Mediterranean Marine Science

early view

Signs of northward expansion of the fireworm Hermodice carunculata in the Spanish Western Mediterranean Sea

NURIA R. DE LA BALLINA, FRANCESCO MARESCA, ENRIC REAL, IGNACIO BAENA-VEGA, SUSANA DÍEZ, ALEJANDRO MARTÍN-ARJONA, SANDRA MALLOL, DAVID DÍAZ

doi: [10.12681/mms.39791](https://doi.org/10.12681/mms.39791)

Research Article

Mediterranean Marine Science
Indexed in WoS (Web of Science, ISI Thomson) and SCOPUS
www.hcmr.gr
DOI: https://doi.org/10.12681/mms.39791

Signs of northward expansion of the fireworm *Hermodice carunculata* in the Spanish Western Mediterranean Sea

Nuria R. de la BALLINA[1], Francesco MARESCA[1], Enric REAL[1], Ignacio BAENA-VEGA[1], Susana DÍEZ[1], Alejandro MARTÍN-ARJONA[2], Sandra MALLOL[1], and David DÍAZ[1]

[1] Centro Oceanográfico de Baleares (IEO-CSIC), 07015, Palma de Mallorca, Spain
[2] Centro Oceanográfico de Málaga (IEO, CSIC), 29002, Málaga, Spain

Corresponding author: Nuria R. de la BALLINA; nuria.rodriguez@ieo.csic.es

Contributing Editor: Sarah FAULWETTER

Received: 18 December 2024; Accepted: 09 May 2025; Published online: 04 June 2025

Abstract

The bearded fireworm *Hermodice carunculata* is a thermophilic polychaeta typically inhabiting the warmer waters of the Atlantic Ocean and the southern Mediterranean Sea. Over the past few years, sightings of this species have become more frequent at higher latitudes along the western Mediterranean (WM) basin, raising concerns about the potential expansion of its distribution range. Here, we present new records of *H. carunculata* obtained from the combination of benthos monitoring programmes, local ecological knowledge, and publicly available information. Furthermore, we investigated whether a northward shift in *H. carunculata* distribution has occurred, based on a temporal comparison of occurrence records before and after the record-breaking marine heat wave of 2022–2023. The present study improves the picture of the geographical distribution of this polychaete in the WM: we report a total of 257 new records of *H. carunculata* along the Mediterranean Spanish coast. The spatial and temporal distribution of these records suggests a northward expansion of the species, according to all data sources. The mean latitude of observations increased by nearly one degree, and the northernmost sightings extended up to 2.2° beyond the previously reported limits. These findings indicate the possible expansion of *H. carunculata* distribution in the Spanish WM and highlight the effectiveness of combining traditional monitoring methods and local ecological knowledge for detecting changes in species distribution.

Keywords: thermophilic species; distribution range expansion; monitoring; marine heatwave; local ecological knowledge.

Introduction

Ocean warming dramatically affects marine ecosystems by altering the structure of benthic communities and causing marine species to change their distribution, abundance, and behaviour (Poloczanska *et al.*, 2016). In the Mediterranean Sea, the surface of Spanish waters is warming up at a higher rate than the global ocean average (Vargas-Yáñez *et al.*, 2023). Moreover, an exceptionally severe and long-lasting marine heat wave (MHW) affected the Mediterranean Sea between 2022 and the end of 2023, mainly in the western basin (Marullo *et al.*, 2023; Serva *et al.*, 2024). While MHWs pose a threat to the survival of many species and habitats (Garrabou *et al.*, 2022), a continuous warming trend promotes a northward expansion of some species with affinity for warmer habitats and enables their settlement on new locations at an unexpectedly high rate (Raitsos *et al.*, 2010; Boudouresque *et al.*, 2024). In this context, the rise of ocean temperatures and, especially, the growing frequency and intensity of MHWs, are allowing thermophilic and opportunistic species to move into new areas (Boudouresque *et al.,* 2024), reshaping marine ecosystems.

Hermodice carunculata (Pallas, 1766) (Annelida, Polychaeta, Amphinomidae) is commonly known as the "bearded fireworm" due to its characteristic tufts of white, sharp, and venomous chaetae. This thermophilic species is widely distributed across tropical and subtropical Atlantic coasts, including the Caribbean Sea, the Gulf of Mexico, the Gulf of Guinea, Brazil, Madeira, the Azores, and the Canary Islands, as well as in the Red Sea and the Mediterranean Sea (Righi *et al.*, 2020). In addition to being an extremely efficient predator of cnidarians (Wolf *et al.*, 2014), *H. carunculata* exhibits a high degree of dietary plasticity, feeding on detritus as well as living, injured, or dead organisms. In the Mediterranean Sea, this generalist species has been observed preying on cnidarians (Mistri & Ceccherelli, 1994; Maldonado *et al.*, 2013; Simonini *et al.*, 2018; Krželj *et al.*, 2020), molluscs (Krželj *et al.*, 2020), and echinoderms (Simonini *et al.*, 2017; Krželj *et al.*, 2020). Moreover, laboratory observations have corroborated that this amphinomid polychaete is also able to feed on crustaceans, annelids, and ascidians (Simonini *et al.*, 2018; Toso *et al.*, 2022). *H. carunculata* prey are generally sedentary and sessile organisms; however, fireworm aggregations have also been observed around dead and wounded mobile organisms, such as fish (Righi *et al.*, 2020; Toso *et al.*, 2022). In the Caribbean Sea, certain fish species can feed on *H. carunculata,* but it has no known predators in the Mediterranean Sea (Righi, 2021).

The opportunistic *H. carunculata* can withstand a wide range of environmental conditions, including variations in temperature, salinity, and oxygen levels, as well as different types of pollution (Schulze *et al.*, 2017; Grimes *et al.*, 2020, 2021). Moreover, like many annelids, *H. carunculata* can regenerate missing body sections after injury, which enhances its resilience (Ahrens *et al.*, 2014; Toso *et al.*, 2024). Altogether, thanks to its opportunistic feeding behaviour and its high tolerance to physicochemical variability, the bearded fireworm is well-adapted to thrive under changing ocean conditions and, in contrast to other less resilient species, may experience population increases that could impact marine ecosystems (Schulze *et al.*, 2017; Grimes *et al.*, 2021; Tiralongo *et al.*, 2023).

In addition to ecological alterations generated by the modification of the ecosystem trophic structure in the Mediterranean basin (Schulze *et al.*, 2017; Simonini *et al.*, 2018; Bosch-Belmar *et al.*, 2024), *H. carunculata* is a growing concern for local economies and cultural activities. Its increased abundance in coastal areas and its scavenging behaviour, particularly preying on fish hooked before hauling operations, can significantly degrade the quality of the catch during fishing efforts (Celona & Comparetto, 2010; Tiralongo *et al.*, 2023). In addition, physical contact with its chaetae causes poisoning and painful injuries in humans, affecting people who inadvertently touch them, such as fishermen, swimmers, and divers (Schulze *et al.*, 2017; Krželj *et al.*, 2020; Righi *et al.*, 2020; Tiralongo *et al.*, 2023).

Hermodice carunculata is a ubiquitous benthic organism and a common component of the infralittoral rocky fauna in the eastern and central Mediterranean Sea (Krželj *et al.*, 2020; Righi *et al.*, 2020); however, despite its potential impact on Mediterranean rocky benthic ecosystems, its geographical distribution remains poorly understood in the western basin. Records of its presence in the Spanish WM coasts are scarce. For instance, it has never been included in the list of marine annelids from continental Spain (Parapar *et al.*, 2012). *H. carunculata* was observed on very rare occasions in the marine reserve Cabo de Palos-Islas Hormigas in the south-eastern part of the Iberian Peninsula (Coma *et al.*, 2011), where it preys on the coral *Oculina patagonica* (De Angelis D'Ossat, 1908). Predation on the gorgonian *Ellisella paraplexauroides* (Stiasny, 1936) has also been recorded in the Chafarinas Islands located in the southern part of the Alboran Sea in the WM basin (Maldonado *et al.*, 2013).

The most recent record of the bearded fireworm in the Iberian Peninsula comes from the Algarve region on the southern coast of Portugal, in the Atlantic Ocean (Encarnação *et al.*, 2019). To our knowledge, there are no published records of *H. carunculata* along the Balearic Islands or the north-eastern Spanish coast. While the observations of *H. carunculata* were previously restricted to the southernmost areas of the Mediterranean Sea, it appears to be expanding northwards from its previously known geographical distribution. Thus, monitoring is essential to assess the current distribution of this polychaete (Righi *et al.*, 2020).

Local Ecological Knowledge (LEK), defined as information derived from stakeholders' experience, can provide valuable details for ecological studies. The use of LEK is a powerful and cost-effective way of monitoring rare species in large geographical areas (Azzurro *et al.*, 2019; Tiralongo *et al.*, 2019; Encarnação *et al.*, 2021). This approach can provide valuable knowledge of species distribution, particularly for eye-catching species that are easy to identify and useful to complement marine biodiversity monitoring programs (Lima *et al.*, 2017; Otero *et al.*, 2024). Methods involving citizen science and LEK have been previously used to better understand *H. carunculata* distribution and expansion in the central Mediterranean Sea (Krželj *et al.*, 2020; Righi *et al.*, 2020).

In this study, we provide new records of presence of the bearded fireworm *H. carunculata* in the Spanish WM Sea through the combination of traditional monitoring and LEK. By examining latitudinal patterns before and after the MHW that affected the region in 2022 and 2023, we tested the hypothesis that the species has expanded into higher latitudes after this period of increased temperature.

Materials and Methods

Occurrence records of the bearded fireworm were obtained by combining different methods.

Monitoring programs

New records of *H. carunculata* were registered during different benthic monitoring programs (MP) performed within the framework of several projects carried out by the research centre *Instituto Español de Oceanografía*:

MP of the infralittoral rocky domain within the mandatory Marine Strategy Framework Directive (MSFD) (Directive 2008/56/EC 2008). This MP is conducted annually along the southern Spanish Atlantic and WM coasts, including the Balearic Islands. Between 2020 and 2024, a total of 181 stations were included in a census. The survey was restricted to infralittoral rocky bottoms between 5 and 18 m depth. At each station, an underwater visual census (UVC) was conducted to characterize benthic assemblages and habitats. These censuses were performed along four transects, by placing 25 quadrats (50 × 50 cm) two meters apart along each transect. Within every quadrant, benthic species were identified and their abundance was recorded.

Long-term MP of the European spiny lobster *Palinurus elephas* (Fabricius, 1787) settlement since 2005, where UVCs have been performed at 17 survey sites in Majorca, Columbretes Islands, and Catalonia for the last 20 years (Muñoz *et al.*, 2021). At each station, a minimum of nine random 50 m^2 transects were established along a similar dive profile over the years. Along these transects, holes and crevices in rocky and coralligenous habitats, at depths between 10 and 40 m, were surveyed.

In these two benthic MPs, the depth and temperature (registered by the dive computer) were recorded for each bearded fireworm observed. Since the bearded fireworm is an easily recognizable species, no specimens were collected for laboratory identification.

