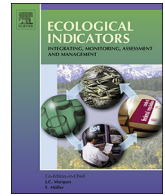


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# Ecological Indicators

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## Ecological indices in long-term acoustic bat surveys for assessing and monitoring bats' responses to climatic and land-cover changes



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### ABSTRACT

Bats are well known for playing an important role in several ecosystem services such as arthropod population control, insect pest suppression in agricultural systems and vector disease control, but also for acting as ecological indicators. Their population dynamics are strongly linked to environmental variations and, in some cases, reflect the health status of ecosystems. Hence, some species have an excellent potential as ecological indicators due to their sensitivity to ecosystem changes. Despite the general decrease of many bat populations worldwide and the recent upsurge in the use of autonomous acoustic detectors, the acoustic monitoring of bat assemblages is still an emerging field in bat research and conservation. Probably due to a general lack of methodological standards and the lack of common ecological indices, few long-term bat acoustic monitoring programs are currently active and data is rarely shared and compared between regions. In this study we propose and adapt a set of different ecological indices that can be used in acoustic surveys designed to detect changes in bat diversity, activity and assemblage composition, all of which can be linked to species' climatic and habitat-related preferences. Using a dataset collected during three years of bat monitoring in Catalonia (NE Iberian Peninsula), we used three traditional indices (richness, activity and Shannon diversity) and developed four new ecological indices (Community Thermal Index, Community Precipitation Index, Community Openness Index and Community Specialization Index) that enabled us to study bat communities and compare them at different spatial and temporal scales. Here, we demonstrate the applicability of these indices in bat monitoring programs. We also provide a consistent tool for generating easy-to-interpret ecological indices when monitoring the short- and long-term responses of bats under the current scenario of global change. Using standardized protocols and robust ecological indices enables studies and datasets to be compared, which in turn promotes the development of proper management and conservation measures via international cooperation.

### 1. Introduction

Bat populations have undergone a serious decline since the second half of the twentieth century (Adams, 2010; Ingersoll et al., 2013; Jones et al., 2009; Kunz and Pierson, 1994; Stebbings, 1988). Some of the major threats affecting these mammals are habitat loss and fragmentation, agricultural intensification, pollution, direct prosecution provoked by myths, legends and superstitions, and global climate change, all of which are factors induced by human activity (Adams, 2010; Blehert et al., 2009; Frick et al., 2019; Ibáñez, 1997; Kalcounis-Rüppell et al., 2007; López-Baucells et al., 2018; Newson et al., 2009; Sherwin et al., 2013; Wickramasinghe et al., 2003; Wiles et al., 2010).

Several authors have reported that bats play a crucial role in ecosystems since they provide services that include arthropod populations control as well as insect pest suppression and fertilization (due to the large-scale use of bat guano) in agriculture (Kasso and Balakrishnan, 2013; Kunz et al., 2011; Patterson et al., 2003; Puig-Montserrat et al., 2015). Additionally, due to their wide geographical range, sensitivity to environmental changes and their correlation with the responses of other taxa, bats are also regarded as important ecological indicators (Fenton, 2003; Jones et al., 2009; López-Baucells et al., 2017; Patterson et al., 2003).

Due to their ability to act as ecological indicators, the monitoring of bat populations is urgently needed not only to assess their population

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trends and status but also to detect environmental changes and determine the magnitude of the impacts on ecosystems altering general ecosystem health. Currently, despite the alarming declines of bat populations, only a few systematic long-term bat monitoring programs such as the North American Bat Monitoring Program (NABat, USA), the National Bat Monitoring Program (NBMP, UK) and the Vigie-Chiro program (France) are being carried out worldwide (Barlow et al., 2015; O'Shea et al., 2003). These programs depend on a widespread network of volunteers who survey a large number of localities using different monitoring techniques. Recently, the British Bat Survey has been created in UK, using only passive acoustic detectors. Similarly, other long-term bat monitoring programs have been initiated in certain Eastern European countries (Hungary, Romania, Ukraine and Bulgaria), some under the umbrella of the Indicator Bats Program (iBats) (Jones et al., 2013) and most of them using TRIM (TRENds and Indices for Monitoring data) as the main analytic protocol (Pannekoek and van Strien, 1996; Pannekoek and van Strien, 2004).

Although monitoring bats is mandatory in Europe for those species included in Annex II and IV of the Habitats Directive (Council Directive 92/43/EEC), very few public national long-term bat-monitoring programs exist in Mediterranean countries, the exception being the Vigie-Nature biodiversity program in France (Kerbiriou et al., 2015). In fact, the agreement on the Conservation of Populations of European Bats (EUROBATS), approved in Europe in 1994 as an international treaty whose aim is to monitor and protect European bat species, encourages all parties to monitor bat populations effectively and has set up a specific working group on bats as ecological indicators.

The standardization of international bat monitoring programs, data management and analysis protocols – above all, in acoustic surveys (Adams et al., 2012; Jones et al., 2013) – is vital as it is not often possible to compare results from studies conducted using different methodologies (Adams et al., 2012). For example, the large number of possible settings on acoustic detectors (Adams et al., 2012; Fenton, 2000; Larson and Hayes, 2000) and the variety of notions of what the term ‘bat pass’ constitutes in acoustic surveys (Kerbiriou et al., 2019; Miller, 2001) hinder comparisons and parallel-running projects. Similarly, the variability in sonotypes in bat species classification (Walters et al., 2012; Wickramasinghe et al., 2003) and the quantifying of assemblage diversity using a wide range of diversity indices also prevent the comparison of results from different studies (Cosson et al., 1999; Moreno and Halfper, 2000; Rex et al., 2008).

