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The soundscape ecology: A new frontier of landscape research and its application to islands and coastal systems

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Abstract Islands and mainland coastal ranges are fragile systems rich in biological endemisms and ecological peculiarities. In these environments, the cultural heritage that represents an important component of the overall ecological complexity is under attack from human pressures (urban sprawl, logistics, fish farming and mass tourism).

Among the most valuable resources pertaining to these environments, the overall emerging sounds (the soundscape) play a relevant role with respect to the maintenance of the sense of a place and its cultural value.

The study of the soundscape requires an epistemology based mainly on the cognitive landscape perspective, and within this theoretical framework, the General Theory of Resources, the Eco-field hypothesis and the soundtope model are also important components.

Among the methods used in soundscape ecology, the analysis of the frequency bins of the acoustic spectrogram can provide proxies for understanding and interpreting acoustic patterns and processes in action across a landscape.

The description of a case-study from a Tyrrhenian coastal system of Northern Italy, via the use of dedicated software and metrics, briefly illustrates the potential of soundscape ecology, which is entirely suitable for achieving a better understanding of the dynamics of island and mainland coastal systems.

Introduction

Islands and coastal systems are bounded regions in which the role of human intervention is particularly intense (Hassan et al., 2005). Indeed, these areas are major draws for tourism, fish farming, transportation facilities and shipping logistics (harbors, lighthouses, etc.). Both systems are also ecosystems that are under human 'attack', and immediate surveys and long-term monitoring schemes are urgently required to prevent further damage and conserve nature and its environmental and cultural value for future generations.

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Islands associated with mainland coastal systems represent frontiers for several ecological, biological and sociological processes, such as migration, population spreading and human demographic concentration. In particular, islands are fragile ecosystems in which endemic biodiversity is often dismantled by the explosive intrusion of alien species (Brockie et al., 1987; Lodge, 1993; Mooney et al., 2005). Islands remain the cradle within which to study speciations and endemisms, and have represented a source of epistemic-theoretical inspiration for generations of ecologists (MacArthur and Wilson, 1967).

Among the different perspectives with which is possible to explore, describe and manage the ecological complexity of such environments, the soundscape may be an excellent proxy for both short- and long-term scientific investigations. The soundscape can be defined as every sound produced by any abiotic and biological component of an ecosystem (geophonies and biophonies, respectively) together with anthropogenic sounds (Anthrophonies) (Pijanowski et al., 2011). It is thus the result of the energy released by both natural processes and human technologies.

The sounds of a landscape are the acoustic context produced and, in turn, perceived in different ways by both animals and humans. In particular, the quality of a soundscape represents an important component among the factors that contribute to creating and preserving the individual and the social wellbeing of resident people (Evans et al., 1995; Evans and Maxwell, 1997; Dumyahn and Pijanowski, 2011). Accordingly, a Hi-Fi acoustic context, which refers to an environment where all sounds may be heard clearly without being crowded or masked by other sounds and noise (Truax, 1999, 2001 p.65), contributes to the overall attraction of a living space for human beings (O'Connor, 2008).

Considering that most islands and coastal systems (at least in the temperate and tropical regions) are chosen by people for recreation and tourism purposes, and that the amenity of these areas is an essential feature for such activities, the acoustic patterns become important indicators of these processes. Consequently, the soundscape approach appears to be an obligatory step for achieving and maintaining their integrity.

The aim of this paper is to illustrate and discuss the potential applications of soundscape ecology in these critical environments. A brief description of the theoretical basis of soundscape ecology, together with its applied methodologies, is also provided. Finally, a case-study from a Mediterranean coastal system is put forward as a practical example of a soundscape assessment.

The epistemological basis of soundscape ecology

The soundscape approach does not simply correspond to the analysis of a collection of sounds, but also pertains to a complex system of identification of sounds and the interpretation thereof. The description of soundscape patterns is an indispensable, but not sufficient, way of studying (ecologically) this matter; a biosemiotic approach is also required to understand and interpret the uses and functions of sounds (Farina, 2012).

The significance of the soundscape largely depends on the individual status of a species and its life traits that intersect acoustic cues.

