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Temporal dynamics in diversity patterns of fish sound production in the Condor seamount (Azores, NE Atlantic)

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1 **Temporal dynamics in diversity patterns of fish sound production**

2 **in the Condor seamount (Azores, NE Atlantic)**

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21 **Abstract**

22 Fish sounds are important components of Azorean soundscapes. Therefore, unraveling

23 their patterns can contribute to a better assessment of local biodiversity dynamics.

24 Passive Acoustic Monitoring (PAM) is a cost-effective, non-intrusive method providing

25 long-term information regardless of weather or logistic conditions, which can be

26 especially useful when monitoring remote areas. Using PAM, we assess temporal

27 dynamics of fish vocal activity in a protected seamount and validate PAM as an

28 important tool for biodiversity assessment in deep-sea fish communities. Thus, we

29 evaluated the annual, seasonal and diel patterns of variation of putative fish sounds

30 identified in an Azorean protected seamount, the Condor (*ca.*190 m depth). Here, 3

31 years (2008, 2010 and 2012) of acoustic data were collected and analyzed for diversity

32 and abundance of the most prevalent fish sounds. We compared abundance and

33 diversity of fish sounds before and after the establishment of the marine protected area

34 in 2010, to assess its initial protection effects. We also compared abundance and

35 biodiversity measures (richness and Shannon diversity index) of acoustic data with

36 fishing data from deep-water longline surveys, to verify if acoustic diversity and

37 taxonomic diversity show a similar trend. Additionally, we estimated a likely distance

38 range of fish sound sources from the acoustic data loggers for local background noise

39 and typical fish sound levels. Estimated detection distance of different fish sounds,

40 considering Condor background noise level and reported fish sound source levels, were

41 typically larger than 10 m and could reach hundreds of meters in some species

42 suggesting that this study potentially targeted sounds of the deep-sea fish fauna. Fish

43 acoustic activity was prevalent at dusks and nights of all years, while no overall

44 seasonal pattern was detected. However, one sound sequence (#1) was dominant in the

45 autumns of all studied period. A decrease in abundance and richness of sounds was

46 observed from 2008 to 2012 in line with the results of fishing surveys. Although

47 unexpected, these consistent trends suggest that PAM provides a reliable representation

48 of fish biodiversity dynamics. Taken together, this study shows that monitoring fish

49 sounds with PAM is a valid and promising tool for fish biodiversity assessment in deep

50 Azorean seamounts.

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52
53 Key-words: Fish sounds, passive acoustic monitoring, Fish sound detection distance,

54 biodiversity, temporal patterns, deep-water fishes.

55

56 1. Introduction

57 Finding effective ways to measure ocean biodiversity and health is paramount to

58 monitor the effects of pressures such as climate change, pollution, coastal development,

59 and overfishing ramp up. Registering sounds emanating from aquatic organisms by

60 using Passive Acoustic Monitoring (PAM) is a cost-effective, non-intrusive tool that is

61 becoming invaluable for long-term oceanic surveys (Lammers et al. 2008). PAM takes

62 advantage of programmable autonomous recording systems that can be deployed at

63 chosen places and depths, which is especially relevant for deep-sea studies, since it

64 allows to collect large datasets in real time at extended temporal and spatial scales, even

65 in remote locations (André et al. 2011). It allows to estimate community composition,

66 population density of different species, as well as temporal and spatial patterns of

67 species distribution and behaviour (Marques et al. 2013; Ruppé et al. 2015; Parsons et

68 al. 2016; Desiderà et al. 2019). Acoustic data can also be used as biodiversity proxies

69 (Browning et al. 2017). Thus, PAM can be an important complementary tool of

70 traditional biodiversity assessments, since acoustic measurements may provide

71 continuous information impossible to gather by other methods, like visual censuses or

72 fishing surveys. For example, it is capable of detecting species that are visually cryptic

73 but acoustically active like toadfish, cusk-eel or snapping shrimps, or aquatic organisms

74 that are acoustically active at night (Staaterman et al. 2017; Picciulin et al. 2019).

75 Therefore, this tool can play a major role in the implementation, monitoring and

76 management of marine protected areas and in monitoring remote areas such as deep-sea

77 environments.

78   In addition to detecting vocal species, PAM may also be used to characterize the

79 overall biophonical component of marine soundscapes, by listening to sounds that are

80 by-products of animal activities such as locomotion, foraging, and breathing (Sueur &

81 Farina 2015). Recently, fish sounds have been studied in an ecological framework to

82 tackle biodiversity, ecology and conservation issues at the population and at the

83 community level (Desiderà et al. 2019). However, in marine environments and

84 particularly in deeper oceanic waters, it is still unclear whether acoustic diversity

85 correlates with fish diversity (Bolgan et al. 2018; Desiderà et al. 2019). Likewise, the

86 effectiveness of PAM in monitoring marine protected areas needs to be established

87 (Picciulin et al. 2019).

88   A significant number of fish species signal acoustically in social contexts such

89 as during reproduction, agonistic interactions (Amorim 2006; Ladich 2019), to maintain

90 group cohesion (Van Oosterom et al. 2016) or while schooling (Larsson 2009). Because

91 acoustic communication in fishes may be influenced by several factors, such as predator

92 avoidance, foraging opportunities, reproductive activity or environmental constraints,

93 fishes may concentrate their calling effort in a particular time of the day or period of the

94 year in association with the prevailing acoustic and ecological contexts (Helfman 1986,

95 McCauley 2012, Ruppé et al. 2015, Rice et al. 2017). The documentation of temporal

96 patterns of abundance and diversity of fish sounds is therefore paramount to interpret

97 acoustic data in terms of biodiversity and ocean health and to establish vocal fishes as

98 indicator species for marine environmental status (Di Iorio et al. 2018).

99   Seamounts are submerged mountains that rise from the seafloor but do not reach

100 the surface. Despite being widespread throughout all oceans' basins, their biodiversity

101 remains still largely unknown (Pitcher et al. 2007). In the Azorean waters, several

102 seamounts have been identified and studied due to the increasing recognition of their

103 importance as biodiversity hotspots (Morato et al. 2008, Morato et al. 2010, Morato et

104 al. 2016). These areas are considered among the remaining pristine places on earth

105 (Pitcher et al. 2007). Seamounts bring together physical conditions, like nutrient

106 upwellings, but mostly an increase of primary or secondary productivity seems to be the

107 main mechanism driving a high biodiversity (Pitcher et al. 2007, Morato et al. 2010).

