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ORIGINAL PAPER

Baseline data for automated acoustic monitoring of Orthoptera in a Mediterranean landscape, the Hymettos, Greece

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Abstract Acoustic emissions of animals serve communicative purposes and most often contain species-specific and individual information exploitable to listeners, rendering bioacoustics a valuable tool for biodiversity monitoring. Recording bioacoustic signals allows reproducible species identification. There is a great need for increased use and further development of automated animal sound recording and identification to improve monitoring efficiency and accuracy for the benefit of conservation. Greece, with its high number of endemic species, represents a hotspot for European Biodiversity, including Orthopteran insects. Songs of many Orthoptera might be employed for the inventorying and monitoring of individual species and communities. We assessed the regional spatio-temporal composition of Orthoptera species at the Hymettos near Athens, which is a Natura 2000 site under constant threat due to the surrounding megacity. Within the framework of the EU Life Plus funded AmiBio project, we documented the Orthopteran species' habitat characteristics, their co-occurrence and phenology. We found, in total, 20 species with seven to ten Orthoptera at locations characterised by diverse vegetation patterns of perennial herbs and bushes. For the purposes of implementation of an automated remote monitoring scheme, we identified sampling sites with high Orthopteran diversity, allowing the monitoring of all singing Orthoptera within single localities. By analysing sound depositories and adding recordings from new sample individuals, we established a song library as prerequisites for future automatic song detection. Based on our results, acoustic recording units have been placed at remote sites at the Hymettos. We discuss recommendations for further studies to fully employ the potential of automated acoustic monitoring of Orthoptera. A reliable assessment of singing Orthoptera needs recording units covering ultrasound. Due to high attenuation and absorbance by the vegetation, particularly of the high frequencies characterising Orthopteran songs, positioning of microphones at sites is critical: the microphone sensor network has to be an order of magnitude denser than for monitoring birds.

Keywords Biodiversity monitoring · Wildlife recording · Autonomous monitoring · Sound · Orthoptera

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Introduction

The 2010 target to reduce or even stop biodiversity loss has been missed (Butchart et al. 2010). Among the many lessons learned from analysing this failure was the notion of inefficient monitoring data and tools, which are a prerequisite for the development of efficient and timely conservation measures. Consequently, monitoring is highlighted in the Convention on Biological Diversity, and forms part of the CBD Strategic Plan for 2011–2020, the decade of biodiversity.

The so-called Aichi targets define five strategic goals, all aiming to improve the status of biodiversity. Within *Strategic Goal E* ("Enhance implementation through participatory planning, knowledge management and capacity building"), Target 19 aims at improving "the knowledge, the science base and the technologies relating to biodiversity" (UNEP/CBD 2010). Several initiatives are developing roadmaps towards this goal, such as the *Biodiversity Indicators Partnership* (BIP 2013) or the pan-European *Streamlining European Biodiversity Indicators* initiative (SEBI 2007). Among the principal requirements for monitoring biodiversity trends are a denser network of observatories, improved data flow and availability (Huettmann et al. 2011) as well as more effective monitoring protocols covering more taxa. Effective monitoring schemes as the process of gathering information for the purpose of drawing inferences about changes in state (Yoccoz et al. 2001; Jones 2011), are the base from which to explore the fauna and flora of a region.

While monitoring schemes are well developed in central and northern Europe, they are scarce or non-existent in most Mediterranean Countries. This is particularly true for Orthoptera (bushcrickets, crickets (Ensifera) and grasshoppers (Caelifera)), which are known as a major component of biodiversity in grasslands and open habitats (Chapman and Joern 1990; Ryszkowski et al. 1993; Lockwood 1997). Orthoptera are keystone species in food webs because of their mostly herbivorous diet and value as prey for large insects, spiders, lizards and birds (Ingrisch and Köhler 1998). They also are good indicators of land use change (Samways 1997; Fartmann et al. 2012) and are especially appropriate for use in open habitats (Gerlach et al. 2013). Despite their value as bioindicators and their high species numbers, insects in general are largely neglected when considering extinction risk (Dunn 2005). Compared with the quite detailed conservation data available for some central European countries like Germany (Maas et al. 2002), we have still rather restricted data from the Mediterranean area. Even if we become aware of Mediterranean Orthopteran species with high conservation needs (e.g. Kati et al. 2006, 2012; Schultner et al. 2012), Orthoptera in general are more known for their potential as pests, threats to farmland, and for posing a conflict between pest management programs and conservation (Lockwood 1997; Samways and Lockwood 1998). Consequently, the majority of Orthopteran data from Greece, including descriptions of new species, are a result of private research initiatives from central European specialists (see summary in Willemse and Willemse 2008). In contrast to a pronounced lack of monitoring data, Greece is home to a high number of species, including a considerable number of endemics (Kenyeres et al. 2009), several with poor recolonization potential and limited distribution ranges. These species are increasingly under threat due to habitat loss and changes in land use, highlighted for a few Orthoptera species from Greece (Kati and Willemse 2001; Kati et al. 2003, 2006, 2012).

Bioacoustic monitoring provides an excellent opportunity for automatic monitoring (Gaston and O'Neill 2004; Digby et al. 2013). Although it is limited to vocalising animal taxa (particularly whales and dolphins, bats, birds and some insects, Obrist et al. 2010), it provides informative and reliable datasets, because microphones can be easily integrated into existing monitoring networks of autonomous stations, like those monitoring other acoustic taxonomic groups (Potamitis 2014). Networks and protocols have already been developed for marine ecosystems, where populations of whales and dolphins are surveyed by a widely spaced network of hydrophones (Zimmer 2011), and to a lesser extent for terrestrial environments (Blumstein et al. 2011). Besides presence-absence data, the use of microphone arrays has the potential to provide information on size and densities of populations (Marques et al. 2013, Frommolt and Tauchert 2014). In addition, continuous regular monitoring allows the elucidation of life-history patterns and phenology. Homogeneous, large-scale reliable data sets of insect phenology are practically non-existent, but baselines should be measured now, particularly in light of the possible changes in insect distributions due to global climate change (Parmesan et al. 1999).

Grasshoppers, bushcrickets and crickets are a species-rich group of acoustically communicating insects, and are already used as indicators of ecosystem health and biodiversity in environmental impact assessments in central Europe (Maas et al. 2002). Some studies already incorporate acoustic signal detection, but concentrate on species-specific signals (Riede 1993), particularly of red-listed species (Fischer et al. 1997). In spite of promising studies of automatic Orthopteran song classification (Dietrich et al. 2004; for grasshoppers: Chesmore and Ohya 2004), most assessments of entire Orthopteran communities still rely on expensive field campaigns, requiring collection of specimens and subsequent time-consuming species determination. Among the difficulties of implementing standardized automatic protocols for acoustic Orthoptera monitoring is the need for large, well-curated reference song libraries and the lack of user-friendly interfaces to train acoustic pattern recognisers.