For this reason, it is imperative to introduce the individually-based perspective of the environment (see f.i. Allen and Hoekstra, 1992, p. 159), and the associated concept of *Umwelt* as a subjectively perceived surrounding (von Uexküll, 1982, 1992). This concept, which was long ignored by ecologists, is a fundamental point when it comes to understanding environmental complexity. In fact, *Umwelt* means a self-centered world in which each species or individual has a semiotic world with which to interact.

In order to better understand the role and importance of the soundscape approach, it is also crucial to consider the cognitive dimension of a landscape.

The landscape can be defined in several ways according to the epistemological basis adopted and the discipline; geographic, ecological and economic are just some of the adjectives that can be associated with the notion of "landscape".

Recently, Farina (2008) defined the landscape as a semiotic interface between organisms and resources, and this essay has been expanded on by the introduction of the concept of the *eco-field* (Farina and Belgrano, 2003, 2006), which is defined as every spatial configuration carrier of meaning that is necessary to track resources.

As argued in the General Theory of Resources recently developed by Farina (2011, 2012), resources may have a dual nature: material, such as food, water and refuge; or immaterial, like safety and cultural heritage. The soundscape can be regarded from a biosemiotic point of view as a collection of acoustic eco-fields that are used by species to track specific resources. For instance, in the world of birds, when an eavesdropping female intercepts the contemporary song of different males, these cues are a spatial configuration carrier of meaning used by this female to identify where the best territory is located. Indeed, song is considered to be an honest signal, and the quality and quantity thereof when uttered by a male is an indication that this individual is the owner and active defender of a place where there are abundant resources, such as food and nesting places. The same process occurs when alarm calls are emitted by a group of individuals; again, their position is an indicator of enemies that are invisible to the eavesdropping subject.

Humans adopt the same strategy; for instance, the siren of an ambulance signals an emergency, while the different tolling of bells may indicate special days or the passing of the hours.

Specifically, sounds from nature are used by animals and humans in different ways according to the function performed at a particular time. In the animal world, the use of acoustic cues to communicate (like in frogs or songbirds) and explore the surroundings (like in bats and dolphins) is extremely diffuse, but only humans have developed a complex and highly plastic language that has differentiated a huge number of regional variants. Moreover, humans produce extra-body sounds, like noises connected to transportation (trains, cars, airplanes and boats), factory activities, and social events (sport, concerts, religious ceremonies, etc.), all of which become part of the soundscape processes.

Relationships between landscape and soundscape

The structure of a landscape and the soundscape sphere are strictly connected, since aspect, morphology, vegetation patterns, human infrastructures and settlements, and animal distribution all correspond with the production of sounds and their propagation. For instance, an attempt to couple landscape architecture and soundscape patterns has recently been proposed by Hedford (2008).

At least three models can explain the relationship between landscape patterns and soundscape features (see Fig. 1). The first assumes a perfect overlap between landscape structure and soundscape distribution, the second assumes a coarser resolution of the soundscape, while the final model considers the soundscape at a finer resolution when compared with the landscape tissue. For instance, this last model seems particularly able to adapt to cope with the acoustic activity of birds, thus paving the way to the "soundtope" hypothesis recently presented by Farina et al. (2011).

This soundtope hypothesis assumes that acoustic conditions allow the presence of intentional, interacting species and that the aural patterns must be regarded as the result of the behavioral reactions of acoustically active individuals. With this premise, the acoustic quality of a place becomes functional with respect to the wellbeing of every vocal organism, and is thus regarded as a resource that is sought out by individuals along with refuge, food, etc.

Specifically, in the landscape scenario, the acoustic context plays an important role in the regulation of bird spatiality, local abundance and their sound activities.

An introduction to soundscape methodologies

In the last few decades, technological developments in the field of acoustic ecology have provided new tools with which to study natural and anthropogenic sounds; of all of these, the introduction of the spectrogram representation of sounds and related metrics have been the most significant steps (see f.i. Hopp et al., 1998). Spectrograms actually reveal the acoustic structure of a sound so that a great deal of information on tone quality, pitch and timbre can be extracted. Early analogue spectrograms were applied to a wide range of sounds, with a particular application being the study of birds and their behavior, which was initially tested by Thorpe (1958).