108 Indeed, many fish species aggregate on seamounts to feed or mate. These include many

109 acoustically active fish species which are commercially or ecologically important, such

110 as the dusky grouper *Epinephelus marginatus*, the sunfish *Mola mola*, the redfish

111 *Sebastes norvegicus,* the tarpon *Megalops atlanticus*, the Atlantic herring *Clupea*

112 *harengus* and the haddock *Melanogrammus aeglefinus* (Fish and Mowbray 1970;

113 Hawkins & Amorim 2000; Bertucci et al. 2015). Therefore, acoustic monitoring may

114 help to unravel the presence of sound producing fish species at seamounts bringing new

115 insights on fish communities inhabiting these diverse and pristine locations. The aims

116 of this study were to test the utility of using acoustic data to (1) assess fish biodiversity

117 in deeper waters (validated with data from fishing surveys), (2) detect temporal patterns

118 of fish vocal activity including (3) changes driven by the shift in marine protection

119 status.

120   In Carriço et al. (2019) we uncovered an important diversity of fish sounds from

121 two Azorean seamounts. Here, we report on the annual, seasonal and diel patterns of

122   occurrence of fish sounds recorded by acoustic data loggers at ca. 190 m depth on

123   Condor seamount, near the 200 m depth upper limit of the bathyal and mesopelagic

124   zones (Priede 2017). Taking advantage from tools such as biodiversity indices, we

125   compare bioacoustic data with longline fishing survey data collected in the same site

126   (150-950 m depth; Menezes & Giacomello 2013). As Condor seamount became

127   protected in 2010 (Giacomello et al. 2013), we evaluate changes in the abundance and

128   diversity of sounds and fish fauna before and just after the establishment of the

129   protected area. Finally, we estimate the attenuation range of fish sound sources to local

130   background noise using typical fish sound levels to evaluate if our dataloggers are

131   targeting sounds of the deep-sea fish fauna and discuss the advantages and limitations of

132   PAM to monitor deep-water areas.

133

134   2. Materials and Methods

135   2.1 Study site

136   The Azores is an archipelago composed of nine volcanic islands and several underwater

137   seamounts. The Condor seamount is located about 17 km southwest of Faial island (Fig.

138   1). In 2010, an area of 242 km^2 (22 km x 11 km) encompassing the entire Condor

139   seamount until ca. 1000 m depth, was designated as a protected area for scientific

140   research through an agreement among local authorities, researchers, fishermen and

141   other stakeholders (Giacomello et al. 2013). Most commercial fisheries became

142   forbidden in the area, and, activities such as seasonal pole-and-line tuna fishing, big

143   game fishing, bait fishing, and scientific or recreational fishing are allowed under a

144   special authorization (Giacomello et al. 2013; Ressurreição & Giacomello 2013).
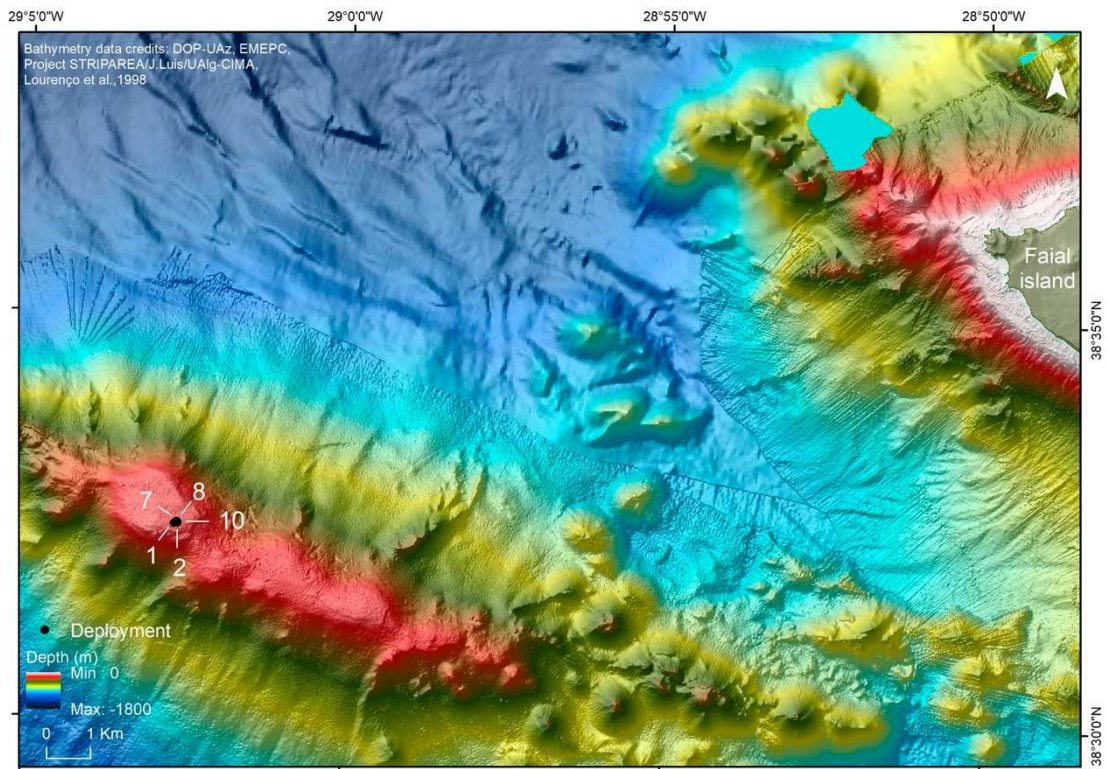
145

146 Fig. 1. Location of the deployment sites of the EARs in the Condor seamount.

147 Recordings were analysed from deployments 1 (38 32.390 N, 29 02.753 W at 190.8 m),

148 2 (38 32.395 N, 29 02.617 W at 193.3 m), 7 (38 32.407 N, 29 02.627 W at 193.4 m), 8

149 (38 32.381 N, 29 02.604 W at 193.1 m) and 10 (38 32.399 N, 29 02.615 W at 193.3 m).

150 The maximum distance among all 5 deployments used was 217 m.

151

152 **2.2 Acoustic recordings**

153 Ten deployments of Ecological Acoustic Recorders (EARs, Lammers et al.

154 2008) were made between 2008 and 2012 in the Condor seamount (Fig. 1). The EAR is

155 an autonomous acoustic recorder with a Sensor Technology SQ26-01 hydrophone and a

156 response sensitivity of −193.14/−194.17 dB re 1 V/µPa (varying between deployments).

157 The frequency response from 1 Hz to 28 kHz varies within ± 1.5 dB. EARs were

158 bottom-moored at an approximate bottom depth of 190 m, while the recorder was kept

159 at 8-10 m from the seafloor. Each deployment recorded for approximately 6-7 months.

160 From these, we selected data from deployments based on recordings availability

161 throughout the year and quality of the recordings. 2008, 2010 and 2012 were analysed

162 and 2009 and 2011 were discarded. These different years allowed to assess the

163 abundance and diversity of fish sound sequences before and after the protection status

164 was implemented. Fish sound sequences are sequences of several isolated sounds of the

165 same type, repeated in a close, stereotyped pattern, ranging from 1 to several sounds

166 (average 2-16 sounds per sequence and with an average sound interval of 0.16-0.75 s),

167 as described in Carriço et al. (2019).