Data provided by stakeholders' knowledge

In the present study, we combined different data sources to maximise the number of quality records. First of all, we explored scientific literature including research journals, books, and gray literature (i.e., conference papers, presentations, dissertations, and technical reports). Biodiversity databases such as OBIS.org (Ocean Biodiversity Information System) and GBIF.org (Global Biodiversity Information Facility) were consulted. Citizen science platforms (i.e., Observation.org, Minka-sdg.org, iNaturalist.org and Observadoresdelmar.es), social media platforms (such as YouTube, Twitter, Bluesky, Instagram, or Facebook) and the press (including magazines, newspapers, and newsletters) were also checked using the following keywords (corresponding to the language indicated in brackets): "*Hermodice carunculata*", "Hermodice", "gusano de fuego", "gusano de fuego barbudo", "gusano fuego" (Spanish), "cuc de foc", "cuc foc" (Catalan), "fireworm", "bearded fireworm" (English), "ver de feu", "ver de feu barbu" (French), "feuerborstenstenwurm", "bart feuerborstenstenwurm" and "feuerwurm" (German). All these data sources were monitored between February and March 2025. In the case of social media and citizen science platforms, photographic evidence was a requirement for a record to be considered valid. Data were double-checked to avoid duplication across different sources. Data obtained from biodiversity databases, citizen science platforms, social media, and general press are hereafter referred to as publicly available information (PAI for short).

We regard professional diving guides as an especially valuable source of LEK, since they continuously work in the same areas throughout each diving season. Therefore, we interviewed expert guides from diving centres located along the Spanish Mediterranean Coast. The interviews took place between February and March 2025. Professional photographers and personnel from Marine Protected Areas (MPAs) were also interviewed. All participants were asked about *H. carunculata* sightings; in case of a positive response, information about the date of the first sighting, the frequency, approximate depth, and coordinates of the sightings was also collected. All records included in this study were provided by divers who were already knowledgeable about the species.

Data analysis

Two complementary analytical approaches were applied to assess potential changes in the latitudinal distribution of *H. carunculata* since 2022. All analyses were conducted separately for each data source (dive centres and PAI), following a consistent methodological framework. This decision was based on inherent differences in the nature and quality of the data: dive centre records reflect repeated and direct observations at specific sites over time, whereas social media posts (only available since the widespread adoption of platforms such as Instagram in 2010) may present greater spatial and temporal variability. Moreover, the relatively recent emergence of social media platforms introduces a temporal bias that can affect estimates of species expansion or changes in distribution, especially when compared with long-term monitoring data. Analysing both datasets independently avoids combining sources with different temporal baselines and levels of control, and allows us to test whether the observed patterns are consistent across data types.

Before analysis, the normality of the distribution of latitude was evaluated using the Shapiro-Wilk test (Shapiro & Wilk, 1965). Due to the lack of normality of the dataset, non-parametric tests were used. First, a Fisher-Pitman permutation test was used to compare latitude distributions between the two defined periods (Fisher, 1935; Pitman, 1937, 1938). Second, to test the hypothesis of northward expansion of the species, a chi-squared test for proportions was applied to assess whether the proportion of recent observations (from 2022 onward) differed significantly across latitude zones (Pearson, 1900). These zones were defined in 2-degree bands ranging from 35° to 45°N, as follows: 35-37°, 37-39°, 39-41°, 41-43°, and 43-45°N. As a visual complement to the statistical analyses, the 95th percentile of latitude was calculated for each period, since a consistent increase in the 95th percentile in the post-2022 period would suggest that the expansion is not driven by isolated occurrences, but rather by a general shift towards higher latitudes. All analyses were performed using R software.

Results

Data collection provided 257 new records of *H. carunculata* with their corresponding geographical information and year of observation. Among them, 11 sightings came from benthic MPs (4.3%), 125 from publicly available information (48.6%), and 121 from diving centre interviews (47.1%). The spatial distribution of these sightings is shown in Figure 1, while their temporal distribution is detailed in Figure 2 (Full data in Appendix A).

Monitoring programs

Benthic MPs provided 11 new records of *H. carunculata* along the Mediterranean Spanish coast and the adjacent Atlantic Ocean. In the infralittoral rocky surveys,

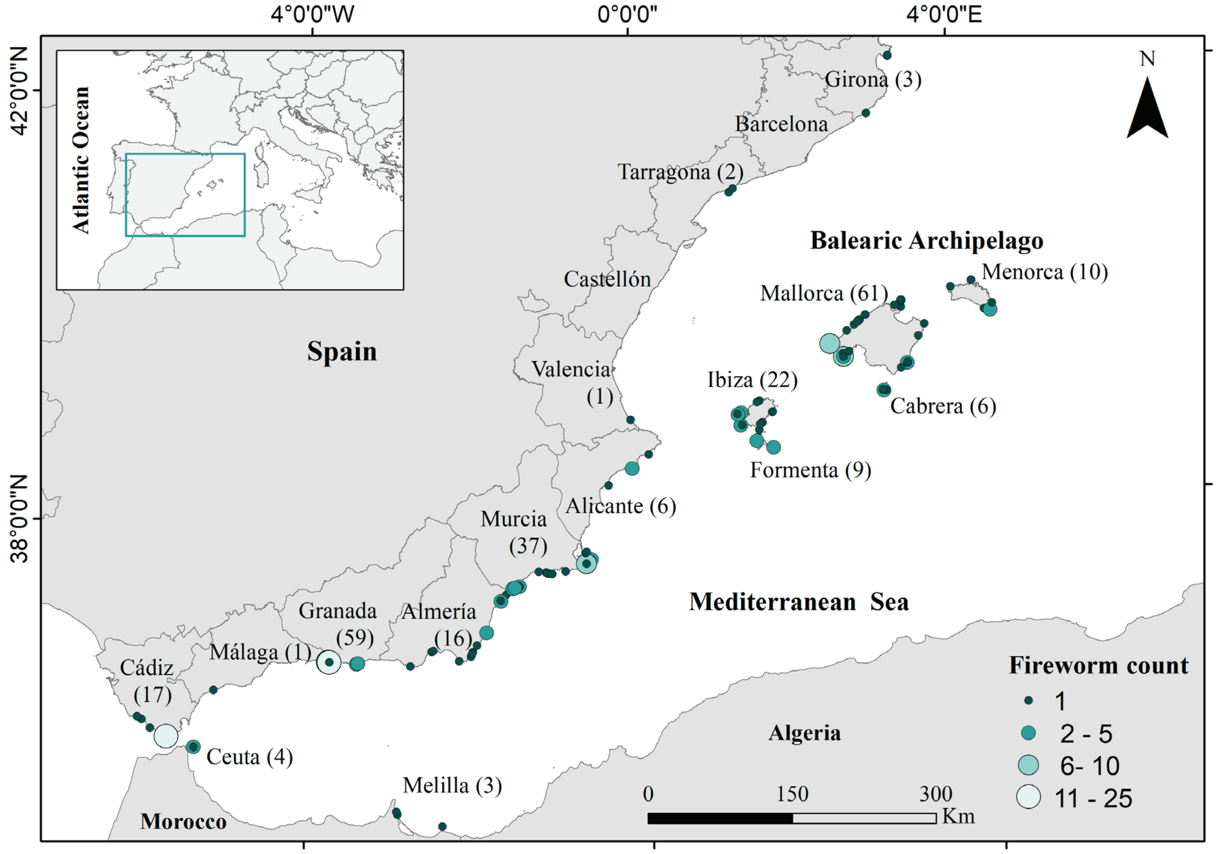


Fig. 1: Distribution of records of *H. caruncula*ta in Spanish WM. The number in brackets indicates the total sightings per province.

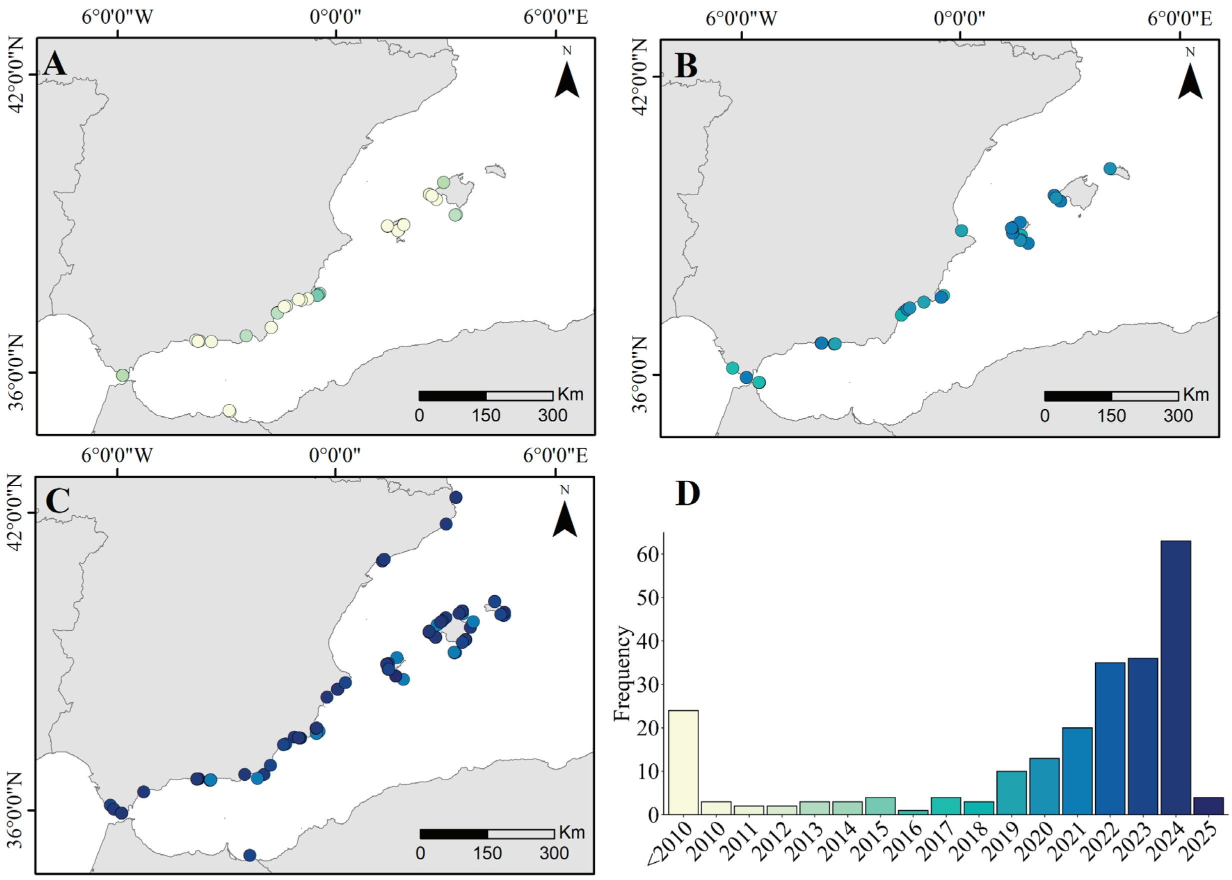


Fig. 2: Geographical distribution of the first record of *H. caruncula*ta divided into different periods; (A) ≤ 2016, (B) 2017-2021, (C) 2022-March 2025. The colours on the maps match the colors of the years in the histogram. Histogram showing the frequency of records per year of reporting (D).

starting in 2020, no bearded fireworms were spotted until 2023, when three specimens of *H. carunculata* were observed in the south of the Iberian Peninsula. In 2024, two additional specimens were spotted (one in the south of the Iberian Peninsula and another in Majorca Island). During the long-term monitoring surveys of *P. elephas* in the Balearic Islands, one specimen of *H. carunculata* was recorded in the Cabrera Archipelago in 2013. During the 2024 survey, one individual was observed on Dragonera Island and four in the Cabrera Archipelago.

Data provided by stakeholders' knowledge

We obtained records of 125 bearded fireworms from six different PAI sources, including biodiversity databases, citizen science platforms, social media, and the press. Most observations came from Instagram (101 records, 80%), followed by iNaturalist (11 records, 8.8%), Facebook (6 records, 4.8%), Minka (4 records, 3.2%), the press (2 records, 1.6%) and Observadoresdelmar (1 record, 0.8%).

