



**HAL**  
open science

## Acoustic monitoring of rock ptarmigan: A multi-year comparison with point-count protocol

Thibaut Marin-Cudraz, Bertrand Muffat-Joly, Claude Novoa, Philippe Aubry, Jean-François Desmet, Mathieu Mahamoud-Issa, Florence Nicolè, Mark van Niekerk, Nicolas Mathevon, Frédéric Sèbe

### ► To cite this version:

Thibaut Marin-Cudraz, Bertrand Muffat-Joly, Claude Novoa, Philippe Aubry, Jean-François Desmet, et al.. Acoustic monitoring of rock ptarmigan: A multi-year comparison with point-count protocol. *Ecological Indicators*, 2019, 101, pp.710-719. 10.1016/j.ecolind.2019.01.071 . hal-02195956

**HAL Id: hal-02195956**

**<https://hal.science/hal-02195956v1>**

Submitted on 21 Oct 2021

**HAL** is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.



Distributed under a Creative Commons Attribution - NonCommercial 4.0 International License

1 **Title: Acoustic monitoring of rock ptarmigan: a multi-year comparison with point-**  
2 **count protocol**

3 **Authors:** Thibaut Marin-Cudraz<sup>a,\*</sup>, Bertrand Muffat-Joly<sup>b</sup>, Claude Novoa<sup>c</sup>, Philippe Aubry<sup>d</sup>,  
4 Jean-François Desmet<sup>e</sup>, Mathieu Mahamoud-Issa<sup>a,f</sup>, Florence Nicolè<sup>g</sup>, Mark H. Van Niekerk<sup>a</sup>,  
5 Nicolas Mathevon<sup>a</sup>, Frédéric Sèbe<sup>a</sup>

6 a: Equipe de Neuro-Ethologie Sensorielle ENES / Neuro-PSI, CNRS UMR 9197, University of Lyon /  
7 Saint-Etienne, 23 rue Docteur Paul Michelon, Saint-Etienne Cedex 2, France.

8 Authors e-mail addresses: thibaut.marincudraz@gmail.com, markh.vn@gmail.com, mathevon@univ-  
9 st-etienne.fr, frederic.sebe@univ-st-etienne.fr

10 b: Unité Faune de Montagne, Direction de la Recherche et de l'Expertise, Office National de la Chasse  
11 et de la Faune Sauvage, 90, impasse les Daudes, 74320 Sevrier, France.

12 Authors e-mail addresses: bertrand.muffat-joly@oncfs.gouv.fr

13 c: Unité Faune de Montagne, Direction de la Recherche et de l'Expertise, Office National de la Chasse  
14 et de la Faune Sauvage, Espace Alfred Sauvy, 66500 Prades, France.

15 Authors e-mail address: claudenovoa@oncfs.gouv.fr

16 d: Cellule d'appui méthodologique, Direction de la Recherche et de l'Expertise, Office National de la  
17 Chasse et de la Faune Sauvage, Saint Benoist, BP 20, 78612 Le Perray-en-Yvelines, France.

18 Authors e-mail addresses: philippe.aubry@oncfs.gouv.fr

19 e: Groupe de Recherches et d'Information sur la Faune dans les Ecosystèmes de Montagne,  
20 Samoëns, France.

21 Authors e-mail addresses: jfdesmet@orange.fr

22 f: Current adress: Department of Behavioral Ecology, Institute of Environmental Sciences, Faculty of  
23 Biology, Adam Mickiewicz University, Umultowska 89, 61-614 Poznań, Poland.

24 Authors e-mail addresses: mathieumahamoudissa@hotmail.fr

25 g: Laboratoire de Biotechnologies Végétales appliquées aux Plantes Aromatiques et Médicinales,  
26 FRE CNRS 3727 - EA 3061, Université de Lyon/Saint-Etienne, 23 rue Docteur Paul Michelon, Saint-  
27 Etienne Cedex 2, France.

28 Authors e-mail addresses: florence.nicole@univ-st-etienne.fr

29 **\*Corresponding author:** Equipe de Neuro-Ethologie Sensorielle ENES / Neuro-PSI, CNRS UMR  
30 9197, University of Lyon / Saint-Etienne, 23 rue Docteur Paul Michelon, Saint-Etienne Cedex 2,  
31 France.

32 *E-mail adress:* thibaut.marincudraz@gmail.com (T. Marin-Cudraz)

33

34 HIGHLIGHTS:

35 Calls of male rock ptarmigans show individual vocal signatures.

36 These signatures allow acoustic censusing of the number of males present in an area.

37 Acoustic sampling is more accurate than point-count protocol.

38

39 ABSTRACT:

40 The cost-effectiveness and reduced human effort employed in setting up acoustic monitoring  
41 in the field makes bioacoustics an appealing option for wildlife monitoring. This is especially  
42 true for secretive vocal species living in remote places. However, acoustic monitoring still  
43 raises questions regarding its reliability when compared to other, human-driven methods. In  
44 this study we compare different approaches to count rock ptarmigan males, an alpine bird  
45 species which lives at high altitudes. The monitoring of rock ptarmigan populations is  
46 traditionally conducted using a point-count protocol, with human observers counting singing  
47 males from a set of different points. We assessed the (1) feasibility and (2) reliability of an  
48 alternative counting method based on acoustic recordings followed by signal analysis and a  
49 dedicated statistical approach to estimate the abundance of males. We then (3) compared  
50 the results obtained with this bioacoustics monitoring method with those obtained through the  
51 point-count protocol approach over three consecutive years. Acoustic analysis demonstrated  
52 that rock ptarmigan vocalizations exhibit an individual stereotypy that can be used to  
53 estimate the abundance of males. Simulations, using subsets of our recording dataset,  
54 demonstrated that the clustering methods used to discriminate between males based on their  
55 vocalizations are sensitive to both the number of recorded signals, as well as the number of  
56 individuals to be discriminated. Despite these limitations, we highlight the reliability of the  
57 bioacoustics approach, showing that it avoids both observer bias and double counting,  
58 contrary to the point-count protocol where this may occur and impair the data reliability.  
59 Overall, our study suggests that bioacoustics monitoring should be used in addition to  
60 traditional counting methods to obtain a more accurate estimate of rock ptarmigan  
61 abundance within Alpine environments.

62

63

64 *Keywords:*

65 acoustic monitoring; rock ptarmigan; point-count protocol; long-term study; individual  
66 information; methodology comparison.

67

## 68 1. Introduction

69 Acoustic monitoring is becoming an effective means to assess wildlife diversity, resulting in  
70 minimal impact to the environment (Towsey et al., 2014; Sueur and Farina, 2015).  
71 Importantly, it enables to focus on species used as bioindicators as well as of patrimonial or  
72 economic concern. The use of acoustic monitoring is usually motivated by the difficulty in  
73 observing the species because of its secretive behavior or the difficulty in accessing its  
74 habitat (Hoodless et al., 2008; Vögeli et al., 2008; Marques et al., 2009; Buxton and Jones,  
75 2012; Dugan et al., 2013; Marques et al., 2013; Andreassen et al., 2014; Ulloa, 2016). Levels  
76 of investigation range from the simple assessment of species' presence/absence to more  
77 complex studies that aim at determining the number of individuals present on an area.  
78 Depending on the species, these approaches may require the discrimination of individuals  
79 (Terry et al., 2005; Pollard et al., 2010), which is only possible when vocalizations contain  
80 individual vocal signatures based on morpho-physical, genetics and/or learning abilities  
81 (Kroodsma, 1982; Tibbetts et Dale, 2007; Catchpole et al., 2008; Taylor and Reby, 2010;  
82 Nowicki and Searcy, 2014; Tamura et al., 2018).

83 Although acoustic monitoring is promising, it still raises several potential issues: high cost of  
84 monitoring material, design of monitoring protocols, analysis of long-duration recorded  
85 signals, weather conditions impacting the quality of the data, needs of bioacoustics experts  
86 for data analysis, and sensitivity to the density of the species (Budka et al., 2015; Linhart and  
87 Šálek, 2017). To the best of our knowledge, acoustic monitoring has not yet replaced other  
88 protocols. Point-counts protocols (Lancia et al., 2005) are still largely used to provide  
89 estimates of the number of individuals. However, these conventional, human-operated  
90 methods are exposed to biases due to inter-individual differences between observers,  
91 unpredictability of field conditions, and biological parameters such as species abundance  
92 (Tyre et al., 2003; Bart et al., 2004; Lotz and Allen, 2007; Elphick, 2008; Fitzpatrick, 2009).  
93 Moreover, individuals of species emitting long-range signals can be counted by several  
94 observers simultaneously, leading to double counting and abundance overestimation.  
95 Besides, human presence can disturb birds' behavior making them stop singing and leading  
96 to population underestimation.

97 While previous works have explored the technical feasibility of acoustic monitoring based on  
98 vocal individual signature (Terry and McGregor, 2002; Hartwig, 2005; Grava et al., 2008;  
99 Policht et al., 2009; Adi et al., 2010; Feng et al., 2014; Budka et al., 2015, 2018; Peri, 2018a)  
100 most field applications were based on sounds recorded from already known individuals  
101 (O'Farrell and Gannon, 1999; Peake and McGregor, 2001; Vögeli et al., 2008; Digby et al.,  
102 2013; Peri, 2018b). To the best of our knowledge, there is no published study investigating

103 the generalization and reliability of an acoustic monitoring approach based on individual  
104 vocal signatures aimed at estimating the number of individuals in real field conditions.  
105 Focusing on the rock ptarmigan *Lagopus muta* in France, the present paper reports a multi-  
106 year study aimed at assessing the potential interests, as well as the caveats, of acoustic  
107 monitoring by comparing performances of this approach with a traditional point-count  
108 methodology.

109 The rock ptarmigan is a bird species that inhabits the northern parts of Eurasia and North  
110 America. In France, its range is restricted to sub-alpine and alpine habitats (altitude > 1800  
111 m) of the Pyrenees and the Alps Mountain ranges (Sale and Potapov, 2013). This species is  
112 secretive and difficult to access. It is highly adapted to its environment, has mimetic plumage  
113 and vocalizes at dawn and dusk (MacDonald, 1970). Population abundances are decreasing  
114 in both the Alps (Imperio et al., 2013; Furrer et al., 2016; Martinoli et al., 2017) and the  
115 Pyrenees, where they are threatened by both climate change and habitat transformation  
116 (Revermann et al., 2012; Bech et al., 2013). Due to these extreme environmental and  
117 selective pressures, rock ptarmigan is often considered as a bioindicator of the ecosystem  
118 health, a sentinel and umbrella species for biodiversity conservation of the alpine  
119 environments (Sandercock et al., 2005; Hanser and Knick, 2011; Henden et al., 2017).

120 During the mating season (May-June), males display courtship rituals, which often includes  
121 simple, pulsatile vocalizations as well as a peculiar “singing in flight” behavior before dawn  
122 (MacDonald, 1970). The flight is hyperbolic, and vocalization starts when the bird reaches  
123 the point of highest altitude. Point-count protocols rely on this acoustic behavior to evaluate  
124 the number of males after they have established their breeding territories (Bossert, 1977).  
125 Although vocalizations are loud and easily heard by an observer, low visibility, birds’ mobility,  
126 frequent harsh weather conditions and other constraints associated with the alpine  
127 environment are likely to increase the possibility of double counting and overestimation of the  
128 monitored population. Conversely, this may also impair song perception by observers  
129 (Andreev, 1971). The use of an acoustic monitoring technique could provide a feasible  
130 alternative as a response to these difficulties and potential biases. Despite these constraints,  
131 rock ptarmigan presents several advantages in terms of monitoring. Vocalizations are easily  
132 recognizable, population densities are generally low (around 5 males/km<sup>2</sup>), and males are  
133 mostly located in stable territories which facilitates their localization and recording.

134 The present study proposes (1) to assess the individual vocal signature embedded in rock  
135 ptarmigan males’ calls, (2) to test the feasibility and reliability of a bioacoustic monitoring  
136 approach over several years, and (3) to compare the results obtained using this approach to  
137 those obtained with a traditional point-count protocol and long-term field observations.

138

## 139 **2. Material and Methods**

140 We performed this study in 2015, 2016 and 2017, at the ski resort of Flaine (French Alps,  
141 Haute-Savoie, 45°59'32.8"N 6°43'44.2"E; altitude: 1600-2500 m).