168   The location of each deployment varied in a range of c. 7-217 m, since the

169 deployment process did not allow an exact placement in the exact same location (Fig.

170 1).

171   The programming (sampling effort) of the data loggers was different in different

172 deployments: deployments 1 (2008) recorded 0.5 min (sampling duration) every 10 min

173 (sampling period); 2 (2008), 7 and 8 (2010) recorded 1.5 min every 15 min at a

174 sampling rate of 50 kHz, while deployment 10 (2012) recorded 60 min every 210 min,

175 at 2 kHz. Considering the different sampling efforts between the three deployments, the

176 daily number of sound sequences (number of sound sequences per day) was

177 standardized according to the respective weighting value for each sampling effort (i.e.

178 each value was multiplied by the ratio between sampling period and sampling duration),

179 so they could be comparable. However, the different sampling efforts may affect the

180 probability of detecting a sound. The cycle of recordings may be mismatched with the

181 cycle of vocalizations (duration, repetition rate, interval) which can contribute to miss

182 some sounds and consequently underestimate their occurrence (Stanistreet et al. 2016).

183 All the recordings were converted to 8 kHz.

184

8

1

2.3 Temporal patterns of acoustic data

Eco-acoustic indices, like the ACI, are mathematical functions which characterize variation of acoustic energy in the time and frequency domains of the soundscape (Browning et al. 2017, Sueur 2018). These indices allow for a holistic approach which evaluates the global acoustic environment as a proxy of species assemblage diversity (Sueur et al. 2008). In marine habitats, however, methodological validations (such as manual inspection of acoustic tracks) are required for understanding which kind of information are highlighted by acoustic indexes in each specific environment (Belghith et al. 2018; Bolgan et al. 2018). Bolgan et al. (2018) showed that the ACI is sensitive to variation of fish sound abundances (i.e. number of sounds) as well as of fish sound diversity (i.e. number of sound types) but it cannot discern between these two parameters. In the light of the above studies, we used the ACI as a tool for quickly exploring our large dataset to identify the acoustic tracks with highest abundance and/or diversity of fish sound sequences. The ACI was calculated on four months of recordings collected during three different years. In particular, the ACI was computed on data from 2008 (April, May, August and November), 2010 (April, June, August and December) and 2012 (March, June, August and November). For the data of 2008 and 2010, the ACI was computed for two bandwidths, 15-2000 Hz and 2000-4000 Hz (bandwidths in which fish sounds are more likely to occur and have most of their acoustic energy); for 2012, the ACI was computed only in the bandwidth 15-1000 Hz (because here the sampling rate was only 2000 Hz), using the plug-in SoundscapeMeter (FFT window size: 512, frequency resolution: 8 kHz, temporal resolution of the ACI algorithm: 0.5 s, noise filter: 0) in the WaveSurfer software (Pieretti et al. 2011). For each month of recordings, a subsample of 5 days was chosen for manual spectrogram inspection within

210   the days with the highest ACI values (Pieretti et al. 2011). Manual spectrogram

211   inspections allowed for a quantification of the number of sound sequences for each

212   sound sequence type (as most sounds occurred in sequences), which could have not

213   been achieved by application of acoustic indexes alone (Bolgan et al. 2018).

214   For the temporal analysis (annual, seasonal and diel), we selected the most

215   common sequences. Manual acoustic analysis measured abundance and diversity of fish

216   sounds sequences.

217   The four most common fish sound sequences were #1, #4, #5 and #10 (Fig. S1;

218   see also Carriço et al. 2019). The remaining sound sequences, due to their lower

219   abundance (abundance range: 1-21 sounds found in the analysed dataset (20 days per

220   year, 3 years)) were included in a single category called 'Others'. These sound

221   sequences could not be attributed to a particular species. The analysis considered day

222   and night periods. The diel patterns were analysed and compared between years (2008

223   and 2010) and seasons: spring (April-May); summer (June-August) and autumn

224   (November-December). 2012 was excluded from the diel analysis because the sampled

225   duty cycle did not allow a balanced sampling of the different periods of the day.

226   Although in the winter months there was also the presence of fish sounds, they were not

227   included in the analysis since there were no recordings for all years.

228   To evaluate diel variations in the fish sound production the diel light phase times

229   for our study site were retrieved for each day with suncalc package in R (Agafonkin &

230   Thieurmel 2018). Dawn period was defined as the time elapsed since the beginning of

231   dawn until the end of sunrise (mean duration: 0.54 h; range for the sampled days: 0.52-

232   0.58 h); day time was defined from the end of the sunrise until the beginning of the

233   sunset (mean duration: 12.8 h; range: 9.35-14.75 h); dusk period was defined from the

234   beginning of the sunset until the end of dusk (mean duration: 0.54 h; range: 0.50-0.58

235 h); and night time was defined since the end of dusk until the beginning of dawn (mean

236 duration: 10.46 h; range 8.08-13.55 h).

237   To evaluate acoustic diversity, we adapted traditional taxonomic biodiversity

238 indices (see below) but used sound sequence types instead of species. The sound

239 sequence richness (number of sound sequence types) and the Shannon index were

240 calculated and compared between seasons and years. Note that, all sound sequence

241 types included in "others" category were considered individually to calculate acoustic

242 diversity.

243

244 **2.4 Detection distance of vocal fishes**

245 To estimate the distance of fish sound sources from the EARS we used known (or

246 estimated) sound levels of seven fish species, *Opsanus tau*, *Pomatochistus pictus*,

247 *Chromis chromis*, *Sebastes pauscipinis*, *Argyrosomus japonicus*, *Pempheris adspersa*

248 and *Halobatrachus didactylus* (Barimo & Fine 1998, Sprague and Luczkovich 2004,

249 Vasconcelos & Ladich 2008, Codarin et al. 2009, Sirovic & Demer 2009, Locascio and

250 Mann 2011, Parsons et al. 2012, Amorim et al. 2013, Radford et al. 2015). Assuming

251 spherical loss with no sound absorption by the medium, the source level (sound level at

252 1 m) was calculated for each of these species, using the equation:

$$SL = 10 \ \log_{10}(RL_{linear} \ r)$$

253 Where, SL, Source Level (dB); RL_{linear}, Received level converted to linear scale and *r*

254 the distance from the fish to the hydrophone as reported for each species. The

255 transmission loss was calculated with:

$$TL = 10 \ \log_{10}(d^2)$$

256 Where, TL, Transmission Loss (dB); and *d*, distance to the source. The attenuation was

257 obtained by subtracting the Transmission Loss from the Source Level for each distance.

258 For background noise level we used mean and range values as in Romagosa et al.

259 (2017) for ambient sound pressure level (based on mean SPL values from 2010 in Fig. 5

260 cf. Romagosa et al. 2017) of Condor seamount in the 18-1000 Hz frequency band.

