A closer look at anthropogenic fiber ingestion in *Aristeus antennatus* in the NW Mediterranean Sea: differences among years and locations and impact on health condition

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HIGHLIGHTS

- Synthetic fibers were identified in stomach and intestine contents
- 84.6% of shrimps contained fibers and 42.4% contained balls of fibers
- Higher fiber load towards the south and off the Barcelona metropolitan area
- Temporal differences in polymer composition of fibers
- No major histological alterations

ABSTRACT

Marine litter is one of the most concerning threats for marine wildlife especially regarding plastics and their micro-sized forms, widely known as microplastics. The present study evaluates mesoscale spatial (230 km, Catalan coast) and temporal (2007 vs 2017-2018, Barcelona area) differences on the ingestion of anthropogenic fibers in the deep-sea shrimp *Aristeus antennatus* in the NW Mediterranean Sea and its relation with shrimp’s health condition. Synthetic fibers with lengths ranging between 0.16 and 37.9 mm were found in both stomach (where sometimes they were tangled up in balls) and intestine contents. The percentage of fiber occurrence was > 65% at each sampling point. Tangled balls of fibers observed in stomach contents exhibited a wide range of sizes (up to a diameter of 1 cm) and were usually composed of fibers of different polymers, sizes and colours. Differences between locations (2018) were found, with greater fiber loads towards the south during spring and a great variability in summer, as shrimps caught off Barcelona showed a nearly thirty-times higher fiber load compared to shrimps from other localities. Highest concentrations were more likely to be related to major sources of fibers and currents in the area. Fiber load in shrimps from 2007 was comparable to that of shrimps captured in 2017 and 2018 (spring) yet a shift in the proportion of acrylic and polyester polymers was detected. No consistent effect on shrimp’s health condition was found, with only a significant negative correlation found between gonadosomatic index and fibers for those shrimps with the highest values of fiber load (caught off Barcelona, summer 2018). Our findings contribute to the knowledge on plastic pollution for the NW Mediterranean Sea and highlight the potential use of this species as a sentinel species for plastic fiber contamination.

SUMMARY OF THE MAIN FINDINGS: “High variability of fiber load in individuals of *Aristeus antennatus* from the NW Mediterranean coast sampled in different locations, years and seasons is described with no evidence of negative impact on health condition.”

KEYWORDS

Fiber ingestion, *Aristeus antennatus*, Mediterranean Sea, Plastic Pollution, Health Condition
1. Introduction

Marine debris in particular plastic as the most common litter type has been identified as one of the major threats for marine ecosystems (UNEP, 2009). Jambeck et al. (2015) estimated that between 4.8 to 12.7 million metric tons (Mt) were entering the ocean in 2010 and more recently, Geyer et al. (2017) highlighted that if current production and waste management trends were to continue, up to 12000 Mt could end up in the environment by 2050. The first synthetic plastic produced, Bakelite, only dates back to the 1950s, which means that plastic production and pollution have had unprecedented growth. Microplastics (plastic items <1 mm, Hartmann et al., 2019) have already been found in aquatic environments all around the world, from remote areas as the Antarctic system (Waller et al., 2017) or the Maldives Islands (Imhof et al., 2017) to coastal shallow areas close to urbanization (Alomar et al., 2016). Likewise, microplastic ingestion seems a widespread phenomenon and to date over 220 different marine species have been found to consume microplastics in the environment (Lusher et al., 2017).

The ubiquity of microplastics has raised awareness in all communities leading to an exponential increase in the number of studies focusing on this topic during the last decades (Lusher et al., 2017). However, the lack of standardized methods has led to hardly comparable results with even some inconsistencies in terminology (Hartmann et al., 2019). Many experimental studies have also attempted to assess the potential impact of microplastics on the health of organisms but consistent results are yet to be found since both negative and neutral responses on feeding, growth, reproduction and survival have been observed (Foley et al., 2018). Moreover, other fibers with anthropogenic origin such as rayon/viscose, essentially made of regenerated cellulose, or dyed cotton fibers, even though being made of naturally occurring polymers (e.g. cellulose) may also raise environmental concerns like their synthetic (i.e. plastic) counterparts (Ladewig et al., 2015).

In order to allow for a correct assessment of hazards and risks posed by microplastics (and other anthropogenic particles) both experimental and field studies are needed. Even though we now have a great list of organisms for which plastic ingestion has been reported, studies focusing on understanding trends on release, transport and fate or on the factors related to microplastic ingestion are still scarce (Beer et al., 2018). Not to mention the importance of assessing whether plastic ingestion is increasing over time following the trends on global plastic production in order to better assess and forecast their potential impact (Beer et al., 2018). So far, only a couple of studies have addressed long-term trends in plastic ingestion in the Baltic and Atlantic Sea (Beer et al., 2018; Courtene-Jones et al., 2019).

The Mediterranean Sea has been described as one of the areas that is most polluted by plastics worldwide (Garcia-Rivera et al., 2018; UNEP/MAP, 2015). High values of microplastic occurrence might be linked to the intense anthropogenic activity alongside the hydrodynamics of an enclosed basin. The great industrial activity and highly developed tourism, together with important fisheries and densely populated coastal segments might account for a great input of marine litter (Eriksen et al., 2014; Ramirez-Llodra et al., 2013). In the NW Mediterranean area, microplastic presence has been reported in surface waters (de Haan et al., 2019; Ruiz-Orejón et al., 2016; Schmidt et al., 2018), beaches (Constant et al., 2019), sediments (Sanchez-Vidal et al., 2018; Woodall et al., 2014) and several organisms, mainly coastal fish (Alomar and Deudero, 2017; Bellas et al., 2016; Collignon et al., 2012; Compa et al., 2018) but also in the deep-sea shrimp Aristaeus antennatus (Carreras-Colom et al., 2018). In the latter, microplastic fibers might...
be retained for longer times compared to other organisms due to the presence of the gastric mill, a common food-grinding structure in decapods, which could hinder passage to the intestine (Watts et al., 2015; Welden and Cowie, 2016a, 2016b). Its action is also thought to favour the formation of tangled up balls of fibers with the corresponding increase in size and posing a major threat for health (Murray and Cowie, 2011).

Aristeus antennatus is an economically and ecologically important species in the deep-sea ecosystem whose biology, including reproduction, diet, population dynamics and most recently, microplastic ingestion, have been studied (Carbonell et al., 2006; Carreras-Colom et al., 2018; Cartes, 1994; Cartes et al., 2018; Demestre, 1995). After a first analysis focused on describing microplastic occurrence in stomachs from Aristeus antennatus collected in 2010-2011 (Carreras-Colom et al., 2018), the analysis of individuals from 2007 from a previous project (BIOMARE) together with new material obtained in 2017-2018, pose a perfect opportunity to test whether the increase in plastic production is somehow reflected in the level of plastic ingestion in Aristeus antennatus in these two time-points. This study analyses the occurrence, size and composition of anthropogenic fibers in the digestive tract of red shrimp (Aristeus antennatus) individuals from different years and locations along the Catalan coast (NW Mediterranean Sea). The main aims are: (1) to assess current (2018) spatial trends in fiber ingestion along the Catalan slope at a mid-scale distance (ca. 230 km), (2) to determine whether current levels of fiber ingestion (2017-2018) differ from those of 10 years ago in shrimps from an area with high anthropogenic pressure (off Barcelona), (3) to relate fiber ingestion to anthropogenic, environmental and biological factors, and (4) to assess the potential impact of fibers on shrimp’s health condition.

2. Materials and methods

2.1. Study area and data collection

Shrimps were collected from three sites along the continental slope of the Catalan coast (NW Mediterranean Sea) from north to south: off Costa Brava, off Barcelona, and off the Ebro Delta. The sampling locations were selected in order to represent areas of different characteristics and levels of anthropogenic impact. The Costa Brava area, selected as the allegedly less impacted area given its less industrial activity and its location, the northern-most location in an area where southwards currents dominate. It is also characterized by the greatest seasonal shift in human population density (increase of about 19% in summer compared to spring) and is under the influence of the Tordera River (54 km length; 9.0 hm³·y⁻¹). The Barcelona area, suspected as the most impacted area given the previously reported values of fiber ingestion there (Carreras-Colom et al., 2018), is close to the largest and most dense urban and industrial areas along the shore and is subject to the influence of the Besòs (58 km length, 98.6 hm³·y⁻¹) and Llobregat (173 km length, 302.3 hm³·y⁻¹) rivers. The area off the Ebro Delta, whilst near a less densely populated area, is under the influence of the Ebro River’s discharge (9281.0 hm³·y⁻¹), which is strongly affected by human activities, specially agriculture but also industry along its catchment area (85569 km²).

Sampling was performed in spring and summer of 2007 (in Barcelona), 2017 (in Barcelona and only spring) and 2018 (all locations and both seasons) within the framework of the research projects BIOMARE (Spanish Ministry of Science and Innovation) and SOMPESCA (Department of Agriculture, Livestock, Fisheries and Food, Catalonia, Spain) on board of commercial fishing vessels operating at depths ranging between 396 and 791 m (see Table 1 for details). All
individuals (n=201, Table 1) were immediately fixed in Davidson’s AFA for 48-56 h and then
preserved in ethanol 70%. Dissection was performed in a safety laminar flow cabinet and the
digestive system (stomach and intestine) was removed and screened for the presence of
anthropogenic particles using a stereomicroscope. For each individual, total body weight (TeW;
eviscerated – without stomach, gonad and hepatopancreas – and without appendices),
cephalothorax length (CL), and hepatopancreas (digestive gland) (HeW) and gonad weight
(GoW) were recorded. Wet weight (0.1 mg) of stomach content (ScW) was also recorded after
plastic screening.