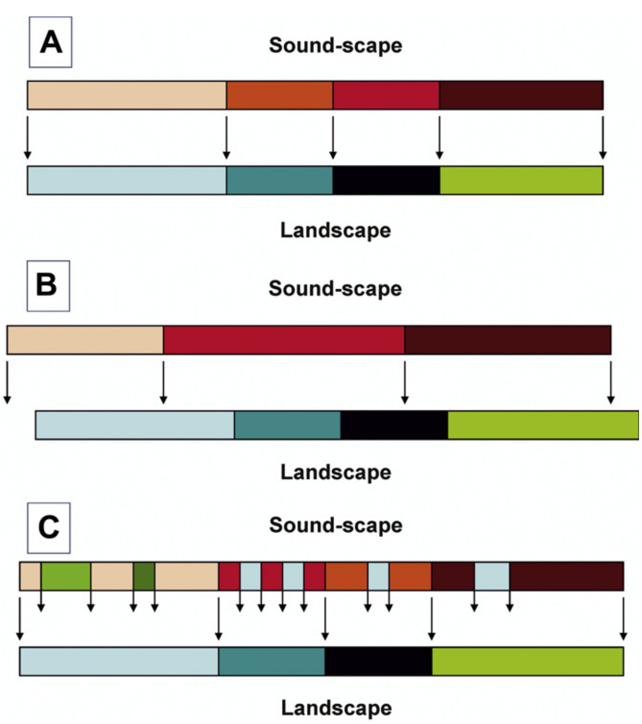

Fig. 1 Models of landscape-soundscape interaction. The three models explaining the relationship between landscape and soundscape patterns: (A) perfect overlapping; (B) coarser resolution of the soundscape; (C) the soundscape has a finer resolution than the landscape tissue.

With the arrival of digital technology, several limitations of analogic recordings have been overcome (Hopp et al., 1998). The better quality of the recordings and the opportunity to collect a greater quantity of field information permits the exploration of new frontiers in the analysis of soundscapes. In particular, it has been possible to both improve ecological studies of animal assemblages and extend behavioral studies from single species to entire communities (f.i. Sueur et al., 2008).

The automatic acoustic recording technique has several advantages. Audio-files become a permanent record that can be archived and cross-validated with other successive audio-samples. Consequently, this approach reduces the likelihood of interpreter errors. It also solves some of the logistical problems that are often experienced in field studies by overcoming the difficulty of finding numerous field experts operating in real time. Contemporarily, this methodology avoids the involuntary disturbance caused to the environment by the field operator, thus becoming a more efficient approach to the study of the acoustic dynamics of the living wild community (Haselmayer and Quinn, 2000; Hobson et al., 2002; Rempel et al., 2005; Scott et al., 2005).

High-quality omni-directional microphones, remote-sensing technology, and new systems with appropriate associated hardware with the capacity to store long audio-files are now available (Monacchi, 2011). These devices (f.i. Zoom H4 recorders) can automatically collect sound data for several hours, with SD memory size and battery duration being the only limiting factors. They also provide an opportunity to record in the wild, whatever the weather conditions, with scheduling on a daily or hourly basis (f.i. SongMeter, Wildlife Acoustics).

Moreover, an array of microphones has been tested and found to be one of the most complete ways of collecting acoustic information in a landscape (Farina et al., 2011).

The innovative hypothesis, which arises from the soundscape methodology, allows new perspectives and representations of the resources and the emergent processes among interacting species living in the environment.

A vast amount of data comes from each acoustic environment, and advanced metrics are required to efficiently extract information. Recently, several authors have tested indexes with the aim being to both infer species richness on a community scale (e.g. Sueur et al., 2008; Depraetere et al., 2012) and characterize the degree of complexity of the acoustic emissions (Pieretti et al., 2011; Farina et al., 2011). In particular, new software in the form of the SoundscapeMeter (Farina et al., 2012) has been specifically produced to process sound data automatically.

An example of the application of soundscape methodologies: the Deiva Marina case-study

The environmental conditions of the coastal systems of the Italian peninsula are characterized by the diffuse degradation of natural vegetation caused by urban sprawl, logistical infrastructures and massive tourist facilities.