142

### 143 *2.1 Counting of singing males*

144 We used three different methods to evaluate males' abundance: a point-count protocol, long-  
145 term observations and acoustic monitoring. The latter was followed by signal processing and  
146 statistical analysis.

147

#### 148 *Point-count protocol*

149 The counting area was delimited empirically to cover roughly 100 hectares (Fig.1). Previous  
150 field observations and literature reviews had suggested that male ptarmigans could be heard  
151 at distances of 500-1000 m (Watson, 1965; Bossert, 1977; Marty and Mossoll-Torres, 2012).  
152 We selected three counting points, approximately 500 m apart from one another to maximize  
153 the listening area (Fig.1). These counting points were located at precisely the same positions  
154 over the three-year period of study. The counting procedure followed that proposed by  
155 Léonard (1995), which was based on the work of Bossert (1977). Three experienced  
156 observers, with previous knowledge of the field (TMC, FS, BMJ; 1 per counting point),  
157 accompanied by volunteers, were placed at each point. As ptarmigan males mainly display  
158 their acoustic signal early in the morning, the observation periods started at 4.30 a.m. and  
159 ended at 5.30 a.m. The observers were positioned 15 min before the beginning of the  
160 observation period. Throughout the observation period, each observer noted on an  
161 observation form (with a drawn map of the area) the timing, the number and the approximate  
162 estimated locations of the vocalizing ptarmigans. At the end of the observation period, BMJ  
163 collected all observers' forms.

164 To estimate the total number of males in the area, we counted 1 male for each group of  
165 neighboring vocalizations indicated on the maps (each group had to be clearly separated  
166 from the others; see Fig. 1). Each male was confirmed by cross-checking the observers'  
167 data. To avoid double-counting by two different observers, vocalizations localized nearby and  
168 heard at approximately the same time (interval < 20 sec.), were considered identical. We  
169 considered the total number of males unambiguously localized as the minimum total number  
170 of males. To take into account ambiguous localizations (e.g. when one observer noted two  
171 birds on the same location while another observer noted a single one) we defined a

172 maximum total number of birds by adding these ambiguous males to the minimum total  
173 number. We thus defined an estimated interval (min-max) of the total number of males. This  
174 procedure was repeated on several consecutive days namely: June 3rd and 4th in 2015 and  
175 2016; June 6th, 7th, 9th in 2017.

176

#### 177 *Long-term observations and acoustic recordings*

178 After the point-counting days, two bioacousticians (TMC and FS) remained in the field for a  
179 period of one month to observe and record all the birds present in the area (recording  
180 material: Sennheiser MKH70 shotgun microphones connected to Marantz PMD 660  
181 recorders; sampling rate: 48000 Hz). This was an important long-term observation effort  
182 aimed at ensuring a thorough knowledge and identification of each bird present within the  
183 area, which may have been acoustically recorded during the point-count protocol. The  
184 resulting number of males spotted by this technique therefore represented the expected  
185 maximum value that could be deduced using the other methods.

186 Despite this effort however, we were only able to record birds during 7, 9, and 15 days in  
187 2015, 2016 and 2017 respectively, primarily due to the harsh weather conditions. We used  
188 two different strategies in order to build up our bank of recordings:

189 1) Recording of non-identified birds before sunrise (4.30 a.m. - 6 a.m.), i.e. during the time  
190 slot corresponding to the spontaneous singing activity peak. Due to the low ambient  
191 luminosity, the recorded males could not be visually observed and identified. The recording  
192 data sets were thus named: “unknown datasets”. Each day, both bioacousticians recorded  
193 from different locations within the study area to sample a maximum number of males.

194 2) Recording of identified birds (6 a.m. – around 10 a.m.). In 2017, we equipped 5 males  
195 present on the area with GPS solar tags (e-obs GmbH, Grünwald, Germany), and used  
196 these tags to pinpoint the males with their individual UHF (Ultra High Frequency)  
197 radiofrequencies. One male had already been equipped with a VHF (Very High Frequency)  
198 radio-emitter collar since 2015. Two additional males were identified using visual cues only.  
199 Both had mated with females and remained within stable and well-defined territories. The  
200 combination of direct observations and GPS localizations greatly minimized the risk of mis-  
201 identifying or confounding males during recordings. A ninth male had its territory on a  
202 neighboring summit (3 km away). As this male was alone on this site and easy to identify, it  
203 was thus added to the recording database (total = 9 birds in 2017).

204 The recording strategy was as follows: after sunrise, when the peak of males' vocal activity  
205 ended, we played back calls from an individual recorded in another area to elicit the focus



206 male's territorial response. This allowed us to record each focus male while double-checking  
207 for its individual identity.

208 In the preceding years (2015 and 2016), we used the same approach although the results of  
209 the field effort were weaker:

210 - June 2016: 5 males recorded. Two of the males were equipped with GPS tags and 3 other  
211 males were identified using visual observations only.

212 - June 2015: 7 males recorded. One male was equipped with a VHF radiotransmitter  
213 necklace; 6 males were identified using visual observations only.

214 The 2015, 2016 and 2017 recording data sets obtained with this method were named "known  
215 datasets".

216

## 217 2.2 Acoustic analysis of recorded signals

### 218 *Data bank of calls*

219 Rock ptarmigan vocalizations are sequences of pulse trains, with energy spread over a  
220 frequency spectrum ranging from 900 to 3700 Hz. There are two major types of calls, namely  
221 short and long calls. These differ by the number of successive pulse trains, namely 3 and 4  
222 respectively (MacDonald, 1970; Watson, 1965). For the present study, we focused on the  
223 short calls, which are the most frequently recorded (Fig. 2). Our annual data bank of calls  
224 consisted of the following:

225 - 2015: 183 short calls, of which 100 were of sufficient quality (in terms of signal-to-  
226 noise ratio) to be analyzed ("unknown" dataset: 75 calls; "known" dataset: 25 calls,  
227  $3.6 \pm 2.4$  calls/male, min = 1 call, max = 8 calls).

228 - 2016: 249 short calls, with 98 of sufficient quality ("unknown" dataset: 66; "known"  
229 dataset: 32 calls,  $6.4 \pm 2.3$  calls/male, min = 4 calls, max = 10 calls).

230 - 2017: 180 short calls, with 133 of sufficient quality ("unknown" dataset: 52 calls;  
231 "known" dataset: 81 calls,  $7.1 \pm 3.9$  calls/male, min = 3 calls, max = 24 calls).

232

233

### 234 *Automatic detection of group of pulses*

235 Due to harsh weather conditions (wind and rain), recorded signals were frequently corrupted  
236 by noise. Before performing the automatic detection of pulses, we first filtered the signals  
237 with a 950-2700 Hz bandpass filter, and then processed a *wavelet continuous transform*

238 (WaveleComp R package, Roesch and Schmidbauer, 2018) to optimize the signal-to-noise  
239 ratio (see Supplementary Material for details).

240 After denoising, amplitude pulses were detected using a customized script (Seewave R  
241 package, Sueur et al., 2008). The absolute amplitude of the signal was first smoothed using  
242 a Daniell kernel (length = 100). The time position of the pulses was then identified using an  
243 amplitude threshold fixed at 3 % of the maximum amplitude of the considered signal.

244 Pulses were gathered in “groups” (G1, G2, G3, see Fig. 2) by automatically measuring  
245 intervals between pulses (Fig. 2c) and computing the ratios between two successive intervals  
246 (Fig. 2d). Ratios superior to 1.7 characterized boundaries between groups of pulses (Sil1 and  
247 Sil2; see Fig. 2b).

248

#### 249 *Measurement of acoustic parameters*

250 We measured 12 acoustic parameters from groups of pulses G1 and G2 (see list in Table 1).  
251 We chose to ignore the G3 group, as the signal-to-noise ratio of this part of the call was  
252 usually very weak (this was mostly due to males flying away from the recorder while singing).

253

254

255 The mean acceleration (Acc.G1) was calculated as follows:

$$Acc = \frac{1}{n-2} \sum_{k=1}^{n-2} \frac{1}{Pr_{k+1} - Pr_k} - \frac{1}{t_{k+2} - t_{k+1}}$$

256 Where  $n$  is number of pulses in G1;  $Pr$  is the pulse rate and  $t$  is the time of occurrence of the  
257 pulse’s maximum amplitude.

258 The normalized Pairwise Variability Index ( $nPVI$ ) is an index commonly used in phonetic  
259 studies (Grabe and Low 2002) to illustrate the variability between consecutive pairs of  
260 intervals:

$$261 \quad nPVI = 100 \times \sum_{k=1}^{n-1} \left| \frac{Pr_k - Pr_{k+1}}{\frac{(Pr_k + Pr_{k+1})}{2}} \right|.$$

262 We used continuous wavelet transformation to calculate the peak frequency parameters  
263 (Fq1.G1 and Fq2.G1). Since pulse locations in the signal had already been calculated, each  
264 pulse was isolated from the original sound, filtered with an 800 Hz -3000 Hz passband filter.  
265 For each pulse, wavelet power spectrum was then calculated. The two scales with the  
266 maximum power were then selected. The scales were further multiplied by the Fourier factor

267  $6 / (2\pi)$  to obtain the classical Fourier periods (Aguiar-Conraria and Soares, 2011) with the  
268 corresponding frequencies. The median of each peak frequency was then calculated across  
269 the entire pulse train. Overall, medians were preferred to means since they are more  
270 conservative and less influenced by possible outliers resulting from analytical errors (e.g. due  
271 to rain drops occurring within a pulse group).

272

### 273 2.3. Acoustic space and individual vocal signatures

274 In order to build a functional tool allowing the acoustic discrimination between rock ptarmigan  
275 males, we proceeded as follows: 1) we built a 4-D acoustic space with a dedicated  
276 discriminant analysis which optimized separation between males using the 2017 “known”  
277 dataset (reference dataset); 2) we used this acoustic space to perform an unsupervised  
278 clustering analysis using the reference dataset for tuning the clustering hyperparameters; 3)  
279 we applied the workflow (centering, projection in the acoustic space and then tuned  
280 clustering) on the 2015, 2016 and 2017 complete data sets to further estimate the number of  
281 males present each year.

282

#### 283 *Acoustic space definition*

284 We analyzed the differences between calls from the individuals of the 2017 “known” dataset  
285 (9 identified males) using powered partial least squares discriminant analysis (PPLS-DA,  
286 Liland and Indahl, 2009; “pls” R package, Mevik et al., 2016). PPLS-DA enables more  
287 accurate analysis of a small sample size with a high number of acoustic parameters, better  
288 than the linear discriminant analysis signatures (Hervé et al., 2018), commonly used in  
289 studies on animal vocalizations. PPLS-DA calculates new variables as combinations of all  
290 centered acoustic variables, leading to a new acoustic space optimizing the discrimination  
291 between individuals. The number of dimensions was chosen by model cross validation  
292 (Szymańska et al., 2012). The mean classification error rate was established after 100 model  
293 cross validations for each number of dimensions (varying between 2 to 11, Fig. 3). We  
294 followed an analog method of the elbow method (Cattell, 1966) to assess the optimal number  
295 of dimensions and we considered the first four PPLS-DA variables, which define a 4-D  
296 acoustic space and explained 36.52 % of the variability (see Results and Fig. 4).

297

298

299 We tested the statistical significance of our PPLS-DA model with a procedure implemented in  
300 the RVAideMemoire package (Westerhuis et al. 2008; Hervé, 2018). The PPLS-DA

301 significance validation is composed of two steps. Firstly, a set of discriminant functions is  
302 obtained from a training data set and secondly, these functions are used to test the  
303 classification on a validation set. The measure of standard error is obtained by analyzing the  
304 correct assignment percentage of 999 random selections of the original data set, which have  
305 been divided into a fitting and testing set.

306

### 307 *Clustering analysis and bootstrap reliability testing*

308 We used an unsupervised classification method (high dimensional data clustering, HDDC,  
309 Bouveyron et al., 2007) to estimate the number of individual males present within the  
310 datasets. HDDC has already been applied on acoustic data with some success (Ulloa, 2018).  
311 HDDA is known to be consistent and reliable with unbalanced datasets because it is based  
312 on gaussian mixture models (Fraley and Raftery, 2002). It is more parsimonious and flexible  
313 than gaussian mixture modelling by adding a noise term within the model covariance  
314 parametrization. The mixture model aims at identifying the meaningful variables for each  
315 cluster and is fitted with the E-M algorithm. The number of mixture components of the model  
316 maximizing the Bayesian information Criterion (BIC, Schwarz, 1978) is set as the number of  
317 clusters. The E-M algorithm is sensible to the selected random points during its initialization.  
318 Thus, we ran the clustering algorithm several times in order to obtain a reliable value for the  
319 number of clusters.