In order to prevent contamination, all material used (scissors, tweezers and Petri dishes) was
rinsed multiple times with filtered water (50 µm metal sieve) and checked for contamination
before use. Cotton lab coat and nitrile gloves were worn at all times. Moreover, an isolation device
adapted from the one proposed by Torre et al. (2016) was used to cover the stereomicroscope and
work area throughout the screening and characterization process. Procedural controls, that is open
Petri dishes filled with filtered water, were placed inside and outside of the isolation device during
digestive content screening in order to assess potential airborne contamination. Only fiber shaped
items were found in both controls. Contamination found in the inside controls (average values of
0.25 fibers per digestive content screened) was four times less abundant than contamination in
outside controls, thus pointing out the efficiency of our isolation device in reducing potential
contamination. Fibers found in inside controls were visually similar to cellulosic fibers, yet they
were short (<0.5 mm), clean and always appeared on the surface of the water (pointing out that
they were deposited from air). Therefore, fibers from digestive contents were only counted if they
were clearly embedded in the digestive content and/or with detritus attached and never when
floating on the surface. Because of that, no correction factor was applied to the final values of
fibers reported.

Environmental and anthropic variables related to plastic sources or pathways into the deep sea
were collected afterwards including: mean river flow (mean value of the water flow at the closest
gauging station to the river mouth possible, in m³/s), total accumulated precipitation (precipitation
accumulated over the last 3 months at the nearest meteorological station, in mm), fishing pressure
(sum of power in kW of the fishing fleet estimated to be operating in the area), population density
(mean values of habitants km⁻² of the coastal area region) and land cover (urban area, agricultural
land and forests in percentage per region). Data was provided by Agència Catalana de l’Aigua
(ACA, 2019), Confederación Hidrográfica del Ebro (SAIH, 2019), Servei Meteorològic de
Catalunya (Metecat, 2019), Departament d’Agricultura, Ramaderia, Pesca i Alimentació
(DARPA, 2019), and Institut d’Estadística de Catalunya (IDESCAT, 2019). The shortest distance
to the coastline (in km) was calculated for each sampling point using QGIS 3.0.3.

2.2. Characterization of anthropogenic particles

Anthropogenic particles were separated, counted and classified into isolated fibers or ball-forming
fibers. Only in one occasion an anthropogenic particle other than a fiber or a ball of tangled fibers,
a film-like particle, was observed. Its colour and size (area) were recorded but it was not included
in further analysis. Isolated fibers were cleaned (organic material attached was removed carefully
with needles), mounted in distilled water and observed by light microscopy. Total length and
mean diameter (calculated on three random measures along the fiber) were measured, and fibers
were then classified into micro- (<1 mm), meso- (1-5 mm) or macro-sized fibers (>5 mm) and
their colour was recorded. Moreover, fibers were classified into five categories according to visual
aspects such as diameter uniformity and cross-section, finishing, striations and signs of wear and surface and backbone texture, following a similar approach to that used in forensic sciences (Bell, 2006) (Supplementary Material, Table S1).

When balls occurred (aggregation of entangled fibers) images were taken without untangling them or entirely removing organic debris (only that loosely attached) in order to estimate the occupying area (BA in mm²). Afterwards, balls were carefully unravelled as much as possible and all newly separated fibers were measured and characterized as stated above for originally isolated fibers (except for the fact that diameter was only measured in 20 randomly selected fibers per ball, and that they were not classified into micro-, meso- or macro-sized fibers). When complete isolation was not possible, the remaining tangles were mounted and the number of fibers, its composition (in proportions) and total length were estimated. Balls were categorized into four categories according to their morphology and size (in terms of the number of fibers and sum of the length of all constituent fibers (TL)) (Table 2). Finally, ball density (BD) was estimated for each ball as BD=BA/TL in mm.

Images and measures were taken using a ProgRes® C3 (JENOPTIK Optical Systems GmbH, Germany) coupled to a Leica DM500B microscope. Up to seventeen colours were reported, but given the low prevalence of some of them, they were grouped into six categories (transparent, blue, red, other bright, other dark, and black).

Fourier-Transformed Infrared Spectrometry (FTIR) was carried out on a randomly selected subsample of 119 anthropogenic fibers (2.9% of the total of fibers screened). This random selection was weighted by the relative abundance of fibers in each sampling, thus including at least a 4% of the fibers found at each sampling point (except for one, where the abundance was over ten times higher than in the rest). Spectra were recorded using a Tensor 27 FTIR spectrometer (Bruker Optik GmbH, Germany) equipped with a diamond attenuated total reflectance (ATR) unit (16 scans/cm⁻¹, 800-3600 cm⁻¹). Resulting spectra were treated (baseline corrections, peak normalization and selection of characteristic band applied) with Spectragryph 1.2.11 (Menges, 2019) and compared with reference spectra (custom-made library of common polymers, Carreras-Colom et al., 2018). Successful identification was considered for similarity values above 70%. The percentage of polymers identified for each category of fibers was calculated and used to determine the polymer composition of the rest of the visually sorted fibers (Supplementary Material, Table S1). Distinction between artificial (e.g. rayon) and natural (e.g. cotton) cellulosic fibers was not possible. Fibers were classified into anthropogenic fibers (including both cellulosic and synthetic fibers) and synthetic fibers (excluding cellulosic fibers).

### 2.3. Shrimp’s health condition

A portion of hepatopancreas and gonad, as well as a portion of muscle of each individual (n=201) and the stomach and intestine walls from selected individuals (n=21) with the greatest or the lowest values of plastic pollution, were processed through routine histologic techniques. Qualitative histological examination by light microscopy was conducted for different organs (muscle, gills, hepatopancreas, gonad and digestive tract – stomach and intestine). Normal structures reported in other shrimp species were used as a basis (Bell and Lightner, 1988). Sexual maturity was also determined according to Carbonell et al. (2006).
238 Shrimp’s health condition was further assessed by relative condition index (as Kn=TeW/EW x100, EW being the expected weight estimated from a length-weight relationship considering all data) (Le Cren, 1951), hepatosomatic index (HSI=HeW/TeW×100) and gonadosomatic index (GSI=GoW/TeW×100). Feeding intensity was measured through a fullness stomach index calculated as follows F=ScW/TeW×100. A second visually determined fullness index was also assigned to each individual from 0% (empty stomachs) to 100% (full stomachs) according to the volume of the content.

2.4. Data analysis

Fiber load was calculated for each individual and organ (stomach/intestine) in terms of total abundance (TA, as the sum of all estimated fibers) and total length (TL, as the sum of the length of all fibers) including all anthropogenic fibers. A corrected fiber load in terms of total length including only synthetic (i.e. plastic) fibers (TLS) was also calculated for each individual. Occurrence of fibers (FO) and balls (BO) was calculated for each sampling point as the number of individuals with anthropogenic fibers or balls/total number of individuals x 100.

Spatial, seasonal and temporal differences in the occurrence of fibers (FO) and balls (BO) were explored by means of Pearson’s Chi-square tests followed by Fisher’s exact test for pairwise tests. Differences in fiber load (in terms of TA, TL, TLs) and ball size (in terms of BA and BD) were analyzed using Kruskal-Wallis tests coupled with Dunn’s post-hoc tests (as data failed to meet normal variance structure). Similarly, spatial, seasonal and temporal (over a 10 year period) differences in the composition of fibers, in terms of organ location, size category (for isolated fibers only), colour and polymer, and ball type were explored through PERMANOVA analysis performed in PRIMER PERMANOVA+6 (Anderson et al., 2008). Permutation p-values were obtained under restricted permutation of raw data (9999 permutations) performed on Bray-Curtis similarity matrices derived from square-root transformed data. In all cases, proportions for each category were used instead of absolute values of abundance or length. A similarity percentages analysis (SIMPER) was carried out afterwards to identify the fiber-related variable that contributed the most to the similarity/dissimilarity of samples.

Correlation amongst detailed descriptors of fiber load (fibers in each location – stomach or intestine content – and according to their size – micro-, meso- and macro-fibers –) with other biological and environmental variables were explored through Cramer’s coefficient and Spearman’s correlation. Generalized linear models (GLM) were used to evaluate how environmental, anthropic and biological variables were related to the occurrence of balls (BO; considered more informative than fiber occurrence) and the total abundance of fibers (TA) in shrimps. BO (as a binary presence/absence variable) and TA individual data was related to location, year, season, CL, K, HSI, F, depth, distance to coastline, accumulated precipitation, river discharge, population density, fishing pressure and land cover. Following Burnham and Anderson (2003), the most parsimonious models were selected using the lowest AIC (Akaike’s Information Criterion). Similarly, effect of the fiber load on health condition of shrimps was explored through GLM in which condition indices (Kn, HSI, GSI – only for females –) were the response variables and fiber load (TA, TL, BA and BD) the explanatory variables. Shrimp’s size, stomach fullness and repletion index, sexual maturity and environmental variables (year, season and locality) were also included as explanatory variables to account for other sources of variability. The best model was used to explore negative effects of fiber load on condition indices. Models were fitted for each sampling point separately when interactions between year, season or locality were found.

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Statistical analysis was carried out using R software, version 3.5.3 (R Foundation for Statistical Computing) (packages vegan, dunn.test, lme and MASS) if not indicated otherwise. Significance levels were fixed at 0.05 for each statistical hypothesis testing.