261

262 **2.5 Patterns of fish assemblages**

263 Data on the temporal and spatial patterns of variation of benthic and benthopelagic fish

264 assemblages on the Condor seamount were obtained from a previously published study

265 (Menezes & Giacomello 2013) that collected longline samples in the 151-1200 m depth

266 interval, from 2003 to 2012 (between September and November). These samples were

267 conducted in autumn: 19 and 20 of November 2003; 15-25 of September 2009; 25

268 September 2010 to 1 of October 2010; 22 of September to 7 of October 2011; 29 of

269 September to 15 of October 2012; according to Table 1 in Menezes & Giacomello 2013.

270 From all the species in Table 2 from Menezes & Giacomello (2013), we selected the

271 species that were caught with the fishing gear at 150-250 m, whose depth range was

272 within the presumed detection range of the hydrophone (see results) and noted the ones

273 that were vocal or potentially vocal (species belonging to the same genus or family of

274 other confirmed vocal species; Carriço et al. 2019). Although some fish species could

275 theoretically be detected several hundred meters away we chose to select fish with its

276 upper catch distribution limit ranging from 150-250 m, to be conservative. The years

277 2009, 2010 and 2012 were considered for the fish surveys.

278

279 **2.6 Biodiversity metrics**

280 For the fish assemblages (fish species) and for acoustic data (sound sequences), we

281 calculated the relative abundance and two biodiversity indices (Species richness and

282 Shannon biodiversity index). The species richness is the number of species present in a

283 community and is a good indicator of diversity, since a community with a higher

284 number of species is characterized by a greater diversity (Magurran 1988; Willig et al.

285 2003). The Shannon Index is also a diversity function which conjugates the number of

286 species present in a community with the relative abundance of each species present in

287 the sample (Magurran 1988; Willig et al. 2003). However, it should be considered that

288 this index condenses two variables into a single metric, is especially sensitive to small

289 samples and does not adequately reflects rare species or sound types (Sandoval et al.

290 2018), which eventually may underestimate a part of the diversity. Also notice that for

291 the comparison of the biodiversity metrics between the acoustic data and the fishing

292 surveys, data were not available for the same years in the period prior to the protection

293 establishment. For the acoustic data only 2008 was available, whereas fishing surveys

294 were only made in 2003 and 2009, and only 2009 was considered.

295

3. Results

296

297 A total of 19300 (SD= 625.1) sound sequences, belonging to 9 different sound

298 sequences types, were found in the 2008 datasets; 3220 (SD= 183.5) sound sequences

299 belonging to 8 sound sequences types were found in the 2010 datasets and, finally, 347

300 (SD=18.6) sound sequences of 5 different sound sequence type were found in the 2012

301 datasets.

302

3.1 Annual patterns

303

304 There was a marked decrease in the total number of registered sound sequences (i.e.

305 sound sequences abundance per day) from 2008 to 2012 (Fig. 2a). This decline in sound

306 sequences abundance was accompanied by a decrease in sound richness (number of

307 sound sequence types, Fig. 2b). Interestingly, higher values of the Shannon Index

308 concerning fish vocalizations were observed in 2010 (Fig. 2c). In Fig. 2d, e and f we

309 report the variation in fish abundance (d) species richness (e) and Shannon index (f) of

310 fish species sampled by longline fishing, between 2009 and 2012, including all fish

311 species considered (total - all the species present at the depths closest to the EARs) or

312 the potentially vocal (vocal and potentially vocal species within the same depths) (see

313 Fig. S2 and S3 for the comparative abundance of each species). Fish species abundance

314 (total or potentially vocal) decreased from 2009 to 2012, following a pattern similar to

315 the acoustic data (Fig. 2d). Total species richness increased in 2010, with a slight

316 decrease in 2012, while potentially vocal species richness was stable in the different

317 years (Fig. 2e). The Shannon Index for taxonomic diversity increased slightly from

318 2009 to 2010 and then decreased in 2012, especially for potentially vocal species (Fig.

319 2f). In summary, the fish abundance and diversity decreased in 2012 compared to

320 previous years. The only exception was in species richness (especially of the potentially

321 vocal fish) that was stable in all the three years.

322 In terms of annual pattern of the occurrence of the different sound sequences,

323 there was an increase in number of sound sequence #1 across the years and a decrease

324 in the number of sound sequence #10 (Fig. 3). The sound sequence #4 and 'Others'

325 mostly occurred in 2010. Sound sequence # 5 decreased in abundance in 2010 and then

326 increased in 2012.