Among the prerequisites for a fully machine-aided acoustical monitoring system is basic knowledge about the community of target species. Within the EU funded AmiBio project we gathered baseline data for Orthopteran diversity in space and time at the Hymettos (Greece) using traditional collecting methods (Jahn et al. 2011, 2012). While we used conventional methods of time consuming field surveys to get the data on the Orthopteran species diversity, we compiled baseline data

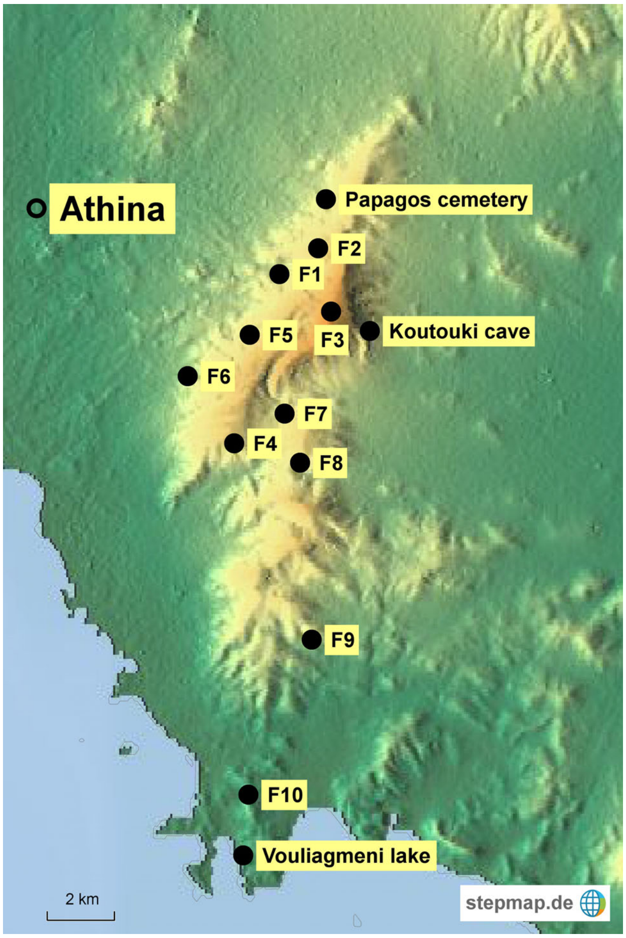


Fig. 1 Map of sampling sites at the Hymettos. Note the close proximity to the metropolis of Athens to the west. F1–F9: Sampling localities as described in Table 1, F10: ARU recording site for *Chorthippus bornhalmi*

to establish an efficient automatized acoustic monitoring system. A further goal of this study was to build-up a sound library for acoustic species identification and further use in automated species detection. Such well-curated sound libraries are not only necessary but crucial for algorithmic identification of species-specific songs (Towsey et al. 2012). We outline the methods and discuss the limitations for a fully automatic approach, giving details to allow other researchers to set up their own monitoring system.

Methods

The area

The Hymettos is a limestone mountain range located in Attica/East central Greece (Fig. 1a), to the east of the megacity Athens. The mountain range is 16 km in the north–south axis and six to seven kilometres from east to west. The Hymettos lies in the European Mediterranean zone, reaching 1,026 m a.s.l. at its highest peak Evzonas. The area has a typical semi-arid Mediterranean climate, with a strong seasonality of dry subtropical summers and warm to temperate winters depending on the altitude. The annual precipitation is only 365 mm, with rainfall mainly during winter, and occasional frost. Most of the Hymettos has rocky ground, and is deforested due to a long history of settlement. The naturally occurring Mediterranean Evergreen Woodland is replaced by planted coniferous forest in the north of the mountain range, formed by the native Aleppo Pine *Pinus halepensis* and the introduced Turkish Pine *Pinus brutia*. Several severe forest fires destroyed large areas of the coniferous pine forest, which are characterized nowadays by secondary replacement vegetation, the dense evergreen scrub communities called Maquis, and the degraded Phrygana, an open dwarf scrub community interspersed with annuals and heath plants (Arianoutsou-Faraggitaki and Diamantopoulos 1985). Other important habitats are calcareous rocky slopes with chasmophytic vegetation (see Classification of habitats: Council Directive 1992), open grasslands on degraded soils, other early successional plant communities and interspersed small limestone caves.

The entire mountain range is surrounded by urban areas, with housing developments built at its slopes. Due to its outstanding diversity in close proximity to the megacity of Athens, Hymettos Natura 2000 Site GR3000006 is essential for the improvement of the quality of life in the metropolis by allowing for the conservation of wild nature in its imminent vicinity (Georghiou et al. 1995). It is also an important central element within a network of a total of five neighbouring Natura 2000 sites. Because of its importance to conservation, the Hymettos is a protected area, managed by the local agency SPAY (www.spay.gr), especially to prevent forest fires.

Most natural history records from the Hymettos date back to the 1930s (Pulmedi and Valis 2006; Ikonomou-Amilli 2007). For Orthoptera in particular no newer published records exist in articles (Willemse and Willemse 2008) or in digitally available data repositories such as GBIF (2010). The data from the nearby landscape of Attica only became available after we started of our research project (Antonatos et al. 2014). To adapt the monitoring protocol we therefore assembled the potential species from published distribution of Orthoptera in Greece (Willemse 1984, 1985a; Willemse and Willemse 2008).

Sampling-methods and sampling sites

A search for Orthoptera from Greece within GBIF (2010) resulted in the small number of 1,433 records from 280 species, even so no records from the Hymettos were found. Therefore, we directly assessed the regional spatio-temporal composition of the Orthoptera species as a prerequisite for appropriate sound monitoring efforts. Whereas monitoring in the temperate zone of Europe is efficient in summer and autumn (Köhler 1998; Badenhauser et al. 2009), most Orthoptera in Greece have either a long adult season or an adult peak in spring to early summer. This holds especially for the majority of Ensifera (Lehmann and Lehmann unpubl. data, Antonatos et al. 2014). Therefore, the Orthopteran fauna (Ensifera—bushcrickets and crickets, Caelifera—grasshoppers) of the Hymettos was investigated by the first author (GL) between 24th and 30th of April 2010. During this period adults and nymphs were sampled. For subsequent song recording of adults, nymphs were reared to adulthood in the laboratory, see rearing protocols below. To add previously undetected species to the list, cursorial visits on the 11th to 18th of June 2010 and the 18th to 24th of November 2010 were conducted by the last author (KR). These visits were mainly for selection of potential permanent ARU sites (Jahn et al. 2011, 2012); hence only short inspections were possible.

Our Orthoptera monitoring at the Hymettos followed the principles outlined by Köhler (1998). However, no formal protocol is published for Orthoptera of the Mediterranean area, so to explore species richness we relied on our substantial knowledge of the Orthoptera of mainland Greece (Lehmann and Heller 1998; Lehmann and Lehmann 2000a, b, 2006, 2008a, b, 2009; Lehmann et al. 2001, 2010; McCartney et al. 2008, 2010).

Due to special authorization, we were able to inspect the Hymettos along gravel roads and tracks otherwise closed for public cars. This allowed exploration of the whole area between the main entrance in the west (close to Papagos Cemetery) and the Koutouki cave at the eastern slope, as well as the southern end in the vicinity of Vouliagmeni lake. We selected nine sampling sites for intensive probing in the Hymettos area on the basis of their expected value to Orthoptera (Fig. 1; Table 1; Fig. 2a–d). Due to the small body size of Orthoptera compared to the vocal vertebrate groups (especially birds) the songs are shifted towards higher frequencies. Physically, this restricts the travel distance of the sound waves by attenuation and filtering through the vegetation (Gerhard and Huber 2002). Therefore, sampling sites were chosen to represent a broad spectrum of microhabitats suitable for Orthoptera within one hectare, in order to maximize species richness detectable by single recording units. As a consequence the selected sampling sites had heterogeneous habitat and topographic structure and we concentrated on species richness and not abundance (Marini et al. 2010). Sampling was undertaken under sunny meteorological conditions during the period of highest Orthoptera activity between 10:00 and 17:00 at temperatures between 20 and 25° C.