### 3. Results

All individuals examined were adults, mostly sexually mature females (stages III-IV in spring; stage IV-V in summer), with sizes (CL) ranging between 22.46 and 47.43 mm. From the total of 201 individuals of Aristeus antennatus screened, 151 (75.12%) were observed to contain at least one plastic fiber and 44 (21.9%) had tangled balls of fibers in the stomach. Only once was a ball (5 fibers) found in the intestine. Overall, more than 65% of shrimps from each sampling point had fibers of some sort (isolated or tangled, in stomach or intestine contents) (Fig. 1, Table 3 and Supplementary Material, Table S2) and only one shrimp had a film-like blue particle (ca. 1.2 mm$^2$) in the stomach. Fibers found exhibited a great range of lengths (from 0.16 to 37.9 mm), widths (from 0.006 to 0.168 mm), colors (up to seventeen) and polymer types, including polyvinyl (49.7%), acrylic (27.5%), polyamide (12.4%), polypropylene (8.6%) and cellulosic (1.8%) fibers. It should be noted that cellulosic fibers counted in digestive contents differed from those of inside controls (airborne contamination) in that they were longer (average values of 3 mm per fiber compared to fibers of <0.5 mm in controls), were observed embedded in digestive content and/or with detritus attached to their surface, and were sometimes unraveled from tangled balls of fibers (clearly not airborne contamination).

Fibers were more common and abundant in stomach contents (FO=78.1%; TL=114.23 mm/individual) than in intestine contents (FO=44.3%; 4.62 mm/individual). Even though there was a positive significant correlation between fiber load in stomach and intestine contents ($\rho=0.283$ and $\rho=0.230$ for TA and TL respectively), fibers found in the stomach accounted for >94% of all fibers identified. Almost all isolated fibers encountered measured >1mm (96.7%) with meso-sized fibers (1-5 mm) being the most abundant size class in both stomach and intestine contents (55.4% and 73.8% respectively). Macro-sized fibers (>5 mm) were the second most abundant size class representing 42.0% of the isolated fibers in stomachs and 21.0% in intestines.

#### 3.1. Differences in fiber ingestion between locations, years and seasons

With regards samples collected in 2018, both spatial and seasonal differences were found (inset Fig. 1, Supplementary Material, Table S2). During spring there was a trend towards a greater load of fibers to the south, especially in the form of stranded fibers, with the highest values of ball occurrence, area and density in the Ebro Delta area (BO: $X^2=16.939$, $p=0.0002$; BA: $X^2=14.582$, $p=0.0007$; BD: $X^2=16.78$, $p=0.0002$). On the other hand, fiber load in summer was higher in shrimps off Barcelona compared to the other localities in terms of TA ($X^2=27.274$, $p<0.001$), TL ($X^2=29.095$, $p<0.001$) and TLs ($X^2=29.567$, $p<0.001$) (inset Fig. 1). Ball occurrence and size was also higher off Barcelona (BO, $X^2=11.585$, $p=0.003$; BA, $X^2=28.358$, $p<0.001$; BD, $X^2=14.707$, $p=0.0006$), and there was a greater occurrence of complex balls (B-IV, $X^2=18.462$, $p=0.0052$; Fig. 2.). Shrimps from this sampling station (off Barcelona city just south of the Llobregat River, P2V) showed the highest fiber loads throughout the study with mean values of fiber load per individual ten times higher than shrimps from other locations or periods (inset Fig. 1, Supplementary Material, Table S2). A total of 16.5 lineal meters of fibers (mean diameter 0.025 mm) were...
recovered from 18 individuals and the maximum load of fibers found in a single shrimp was 2.35 m (of which at least 98% was plastic).

Shrimps from Barcelona in 2018 also showed the greatest seasonal (spring vs summer) shift in fiber load (over twenty times higher values of TA and TL, and balls twice as frequent and dense), whereas in Costa Brava and the Ebro Delta areas, only minor differences between seasons were found: a significant decrease in TA and TL of fibers in intestine contents (Costa Brava: TA, \(X^2=10.436, p=0.0012\); TL, \(X^2=9.0985, p=0.0025\); Ebro Delta: TA, \(X^2=6.7036, p=0.0096\); TL, \(X^2=3.5061, p=0.061\); inset Fig. 1., Supplementary Material, Table S2) and an increase in BO (only in Costa Brava, Fisher’s exact test, \(p=0.018\)). It should be noted that only one shrimp from spring samplings in Costa Brava had a ball of fibers in the stomach, the lowest percentage of BO throughout the study.

In terms of fiber characterization, differences in polymer, colour and size composition were found between locations in 2018. In spring, shrimps from Costa Brava showed a different polymer composition compared to the rest of localities (\(p=0.0125, 9947\) unique perms) with a higher proportion of cellulosic fibers. In summer, shrimps from Barcelona presented a more marked dominance of PET and acrylic fibers (Fig. 3). With regards colour, differences were only found between the Costa Brava and Barcelona areas (spring: \(p=0.0021, 9948\) unique perm.; summer: \(p=0.0024, 9948\) unique perm.) with a larger proportion of coloured fibers in Barcelona. The mean proportion of each colour category was between 4-8%, except for transparent and translucent fibers accounting for nearly 60%, whereas in Costa Brava transparent alongside black (spring) and blue (summer) were the dominant colours (Fig. 4). Finally, differences in size composition were only found between Barcelona and the Ebro Delta areas in spring (\(p=0.046, 9959\) unique perms) and between seasons for both shrimps from the Ebro Delta (\(p=0.0474, 2645\) unique perms) and the Costa Brava (\(p=0.0096, 979\) unique perms) with a significant increase in the proportion of >5 mm fibers in summer.

Analyses on shrimps from different years (2007, 2017 and 2018) showed a great difference between summer samples from 2018 and the others, with values of fiber load (TA and TL) in 2018 nearly thirty times the values from summer 2007 (Fig. 5, Supplementary Material, Table S3; TA: \(X^2=22.003, p<0.001\); TL, \(X^2=21.928, p<0.001\)). On the other hand, shrimps sampled in 2017 (spring) showed lower values of fiber load compared to either 2007 (TL \(X^2=6.6151, p=0.01\)) and 2018 (TL \(X^2=4.7172, p=0.03\)) samplings (Fig. 5, Supplementary Material, Table S3), yet values were in the same order of magnitude. The seasonal trend observed in 2018 (ten-fold increase in summer compared to spring) was not observed in 2007. No significant differences in isolated fiber’s size or fiber colour composition were found between past (2007) and present (2017, 2018) years, either. Only a significant change in the polymer composition was observed (spring: \(p=0.0287, 9950\) unique perms; summer: \(p=0.011, 9937\) unique perms), with a significant shift in the proportion of acrylic and PET fibers (Fig. 6).

### 3.2. Factors related to fiber load in *Aristaeus antennatus*

All total fiber load descriptors (TA, TL, BA and BD) were highly correlated (\(\rho>0.8\)). Spearman’s correlation coefficient decreased when the location (intestine or stomach; \(\rho<0.3\)) and size (<1, 1-5 and >5 mm) of fibers encountered was considered (\(\rho<0.33\)). Size of balls (in terms of BA, BD and TL of tangled up fibers) was positively correlated with the abundance of meso- (1-5 mm; \(\rho=0.356\)) and macro-sized (>5 mm; \(\rho=0.269\)) isolated fibers in the stomach. The abundance of
stomach fibers (sizes 1-5 and >5 mm) was weakly ($\rho=0.210$ and $\rho=0.187$, respectively) but significantly correlated to stomach fullness. No other significant correlations with shrimp size, fullness or condition indices were found.

The results of the GLM identified that both the likelihood of BO and the values of TA in *A. antennatus* were mostly related to environmental and anthropic variables rather than biological ones. The best-fitting model for BO (AIC=231.46) included trawl depth, population density, season and location. Individuals were more likely to contain tangled balls of fibers in areas with higher population density ($z=-3.432, p<0.001$) and at greater depths ($z=-4.440, p<0.001$). Also, shrimps collected in summer and from the Delta area were more likely to contain balls ($z=-3.124, p=0.002$, and, $z=-3.524, p<0.001$, respectively); however, the influence of this covariates on BO was smaller than trawl depth and population density. The second best-fitting model (AIC=233.44) also included accumulated precipitation as a covariate yet its influence on BO was not significant ($z=-0.140, p=0.88$). Analysis of factors related to TA showed a similar outcome, with the best-fitting model again including location, depth and population density ($p<0.001$) in addition to year, fishing intensity and CL (the only biological variable included in any model). Higher values of TA were more likely to occur in shrimps collected in 2007, yet the magnitude of influence of this covariate was the smallest in this model. Shrimps with a smaller CL ($p<0.001$) had lower values of TA; which could be driven by the fact that shrimps from Blanes, where the lowest values of fiber load were found, also were some of the smallest individuals analyzed. Similarly, the negative relationship observed between TA and fishing intensity ($p<0.001$) could be driven by the fact that extremely high values of TA were found in Barcelona, where fishing intensity is lower.

### 3.3. Relationship between fiber ingestion and shrimp’s health condition

Model selection showed that most of the models exploring the relationship between condition indices (Kn, HSI and GSI as response variables) and fiber and ball occurrence and fiber load were best fitted without fiber-related variables, with the variability in condition indices being mostly related to CL and season. HSI was higher in spring samplings (average values ranging 2.96–5.72 in spring compared to 6.29–8.02 in summer, $p<0.05$), whereas GSI values were higher in summer (0.38–1.63 compared to 3.11–6.67, $p<0.05$), except for shrimps from the Ebro Delta (Supplementary Material, Table S4). These differences were more pronounced in bigger, older and more mature individuals. No differences were observed for Kn in relation to CL nor season. A significant negative relationship between fiber load (TL) and GSI was found ($F_{1,16}=10.77, p=0.0047, R^2=0.3649$) only for P2V sampling (off Barcelona, summer 2018). Shrimps with the highest load of fibers (150 cm individual$^{-1}$) showed values of GSI about 60% lower compared to those shrimps with the smallest load of fibers (5 cm individual$^{-1}$).