In any large-scale monitoring program standardized methodologies are paramount. The use of ecological indices is a useful technique that allows us to assess the effect of environmental changes based on specific bioindicator taxa. The responses of the target taxa reflect ecosystem responses, which will thus allow us to relate specific changes to ecosystem changes. The development of protocols and ecological indices facilitates the use of standardized measures and the comparison of results generated by different studies. In recent decades, new community indices have been developed for other taxa that are able to quantify assemblage responses to different environmental stressors such as climate change and landscape composition. Julliard et al. (2006) created the Community Specialization Index (CSI) for European bird assemblages. This index allows us to assess the niche complexity and the degree of disturbance in any given ecosystem in terms of the total amount of specialist or generalist species found therein, which assumes that the most disturbed ecosystems will lose niches and consequently will lead to the presence of more generalist species. Devictor et al. (2012) developed the Community Thermal Index (CTI) for butterflies and birds to measure the changes in assemblage composition in response to temperature variation, which may be directly connected to climate change. Herrando et al. (2016) developed an index of habitat preference along an open-forest gradient – also applicable to butterfly and bird assemblages – that provides information about assemblages' responses in terms of structural land-cover changes.

By contrast, although many studies have underlined the role of bats

as ecological indicators, no standardized ecological index has ever been developed for this group. Developing ecological indices for bat assemblages would strengthen the consistency and comparability of long-term monitoring schemes, which is of vital importance and a priority in conservation. For this study, seven indices (Richness; Shannon Diversity Index; Bat Activity; Community Thermal Index, CTI; Community Precipitation Index, CPI; Community Openness Index, COI; and Community Specialization Index, CSI) were selected jointly for the first time to characterize local bat assemblages. We used an acoustic dataset collected with autonomous ultrasound detectors in Catalonia over a period of three years in order to illustrate their potential as ecological indicators. Our aim was to assess how the combination of these indices reflects the responses of bat assemblages under the current scenario of global change. Three of these indices are traditionally and widely used (Richness, Bat Activity and Shannon Diversity Index), while the remaining four (CTI, CPI, COI and CSI) are adapted environmental indices (climatic and habitat-related). The ultimate goal of this study was to provide easy-to-use ecological indices for land managers, researchers and conservationists to monitor bat assemblages and their responses to environmental changes. In order to assess this, we aimed to i) adapt and illustrate the use of all seven indices with Iberian bat species; ii) apply these seven indices to a three-year-long dataset of acoustic data collected in Catalonia, and iii) discuss potential uses of these indices for comparing bat communities at both spatial (similar habitats from different sampling locations) and temporal (same sampling locations over time) scales.

## 2. Materials and methods

### 2.1. Study area

This study was carried out in Catalonia (NE Iberian Peninsula). Despite its small size (32,108 km<sup>2</sup>), it embraces many different climatic regions: Mediterranean littoral climate (along the 580 km of coastline), Mediterranean continental climate (centre and west) and Atlantic or alpine climates (Pyrenees). The orography and altitudinal range (from 0 to 3143 m a.s.l.) of this region also favours the existence of a great variety of habitats and microclimates, thereby ensuring important levels of biodiversity.

Bats were surveyed using pairs of passive acoustic detectors (one generally in an open area and another in a closed area), having surveyed a total of 90 sampling points (localities) in over 10 different habitats at altitudes ranging from 0 to 1842 m a.s.l. (Fig. 1). Sampling points were located mostly within natural parks and other protected areas (80), with just a few on unprotected areas (10). Twenty-six sampling points were established in coniferous forests, 17 in *Quercus ilex* forests, 10 in mixed deciduous forests, 10 in shrublands, six in arable land, five in urban areas, four in *Fagus sylvatica* forests, four in wetlands, three in *Quercus suber* forests, three in tree crops and two in meadows. Sampling points were selected according to the historical sites monitored by the Natural Sciences Museum of Granollers, being able to work with highly robust data.

### 2.2. Data collection

All the recordings gathered (2016–2018) during a total of 12,960 h of acoustic sampling were stored in a single acoustic database as part of the Catalan bat monitoring programme carried out in the NE Iberian Peninsula by the Natural Sciences Museum of Granollers ([www.batmonitoring.org](http://www.batmonitoring.org)). A single acoustic detector was placed at each sampling point between end of spring and early summer, prior to juvenile recruitment but when bats are already fully active (from mid-May to mid-July) (Altringham et al., 1996). Detectors were set during seven consecutive nights from sunset (19.00 approx., solar time) to sunrise (05.00 approx., solar time). We used Wildlife Acoustics SM2Bat, SM3Bat and SM4Bat detectors (High Pass Filter = 12 KHz; all the



**Fig 1.** Altitudinal map of Catalonia with the pairs of sampling points (in red) used in this study. This figure was prepared using a map licensed under the Creative Commons Attribution-Share Alike 3.0 Unported license (Wikimedia Commons: Blank Map – Mediterranean 1.svg).

settings used can be checked in the monitoring programme website) in each habitat with microphones at an approximate height of 2 m above ground level. To avoid biases in the data analysis, artificial elements favouring the presence of bats such as buildings or artificial light were avoided and all detectors were placed at least 200 m away from this type of structures (Russ and Montgomery, 2002; Rydell, 1992).

### 2.3. Acoustic data analysis and bat call classification

Following the protocol used by the Natural Sciences Museum of Granollers, an automatic species identification analysis was carried out using a combination of two automatic classifiers, Tadarida (Bas et al., 2017) and BatClassify (developed by Christ Scott, UK). Then, a manual post-validation process was performed on all files using Avisoft-SASLab Pro software developed by Raimund Specht (Avisoft Bioacoustics, Berlin, Germany, <http://www.avisoft.com>). The open software Tadarida (developed to be run on relatively powerful computers) was adapted for domestic desktops and laptops. In order to combine the classifiers and optimise the validation process, a series of R scripts were developed to gather and sort all the results into a single dataset. During the classification process we classified acoustic data either into known species or conservative sonotypes (mixed-species group), when an accurate assignment of a call to a determinate species was not possible (Jung et al., 2012; Torrent et al., 2018). In the case of *Myotis* species, we decided to classify this group within two different sonotypes, according to its echolocation call characteristics and, hence, its body size (Dietz and von Helversen, 2004): Small *Myotis* sonotype (maximum intensity frequency around 50 kHz) and Large *Myotis* sonotype (maximum intensity frequency around 30 kHz). All recordings were meticulously supervised by an expert to correct and validate the automatic

classifications.