320 The 2017 'known' reference dataset was used for tuning the HDDC hyperparameters ( $K = 9$   
321 clusters in 2017; the covariance model  $M$ ; the threshold  $t$  used to parametrize the dimension  
322 of each cluster; see R package HDclassif, Bergé et al., 2012 for details). Each call was  
323 represented by its 4 acoustic dimensions previously calculated through PPLS-DA. We tested  
324 10 values of  $t$  namely: 0.000001, 0.00001, 0.0001, 0.01, 0.03, 0.05, 0.07, 0.1, 0.15, 0.2  
325 (adapted from Ulloa, 2018) and the 14 possible models of covariance parametrization. Each  
326 association of  $t$  and  $M$  value were tested.

327 The clustering algorithm was run 100 times for each association. For each run, we measured  
328 the similarity between the clustering output and the clustering membership with the adjusted  
329 Rand Index (ARI, Hubert and Arabie, 1985; package mclust, Scrucca et al., 2016). The ARI  
330 ranges from -1 to 1 and is an indicator of the concordance of two classifications for the same  
331 dataset: when  $ARI = -1$ , the classifications are totally opposed, or different. When  $ARI = 0$ ,  
332 the classifications are considered random; when  $ARI = 1$ , they are identical. The mean ARI  
333 was then calculated for the 100 values and the tuning parameters associated with the  
334 highest mean were selected. The maximum mean adjusted Rand Index ( $ARI = 0.91$ ) was

335 found for the simplest covariance model (“abqd”) and a threshold value of 0.1 was assigned.  
336 We thus used these tuning parameters.

337 Once  $M$  and  $t$  fitted with our data, the reliability of the clustering process was further tested  
338 using sub-sets of the 2017 reference ‘known’ dataset. Subsets were built by randomly  
339 sampling several various males (random sampling of 1 to 9 males; 900 subsets; 100  
340 trials/subset) or a various total number of calls (random sampling of 20 to 81 calls; 6200  
341 subsets; 100 trials/subset). We tested models with  $K$  values ranging from 1 to 20.

342

#### 343 2.4 Comparison between counting methods

344 To assess the number of males through the acoustic analysis of calls, we performed the  
345 clustering analysis on each year separately, using the entire datasets obtained by pooling  
346 “known” and “unknown” calls (100 trials/year). The male of 2017 that was geographically  
347 isolated was however excluded because it was located outside the point-counting area. We  
348 calculated the 4 dimensions of each call using the PPLS-DA functions previously defined  
349 with the 2017 “known” dataset for each year separately. Each acoustic dataset was centered  
350 before its projection in the 2017 acoustic space by subtracting the means of each acoustic  
351 variable calculated on the 2017 “known” dataset.

352 The number of males (i.e. the number of acoustic clusters) estimated for each year through  
353 the clustering analysis was then compared with the number of males estimated through the  
354 two other counting methods, i.e. 1) the point-count protocol and 2) the long-term observation.

355 All the acoustic and statistical analysis was performed on R version 3.5.0 (R core team,  
356 2018).

357

### 358 **3. Results**

#### 359 3.1 Acoustic discrimination between males and definition of the acoustic space

360 The PPLS-DA identified significant acoustic differences between ptarmigan males, with 4  
361 significant functions that allowed maximizing individual separation (Fig. 4, mean classification  
362 rate = 79 %; min-max classification rate per individual = 0 – 100 %;  $p = 0.001$ ). Table 2  
363 shows the correlation between each of the 4 components, the acoustic variables and shows  
364 that all parameter types (pulse number, pulse rate, durations, frequency parameters)  
365 contribute towards separating the males.

366

367

368

369

### 370 3.2 Reliability of High Dimensional Data Clustering

371 To test the reliability of HDDC, we compared the median number of males obtained through  
372 resampled HDDC with the actual number of males of each sub-data set. As displayed in Fig.  
373 5, HDDC gives a reliable estimate of the number of recorded males if this number does not  
374 exceed 5 individuals. HDDC underestimates the number of recorded males when 6 or more  
375 individuals were included in the sub-dataset. It also underestimates the number of recorded  
376 males, when the number of vocalizations in the sub-datasets are sampled, and consistently  
377 predicts 7 clusters (i.e. 7 individuals) for sub-datasets composed of a minimum of 33  
378 vocalizations (i.e. 41 % of the total number of calls) (Fig. 5b).

379

### 380 3.3 Comparison of counting methods' reliability

381 In 2017 and 2016, the most congruent results were given by the acoustic monitoring and  
382 long-term observation. In both years, the point-count protocol resulted in a lower estimation  
383 than the two other counting methods. Still, the long-term results were reached by the point-  
384 count intervals for at least one day per year. Estimation through the point-count protocol  
385 appears to be highly dependent on the day of observation (this is particularly obvious in  
386 2017, with an estimate of 5-8 males on the first day *versus* 4-5 males on the second day).

387 The 2015 results differed significantly from those of 2016 and 2017, with an apparent under-  
388 estimation of the number of males through the acoustic monitoring method compared to  
389 long-term observations. However, the distribution is widespread and looks bimodal, with the  
390 second mode (6 clusters) being close to the actual number of males (7 individuals). This can  
391 be clearly seen in Fig. 6 which displays the number of males estimated by each counting  
392 method (point-count protocol, long-term observation, acoustic monitoring).

393

## 394 4. Discussion

395 4.1 Does the acoustic space built from recordings encompass the vocal variability of rock  
396 ptarmigan males?

397 The relative inconsistency of individual males' vocal signature might limit the bioacoustics  
398 approach. Although the mean PPLS-DA classification rate of recorded calls was around  
399 80%, individual rates differed greatly among males (from 0% to 100%). Moreover, the  
400 discriminant functions used to build the acoustic space explained only 36% of the total

401 acoustic variability of calls. A significant proportion of the variability remains out of reach,  
402 suggesting that individual identity is not the only factor driving the calls' structure. Rock  
403 ptarmigan' vocalizations are sequences of stereotyped pulses with few frequency  
404 modulations. The acoustic variation between individuals may thus be reduced when  
405 compared to other bird species with more complex signals. Ptarmigan are non-oscine birds  
406 (Kroodsma et al., 1982; Slater, 1989), and their vocalizations thus lack then the individual  
407 variability that could have been induced by song learning. Inter-individual differences in  
408 ptarmigan acoustic signals mostly result from differences in their genetic background and  
409 their physiological conditions. It is known that ptarmigan males are highly philopatric and  
410 closely related genetically in the Alps at large scale (Caizergues et al., 2003). In addition to  
411 this, a genetic study of a closely related species, the red grouse (*Lagopus lagopus scoticus*),  
412 showed that males were highly related at local scales (Piertney et al., 1998). The genetic  
413 variability between rock ptarmigan males is thus rather low. Moreover, the highly variable  
414 alpine weather conditions should promote great annual variations in food availability,  
415 especially due to snow cover and the timing of snow melt (Körner, 2003; Edwards, 2007;  
416 Jonas, 2008). Thus, males' physiological state might be different both between individuals  
417 (e.g. depending on the individual food intake in each territory) and from year to year within  
418 individuals (depending on the availability of resources). The variability from year to year is of  
419 special concern as vocalizations from the same male could be very different each year, thus  
420 impairing recapturing males over consecutive years using acoustics only. For this reason, we  
421 considered each year independently within the present study.

422 Our analysis demonstrates that, despite these potential limitations and thanks to their low  
423 densities in France (few males present on the same area), it is possible to rely on individual  
424 vocal signatures to identify local rock ptarmigan males (Linhart and Šálek, 2017) and,  
425 ultimately, to count them. The first requirement is to include only high-quality recordings in  
426 the analysis step (recordings are regularly corrupted by background noise, mostly induced by  
427 wind). Besides, analysis should be mainly performed on the temporal acoustics parameters,  
428 since these are less influenced by noise than the frequency cues. These conservative  
429 choices and the fact that, by design, PPLS-DA optimizes the separation between males and  
430 not the explained variability, can partly explain the low percentage found. Nevertheless, we  
431 were still able to separate the males well enough for our purpose.

432

#### 433 4.2 High dimensional data clustering

434 A second potential limitation of the bioacoustics method may arise in cases where some  
435 males are represented by only a few recordings, resulting in unbalanced recording datasets.

436 HDDC is a model-based clustering, fitted by maximizing log-likelihood estimation (MLE),  
437 itself based on the probabilities of clusters membership. The likelihood will tend to favour  
438 clusters forming large and homogenous groups of points (Fraley and Raftery, 1998). When  
439 the recording dataset is strongly unbalanced between males, individuals with few  
440 vocalizations can be confounded (i.e. included in the same cluster) with other males that  
441 show close vocalization characteristics. One of the males was overrepresented in the 2017  
442 “known” dataset and its calls formed a cluster that incorporated vocalizations from some  
443 other males. This resulted in an underestimated total number of individuals. After removing  
444 this male from the dataset (for comparing between methods), the number of estimated  
445 clusters was higher and more reliable. Unbalanced situations are more likely to arise when  
446 the recording effort is mitigated, as was the case in 2015. This caused HDDC to under-  
447 perform, resulting in an underestimation of the number of males present in the observation  
448 area. Such a difference can be explained when looking at the call’s clusters obtained through  
449 the HDDC method for each year, using both ‘known’ and ‘unknown’ data sets (Fig. 7). In  
450 2015, the vocalizations were mostly from unknown emitters. As a result, clusters strongly  
451 overlapped each other. Conversely, 2016 and 2017 vocalizations are more clearly separated  
452 into homogenous groups. The recording sampling effort must then be homogeneous over the  
453 whole study area and cautiously planned to optimize the representativity of recording banks  
454 (Heupel et al., 2006).

455

456

#### 457 4.3 Sampling effort and balance

458 An adequate acoustic dataset needs a major field effort, due to frequent harsh weather  
459 conditions and difficulties associated with approaching males’ territories. Despite these  
460 constraints, comparable results were found between bioacoustics and long-term methods.  
461 Long-term observations seem the most reliable approach, although not feasible on a regular  
462 schedule given the required workforce. However, most of the vocalizations were obtained  
463 using playbacks and males were recorded directly within their territories (“known” datasets).  
464 Marginal males were included (Fig. 1) as we assumed that they could be heard and could fly  
465 inside the study area. The area of interest was therefore slightly larger than the area covered  
466 by the point-count protocol. This increased the probability of male detection during the  
467 acoustic monitoring compared to the point-count protocol. Conversely, point-count monitoring  
468 appears to be less accurate, with a greater variability of males’ abundance estimations  
469 between counting days.



470 The reduced reliability of the point-count census is not surprising, given that observers focus  
471 generally on only one observation day. We extended the counting period for a few days to  
472 show the variability of this method in this study. Weather conditions (e.g. wind speed) and  
473 variation in males' motivation to vocalize may impair the detectability of males. Moreover, the  
474 number of males present in the area fluctuates through the season and between observation  
475 days. In contrary to northern latitudes (Unander and Steen, 1985; Cotter, 1999), ptarmigan  
476 males differ in their arrival dates depending on their mating status. Mated males return to  
477 their territory in late summer / autumn, while single males arrive only in spring of the  
478 subsequent year. Snow cover plays an important role in the availability of territories and  
479 reproductive success of the species (Novoa et al., 2008) by delaying the males' arrival (one  
480 of the 2015 males equipped with VHF was not present in 2016 –a year during which snow  
481 covered its territory- but arrived in late June in 2017, when the snow cover of its territory  
482 started to dissipate).

483 Point-count census is a “one-shot” process: it estimates the number of males at a given day  
484 whereas bioacoustics and long-term observation estimations are obtained over larger time  
485 periods. The point-count protocol is therefore not able to capture changes throughout the  
486 mating season. In practice, only long-term monitoring using direct observations or acoustic  
487 recordings could overcome this variability.