No histological changes or alterations from the normal tissular pattern in this species were observed in the organs and tissues examined, not even in those supposed to be in direct contact with balls of tangled fibers such as the cuticle and the epithelium of the digestive system. In addition, no parasites or relevant histopathological findings were found in this study.

### 4. Discussion

Fiber ingestion by the deep-sea shrimp *Aristeus antennatus* is reported from every sampled location and period reinforcing the idea that it is a widespread and recurrent phenomenon that
dates back more than ten years for this species in the Catalan Sea (NW Mediterranean Sea). Extremely concerning values for shrimps caught off Barcelona have been observed, with values of over 1 m of accumulated fiber length in at least seven individuals. As already pointed out in a previous work in this species (Carreras-Colom et al., 2018), fiber ingestion might be the result of intended or unintended consumption while feeding on benthos where fibers might be present following sedimentation.

Our results show high values of fiber occurrence 84.6% (78.1% when only considering the stomach) and ball occurrence (42.4%) very similar to those reported by Murray and Cowie (2011) for Nephrops norvegicus in the Clyde Sea (83% of fiber occurrence and 50% of ball prevalence in stomachs). The values for both stomach fiber and ball occurrence in shrimps captured off Barcelona in summer of 2007 and 2018 were higher than those found in the same area in summer of 2010 (Carreras-Colom et al., 2018; 25.9% of fiber occurrence and 3.7% of ball occurrence). These higher values could be due to either differences in depth (512-791 m this study and about 1000 m in the previous one) or to great variability in the environmental concentrations of anthropogenic fibers, and thus availability to shrimps.

Presence of fibers in the intestine is reported for the first time in A. antennatus. According to our results, fiber loads are much lower in the intestine than in the stomach suggesting that this route of egestion might be relatively unimportant. Given the length of most of the isolated fibers (97.4% >1 mm and 42.0% >5 mm), not to mention the size of tangled balls of fibers, passage through the pyloric stomach into the intestine is thought to be limited due to the narrowing at the entrance of the intestine and the action of the gastric mill (Welden and Cowie, 2016b). Saborowski et al. (2019) observed that microbeads and small fibers (<100 µm) were passed through the stomach and into the gut in individuals of Palaemon varidans, whereas long fibers (>100 µm) could not be transferred and remained in the stomach. Moreover, longer fibers might be more prone to be knotted into balls by the action of the gastric mill’s, increasing overall size and thus hampering passage down the gut (Welden and Cowie, 2016b). On the other hand, the action of the gastric mill combined with the cutting effect of numerous shell remains (from prey like bivalves or pteropods, common items found as part of A. antennatus diet, (Cartes, 1994)) could also facilitate, to a lesser degree, plastic egestion by breaking down fibers (Watts et al., 2015). Ultimately, moulting is the most plausible route of significant fiber elimination. During ecdysis, the stomach of decapods, including the gastric mill, is replaced and expelled. Welden and Cowie (2016b) confirmed the presence of microplastics inside the stomach linings of N. norvegicus previously fed with microplastics and the absence of microplastics in the stomach of moulting individuals.

The nearly exclusive presence of fibers in A. antennatus is in accordance with results reported for other crustaceans such as the brown shrimp, Crangon crangon, from the North Sea (Devriese et al., 2015) and the Norway lobster, N. norvegicus, from the Clyde Sea (Murray and Cowie, 2011; Welden and Cowie, 2016b). In all these studies, most of the items found were fibers with only some pieces of films and a granule being identified. Besides being more easily ingested and retained, the predominance of fibers in the environment could also explain this bias. In a recent review, Gago et al. (2018) suggested that fibers are more abundant than other shapes in seawater and sediments. Though this statement should be treated with caution as values obtained through very different methodologies were compared, fiber predominance is supported in our study area as separately reported for sediments (Sanchez-Vidal et al., 2018) and several pelagic and demersal fish species (Bellas et al., 2016; Compa et al., 2018; Nadal et al., 2016).
Hydrodynamic processes such as dense-shelf water cascading, severe coastal storms, offshore convection and saline subduction, known for their importance on the transport of sediments and organic matter to the deep sea (Canals et al., 2006), are also key processes on the transport of fibers to deep areas where they accumulate and become available for deep-sea organisms like A. antennatus (Bagaev et al., 2017; Woodall et al., 2014). These above-mentioned hydrodynamic processes have been pointed out as the main factors explaining marine litter occurrence along spatial gradients in the NW Mediterranean Sea (Tubau et al., 2015). In particular, the Northern Current, which flows southwards along the edge of the continental shelf (Font et al., 1988), might help explain the trend towards an increased fiber presence in shrimps towards the south during spring. The potential of the Northern Current in leading to a progressive accumulation of microplastics along its path was already pointed out by de Haan et al., (2019), whose study reported higher values of microplastic particles in Catalan surface waters \((0.183 \pm 0.158 \text{ items m}^{-2})\) compared to those reported in the Gulf of Lions \((0.08 \pm 0.03 \text{ items m}^{-2}; \text{Pedrotti et al., 2016})\).

In addition, local sources of fibers could also be more abundant, especially in the area off Barcelona, near to densely populated areas, but also off the Ebro Delta, which might receive an indirect influence of human activities through the discharge of the Ebro River. Galimany et al. (2019) attributed higher densities of plastic litter in shallow \((5.6 - 67.7 \text{ m})\) fishing grounds near Barcelona \(\approx 60 \text{ kg km}^{-2}\) compared to the Ebro Delta \(<5 \text{ kg km}^{-2}\) to inland mismanagement and riverine outflows being more intense in the former. Similarly, values of marine litter reported by Galgani et al. (1995) and Garcia-Rivera et al. (2018) were also higher near Barcelona compared to other areas of the Catalan coast. However, studies reporting environmental concentrations of microplastics in the area are either scarce or hardly comparable (Supplementary Material, Table S5), specially the regarding deep-sea environment. So far, only one study has been conducted in the Blanes area, targeting sediments of the submarine canyon and its adjacent slope, with values of microplastic fibers ranging between 5000 and 12000 fibers \(\text{m}^2\) (about 70% of them being cellulosic fibers). For the sampled areas off Barcelona and the Ebro Delta only values of either microplastics in surface waters or coastal and beach sediment can be found in the literature, which are hardly relatable to plastic ingestion in shrimps.

The great difference in fiber load (ten-fold increase) observed between spring and summer samplings from Barcelona is believed to be caused by the increase in environmental concentrations leading to increased ingestion by shrimps. This increase should have occurred in a rather short period of time which, in addition to a significant increase mostly of long fibers (>1 mm), would suggest that pollution sources were close (Isobe et al., 2019). Moreover, in the NW Mediterranean, flux of (total) particles arriving at bathyal depths (to 1000 m) near the bottom are important in spring and peak at the end of June, just before the peak observed for fibers in shrimps in July, decreasing later in summer (Miquel et al., 1994). De Haan et al. (2019) also observed a great variability along the Catalan coast finding both their lowest and highest microplastic abundances \((0.01 \text{ items m}^{-2} \text{ and } 0.5 \text{ items m}^{-2})\) only ~60 km apart and during the same period of the year.

Fiber sources include clothing (Browne et al., 2011), polymer manufacturing and processing industries (Lechner and Ramler, 2015). Most of the research concerning microplastics has been focused on the first one, with several studies pointing at the shedding of fibers while washing clothes as a major source of microplastics into the ocean (Salvador Cesa et al., 2017). However, recent works focused on the efficiency of wastewater treatment plants have shown that they actually have an efficient performance on removing fibers thanks to the tendency of fibers to mix intimately with the cellulosic matrix of the influents and aggregate into flocs that can be easily
retained in sieves (Carr et al., 2016). Therefore, even though fibers might escape wastewater treatment plants to some extent, this source might not contribute as much as it was thought initially (Carr, 2017; Carr et al., 2016). Alternative significant dispersive pathways would include atmospheric fallout, household dust, wastewater treatment plants disposals and storm-water runoff (Dris et al., 2017; Siegfried et al., 2017; Wagner and Lambert, 2018). The latter could play a key role in the Mediterranean area where the regime and hydrography are characterised by seasonal storm-like events leading to flash floods (Tubau et al., 2015). These abrupt increases in rainfall can also occasionally lead to combined sewer and storm-water overflows with a large impact on the receiving coastal waters. Increased river discharge usually creates great plumes in river mouths revealing the great amounts of sediments transported in these events. There is an absence of studies in the area on the specific occurrence of microplastics during these events, yet given that all Catalan rivers drain well-urbanized watersheds presence of fibers could be expected (de Haan et al., 2019; Sanchez-Vidal et al., 2013; Tubau et al., 2015). The precipitation regime in 2018 was extraordinary, especially in the Barcelona area (984.2 mm by the end of the year compared to the mean value of 580.6 mm for the past 10 years (Meteocat, 2019)), which might explain the great values of fiber load found in shrimps from that location in summer (considered an outlier as they were 10-30 times higher than fiber loads observed in other locations). An increase in the C/N ratio (~10), indicative of continental inputs in the sedimented organic matter, was also reported in the same area of study (off Barcelona at the head of the Besòs Canyon at 600 m) after 2-3 months following the maximum river discharge (Rumo et al., 2015). Similar fluctuations on the occurrence of plastics after increased rainfall episodes have been reported in estuary environments (Dantas et al., 2012; Lima et al., 2014) and the Turkish Mersin Bay where a 14-fold increase was observed (Gündoğdu et al., 2018). In the latter, a significant change in the polymer composition was also observed, with up to eight new different polymers being identified in the post-flood period. In our results, only a slight increase in the proportion of PET and acrylic fibers, which were already the most abundant categories, was detected.