Table 1 Habitat descriptions of the sample sites, including georeference data using the ETRS89 standard

Site	Habitat description
F1	Mosaic of scattered olive trees (*Oliva europaea*) and an understory of mesophilic grassland, at a height of 30–70 cm, interspersed with annual herbs and 100 % ground cover. Mediterranean bushes on a woody fringe surrounded the area. Coordinates: 37.962°N, 23.798°E
F2	A mixture of semi-open Phrygana with annual plants on a steep slope, covering 70 %. Rocks and bare ground, with small pine trees forming the remaining 30 %. Coordinates: 37.969°N, 23.811°E
F3	A mixture of Maquis and Phrygana vegetation. Small Oaks (*Quercus ilex*) and pine trees (*Pinus halepensis*) form dense bushes, interspersed with a diverse flora of perennial herbs. The bare ground is stony, ground cover 80 %. Coordinates: 37.952°N, 23.815°E
F4	Similar vegetation mixture of Maquis and Phrygana as in 3. Coordinates: 37.917°N, 23.783°E
F5	Valley with some solitary trees growing on the ground level. Wind protected habitat due to the surrounding limestone. The mixed mesophilic grassland is interspersed with annual herbs of a height of 30–70 cm, ground cover 90 %. Coordinates: 37.946°N, 23.788°E
F6	Big bushes of the Genus *Genista* scattered over the stony ground dispersed by annuals up to a height of 1 m. A lot of yellow flowering annuals, only a few small trees, ground cover 70 %. Coordinates: 37.935°N, 23.767°E
F7	Track along dry steep slopes, bare stony ground up to 80 %, some trees (*Quercus ilex, Pinus halepensis*) and bushy vegetation. Exposition to the south, habitat sunny and hot, annual herbs up to a height of 20 cm, ground cover 60 %. Coordinates: 37.925° N, 23.800° E
F8	Sloping area dominated by tall dry grass up to one meter between scattered stones, no trees, very dry early in season, ground cover up to 80 %. Coordinates: 37.912°N, 23.805°E
F9	Steep slopes dominated by small bushes up to 50 cm and some grass, scattered stones. Very dry, southward exposition, bare ground without trees. Cover of the ground 50 %. Small limestone cave. Coordinates: 37.865°N, 23.809°E

Before entering a sampling site, we detected singing species by ear and with the help of an ultrasound detector (D200, Petterson). Afterwards the observer (GL) searched directly for specimens, inspecting the area following wavy lines. Flushed Orthoptera were netted, and acoustically detected individuals were actively searched for. Special attention was given to explore specialized structures like dense bushes and cracks. Sweep netting was also performed to increase specimen numbers and the likelihood of detecting small and vegetation hidden species (Gardiner et al. 2005, Nagy et al. 2007; Schirmel et al. 2010). Survey duration was proportional to habitat area and diversity (Báldi and Kisbenedek 1999), lasting 2 h per hectare or

Fig. 2 Habitat aspects of the sample sites. (**a**) F2, (**b**) F3. (**c**) F6, (**d**) F9

stopped when no new species was found within 15 min (Nufio et al. 2009). In cooperation with the bat expert Ulrich Marckmann, it was also possible to investigate a few limestone caves, to search for cave crickets.

Collecting and identification

Specimens of bushcrickets and grasshoppers were observed and photographed in the field, and around 100 were collected for sound recording and to deposit voucher specimens. Identification of species was based largely on the fundamental keys by Harz (1969, 1975; Willemse (1985b). For taxonomic complex groups, reviews are available for a subgroup of the grasshopper genus *Chorthippus* (Willemse et al. 2009) and the bushcricket genus *Poecilimon* (Willemse 1982; Heller 1984; Willemse and Heller 1992), including the *P. propinquus*-group (Lehmann 1998; Lehmann et al. 2006). Furthermore, we used specimens collected during extensive field work in mainland Greece (Lehmann and Heller 1998; Lehmann and Lehmann 2000a, b, 2006, 2008a, b, 2009; Lehmann et al. 2001, 2010; McCartney et al. 2008, 2010) deposited in the collection of A.W. Lehmann (CL), as well as the collections of the Museum Alexander Koenig, Bonn (ZFMK) and the Museum of Natural History Berlin (ZMHB) as a reference. We adopted Fauna Europaea nomenclature, which is compiled and continuously updated in accordance with new results (Heller 2012).

Rearing

During the April survey period the adults of some species were evident, whilst others were still in their nymphal stage. Whereas determination keys for nymphal Orthoptera are available for central Europe (Oschmann 1969; Ingrisch 1977), data on Mediterranean Orthopteran nymphs are scarce. However, rearing of a substantial number of species over the past 20 years from field-collected nymphs or eggs enabled us to assign individuals to the nymphal stage and name the species in most cases, and if not at least to the genus or species group. Comparisons of the number of nymphal stages are available for Acrididae (Uvarov 1977) and for Orthopteran species reaching middle Europe (Ingrisch and Köhler 1998). In those cases where small nymphs did not allow unambiguous determination or song recordings were planned, individuals were reared to adulthood. Live nymphs were brought to Germany and kept in 200 or 500 ml jars depending on their body size and reared according to their feeding type. Herbivorous bushcrickets were fed with our standard food mixture of *Taraxacum* leaves and bee pollen from a health store (Lehmann and Lehmann 2008a). Omnivorous species got additional dry fish food (TetraMin®, Tetra Company) and in the case of seed-feeding species additional rye seeds (Lehmann 2007). Grass feeding Caelifera were fed with a mixture of garden-grown grasses.

Phenology

During our survey, a large number of species occurred as nymphs. Based on existing life-cycle data of European Orthoptera, we made an estimate on the phenology of adults in the area. Such phenology data will facilitate the selection of the appropriate time windows for automatic recordings at the Hymettos. The Orthoptera of the suborder Caelifera are quite uniform in their life-cycles; most have 4–5 nymphal stages before reaching adulthood (Uvarov 1977; Ingrisch and Köhler 1998). Under field conditions, every nymphal period lasts approximately 10 days. Bushcrickets (Ensifera) have a slightly higher number of nymphal stages, ranging normally from six to seven, which last on average approximately 7 days (Ingrisch 1977; Helfert 1980; Ingrisch and Köhler 1998). Orthopteran longevity is seldom reported, but in the laboratory individuals of both the bushcrickets (Helfert 1980) and the grasshoppers can live for more than 120 days (Thorens 1994; Köhler and Held 2000; Köhler 2012). Thus, we used a lifespan of 120 days in our phenology estimate.

Species associations

To choose appropriate localities for bioacoustic sampling, we evaluated several species diversity indices. We used species richness, similarity between localities in species composition using the Jaccard's index and species associations using the Agrell's index. The well-established Jaccard index uses presence-absence data for measuring the diversity in species occurrence between localities. Several indices exist for this purpose (Koleff et al. 2003) and there is ongoing debate about their correct usage (Jurasinski et al. 2009; Tuomisto 2010a, b; Jurasinski et al. 2012). Nonetheless, the Jaccard's index is the simplest and a very intuitive measurement of similarity for presence/absence data. To calculate which species occur commonly together, we used Agrell's index to assess typical species assemblages (Kratochwil and Schwabe 2001).

Sound recording and analysis

We searched online in existing depositories for sound recordings of species expected to occur at the Hymettos to build up a reference sound library. With 541 recordings, the SYSTAX multimedia database (http://www.biologie.uni-ulm.de/systax/index.html) is by far the richest source. Most of the songs were recorded both during extensive field-work and in the laboratory by Klaus-Gerhard Heller, with complementary data available in his ground-breaking book on European bushcricket sound communication (Heller 1988). Recordings were digitized and databased within the DORSA virtual digital museum project (Ingrisch et al. 2004; Lampe et al. 2005). We completed the existing sound archive with recordings made from captive individuals collected during our monitoring of the Hymettos. We recorded sounds from field-collected adults and from nymphs as soon as they moulted into adulthood. Sound recordings were performed in an anechoic chamber under laboratory conditions at the Museum of Natural History, Berlin by KF. Animals were placed in small mesh gauze cages, where they could freely move. In the case of nocturnal species the light was switched off after a short light period, to stimulate singing activity. The temperature during the recording was documented with data loggers. All sound recordings were made with a FOSTEX FR2-LE compact flash recorder at a sampling rate of 96 kHz with 24 bit data depth using cardioid Sennheiser MKH40 P48 condenser microphones. The microphones were at a distance of 20 and 40 cm from the singing individuals. All sounds described here are stored at the Animal Sound Archive (Frommolt et al. 2006) of the Museum of Natural History, Berlin. Sound analysis was carried out with RavenPro 1.4 (Cornell Lab of Ornithology).

