote, J.R., 2014. Dawn chorus start time variation in a temperate bird community: relationships with seasonality, weather, and ambient light. J. Ornithol. http://dx.doi.org/10.1007/s10336-014-1071.

Burt, J.M., Vehrencamp, S.L., 2005. 15. Dawn chorus as an interactive communication network. In: McGregor, P.K. (Ed.), Animal Communication Networks. PP. Cambridge University Press, Cambridge, UK.

Bystrak, D., 1981. The North American breeding bird survey. Stud. Avian Biol. 6, 34–41.

Carey, C., 2002. Incubation in extreme environments. In: Deeming, C.H. (Ed.), Avian Incubation: Behaviour, Environment, and Evolution. Oxford University Press, Oxord, UK, pp. 238–253.

Carey, C., 2009. The impacts of climate change on the annual cycles of birds. Philos. Trans. R. Soc. B 364, 3321–3330.

Chambers, L.E., Hughes, L., Weston, M.A., 2005. Climate change an its impact on Australia's avifauna. *Emu* 105, 1–20.

Chmielewski, F.M., Rötzer, T., 2001. Response of tree phenology to climate change across Europe. Agric. For. Meteorol. 108, 101–112.

Cleland, E.E., Chuine, I., Menzel, A., Mooney, H.A., Schwartz, M.D., 2007. Shifting plant phenology in response to global change. TREE 22 (7), 357–365.

Cosens, S.E., Falls, J.B., 1984. A comparison of sound propagation and song frequency in temperate marsh and grassland habitats. Behav. Ecol. Sociobiol. 15, 161–170.

Crick, H.Q.P., 2004. The impact of climate change on birds. Ibis 146 (Suppl.1), 48–56.

Crump, M.L., Scott Jr., N.J., 1994. Visual Encounter Surveys. In: Heyer, W.R., Donnelly, M.A., McDiarmid, R.W., Hayek, L.C., Foster, M.S. (Eds.), Measuring and Monitoring Biological Diversity: Standard Methods for Amphibians. Smithsonian Institution Press, Washington, DC, pp. 84–92.

Crutzen, P., Stoermer, E., 2000. The Anthropocene, global change. IGBP Newsl. 41, 17–18.

Cuthill, I.C., MacDonald, W.A., 1990. Experimental manipulation of the dawn and dusk chorus in the blackbird *Turdus merula*. Behav. Ecol. Sociobiol. 26, 209–216.

Dabelsteen, T., Mathevon, N., 2002. Why do songbirds sing intensively at dawn? A test of the acoustic transmission hypothesis. Acta Ethol. 4, 65–72.

Desjonquères, C., Rybak, F., Depraetere, M., Gasc, A., Le Viol, I., Pavoine, P., Sueur, J., 2015. First description of underwater acoustic diversity in three temperate ponds. PeerJ 3. http://dx.doi.org/10.7717/peerj.1393.

Deutsch, C.A., Tewksbury, J.J., Huey, R.B., Sheldon, K.S., Ghalambor, C.K., Haak, D.C., Martin, P.R., 2008. Impacts of climate warming on terrestrial ectotherms across latitude. Proc. Natl. Acad. Sci. 105, 6668–6672.

Dubois, P.J., 2007. Les oiseaux allochtones en France: statut et interactions avec les especes indigenes. Ornithos 14 (6), 329–364.

Dumm, D., Crutchfield, J.P., 2013. Entomogenic climate change. Santa Fe Institute Working Paper 08-05-XXX.

Easterling, D.R., Meehl, G.A., Parnesan, C., Changnon, S.A., Karl, T.R., Mearns, L.O., 2000. Climate extremes: observations, modeling, and impacts. Science 289, 2068–2074.

Ey, E., Fischer, J., 2009. The "acoustic adaptation hypothesis" — a review of the evidence from birds, anurans and mammals. Bioacoustics 19, 21–48.