The great increase in fiber load observed in summer (compared to spring) in shrimps from Barcelona in 2018 was not identified in any of the other seasonal comparisons, neither in the same area (2007) nor in other localities (2018). Possible explanations regarding 2018 samples for the northernmost area (Costa Brava) might be the lower input throughout the year, as a site with less anthropogenic pressure, while in the southernmost area (Ebro Delta) it could be related to the time of sampling (in late summer, nearly 1.5 months after the summer samplings in other localities). This short period of time might have been enough for a significant proportion of the shrimp population to moult and get rid of the highest concentrations acquired in late spring and early summer. Unlike other crustaceans that brood eggs and for which moulting is limited to certain periods, *A. antennatus* shows high proportions of individuals moulting throughout the year and especially during summer (values over 50% of the population) in which moulting optimizes fertilization (Demestre, 1995). Since moulting activity is so intense in summer, and considering that moulting implies a complete or at least significant loss of fibers in the stomach, the idea that shrimps from Barcelona acquired fibers rapidly owing to an exposure to high concentrations in the environment is reinforced.

Our results on plastic ingestion in shrimps from different periods (2007 compared to 2017 and 2018), with the exception of one sampling considered an outlier (Barcelona, summer 2018), suggest that the level of fiber ingestion in that particular location (off Barcelona) could have remained at a similar level (between 22.5 and 62.37 mm ind\(^{-1}\) in average). Beer et al. (2018) also reported no changes in the average values of plastic ingestion in planktivorous fishes from the
Baltic Sea across three decades. These results seem unexpected given the increase in global plastic and fiber production (Geyer et al., 2017; Jambeck et al., 2015) and point out the need to better understand the fate of anthropogenic fibers once they enter marine ecosystems. In individuals sampled monthly from Barcelona and Costa Brava for diet studies back in 1988-1989, occurrence of fibers and balls was also noted (Cartes, 1994), yet not described in detail. Although the study was mostly focused on identifying the items – prey – found in stomach contents and measures to prevent airborne contamination for fibers were not adopted (so, fiber occurrence could be underestimated) occurrence of fibers in shrimps from off Costa Brava (32.1%) was slightly lower than in Barcelona (42.9%), as reported in our study. Moreover, balls, which are unlikely to come from airborne contamination, showed the same spatial pattern described in this study for 2018 spatial trends, with a clear higher occurrence off Barcelona (19.8%) than off Costa Brava (7.1%) (Supplementary Material, Fig. S1.). Similarly, Carreras-Colom et al. (2018) reported the highest values of fiber and ball occurrence near Barcelona (52.1% of fiber occurrence and 18.3% of ball occurrence for the period 2008-2011) in a survey in the Catalan Sea. These findings, together with the relevance of population density as a covariate in our models predicting the likelihood of balls and the fiber load, support the idea that the area off Barcelona is, and has probably been for the past years, an impacted area for microplastics. More studies, focusing on environmental concentrations or plastic ingestion in other species, are needed to draw more definite conclusions on temporal trends for specific fiber loads, yet it seems clear that at least the occurrence of fiber ingestion in this species has remained rather high (>40%) throughout the past ten years.

Further, we did find a significant shift in the polymer composition, which might be related to a shift in production and usage trends. Shrimps caught in 2007 showed a greater proportion of acrylic fibers whereas in 2017-2018 the most common type was polyester. The global acrylic fiber market has declined in recent years, especially in Europe, in favour of polyesters, which have a price advantage thanks to large-scale production, better raw material availability, and recyclability (HIS Markit, 2016).

In general terms, the synthetic polymers identified and their contribution (in order of predominance: polyester, acrylic, polyamide and polypropylene), except for the lack of polyethylene, are in accordance with those reported in other studies encountering fibers in the environment (Browne et al., 2011; Murphy et al., 2016; Sanchez-Vidal et al., 2018). The highest proportion of cellulosic fibers in shrimps was found in the Costa Brava area, where Sanchez-Vidal et al. (2018) particularly reported the dominance of cellulosic fibers over other synthetic polymers. Cellulosic fibers, which can be natural (e.g. cotton) or artificial (e.g. rayon), were found in a low proportion overall and were not eliminated from analyses as they were sometimes observed to be part of balls thus posing a physical threat to food passage and ultimately shrimp’s health. In fact, balls were composed of a diverse suite of fibers from different colours, sizes (length and diameter) and even polymers, rather than being consistent in appearance (Rochman et al., 2019). This diverse composition, together with their morphology, with some balls seemingly been made up of other small bundles, might suggest that their origin is diverse.

General condition of shrimps, as assessed through condition indices and histology of main organs, showed no consistent negative impact of fiber ingestion nor any sign of other potential stressors (i.e. prolonged starvation, extreme environmental conditions). Histological alterations such as inflammatory responses or alterations of the epithelia as the ones reported in experimental exposures to polyethylene microplastics (Rodriguez-Seijo et al., 2017; Von Moos et al., 2012) were not observed. Variability on body indices, especially HSI and GSI, was mostly related to season and shrimp’s size which are, indeed, related to the ecology of the species (feeding rate and
reproduction according) (Cartes et al., 2018). Works under controlled conditions have
successfully described reduced body condition indices after long-term exposures (eight months)
to microplastics (Welden and Cowie, 2016a). Besides the size and position of balls, blockage of
food passage did not seem to occur, as occurrence of intestinal contents was high in most of the
shrimps with balls. Some items of their ordinary diet include hard shells (e.g. bivalves,
gastropods) or carapaces (e.g. other small crustaceans) amongst others (Cartes, 1994); hence, their
digestive system might be able to cope with hard, resilient big items. Moreover, deep-sea, benthic
organisms have evolved to be able to handle mixtures of edible and non-edible particles
(Ogonowski et al., 2018). In fact, the presence of fibers was correlated with higher stomach
fullness (volume), suggesting that there was no false satiation effect. The only negative correlation
observed was between the fiber load and the gonadosomatic index (GSI) of shrimps off Barcelona
(the sampling with the highest mean values of fiber ingestion). A recent meta-analysis of
microplastics effects on aquatic organisms (Foley et al., 2018), reported that reproduction was the
least commonly affected function, in contraposition to growth, consumption or survival. Given
that the GSI is linked to energy reserves and trophic condition one would expect a certain delay
between the ingestion and accumulation of fibers and a significant effect on GSI. It seems
unlikely, with this rather fast increase in fiber load (over a two-month period), without a negative
impact on stomach fullness, general body condition index or clear histopathological effects
identified, that the presence of fibers on its own is the cause of reduced GSI. The fact that this
correlation was only found in shrimps off Barcelona, after episodes of great rainfall and river
discharge, could suggest the arrival of pulses of other pollutants (Koenig et al., 2013), with
specific, unknown, mechanisms to produce a faster impact on reproduction (Kirby et al., 1999).
In a parallel study performed in 2007, values of organic pollutants (PCBs, DDTs and PAHs) in
sediments of the same area (off Barcelona) were considered low, and chemical exposure was
regarded to have little influence on specific fish biomarkers (Solé et al., 2010). On the contrary,
Sánchez-Avila et al. (2012), estimated a significant pollution risk (organic micropollutants) for
sensitive mysid shrimps in coastal waters. Regarding heavy metals, a depocenter with high trace-
metal contents (enrichment factors ranging between 1.2 and 10) was identified in front of the
Llobregat river (Palanques et al., 2008). However, in the same work authors noted a high small-
size variability and that a significant dilution of metal concentration occurred deeper in the
canyons. Since A. antennatus obtains macrofaunal prey from both outside and inside canyons
(Cartes, 1994) a real relationship with heavy metals cannot be established without a specific study.
Therefore, among other factors, possible negative effects or interactions with organic pollutants
or heavy metals on shrimp’s health could not be discarded.

CONCLUSIONS

Our findings demonstrate that Aristeus antennatus can experience acute episodes of plastic fiber
accumulation in the digestive tract yet no consistent signs of a negative impact of fibers on
shrimp’s health condition were observed. Throughout the study, high values of fiber occurrence
were found, especially in those areas where higher inputs of fibers into the environment are
expected due to great anthropogenic pressure (high population density) and episodes of increased
precipitation and river discharge. The variability in fiber ingestion observed in A. antennatus
among locations and between years could suggest the potential for using this species as a monitor
for fiber contamination in the deep-sea. Finally, but importantly, the results obtained demonstrate
the need to improve our waste management policies, especially regarding anthropogenic fibers
for which sources and pathways into the ocean are yet to be clearly identified.
Acknowledgements

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Fig. 1. Map of the study area showing the occurrence of fibers and balls and the mean total length of fibers (TL) per individual in Aristeus antennatus captured along the Catalan coast in spring (sp) and summer (su) of 2018. Occurrence values in percentage of individuals are displayed in the top right corner with vertical bars in white fill color for all fibers (isolated or tangled) and black fill color for balls (tangled fibers). Mean values (± standard error) of TL in mm per individual are depicted with vertical bars in white fill color for fibers in the stomach and dark fill color for fibers recovered from the intestine content. Main rivers (Tordera, Besós, Llobregat and Ebro) and industrial (orange) and urban (magenta) areas are also represented. The background map is from EMODnet Bathymetry Consortium (2016): EMODnet Digital Bathymetry (DTM). https://doi.org/10.12770/c7b53704-999d-4721-b1a3-04ec60e87238. Land and urban areas data reprinted from SIOSE [www.siose.es] under a CC BY licence, original copyright 2016. River data reprinted from [aca.gencat.cat] under a CC BY licence, original copyright 2012. (For interpretation of the references to color the reader is referred to the web version of this article.)
Fig. 2. Spatial (three localities: CB – Costa Brava, BC – Barcelona, ED – Ebro Delta) and seasonal (A – spring, B – summer) values of ball occurrence according to their category (form small and simple to big and complex: B-I, B-II, B-III, B-IV).