488 In addition, our study was able to test the reliability of the census method based on the  
489 number of individuals and the number of signals taken into consideration. We showed that a  
490 minimum number of sampled vocalizations were necessary (approximately 33 vocalizations  
491 for 9 individuals, Fig. 5B) to ensure a consistent assessment of males' number. Although the  
492 efficiency of the clustering method is density dependent, this is on a smaller scale than those  
493 of classical counting methods (Budka et al., 2015; Linhart and Šálek, 2017). To apply our  
494 analysis methodology across populations in different locations, we would probably need to  
495 consider a range of higher signal diversities. The generalization of our study would thus need  
496 to train our statistical model (PPLS-DA) with recordings from identified males, from other rock  
497 ptarmigan populations, to encompass greater signal variability and to avoid staying at local  
498 scale variability.

499

#### 500 4.4 Is bioacoustics monitoring a good solution for rock ptarmigan population monitoring?

501 The choice of a monitoring method is the result of a balance between the scale of the study  
502 and the expected results. At a fixed cost, the same number of automatic recorders allow to  
503 gather precise information regarding males' abundance and locations within a restricted area  
504 or could provide simple presence/absence survey of a wider region. Besides, the

505 bioacoustics approach could enable the censusing of more areas without requiring an  
506 increase of the number of observers and/or days of observation. This may be particularly  
507 advantageous in large and remote mountain massifs where rock ptarmigan habitats can be  
508 situated in remote areas.

509

## 510 **References**

511 Adi, K., Johnson, M.T., Osiejuk, T.S., 2010. Acoustic censusing using automatic vocalization  
512 classification and identity recognition. *J. Acoust. Soc. Am.* 127, 874–883.

513 <https://doi.org/10.1121/1.3273887>

514 Aguiar-Conraria, L., Soares, M.J., 2011. The continuous wavelet transform: a primer  
515 (workingPaper). Universidade do Minho. Núcleo de Investigação em Políticas Económicas  
516 (NIPE).

517 Andreassen, T., Surlykke, A., Hallam, J., 2014. Semi-automatic long-term acoustic  
518 surveying: A case study with bats. *Ecol. Inform.* 21, 13–24.

519 <https://doi.org/10.1016/j.ecoinf.2013.12.010>

520 Andreev, A.V., 1971. Ecological characteristics of *Lagopus mutus* on the commander  
521 islands. *Zoologicheskii Journal* 50, 1260–1262.

522 Bart, J., Droege, S., Geissler, P., Peterjohn, B., Ralph, C.J., 2004. Density estimation in  
523 wildlife surveys. *Wildlife Soc. B.* 32, 1242–1247.

524 [https://doi.org/10.2193/00917648\(2004\)032\[1242:DEIWS\]2.0.CO;2](https://doi.org/10.2193/00917648(2004)032[1242:DEIWS]2.0.CO;2)

525 Bech, N., Barbu, C.M., Quéméré, E., Novoa, C., Allienne, J.F., Boissier, J., 2013. Pyrenean  
526 ptarmigans decline under climatic and human influences through the Holocene. *Heredity*  
527 111, 402–409. <https://doi.org/10.1038/hdy.2013.62>

528 Bergé, L., Bouveyron, C., Girard, S., 2012. HDclassif: An R Package for Model-Based  
529 Clustering and Discriminant Analysis of High-Dimensional Data. *J. Stat. Softw.* 46.

530 <https://doi.org/10.18637/jss.v046.i06>

531 Bossert, A., 1977. Bestandesaufnahme am Alpenschneehuhn *Lagopus mutus* im  
532 Aletschgebiet. *Der Ornithologische Beobachter* 95–98.

533 Bouveyron, C., Girard, S., Schmid, C., 2007. High-dimensional data clustering. *Comput. Stat.*  
534 *Data An.* 52, 502–519. <https://doi.org/10.1016/j.csda.2007.02.009>

535 Budka, M., Wojas, L., Osiejuk, T.S., 2015. Is it possible to acoustically identify individuals  
536 within a population? *J. Ornithol.* 156, 481–488. <https://doi.org/10.1007/s10336-014-1149-2>

537 Budka, M., Deoniziak, K., Tumiel, T., Woźna, J.T., 2018. Vocal individuality in drumming in  
538 great spotted woodpecker—A biological perspective and implications for conservation. PLoS  
539 ONE 13, e0191716. <https://doi.org/10.1371/journal.pone.0191716>

540 Buxton, R.T., Jones, I.L., 2012. Measuring nocturnal seabird activity and status using  
541 acoustic recording devices: applications for island restoration: Acoustic Monitoring of  
542 Nocturnal Seabirds. J. Field Ornithol. 83, 47–60. [https://doi.org/10.1111/j.1557-  
543 9263.2011.00355.x](https://doi.org/10.1111/j.1557-9263.2011.00355.x)

544 Caizergues, A., Bernard-Laurent, A., Brenot, J.-F., Ellison, L., Rasplus, J.Y., 2003.  
545 Population genetic structure of rock ptarmigan *Lagopus mutus* in Northern and Western  
546 Europe. Mol. Ecol. 12, 2267–2274. <https://doi.org/10.1046/j.1365-294X.2003.01889.x>

547 Catchpole, C., Slater, P.J.B., Mann, N., 2008. Bird song: biological themes and variations.  
548 Cambridge University Press, Cambridge.

549 Cattell, R.B., 1966. The Scree Test For The Number Of Factors. Multivar. Behav. Res. 1,  
550 245–276. [https://doi.org/10.1207/s15327906mbr0102\\_10](https://doi.org/10.1207/s15327906mbr0102_10)

551 Cotter, R.C., 1999. The Reproductive Biology of Rock Ptarmigan (*Lagopus mutus*) in the  
552 Central Canadian Arctic. ARCTIC 52. <https://doi.org/10.14430/arctic906>

553 Digby, A., Towsey, M., Bell, B.D., Teal, P.D., 2013. A practical comparison of manual and  
554 autonomous methods for acoustic monitoring. Methods Ecol. Evol. 4, 675–683.  
555 <https://doi.org/10.1111/2041-210X.12060>

556 Edwards, A.C., Scalenghe, R., Freppaz, M., 2007. Changes in the seasonal snow cover of  
557 alpine regions and its effect on soil processes: A review. Quaternary International, The Soil  
558 Record of Quaternary Climate Change 162–163, 172–181.  
559 <https://doi.org/10.1016/j.quaint.2006.10.027>

560 Elphick, C.S., 2008. How you count counts: the importance of methods research in applied  
561 ecology. J. Appl. Ecol. 45, 1313–1320. <https://doi.org/10.1111/j.1365-2664.2008.01545.x>

562 Feng, J.-J., Cui, L.-W., Ma, C.-Y., Fei, H.-L., Fan, P.-F., 2014. Individuality and Stability in  
563 Male Songs of Cao Vit Gibbons (*Nomascus nasutus*) with Potential to Monitor Population  
564 Dynamics. PLoS ONE 9, e96317. <https://doi.org/10.1371/journal.pone.0096317>

565 Fitzpatrick, M.C., Preisser, E.L., Ellison, A.M., Elkinton, J.S., 2009. Observer bias and the  
566 detection of low-density populations. Ecol. Appl. 19, 1673–1679. [https://doi.org/10.1890/09-  
567 0265.1](https://doi.org/10.1890/09-0265.1)

568 Fraley, C., Raftery, A.E., 2002. Model-Based Clustering, Discriminant Analysis, and Density  
569 Estimation. *J. Am. Stat. Assoc.* 97, 611–631. <https://doi.org/10.1198/016214502760047131>

570 Furrer, R., Schaub, M., Bossert, A., Isler, R., Jenny, H., Jonas, T., Marti, C., Jenni, L., 2016.  
571 Variable decline of Alpine Rock Ptarmigan (*Lagopus muta helvetica*) in Switzerland between  
572 regions and sites. *J. Ornithol.* 157, 787–796. <https://doi.org/10.1007/s10336-016-1324-8>

573 Grabe, E., Low, E.L., 2002. Durational variability in speech and the rhythm class hypothesis.  
574 *Papers in laboratory phonology* 7.

575 Grava, T., Mathevon, N., Place, E., Balluet, P., 2008. Individual acoustic monitoring of the  
576 European Eagle Owl *Bubo bubo*. *Ibis* 150, 279-287. [https://doi.org/10.1111/j.1474-](https://doi.org/10.1111/j.1474-919X.2007.00776.x)  
577 [919X.2007.00776.x](https://doi.org/10.1111/j.1474-919X.2007.00776.x)

578 Hanser, S.E., Knick, S.T., 2011. Greater sage-grouse as an umbrella species for shrubland  
579 passerine birds: a multiscale assessment, in: Steven T. Knick, John W. Connelly (Eds.),  
580 *Greater Sage-Grouse*. Reston, VA, pp. 475–488.

581 Hartwig, S., 2005. Individual acoustic identification as a non-invasive conservation tool: an  
582 approach to the conservation of the african wild dog *Lycaon pictus* (temminck, 1820).  
583 *Bioacoustics* 15, 35–50. <https://doi.org/10.1080/09524622.2005.9753537>

584 Henden, J.-A., Ims, R.A., Fuglei, E., Pedersen, Å.Ø., 2017. Changed Arctic-alpine food web  
585 interactions under rapid climate warming: implication for ptarmigan research. *Wildlife Biol.*  
586 *wlb.00240*. <https://doi.org/10.2981/wlb.00240>

587 Hervé, M., 2018. *RVAideMemoire: Testing and Plotting Procedures for Biostatistics*.

588 Hervé, M.R., Nicolè, F., Lê Cao, K.-A., 2018. Multivariate Analysis of Multiple Datasets: a  
589 Practical Guide for Chemical Ecology. *J. Chem. Ecol.* 44, 215–234.  
590 <https://doi.org/10.1007/s10886-018-0932-6>

591 Heupel, M.R., Semmens, J.M., Hobday, A.J., 2006. Automated acoustic tracking of aquatic  
592 animals: scales, design and deployment of listening station arrays. *Mar. Freshwater Res.* 57,  
593 1–13. <https://doi.org/10.1071/MF05091>

594 Hoodless, A.N., Inglis, J.G., Doucet, J.-P., Aebischer, N.J., 2008. Vocal individuality in the  
595 roding calls of Woodcock *Scolopax rusticola* and their use to validate a survey method. *Ibis*  
596 150, 80-89. <https://doi.org/10.1111/j.1474-919X.2007.00743.x>

597 Hubert, L., Arabie, P., 1985. Comparing partitions. *J. Classif.* 2, 193–218.  
598 <https://doi.org/10.1007/BF01908075>

599 Imperio, S., Bionda, R., Viterbi, R., Provenzale, A., 2013. Climate Change and Human  
600 Disturbance Can Lead to Local Extinction of Alpine Rock Ptarmigan: New Insight from the  
601 Western Italian Alps. PLoS ONE 8, e81598. <https://doi.org/10.1371/journal.pone.0081598>

602 Jonas, T., Rixen, C., Sturm, M., Stoeckli, V. How alpine plant growth is linked to snow cover  
603 and climate variability. *Journal of Geophysical Research: Biogeosciences* 113.  
604 <https://doi.org/10.1029/2007JG000680>

605 Körner, C., 2003. *Alpine Plant Life: Functional Plant Ecology of High Mountain Ecosystems*.  
606 Springer-Verlag Berlin Heidelberg, New-York. <https://doi.org/10.1007/978-3-642-18970-8>

607 Kroodsma, D.E. (Ed.), 1982. *Production, perception, and design features of sounds, Acoustic*  
608 *communication in birds*. Acad. Pr., New York.

609 Kroodsma, D.E., Miller, E.H., Ouellet, H., 1982. *Acoustic Communication in Birds: Song*  
610 *learning and its consequences*. Acad. Pr., New York.

611 Lancia, R.A., Kendall, W.L., Pollock, K.H., Nichols, J.D., 2005. Estimating the number of  
612 animals in wildlife populations, in: Clait E. Braun (Ed.), *Techniques for Wildlife Investigations*  
613 *and Management*. Wildlife Society, Bethesda, Maryland, pp. 106–153.

614 Léonard, P., 1995. Méthode de dénombrement des Lagopèdes alpins mâles au chant et  
615 présentation des résultats. *Bull. mens. Off. natl. chasse* 199.