Interviews with diving guides provided 121 new records of *H. carunculata*. We contacted a total of 273 diving centres located within the study area, 201 (73.6%) of which participated in the survey, with 89 (44.3%) reporting the observation of *H. carunculata* specimens. We grouped these sightings according to the frequency of appearance: 40 were "rare" sightings (a single time observation, 45%); 18 were "occasional" (1-3 observations per season, 20.2%), and the remaining 31 were "frequent" (more than the three observations per season, 34.8%) (Fig. 3).

It is worth noting that 12 guides (13.8%) perceived an increase in the presence of the *H. carunculata* in their work area. Namely, seven reports of such an increase were located in the Balearic archipelago (three in Ibiza Island and four in Majorca Island), two in Murcia, and three in Almería (Fig. 3). All of these regions belong to the eastern coast of the Iberian Peninsula. Conversely, only two centres reported a decrease in the appearance of the fireworm, both of them in Tarifa (Strait of Gibraltar).

Changes in Latitudinal distribution

The potential shift in the latitudinal distribution of *H. carunculata* observations was evaluated before and after the 2022 MHW (Table 1). In the dive centre dataset, the Fisher-Pitman permutation test showed a significant latitudinal shift between periods ($Z = -2.35$, $p = 0.0184$, Fig. 4a). The mean latitude increased from 37.80° to 38.59° ($\Delta = 0.79°$), and the maximum recorded latitude shifted from 40.05° to 42.25° ($\Delta = 2.20°$). The number of observations was over twofold relative to 2022, increasing from 32 to 73 (+128%). In PAI, a significant difference in latitudinal distribution was also detected using the Fisher-Pitman permutation test, ($Z = -2.00$, $p = 0.05$, Fig. 4b).

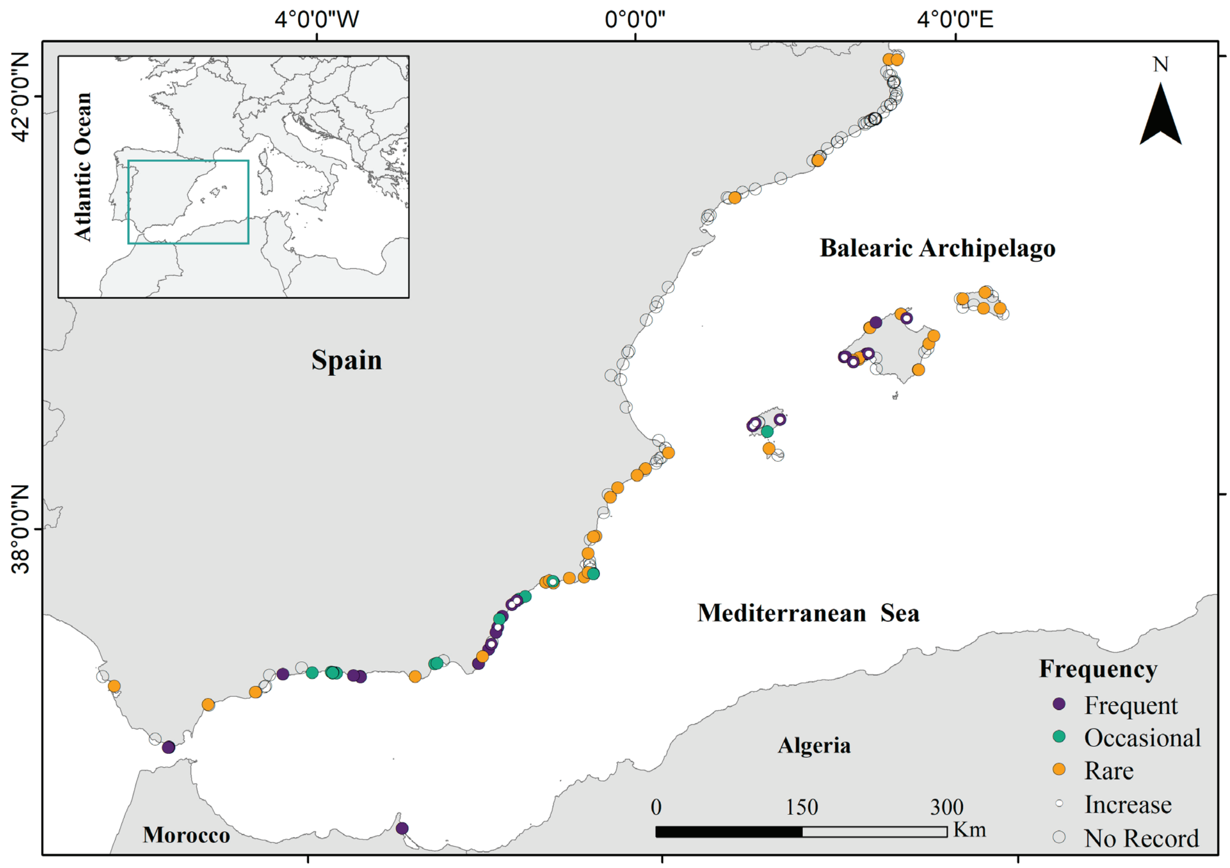


Fig. 3: Frequency of observation of *H. carunculata* according to interviews. Each point corresponds to a diving centre. White dots show the centres that perceived an increase in the presence of the bearded fireworm. Empty circles indicate diving centres that reported not having seen the species.

Table 1. Number of observations of *H. carunculata* recorded before and after 2022 across latitude bands, based on data collected from dive centre interviews and PAI.

Latitude	Before 2022	From 2022 onward	Total
Dive Centre Interviews			
35-37	11	13	24
37-39	15	17	32
39-41	6	27	33
41-43	0	4	4
PAI			
35-37	3	13	16
37-39	5	25	30
39-41	6	33	39
41-43	4	15	19

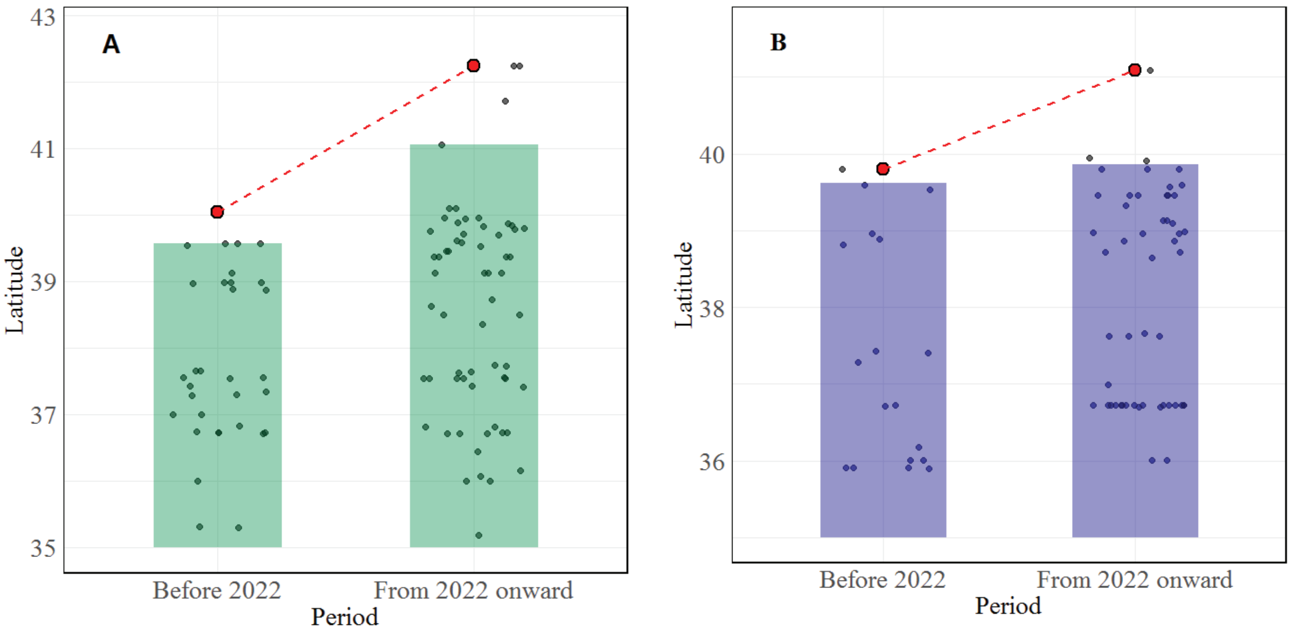


Fig. 4: Changes in the latitudinal distribution of *H. carunculata* observations between the periods before 2022 and from 2022 onward, based on: A) data from dive centres and B) data gathered from PAI. Each point represents an individual observation. In both panels, red circles indicate the maximum latitude recorded in each period, and dashed lines connect these values to highlight their displacement. Shaded areas (green in panel A and purple in panel B) represent the 95th percentile of the latitude distribution.

The mean latitude increased from 37.38° to 38.16° (Δ = 0.8°), and the maximum latitude shifted from 39.80° to 41.09° (Δ = 1.29°).

Frequency of fireworm observations

In the dive centre dataset, the chi-squared test for proportions revealed a significant difference in the distribution of the recent observations of *H. carunculata* across different latitudes ($X^2 = 9.54$, df = 3, $p = 0.023$). The proportion of recent records was relatively balanced in the southern bands (54.2% in the 35–37°N band and 53.1% in the 37–39°N band) but increased markedly in northern latitudes, reaching 81.8% in the 39–41°N band. In the northernmost band (41–43°N), the four *H. carunculata* observations were recorded after 2022, representing a shift from zero to four historical records in this zone (Table 1, Fig. 5A). The chi-squared test for proportions in the PAI dataset was not statistically significant ($X^2 = 2.29$, df = 3, $p = 0.514$), indicating that the proportion of recent records did not vary significantly across latitude bands. In contrast to the dive centre dataset, where a clear accumulation of recent observations was detected at higher latitudes, PAI records of *H. carunculata* sightings were more evenly distributed across latitude zones, with no apparent concentration of sightings in the northernmost bands (Table 1, Fig. 5B).

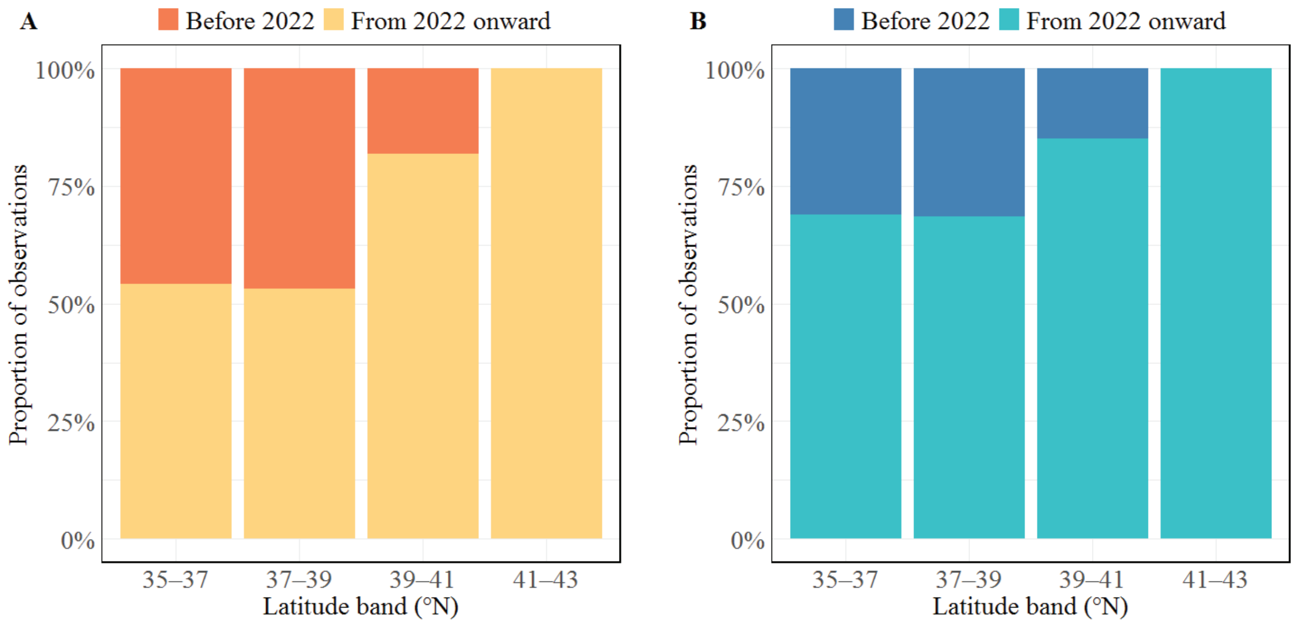


Fig. 5: Proportion of *H. carunculata* observations across latitude intervals and time elapsed since the species was first detected in each range, based on A) data from dive centres and B) data gathered from PAI. Each bar shows the relative proportion of observations within a specific latitude band (35-37°, 37-39°, 39-41°, and 41-43°) before and after 2022.