Farina, A., 2012. A biosemiotic perspective of the resource criterion: toward a general theory of resources. Biosemiotics 5, 17–32.

Farina, A., James, P., 2015. Acoustic community structure and dynamics: a fundamental component of ecoacoustics. Biosystems (submitted for publication).

Farina, A., 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, Bari, pp. 365–372.

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

Farina, A., Pieretti, N., Morganti, N., 2013. Acoustic patterns of an invasive species: the red-billed leiothrix (*Leiothrix lutea* Scopoli 1786) in a Mediterranean shrubland. Bioacoustics 22 (3), 175–194.

Farina, A., James, P., Bobryk, C., Pieretti, N., Lattanzi, E., McWilliam, J., 2014. Low cost (audio) recording (LCR) for advancing soundscape ecology towards the conservation of sonic complexity and biodiversity in natural and urban landscapes. Urban Ecosyst. 17, 923–944.

Farina, A., Ceraulo, M., Bobryk, C., Pieretti, N., Quinci, E., Lattanzi, E., 2015. Spatial and temporal variation of bird dawn chorus and successive acoustic morning activity in a Mediterranean landscape. Bioacoustics http://dx.doi.org/10.1080/09524622.2015.1070282.

Figueira, L., Tella, J.L., Camargo, U.M., Ferraz, G., 2015. Autonomous sound monitoring shows higher use of Amazon old growth than secondary forest by parrots. Biol. Conserv. 184, 27–35.

Fitzpatrick, J.W., Lammertink, M., Luneau Jr., M.D., Gallagher, T.W., Harrison, B.R., Sparling, G.M., Rosenberg, K.V., Rohrbaugh, R.W., Swarthout, E.C., Wrege, P.H., Swarthout, S.B., Dantzker, M.S., Charif, R.A., Barksdale, T.R., Remsen Jr., J.V., Simon, S.D., Zollner, D.,