### 2.4. Indices calculation

Seven community indices were calculated per night in each sampling point:

- i. Richness was considered as the total number of bat species detected, as defined by Magurran (1988).
- ii. The Shannon – Wiener Diversity Index was obtained using the equation below:

$$H' = - \sum_{i=1}^s p_i \ln p_i$$

where  $p_i$  is the proportion ( $n/N$ ) of bat passes of one particular species ( $n$ ) divided by the total bat passes of all species found ( $N$ ),  $\ln$  is the natural log,  $\Sigma$  is the sum of the calculations, and  $S$  is the number of different species.

- iii. Bat Activity was assessed in order to obtain a relative measure of total bat abundance per unit of time ('total number of bat passes/hour'). A 'bat pass' was defined as a sequence of two or more echolocation pulses made by a bat species passing a bat detector (Kalcounis et al., 1999; Rautenbach et al., 1996; Thomas and West, 1989) within a five-second sound file (Millon et al., 2015; Torrent et al., 2018). Thus, it was calculated by averaging the number of all bat passes per time unit (hour) during each sampling night.
- iv. Bat Community Thermal Index (bCTI). First, we estimated the Species Thermal Index (STI) (Devictor et al., 2012) for each species,

computed as the average temperature in the Spanish occurrence range of the species. This is a region-specific method since the species behaviour may change depending on the latitude and also due to the fact that it is very difficult to obtain enough data to evaluate this approach at European level. In order to calculate this index we compiled all bat captures registered in the Spanish Inventory of Terrestrial Species dataset (Inventario Español de Especies Terrestres, IEE) (Ministerio para la Transición Ecológica, Gobierno de España). The annual mean temperature for each locality-report was directly obtained from the WorldClim-Global Climate Data website (climate data for 1970–2000, with a spatial resolution of about 1 km<sup>2</sup>, <http://www.worldclim.org/>) and then all values were averaged. The STI of sonotypes (with more than one species) was calculated by averaging the STI of all species included within each group. However, for *Plecotus* sp., due to the great differences in altitudinal habitat selection, we carried out a specific altitudinal correction based on their theoretical occurrence (see [Supplementary Material](#) for more information about the detectability correction). Finally the bCTI was calculated for each locality by summing the STI values of all species/sonotypes detected at a given sampling point weighted by their corresponding Bat Activity in this locality.

$$bCTI = \frac{\sum_{i=1}^S STI_i \times Bat\ Activity_{ij}}{Total\ Bat\ Activity_j}$$

where  $STI_i$  is the Species Thermal Index of a given species  $i$ ,  $Bat\ Activity_{ij}$  the number of bat passes/hour for species  $i$  in a given locality  $j$ ,  $Total\ Bat\ Activity_j$  the total number of bat passes/hour of all species in a locality  $j$ ,  $\Sigma$  is the sum of the calculations and  $S$  is the number of different species.

- v. Bat Community Precipitation Index (bCPI). The calculation of this new index is identical to the previous case, except that for the Species Precipitation Index (SPI) calculation we used precipitation maps to extract the average annual precipitation per each locality.

$$bCPI = \frac{\sum_{i=1}^S SPI_i \times Bat\ Activity_{ij}}{Total\ Bat\ Activity_j}$$

where  $SPI_i$  is the Species Precipitation Index of a given species  $i$ ,  $Bat\ Activity_{ij}$  the number of bat passes/hour for species  $i$  in a given locality  $j$ ,  $Total\ Bat\ Activity_j$  the total number of bat passes/hour of all species in a given locality  $j$ ,  $\Sigma$  is the sum of the calculations and  $S$  is the number of different species.

To assess the degree of correlation between the characteristic temperature and precipitation values per species, additionally a Pearson's correlation test was carried out on the species-specific indices STI and SPI.

- vi. Bat Community Openness Index (bCOI). First we estimated the Species Openness Index (SOI) using land cover information taken from the Catalan Habitat Cartography (Departament de Medi Ambient i Habitatge 2005; 1:50,000 scale, 30 × 30 m resolution). We reclassified all habitat categories as either 'open' or 'forest'. Then, buffers with a radius of 100 m were established around each sampling point to calculate the percentage of forest area. In order to obtain the SOI, we carried out generalized linear mixed models (GLMMs) with a Poisson error distribution for each species/sonotype, taking into account the average bat activity of a given species at a given sampling point as the response variable, the proportion of forest found within the buffer as the independent variable and the locality as the random factor. The slope of each species-specific GLMM was extracted and used as the SOI. Negative or positive SOI values indicate open or forest habitat preferences, respectively.

Finally, to calculate the Community Openness Index for each sampling point, we summed the SOI values of all species/sonotypes detected at that sampling point weighted by their corresponding Bat Activity in this locality.

$$bCOI = \frac{\sum_{i=1}^S SOI_i \times Bat\ Activity_{ij}}{Total\ Bat\ Activity_j}$$

where  $SOI_i$  is the Species Openness Index of species  $i$ ,  $Bat\ Activity_{ij}$  the number of bat passes/hour for species  $i$  in a given locality  $j$ ,  $Total\ Bat\ Activity_j$  the total number of bat passes/hour of all species in a given locality  $j$ ,  $\Sigma$  is the sum of the calculations and  $S$  is the number of different species.