Discussion

Our results reveal a consistent expansion in the distribution of *H. carunculata* in all data sources. Previous *H. carunculata* observations were largely restricted to southern locations, such as Cabo de Palos (Murcia) (Coma *et al.*, 2011; Ramos-Esplá *et al.*, 2014) and the Chafarinas Islands (Alboran Sea) (Maldonado *et al.*, 2013; Sánchez-Tocino *et al.*, 2017). To our knowledge, there were no records in the literature of *H. carunculata* in the Spanish Mediterranean Sea north of Murcia. The absence of records in higher latitudes, including the Balearic archipelago and north-eastern mainland coasts, reflected a knowledge gap regarding *H. carunculata* distribution in the WM Sea. Here, we report 257 new records of *H. carunculata* located along the Mediterranean Spanish coast. Among these, 120 records were located further north of its previously documented distribution (Figs 1 and 2). In some cases, the presence of the fireworm in particular locations had not been documented but was known to the local stakeholders; in other cases, the novel records might indicate the expansion of the species.

The expansion of *H. carunculata* may coincide temporally with the extreme MHW of 2022-2023, suggesting a potential link between thermal anomalies and the redistribution of this thermophilic species. In 2022, intense Mediterranean MHWs were registered. They were characterised by a long duration (Balearic Islands), high cumulative intensity (Tarragona, Catalonia), and high number of days with temperatures over 28 ºC (Dragonera and Palma, Majorca) (Juza *et al.*,2024). The following year, another exceptionally prolonged MHW was registered in the Mediterranean Sea, reaching high temperature values in the summer in the Alboran and Balearic Seas, and above-average values that lasted until winter (Simon, 2024). This increase in water temperature is consistent with the meridionalization of marine communities, defined as the northward migration of thermophilic biota that was previously restricted to southern sectors of the Mediterranean Sea (Coll *et al.*, 2010; Bianchi *et al.*, 2018). This phenomenon has been reported for many invertebrate species in the Mediterranean Sea, as global warming intensifies (Bianchi *et al.*, 2018; Pérez-Portela *et al.*, 2019; Martín-Arjona *et al.*, 2024). Since the recent invasion of *H. carunculata* of the central Mediterranean Sea and the Thyrrenian Sea was corroborated (Krželj *et al.*, 2020; Righi *et al.*, 2020), scientists have been warning about the possibility of future population expansions from the southern and eastern Mediterranean basins towards the northern and western regions (Righi *et al.*, 2019, 2020). This expansion is most likely driven by a rise in average water temperatures, as *H. carunculata* is thermophilic. According to this hypothesis, *H. carunculata* would be both a “native invader” (Simberloff, 2011), a species that has become invasive within its native range, and a “neonative”, a range-expanding species responding to human-induced environmental change like the ongoing seawater warming (Essl *et al.*, 2019; Righi *et al.*, 2020; Toso *et al.*, 2022).

Our spatial analysis of occurrence records revealed a marked change in the distribution of *H. carunculata* before and after MHW. Our statistical analysis indicated a northward expansion of *H. carunculata* after 2022. Significant differences in the latitudinal distribution were observed before and after the MHWs of 2022 using data from dive centres and PAI datasets. Similarly, the increase in the 95^{th} percentile of latitudinal occurrence suggests that this expansion is not driven by isolated outliers but rather reflects a broader trend of expansion towards higher latitudes.

Furthermore, our analysis of dive centres datasets is in keeping with the recent records in northern latitude bands, reinforcing the hypothesis of *H. carunculata* range expansion. Despite the lack of information on how long each dive centre has been operating, or on the intensity of their seasonal diving activity (which could affect detection probability), several observations support the interpretation of a true range expansion of the species. In particular, a marked increase in recent records in higher latitudes, often in areas where the species had never been reported, suggests that the observed pattern is not solely attributable to increased sampling or observer effort.

On the other hand, differences in latitudinal distribution before and after the MHW were more nuanced in the PAI dataset. This may be partially explained by the greater spatial and temporal variability inherent to social media and online biodiversity records, which often lack systematic sampling protocols and may be influenced by an uneven reporting effort. Moreover, the PAI dataset included sources with different periods of operation (some social platforms, such as Twitter or YouTube, have been active since the mid-2000s, while others, like Instagram, emerged later), which introduces an additional layer of temporal heterogeneity that may influence detectability. Nevertheless, the coherence in the direction of change across datasets, combined with ecological plausibility of temperature-driven expansion, supports the interpretation of a genuine shift in *H. carunculata* distribution. The onset of this expansion following the onset of an unprecedented MHW further strengthens this link, even if causation cannot be definitively established.

Statistical tests also support the theory of a possible expansion of the bearded fireworm, since we show that a northwards shift in its distribution coincides with the ongoing seawater warming in WM (Marullo *et al.*, 2023; Vargas-Yáñez *et al.*, 2023). In this regard, it is worth noting that the metabolic rate of *H. carunculata* is temperature-dependent (Toso *et al.*, 2020; Bosch-Belmar *et al.*, 2024); hence, warmer waters can boost its distribution, abundance, seasonal activity, sexual reproduction, and predator-prey interactions (Righi *et al.*, 2020; Toso *et al.*, 2020; Bosch-Belmar *et al.*, 2024). The extreme thermal conditions recorded during the 2022-2023 MHW may thus favour the optimal conditions for the fireworm to colonise new areas and/or increase its density in areas where it already exists (Righi *et al.*, 2019). In this regard, 13.8% of the dive centres noticed an increase in the presence of *H. carunculata.*

The expansion of *H. carunculata* into more temperate zones raises important ecological concerns, particularly in habitats where vulnerable benthic organisms play a key structural role (Bosch-Belmar *et al.*, 2024; Azzola *et al.*, 2025). Corals play a pivotal role in shaping shallow infralittoral rocky habitats (Terrón-Sigler *et al.*, 2016; Kersting *et al.*, 2017) but are vulnerable to ocean warming (Terrón-Sigler *et al.*, 2016; Garrabou *et al.*, 2022). *H. carunculata* is known to be a voracious corallivore (Wolf *et al.*, 2014) and poses a significant threat to coral species acting as a vector for coral diseases, serving as a winter reservoir for coral pathogens (Sussman *et al.*, 2003, Bonacolta *et al*., 2025), and scavenging weakened corals (Wolf *et al.*, 2014). Consequently, an expansion of the bearded fireworm habitat is particularly concerning for resident anthozoans and endemic key habitat-forming species in the Mediterranean Sea (Bosch-Belmar *et al.*, 2024; Azzola *et al.*, 2025). In fact, some stakeholders observed *H. carunculata* preying on the cnidarians *Paramuricea clavata* (Risso, 1826) and *Anemonia viridis* (Forsskål, 1775), which is in line with previous reports across the basin (Mistri & Ceccherelli, 1994; Celona & Comparetto, 2010; Prevedelli *et al.*, 2016). The invasive potential of *H. carunculata*, sustained by its biological traits (high environmental tolerance, efficient defence mechanisms, teleplanic larvae and omnivorous predatory diet) (Schulze *et al.*, 2017), may cause tangible consequences for the local economy and cultural activities in the area (Celona & Comparetto, 2010; Tiralongo *et al.*, 2023), going beyond ecological disruptions.

Altogether, our findings underscore the critical role of long-term MPs for identifying the introduction of invasive and opportunistic species (and their effects on littoral ecosystems), as already highlighted in the WM (Martín-Arjona *et al.*, 2024). Marine biodiversity MPs are effectively complemented by the use of LEK (Lima *et al.*, 2017; Encarnação *et al.*, 2021; Otero *et al.*, 2024). In particular, LEK collected from expert divers has been recently regarded as critical for marine conservation strategies along the Spanish Mediterranean Coast (Garcia-Bustos, 2025). The combination of long-term MPs and LEK has been particularly effective in documenting the recent expansion of *H. carunculata* (Righi *et al.*, 2020). The success of these complementary approaches is rooted in the early detection of the bearded fireworm sightings at increasing frequency through MPs, as well as fruitful data collection through LEK from divers. In addition, surveying through MP and LEK allows a broader spatial coverage and increased detection capacity, especially in areas less frequently surveyed by scientists. In this context, our findings reinforce the need for adaptive management strategies capable of responding to species redistribution driven by climate change. In rapidly warming seas, combining formal scientific monitoring with contributions from informed stakeholders can provide timely and robust information for decision-making. The observed spread of *H. carunculata* exemplifies the growing need to integrate ecological, climatic, and social data to aid environmental conservation under changing ocean conditions.

Acknowledgements

We warm-heartedly thank all the citizen science platforms and especially all the dive guides, who generously and passionately contributed valuable knowledge acquired through their experience. Both monitoring programs were carried out inside and outside Marine Protected Areas (MPAs), therefore, the progress of these surveys would not have been possible without all the necessary permissions granted by the management teams of the MAPs. We would like to thank the whole INFRA team for their invaluable cooperation during the sampling expeditions, and the crews of the R/Vs ‘Francisco de Paula Navarro’ and ‘SOCIB’.

This research is part of the Monitoring of Marine Strategies, Marine Environment Assessment and Definition of Good Environmental Status (ESMARES3) project, carried out by the IEO-CSIC as part of the Interdepartmental Collaboration Agreement between the Ministry for Ecological Transition and the Demographic Challenge and the Ministry of Science, Innovation and Universities of Spain. It is co-funded by the European Fund for Maritime, Fisheries and Aquaculture (FEMPA).

Authors’ contributions: Conceptualization and design of the study NRB, FM, DD; writing-original draft preparation NRB, FM, ER; writing – review NRB, FM, ER, IB-V, SD, AM-A, SM, DD; data acquisition NRB, FM, ER, IB-V, AM-A, SD, DD; data visualization and review NRB, FM, ER, DD. All authors have read and agreed to the published version of the manuscript.

References

Ahrens, J.B., Kudenov, J.D., Marshall, C.D., Schulze, A., 2014. Regeneration of posterior segments and terminal structures in the bearded fireworm, *Hermodice carunculata* (Annelida: Amphinomidae). *Journal of Morphology*, 275 (10), 1103-1112.