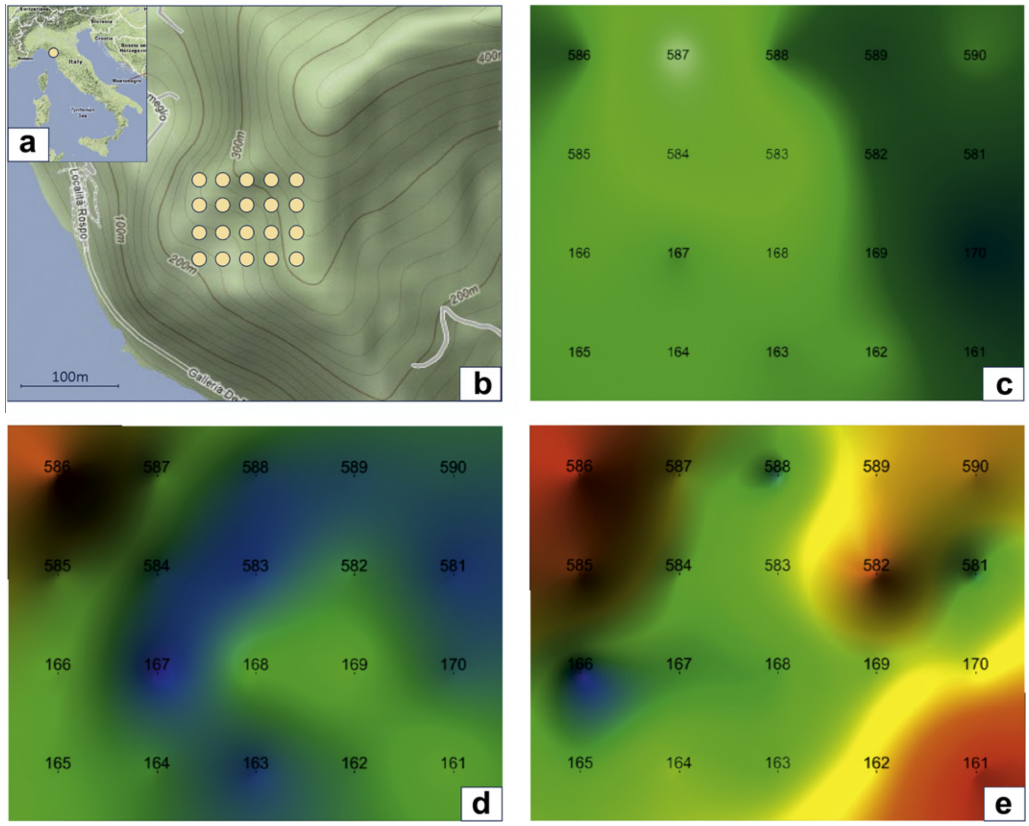

Fig. 2 Study area, vegetation coverage and soundscape dynamics. Location of the Deiva Marina site (a) (44°13′31″N, 9°30′22″E). An array of 20 recorders, spaced 25 m from each other, has been placed in the study area during the course of 23 sessions from February to July 2011 (b). The openness of the vegetation canopy was estimated from a fish-eye survey based on 182 samples along the line transects (c). The Soundscape Meter (Farina, 2012) has been used to process the sound data applying the ACI algorithm (Pieretti et al., 2011). Examples of the output of the bird soundscape reported for March 2011 (d), and May 2011 (e) show that the spatial dynamics of bird acoustic cues respond to the environmental complexity at a very small grain resolution.

Despite this vast anthropogenic disturbance, well preserved fragments of Mediterranean maqui still survive in some areas, such as along the oriental coast of the Liguria Region.

In one of these Mediterranean maqui patches, a long-term ecological research station has been in use since 2010, with the aim being to investigate not only the dynamics of a bird community, but to also provide indications on how to manage this area wherein wild fires, rural abandonment and woodland recruitment are factors in the creation of a patchy mosaic.