Fig. 3. Polymer composition of fibers recovered from Aristeus antennatus sampled along the Catalan coast (off Costa Brava (CB), off Barcelona city (BC) and off the Ebro Delta (ED)) in spring (top line) and summer (bottom line) in 2018. PA = polyamide; PET = Polyethylene terephthalate; PP = polypropylene.
Fig. 4. Color composition of fibers recovered from individuals of *Aristeus antennatus* along the Catalan coast (off Costa Brava - CB, off Barcelona city – BC, and off the Ebro’s Delta - ED) during spring and summer of 2018. Dark category included from green to purple dark colors others than black and blue. Bright category included yellow to turquoise bright colors others than red or bright blue.

Fig. 5. Mean values (± standard error) of fiber load (TL) per individual of *Aristeus antennatus* captured in the area off Barcelona (BC) in spring (sp) and summer (su) of 2007, 2017 or 2018. See Table 1 for details on the sampling.
Fig. 6. Polymer composition of fibers recovered from individuals of *Aristeus antennatus* off Barcelona in different periods (2007 - left, 2017/18 - right) and seasons (spring – top; summer – bottom). Values from different localities (in front of the Besòs river mouth and just south from Llobregat’s river, see Table 1 for details) were grouped and the mean value is depicted. PA = polyamide; PET = polyethylene terephthalate; PP = polypropylene.

<table>
<thead>
<tr>
<th>Code</th>
<th>Coordinates</th>
<th>Loc</th>
<th>Season</th>
<th>Year</th>
<th>Depth</th>
<th>n</th>
<th>CL (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>B2B</td>
<td>41.15 N; 2.40 E</td>
<td>BC</td>
<td>sp</td>
<td>2007</td>
<td>790</td>
<td>16</td>
<td>35.0-47.4</td>
</tr>
<tr>
<td>B3B</td>
<td>41.15 N; 2.40 E</td>
<td>BC</td>
<td>su</td>
<td>2007</td>
<td>790</td>
<td>31</td>
<td>22.9-46.6</td>
</tr>
<tr>
<td>B3V</td>
<td>41.07 N; 2.22 E</td>
<td>BC</td>
<td>su</td>
<td>2007</td>
<td>791</td>
<td>20</td>
<td>22.5-44.7</td>
</tr>
<tr>
<td>P0B</td>
<td>41.18 N; 2.39 E</td>
<td>BC</td>
<td>sp</td>
<td>2017</td>
<td>785</td>
<td>25</td>
<td>33.8-42.5</td>
</tr>
<tr>
<td>P1G</td>
<td>41.39 N; 3.25 E</td>
<td>CB</td>
<td>sp</td>
<td>2018</td>
<td>641</td>
<td>22</td>
<td>26.8-31.2</td>
</tr>
<tr>
<td>P1V</td>
<td>41.04 N; 2.05 E</td>
<td>BC</td>
<td>sp</td>
<td>2018</td>
<td>759</td>
<td>23</td>
<td>26.8-35.6</td>
</tr>
<tr>
<td>P1D</td>
<td>40.13 N; 1.23 E</td>
<td>ED</td>
<td>sp</td>
<td>2018</td>
<td>551</td>
<td>9</td>
<td>33.4-37.3</td>
</tr>
<tr>
<td>P2G</td>
<td>41.47 N; 2.81 E</td>
<td>CB</td>
<td>su</td>
<td>2018</td>
<td>396</td>
<td>20</td>
<td>25.9-31.9</td>
</tr>
<tr>
<td>P2V</td>
<td>41.11 N; 1.94 E</td>
<td>BC</td>
<td>su</td>
<td>2018</td>
<td>572</td>
<td>18</td>
<td>31.1-38.3</td>
</tr>
<tr>
<td>P2D</td>
<td>40.33 N; 1.32 E</td>
<td>ED</td>
<td>su</td>
<td>2018</td>
<td>425</td>
<td>17</td>
<td>33.1-40.7</td>
</tr>
</tbody>
</table>

Table 2. Visual classification of balls (aggregation of tangled up fibers) based on three main criteria: morphology, number of constituent fibers and sum of the length of all constituent fibers (TL).

<table>
<thead>
<tr>
<th>Type</th>
<th>Description</th>
<th>Constituent fibers</th>
<th>TL (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>B-I</td>
<td>Very loose ball. Sometimes aggregation depends strongly on attached organic matter. No core. Easy to untangle.</td>
<td>&lt;5</td>
<td>&lt;50</td>
</tr>
<tr>
<td>B-II</td>
<td>Medium-loose ball. Loose core. Can be easily unravel (sometimes only braided).</td>
<td>10-20</td>
<td>50-100</td>
</tr>
<tr>
<td>B-III</td>
<td>Tight ball. Not only braided but also with several knots. One tight core. Difficult to unravel.</td>
<td>30-50</td>
<td>100-200</td>
</tr>
<tr>
<td>B-IV</td>
<td>Tight large ball. More than one tight core or an extended one, with several complex knots. Impossible to untangle completely without breaking fibers.</td>
<td>&gt;50</td>
<td>&gt;200</td>
</tr>
</tbody>
</table>
Supplementary material

A closer look at anthropogenic fiber ingestion in *Aristeus antennatus* in the NW Mediterranean Sea: differences among years and locations and impact on health condition

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Table S1. Categorization of fibers encountered in the digestive system of *Aristeus antennatus* according to visual characteristics (general aspect) and results of the identification of 119 anthropogenic fibers (2.9% of the total) by means of FTIR (percentage of each polymer identified in %). Polymers identified Acr. = Acrylic; Cel. = Cellulose; PA = Polyamide; PET = Polyethylene terephthalate; PP = Polypropylene.

<table>
<thead>
<tr>
<th>Category</th>
<th>Description</th>
<th>Polymer identified (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Acr.</td>
</tr>
</tbody>
</table>
| A        | Uniform diameter and round cross-section  
Sometimes with wide molten or frayed ends  
Generally smooth surface texture. Granular backbone texture.  
Pilling or fraying surface when damaged  
Mostly transparent, yellowed or brownish | 0   | 0   | 70.8 | 16.7 | 12.5 |
| B        | Mostly uniform diameter (sometimes with molten bends) and round cross-section  
Clean ends, sometimes molten  
Smooth surface texture. Refringent. Usually with delustrant agents visible as a bubbly backbone texture  
Generally transparent or bright colored | 8.1 | 0   | 0   | 81.1 | 10.8 |
| C        | Non-uniform diameter, flat or film-like  
Diagonal-cut ends  
Wrinkled surface with angular edges. Sometimes fraying surface  
Mostly transparent, blue or black, usually non-uniform | 0   | 100 | 0   | 0   | 0   |
| D        | Non-uniform diameter with dumbbell cross-section  
Usually with fraying ends  
Smooth and homogeneous surface and backbone texture.  
Mostly transparent or bright colors | 80  | 0   | 0   | 14.3 | 5.7 |
| E        | Non-uniform diameter with almost round-section  
Generally clean ends  
Wrinkled with smoothed or round edges  
Mostly smooth texture (no fraying)  
Mostly with dark colors | 10  | 20  | 0   | 70  | 0   |
Table S2. Descriptive parameters for fiber occurrence and load in individuals of *Aristeus antennatus* from three localities along the Catalan Coast (off Costa Brava, off Barcelona city, and off Ebro Delta) for spring and summer samplings in 2018 and according to their location in the digestive tract (stomach or intestine). Significant differences are indicated with superscripts as follows: seasonal differences (within the same locality) are denoted with numbers and spatial differences (within the same season) are indicated with letters (low case letters for spring and capital letters for summer). Absence of letters or numbers indicates no differences were found. Mean values ± standard deviation are given except for occurrence values (in percentage). FO: fiber occurrence; TA: total abundance of fiber per individual; TL: total length of fibers per individual; TLs: total length of synthetic fibers per individual; BO: ball occurrence; BA: estimated area per ball; BD: estimated density per ball.