2005. Ivory-billed woodpecker (*Campephilus principalis*) persists in continental North America. Science 308 (5727), 1460–1462.
Forman, R.T.T., Godron, M., 1981. Patches and structural components for a landscape. Bioscience 31 (10), 733–740.
Freeberg, T.M., Lucas, J.R., Krams, I., 2012. The complex call of the Carolina chickadee. What can the chick-a-dee call teach us about communication and language? Am. Sci. 100, 398–407. http://dx.doi.org/10.1511/2012.98.398 (04/2012).
Gage, S.H., Axel, A.C., 2014. Visualization of temporal change in soundscape power of a Michigan lake habitat over a 4-year period. Ecol. Inf. 21, 100–109.
Gage, S.H., Miller, C.A., 1978. A Long-term Bird Census in Spruce Budworm-prone Balsam fir Habitats in Northwestern New Brunswick. Fisheries and Environment Canada, Canadian Forest Service, Maritimes Forest Research Centre, Fredericton, NB (Information Report M-X-84. 6 pp.).
Gage, S.H., Joo, W., Kasten, E.P., Fox, J., Biswas, S., 2015. Acoustic observations in agricultural landscapes. In: Hamilton, S.K., Doll, J.E., Robertson, G.P. (Eds.), The Ecology of Agricultural Ecosystems: Long-term Research on the Path to Sustainability. Oxford University Press, New York, New York, USA, pp. 360–377.
Gasc, A., Sueur, J., Jiguet, F., Devictor, V., Grandcolas, P., Burrow, C., Depraetere, 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.
Gibbs, J.P., Breisch, A.R., 2001. Climatic warming and calling phenology of frogs near Ithaca, New York, 1900–1999. Conserv. Biol. 15, 1175–1178.
Gillooly, J.F., Ophir, A.G., 2010. The energetic basis of acoustic communication. Proc. R. Soc. B 277, 1325–1331.
Gordo, O., 2007. Why are bird migration dates shifting? A review of weather and climate effects on avian migratory phenology. Clim. Res. 35, 37–58.
Greenfield, M.D., 1994. Synchronous and alternating choruses in insects and anurans: common mechanisms and diverse functions. Am. Zool. 34, 600–615.
Gregory, R.D., Willis, S.G., Jiguet, F., Voříšek, P., Klvanová, A., van Strien, A., et al., 2009. An indicator of the impact of climatic change on European bird populations. PLoS One http://dx.doi.org/10.1371/journal.pone.0004678.
Hau, M., Wikelski, M., Wingfield, J.C., 1998. A neotropical forest bird can measure the slight changes in tropical photoperiod. Proc. R. Soc. Lond. 265, 89–95.
Hawkes, L.A., Broderick, A.C., Godfrey, M.H., Godley, B.J., 2007. Investigating the potential impacts of climate change on a marine turtle population. Glob. Chang. Biol. 13, 1–10.
Henriquez, A., Alonso, J.B., Travieso, C.M., Rodriguez Herrera, B., Bolanos, F., Alpizar, P., Lopez de Ipina, K., Henriquez, P., 2014. An automatic acoustic bat identification system based on the audible spectrum. Expert Syst. Appl. 41, 5451–5465.
Henwood, K., Fabrick, A., 1979. A quantitative analysis of the dawn chorus: temporal selection for communicatory optimization. Am. Nat. 114, 260–274.
Herrando, S., Llimona, F., Brotons, L., Quesada, J., 2010. A new exotic bird in Europe: recent spread and potential range of red-billed leiothrix *Leiothrix lutea* in Catalonia (northeast Iberian Peninsula). Bird Stud. 57, 226–235.
Hester, K.C., Peltzer, E.T., Kirkwood, W.J., Brewer, P.G., 2008. Unanticipated consequences of ocean acidification: a noisier ocean at lower pH. Geophys. Res. Lett. 35, L19601.
Hoi-Leitner, M., Nechtelberg, H., Hoi, H., 1995. Song rate as a signal for nest site quality in blackcaps (*Sylvia atricapilla*). Behav. Ecol. Sociobiol. 37, 399–405.
Holm, S.R., Svenning, J.-C., 2014. 180,000 years of climate change in Europe: avifaunal responses and vegetation implications. PLoS One 9 (4), e94021. http://dx.doi.org/10.1371/journal.pone.0094021 (PMID: 24718387).
Hughes, L., 2000. Biological consequences of global warming: is the signal already apparent? Trends Ecol. Evol. 15, 56–61.