This investigation, which was carried out near Deiva Marina and reported in detail in Farina et al. (in prep), was strengthened with the dislocation of a recording matrix in order to explore the acoustic dynamics of the entire territory. The results reveal a complex system of interacting birds which, over the course of the seasons, create different spatial configurations of sound patterns. A gradual spatial turnover along the recording sessions was also registered: at the start of the breeding season, acoustic activity is principally concentrated in two main regions of the study area, which is progressively filled by sounds from March to June. The high spatial resolution with which birds cope with the environmental conditions in this investigation (see Fig. 2) highlights that local perturbations (wild fires, logging, dissections by new roads or electrical facilities) can have severe effects on bird diversity and abundance.

The turnover of the acoustic patterns observed supports the soundtope hypothesis: birds create temporary aggregations that are connected to the potential acoustic transmission of sounds.

A further element of concern is the presence of an alien bird, the *Leiothrix lutea*, a species with a marked characteristic of invasiveness (Male et al., 1998), which has recently become a widespread presence in the study area and the neighboring regions (Puglisi et al., 2009). The loudness of this species is one of the most important factors in its demographic success, as has emerged from a recent investigation (Farina et al., in prep).

These initial outcomes confirm how important the acoustic information that flows across a landscape is (not only for birds), as well as the risks connected to the involuntary introduction of new species in a fragile and isolated system like the one described in this example.

These results are encouraging in terms of the validity of the methods when it comes to monitoring the acoustic cues produced in a landscape, and these approaches allow us to consider the possibility of applying them to different scales inside coastal landscapes.

A long-term monitoring scheme, with recording devices spaced on a grid of selected points, could be one of the best investigative approaches to assessing environmental dynamics and human impact on such coastal systems.

Discussion

Islands and mainland coastal systems are valuable environments either for their intrinsic cultural heritage or for the purposes of recreation. In these islands, geographic isolation has led to biological endemism, peculiar ecology and a unique human culture, all of which are at risk from new global, economic models. Along the mainland coasts, a large extension of land has recently been subjected to tourism leisure expansion, which has modified both several land uses and human traditions. Both systems are suffering due to such "modernization" of the human lifestyle.

Significant human pressure, coupled with the great fragility of these systems, urgently requires continuous environmental assessment, as well as an adaptive, efficient and innovative method of monitoring.

Among the new methods produced by modern technology, the study of the sounds of nature has proved to be an important and rapid way to investigate the human-landscape interactions (Barber et al., 2011) that nowadays still represent processes that are insufficiently understood.

In a cultural landscape, the soundscape is the result of an ancient co-evolution between human culture and natural processes, and the resulted blend becomes the peculiarity of a place (O'Connor, 2008).

In reality, most conservation strategies are focused on the conservation of natural habitats, species and their aggregation. Unfortunately, little attention has been paid to the preservation of the acoustic heritage that greatly contributes to the maintenance of the sense of a place, which in turn generates a social identity (Dumyahn and Pijanowski, 2011).

In a well-preserved cultural landscape, the sounds produced by the traditional activities of people, and the acoustic signals used to communicate, are an integral part of a cultural heritage and important factors when it comes to assuring local people of a context of a high standard of living.

Moreover, peace and quiet, which are leading resources in today's economic scenario, are essential attributes with which to evaluate the level of amenity offered by these environments, particularly for visitors who are fleeing from noise polluted urban areas. The acoustic quality of these landscapes is an indispensable feature to ensure their recreational use, both for those living in them and holiday-makers.

In many island and mainland coastal systems, such as along the Catalan coasts (Otero et al., 2013), the traditional culture has disappeared and new human dynamics have been established. These new lifestyles require a long period of adjustment during which the biosemiotic network, which regulates the exchange of meaningful information between organisms, is working to restore a functioning net.

Moreover, the soundscape approach can be a powerful tool for long-term monitoring schemes, including for assessing biodiversity turnover (invasions, extinctions, changes in local abundance) in island and mainland coastal systems.

In conclusion, the soundscape represents a group of immaterial resources that are ecologically, culturally and economically valuable. With these premises, soundscape ecology seems to be a worthy new epistemological path and an efficient tool in ecological research, also establishing a strong link with landscape ecology, bio-acoustics and urban planning practices (Truax, 2001; Hedford, 2008).

At this point in time, monitoring and post-processing standardization, coupled with a worldwide net of acoustic archives, are considered to be important ways of addressing the development of the soundscape ecology operating in every environmental context, including in islands and mainland coastal systems.

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