Azzola, A., Montefalcone, M., Righi, S., Cenni, E., Robello, C. *et al.*, 2025. Cascading effects of global warming: evidence for the impact of range-expanding thermophilic species invasion on resident species. *Biological Invasions*, 27 (1), 1-8.

Azzurro, E., Sbragaglia, V., Cerri, J., Bariche, M., Bolognini, L. *et al.*, 2019. Climate change, biological invasions, and the shifting distribution of Mediterranean fishes: A large-scale survey based on local ecological knowledge. *Global Change Biology*, 25 (8), 2779-2792.

Bianchi, C.N., Caroli, F., Guidetti, P., Morri, C., 2018. Seawater warming at the northern reach for southern species: Gulf of Genoa, NW Mediterranean. *Journal of the Marine Biological Association of the United Kingdom*, 98 (1), 1-12.

Bonacolta, A.M., Weiler, B.A., Grimes, C.J., Trznadel, M., Vermeij, M.J.A. *et al*. 2025. Fireworms are a reservoir and potential vector for coral-infecting apicomplexans. *The ISME Journal*, wraf078.

Bosch-Belmar, M., Tantillo, M.F., Sarà, G., 2024. Impacts of increasing temperature due to global warming on key habitat-forming species in the Mediterranean Sea: Unveiling negative biotic interactions. *Global Ecology and Conservation*, 50, e02844

Boudouresque, C.F., Astruch, P., André, S., Belloni, B., Blanfuné, A. *et al.,* 2024. The Heatwave of Summer 2022 in the North-Western Mediterranean Sea: Some Species Were Winners. *Water (Switzerland)*, 16 (2), 219.

Celona, A., Comparetto, G., 2010. Prime osservazioni sulla predazione opportunistica del “vermocane” *Hermodice carunculata* (Pallas, 1766), ai danni della piccola pesca artigianale nelle acque di Lampedusa (is. Pelagie). In Annales: *Series Historia Naturalis* (Vol. 20, No. 1, p. 15-20). Scientific and Research Center of the Republic of Slovenia.

Coll, M., Piroddi, C., Steenbeek, J., Kaschner, K., Lasram, F.B.R. *et al.*, 2010. The biodiversity of the Mediterranean Sea: Estimates, patterns, and threats. *PLoS one*, 5 (8), e11842.

Coma, R., Serrano, E., Linares, C., Ribes, M., Díaz, D. *et al.,* 2011. Sea urchins predation facilitates coral invasion in a marine reserve. *PLoS one*, 6 (7), e22017.

Encarnação, J., Teodósio, M.A., Morais, P., 2021. Citizen Science and Biological Invasions: A Review. *Frontiers in Environmental Science*, 8, 602980.

Encarnação, J., Morais, P., Baptista, V., Cruz, J., Teodósio, M.A., 2019. New evidence of marine fauna tropicalization off the Southwestern Iberian Peninsula (Southwest Europe). *Diversity*, 11 (4), 48.

Essl, F., Dullinger, S., Genovesi, P., Hulme, P.E., Jeschke, J.M. *et al.*, 2019. A Conceptual Framework for Range-Expanding Species that Track Human-Induced Environmental Change. *BioScience*, 69 (11), 908-919.

Fisher, R., 1935. *The design of experiments*. Oliver & Boyd, London, 274.

Garcia-Bustos, V., 2025. Conservation Attitudes and Perceived Biodiversity Among Divers on the Spanish Mediterranean Coast: Insights from Local Ecological Knowledge. In: *Oceans* (Vol. 6, No. 1, p. 4). MDPI.

Garrabou, J., Gómez-Gras, D., Medrano, A., Cerrano, C., Ponti, M. *et al.*, 2022. Marine heatwaves drive recurrent mass mortalities in the Mediterranean Sea. *Global* Change Biology, 28 (19), 5708-5725.

Grimes, C.J., Petersen, L.H., Schulze, A., 2021. Differential gene expression indicates modulated responses to chronic and intermittent hypoxia in corallivorous fireworms (Hermodice carunculata). Scientific Reports, 11 (1), 11110.

Grimes, C.J., Paiva, P. C., Petersen, L. H., Schulze, A. 2020. Rapid plastic responses to chronic hypoxia in the bearded fireworm, *Hermodice carunculata* (Annelida: Amphinomidae). *Marine Biology*, 167 (9), 140.

Juza, M., de Alfonso, M., Fernández-Mora, À., 2024. Coastal ocean response during the unprecedented marine heat waves in the western Mediterranean in 2022. *State Planet*, 4, 1-11.

Kersting, D.K., Cebrian, E., Verdura, J., Ballesteros, E., 2017. A new *Cladocora caespitosa* population with unique ecological traits. *Mediterranean Marine Science*, 18 (1), 38-42.

Kržielj, M., Cerrano, C., Di Camillo, C.G., 2020. Enhancing diversity knowledge through marine citizen science and social platforms: The case of *Hermodice carunculata* (Annelida, Polycheta). *Diversity*, 12 (8), 311.

Lima, M.S.P., Oliveira, J.E.L., de Nóbrega, M.F., Lopes, P.F.M., 2017. The use of Local Ecological Knowledge as a complementary approach to understand the temporal and spatial patterns of fishery resources distribution. *Journal of Ethnobiology and Ethnomedicine*, 13, 1-12.

Maldonado, M., López-Acosta, M., Sánchez-Tocino, L., Sitjà, C., 2013. The rare, giant gorgonian *Ellisella paraplexauroides*: Demographics and conservation concerns. *Marine Ecology Progress Series*, 479, 127-141.

Martín-Arjona, A., Muñoz-Caballero, A., Serrano, A., Díaz-Viñolas, D., Urra, J., 2024. The thermophilic sea anemone *Telmatactis cricoides* (Cnidaria, Hexacorallia) in the western Mediterranean: Filling gaps in the knowledge of the distribution. *Journal of the Marine Biological Asso-*

ciation of the United Kingdom, 104, 1-5.

Marullo, S., Serva, F., Iacono, R., Napolitano, E., di Sarra, A. *et al.*, 2023. Record-breaking persistence of the 2022/23 marine heatwave in the Mediterranean Sea. *Environmental Research Letters*, 18 (11), 114041.

Mistri, M., Ceccherelli, V., 1994. Growth and secondary production of the Mediterranean gorgonian *Paramuricea clavata*. *Marine Ecology Progress Series*, 103, 291-296.

Muñoz, A., Goñi, R., Linares, C., Kersting, D., Stobart, B. *et al.*, 2021. Exploration of the inter-annual variability and multi-scale environmental drivers of European spiny lobster, *Palinurus elephas* (Decapoda: Palinuridae) settlement in the NW Mediterranean. *Marine Ecology*, 42 (3), e12654.

Otero, P., Velasco, E., Valeiras, J., 2024. Surveillance of coastal biodiversity through social network monitoring. *Ecological Informatics*, 80, 102515.

Parapar, J., Alós, C., Núñez, J., Moreira, J., López, E. *et al.*, 2012. *Fauna Ibérica, Volume 36: Annelida: Polychaeta III*., Ed. R. M.A. Madrid: Museo Nacional de Ciencias Naturales (CSIC).

Pearson, K., 1900. X. On the criterion that a given system of deviations from the probable in the case of a correlated system of variables is such that it can be reasonably supposed to have arisen from random sampling. *The London, Edinburgh, and Dublin Philosophical Magazine and Journal of Science*, 50 (302), 157-175.

Pérez-Portela, R., Wangensteen, O.S., Garcia-Cisneros, A., Valero-Jiménez, C., Palacín, C. *et al.*, 2019. Spatio-temporal patterns of genetic variation in *Arbacia lixula*, a thermophilous sea urchin in expansion in the Mediterranean. *Heredity*, 122 (2), 244-259.

Pitman, E.J.G., 1937. Significance Tests Which May be Applied to Samples from Any Populations. II. The Correlation Coefficient Test. *Journal of the Royal Statistical Society Series B: Statistical Methodology*, 4, 225-232.

Pitman, E.J.G., 1938. Significance Tests which May be Applied to Samples from any Populations: III. The Analysis of Variance Test. *Biometrika*, 29 (3/4), 322-335.

Poloczanska, E.S., Burrows, M.T., Brown, C.J., Molinos, J.G., Halpern, B.S. *et al.*, 2016. Responses of marine organisms to climate change across oceans. *Frontiers in Marine Science* 3, 1-21.

Prevedelli, D., Fai, S., Righi, S., Simonini, R., 2016. Predation on *Anemonia viridis* (Actiniaria) by *Hermodice carunculata* (Annelida: Amphinomidae): preliminary data. *Biologia Marina Mediterranea*, 23 (1), 240-242.

Raitsos, D.E., Beaugrand, G., Georgopoulos, D., Zenetos, A., Pancucci-Papadopoulou, A.M. *et al.*, 2010. Global climate change amplifies the entry of tropical species into the eastern Mediterranean Sea. *Limnology and Oceanography*, 55 (4), 1478-1484.

Ramos-Esplá, A.A., Rubio-Portillo, E., Izquierdo-Muñoz, A., Antón, I., 2014. Monitoring global warming in the SE of Iberian Peninsula (Western Mediterranean). Recent introductions of species of warm affinities. *CIESM International Scientific Forum*.

Righi, S., 2021., *Ecology and physico-chemical weapons of the Mediterranean range-expanding fireworm* Hermodice carunculata *(Annelida)*. PhD Thesis. University of Modena and Reggio Emilia, Italy.

Righi, S., Prevedelli, D., Simonini, R., 2020. Ecology, distribution and expansion of a Mediterranean native invader, the fireworm *Hermodice carunculata* (Annelida). *Mediterranean Marine Science*, 21 (3), 558-574.

Righi, S., Maletti, I., Maltagliati, F., Castelli, A., Barbieri, M. *et al.*, 2019. Morphometric and molecular characterization of an expanding Ionian population of the fireworm *Hermodice carunculata* (Annelida). *Journal of the Marine Biological Association of the United Kingdom*, 99 (7), 1569-1577.

Sánchez-Tocino, L., De La Linde Rubio, A., Sol Lizana Rosas, M., Pérez Guerra, T., Tierno De Figueroa, J.M., 2017. Pruning treatment: A possible method for improving the conservation status of a *Ellisella paraplexauroides* Stiasny, 1936 (Anthozoa, Alcyonacea) population in the Chafarinas Islands? *Mediterranean Marine Science*, 18 (3), 479-485.

Schulze, A., Grimes, C.J., Rudek, T.E., 2017. Tough, armed and omnivorous: *Hermodice carunculata* (Annelida: Amphinomidae) is prepared for ecological challenges. *Journal of the Marine Biological Association of the United Kingdom*, 97 (5), 1075-1080.

Serva, F., Marullo, S., Iacono, R., Napolitano, E., Santoleri, R., 2024. Drivers of persistent marine heatwaves in the Mediterranean in recent years. *Nuovo Cimento della Societa Italiana di Fisica*, *C* 47, 1-4.

Shapiro, S.S., Wilk, M.B., 1965. An Analysis of Variance Test for Normality (Complete Samples). *Biometrika*, 52 (3-4), 591-611.

Simberloff, D., 2011. Native Invaders. In: *Encyclopedia of Biological Invasions*, (University of California Press), 472-475.

Simon, A., 2024. Main features of summer 2023 MHWs and trends in air-sea interactions related to the long-term evolution of MHWs in the Mediterranean. 77-84.

Simonini, R., Maletti, I., Righi, S., Fai, S., Prevedelli, D., 2018. Laboratory observations on predator–prey interactions between the bearded fireworm (*Hermodice carunculata*) and Mediterranean benthic invertebrates. *Marine and Freshwater Behaviour and Physiology*, 51 (3), 145-158.