Huntley, B., Collingham, Y.C., Green, R.E., Hilton, G.M., Rahbek, C., Willis, S.G., 2006. Potential impacts of climatic change upon geographical distributions of birds. Ibis 8–28.
Hutchinson, G.E., 1957. Concluding remarks. Cold Spring Harb. Symp. Quant. Biol. 22, 415–427.
Hutchinson, G.E., 1978. An Introduction to Population Ecology. Yale University Press, New Haven, CT.
Inouye, D.W., Barr, B., Armitage, K.B., Inouye, B.D., 2000. Climate change affecting altitudinal migrants and hibernating species. PNAS 97 (4), 1630–1633.
International, B.L., 2013. *Campephilus principalis*. IUCN Red List of Threatened Species (Version 2013.2).
IPCC, 2013. Summary for policymakers. In: Stocker, T.F., Qin, D., Plattner, G.-K., Tignor, M., Allen, S.K., J (Eds.), Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change.
IPCC, 2014. https://ipcc-wg2.gov/AR5/report/.
Jaafar, H., Ramli, D.A., Shahrudin, S., 2013. MFCC Based Frog Identification System in Noisy Environment. http://dx.doi.org/10.1109/ICSIPA.2013.6707989.
Joo, W., Gage, S.H., Kasten, E.P., 2011. Analysis and interpretation of variability in soundscapes along an urban–rural gradient. Landsc. Urban Plan. 103, 259–276.
Kacelnik, A., 1979. The foraging efficiency of great tits (*Parus major*) in relation to light intensity. Anim. Behav. 27, 237–242.
Kasten, E.P., McKinley, P.K., Gage, S.H., 2010. Ensemble extraction for classification and detection of bird species. Ecol. Inf. 5 (3), 153–166.
Kasten, E.P., Gage, S.H., Fox, J., Joo, W., 2012. The remote environmental assessment laboratory's acoustic library: an archive for studying soundscape ecology. Ecol. Inf. 12, 50–67.
Klaus, S.P., Lougheed, S.C., 2013. Changes in breeding phenology of eastern Ontario frogs over four decades. Ecol. Evol. 3 (4), 835–845.
Krams, I., 2001. Perch selection by singing chaffinches: a better view of surroundings and the risk of predation. Behav. Ecol. 12, 295–300.
Krause, B., 1987. Bioacoustics, habitat ambience in ecological balance. Whole Earth Rev. 57, 14–18.
Krause, B., 1993. The niche hypothesis. Soundsc. Newsl. 6, 6–10.
Krause, B., 2002. Wild soundscapes in the national parks: an educational program guide to listening and recording. National Park Service, pp. 1–86.
Krause, B., 2012. The Great Animal Orchestra, Little. Brown & Co., New York, USA.
La Sorte, F.A., Jetz, W., 2010. Avian distributions under climate change: towards improved projections. J. Exp. Biol. 213, 862–869.
Laiolo, P., 2008. Characterizing the spatial structure of song-bird cultures. Ecol. Appl. 18, 1774–1780.
Laiolo, P., Tella, J., 2006. Landscape bioacoustics allow detection of the effects of habitat patchiness on population structure. Ecology 87, 1203–1214.
Larom, D., Garstang, M., Payne, K., Raspet, R., Lindeque, M., 1997. The influence of surface atmospheric conditions on the range and area reached by animal vocalizations. J. Exp. Biol. 200, 421–431.
Lengagne, T., Slater, P.J.B., 2002. The effects of rain on acoustic communication: tawny owls have good reason for calling less in wet weather. Proc. R. Soc. Lond. B 269, 2121–2125.
Lengagne, T., Aubin, T., Lauga, J., Jouventin, P., 1999. How do king penguin (*Aptenodytes patagonicus*) apply the mathematical theory of information to communicate in windy conditions? Proc. R. Soc. Lond. B 266, 1623–1628.
Lieth, H., 1974. Phenology and Seasonality Modelling. Springer, Berlin, Germany.
Llusia, D., Marquez, R., Beltran, J.F., Benitez, M., Do Amara, J., 2013. Calling behaviour under climatic change: geographical and seasonal variation of calling temperatures in ectotherms. Glob. Chang. Biol. 19, 2655–2674.
Lomolino, M.V., Pijanowski, B.C., Gasc, A., 2015. The silence of biogeography. J. Biogeogr. 42, 1187–1196.
Lucas, T.C.D., Moorcroft, E.A., Freeman, R., Rowcliffe, J.M., Jones, K.E., 2015. A generalised random encounter model for estimating animal density with remote sensor data. Methods Ecol. Evol. (in press).