- vii. Bat Community Specialization Index (bCSI). This index highlights the occurrence or non-occurrence of a given species – as opposed to its abundance – at the sampling points. First, we calculated Species Specialization Indices (SSI) (adapted from [Julliard et al. \(2006\)](#)) by considering the frequency of occurrence rather than bat activity. We established buffers with a radius of 100 m around each sampling point; then an habitat was assigned to each sampling point based on which habitat type occupied the largest surface area in the buffer according to local cartography (Departament de Medi Ambient i Habitatge 2005; 1:50,000 scale, 30 × 30 m resolution). Thus, per each sampling night, the frequency of occurrence of a given species was quantified as follows: species absence was considered as 0 and species presence as 1. Then, we used the coefficient of variation (standard deviation/average) of the frequency of occurrence to quantify each SSI value. Higher values of SSI indicate a more specialist species/sonotype, while a species/sonotype present in all habitats on all sampled nights would have a SSI value of 0, suggesting a generalist character. Finally, to calculate the Community Specialization Index for each sampling point, we summed the SSI values of all species/sonotype detected at a sampling point weighted by their corresponding Bat Activity in this locality.

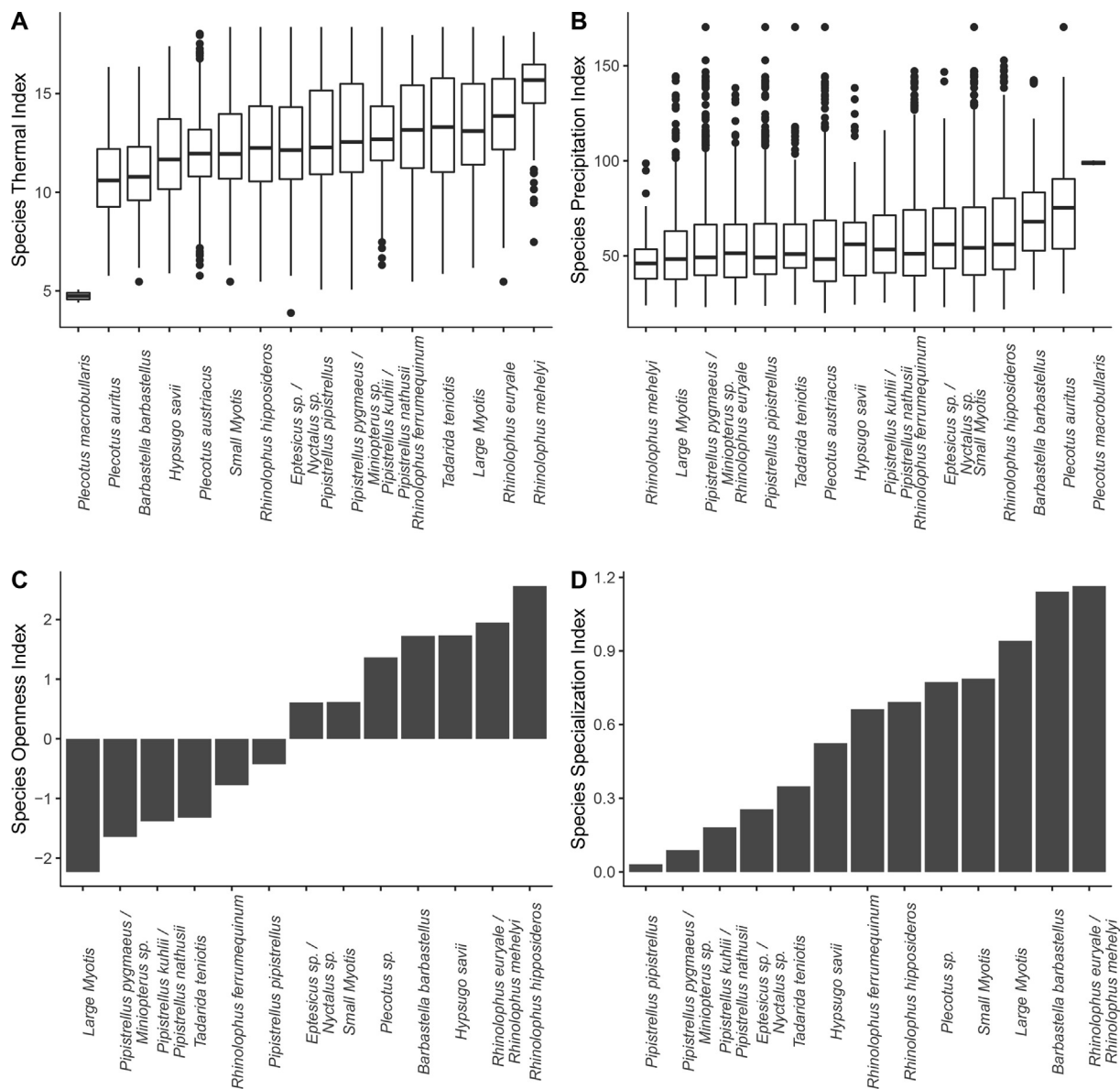
$$bCSI = \frac{\sum_{i=1}^S SSI_i \times Bat\ Activity_{ij}}{Total\ Bat\ Activity_j}$$

where  $SSI_i$  is the Species Specialization Index of a given species  $i$ ,  $Bat\ Activity_{ij}$  the number of bat passes/hour for species  $i$  in a given locality  $j$ ,  $Total\ Bat\ Activity_j$  the total number of bat passes/hour of all species in a given locality  $j$ ,  $\Sigma$  is the sum of the calculations and  $S$  is the number of different species.

## 2.5. Applications of the indices

To illustrate the potential of these ecological indices we selected a single sampling point (Molleres de Gresolet) in a coniferous forest in the Cadí-Moixeró Natural Park. We first compared the values for all indices obtained from this locality in a given year (i.e. 2018) with the results from all other sampling points located in the same habitat type. In order to obtain easy-to-understand and self-explanatory plots, kernel-density histograms of all indices were plotted with their associated kernel-density lines per index and habitat type, using the 'ggplot' R package ([Wickham, 2009](#)). The average value for each index in the selected locality was represented at the top of the general values distribution. This representation allows for a quick visual analysis of the results obtained in the selected locality in relation to the general distribution of each index in a certain habitat type.