Simonini, R., Righi, S., Maletti, I., Fai, S., Prevedelli, D., 2017. Bearded versus thorny: The fireworm *Hermodice carunculata* preys on the sea urchin *Paracentrotus lividus*. *Ecology*, 98 (10), 2730-2732.

Sussman, M., Loya, Y., Fine, M., Rosenberg, E., 2003. The marine fireworm *Hermodice carunculata* is a winter reservoir and spring-summer vector for the coral-bleaching pathogen *Vibrio shiloi*. *Environmental Microbiology*, 5 (4), 250-255.

Terrón-Sigler, A., León-Muez, D., Peñalver-Duque, P., Gálvez-César, R., Espinosa Torre, F., 2016. Geographic distribution of *Astroides calycularis* (Scleractinia: Dendrophylliidae) as a baseline to assess future human impacts on the Southern Iberian Peninsula. *Journal of the Marine Biological Association of the United Kingdom*, 96 (5), 1181-1189.

Tiralongo, F., Oscar, A., Tibullo, D., Tondo, E., Martire, L. *et al.*, 2019. Monitoring uncommon and non-indigenous fishes in Italian waters : One year of results for the AlienFish project. *Regional Studies in Marine Science*, 28, 100606.

Tiralongo, F., Marino, S., Ignoto, S., Martellucci, R., Lombardo, B.M. *et al.*, 2023. Impact of *Hermodice carunculata* (Pallas, 1766) (Polychaeta: Amphinomidae) on artisanal fishery: A case study from the Mediterranean sea. *Marine Environmental Research*, 192, 106227.

Toso, A., Mammone, M., Rossi, S., 2024. Effect of temperature and body size on anterior and posterior regeneration in *Hermodice carunculata* (Polychaeta, Amphinomidae). *Marine Biology*, 171 (8), 152.

Toso, A., Boulamail, S., Lago, N., Pierri, C., Piraino, S. *et al.*, 2020. First description of early developmental stages of the native invasive fireworm *Hermodice carunculata* (Annelida, Amphinomidae): A cue to the warming of the mediterranean sea. *Mediterranean Marine Science*, 21 (2), 442-447.

Toso, A., Furfaro, G., Fai, S., Giangrande, A., Piraino, S., 2022. A sea of fireworms? New insights on ecology and seasonal density of *Hermodice carunculata* (Pallas, 1766) (Annelida) in the Ionian Sea (SE Italy). *European Zoological Journal*, 89 (1), 1104-1114.

Vargas-Yáñez, M., Moya, F., Serra, M., Juza, M., Jordà, G. *et al.*, 2023. Observations in the Spanish Mediterranean Waters: A Review and Update of Results of 30-Year Monitoring. *Journal of Marine Science and Engineering*, 11 (7), 1284.

Wolf, A.T., Nugues, M.M., Wild, C., 2014. Distribution, food preference, and trophic position of the corallivorous fireworm *Hermodice carunculata* in a Caribbean coral reef. *Coral Reefs*, 33, 1153-1163.

Appendix

Appendix A: Summary of *Hermodice carunculata* records

The table presented in this appendix includes all the records of *Hermodice carunculata* provided by the different sources mentioned in the manuscript. The coordinates in the table are approximated to the best information available, whereas the columns Yr_first and Yr_last indicate the years of first and last observation of the bearded fireworm respectively. In some occasions the dive centres were providing statements like "…since many years" or "…it has always been there" and in these cases the authors agreed that the year of first observation should be marked as 2000.

ID	Source	Province	Location	Yr_first	Yr_last	Latitude	Longitude	Depth
1	Diving	Almeria	Sabinar	2024		36.8186º N	2.5325º W	
2	Diving	Almeria	Sabinar	2013	2023	36.8247º N	2.5126º W	10-15m
3	Diving	Almeria	Sabinar			36.6833º N	2.7827º W	12-14m
4	Diving	Almeria	Cabo_Gata	2024	2024	36.8123º N	2.0487º W	10-15m
5	Diving	Almeria	Cabo_Gata		2024	36.7695º N	2.0717º W	8-12m
6	Diving	Almeria	Villaricos	2000	2024	37.2926º N	1.7183º W	20m
7	Diving	Almeria	Cabo_Gata	2019	2024	37.3477º N	1.6509º W	> 12m
8	Diving	Almeria	Negras	2022		36.8769º N	2.0018º W	6m
9	Diving	Almeria	Cabo_Gata	2018	2024	37.2852º N	1.7143º W	15-20m
10	Diving	Almeria	Cabo_Gata		2024	37.2852º N	1.7143º W	
11	Diving	Almeria	Cabo_Gata		2024	36.7978º N	2.0587º W	8-12m
12	Diving	Almeria	San_Andres	2000	2024	36.9919º N	1.886º W	
13	Diving	Almeria	San_Andres	2000	2024	36.9919º N	1.886º W	12-20m
14	Diving	Cadiz	Tarifa	2024		36.003º N	5.605º W	
15	Diving	Cadiz	Tarifa	2014	2024	36.003º N	5.605º W	12-18m
16	Diving	Cadiz	Tarifa	2023	2024	36.003º N	5.605º W	12-15m
17	Diving	Cadiz	Tarifa	2024		36.003º N	5.605º W	18m
18	Diving	Cadiz	Tarifa	2014	2024	36.003º N	5.605º W	>15m
19	Diving	Cadiz	Tarifa		2024	36.003º N	5.605º W	12-20m
20	Diving	Granada	Calahonda	2024		36.7083º N	3.3894º W	> 14m
21	Diving	Granada	Herradura	2000	2024	36.7192º N	3.7273º W	9-20m
22	Diving	Granada	Herradura	2018	2024	36.7218º N	3.7351º W	10-20m
23	Diving	Granada	Herradura	2024		36.7192º N	3.7273º W	> 14m
24	Diving	Granada	Herradura			36.7218º N	3.7351º W	
25	Diving	Granada	Herradura		2024	36.7189º N	3.7265º W	
26	Diving	Granada	Herradura	2000	2024	36.7398º N	3.7868º W	12-20m
27	Diving	Granada	Herradura			36.7217º N	3.7356º W	10-20m
28	Diving	Granada	Herradura	2024		36.7232º N	3.7368º W	
29	Diving	Granada	Marina_Este	2023		36.7199º N	3.728º W	7m
30	Diving	Granada	Marina_Este	2010		36.7201º N	3.7283º W	
31	Diving	Granada	Marina_Este		2023	36.7201º N	3.7283º W	15m
32	Diving	Granada	Marina_Este	2000	2025	36.7201º N	3.7283º W	
33	Diving	Granada	Calahonda	2022	2024	36.7083º N	3.3894º W	10-14m
34	Diving	Granada	Calahonda	2019	2024	36.7085º N	3.3899º W	10-15m
35	Diving	Málaga	Estepona	2024		36.4438º N	5.0699º W	6m
36	Diving	Cabrera	Imperial	2012		39.1254º N	2.9579º E	
37	Diving	Formentera	Gavina	2023	2024	38.7208º N	1.3824º E	
38	Diving	Ibiza	Illots_Ponent	2000	2024	38.9728º N	1.1666º E	12-18m
39	Diving	Ibiza	St_Eulalia	2000	2024	38.9822º N	1.5782º E	
40	Diving	Ibiza	Islotes_Ibiza	2000	2024	38.8885º N	1.4541º E	15-25m
41	Diving	Ibiza	Islotes_Ibiza	2000	2024	38.8746º N	1.4265º E	15-25m

Continued

Appendix A continued

ID	Source	Province	Location	Yr_first	Yr_last	Latitude	Longitude	Depth
42	Diving	Ibiza	St_Eulalia	2000	2024	38.984º N	1.5844º E	15-20m
43	Diving	Ibiza	Islotes_Ibiza	1994	2024	38.9789º N	1.1604º E	15-20m
44	Diving	Mallorca	Pollensa		2024	39.9464º N	3.2063º E	18-30m
45	Diving	Mallorca	Pollensa	2022	2024	39.9574º N	3.214º E	10-20m
46	Diving	Mallorca	Levante	2022	2024	39.8908º N	3.2017º E	10-20m
47	Diving	Mallorca	Cabrera			39.1322º N	2.9218º E	
48	Diving	Mallorca	Levante			39.3676º N	3.2368º E	
49	Diving	Mallorca	Levante	2024		39.3701º N	3.2406º E	6-15m
50	Diving	Mallorca	Levante	2024		39.3753º N	3.2421º E	6-15m
51	Diving	Mallorca	Levante	2024		39.3709º N	3.239º E	28m
52	Diving	Mallorca	Levante	2024		39.3676º N	3.2368º E	16m
53	Diving	Mallorca	Tramuntana	2024		39.8411º N	2.7647º E	
54	Diving	Mallorca	Andratx	2023		39.5327º N	2.3869º E	8m
55	Diving	Mallorca	Levante	2024		39.6131º N	3.3917º E	10m
56	Diving	Mallorca	Pollensa	2024		39.9439º N	3.2027º E	20m
57	Diving	Mallorca	Dragonera	2000		39.5729º N	2.3025º E	
58	Diving	Mallorca	Dragonera	2000	2024	39.5729º N	2.3025º E	
59	Diving	Mallorca	Dragonera	2000	2024	39.5729º N	2.3025º E	20-30m
60	Diving	Mallorca	Dragonera	2024		39.7959º N	2.6929º E	
61	Diving	Mallorca	Calvia	2000	2024	39.4623º N	2.4717º E	10-19m
62	Diving	Mallorca	Calvia			39.4623º N	2.4717º E	
63	Diving	Mallorca	Calvia	2024		39.4623º N	2.4717º E	20-30m
64	Diving	Mallorca	Calvia			39.4623º N	2.4717º E	
65	Diving	Mallorca	Tramuntana	2024	2024	39.7802º N	2.6634º E	7-12m
66	Diving	Mallorca	Andratx	2000		39.5352º N	2.3654º E	
67	Diving	Mallorca	Levante	2022		39.72º N	3.4736º E	2-4m
68	Diving	Mallorca	Calvia	2024		39.4623º N	2.4717º E	
69	Diving	Mallorca	Pollensa	2024		39.9575º N	3.2038º E	20m
70	Diving	Mallorca	Calvia			39.4916º N	2.4715º E	
71	Diving	Mallorca	Tramuntana	2022		39.7025º N	2.5283º E	10m
72	Diving	Mallorca	Tramuntana	2024	2024	39.7566º N	2.6209º E	7-12m
73	Diving	Mallorca	Tramuntana	2024		39.7802º N	2.6634º E	
74	Diving	Mallorca	Calvia	2024		39.4623º N	2.4717º E	
75	Diving	Mallorca				39.5086º N	2.5454º E	
76	Diving	Menorca	Mahon	2023	2024	39.8033º N	4.295º E	10m
77	Diving	Menorca	Fornells	2022		40.0942º N	4.0765º E	12m
78	Diving	Menorca	Fornells	2023		40.0935º N	4.0772º E	20m
79	Diving	Menorca	Ciutadella	2020		40.0479º N	3.8211º E	15-20m
80	Diving	Menorca	Mahon	2025		39.8653º N	4.3077º E	10m
81	Diving	Menorca	Cap_Font	2023	2024	39.8224º N	4.2071º E	8-10m
82	Diving	Alicante	Cabo_Hortes	2024		38.352º N	0.4104º W	4m
83	Diving	Alicante	Benidorm	2024		38.5035º N	0.1317º W	7-14m
84	Diving	Alicante	Benidorm	2023		38.5029º N	0.1229º W	
85	Diving	Alicante	Benidorm	2024		38.5029º N	0.1229º W	15m
86	Diving	Alicante	Calpe	2023		38.6313º N	0.0793º E	20m
87	Diving	Alicante	Cabo_Tinoso	2019		37.5394º N	1.1449º W	
88	Diving	Barcelona	Tosa_Mar	2024		41.7203º N	2.9402º E	
89	Diving	Girona	Cap_Creus	2024		42.2385º N	3.2585º E	