<table>
<thead>
<tr>
<th></th>
<th>Costa Brava</th>
<th>Barcelona city</th>
<th>Ebro Delta</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>spring</td>
<td>summer</td>
<td>spring</td>
</tr>
<tr>
<td><strong>STOMACH</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>FO (%)</td>
<td>68.2</td>
<td>60.0&lt;sup&gt;A&lt;/sup&gt;</td>
<td>80.8</td>
</tr>
<tr>
<td>TA (n fibers/ind)</td>
<td>1.82 ± 2.11&lt;sup&gt;a&lt;/sup&gt;</td>
<td>10.0 ± 29.59&lt;sup&gt;A&lt;/sup&gt;</td>
<td>7.48 ± 17.90&lt;sup&gt;1,b&lt;/sup&gt;</td>
</tr>
<tr>
<td>TL (mm of fibers/ind)</td>
<td>6.44 ± 7.05&lt;sup&gt;a&lt;/sup&gt;</td>
<td>33.34 ± 71.32&lt;sup&gt;A&lt;/sup&gt;</td>
<td>32.36 ± 54.22&lt;sup&gt;1,b&lt;/sup&gt;</td>
</tr>
<tr>
<td>BO (%)</td>
<td>4.5&lt;sup&gt;1,a&lt;/sup&gt;</td>
<td>35.0&lt;sup&gt;2,A&lt;/sup&gt;</td>
<td>34.8&lt;sup&gt;1,b&lt;/sup&gt;</td>
</tr>
<tr>
<td>BA (mm&lt;sup&gt;2&lt;/sup&gt;/ball)</td>
<td>1.02&lt;sup&gt;1,*a&lt;/sup&gt;</td>
<td>1.73 ± 0.98&lt;sup&gt;2,A&lt;/sup&gt;</td>
<td>2.06 ± 0.26&lt;sup&gt;1,b&lt;/sup&gt;</td>
</tr>
<tr>
<td>BD (mm&lt;sup&gt;2&lt;/sup&gt;/mm&lt;sup&gt;2&lt;/sup&gt;·ball)</td>
<td>17.37&lt;sup&gt;1,*a&lt;/sup&gt;</td>
<td>36.55 ± 26.20&lt;sup&gt;2,A&lt;/sup&gt;</td>
<td>32.36 ± 41.88&lt;sup&gt;1,b&lt;/sup&gt;</td>
</tr>
<tr>
<td><strong>INTESTINE</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>FO (%)</td>
<td>50.0&lt;sup&gt;1&lt;/sup&gt;</td>
<td>5.0&lt;sup&gt;2,A&lt;/sup&gt;</td>
<td>30.4&lt;sup&gt;1&lt;/sup&gt;</td>
</tr>
<tr>
<td>TA (n fibers/ind)</td>
<td>0.91 ± 1.11&lt;sup&gt;1&lt;/sup&gt;</td>
<td>0.05 ± 0.22&lt;sup&gt;2,A&lt;/sup&gt;</td>
<td>0.65 ± 1.23&lt;sup&gt;1&lt;/sup&gt;</td>
</tr>
<tr>
<td>TL (mm of fibers/ind)</td>
<td>2.19 ± 2.86&lt;sup&gt;1&lt;/sup&gt;</td>
<td>0.27 ± 1.20&lt;sup&gt;2,A&lt;/sup&gt;</td>
<td>2.62 ± 8.06&lt;sup&gt;1&lt;/sup&gt;</td>
</tr>
<tr>
<td><strong>TOTAL</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>FO (%)</td>
<td>77.3</td>
<td>65.0&lt;sup&gt;A&lt;/sup&gt;</td>
<td>95.7</td>
</tr>
<tr>
<td>TA (n fibers/ind)</td>
<td>2.73 ± 2.69&lt;sup&gt;a&lt;/sup&gt;</td>
<td>10.05 ± 29.58&lt;sup&gt;A&lt;/sup&gt;</td>
<td>8.13 ± 17.78&lt;sup&gt;1,b&lt;/sup&gt;</td>
</tr>
<tr>
<td>TL (mm of fibers/ind)</td>
<td>8.63 ± 7.74&lt;sup&gt;a&lt;/sup&gt;</td>
<td>33.61 ± 71.19&lt;sup&gt;A&lt;/sup&gt;</td>
<td>34.98 ± 53.60&lt;sup&gt;1,b&lt;/sup&gt;</td>
</tr>
<tr>
<td>TLs (mm of plastic/individual)</td>
<td>7.07 ± 6.66&lt;sup&gt;a&lt;/sup&gt;</td>
<td>32.03 ± 70.99&lt;sup&gt;A&lt;/sup&gt;</td>
<td>34.65 ± 53.12&lt;sup&gt;1,b&lt;/sup&gt;</td>
</tr>
</tbody>
</table>

* Only one ball found.
Table S3. Descriptive parameters for fiber occurrence and load in individuals in individuals of *Aristeus antennatus* off Barcelona city (just in front of the Besòs River or just south of the Llobregat River) for spring and summer samplings in 2007, 2017 and 2018, and according to their location in the digestive tract (stomach or intestine). Significant differences are indicated with superscripts as follows: seasonal differences (within the same year and locality) are denoted with numbers and temporal differences (within the same season and locality) are indicated with letters (low case letters for spring and capital letters for summer). Mean values ± standard deviation are given except for occurrence values (in percentage). FO: fiber occurrence; TA: total abundance of fibers per individual; TL: total fiber length; TLs: total length of synthetic fibers per individual; BO: ball occurrence; BA: ball area; BD: ball density. More details on each sampling station can be found in Table 1.

<table>
<thead>
<tr>
<th></th>
<th>Besòs</th>
<th>Llobregat</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>spring (B2B)</td>
<td>summer (B3B)</td>
</tr>
<tr>
<td>STOMACH</td>
<td></td>
<td></td>
</tr>
<tr>
<td>FO (%)</td>
<td>93.8 ± 7.54 1a</td>
<td>71.0 ± 1 1</td>
</tr>
<tr>
<td>TA (n fibers/ind)</td>
<td>6.38 ± 7.54 1a</td>
<td>15.32 ± 6.55 1</td>
</tr>
<tr>
<td>TL (mm of fibers/ind)</td>
<td>42.87 ± 51.89 1a</td>
<td>61.75 ± 99.05 1</td>
</tr>
<tr>
<td>BO (%)</td>
<td>50.0 ± 1.88 1a</td>
<td>38.7 ± 1 1</td>
</tr>
<tr>
<td>BA (mm2/ball)</td>
<td>2.97 ± 1.88 1a</td>
<td>3.60 ± 3.12 1</td>
</tr>
<tr>
<td>BD (mm/mm2·ball)</td>
<td>27.58 ± 17.70 1a</td>
<td>50.34 ± 28.62 1</td>
</tr>
<tr>
<td>INTESTINE</td>
<td></td>
<td></td>
</tr>
<tr>
<td>FO (%)</td>
<td>68.8 ± 1.59 1a</td>
<td>32.3 ± 2 1</td>
</tr>
<tr>
<td>TA (n fibers/ind)</td>
<td>1.50 ± 1.59 1a</td>
<td>0.55 ± 1.09 2</td>
</tr>
<tr>
<td>TL (mm of fibers/ind)</td>
<td>5.67 ± 8.12 1a</td>
<td>2.03 ± 5.49 2</td>
</tr>
<tr>
<td>TOTAL</td>
<td></td>
<td></td>
</tr>
<tr>
<td>FO (%)</td>
<td>1000 ± 1.88 1a</td>
<td>74.2 ± 1 1</td>
</tr>
<tr>
<td>TA (n fibers/ind)</td>
<td>7.88 ± 7.86 1a</td>
<td>15.87 ± 26.51 1</td>
</tr>
<tr>
<td>TL (mm of fibers/ind)</td>
<td>48.54 ± 53.19 1a</td>
<td>63.78 ± 98.23 1</td>
</tr>
<tr>
<td>TLs (mm of synthetic fibers/individual)</td>
<td>47.65 ± 53.78 1a</td>
<td>62.37 ± 95.42 1</td>
</tr>
</tbody>
</table>
Table S4. Studies conducted in the NW Mediterranean Sea reporting environmental concentrations of microplastics or marine litter.

<table>
<thead>
<tr>
<th>Location</th>
<th>Year</th>
<th>Size range (mm)</th>
<th>Analysis Method</th>
<th>Depth range (m)</th>
<th>Particle concentrations average ± SD units</th>
<th>Source</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Blanes</td>
<td>2018</td>
<td>0.16-22.4</td>
<td>Digestive content screening</td>
<td>396-641</td>
<td>6.399 ± 21.12 fibers · ind⁻¹ mm · ind⁻¹</td>
<td>Our study</td>
<td></td>
</tr>
<tr>
<td>Barcelona</td>
<td>2007</td>
<td>0.35-37.7</td>
<td>Digestive content screening</td>
<td>790</td>
<td>9.78 ± 48.12 fibers · ind⁻¹ mm · ind⁻¹</td>
<td>Our study</td>
<td></td>
</tr>
<tr>
<td>Barcelona</td>
<td>2017-2018</td>
<td>0.21-37.3</td>
<td>Digestive content screening</td>
<td>572-785</td>
<td>58.66 ± 324.37 fibers · ind⁻¹ mm · ind⁻¹</td>
<td>Our study</td>
<td></td>
</tr>
<tr>
<td>Delta</td>
<td>2018</td>
<td>0.62-37.9</td>
<td>Digestive content screening</td>
<td>425-551</td>
<td>60.49 ± 12.83 fibers · ind⁻¹ mm · ind⁻¹</td>
<td>Our study</td>
<td></td>
</tr>
</tbody>
</table>