616 Liland, K.H., Indahl, U.G., 2009. Powered partial least squares discriminant analysis. *J.*  
617 *Chemometr.* 23, 7–18. <https://doi.org/10.1002/cem.1186>

618 Linhart, P., Šálek, M., 2017. The assessment of biases in the acoustic discrimination of  
619 individuals. PLoS ONE 12, e0177206. <https://doi.org/10.1371/journal.pone.0177206>

620 Lotz, A., Allen, C.R., 2007. Observer Bias in Anuran Call Surveys. *J. Wildlife Manage.* 71,  
621 675–679. <https://doi.org/10.2193/2005-759>

622 MacDonald, S.D., 1970. The breeding behavior of the Rock Ptarmigan. *Living Bird* 9, 195–  
623 238.

624 Marques, T.A., Thomas, L., Martin, S.W., Mellinger, D.K., Ward, J.A., Moretti, D.J., Harris,  
625 D., Tyack, P.L., 2013. Estimating animal population density using passive acoustics: Passive  
626 acoustic density estimation. *Biol. Rev.* 88, 287–309. <https://doi.org/10.1111/brv.12001>

627 Marques, T.A., Thomas, L., Ward, J., DiMarzio, N., Tyack, P.L., 2009. Estimating cetacean  
628 population density using fixed passive acoustic sensors: An example with Blainville's beaked  
629 whales. *J. Acoust. Soc. Am.* 125, 1982–1994. <https://doi.org/10.1121/1.3089590>

630 Martinoli, Alessio, Preatoni, D.G., Bisi, F., Gagliardi, A., Martinoli, Adriano, 2017. Where is  
631 the pulse to have the finger on? A retrospective analysis of two decades of Alpine Galliforms  
632 (Aves: Galliformes) census and game bag data in Italy. *Eur. J. Wildlife Res.* 63.  
633 <https://doi.org/10.1007/s10344-017-1122-5>

634 Marty, E., Mossoll-Torres, M., 2012. Point-count method for estimating rock ptarmigan  
635 spring density in the Pyrenean chain. *Eur. J. Wildlife Res.* 58, 357–363.  
636 <https://doi.org/10.1007/s10344-011-0541-y>

637 Mevik, B.-H., Wehrens, R., Liland, K.H., 2016. pls: Partial Least Squares and Principal  
638 Component Regression.

639 Novoa, C., Besnard, A., Brenot, J.F., Ellison, L.N., 2008. Effect of weather on the  
640 reproductive rate of Rock Ptarmigan *Lagopus muta* in the eastern Pyrenees: Weather and  
641 rock ptarmigan reproductive rate. *Ibis* 150, 270–278. [https://doi.org/10.1111/j.1474-](https://doi.org/10.1111/j.1474-919X.2007.00771.x)  
642 [919X.2007.00771.x](https://doi.org/10.1111/j.1474-919X.2007.00771.x)

643 Nowicki, S., Searcy, W.A., 2014. The evolution of vocal learning. *Curr. Opin. Neurobiol.* 28,  
644 48–53. <https://doi.org/10.1016/j.conb.2014.06.007>

645 O'Farrell, M.J., Gannon, W.L., 1999. A Comparison of Acoustic Versus Capture Techniques  
646 for the Inventory of Bats. *J. Mammal.* 80, 24–30. <https://doi.org/10.2307/1383204>

647 Peake, T.M., McGregor, P.K., 2001. Corncrake *Crex crex* census estimates: a conservation  
648 application of vocal individuality. *Anim. Biodiv. Conserv.* 24, 1, 81-90.

649 Peri, A., 2018a. A comparison of three methods for planning a census of Tawny Owl (*Strix*  
650 *aluco*) populations living at high territorial density. *Bioacoustics* 27, 245–260.  
651 <https://doi.org/10.1080/09524622.2017.1326164>

652 Peri, A., 2018b. Censusing a tawny owl (*Strix aluco*) population living at high density merging  
653 two consolidated techniques. *Écoscience* 1–9.  
654 <https://doi.org/10.1080/11956860.2018.1455370>

655 Piertney, S.B., Maccoll, A.D.C., Bacon, P.J., Dallas, J.F., 1998. Local genetic structure in red  
656 grouse (*Lagopus lagopus scoticus*): evidence from microsatellite DNA markers. *Molecular*  
657 *Ecology* 7, 1645–1654. <https://doi.org/10.1046/j.1365-294x.1998.00493.x>

658 Policht, R., Petru, M., Lastimoza, L., Suarez, L., 2009. Potential for the use of vocal  
659 individuality as a conservation research tool in two threatened Philippine hornbill species, the  
660 Visayan Hornbill and the Rufous-headed Hornbill. *Bird Conserv. Int.* 19, 83.  
661 <https://doi.org/10.1017/S0959270908008228>

662 Pollard, K.A., Blumstein, D.T., Griffin, S.C., 2010. Pre-screening acoustic and other natural  
663 signatures for use in noninvasive individual identification. *J. Appl. Ecol.* 47, 1103–1109.  
664 <https://doi.org/10.1111/j.1365-2664.2010.01851.x>

665 Revermann, R., Schmid, H., Zbinden, N., Spaar, R., Schröder, B., 2012. Habitat at the  
666 mountain tops: how long can Rock Ptarmigan (*Lagopus muta helvetica*) survive rapid climate  
667 change in the Swiss Alps? A multi-scale approach. *J. Ornithol.* 153, 891–905.  
668 <https://doi.org/10.1007/s10336-012-0819-1>

669 Roesch, A., Schmidbauer, H., 2018. WaveletComp: Computational Wavelet Analysis.

670 Sale, R., Potapov, R., 2013. Grouse Of The World. New Holland.

671 Sandercock, B.K., Martin, K., Hannon, S.J., 2005. Demographic consequences of age-  
672 structure in extreme environments: population models for arctic and alpine ptarmigan.  
673 *Oecologia* 146, 13–24. <https://doi.org/10.1007/s00442-005-0174-5>

674 Scrucca, L., Fop, M., Murphy, T.B., Raftery, A.E., 2016. mclust 5: Clustering, Classification  
675 and Density Estimation Using Gaussian Finite Mixture Models. *The R Journal* 8, 1, 289-317.

676 Slater, P.J.B., 1989. Bird song learning: causes and consequences. *Ethol. Ecol. Evol.* 1, 19–  
677 46. <https://doi.org/10.1080/08927014.1989.9525529>

678 Sueur, J., Aubin, T., Simonis, C., 2008. Seewave: a free modular tool for sound analysis and  
679 synthesis. *Bioacoustics* 18, 213–226.

680 Sueur, J., Farina, A., 2015. Ecoacoustics: The Ecological Investigation and Interpretation of  
681 Environmental Sound. *Biosemiotics* 8, 493–502. <https://doi.org/10.1007/s12304-015-9248-x>

682 Szymańska, E., Saccenti, E., Smilde, A.K., Westerhuis, J.A., 2012. Double-check: validation  
683 of diagnostic statistics for PLS-DA models in metabolomics studies. *Metabolomics* 8, 3–16.  
684 <https://doi.org/10.1007/s11306-011-0330-3>

685 Tamura, N., Boonkhw, P., Prayoon, U., Kanchanasaka, B., Hayashi, F., 2018. Mating calls  
686 are a sensitive indicator of phylogenetic relationships in tropical tree squirrels (*Callosciurus*  
687 *spp.*). *Mamm. Biol.* <https://doi.org/10.1016/j.mambio.2018.05.006>

688 Taylor, A.M., Reby, D., 2010. The contribution of source-filter theory to mammal vocal  
689 communication research: Advances in vocal communication research. *J. Zool.* 280, 221–236.  
690 <https://doi.org/10.1111/j.1469-7998.2009.00661.x>

691 Terry, A.M., Peake, T.M., McGregor, P.K., 2005. The role of vocal individuality in  
692 conservation. *Front. Zool.* 2, 1, 10. <https://doi.org/10.1186/1742-9994-2-10>

693 Terry, A.M.R., McGregor, P.K., 2002. Census and monitoring based on individually  
694 identifiable vocalizations: the role of neural networks. *Anim. Conserv.* 5, 103–111.  
695 <https://doi.org/10.1017/S1367943002002147>

696 Tibbetts, E.A., Dale, J., 2007. Individual recognition: it is good to be different. *Trends Ecol.*  
697 *Evol.* 22, 529–537. <https://doi.org/10.1016/j.tree.2007.09.001>

698 Towsey, M., Parsons, S., Sueur, J., 2014. Ecology and acoustics at a large scale. *Ecol.*  
699 *Inform.* 21, 1–3. <https://doi.org/10.1016/j.ecoinf.2014.02.002>

700 Tyre, A.J., Tenhumberg, B., Field, S.A., Niejalke, D., Parris, K., Possingham, H.P., 2003.  
701 Improving precision and reducing bias in biological surveys: estimating false-negative error  
702 rates. *Ecol. Appl.* 13, 1790–1801. <https://doi.org/10.1890/02-5078>

703 Ulloa, J.S., Aubin, T., Llusia, D., Bouveyron, C., Sueur, J., 2018. Estimating animal acoustic  
704 diversity in tropical environments using unsupervised multiresolution analysis. *Ecol. Indic.* 90,  
705 346–355. <https://doi.org/10.1016/j.ecolind.2018.03.026>

706 Ulloa, J.S., Gasc, A., Gaucher, P., Aubin, T., Réjou-Méchain, M., Sueur, J., 2016. Screening  
707 large audio datasets to determine the time and space distribution of Screaming Piha birds in  
708 a tropical forest. *Ecol. Inform.* 31, 91–99. <https://doi.org/10.1016/j.ecoinf.2015.11.012>

709 Unander, S., Steen, J.B., 1985. Behaviour and Social Structure in Svalbard Rock Ptarmigan  
710 *Lagopus mutus hyperboreus*. *Ornis Scand.* 16, 198–204. <https://doi.org/10.2307/3676631>

711 Vögeli, M., Laiolo, P., Serrano, D., Tella, J.L., 2008. Who are we sampling? Apparent  
712 survival differs between methods in a secretive species. *Oikos* 117, 1816–1823.  
713 <https://doi.org/10.1111/j.1600-0706.2008.17225.x>

714 Watson, A., 1965. A population study of ptarmigan (*Lagopus mutus*) in Scotland. *J. Anim.*  
715 *Ecol.* 34, 1, 135–172. doi:10.2307/2373

716 Westerhuis, J.A., Hoefsloot, H.C.J., Smit, S., Vis, D.J., Smilde, A.K., van Velzen, E.J.J., van  
717 Duijnhoven, J.P.M., van Dorsten, F.A., 2008. Assessment of PLS-DA cross validation.  
718 *Metabolomics* 4, 81–89. <https://doi.org/10.1007/s11306-007-0099-6>

719

## 720 **Acknowledgements**

721 This research was supported by the University of Lyon / Saint-Etienne (PhD stipend to TMC,  
722 research support), the ONCFS (Office National de la Chasse et de la Faune Sauvage),  
723 CeLyA (Centre Lyonnais d'Acoustique) and the Institut universitaire de France (NM). The  
724 Domaine Skiable de Flaine logistically supported the study. We would like to warmly thank