Continued

Appendix A continued

ID	Source	Province	Location	Yr_first	Yr_last	Latitude	Longitude	Depth
90	Diving	Girona	Cap_Creus	2024		42.2446º N	3.2571º E	17m
91	Diving	Tarragona	Tarragona	2024		41.0555º N	1.1782º E	18-19m
92	Diving	Melilla	Melilla	2000	2024	35.2939º N	2.9309º W	6-12m
93	Diving	Melilla	Melilla	2000	2024	35.3177º N	2.9457º W	8-15m
94	Diving	Murcia	Mazarron	2024		37.5581º N	1.2637º W	5 m
95	Diving	Murcia	Cabo_Palos	2010		37.6623º N	0.637º W	4-5 m
96	Diving	Murcia	Cabo_Palos	2017		37.6623º N	0.637º W	5-15 m
97	Diving	Murcia	Cabo_Palos			37.6623º N	0.637º W	18-20 m
98	Diving	Murcia	Cabo_Palos	2024		37.6623º N	0.637º W	8m
99	Diving	Murcia	Cabo_Palos	2024		37.6623º N	0.637º W	13-20m
100	Diving	Murcia	Cabo_Palos	2015	2022	37.6463º N	0.6658º W	15m
101	Diving	Murcia	Cabo_Palos	2023		37.6463º N	0.6658º W	15-25m
102	Diving	Murcia	Cabo_Cope	1994	2024	37.4211º N	1.4916º W	12-14 m
103	Diving	Murcia	Cabo_Cope	2023	2024	37.4211º N	1.4916º W	
104	Diving	Murcia	Cabo_Cope	2000	2024	37.4211º N	1.4916º W	7m
105	Diving	Murcia	Cabo_Palos	2024		37.6241º N	0.699º W	
106	Diving	Murcia	Cabo_Tinoso	2024		37.5353º N	1.1068º W	
107	Diving	Murcia	Cabo_Tinoso			37.5404º N	1.1543º W	14m
108	Diving	Murcia	Cabo_Palos	2015	2022	37.6241º N	0.699º W	10m
109	Diving	Murcia	Isla_Fraile	1994	2024	37.4077º N	1.5454º W	12-14m
110	Diving	Murcia	Isla_Fraile	2023	2024	37.4077º N	1.5454º W	
111	Diving	Murcia	Manga	2024		37.727º N	0.7056º W	
112	Diving	Murcia	Cabo_Tinoso	2023		37.5403º N	1.1552º W	8m
113	Diving	Murcia	Manga	2024		37.7361º N	0.6925º W	10-18m
114	Diving	Murcia	Cabo_Tinoso	2024	2024	37.5386º N	1.142º W	9-15m
115	Diving	Murcia	Cabo_Tinoso			37.5396º N	1.1438º W	
116	Diving	Murcia	Cabo_Tinoso	2024	2024	37.539º N	1.1409º W	
117	Diving	Murcia	Cabo_Tinoso	2004		37.5574º N	0.9441º W	15-25m
118	Diving	Murcia	Cabo_Tinoso	2011	2012	37.5353º N	1.1068º W	
119	Diving	Murcia	Cabo_Tinoso	2000	2024	37.5508º N	1.175º W	10m
120	Diving	Murcia	Cabo_Tinoso	2024	2024	37.5411º N	1.1589º W	
121	Diving	Murcia	Cabo_Tinoso	2024		37.5353º N	1.1068º W	12-15m
122	Facebook	Mallorca	Calvia	2020		39.4623º N	2.4717º E	10-25m
123	Facebook	Mallorca	Calvia	2022		39.4623º N	2.4717º E	10-25m
124	Facebook	Menorca	Mahon	2024		39.8035º N	4.28º E	18-20m
125	Facebook	Granada	Almunecar	2025		36.7259º N	3.6937º W	
126	Facebook	Ibiza	Islotes_Ibiza	2015		38.8898º N	1.4512º E	
127	Facebook	Valencia	Miramar	2019		38.961º N	0.124º W	
128	Inaturalist	Almeria	Cabo_Gata	2013		37.2822º N	1.7189º W	
129	Inaturalist	Cadiz	Tarifa	2024		36.003º N	5.605º W	
130	Inaturalist	Cadiz	Tarifa	2015		36.003º N	5.605º W	
131	Inaturalist	Cadiz	Tarifa	2011		36.003º N	5.605º W	
132	Inaturalist	Granada	Almunecar	2012		36.727º N	3.6931º W	
133	Inaturalist	Granada	Herradura	2024		36.7189º N	3.7265º W	
134	Inaturalist	Granada	Calahonda	2010		36.7085º N	3.3899º W	
135	Inaturalist	Formentera	Es_Freu	2021		38.7353º N	1.3944º E	
136	Inaturalist	Mallorca	Calvia	2022		39.4625º N	2.4728º E	
137	Inaturalist	Ceuta	Ceuta	2019		35.9008º N	5.2725º W	

Continued

Appendix A continued

ID	Source	Province	Location	Yr_first	Yr_last	Latitude	Longitude	Depth
138	Inaturalist	Murcia	Cabo_Palos	2021		37.6241º N	0.699º W	
139	Instagram	Almeria	Cabo_Gata	2022		36.7305º N	2.2093º W	
140	Instagram	Almeria	Cabo_Gata	2023		36.9928º N	1.884º W	
141	Instagram	Cadiz	Barbate	2017		36.1821º N	5.9476º W	
142	Instagram	Cadiz	Tarifa	2017		36.003º N	5.605º W	
143	Instagram	Cadiz	Tarifa	2020		36.003º N	5.605º W	
144	Instagram	Cadiz	Tarifa	2021		36.003º N	5.605º W	
145	Instagram	Cadiz	Tarifa	2024		36.003º N	5.605º W	
146	Instagram	Cadiz	Tarifa	2016		36.003º N	5.605º W	
147	Instagram	Granada	Calahonda	2019		36.701º N	3.4089º W	
148	Instagram	Granada	Calahonda	2021		36.701º N	3.4089º W	
149	Instagram	Granada	Calahonda	2021		36.701º N	3.4089º W	
150	Instagram	Granada	Calahonda	2023		36.701º N	3.4089º W	
151	Instagram	Granada	Calahonda	2023		36.7015º N	3.4087º W	
152	Instagram	Granada	Calahonda	2024		36.7015º N	3.4087º W	
153	Instagram	Granada	Herradura	2019		36.7217º N	3.7356º W	
154	Instagram	Granada	Herradura	2020		36.7217º N	3.7356º W	
155	Instagram	Granada	Herradura	2019		36.7217º N	3.7356º W	
156	Instagram	Granada	Herradura	2022		36.7217º N	3.7356º W	
157	Instagram	Granada	Herradura	2022		36.7217º N	3.7356º W	
158	Instagram	Granada	Herradura	2022		36.7217º N	3.7356º W	
159	Instagram	Granada	Herradura	2022		36.7217º N	3.7356º W	
160	Instagram	Granada	Herradura	2022		36.7217º N	3.7356º W	
161	Instagram	Granada	Herradura	2022		36.7217º N	3.7356º W	
162	Instagram	Granada	Herradura	2022		36.7217º N	3.7356º W	
163	Instagram	Granada	Herradura	2022		36.7217º N	3.7356º W	
164	Instagram	Granada	Herradura	2023		36.7217º N	3.7356º W	
165	Instagram	Granada	Herradura	2023		36.7217º N	3.7356º W	
166	Instagram	Granada	Herradura	2023		36.7217º N	3.7356º W	
167	Instagram	Granada	Herradura	2023		36.7217º N	3.7356º W	
168	Instagram	Granada	Herradura	2023		36.7217º N	3.7356º W	
169	Instagram	Granada	Herradura	2023		36.7217º N	3.7356º W	
170	Instagram	Granada	Herradura	2024		36.7217º N	3.7356º W	
171	Instagram	Granada	Herradura	2024		36.7217º N	3.7356º W	
172	Instagram	Granada	Herradura	2024		36.7217º N	3.7356º W	
173	Instagram	Granada	Herradura	2024		36.7217º N	3.7356º W	
174	Instagram	Granada	Herradura	2024		36.7217º N	3.7356º W	
175	Instagram	Granada	Herradura	2024		36.7217º N	3.7356º W	
176	Instagram	Granada	Herradura	2024		36.7217º N	3.7356º W	
177	Instagram	Granada	Marina_Este	2021		36.7201º N	3.7283º W	
178	Instagram	Granada	Marina_Este	2021		36.7201º N	3.7283º W	
179	Instagram	Granada	Marina_Este	2022		36.7201º N	3.7283º W	
180	Instagram	Granada	Marina_Este	2022		36.7201º N	3.7283º W	
181	Instagram	Granada	Marina_Este	2022		36.7201º N	3.7283º W	
182	Instagram	Granada	Marina_Este	2023		36.7201º N	3.7283º W	
183	Instagram	Granada	Marina_Este	2023		36.7201º N	3.7283º W	
184	Instagram	Granada	Marina_Este	2025		36.7201º N	3.7283º W	
185	Instagram	Formentera	Es_Freu	2018		38.8179º N	1.4123º E	