Luo, J., Koselj, K., Zsebok, S., Siemers, B.M., Goerlitz, H.R., 2013. Global warming alters sound transmission: differential impact on the prey detection ability of echolocating bats. J. R. Soc. http://dx.doi.org/10.1098/rsif.2013.0961.
Marten, K., Marler, P., 1977. Sound transmission and its significance for animal vocalization. I. Temperate habitats. Behav. Ecol. Sociobiol. 2, 271–290.
Martin, T.E., 2001. Abiotic vs. biotic influences on habitat selection of coexisting species: climate change impacts? Ecology 82 (1), 175–188.
Mason, R., Roe, P., Towsey, M., Zhang, J., Gibson, J., Gage, S.H., 2008. Towards an acoustic environmental observatory. 4th IEEE International Conference on e-Science. Digital Object Identifier, Indianapolis, IN, pp. 135–142 http://dx.doi.org/10.1109/eScience.2008.16 (8 pp.).
McCarty, J.P., 2001. Ecological consequences of recent climate change. Conserv. Biol. 15, 320–331.
Mellinger, D.K., Clark, C.W., 1997. Methods for automatic detection of mysticete sounds. Mar. Freshw. Behav. Physiol. 29, 163–181.
Menzel, A., et al., 2006. European phenological response to climate change matches the warming pattern. Glob. Chang. Biol. 12, 1969–1976.
Merchant, N.D., Fristrup, K.M., Johnson, M.P., Tyack, P.L., Witt, M.J., Blondel, P., Parks, S.E., 2015. Measuring acoustic habitats. Methods Ecol. Evol. 6, 257–265.
Miller, J.H., Kloepper, L.N., Potty, G.R., Spivack, A.J., D'Hondt, S., Turner, C., 2014. The Effects of pH on Acoustic Transmission Loss in an Estuary. JASA Express Letters (in preparation).
Moller, A.P., 2010. When climate change affects where birds sing. Behav. Ecol. 22, 212–217.
Monacchi, D., 2014. Fragments of extinction. Leonardi Music Journal 23. MIT Press.
Morse, D.H., 1989. Song patters of warblers at dawn and dusk. Wilson Bull. 101 (1), 26–35.
Morton, S., 1975. Ecological sources of selection on avian sounds. Am. Nat. 109, 17–34.
Moskwik, M., Thom, T., Barnhill, L.M., Watson, C., Koches, C., Kilgo, J., Hulsland, B., 2013. Search efforts for ivory-billed woodpecker in South Carolina. South. Nat. 12 (1), 73–84.
Moss, S., 1998. Predictions of the effects of global change on Britain's birds. Br. Birds 91, 307–325.
Narins, P.M., Meenderink, W.F., 2015. Climate change and frog calls: long-term correlations along a tropical altitudinal gradient. Proc. R. Soc. B 281, 20140401. http://dx.doi.org/10.1098/rspb.2014.0401.
Nischck, F., Riede, K., 2001. Bioacoustics of two cloud forest ecosystems in Ecuador compared to lowland rainforest with special emphasis on singing cricket species. In: Nieder, J., Barthlott, W. (Eds.), Epiphytes and Canopy Fauna of the Otongan Rain Forest (Ecuador) vol. 2 of 2. Results of the Bonn - Quito epiphyte project, funded by the Volkswagen Foundation, pp. 217–224.
Ospina, O.E., Villanueva-Rivera, L.J., Corrado-Bravo, C.J., Aide, T.M., 2013. Variable response of anuran calling activity to daily precipitation and temperature: implications for climate change. Ecosphere 4 (4), 1–12.
Parker III, T.A., 1991. On the use of tape recorders in avifaunal surveys. Auk 108, 443–444.
Parmesan, C., 2006. Ecological and evolutionary responses to recent climate change. Annu. Rev. Ecol. Evol. Syst. 37, 637–669.
Pekin, B.P., Jung, J., Villanueva-Rivera, L.J., Pijanowski, B.C., Ahumada, J.A., 2012. Modeling acoustic diversity using soundscape recordings and LIDAR-derived metrics of vertical forest structure in a neotropical rainforest. Landsc. Ecol. 2012. http://dx.doi.org/10.1007/s10980-012-9806-4 (27,1513–1522).
Piercy, J.J.B., Codling, E.A., Hill, A.J., Smith, D.J., Simpson, S.D., 2014. Habitat quality affects sound production and likely distance of detection on coral reefs. Mar. Ecol. Prog. Ser. 516, 35–47.
Pieretti, N., Farina, A., 2013. Application of a recently introduced index for acoustic complexity to an avian soundscape with traffic noise. J. Acoust. Soc. Am. 134, 891–900.
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, 868–873.