Sound sequences
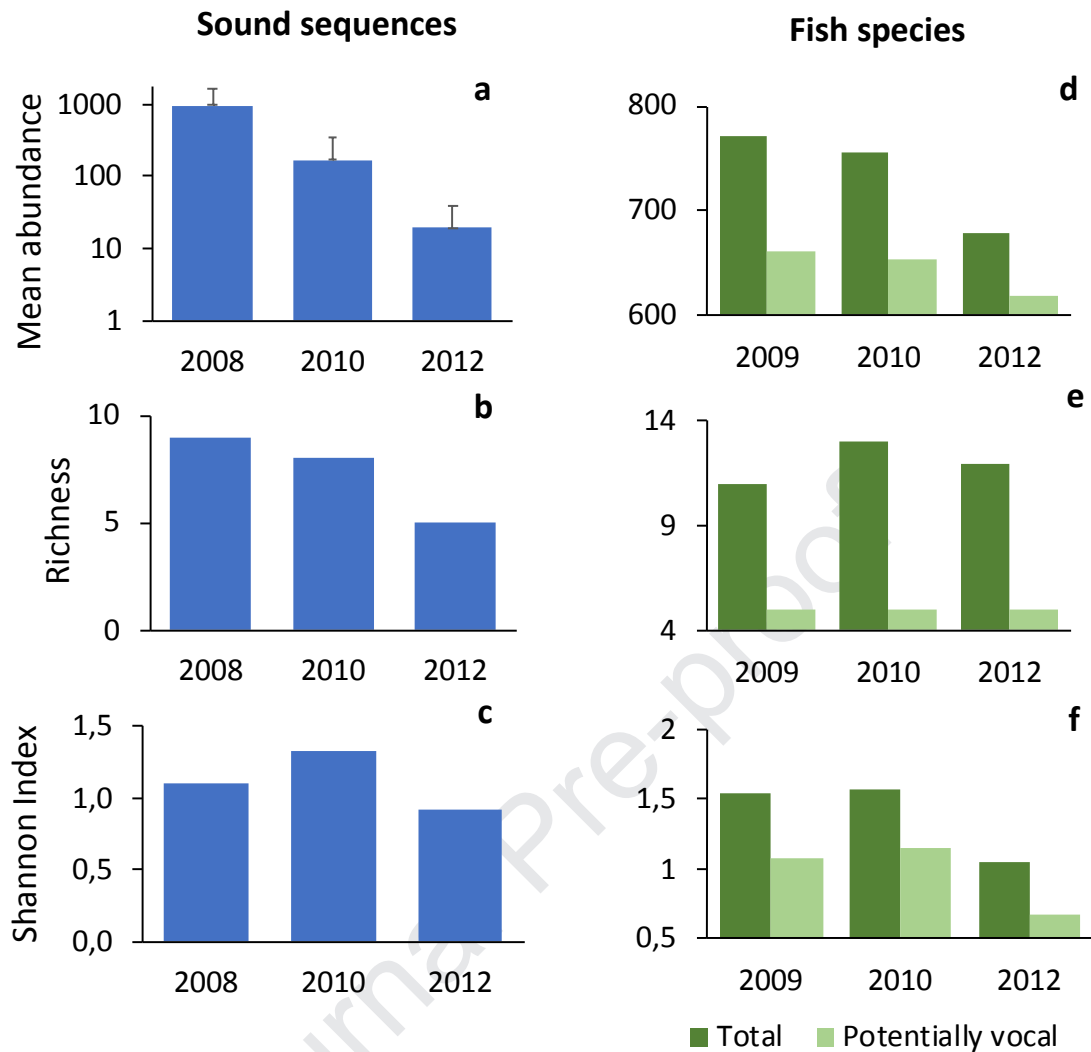
Fish species

Fig. 2. Annual patterns in fish sound sequences and fish assemblages sampled by longline fishing (from Table 2 in Menezes & Giacomello 2013), including a sub-sample of species present at depths within putative acoustic detection range from the EARs (Total) and a sub-sample of these species including only the vocal and potentially vocal fish species (Potentially vocal). Sound abundance (a) represents means of the total number of sounds per day (logarithmic scale) and standard deviation (represented by error bars) (N=20 days per year); Richness (b) represents the number of unique sound sequence types that were detected in the recordings, calculated yearly; Shannon Index (c) represents the number of sound sequence types conjugated with the relative abundance of each sequence type, calculated yearly. Abundance in fish species (d)

338 represents total number of individuals reported, where richness (e) represents the

339 number of species collected in the fish surveys (per year) and the Shannon Index (f)

340 represents the number of species conjugated with the relative abundance of each specie

341 (per year); for total and potentially vocal species.

342
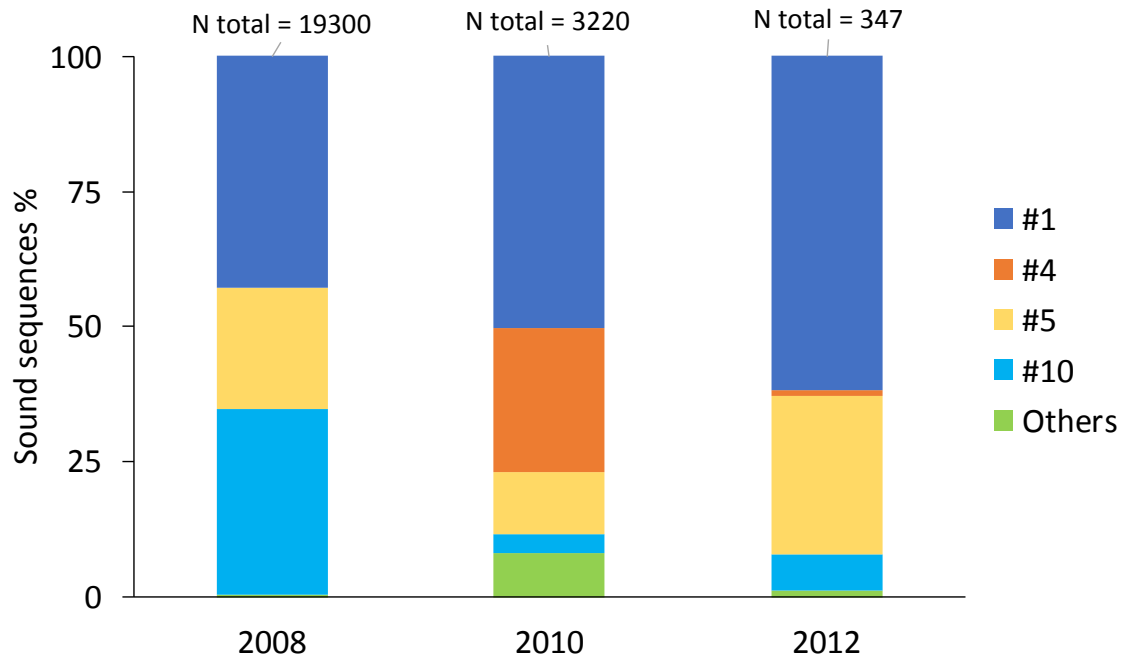
345 Fig. 3. Annual patterns in fish sounds: proportion of sound sequences types per year.

346 Average abundance based on 20 sampled days per year. Total number of sound

347 sequences for each year indicated above the bars. Note that in 2008 "Others" occurred

348 only 0.5% and are not noticeable.

349

350 **3.2 Seasonal patterns**

351 There was a higher number of fish sound sequences in spring and autumn 2008, in

352 summer and autumn 2010 and in summer 2012 (Fig. 4). In other words, there was no

353 consistent seasonal pattern over the studied years. In terms of the occurrence of a

354 particular sound sequence, sound sequence #1 was dominant in autumn in all three

16

1

355 years, whereas sound sequence #5 and sound sequence #10 had a higher incidence in

356 spring and summer 2008 and 2012. Sound sequence #4 was strongly present in spring

357 and summer 2010.
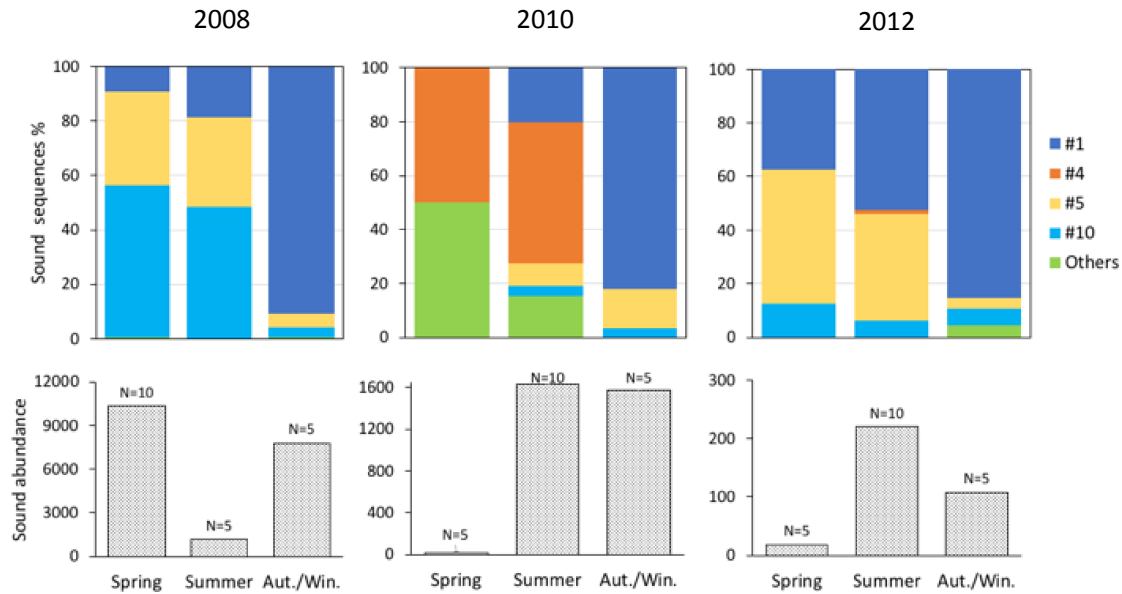
358

359 Fig. 4. Seasonal patterns in fish sound sequences for the three years (2008, 2010, 2012):

360 diversity (proportion of each sound sequence, top section) and abundance (total number