Continued

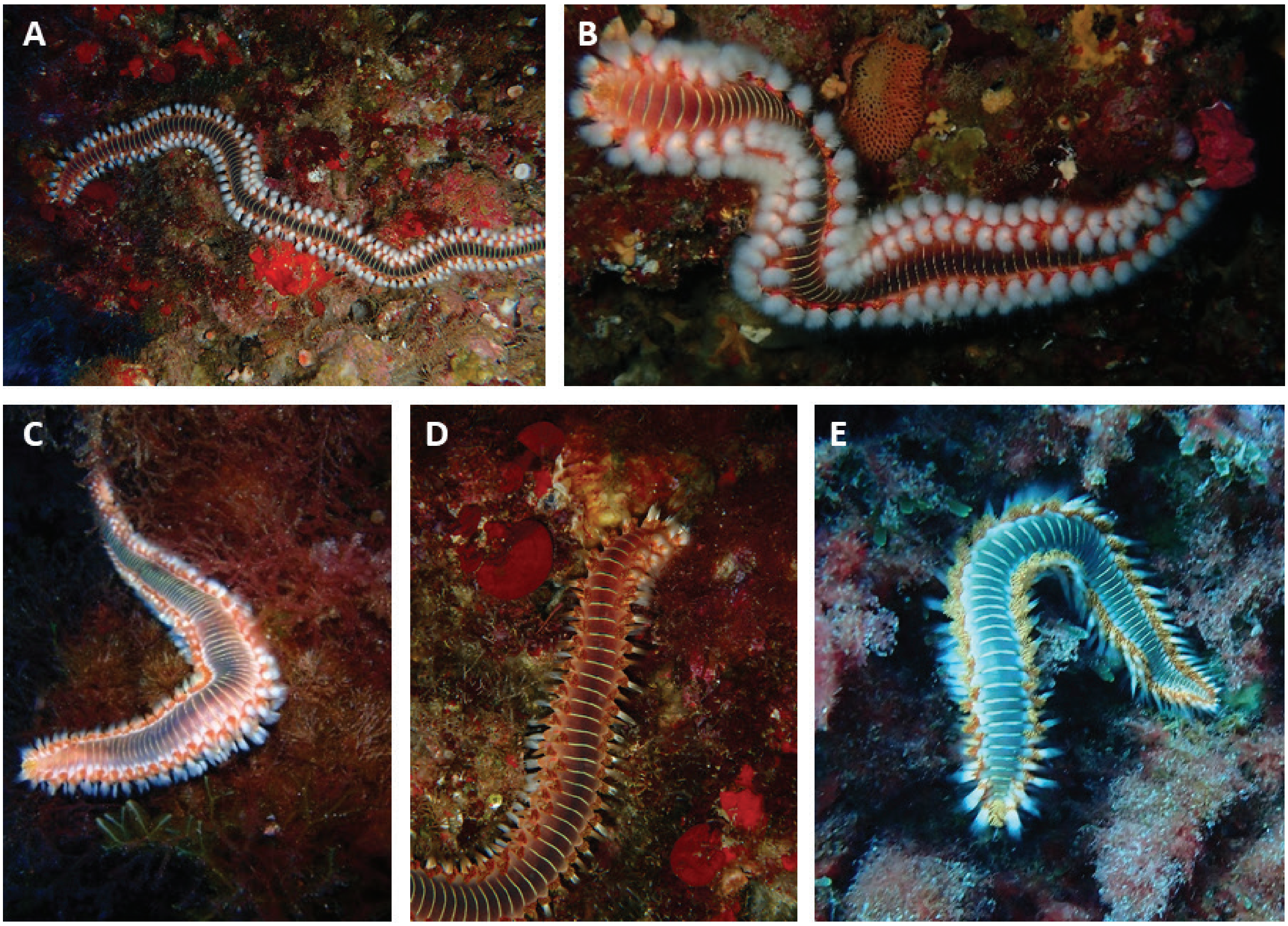
Appendix A continued

ID	Source	Province	Location	Yr_first	Yr_last	Latitude	Longitude	Depth
186	Instagram	Formentera	Gavina	2022		38.7188º N	1.3794º E	
187	Instagram	Formentera	Mola	2021		38.6494º N	1.5744º E	
188	Instagram	Formentera	Mola	2022		38.6494º N	1.5744º E	
189	Instagram	Formentera	Gavina	2020		38.7188º N	1.3794º E	
190	Instagram	Formentera	Gavina	2022		38.7188º N	1.3794º E	
191	Instagram	Formentera	Gavina	2025		38.7188º N	1.3794º E	
192	Instagram	Ibiza	Islotes_Ibiza	2024		38.9565º N	1.1879º E	17m
193	Instagram	Ibiza	Illots_Ponent	2019		38.868º N	1.1938º E	
194	Instagram	Ibiza	Illots_Ponent	2021		38.868º N	1.1938º E	
195	Instagram	Ibiza	Illots_Ponent	2022		38.868º N	1.1938º E	
196	Instagram	Ibiza	Illots_Ponent	2021		38.9824º N	1.2058º E	
197	Instagram	Ibiza	Ibiza_Norte	2022		39.0923º N	1.4318º E	
198	Instagram	Ibiza	Illots_Ponent	2021		38.9859º N	1.2066º E	
199	Instagram	Ibiza	Illots_Ponent	2023		38.9859º N	1.2066º E	11m
200	Instagram	Ibiza	Ibiza_Norte	2021		39.0808º N	1.4009º E	20m
201	Instagram	Ibiza	Islotes_Ibiza	2019		38.9713º N	1.1668º E	
202	Instagram	Ibiza	Islotes_Ibiza	2021		38.9713º N	1.1668º E	
203	Instagram	Ibiza	Islotes_Ibiza	2022		38.9713º N	1.1668º E	
204	Instagram	Ibiza	Islotes_Ibiza	2024		38.9713º N	1.1668º E	
205	Instagram	Ibiza	Illots_Ponent	2023		38.8703º N	1.2101º E	
206	Instagram	Mallorca	Cabrera	2023		39.1267º N	2.9589º E	
207	Instagram	Mallorca	Cabrera	2022		39.1353º N	2.9232º E	
208	Instagram	Mallorca	Dragonera	2023		39.5731º N	2.3029º E	
209	Instagram	Mallorca	Dragonera	2020		39.5888º N	2.3171º E	
210	Instagram	Mallorca	Dragonera	2020		39.5888º N	2.3171º E	
211	Instagram	Mallorca	Dragonera	2021		39.5888º N	2.3171º E	
212	Instagram	Mallorca	Dragonera	2021		39.5888º N	2.3171º E	
213	Instagram	Mallorca	Dragonera	2021		39.5888º N	2.3171º E	
214	Instagram	Mallorca	Dragonera	2021		39.5888º N	2.3171º E	
215	Instagram	Mallorca	Dragonera	2024		39.5888º N	2.3171º E	
216	Instagram	Mallorca	Calvia	2020		39.4623º N	2.4717º E	
217	Instagram	Mallorca	Calvia	2023		39.4623º N	2.4717º E	
218	Instagram	Mallorca	Calvia	2023		39.4623º N	2.4717º E	
219	Instagram	Mallorca	Calvia	2021		39.4625º N	2.4728º E	
220	Instagram	Mallorca	Calvia	2022		39.4625º N	2.4728º E	
221	Instagram	Mallorca	Calvia	2022		39.4625º N	2.4728º E	
222	Instagram	Mallorca	Calvia	2024		39.4625º N	2.4728º E	
223	Instagram	Mallorca	Calvia	2023		39.9508º N	3.2085º E	
224	Instagram	Mallorca	Andratx	2020		39.5338º N	2.3643º E	
225	Instagram	Mallorca	Pollensa	2024		39.9139º N	3.1234º E	
226	Instagram	Mallorca	Tramuntana	2014		39.7969º N	2.6842º E	
227	Instagram	Menorca	Mahon	2023		39.8016º N	4.282º E	
228	Instagram	Menorca	Mahon	2022		39.8035º N	4.28º E	
229	Instagram	Menorca	Mahon	2022		39.8035º N	4.28º E	
230	Instagram	Ceuta	Ceuta	2020		35.9064º N	5.2857º W	
231	Instagram	Ceuta	Ceuta	2020		35.9064º N	5.2857º W	
232	Instagram	Murcia	Aguilas	2020		37.4003º N	1.5695º W	

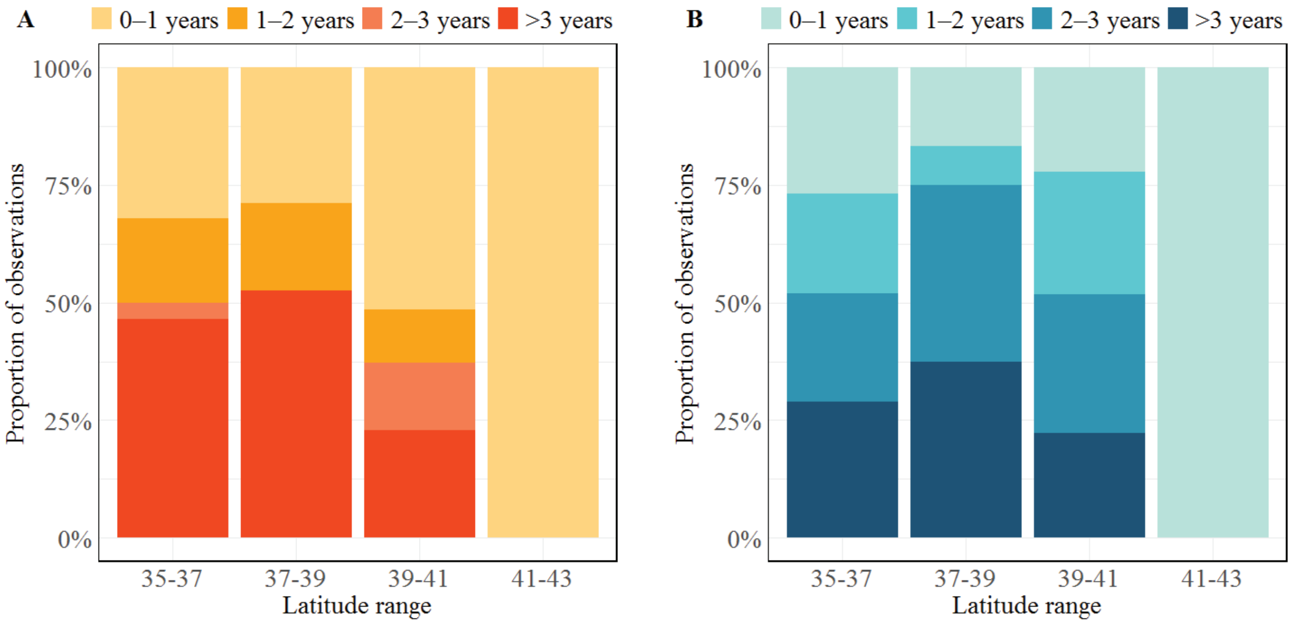
Continued

Appendix A continued

ID	Source	Province	Location	Yr_first	Yr_last	Latitude	Longitude	Depth
233	Instagram	Murcia	Aguilas	2021		37.4003º N	1.5695º W	
234	Instagram	Murcia	Cabo_Palos	2022		37.6623º N	0.637º W	
235	Instagram	Murcia	Cabo_Palos	2021		37.6241º N	0.699º W	
236	Instagram	Murcia	Cabo_Palos	2022		37.6241º N	0.699º W	
237	Instagram	Murcia	Cabo_Palos	2022		37.6241º N	0.699º W	
238	Instagram	Murcia	Cabo_Palos	2022		37.6241º N	0.699º W	
239	Instagram	Murcia	Cabo_Cope	2020		37.4275º N	1.5008º W	
240	Minka-Sdg	Granada	Herradura	2024		36.7257º N	3.7326º W	
241	Minka-Sdg	Mallorca	Levante	2023		39.3247º N	3.1561º E	
242	Minka-Sdg	Mallorca	Calvia	2024		39.4623º N	2.4717º E	
243	Minka-Sdg	Tarragona	Tarragona	2024		41.0897º N	1.2285º E	
244	Obsmar	Ceuta	Ceuta	2017		35.908º N	5.2863º W	
245	Own_UVC	Cadiz	Barbate	2023		36.1552º N	5.8929º W	10.9m
246	Own_UVC	Cadiz	Bolonia	2024		36.0766º N	5.7968º W	9m
247	Own_UVC	Chafarinas	Buticlan	2023		35.1793º N	2.4185º W	9m
248	Own_UVC	Granada	Marina_Este	2023		36.7203º N	3.7272º W	9.5m
249	Own_UVC	Mallorca	Tramuntana	2024		39.8412º N	2.7629º E	24m
250	Own_UVC	Cabrera	Cabrera	2013		39.1224º N	2.9351º E	38m
251	Own_UVC	Cabrera	Cabrera	2024		39.1224º N	2.9351º E	28m
252	Own_UVC	Cabrera	Cabrera	2024		39.1224º N	2.9351º E	20m
253	Own_UVC	Cabrera	Cabrera	2024		39.1224º N	2.9351º E	19m
254	Own_UVC	Cabrera	Cabrera	2024		39.1224º N	2.9351º E	17.7m
255	Own_UVC	Mallorca	Dragonera	2024		39.583º N	2.3062º E	32m
256	Press	Ibiza	Islotes_Ibiza	2024		38.9679º N	1.1659º E	
257	Press	Mallorca	Calvia	2024		39.4625º N	2.4713º E	



Appendix B. Images of some of the new records of *H. carunculata*.



Appendix C. Proportion of *H. carunculata* observations across latitude intervals and time elapsed since the species was first detected.