Field sound recording by automated recording units

Song Meter SM-2 units equipped with two SMX-II electret microphones (Wildlife Acoustics, Inc., Maynard, USA) were used as autonomous acoustic recording units (ARUs) to collect baseline data beginning in May 2010. Units were tested at our collection sites and subsequently installed permanently at four selected sites until the end of the AmiBio-project in April 2013 (for details see www.amibio-project.eu). Although the Hymettos is a rather remote area with car access limited to authorities, we chose hidden spots to place the ARUs to minimize the likelihood of destruction or theft of the recorders. Units were programmed to record for 5 min, 2 times per hour, in stereo-mode at a sampling rate of 48 kHz and 16-bit resolution. The recordings covered a frequency range from 100 Hz to 24 kHz. Files were stored on 4 exchangeable 32 GB SD-cards. ARUs were powered by four 1.5 V monocell batteries, which worked for about 1 month autonomously, after which SD-cards and batteries had to be replaced. Adobe Audition was used for quick screening of sound files, and subsequent generation of shorter sound files, containing the signal of the target species, called snippets. The grasshopper song displayed in Fig. 7 was recorded by placing an ARU on the ground, in the middle of a

Table 2 Orthoptera distribution at the Hymettos sample sites F1–F9 in April 2010, see Table 1 for habitat specifications and Fig. 1 for locality

Species	Suborder E = Ensifera C = Caeliefera	Sample site									Sites per species
		F5	F9	F4	F6	F2	F7	F8	F3	F1	
Platycleis albopunctata grisea	**E**	**N 3–4**	**N 6**	**N 1**	**N**	**N 4**		**N 5–6**	**N 3**		7
Chorthippus bornhalmi	**C**	**N 3**	**ad**	**N 1**	**ad**	**ad**	**ad**	**ad**			7
Chorthippus vagans dissimilis	**C**	**N 1**	**N 4**	**N 1**	**N 3**	**N 1**	**N 3**				6
Acrometopa s. servillea	E	**N 3**		**N 3**	**N 3**					**N 2–4**	4
Celes variabilis	C	N 2	N 2	N 1	N 2						4
Calliptamus barbarus	**C**		N 3	N 2	N 2						3
Tettigonia viridissima	E	**N 3**	**N 3**								2
Pyrgomorpha conica	C		ad				ad				2
Dociostaurus maroccanus	**C**		N 3	N 1							2
Poecilimon propinquus	**E**	**ad**									1
Decticus albifrons	**E**	**N 1–3**									1
Drymadusa d. dorsalis	E	**N 4**									1
Anacridium aegyptium	**C**	ad									1
Rhacocleis werneri	E				**N 3**						1
Glyphanus obtusus	C		N 3								1
Pezotettix giornae	C					N1					1
Dolichopoda petrochilosi	E		ad: cave living								1
Number of species		10	(10) 9	7	7	4	3	2	1	1	

Records per species is the sum of sample sites at which each species was found. Species are sorted in descending order according to their recording frequency; sample sites are sorted from left to right along their species richness. Species using long-range acoustic communication are marked in bold

Suborder: *E* = Ensifera, *C* = Caelifera. *ad* = adults, *N* = nymphs, stadium 1–5 in Caelifera and 1–7 in Ensifera

population of *Ch. bornhalmi,* detected during an inspection in November 2010. Air temperature was recorded by an on-board sensor of the Song Meter SM-2, additional temperature recordings were made by a thermometer (Casio Thermosensor AQW-101) placed next to the recorder. However, sun radiation affects body temperature, which can differ considerably from air temperature, even on partially sunny days.

Results

During our biodiversity inventory we were able to assess the distribution of the Orthopteran species at the Hymettos. We found 20 Orthopteran species on the Hymettos, representing both suborders Ensifera (bushcrickets and crickets) and Caelifera (grasshoppers). Seventeen species were found during our monitoring in April (Table 2), a further three species (*Oecanthus pellucens*, *Oedipoda germanica*, *Sphingonotus rubescens*) were added during a June excursion. The resulting number of 20 species represents seven percent of the total Orthoptera fauna of Greece. Based on the available data of the Athens area, we estimated a maximum number of 65 Orthoptera species to occur in the area. However, the Hymettos is a calcareous, mountainous region with a limited habitat composition. The area is dominated by dry forests, which are mostly free of Orthoptera, and an assemblage of dry grass- and bushland. This excludes all species which are associated with water courses, swamps, moist biotopes or broad-leaved forest. Because of the relative uniformity of the available habitat mixtures in the area (Table 1), we consider the species list to be quite complete (Table 3).

According to the available data, we observed clear phenological differences between the Orthopteran species at the Hymettos (Table 2). While a quarter of the species occurred as adults, the majority of the summer species were found as nymphs in April. Five species were found as adults in April, including the winter specialist *Anacridium aegyptium*, which produces a rattling sound during flight, but not during normal activities. Another species occurring as an adult early in the year is the spring-early summer species *Pyrgomorpha conica*, which also produces no sound for communication. The eastern Greek endemic cricket *Dolichopoda petrochilosi* is also a non-calling species, restricted to caves. The two other species found as adults are of substantial interest. One is the bushcricket *Poecilimon propinquus,* which has a short adult season from April to May. This species is endemic to a small part of Eastern Greece and might be useful as a indicator

Table 3 Estimated adult season of 19 Orthopteran species found at Hymettos

Species / Month	J	F	M	A	M	J	J	A	S	O	N	D
Anacridium aegyptium	x	x	x	x					x	x	x	x
Chorthippus bornhalmi				x	x	x	x	x	x	x	x	
Pyrgomorpha conica				x	x	x						
Poecilimon propinquus				x	x							
Platycleis a. grisea					x	x	x	x	x			
Acrometopa s. servillea						x	x	x	x			
Drymadusa dorsalis						x	x	x				
Glyphanus obtusus						x	x	x				
Calliptamus barbarus						x	x	x	x			
Chorthippus vagans dissimilis						x	x	x	x			
Tettigonia viridissima						x	x	x	x			
Rhacocleis werneri						x	x	x	x			
Decticus albifrons						x	x	x	x			
Oecanthus pellucens*						x	x	x	x			
Dociostaurus maroccanus						x	x	x	x			
Celes variabilis						x	x	x	x			
*Oedipoda germanica**						x	x	x	x			
*Sphingonotus rubescens**						x	x	x	x			
Pezotettix giornae							x	x	x			

Species using long-range acoustic communication are marked in bold, and their phenology shaded grey. The three species marked with an asterisk (*) were found as adults in summer; their adult season was estimated based on data from other parts of Greece (Lehmann and Lehmann, unpubl. data). Species sorted by their adult phenology. The cave living *Dolichopoda petrochilosi* is excluded from this table, due to its unique habitat requirements

species for intact habitats. The last is the common grasshopper *Chorthippus bornhalmi,* which produces several generations throughout the year, making it the species with the longest adult occurrence, from April to autumn. A population with stridulating males was even found in November (see Fig. 7).

Based on the captures of nymphs in the field we were able to estimate the resulting adult season of the Orthopteran species throughout the year (Table 3). The majority of species showed a clear summer phenology, with adults occurring from June through September.

Species richness varied from just one (localities F1 and F3) up to 10 (localities F9 and F5). Localities hosting seven to ten Orthopteran species (Table 2) are characterized by a diverse vegetation of perannual herbs and bushes (Table 1). While Caelifera in the region are predominantly ground- (terricol) or grass-living (graminicol) and graminivorous, the Ensifera include both ground inhabiting (terri-graminicol) and bush dwelling (arbusticol) species with feeding types from herbivorous to carnivorous.

The six most common Orthopteran species at the Hymettos occur frequently together (Table 4). Five of them are terri-graminicol species, out of which three communicate acoustically (*Ch. bornhalmi, Ch. v. dissimilis and P. a. grisea*). These three species might form the main song chorus at the Hymettos. The only arboricolous species to be regularly detected is *A. s. servillea*, which occurs frequently in the same habitats, but on bushes or long-stemmed plants. However, four singing species, all of them bushcrickets, were found only once. They might be preferred targets for bioacoustic monitoring at the Hymettos.