With the aim of detecting temporal changes in bat assemblages at a given locality, the temporal trends of the seven indices were studied using generalized linear models. We used the value for all 'indices' as the response variable and the 'year' as the fixed factor. Models were run with the basic R Stats package. Plots were built with the package



**Fig 2.** Species-specific indices for: (A) Species Thermal Index (STI), arranged from coldest to hottest values; (B) Species Precipitation Index (SPI), arranged from driest to most humid values; (C) Species Openness Index (SOI), arranged from open-associated (negative) to forest-associated (positive) values; (D) Species Specialization Index (SSI) obtained for each species/sonotype, arranged from generalist to specialist values.

'ggplot2' (Wickham, 2009). Trend lines were associated to each model, and the corresponding p-value and  $R^2$  were used to test whether the trends were significant or not and the explanatory capacity of the models. Additionally, for the three year study period, these trends were also assessed for a selected habitat (including all localities) using generalized linear mixed models (glmm) with a Gaussian distribution. The indices were the response variable, while 'year' was considered as the fixed factor and 'locality' was used as the random factor. We calculated all glmm models with *lmer* function of the package 'lme4' R package (Bates et al., 2014). The effect of 'year' was plotted using the function *allEffects* of the 'effects' R package (Fox et al., 2018), with their correspondent associated p-value. All statistical analyses were performed with R version 3.4.3 for Windows (R Core-Team, 2015).

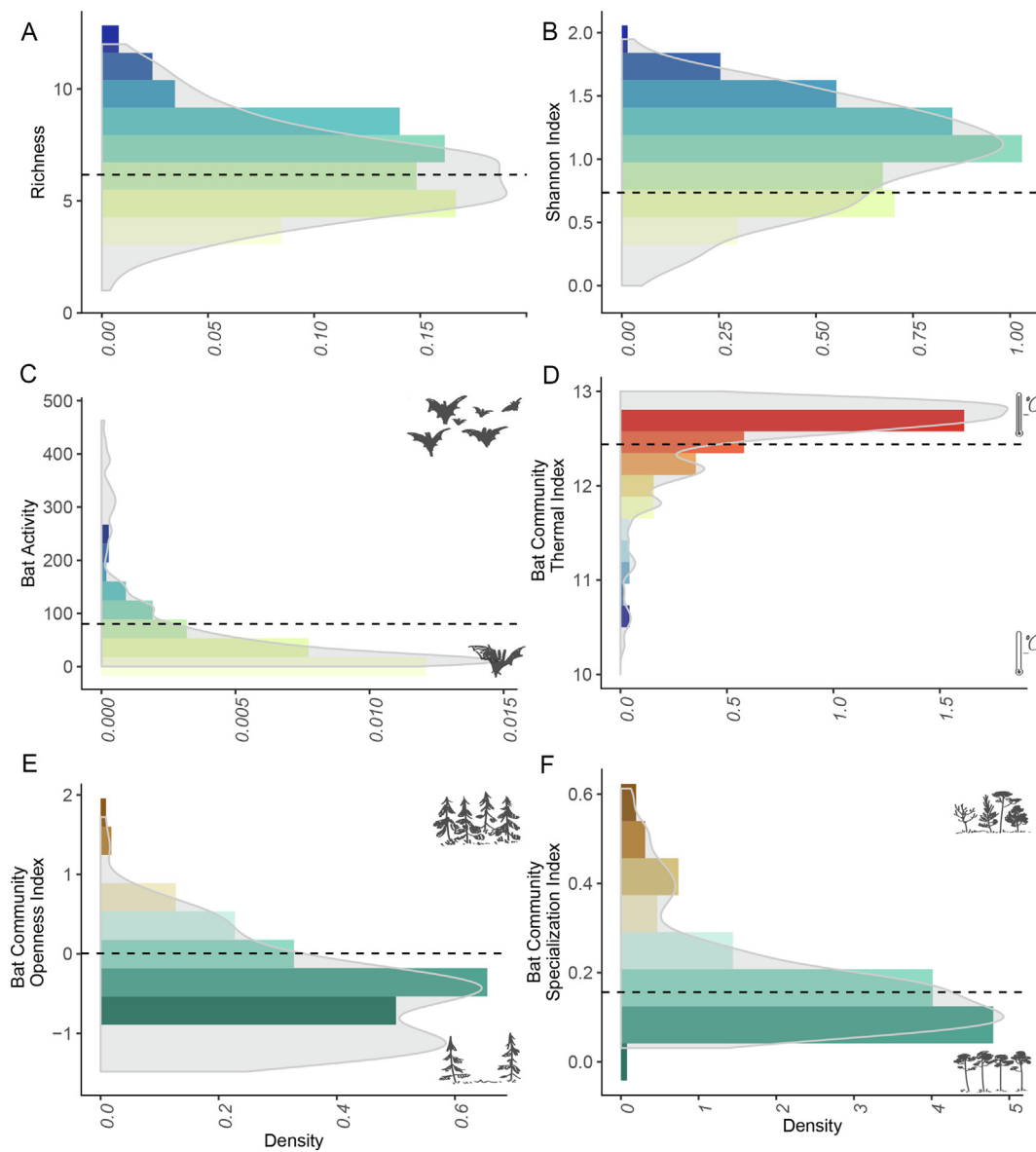
### 3. Results

#### 3.1. Adaptation and calculation of specific indices: STI, SPI, SOI, SSI

To develop the community indices, we first calculated the species-

specific indices by characterizing each species/sonotype with specific values of STI, SPI, SOI and SSI (Fig. 2, Table S1, Table S2). A clear ascending gradient for the STI was observed for all 15 species/sonotypes, from *Plecotus macrobullaris* (the lowest value) to *Rhinolophus mehelyi* (the highest value) (Fig. 2A). For the SPI, a similar ascending gradient was found between the same two species but in almost the inverted order (Fig. 2B). When considering the habitat-related indices, a SOI gradient was detected between all categories, from *Large Myotis* and pipistrelle groups to *Barbastella barbastellus*, *Hypsugo savii* and *Rhinolophus euryale/mehelyi* and *R. hipposideros* species, the former being associated with open areas and the latter with forested habitats (Fig. 2C). Our results for the SSI showed a similar pattern: pipistrelle groups had the most generalist associated values, while *R. euryale/mehelyi* and *B. barbastellus* had the most specialist values (Fig. 2D).