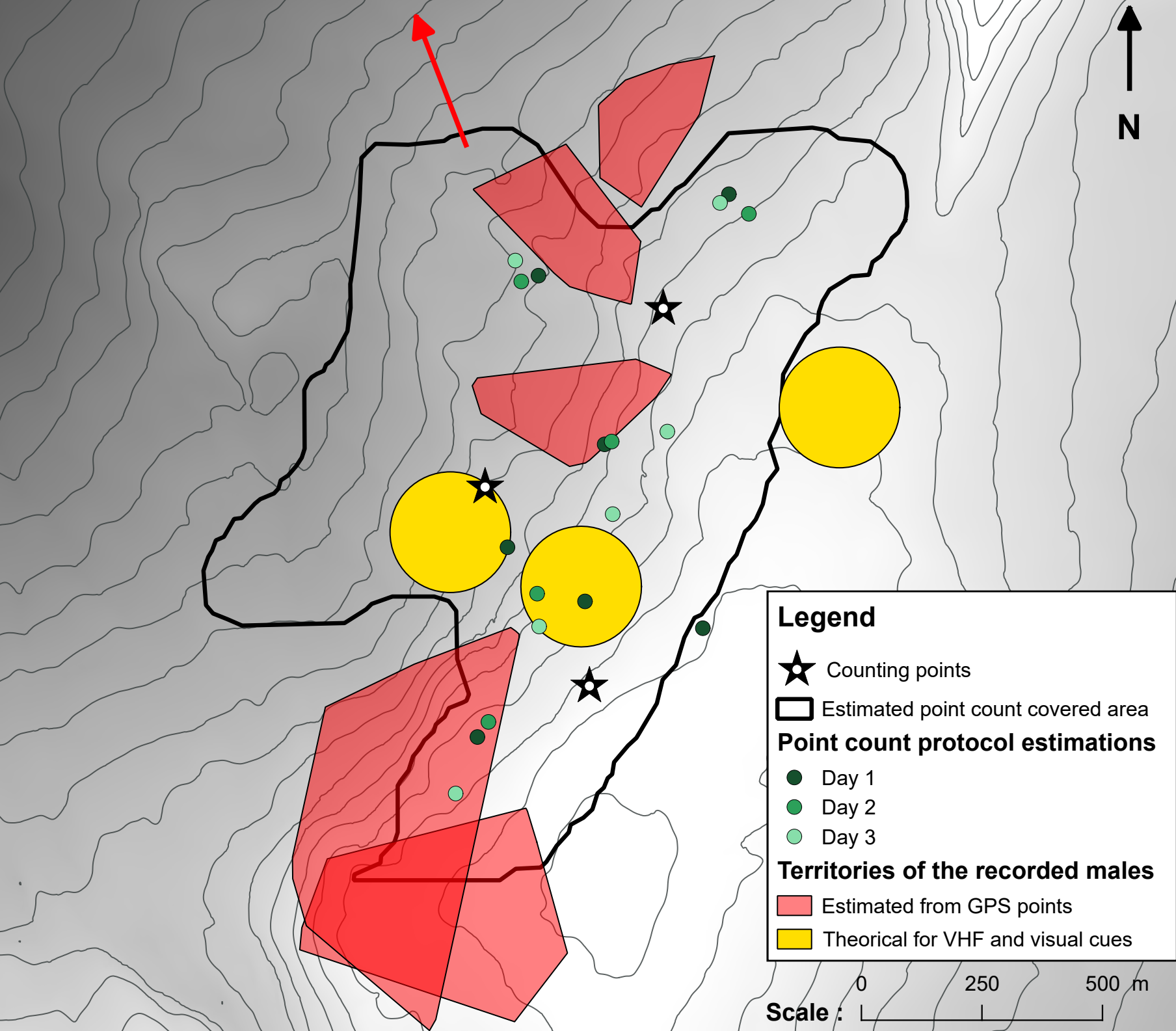


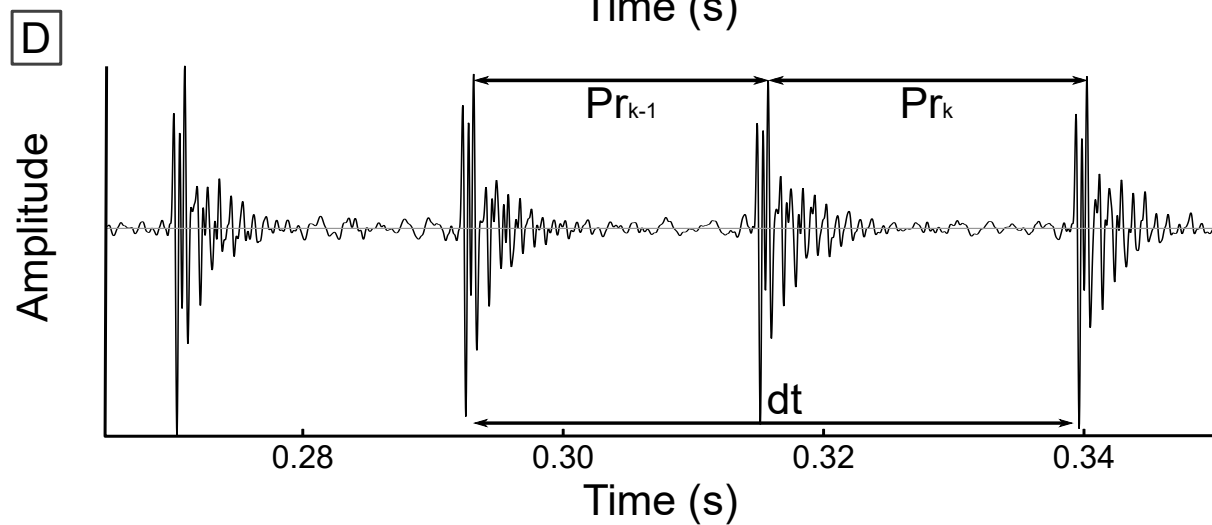
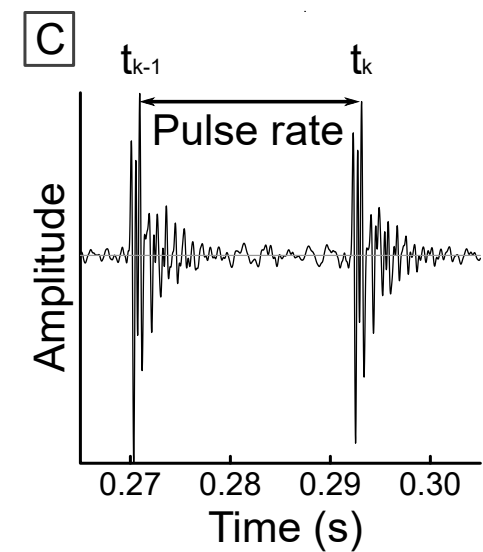
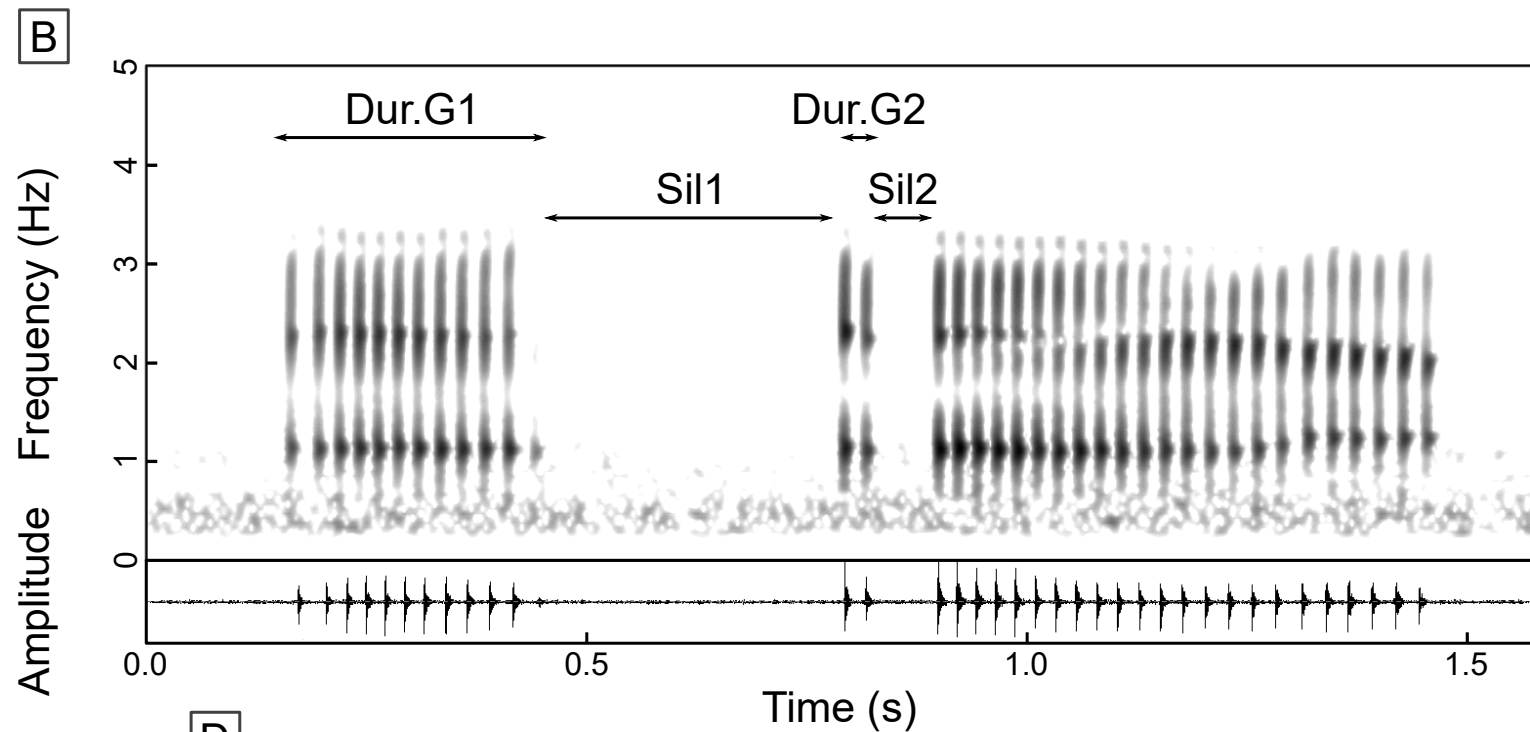
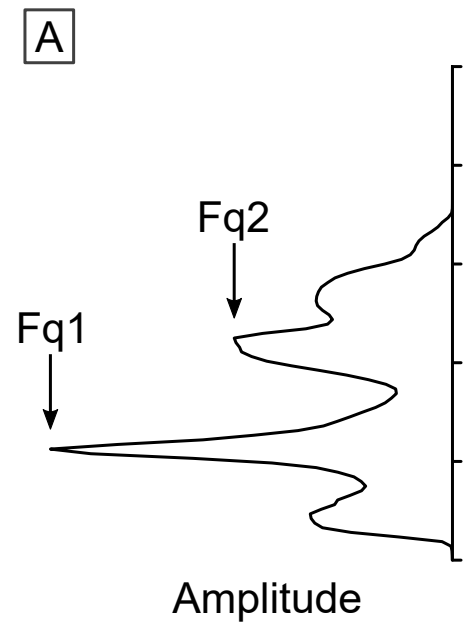
725 Fabrice Antoine, Marc Arvin-Berod, Thomas Betton, Loïc Berger, Sébastien Bernard, Michel  
726 Bouchard, Félicien Bros, Léna De Framond Benard, Etienne Marlé, Joël Prince, Aymeric  
727 Richard, Fanny Ryback, and Théophile Yeme who willingly volunteered to participate into the  
728 point-counts. We thank two anonymous reviewers for their helpful comments. The authors  
729 declare no conflict of interest.