Pijanowski, B.C., Villanueva-Riiera, L.J., Dumyahn, S.L., Farina, A., Krause, B.L., Napoletano, B.M., Gage, S.H., Pieretti, N., 2011a. Soundscape ecology: the science of sound in the landscape. Bioscience 61, 203–216.
Pijanowski, B.C., Farina, A., Gage, S.H., Dumyahn, S.L., Krause, B.L., 2011b. What is soundscape ecology? An introduction and overview of an emerging new science. Land. Ecol. 26, 1213–1232.
Puglisi, L., Bosi, E., Corsi, I., Del Sere, M., Pezzo, F., Sposimo, P., Verducci, D., 2009. Usignolo del Giappone. 16(1–2). Bengalino and Co: Alieni in Toscana, Alula, pp. 426–431.
Pulliam, H.R., 1988. Sources, sinks, and population regulation. Am. Nat. 132, 652–661.
Qi, J., Gage, S.H., Joo, W., Napoletano, B., Biswas, S., 2008. Soundscape characteristics of an environment: a new ecological indicator of ecosystem health. In: Ji, W. (Ed.), Wetland and Water Resource Modeling and Assessment. CRC Press, New York, New York, USA, pp. 201–211.
Ralph, C.J., Scott, J.M. (Eds.), 1981. Estimating Numbers of Terrestrial BirdsStudies in Avian Biology, No. 6. Cooper Ornithological Society, Lawrence, Kansas.
Ralph, C.J., Guepel, G.R., Pyle, P., Martin, T.E., DeSante, D.F., 1993. Handbook of Field Methods for Monitoring Landbirds, Pacific Southwest Research Station. U.S. Forest Service, Albany, CA.
Richards, D.G., Wiley, R.H., 1980. Reverberations and amplitude fluctuations in the propagation of sound in a forest: implications for animal communication. Am. Nat. 115, 381–399.
Risch, D., Castellote, M., Clark, C., Davis, G., Dugan, P., Hodge, L., Kumar, A., Lucke, K., Mellinger, D., Nieukirk, S., Popescu, C., Ramp, C., Read, A., Rice, A., Silva, M., Siebert, U., Stafford, K., Verdaat, H., Van Parijs, S., 2014. Seasonal migrations of North Atlantic minke whales: novel insights from large-scale passive acoustic monitoring networks. Mov. Ecol. 2, 24.
Rodriguez, A., Gasc, A., Pavoine, S., Grandcolas, P., Gaucher, P., Sueur, J., 2014. Temporal and spatial variability of animal sound within a Neotropical forest. Ecol. Inf. 21, 133–143.
Rubenstein, D.I., 1992. The greenhouse effect and changes in animal behavior: effects on social structure and life-history strategies. In: Peters, R.L., Lovejoy, T.E. (Eds.), Global Warming and Biological Diversity. Yale University Press, New Haven, pp. 180–192.
Shannon, C.E., Weaver, W., 1949. The Mathematical Theory of Communication. University of Illinois Press, Urbana (117 pp.).
Silvertwon, J., 2009. A new dawn for citizen science. TREE 24 (9), 467–471.
Simpson, S.D., Munday, P.L., Wittenrich, M.L., Manassa, R., Dixson, D.L., Gagliano, M., Yan, H.Y., 2011. Ocean acidification erodes crucial auditory behaviour in a marine fish. Biol. Lett. 7, 917–920.
Snell-Rood, E.C., 2012. The effect of climate on acoustic signals: does atmospheric sound absorption matter for bird song and bat echolocation? J. Acoust. Soc. Am. 131, 1650–1658.
Staicer, C.A., Spector, D.A., Horn, A.G., 1996. The dawn chorus and other diel patterns in acoustic signaling. In: Kroodsma, D.E., Miller, E.H. (Eds.), Ecology and Evolution of Acoustic Communication in Birds. Cornell University Press, *Ithaca*, NY.
Steelman, C.K., Dorcas, M.E., 2010. Anuran calling survey optimization: developing and testing predictive model of anuran calling activity. J. Herpetol. 44 (1), 61–68.