**Surface waters**

<table>
<thead>
<tr>
<th>Location</th>
<th>Year</th>
<th>Size range (mm)</th>
<th>Analysis Method</th>
<th>Depth range (m)</th>
<th>Particle concentrations average ± SD units</th>
<th>Source</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Blanes a</td>
<td>2011-2012</td>
<td>0.33-5</td>
<td>Manta trawl (335 µm)</td>
<td>0</td>
<td>80000-160000 items · km⁻²</td>
<td></td>
<td>No exact values given for the specific area of Blanes.</td>
</tr>
<tr>
<td>Blanes a</td>
<td>2015</td>
<td>0.33-5</td>
<td>Manta trawl (335 µm)</td>
<td>0</td>
<td>0.497 ± 0.080 items · m⁻² mg⁻²·m⁻²</td>
<td>[2]</td>
<td>Fibers were not counted.</td>
</tr>
<tr>
<td>Barcelona b</td>
<td>2011-2012</td>
<td>0.33-5</td>
<td>Manta trawl (335 µm)</td>
<td>0</td>
<td>&gt;320000 items · km⁻²</td>
<td></td>
<td>No exact values given for the specific area of Barcelona.</td>
</tr>
<tr>
<td>Barcelona b</td>
<td>2015</td>
<td>0.33-5</td>
<td>Manta trawl (335 µm)</td>
<td>0</td>
<td>0.110 ± 0.023 items · m⁻² mg⁻²·m⁻²</td>
<td>[2]</td>
<td>Fibers were not counted.</td>
</tr>
<tr>
<td>Catalan coast</td>
<td>2015</td>
<td>0.33-5</td>
<td>Manta trawl (335 µm)</td>
<td>0</td>
<td>0.183 ± 0.158 ±0.025 items · m⁻² mg⁻²·m⁻²</td>
<td>[2]</td>
<td>Fibers were not counted.</td>
</tr>
<tr>
<td>Balearic Basin</td>
<td>2013</td>
<td>0.2-1000</td>
<td>Neuston net (200 µm)</td>
<td>0.2</td>
<td>549.6 ± 0.025 g · km⁻²</td>
<td>[3]</td>
<td>Broader area than our study area.</td>
</tr>
<tr>
<td>Gulf of Lion</td>
<td>2010</td>
<td>0.33-5</td>
<td>Manta trawl (335 µm)</td>
<td>0</td>
<td>0.06 ± 0.23 items · m⁻³ mg⁻²·m⁻³</td>
<td>[4]</td>
<td>Close, yet not our area of study.</td>
</tr>
<tr>
<td>Gulf of Lion</td>
<td>2015</td>
<td>0.2-5</td>
<td>WP2 net (200 µm)</td>
<td>0</td>
<td>0.23 ± 0.20 items · m⁻³ mg⁻²·m⁻³</td>
<td>[5]</td>
<td>Close, yet not our area of study.</td>
</tr>
<tr>
<td>W Mediterranean</td>
<td>2010</td>
<td>0.33-5</td>
<td>Manta trawl (335 µm)</td>
<td>0</td>
<td>0.116 ± 2.02 mg · m⁻³</td>
<td>[4]</td>
<td>Much broader area than our study area.</td>
</tr>
<tr>
<td>All Mediterranean</td>
<td>2011-2012</td>
<td>0.33-5</td>
<td>Manta trawl (335 µm)</td>
<td>0</td>
<td>129682 ± 62.211 items · km⁻² mg⁻²·km⁻²</td>
<td>[1]</td>
<td>Much broader area than our study area.</td>
</tr>
<tr>
<td>All Mediterranean</td>
<td>2011-2012</td>
<td>&gt;5</td>
<td>Manta trawl (335 µm)</td>
<td>0</td>
<td>5700 ± 5000 items · km⁻² mg⁻²·km⁻²</td>
<td>[1]</td>
<td>Much broader area than our study area.</td>
</tr>
<tr>
<td>Location</td>
<td>Date</td>
<td>Value</td>
<td>Type</td>
<td>Method</td>
<td>Density</td>
<td>Units</td>
<td>Source</td>
</tr>
<tr>
<td>-------------------------------</td>
<td>---------------</td>
<td>---------------</td>
<td>--------------------------</td>
<td>-------------------</td>
<td>--------------------</td>
<td>-------------------</td>
<td>-------------</td>
</tr>
<tr>
<td>Sardinian-Balearic transect</td>
<td>2013-2016</td>
<td>&gt;200</td>
<td>Visual survey</td>
<td>0</td>
<td>2.5</td>
<td>items · km⁻²</td>
<td>[6]</td>
</tr>
<tr>
<td><strong>Coastal sediments / Beach sand</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Barcelona b</td>
<td>2015-2017</td>
<td>&lt;5*</td>
<td>Beach sediment</td>
<td>0</td>
<td>148</td>
<td>items · kg⁻¹</td>
<td>[7]</td>
</tr>
<tr>
<td>Ebro Delta c</td>
<td>2017</td>
<td>&lt;0.05- &gt;0.3</td>
<td>Beach sediment</td>
<td>0-5</td>
<td>422 ± 119</td>
<td>items · kg⁻¹</td>
<td>[8]</td>
</tr>
<tr>
<td>Cap Croisette (Gulf of Lion)</td>
<td>2016</td>
<td>0.063 – 5</td>
<td>Beach sediment</td>
<td>0</td>
<td>4,654</td>
<td>items · m⁻²</td>
<td>[9]</td>
</tr>
<tr>
<td>Balearic Islands</td>
<td>2013</td>
<td>0.063 – 5</td>
<td>Subtidal sediment</td>
<td>8-10</td>
<td>0.27</td>
<td>items · g⁻¹</td>
<td>[10]</td>
</tr>
<tr>
<td><strong>Seafloor</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Blanes a</td>
<td>1994-1996</td>
<td>macro</td>
<td>Trawl composition</td>
<td>40-1600</td>
<td>~1,600</td>
<td>items · km⁻²</td>
<td>[12]</td>
</tr>
<tr>
<td>Blanes a</td>
<td>1999-2011</td>
<td>macro</td>
<td>Trawl composition</td>
<td>35-4500</td>
<td>31.1</td>
<td>items · ha⁻¹</td>
<td>[13]</td>
</tr>
<tr>
<td>Blanes a</td>
<td>2009</td>
<td>macro</td>
<td>Trawl composition</td>
<td>900-2700</td>
<td>0.02-3264.6</td>
<td>kg · km⁻²</td>
<td>[14]</td>
</tr>
<tr>
<td>Blanes a</td>
<td>2015</td>
<td>macro</td>
<td>Visual survey</td>
<td>860-1509</td>
<td>1559</td>
<td>items · km⁻²</td>
<td>[15]</td>
</tr>
<tr>
<td>Barcelona b</td>
<td>1993-1994</td>
<td>macro</td>
<td>Trawl composition</td>
<td>-</td>
<td>1762.6</td>
<td>items · km⁻²</td>
<td>[16]</td>
</tr>
<tr>
<td>Cap de Creus</td>
<td>2009</td>
<td>20-500</td>
<td>Trawl composition</td>
<td>40-80</td>
<td>60.03</td>
<td>items · ha⁻¹</td>
<td>[17]</td>
</tr>
<tr>
<td>Catalan coast</td>
<td>2007-2017</td>
<td>&gt;20</td>
<td>Trawl composition</td>
<td>0-800</td>
<td>~3.1</td>
<td>kg · km⁻²</td>
<td>[18]</td>
</tr>
</tbody>
</table>

*a Equivalent to our Costa Brava sampling location  
*b Equivalent to our Barcelona sampling location  
*c Equivalent to our Delta sampling location


Table S5. Summary of biological parameters, including size and body condition indices, for each sampling station. Mean values ± SD are given.

<table>
<thead>
<tr>
<th>Code</th>
<th>n</th>
<th>CL (mm)</th>
<th>Kn</th>
<th>HSI</th>
<th>GSI</th>
</tr>
</thead>
<tbody>
<tr>
<td>B2B</td>
<td>16</td>
<td>35.0-47.4</td>
<td>0.957 ± 0.070</td>
<td>6.29 ± 1.67</td>
<td>0.40 ± 0.20</td>
</tr>
<tr>
<td>B3B</td>
<td>31</td>
<td>22.9-46.6</td>
<td>0.957 ± 0.064</td>
<td>4.31 ± 1.97</td>
<td>3.11 ± 3.14</td>
</tr>
<tr>
<td>B3V</td>
<td>20</td>
<td>22.5-44.7</td>
<td>0.978 ± 0.074</td>
<td>2.96 ± 1.49</td>
<td>3.43 ± 2.34</td>
</tr>
<tr>
<td>P0B</td>
<td>25</td>
<td>33.8-42.5</td>
<td>1.051 ± 0.073</td>
<td>6.48 ± 1.54</td>
<td>0.39 ± 0.23</td>
</tr>
<tr>
<td>P1G</td>
<td>22</td>
<td>26.8-31.2</td>
<td>1.013 ± 0.100</td>
<td>7.36 ± 1.18</td>
<td>0.38 ± 0.22</td>
</tr>
<tr>
<td>P1V</td>
<td>23</td>
<td>26.8-35.6</td>
<td>1.019 ± 0.066</td>
<td>8.02 ± 2.31</td>
<td>1.63 ± 1.00</td>
</tr>
<tr>
<td>P1D</td>
<td>9</td>
<td>33.4-37.3</td>
<td>1.026 ± 0.066</td>
<td>5.91 ± 1.73</td>
<td>0.34 ± 0.22</td>
</tr>
<tr>
<td>P2G</td>
<td>20</td>
<td>25.9-31.9</td>
<td>1.023 ± 0.088</td>
<td>5.72 ± 1.80</td>
<td>3.73 ± 2.12</td>
</tr>
<tr>
<td>P2V</td>
<td>18</td>
<td>31.1-38.3</td>
<td>0.984 ± 0.050</td>
<td>5.54 ± 1.24</td>
<td>6.67 ± 2.34</td>
</tr>
<tr>
<td>P2D</td>
<td>17</td>
<td>33.1-40.7</td>
<td>0.994 ± 0.062</td>
<td>5.39 ± 1.05</td>
<td>1.26 ± 0.93</td>
</tr>
</tbody>
</table>

Fig. S1. Map of the study area showing the occurrence of balls (BO in %) in stomachs of *Aristeus antennatus* captured along the Catalan coast during 1988-1989 in a monthly sampling (n=768 specimens analyzed for diet studies). BO is calculated as the percentage of individuals with balls (tangled up fibers) over the total of individuals analyzed per each sampling. Largest circles represent BO = 20%. Differences in color intensity compared to the legend presented are due to the superposition of values for individuals from different samplings.