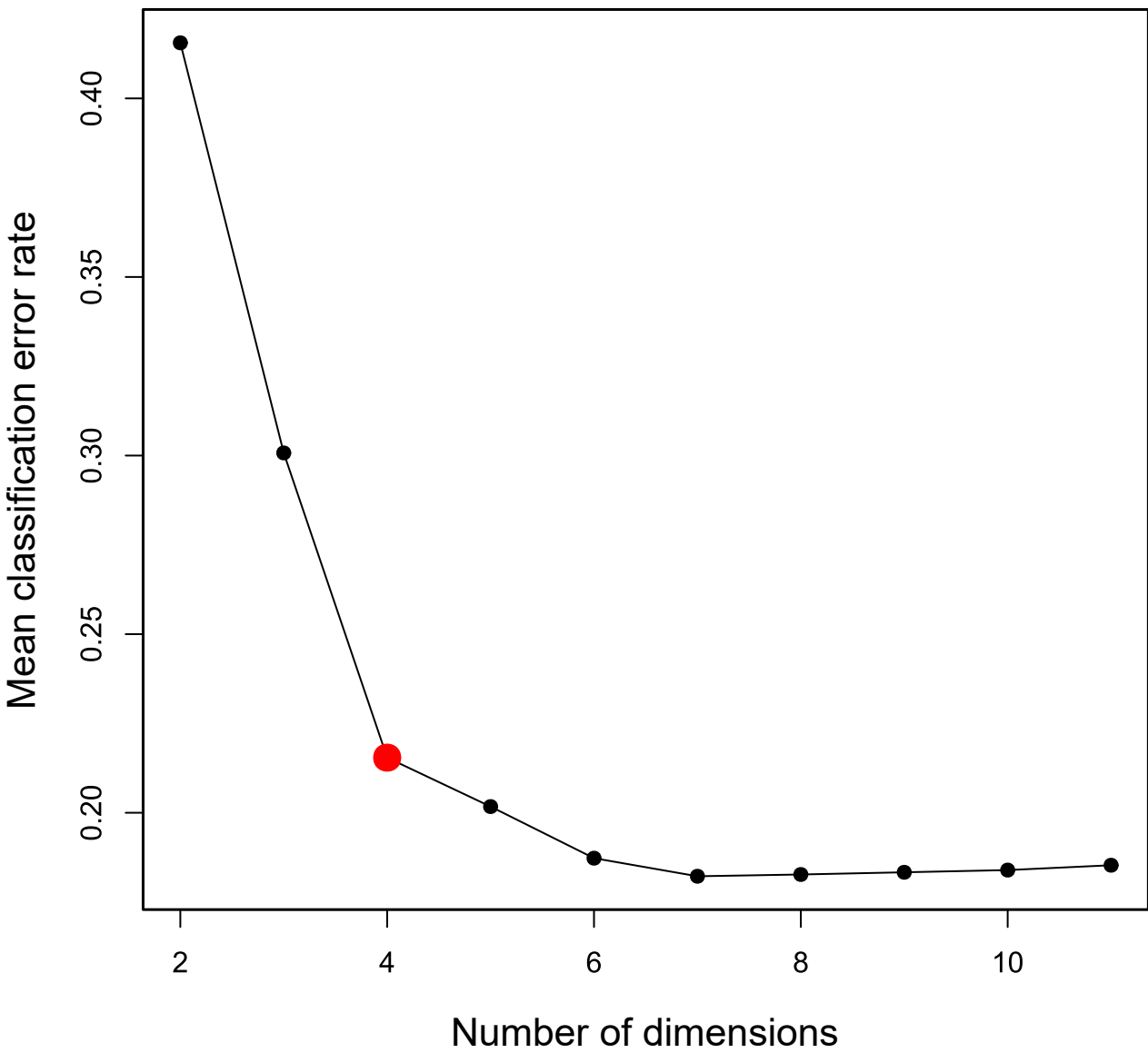
730

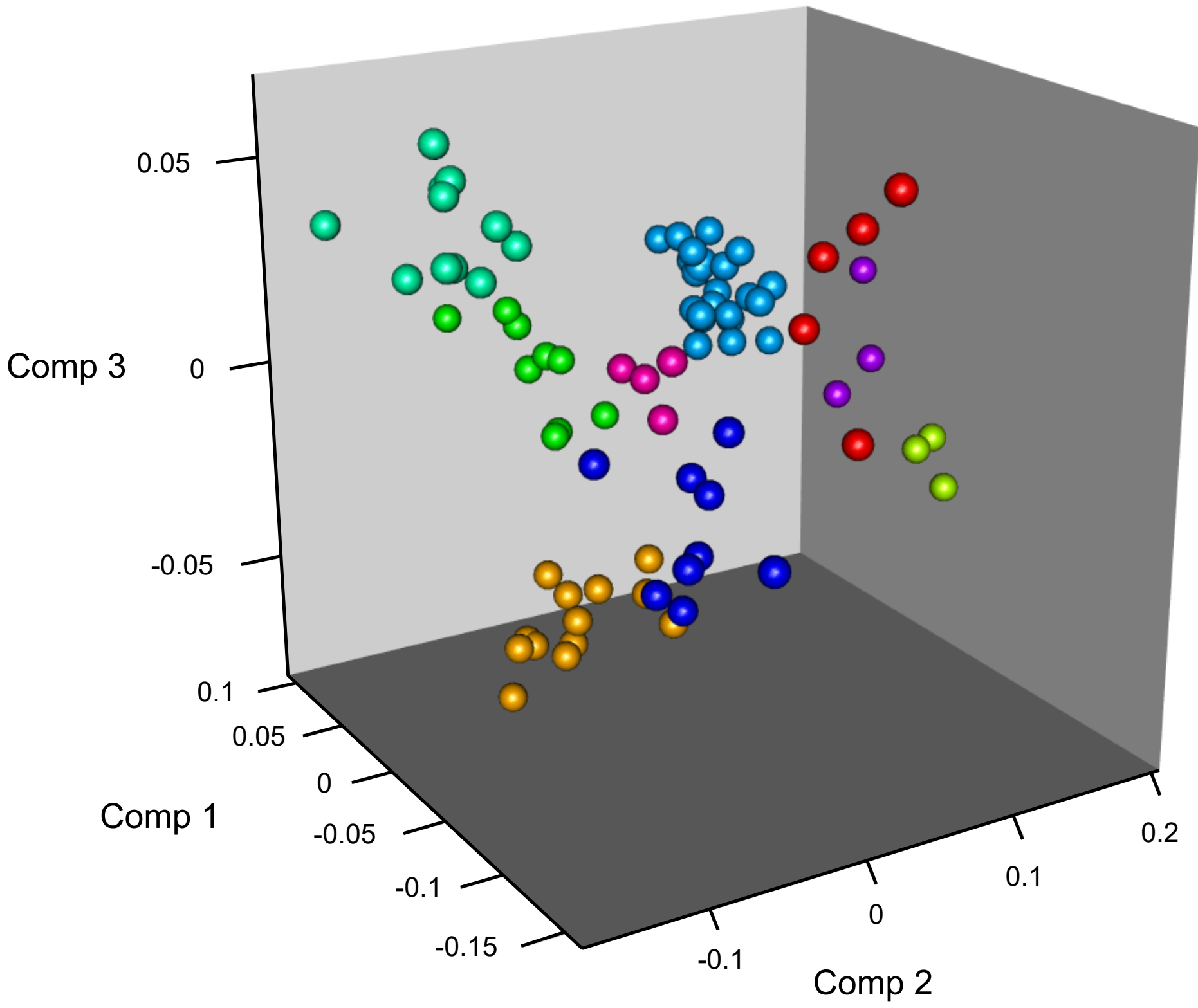
731 **Author contribution statement**

732 TMC, FS, BMJ, JFD, MMI, FN, PA, CN and NM conceived the ideas and designed the  
733 methodology; BMJ captured the males, equipped the GPS collar and organized the point-  
734 count protocols. TMC and FS collected the acoustic data; TMC, MMI, FN analyzed the data;  
735 TMC, FS and NM wrote the manuscript. All authors contributed critically to the drafts and  
736 gave final approval for publication.