361 of sound sequences, bottom section). Average abundance based on 5 day sampled per

362 month.

363

364 **3.3 Diel patterns**

365 A higher abundance of sound sequences was observed at dusk and night for both 2008

366 and 2010 (representing 69,2 % and 79,5% of observed sound sequences respectively),

367 with the sound sequence #1 and #10 being the most prevalent (Fig. 5). Sound sequence

368 #1 occurred in all periods but less during the day (Fig. 5B). Its presence at dawn and

369 dusk increased from 2008 to 2010. Sound sequence #10 was infrequent at night. It was

370 predominantly present from dawn to dusk in 2008 but only at dusk in 2010. Sound

371 sequence #5 was present in all the periods of the day except for dawn in 2010. Sound

372   sequence #4 seemed to be restricted to the day period of 2010. The others sound

373   sequences were mainly present at dawn and dusk of 2010.
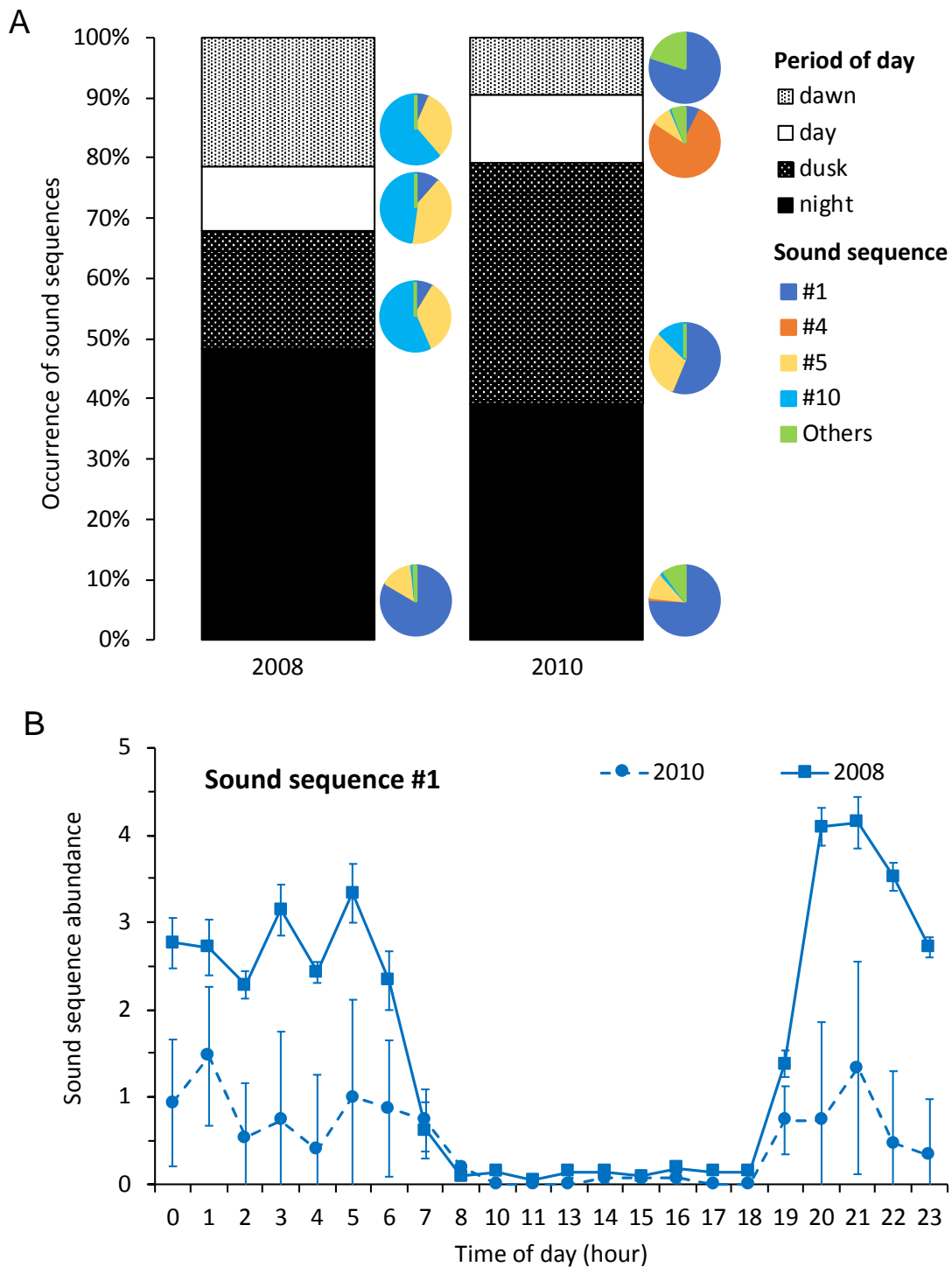
374

375   Fig. 5. Diel patterns of occurrence fish sounds in 2008 and 2010. A - Bars indicate the

376   proportion of occurrence of sound sequences (sum of all sequence types per hour)

377   according to different periods of the day, while pies depict the proportion of sound

378 sequences occurring in each period of day (N=20 sampled days per year). B – Mean (±

379 S.D.) abundance of the most abundant sound sequence (#1) throughout the day (24 h).

380

381 **3.4 What is the detection distance of vocal fishes in this study?**

382 Attenuation of vocalizations of seven fish species reported in literature to ambient noise

383 level characterising our recording site are depicted in Fig. 6. Sounds from these species

384 can propagate at different distances, with some species theoretically being heard over

385 great distances (Table S1). The sound received levels of three species (out of the seven

386 considered) would be higher than the mean background up to a max of 20 m distance,

387 while the sounds of two species could be detected much further, up to 1 km. In contrast,

388 *P. pictus* source level is below minimum ambient noise level, which make it hard to be

389 heard at more than just a few centimetres while *S. pauscipinis* received level are above

390 the ambient noise level only up until to a distance of 6 to 8 m. Similarly, *H. didactylus*,

391 *O. tau* and *C. chromis* received levels are above the ambient noise level up to a distance

392 of about 10-20 m. In contrast, in two species, *P. adspersa* and *A. japonicus,* the source

393 level is so enhanced that the received levels are above the mean ambient noise level up

394 to a distance of 1000 m, allowing these species to be detected at much greater distances.