Sueur, J., Farina, A., 2015. Ecoacoustics: the ecological investigation and interpretation of environmental sound. Biosemiotics http://dx.doi.org/10.1007/s12304-015-9248-x.
Sueur, J., Sanborn, A.F., 2003. Ambient temperature and sound power of cicada calling songs (Hemiptera: Cicadidae: Tibicina). Physiol. Entomol. 28, 340–343.
Sueur, J., Pavoine, S., Hamerlynck, O., Duvail, S., 2008. Rapid acoustic survey for biodiversity appraisal. PLoS One 3, 1–9.
Sueur, J., Farina, A., Gasc, A., Pieretti, N., Pavoine, S., 2014. Acoustic indices for biodiversity assessment and landscape investigation. Acta Acustica United With Acustica. 100, pp. 772–781.
Thomas, R.J., 1999. The effect of variability in the food supply on the daily singing routines of European robin: a test o a stochastic dynamic programming model. Anim. Behav. 57, 365–369.
Thomas, R.J., Cuthill, I.C., 2002. Body mass regulation and the daily singing routines of European robins. Anim. Behav. 63, 285–295.
Thomas, R.J., Szekely, T., Cuthill, I.C., Harper, D.G.C., Newson, S.E., Frayling, T.D., Wallis, P.D., 2002. Eye size in birds and the timing of song at dawn. Proc. R. Soc. Lond. B 269, 831–837.
Tobias, J.A., Planqué, R., Cram, D.L., Seddon, N., 2014. Species interactions and the structure of complex communication networks. Proc. Natl. Acad. Sci. 111 (3), 1020–1025.
Towsey, M., Wimmer, J., Williamson, I., Roe, P., 2014a. The use of acoustic indices to determine avian species richness in audio-recordings of the environment. Ecol. Inf. 21, 110–119.
Towsey, M., Zhang, L., Cottman-Fields, M., Wimmer, J., Zhang, J., Roe, P., 2014b. Visualization of long-duration acoustic recordings of the environment. Procedia Comput. Sci. 29, 703–712.
Tucker, D., Gag, S., Williamson, I., Fuller, S., 2014. Linking ecological condition and the soundscape in fragmented Australian forests. Landsc. Ecol. 29, 745–758.
Verner, J., 1985. Assessment of counting techniques. Curr. Ornithol. 2, 247–302.
Wallschager, D., 1980. Correlation of song frequency and body weight in passerine birds. Experientia 36, 412.
Walther, G.R., Post, E., Convey, P., Menzel, A., Parmesan, C., Beebee, T.J.C., Fromentin, J.M., Hoegh-Guldberg, O., Bairlein, F., 2002. Ecological responses to recent climate change. Nature 416, 389–395.
Wiley, R.H., 1991. Association of song properties with habitats for territorial oscine birds of eastern North America. Am. Nat. 138 (4), 973–993.
Wiley, R.H., Richards, D.G., 1978. Physical constraints on acoustic communication in the atmosphere: implications for the evolution of animal vocalization. Behav. Ecol. Sociobiol. 3, 69–94.
Williams, S.E., Bolitho, E.E., Fox, S., 2003. Climate change in Australian tropical rainforests: an impeding environmental catastrophe. Proc. R. Soc. Lond. B 270, 1887–1892.
Wong, B.B., Cowling, A.N.N., Cunningham, R.B., Donnelly, C.F., Cooper, P.D., 2004. Do temperature and social environment interact to affect call rate in frogs (*Crinia signifera*)? Aust. Ecol. 29, 209–214.
Wysocki, L.E., Montey, K., Popper, A.N., 2009. The influence of ambient temperature and thermal acclimation oh hearing in a eurythermal and a stenothermal otophysan fish. J. Exp. Biol. 212, 3091–3099.