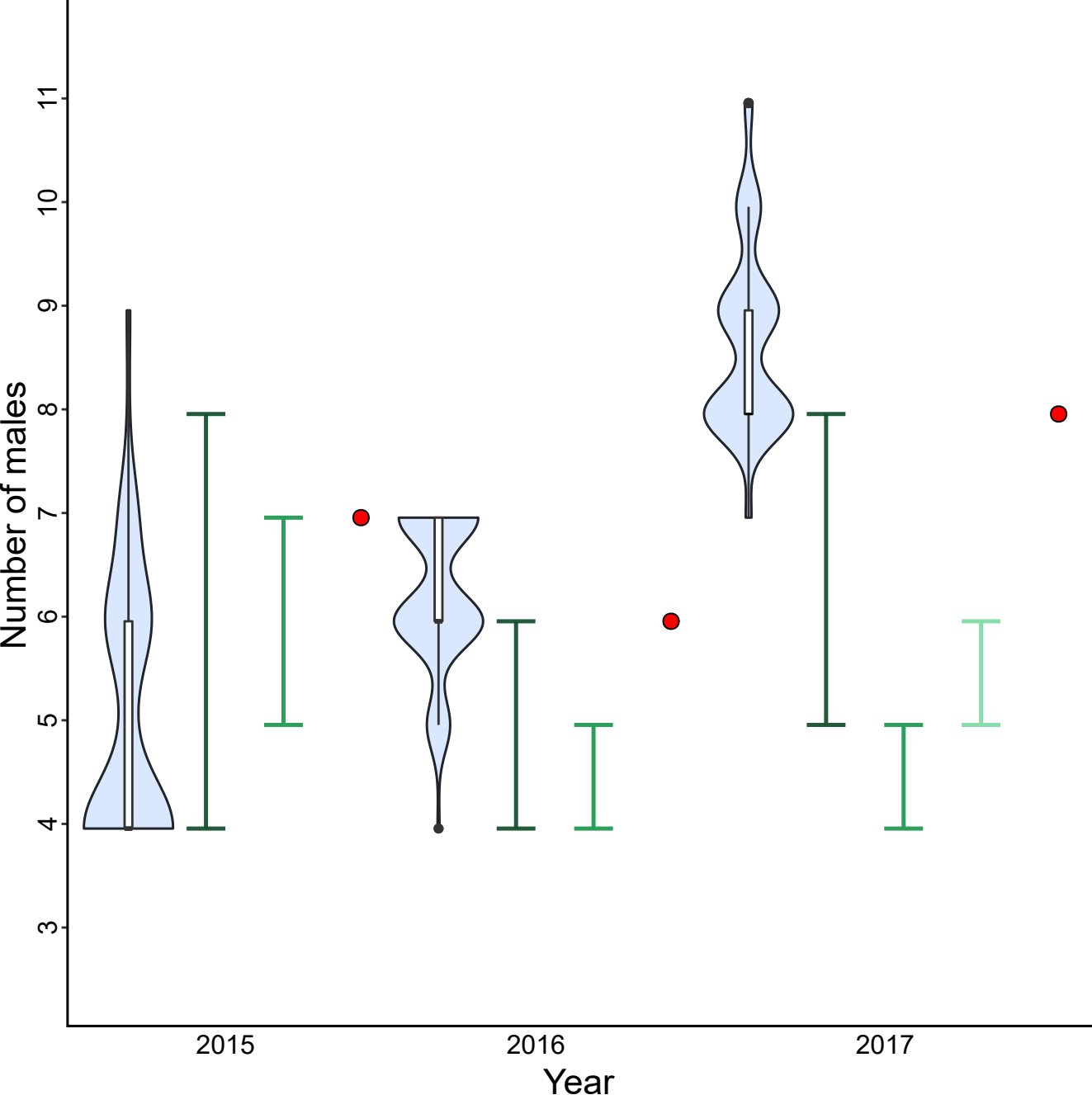




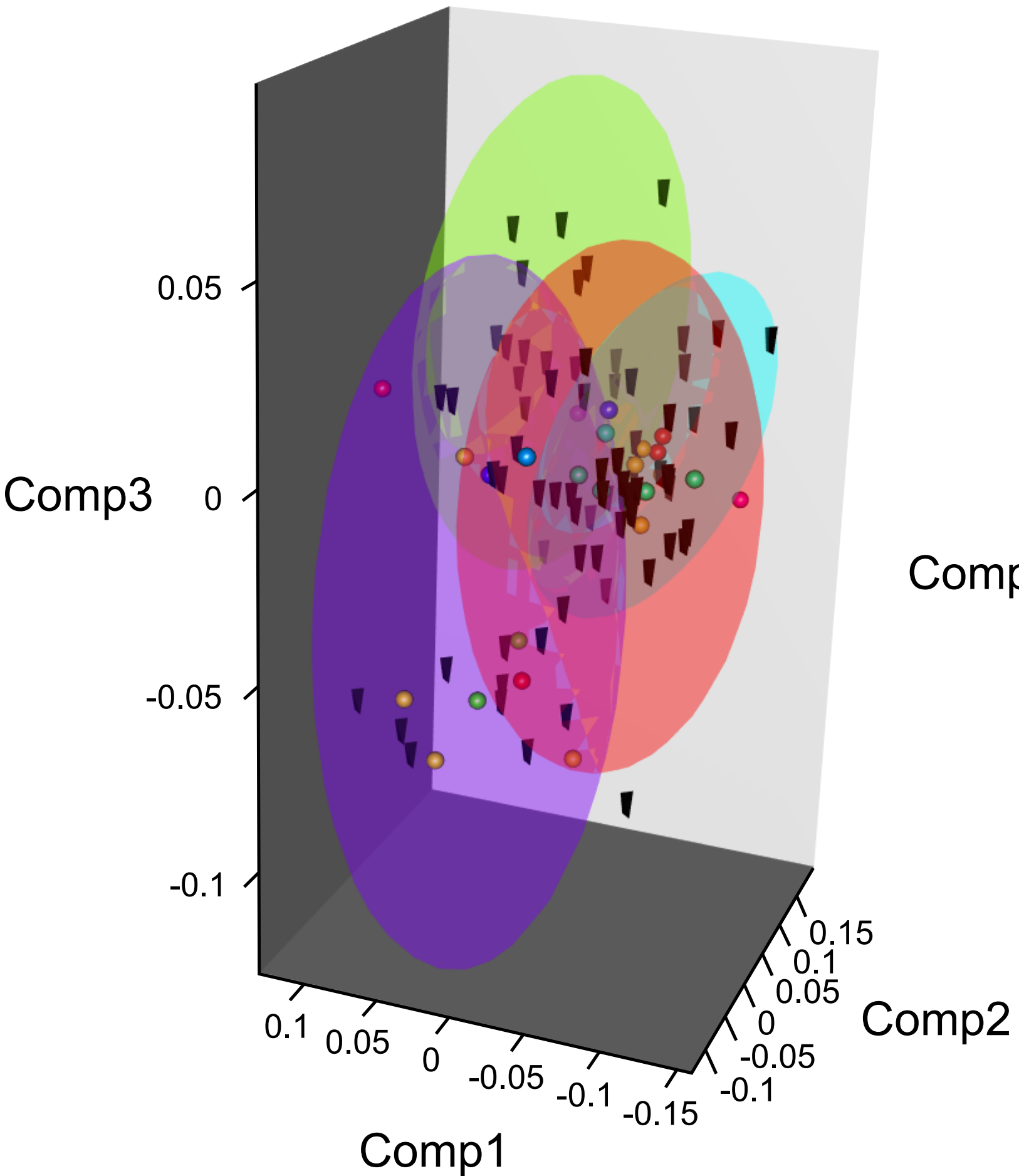




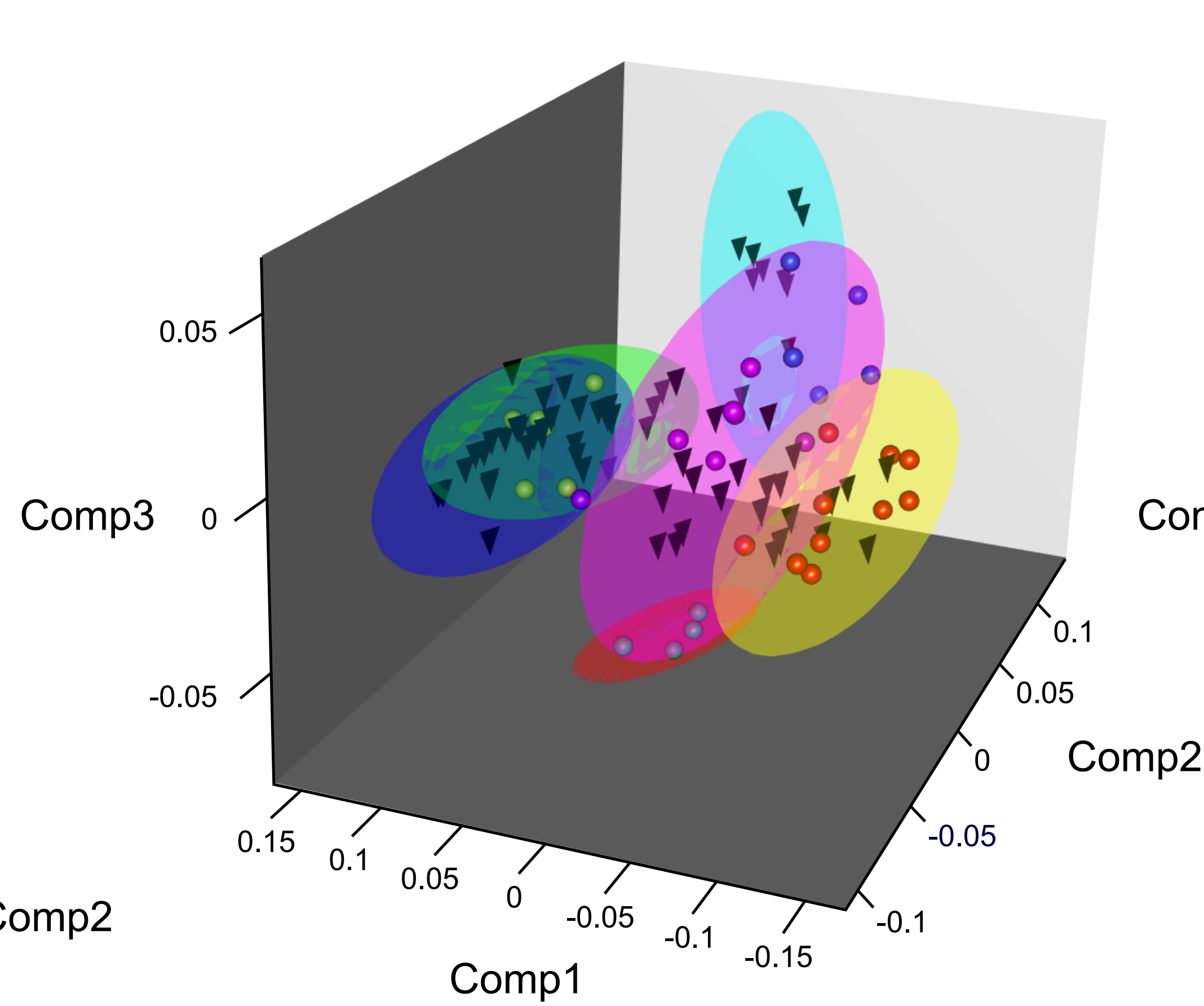




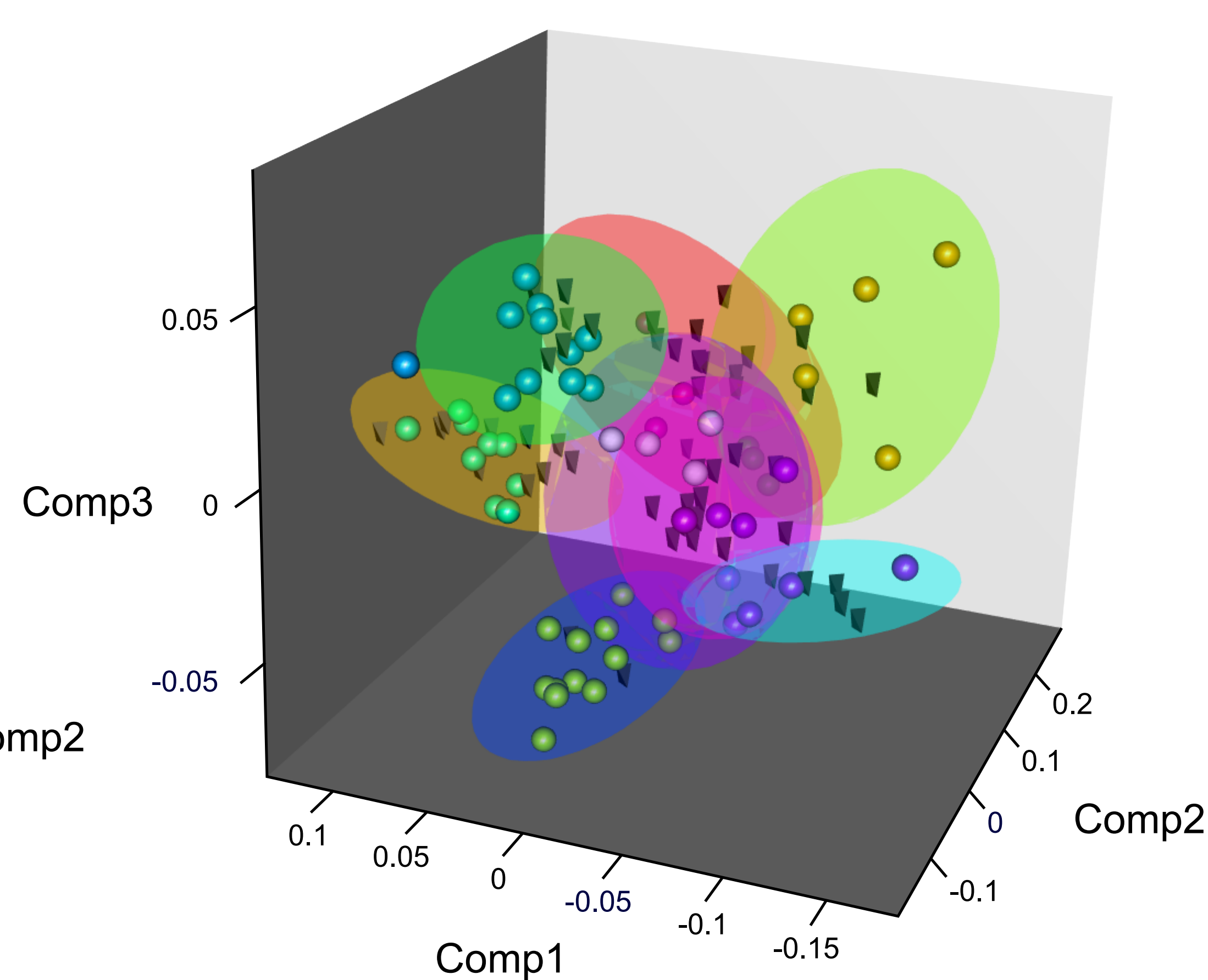
2015



2016



2017





## Tables

Category	Acoustic parameter		Mean $\pm$ sd	Min	Max
<b>Pulse number</b>	Number of pulses in G1	Pln.G1	15.88 $\pm$ 3.51	8.0	25.0
	Number of pulses in G2	Pln.G2	2.47 $\pm$ 0.55	2.0	4
<b>Temporal</b>	G1 duration (sec)	Dur.G1	0.31 $\pm$ 0.06	0.18	0.47
	G2 duration (sec)	Dur.G2	0.031 $\pm$ 0.009	0.016	0.054
	Duration between G1 and G2 (sec)	Sil1	0.38 $\pm$ 0.03	0.33	0.48
	Duration between G2 and G3 (sec)	Sil2	0.09 $\pm$ 0.02	0.048	0.14
	Pulse rate Median in G1 (sec)	Plr.G1	0.021 $\pm$ 0.0031	0.0145	0.028
	Pulse rate median in G2 (sec)	Plr.G2	0.022 $\pm$ 0.0034	0.0147	0.031
<b>Pulse rate</b>	Mean acceleration in G1	Acc.G1	22.51 $\pm$ 24.32	-31.22	130.59
	nPVI in G1	nPVI.G1	5.42 $\pm$ 3.98	1.56	28.76
	nPVI in G2	nPVI.G2	4.16 $\pm$ 6.34	0	20.84
	Median of the first peak frequency in G1 (Hz)	Fq1.G1	1.12 $\pm$ 0.06	0.97	1.30
<b>Frequency</b>	Median of the second peak frequency G1 (Hz)	Fq2.G1	2.25 $\pm$ 0.11	1.93	2.50

**Table 1.** Acoustic parameters describing the acoustic structure of the male ptarmigan call.

Acoustic variables	Comp 1	Comp 2	Comp 3	Comp 4
<b>Pln.G1</b>	0.86	0.16	0.30	0.061
<b>Pln.G2</b>	0.69	0.24	0.40	0.051
<b>Dur.G1</b>	0.80	0.44	0.15	0.11

<b>Dur.G2</b>	0.58	0.17	0.18	0.013
<b>Sil1</b>	-0.45	0.42	0.53	0.22
<b>Sil2</b>	0.22	0.36	0.71	0.25
<b>Plr.G1</b>	0.48	0.29	0.63	0.22
<b>Plr.G2</b>	0.53	0.26	0.43	0.097
<b>nPVI.G1</b>	0.058	0.48	0.023	0.030
<b>nPVI.G2</b>	0.46	0.26	-0.19	0.49
<b>Acc.G1</b>	0.079	0.13	0.35	-0.45
<b>Fq1.G1</b>	0.34	0.69	0.47	0.020
<b>Fq2. G1</b>	0.76	-0.43	0.049	0.21

**Table 2.** Correlation between acoustic variable and PLS-DA components