395 These calculations are theoretical and, furthermore, we do not know the source species

396 responsible for the recorded sounds; however, this exercise highlights that the EARs

397 located at about 190 m depth may have record fish sounds from some species vocalizing

398 at depths greater than 200 m, allowing it to potentially target sound of the deep-sea fish

399 fauna.

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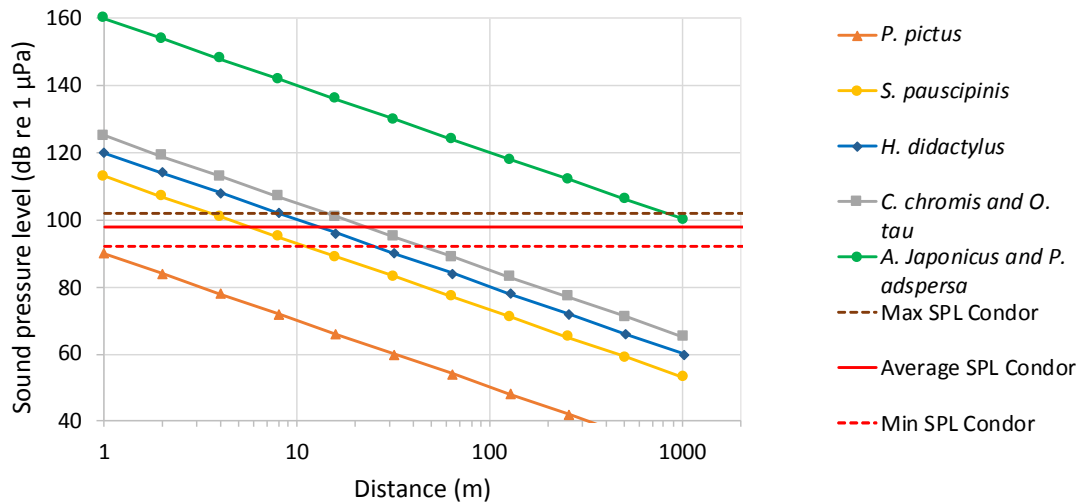
Fig. 6 – Attenuation of several fish species' vocalizations which source levels are reported in literature (*Opsanus tau* (Barimo & Fine 1998), *Pomatochistus pictus* (Amorim et al. 2013), *Chromis chromis* (Codarin et al. 2009), *Sebastes pauscipinis* (Sirovic & Demer 2009), *Argyrosomus japonicus* (Parsons et al. 2012), *Pempheris adspersa* (Radford et al. 2015) and *Halobatrachus didactylus* (Vasconcelos & Ladich 2008)). Average and range ambient sound pressure level measured at Condor for the frequency band 18-1000 Hz by Romagosa et al. (2017) is also depicted. Distance is presented in logarithmic scale.

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4. Discussion

The development of new tools to assess the state of ecosystems and anthropogenic impacts is a priority to establish effective mitigation measures. Passive acoustic monitoring can contribute to the collection of important data from deep, dark and remote areas of the ocean with a minimal impact to the ecosystem at large geographical and temporal scales (Staaterman et al. 2017). Here, we present the first study addressing temporal patterns of the vocal fish community inhabiting deep waters around a seamount habitat. Data collected over an extended temporal scale allowed the

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419   characterization of annual, seasonal and diel rhythms of fish sound production and the

420   comparison of the observed acoustic patterns with variation of fish assemblages

421   surveyed by longline fishing for a similar time frame (Menezes & Giacommello 2013).

422   During the sampled period, there was a change in the protection status of Condor

423   seamount which was closed to fishing in June of 2010 for conservation and research

424   purposes (Giacomello et al. 2013).

425   Annual patterns for the most abundant fish sound sequences recorded in Condor

426   seamount were investigated. There was a decrease in the mean abundance of sounds and

427   in sound richness (the number of sound sequence types) from 2008 to 2012, while a

428   higher biodiversity was only observed in 2010. The observed acoustic trends were in

429   line with the variations in fish assemblages estimated by fishing. The decrease in the

430   fish assemblages may have caused a reduction in the number of sounds, since fewer fish

431   will produce fewer sounds. Abundance and the biodiversity Shannon Index presented

432   similar annual trends for both fish assemblages and acoustic data, validating PAM for

433   monitoring fish biodiversity in underwater seamounts and at relatively high depths.

434   Consistently, in 2013, the fish community from Condor was also surveyed visually

435   using remotely-operated vehicles (ROV) which sampled 15 species in common with the

436   species recorded by longline, for a total of 51 taxa registered by the ROV and 48 by

437   longline fishing. Fish species sampled by both methods included some potential vocal

438   species with commercial value like *Pagelus bogaraveo* (Perciformes), *Helicolenus*

439   *dactylopterus*, *Pontinus kuhlii* (Scorpaeniformes)*, Phycis phycis* (Gadiformes) (Meneses

440   & Giacomello 2013, Porteiro et al. 2013). This highlights the importance of combining

441   different sampling methodologies for the validation of one particular method. Other

442   studies have pursued such validations. Desiderá et al. (2019) found a strong association

443   between acoustic and visually assessed fish diversity in rocky Mediterranean shallow

444   habitats. Positive relationships between visual surveys and acoustic diversity (measured

445   by the ACI index) were found in Bertucci et al. (2016) and Harris et al. (2016) in

446   shallow marine environments. The fact that fishing and acoustic surveys seem to obtain

447   similar results, leads us to consider PAM as useful and effective instrumental for

448   monitoring fish communities or target vocal species in conservation projects, not only

449   in shallow marine waters but also in deeper and less accessible ocean environments.

450   To the best of our knowledge, this is the first study that relates fish sound

451   abundance and diversity with direct surveys of deep-water fish fauna. Few studies have

452   reported sound production by fishes from the deep-sea (Bonaparte 1832, Cato 1978,

453   Mann and Jarvis 2004, Rountree et al. 2012, McCauley & Cato 2016, Wall et al. 2017,

454   Parmentier et al. 2018, Rieira et al. 2020). Moreover, beyond the scarcity of recordings

455   of vocalizations from deep-sea fish, a few anatomical studies have reported the presence

456   of muscles attached to the swimbladder (Marshall 1967, Nguyen et al. 2008, Ali et al.