The Pearson's correlation coefficient obtained for STI and SPI was 0.84, which indicates that these two indices are highly correlated. For this reason, and due to the more readily understood effects of temperature on bat communities, the SPI index was excluded from the rest of the analyses.



**Fig. 3.** Kernel density histograms of the value distributions for all indices obtained per night for a certain type of habitat (e.g. coniferous forest) in a single year (e.g. 2018): (A) Richness, (B) Shannon Index, (C) Bat Activity, (D) Community Thermal Index (STI), (E) Community Openness Index (SOI), (F) Community Specialization Index (SSI). The dotted black line represents the position of the corresponding averaged index value obtained from the selected locality (Molleres de Gresolet).

### 3.2. Community indices calculation and applications

The locality Molleres de Gresolet, with an associated habitat of coniferous forest, was selected to illustrate the potential applications of these newly defined indices to bat assemblages. The comparison between a given locality in a single year and all localities with the same associated habitat are plotted in Fig. 3. The value of each index from Molleres de Gresolet (2018) can be easily compared with the index distribution (calculated using all localities with the same associated habitat). The average Richness of the selected location was around six species and the Shannon Index around 0.75, intermediate values compared to the general average Richness and Shannon Index for coniferous forests. Bat Activity was higher than the most usual bat activity recorded for this type of forests. By contrast, the CTI was lower than the most common CTI values for this habitat (thus, being a bat assemblage with more species associated to low temperatures), while for habitat-related indices, both the COI and the CSI were located in intermediate positions.

The results from Molleres de Gresolet over a period of three years

(2016–2018) were used to calculate temporal trends (Fig. 4). The p-values of the temporal trends were no significant, thereby indicating no significant changes between 2016 and 2018, being the associated  $R^2$  very low.

When assessing the global temporal trends for all indices in a given habitat type (e.g. ‘Coniferous’ in the current example), we obtained marginally significant trends (p-value < 0.1) for three out of six indices (Community Thermal Index, Community Openness Index, Community Specialization Index) (see Fig. S2 in the Supplementary Material).

## 4. Discussion

An important part of this project involved the development of several ecological indices for characterizing bat assemblages and proposed new baseline measures for bat and ecosystem monitoring. We adapted and calculated seven indices for these taxa as a means of obtaining an accurate characterization of their assemblages over time in different types of temperate habitats. We have demonstrated that it is not only

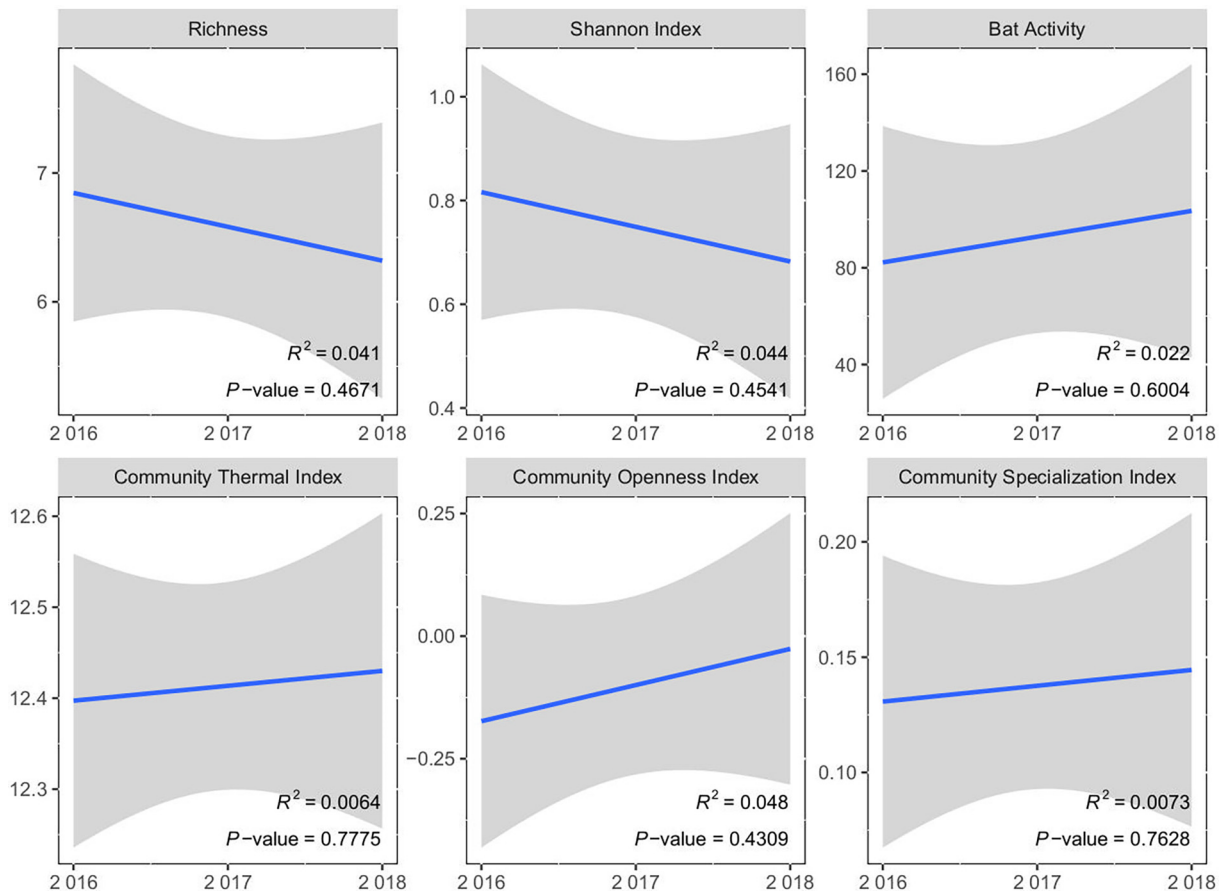


Fig. 4. Temporal trends of all indices obtained from Molleres de Gresolet in 2016–2018. Blue lines represent the trend lines for each index with their corresponding  $P$ -values and  $R^2$ . The shaded area corresponds to the 95% confidence interval for predictions from each generalized linear model.

possible to successfully characterize bat assemblages at a certain moment in time and space but that it is also possible to compare them, detect temporal trends and relate environmental changes to variations in their composition. To date only a few authors have developed ecological indices for bats; Regnery et al. (2013), for example, adapted the SSI from Julliard et al. (2006) but focused on tree/roost microhabitats for bioindication rather than bat species. We used instead European bat assemblages and propose here for the first time a set of several complementary ecological indices that can be used as part of long-term bat monitoring programs.

#### 4.1. Adaptation and calculation of specific indices: STI, SPI, SOI and SSI

The specific indices of temperature (STI), precipitation (SPI), openness (SOI) and specialization (SSI) obtained through objectively collected data closely matched current knowledge of Iberian bat species collected by researchers over the past decades (Dietz and Kiefer, 2016; Flaquer and Puig, 2012; Schober et al., 1996).

The lowest STI were found for *Plecotus macrobullaris* (typical species of alpine meadows), *P. auritus* and *Barbastella barbastellus* (both typical species of forest and montane habitats) (Alberdi et al., 2015; Ekman and Jong, 1996; Kaňuch et al., 2008; Kühnert et al., 2016; Lučan et al., 2009), which corroborates the fact that they are mostly found in areas of colder climatic conditions (Fig. 2A). Similarly, the highest STI was detected for *Rhinolophus euryale* and *R. mehelyi*, two typical low-altitude species that inhabit warmer areas (Rebelo et al., 2010; Russo and Jones, 2003; Russo et al., 2002), which is logical given that they are normally found in the Mediterranean region (Fig. 2A). Similarly, we detected a species order in the precipitation gradient (Fig. 2B) that was almost totally contrary, the lowest SPI being found in *R. mehelyi*, the pipistrelle

groups and *Tadarida teniotis*, which are also typical species of dry Mediterranean areas. The highest SPI were found in *P. macrobullaris*, *P. auritus* and *B. barbastellus*, three species that are more associated with humid areas (Alberdi et al., 2015; Ekman and Jong, 1996; Kaňuch et al., 2008; Kühnert et al., 2016; Lučan et al., 2009; Rebelo et al., 2010). Due to the close correlation detected between these two indices in our data, we conserved only the STI in the rest of the analysis since the knowledge of the effects of temperature on the biology and ecology of bats is more advanced than that of precipitation.

The most negative SOI indices were found for all pipistrelle-like species and Large *Myotis*, which are commonly found in open and semi-open environments (Downs and Racey, 2006; Kusch et al., 2004); this indicates that our quantification of these species' preferences for open habitats (i.e. SOI) is robust (Fig. 2C). Likewise, the high SOI found for *Rhinolophus hipposideros*, *Barbastella barbastellus*, *Hypugo savii* and *Rhinolophus euryale*, all forest-dwelling species (Kaňuch et al., 2008; Reiter et al., 2013; Russo et al., 2002; Zahn et al., 2002), also confirms the reliability of the species-specific gradient (Fig. 2C). On the other hand, the SSI reveals the more generalist character of pipistrelle-like species and *Eptesicus* sp./*Nyctalus* sp., groups found in almost all types of habitats and ecosystems, as well as the more specialist character of *B. barbastellus* and *R. euryale*, which are more restricted to forest habitats (Fig. 2D) (Dietz and Kiefer, 2016; Kaňuch et al., 2008; Kusch et al., 2004; Russo et al., 2002). As in the case of climate-related indices, the high level of constancy between our results and the baseline knowledge we have regarding the habitat preference of bat species is evidence of how the indices proposed by Devictor et al. (2012), Julliard et al. (2006) and Herrando et al. (2016) are consistent and robust, as well as its suitability for use with European bat species.

## 4.2. Community indices and applications

Once the specific indices were obtained, we calculated the community indices and illustrated how to use them in a real case study. By comparing a specific locality with all other localities with the same associated habitat we proved that the use of histograms with their corresponding kernel density lines is a useful way of visually inspecting and detecting whether or not the values obtained in a selected locality are low, intermediate or high. For example, it is worth highlighting the relatively low CTI and the high levels of bat activity detected at Molleres de Gresolet. Our results would seem to be robust since this locality consists of a coniferous forest located at altitude (1560 m a.s.l.), which implies lower temperatures as reflected in the CTI value. This locality is also located near a mature mixed forest of beech and coniferous trees, which favours roost-site availability, and is also close to a lake (2 km), a feature that could also encourage the presence of more bats.

In terms of the temporal trend evaluation, our analyses allowed us to assess the temporal changes occurring in community indices at a given locality or habitat over time. For example, at Molleres de Gresolet, we detected no significant trends of the indices over time (with data from 2016 to 2018). Although it is possible that no changes in the bat community were occurring in this locality within that time interval, this fact could also be due given the short temporal period we used. When we tried to analyse global trends in a certain habitat type (e.g. coniferous forests), clear temporal trends were also difficult to detect. In this case, although we obtained marginally significant trends in three of the six indices (probably due to the large number of nights surveyed), there were no clear patterns (see trends in Fig. S2 in the supplementary materials). It is also important to note that at a local scale reliably bat community changes may be more easily detected due to local yearly climatic variations, while detecting global trends may require longer temporal datasets.

In general, the newly proposed ecological indices provide very visual and easy-to-understand information about bat assemblages from a single locality or a given habitat type. We initially developed these indices to meet the demands of conservation managers working in natural areas, who required simple protocols that would provide support for their management actions. As well, private entities are increasingly becoming interested in these methods which provide an integrated vision of an entire ecosystem. Thus, the use of these indices will be of great use for both the managers of protected areas and private companies as ways of improving, establishing and developing adequate management and conservation measures. CTI will allow us to detect responses in bat assemblage composition that are related to the changes in environmental temperature that are predicted to occur under a scenario of climate change. Similarly, the COI will facilitate the monitoring of changes in ecosystem structure (e.g. deforestation episodes or reforestation processes causing the loss of open areas). Fluctuations in the CSI will indicate changes in habitat stability if the following general assumption is accepted: specialist species are associated with more specialized communities and stable environments in space and time; conversely, generalist species adapt to the lack of stability in ecosystems and are more abundant when the rest of the community is also habitat-generalist (Julliard et al., 2006; Wilson and Yoshimura, 1994). Hence, we have illustrated how these ecological indices can detect climate and landscape changes through variations in their community values, thereby reflecting the ecological pressures on a given habitat.

On the other hand, we also acknowledge potential caveats of these indices mostly due to detectability variation of the species. High-frequency and low intensity echolocation calls weaken faster than lower frequency and higher intensity ones (Lawrence and Simmons, 1982). Hence, some species might be more probably underestimated than others by acoustic detectors. However, in our case we assume an equal detectability bias in all monitoring sites which minimise any potential detrimental bias of the use of these indices. It is also important to

mention that density of refugees can affect most of our suggested indices. This factor is normally unpredictable, as many roosts are not well-known, especially for forest-dwelling bats. However, due to the fact that we work with relatively large datasets we expect this bias to remain minimized.

## 4.3. State of knowledge and opportunities for future research

Long-term databases have been used to obtain temporal trends in butterfly (CTI) and bird populations (COI) (Devictor et al., 2012; Herrando et al., 2016; Herrando et al., 2019, respectively). In the present study, we applied this method to detect temporal changes in bat assemblages, which could be linked to structural changes in ecosystems. We highlight here the need to develop long-term monitoring programs to accurately assess the status of bat populations and assemblages, and ecosystem structures and functions, as well as to help envisage the short- and long-term effects and consequences of management interventions. Only then we will be able to develop adequate management protocols and test their effectiveness by evaluating the ecological responses to these measures and by readapting them over time whenever necessary (Lindenmayer and Likens, 2009). Furthermore, we also feel that it is important to emphasize that, given the need to establish international standardized protocols for bat monitoring, this method has a robust potential for use as a complementary standardized measure of species level monitoring, especially in the Mediterranean region, where there are few existing trans boundary long-term monitoring programs. While species-specific monitoring is essential to understand the conservation status and the fate of individual species, the indices we propose are very useful to detect overall changes in the environment. Hence, we encourage governments and researchers to use these indices in their ecological studies and to ensure that they are comparable between countries, thereby facilitating international cooperation and the implementation of large-scale conservation measures.

Amongst the current standardized protocols, TRIM is one of the best known and most widely used techniques. TRIM is a well-established method used to estimate population trends (Pannekoek and van Strien, 1996; Pannekoek and van Strien, 2004) and has been widely used by several authors to estimate trends in bat populations (Froidevaux et al., 2017; Piksa and Nowak, 2013; Uhrin et al., 2010; Van der Meij et al., 2015). TRIM evaluates series of count data and so requires information regarding bat abundance, which is usually obtained by direct roost counts (e.g. the National Bat Monitoring Programme of the Bat Conservation Trust, UK) or car- and point-based acoustic surveys (e.g. Bat Conservation Ireland, Roche et al. 2011; the Vigie Nature conservation programme, France; Kerbirou et al., 2015).

In our study we propose a new method for estimating population trends using acoustic surveys that take advantage of the recently developed Passive Acoustic Monitoring (PAM) technique. The use of autonomous ultrasonic detectors enables us to simultaneously sample a greater number of locations for longer periods of time, using systematic and less biased protocols. This increases not only the sample size but also the known range of bat species being monitored, given that it adds new species that are hard to detect in roosts and that hitherto have been neglected. Furthermore, acoustic surveys are a passive sampling method that produce no stress in bats (Flaquer et al., 2007). In addition, we emphasize the innovative character of the ecological indices proposed, since they allow a more meaningful ecological interpretation of the data obtained in bat monitoring programs. Finally, we also acknowledge that these indices do not substitute the species level monitoring programs (which are essential for bat species conservation) but complement them.

## 5. Conclusions

The monitoring of bat assemblages is an essential task due to their current worldwide decline. Furthermore, bats are very sensitive to

environmental changes and are closely correlated with other taxa (Ingersoll et al. 2013; Jones et al., 2009; Sherwin et al., 2013). Through bat monitoring, we can obtain information about the health status of ecosystems, which means that they are optimal ecological indicators (Fenton, 2003; Jones et al., 2009; López-Baucells et al., 2017; Patterson et al., 2003). Hence, our indices are a pioneer, accessible, user-friendly and easy-to-use tool that land managers, researchers, stakeholders and conservationists can use to monitor the responses of bat communities as indicators of ecosystem changes under the current scenario of global change. This is one of the few studies that have developed ecological indices for bat species and so provides baseline measures for bat and ecosystem long-term monitoring. We strongly recommend the use of these indices as a standardized method for monitoring communities and as a means of promoting international cooperation in bat conservation.

### Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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### Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.ecolind.2019.105849>.

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