Species composition was quite similar for the species-rich habitats. Using presence-absence data, diversity in species occurrence between localities was above 50 percent for F4 to F6 and F9 (Fig. 3).

Sound recording and analysis

As a result of online assessment, hundreds of song recordings of the 20 Orthoptera species found at the Hymettos are stored in our reference sound library integrated into the SYSTAX multimedia database (www.biologie.uni-ulm.de/systax/index.html). We completed our archive with recordings from captive individuals, collected at the Hymettos. Twelve selected recordings from three species are accessible at the Animal Sound Archive (www.animalsoundarchive.org) by searching the database for "amibio" as filename or for "Hymettos" as Scenic area using the Advanced Search method.

During our monitoring, which included human listening, made more efficient by using an ultrasound detector, the grasshopper *Ch. bornhalmi* and the bushcricket *P. propinquus* were also detected by their sounds. Based on our study, detectable songs are produced by all Ensifera species of the region (excluding the silent cave cricket *D. petrochilosi)*, but only 22 percent of the Caelifera produce sound loud enough for human and ultrasound-detector-aided detection in the field (Table 3). Acoustic parameters of the calling songs allowed for the acoustic delimitation of species. One distinguishing feature between Orthopteran songs is their frequency range, which clearly separates the species (Table 5). Three out of seven bushcrickets (Ensifera–Tettigoniidae) sing in the ultrasound not detectable by the human ear. This explains why using an ultrasound detector was a meaningful addition to the monitoring protocol. The only cricket (Ensifera–Gryllidae) found at the Hymettos, the bell cricket *O. pellucens*, sings very loudly in the sonic range (Table 5), whereas the two Caeliferan species *Chorthippus bornhalmi and Ch. vagans* have their greatest sound energy in the sonic range as well, but with reduced loudness.

To illustrate these typical differences, we provide data on the widespread *Ch. bornhalmi* and *P. propinquus*. The grasshopper *Ch. bornhalmi* sings in an up and down waving manner using its hind legs, producing long verses of 4–5 s duration. The two-leg system further allows

Table 4 Co-occurrence of the Orthopteran species at Hymettos, indicated by Agrell's index

Species	Cv	Pa	Cv	As	Cb	Tv	Dm	Pc	Pp	Da	Dd	Aa	Go	Rw	Pg
Ch. bornhalmi	6	6	4	3	3	2	2	2	1	1	1	1	1	1	1
Ch. v. dissimilis		5	4	3	3	2	2	2	1	1	1	1	1	1	1
P. a. grisea			4	3	3	2	2	1	1	1	1	1	1	1	1
C. variabilis				3	3	2	2	1	1	1	1	1	1	1	
A. s. servillea					2	1	1		1	1	1	1		1	
C. barbarus						1	2	1					1	1	
T. viridissima							1	1	1	1	1	1	1		
D. maroccanus								1					1		
P. conica													1		
P. propinquus										1	1	1			
D. albifrons											1	1			
D. d. dorsalis												1			
A. aegyptium															
G. obtusus															
Rh. werneri															
P. giornae															

Black markings: co-occurrence at 5 or 6 sites out of 9, dark grey: 4, light grey 3 co-inhabited sites. Species using long-range acoustic communication are marked in bold

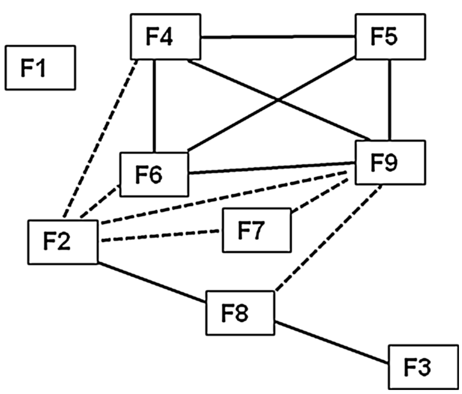


Fig. 3 Similarity in Orthopteran species composition between sample sites using Jaccard's index. *Black lines* species identity 40–50 %, *dotted lines* species identity 30–40 %. *No lines* species identity <30 %. The four habitats F4–F6 and F9 had a high degree of species identity. Monitoring acoustic activity at sites F5 and F6 would cover all identified calling Orthopteran species at the Hymettos simultaneously. The high similarity in species composition at sites F2-3 and F8 is based on a restricted species number of the most common species at the Hymettos, compare Table 2

for complex rhythmic patterns, because the legs can be used independently on the opposite sides of the body. Males of *Ch. bornhalmi* produce songs with rising sound amplitude levels over time, along with a ramp-shaped increase of the frequency range over the first second of the verse. The sound energy is radiated in the frequencies between 5 and 30 kHz, with most energy in the sonic range (Fig. 4).

In contrast, male bushcrickets *Poecilimon propinquus* produce songs by a single closing movement of the wings. The resulting verses are short, lasting 60–140 ms in length.

Table 5 Main song frequency of the Ensifera species at Hymettos

Genus	Species	Song frequency [kHz]	Source
Acrometopa	*s. servillea*	7–18	Heller (1988)
Poecilimon	***propinquus***	**15–30**	This article, Fig. 5
Tettigonia	*viridissima*	12	Heller (1988)
Decticus	*albifrons*	10	Heller (1988)
Platycleis	***a. grisea***	**20–30**	Heller (1988)
Drymadusa	*d. dorsalis*	7	Heller (1988)
Rhacocleis	***werneri***	**25–90**	Heller (1988)
Oecanthus	*pellucens*	2.5–3.5	Roesti and Keist (2009)

Species with their song spectrum in the ultrasound -above 20 kHz—are marked in bold

They are regularly repeated to form long-lasting series of up to 109 syllables per minute. Compared to the grasshopper song, there is little modulation in either amplitude or in the frequency domain. The frequency ranges between 16 and 35 kHz, and most energy lies in the ultrasonic range (Fig. 5). These two species thus depict the many differences which allow most Caelifera songs to be distinguished from those of Ensifera. The most important differences are the more complex rhythms in Caelifera and the very regular repetition of song elements in Ensifera.

Whereas Caelifera sing exclusively during the day, the bushcricket *P. propinquus* is vocal strictly during the night, with an onset of singing twenty minutes after darkness. The acoustic activity increases steadily over the next 70 min and reaches a steady plateau after that time (Fig. 6). Thus chronological activity patterns can be used to distinguish between night-active species, as *P. propinquus*, and day-active singers like *Ch. bornhalmi*.

Field sound recording by automated recording units

Preliminary analyses of sound recordings made with automatic recording units in the Hymettos area indicate that Orthopteran species could be recognized by acoustic parameters (Fig. 7): despite the high anthropogenic noise level in the sonic range up to 4 kHz, songs of *Chorthippus bornhalmi* could be detected easily, due to the typical acridid broad frequency range between 6 and 20 kHz. The respective sections could be isolated as "snippets" of 15 s length. Further analysis of the fine temporal structure of such isolated snippets allowed unambiguous determination of *Ch. bornhalmi* songs, based on species-specific song parameters such as verse length, echeme length and rhythm (Fig. 4, 7 respectively).

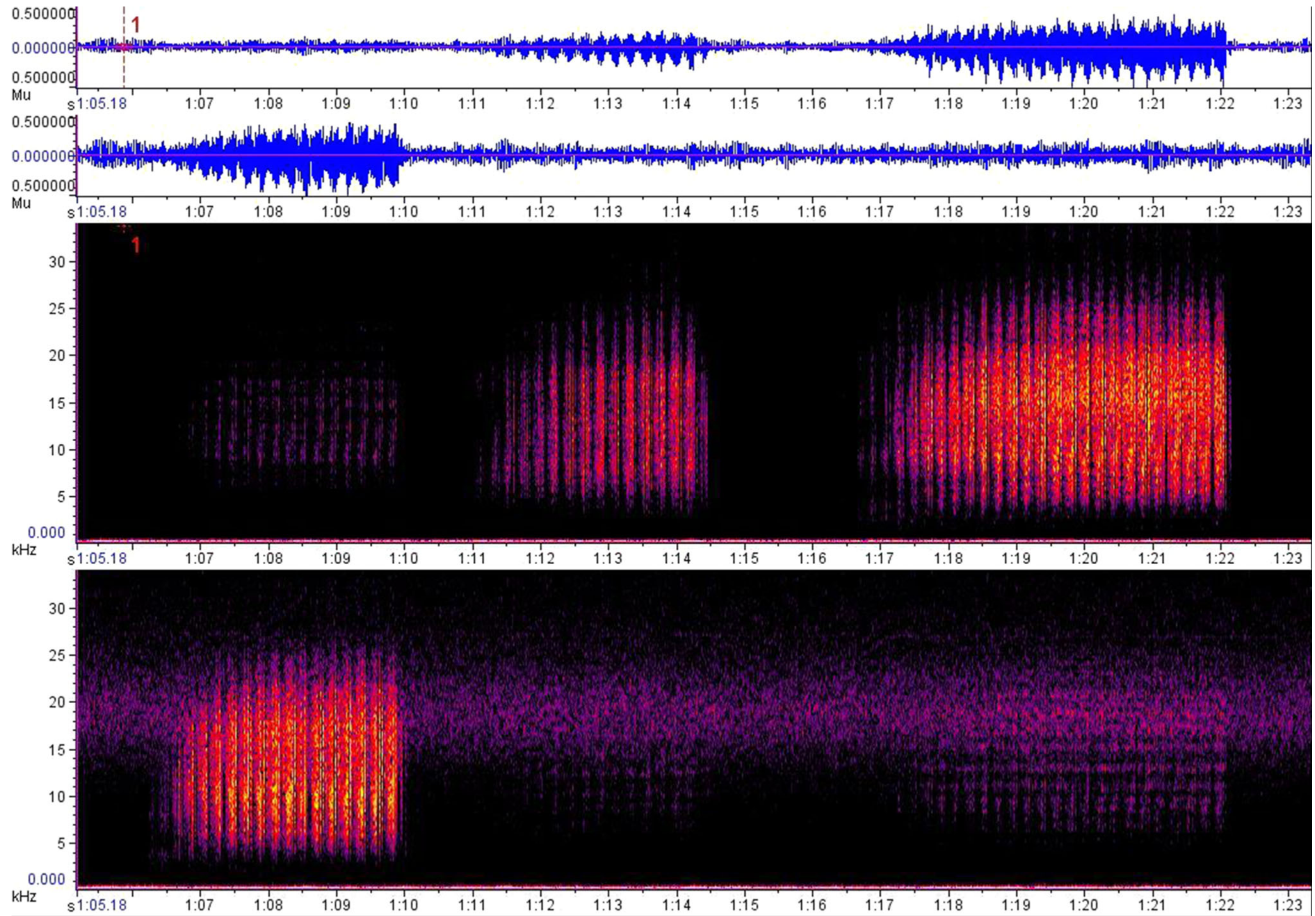


Fig. 4 Waveform (*upper part*) and spectrogram (*lower part*) of two male *Chorthippus bornhalmi* recorded in an anechoic chamber. The two tracks represent the songs of the two males, who are alternating their songs as part of acoustic competition. On the first channel two songs of one animal are clearly visible. The song of the other animal can be clearly seen at the second channel (Recording archived as Chorthippus_bornhalmi_Amibio0001_03.wav)

Discussion

In comparison to Europe as a whole, Greece is an Orthopteran species-rich area, where new species are still being described. Currently, 285 species and subspecies of Orthoptera are reported for the Greek mainland (Willemse and Willemse 2008; Heller 2012). This provides a hither-to unexplored opportunity for integration of Orthoptera into monitoring schemes. A search for Orthoptera from Greece within GBIF (2010) resulted in 1433 records from 280 species. This record number is very small compared to Orthoptera mapping schemes in Middle Europe, which are based on 100.000 records for areas of comparable size (e.g. Detzel 1998; Schlumpfrecht and Waeber 2003). In addition, the GBIF data from Greece are provided by only five institutions, all situated outside the country. Among the main data providers are institutions already participating in the AmiBio project (Jahn et al. 2011, 2012), such as ZFMK's Orthopteran collection, SYSTAX, including ZFMK's sound collection of the DORSA project (Lampe et al. 2005), and the Animal Sound Archive (Frommolt et al. 2006). It is not surprising that Orthopteran diversity at the Hymettos is much smaller than the total diversity in Greece, as it covers less than one percent of the country's territory. Mountain ranges in Greece harbour specific sets of endemic species (Willemse 1984). From over 40 species of the genus *Poecilimon* in Greece (Willemse and Heller 1992; Willemse and Willemse 2008), only one to three species regularly occur together; a maximum of five species was found topotopically in meadows of the Vernon Mountains southwest of Florina (Lehmann 1998). Our premonitoring database, using distribution data from the Hymettos–Athens area (Willemse 1984, Willemse 1985a, b; Willemse and Willemse 2008), estimated a maximum number of 65 species to occur in this region of Greece. However this was not corrected for the limited habitats available at the Hymettos. This calcareous, mountainous area is dominated by dry pine forests, mostly free of Orthopterans, and an assemblage of dry grass- and bushland. This excludes all species which are associated with

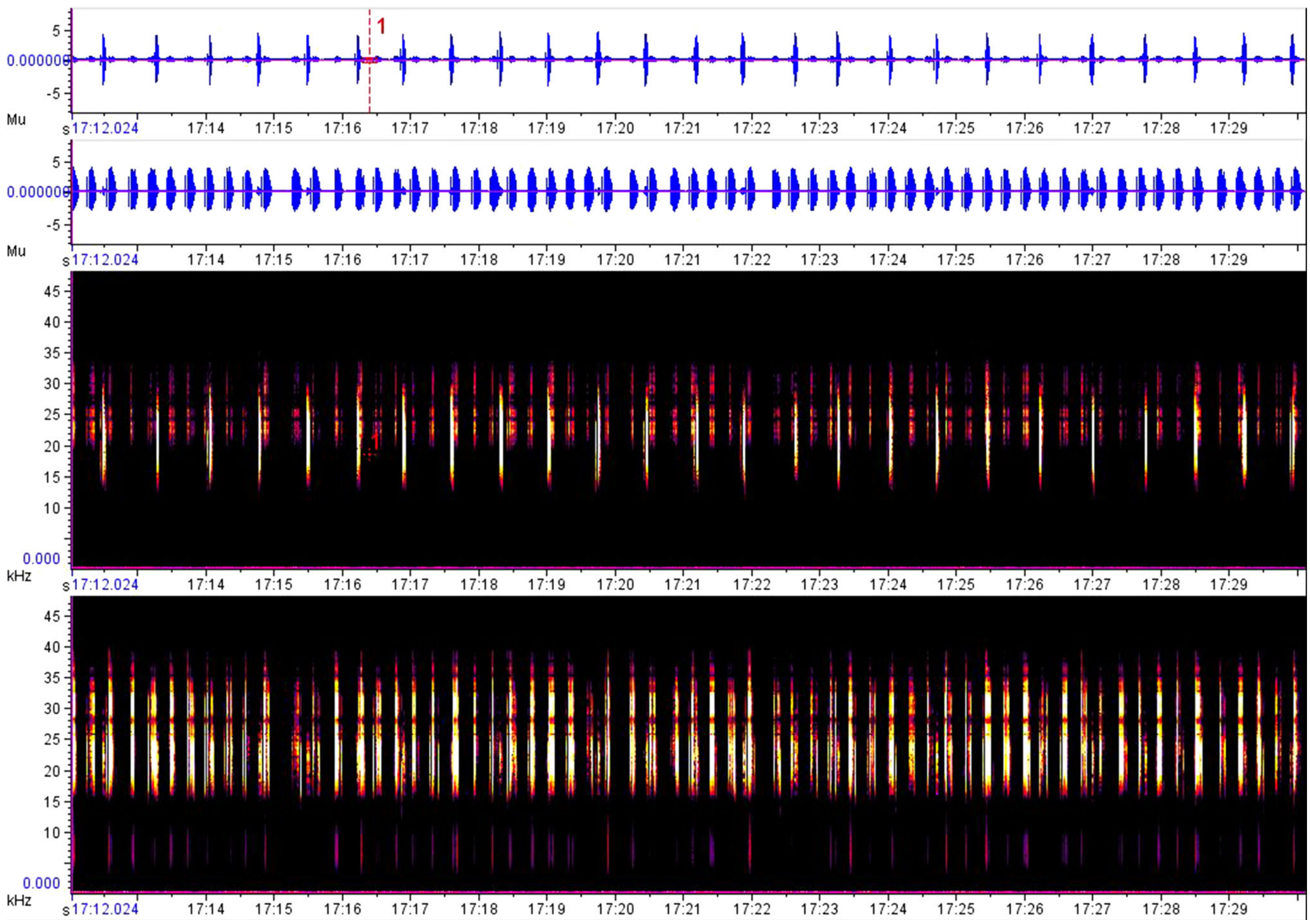
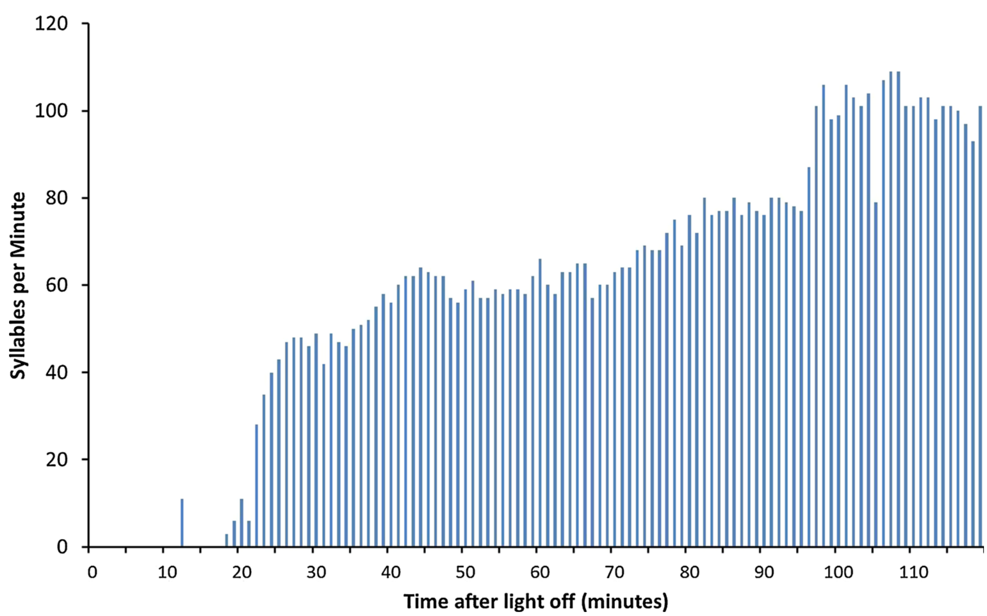


Fig. 5 Waveform and spectrogram of the songs of two male *Poecilimon propinquus* recorded in an anechoic chamber. The two tracks represent the songs of two different males (Recording archived as 481 Poecilimon_propinquus_Amibio0001_05.wav)

Fig. 6 Vocal activity of a single *P. propinquus* male, recorded in an anechoic chamber after switching off the light



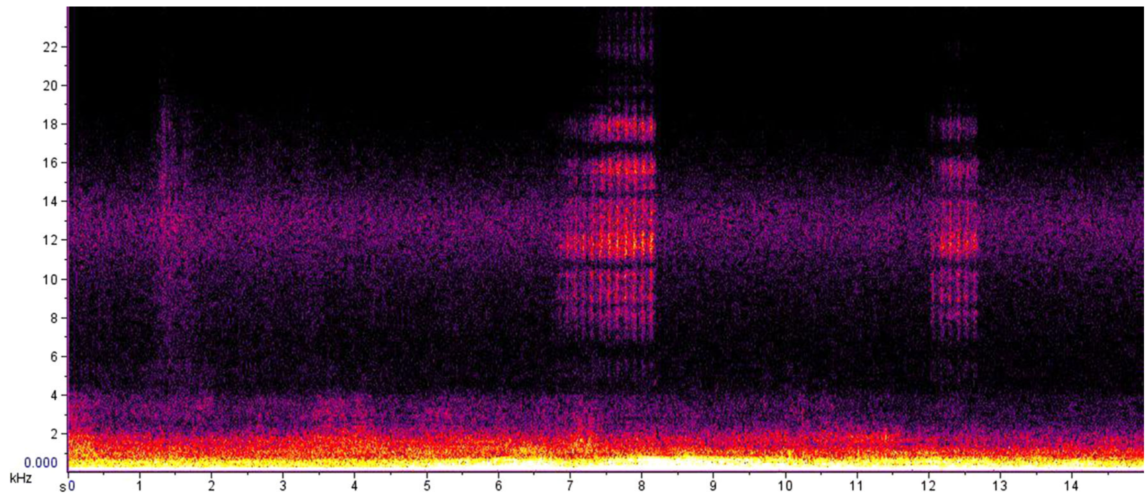


Fig. 7 Spectrogram of two loud and a third faint song of *Chorthippus bornhalmi* recorded with an Automatic Recording Unit (ARU) in the southern Hymettos area near Vouliagmeni (November 2010, air temperature 14 °C)

water courses, swamps, moist biotopes or broad-leaved forest. Thus our inventory resulted in a total of 20 Orthopteran species, a figure very similar to the 19 and 22 species found at lowlands and a mountain range of the same region (Antonatos et al. 2014). Nonetheless the species list only partly overlaps due to different habitats in the areas, and there is still a chance of discovering additional taxa of sound-producing Orthoptera, once the AmiBio monitoring stations are installed and working continuously.

Species richness was unevenly distributed over the localities sampled; with higher species numbers found in habitats with a diversity of perennial herbs and bushes. Nonetheless, the ground-living terri-graminicol species *Chorthippus bornhalmi* and *Platycleis a. grisea* were the dominating species in the area. They were still recorded in degraded habitats and shared the greatest number of localities, resulting in a high Agrell's index for species co-occurrence. In contrast, many Ensifera species were rarely found, restricted to single sites, making them prime candidates for habitat differentiation. This applies especially for the short-winged and therefore dispersal-restricted bushcricket *Poecilimon propinquus*. This species is of special interest for the region, as the Hymettos is the type locality (Brunner von Wattenwyl 1878) and it is an endemic of north-eastern Peloponnese and the province Attica (Willemse and Heller 1992; Lehmann 1998; Willemse and Willemse 2008). Within its limited range, the species seems to be under constant threat from intensifying agricultural land use (Lehmann 1998; Lehmann and Lehmann unpubl. data). A second interesting species is the bushcricket *Rhacocleis werneri*, which was previously restricted to the large islands Euboea, and only recently found on the Greek mainland in the east of the peninsula Attica (Willemse and Willemse 2008; Antonatos et al. 2014). Its occurrence at Hymettos marks a considerable extension of the former known range. Despite the strong taxonomic basis of Orthopteran research in Greece (Willemse 1984, 1985a, b; Willemse and Willemse 2008; Willemse et al. 2009), data on habitat preferences of Greek Orthoptera are seldom reported (Szijj 1992) and based, for most species, on our own expert knowledge. There has been progress in recent years to evaluate the conservation needs of Orthoptera in Greece; however, these have been restricted to northern parts of the country like the Dadia reserve (Kati and Willemse 2001; Kati et al. 2003); the Grammos mountains (Zografou et al. 2009) and wetlands in Epirus (Kati et al. 2006, 2012). Further data needs to be compiled to provide concrete habitat management recommendations. Considering that AmiBio's monitoring stations will generate large data sets on the presence and activity patterns of Orthoptera, the AmiBio project will further our knowledge on the population dynamics and ecological requirements of this sound-emitting insects in Greece.

A further goal of this study was to build up a sound library for acoustic species identification and further use in automated species detection. As a result of online assessment and additional recording by our team, hundreds of song recordings of the 20 Orthopteran species found at the Hymettos are stored in our reference sound library. We have integrated this library into the SYSTAX multimedia database (http://www.biologie.uni-ulm.de/systax/index.html). Most of the songs were recorded both during extensive field-work and in the laboratory by Klaus-Gerhard Heller, with complementary data available in his ground-breaking book on European bushcricket sound communication (Heller 1988). Hosting of this unique sound source within SYSTAX was partly supported by the DORSA virtual digital museum (Ingrisch et al. 2004; Lampe et al. 2005). We were able to complete our sound archive with recordings made from captive individuals under controlled conditions collected at the Hymettos. The first recordings are made accessible to the public through the Animal Sound Archive (Frommolt et al. 2006). Such a sound base is not only necessary but crucial for any automated sound detection (Towsey et al. 2012).

However, what kind of baseline data and requirements can be recommended to other researchers wishing to set up an automatic acoustic monitoring for Orthoptera? Generally, any acoustic inventories must be adapted for the particular animal group (overview in Obrist et al. 2010). No standard protocol for bioacoustic monitoring exists (Riede 1998), even if some requirements for insects are summarized by Brandes (2005). Based on our results we will discuss a variety of obstacles and pitfalls for automatic recording units (ARUs).

From our baseline results it is especially clear that choosing the appropriate sample site for your question is important. By concentrating on species richness and neglecting population density, we identified localities with the potential to monitor all acoustically communicating Orthopteran species simultaneously at Hymettos (Table 2; Fig. 3). We found those habitats rich in herbaceous plants, which we therefore recommend as important for monitoring in the area, especially the sites F5 and F6. However, recordings of multi-insect communities might be a challenge for the detection software; therefore differences in temporal acoustic activity might be important. In regard to acoustic signalling of Orthoptera there are great differences in their seasonal representation. There is high phenological concordance of species at the Hymettos, allowing the recording of eight loud acoustically communicating Orthoptera simultaneously in a broad time-window during summer (Table 3). However, the spring species *P. propinquus* requires recording during its 5 week adult season in April–May, during which period very few other Orthoptera are acoustically active at the Hymettos, although the widespread grasshopper *Ch. bornhalmi* with its very broad adult season is a noteworthy exception (Antonatos (Antonatos et al. 2014). Furthermore, daily song activity was identified as useful for species differentiation. Whereas the majority of species call during the day, the bushcricket *Poecilimon propinquus* showed a strict nocturnal singing activity, starting after dark and increasing over the next hour (Fig. 6). This will allow temporal segregation when analysing multiple species recordings.

A limitation for ARUs to record Orthopteran sounds is the limited travel distance of the sound waves produced by such small insects (Römer 1993). It might therefore be necessary to use several microphones for each data logger to ensure recordings are made at different vegetation heights. Most bushcricket species sang from bushes and the top of herb plants, whereas grasshoppers principally sang on the ground and in grassy microhabitats. A second problem can be circumvented by using several microphones at the same ARU: if a singing specimen is sitting right in front of a microphone, no other sound can be recorded. Such a scenario is most likely in very dense populations of certain species.

Sounds produced by animals exhibit clear hierarchical features (Catchpole and Slater 1995). Whereas bird songs can be very complex and variable, calls of frogs and insects have basic features of reduced or absent variation (Towsey et al. 2012). Orthoptera are no exception; the species-specific and stereotyped calling (Gerhardt and Huber 2002) provides very reliable characters for species identification (e.g. Heller 1988; Ragge and Reynolds 1998; Roesti and Keist 2009). There is a unifying terminology for Orthopteran song features, which describes the hierarchically structured songs (Heller 1988; Ragge and Reynolds 1998; Gerhardt and Huber 2002). The newly recorded songs from the Hymettos clearly show the basic Orthopteran song types. One feature being the spectral characteristics of sounds, with the songs of grasshoppers characterized by frequencies mainly in the sonic range (Fig. 4) and complex temporal patterns due to varying intensities (Fig. 4). In contrast, several bushcrickets have peak frequencies in the ultrasound with most sound energy radiated above 20 kHz (Table 5). The endemic *Poecilimon propinquus* represents a bushcricket species with such a song exclusively in the ultrasound and a constant pulse repetition rate (Fig. 5). This represents a potential technical challenge for most automated monitoring devices. Even if commercial ultrasonic recorders on the market are able to cover this high frequency range as well, the sampling rate has to be higher, increasing the resources needed to store and analyse the data. In addition, ultrasound is readily absorbed by a moist (high humidity) atmosphere and plant material, further limiting the detection range (Römer 1993). Therefore, the microphone sensor network has to be an order of magnitude denser than for monitoring birds.

Combining several of the above mentioned song characteristics might allow for automatic song detection (Riede 1998) with automated feature extraction (Riede et al. 2006). Acoustic pattern recognition has become an important tool in bioacoustic research especially in the context of bioacoustic monitoring for nature conservation (Fristrup and Mennit 2012). The aim of bioacoustic monitoring is to estimate species composition and distribution (Marques et al. 2013) on the basis of long-term acoustic recordings. A significant advantage of long term acoustic recordings is that, with relatively little effort, the complete spectrum of species can be detected at a particular location. Recording devices have only to be brought into the field at the beginning of the reproductive period and could be collected at the end of the season. Although automated acoustic monitoring has been deployed successfully for bats (Meyer et al. 2010), whales (Zimmer 2011) and birds (Frommolt et al. 2012), it is still in development for most other animal groups (Frommolt et al. 2008). The AmiBio project deployed a prototype hardware system in the field that gathered and transmitted recordings to a central station, which is composed of a receiver, decoder and a computer. To evaluate such large acoustic data sets effectively a wide range of pattern recognition algorithms based on spectrogram template matching, acoustic feature extraction or Hidden Markov Models have been developed (Bardeli et al. 2010; Boucher et al. 2012a; Leqing and Zhen 2010; Towsey et al. 2012; Potamitis et al. 2014). Some focal species can be detected with an accuracy of 95 % or better, even in sound recordings contaminated with strong background noise (Bardeli et al. 2010; Boucher et al. 2012a), and some progress has been made in multispecies sorting by spectral features (Potamitis 2014). However, expert knowledge is still needed to validate the acoustic identification (Towsey et al. 2012) and previous research has also proven that high quality recordings are needed as a reference (Boucher et al. 2012b). For insects pattern recognition algorithms were applied for clean recordings with low background sounds (Riede et al. 2006). Four species of British grasshoppers could be successfully detected in long-term acoustic recordings even in the presence of background noise (Chesmore and Ohya 2004). Apart from these promising approaches, present detection software still needs many sound recordings for training and can only be used by experts, hindering its broader implementation at the moment.

By inspecting our first available recordings from the prototype field stations both visually and acoustically, we were able to recognize Orthopteran sounds. This method was labour-intensive, but was successful as an initial step, as illustrated by the most common species at the Hymettos, the grasshopper *Chorthippus bornhalmi* (Fig. 7). Up to now we do not have an acoustic recognition system that would allow determining species composition in natural habitats by vocalizations with reliable accuracy. Nonetheless our pilot study at the Hymettos is a promising starting point, which shows that the first steps have been reached for assessing the Orthopteran species contribution and establishing a sound library of high quality recordings. Acoustic recording stations now exist at the Hymettos and at an increasing number of other monitoring sites. The next step is the development of software for automated song identification at the species level. We have to note that in addition to the development of effective pattern recognition algorithms, there is a need for experimental studies to explore the potential of acoustic recordings for population density estimates.

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