457   2016, Parmentier et al. 2018, Fine et al. 2018), a common feature in several fish that

458   produce sounds (Fine and Parmentier 2015). While acoustics may be the preferred mode

459   of communication for fish active at night (Ruppé et al. 2015) and/or in a dark

460   environment like the deep-sea (Mann and Jarvis, 2004), until not long-ago technology

461   did not allow us to record at those depth for long periods of time (Wall et al., 2017,

462   Bolgan et al. 2020).

463   The change in the protection status of Condor seamount in 2010 afforded an

464   opportunity to observe changes in fauna biodiversity. Although we expected an increase

465   in fish sound sequences abundance and diversity after 2010, as a result of fisheries

466   interdiction, neither an increase in fish species abundance/biodiversity nor in fish

467   acoustic abundance/biodiversity was observed. However, this may be explained by the

468   amount of time needed for the ecosystem to recover and therefore an extended period of

469   observation would be essential to see the reserve effects in fish and, consequently,

470   acoustic biodiversity. Moreover, due to the system resilience, the observed decrease in

471   the abundance and biodiversity of both sounds and species, may be due to negative

472   impacts from previous years, that take some time to became visible (Holling 1973), like

473   the fishing pressure or marine pollution that has been occurring in the past years. In

474   addition, some current fishing practices outside the protected area, also associated with

475   some non-compliance observed inside the reserve (Rosa, personal communication) may

476   also have a significant impact in biodiversity recorded in the area and impact the speed

477   for the system's recovery. Hence, the reduced time after the reserve establishment (2

478   years) may have not been enough to produce positive observable effects in species and

479   sound abundances as reserve effects typically take more than 10 years to get established

480   (Edgar et al. 2014). Indeed, more recent data from demersal longline fishing in Condor

481   revealed an increase in the abundance and biomass of the commercial specie *Pagelus*

482   *bogaraveo* (Giacomello, personal communication; Rosa et al. 2018), which is a

483   potentially vocal species (Carriço et al. 2019). Future studies comparing acoustic data

484   with fishing surveys from more recent years, are necessary to ascertain the relation

485   between the acoustic and the fishing data observed in this study and its relation with

486   MPA effects.

487   Regarding finer-scale temporal patterns of fish sounds at Condor seamount, we

488   found a higher number of fish sounds in spring and autumn for 2008, in summer and

489   autumn for 2010 and in summer for 2012. Although we did not find an obvious seasonal

490   pattern in fish sound abundance, sound sequence type #1 was consistently present in the

491   three sampled years and occurred more frequently in autumn/winter months. Studies on

492   fish sound occurrence in deeper environments have been the subject of few studies

493   (Wall et al. 2013; Wall et al. 2014), but several have described seasonal patterns in

494 shallow water (< 40m depth; McCauley & Cato 2000, Montie et al. 2015, Rice et al.

495 2016, Pine et al. 2017, Sánchez-Gendriz & Padovese 2017). Differences in water

496 temperature, seasonal movements or migrations, food availability and changes in fish

497 behaviour like reproduction may explain some of the seasonal patterns of the fish

498 calling activity in deep waters (McCauley & Cato 2000, Nguyen et al. 2008, Rice et al.

499 2016, Sánchez-Gendriz & Padovese 2017). Radford et al. (2008) found that the ambient

500 noise was more intense in summer in a shallow temperate reef in New Zealand due to

501 crustaceans and fish chorus. For daily variations, we observed a higher incidence of

502 sounds at night and dusk, in line with other studies (Locascio & Mann 2008, Parsons et

503 al. 2016). McCauley & Cato (2000) and Rice et al. (2017) also found nocturnal

504 dominant patterns in fish chorusing. Various species of fish exhibit diel behavioural

505 cycles (Helfman 1986), including in sound production (Parsons et al. 2016, Rice et al.

506 2017). Acoustic communication seems to follow these patterns (Ruppé at al. 2015) as it

507 is associated with behaviours that present daily cycles such as foraging and agonistic

508 interactions (Amorim 2006; Macaulay 2012). Additionally, since a significant part of

509 the acoustic communication in fishes is related with reproduction activity, which occurs

510 mostly at night (Macaulay 2012; Rice et al. 2017, Staaterman et al. 2017), this may also

511 influence daily rhythms and seems to agree with the observed patterns for Condor. The

512 production of sound at night and in periods with less light can also be a way to avoid

513 and minimize predation risk and a better way to find mates than visual displays (Wilson

514 et al. 2014). Note that, although at the studied depth (*ca.* 190 m) there is only dim light,

515 it still has slight daily changes in light intensity, that associated with other factors like

516 vertical migrations (in turn also related with light level changes) (Brierley 2014; Afonso

517 et al. 2014, Cascão et al. 2017) might influence the presence and vocalization of certain

518 species, contributing to the observed diel patterns. Although the behaviour of deeper-

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519 water fishes is far from being well understood, PAM could potentially provide

520 information about the environmental quality and habitat health by monitoring fish

521 sound patterns. Sound production is typically associated with particular behaviours and

522 fish behaviour is the first endpoint to be affected by stressors (van der Sluijs et al. 2011,

523 Sharma 2019). Examples are noise pollution, overexploitation, habitat fragmentation or

524 diseases that can contribute to changes in the characteristic of a soundscape from a

525 given area (Laiolo 2010).

526 Fig. 6 highlights the fact that some fish species can be monitored at larger

527 distances than others. For example, Gobiidae species can only be recorded very close to

528 the hydrophone (few cm; Lugli & Fine 2007; Amorim et al. 2018), thus having no

529 potential to be monitored with PAM. The remaining species, however, could be

530 detected > 10 m away, and some, like Pempheridae or Sciaenidae (Sprague and

531 Luczkovich 2004, Parsons et al. 2012, Radford et al. 2015), are expected to have much

532 higher propagation distances, being good candidates to be monitored with PAM over

533 large spatial scales. The fact that most species are detected at 10 m or more support the

534 idea that the EARs could have recorded fish sounds emitted at depths below 200 m, i.e.

535 from deep-waters.

536

537 **5. Conclusions**

538 In conclusion, this study highlights the presence of diel periodicity (more sounds at

539 night), as well as seasonal and yearly variations in fish calling activity in a seamount at

540 *ca*. 190 m depth. However, seasonality appears to be less restricted in time than in

541 shallower water. The comparison of the acoustic recordings with traditional fish surveys

542 suggests that data from both approaches vary in parallel over the years, strongly

543 indicating that ecological changes are therefore reflected on both datasets; this

544 approach, to the best of our knowledge, has never been applied before. We suggest that

545 passive acoustic monitoring can play a fundamental role in assessing deep-water fish

546 abundance and diversity dynamics. Studies of this kind at even greater depths are

547 therefore strongly encouraged.

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Highlights

• Diel patterns of fish sounds were detected at ca. 190 m depth.

• Highest abundances of sound sequences were observed at dusk and night.

• Trends of abundance and diversity of vocalizations were similar to catch trends in fishery surveys.

• Acoustic monitoring is a useful tool to assess biodiversity in deep seamounts.

Declaration of interests

☒ 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.

☐The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: