https://doi.org/10.5194/sp-2024-16
Preprint. Discussion started: 20 September 2024

STATE OF THE PLANET Discussions

Record-breaking 2023 temperatures in the Mediterranean Sea, proliferation of bioinvaders, and impacts on fisheries: a chain reaction?

Riccardo Martellucci [1], Francesco Tiralongo [2], Sofia F. Darmaraki [3], Michela D'Alessandro [1], Giorgio Mancinelli [4], Emanuele Mancini [4], Roberto Simonini [5], Milena Menna [1], Annunziata Pirro [1], Diego Borme [1], Rocco Auriemma [1], Marco Graziano [1], Elena Mauri [1]

[1] National Institute of Oceanography and Applied Geophysics (Trieste, Italy)
[2] University of Catania (Catania, Italy)
[3] Foundation for Research and Technology Hellas (Heraklion, Greece)
[4] University of Salento (Lecce, Italy)
[5] University of Modena and Reggio Emilia (Modena, Italy)
Corresponding author: rmartellucci@ogs.it

Abstract

In 2023, global mean air temperatures reached unprecedented highs, characterized by record-breaking temperature events, and the Mediterranean Sea experienced the longest Marine Heatwave (MHW) in four decades. This marginal sea, rich in biodiversity, is threatened by rising temperatures that favor the spread of invasive species such as the Atlantic blue crab (*Callinectes sapidus*) and the bearded fireworm (*Hermodice carunculata*). Along the Italian coasts, bivalve fisheries face considerable economic losses due to the spread of the Atlantic blue crab, an invasive species that manifests aggressive feeding behavior, while artisanal fisheries are negatively impacted due to the proliferation of the bearded fireworm, a thermophilic polychaetae that also poses a health risk to humans due to its venomous setae. In this study, we investigate the effects of the long-term and extreme seawater temperature increase on the proliferation of *C. sapidus* and *H. carunculata* along the Italian coasts, and their socio-economic impacts, through an evaluation of fish market data and online survey responses. The analysis focuses on the coastal area of Po Delta in the northern Adriatic Sea and two coastal areas of Sicily, both of which experienced multiple, prolonged and intense MHWs during 2023 . .The increased seawater temperatures have probably contributed to an increase in the monthly biomass of blue crabs in the northern Adriatic, indicating a break of the species winter dormancy that favors their survival and reproduction rates. A similar warming trend has likely led to an increase in the sightings of *H. carunculata* along the Sicilian coasts, posing health risks and impacting local fisheries .

The development of effective mitigation strategies is essential to control the spread and impact of invasive species . The Italian government, for example, has implemented measures, such as increased harvesting and the promotion of the culinary use of the blue crab, to manage its population. . In addition, the innovative uses for invasive species, such as the use of *H. carunculata* in waste processing, have been explored, to both control its spread and provide economic benefits. Thus, the sustainability of Mediterranean marine ecosystems and coastal communities requires robust interdisciplinary collaboration to address the challenges posed by biological invasions and climate change in the region.

https://doi.org/10.5194/sp-2024-16
Preprint. Discussion started: 20 September 2024

1.Introduction

The Mediterranean Sea, one of the world's most biodiverse marine ecosystems (Coll et al. 2010), is currently facing unprecedented challenges due to climate change-induced extreme warm temperature events, known as marine heatwaves (MHWs) (Darmaraki et al., 2019). Over the past decades, the basin has seen an increase in the frequency, intensity, and duration of these record-breaking episodes, largely due to the mean warming trend of Mediterranean Sea Surface Temperature (SST), ranging between 0.035-0.041 °C/year (EU Copernicus Marine Service Product, 2022a), nearly double the corresponding global SST trend of 0.015 ± 0.001 °C/year (EU Copernicus Marine Service Product, 2022b). This has substantial implications for the region's biodiversity and economy, as the worming trend and MHWs can facilitate the proliferation of invasive species (Joyce et al., 2024).

Among the species that pose a significant threat are the Atlantic blue crab (*Callinectes sapidus*) and the bearded fireworm (*Hermodice carunculata*), which have gained attention, as a result of their rapid expansion and adverse impacts on Italian fisheries (Heilskov et al., 2006, Riera et al., 2014, Simonini et al. 2019, Righi et al., 2020, Bardelli et al., 2023, Tiralongo et al., 2023). In particular, *C. sapidus*, native to the Atlantic, has rapidly colonized Italian coastlines (Mancinelli et al., 2021). Characterized by its voracious predatory behavior and opportunistic feeding habits (Mancinelli et al., 2021), *C. sapidus* has led to substantial economic losses on bivalve fisheries and formidable challenges to native species (Clavero et al. 2022). Similarly, the bearded fireworm (*H. carunculata*), a thermophilic polychaete, has become prevalent in Italian waters, adversely impacting artisanal fisheries by both ruining the catch and posing health risks to humans (Heilskov et al., 2006, Riera et al., 2014, Simonini et al. 2019, Righi et al., 2020, Bardelli et al., 2023, Tiralongo et al., 2023). Indeed, with its venomous setae, *H. carunculata* is capable of causing painful stings to humans, with burning and erythema upon physical contact. Furthermore, *H. carunculata* represents an ecological disruptor as well as a direct threat to the well-being of coastal communities. The resilience of both species to environmental stressors and rapid population expansion highlight the urgency of addressing the compounding risks of climate change and bioinvaders with comprehensive management strategies.

The year 2023 marked a turning point, with mean global air temperatures reaching unprecedented peaks (Copernicus, 2024). The European continent encountered its second-warmest year on record, with the Mediterranean basin experiencing a series of extreme temperature events (Marullo et al., 2023). Of notable concern was the occurrence of the longest-recorded and one of the strongest surface MHWs over the past four decades, that persisted in the northwest Mediterranean from May 2022 until the boreal spring of 2023 (Marullo et al., 2023; Pirro et al., 2024 OSR8). At its peak in July 2022, this MHW covered almost the entire western Mediterranean basin, with maximum daily SST anomalies reaching about 2.6°C and 4.3°C and the anomalously warm conditions being comparable to the summer MHW of 2003 (Guinaldo et al., 2023). The long duration of the event was attributed to a combination of anomalously low wind speeds, high insolation, and weak vertical mixing in the ocean. This event had far-reaching effects on marine life and coastal communities.

This study aims to explore the expansion and increase in abundance of *C. sapidus* and *H. carunculata* in relation to the mean and extreme warming in two coastal areas of Italy, particularly during the MHWs of 2022/2023. Relevant socio-economic implications were also assessed through the analysis of fish market data and the responses on

https://doi.org/10.5194/sp-2024-16
Preprint. Discussion started: 20 September 2024

questionnaires administered to local fishermen and completed online, which addressed issues related to the bioinvasion of these species. Furthermore, we discuss possible solutions to mitigate the invasion of these species.

2. Methods

2.1 Study areas

2.1.1 The Po river delta

The study was conducted in two different regions within Italian waters: two adjacent lagoons in the Northern Adriatic Sea (Canarin and Scardovari) and two coastal areas of Sicily. The two lagoons under investigation in the Northern Adriatic Sea are transitional and shallow-water environments situated within the Po Delta and are connected with the sea and various river branches (Figure 1). As they are directly influenced by the Po River outflows, these regions exhibit highly dynamic hydro-morphological features and undergo rapid changes due to biotic and abiotic forces (Maicu et al., 2018; Franzoi et al., 2023). Despite facing various forms of anthropogenic pressure that have progressively altered their natural ecological characteristics (Franzoi et al., 2023), the lagoons support several clam and oyster farms, which constitute the main production activities and vital economic resources at both local and regional scales (Turolla et al., 2008; Donati & Fabbro, 2010; Bordignon et al., 2020).

The Scardovari Lagoon spans an area of 32 km², has an average depth of 1.5 meters (Mistri et al., 2018), and is connected to the sea via two inlets located at the northeast and southwest of the basin. The Canarin Lagoon covers an area of about 6.4 km² in the southern part of the study area, with an average depth of 0.9 meters (Figure 1). It is connected to the Adriatic Sea through a shallow, approximately 200-meter-wide mouth with a maximum depth of 2.5 meters.

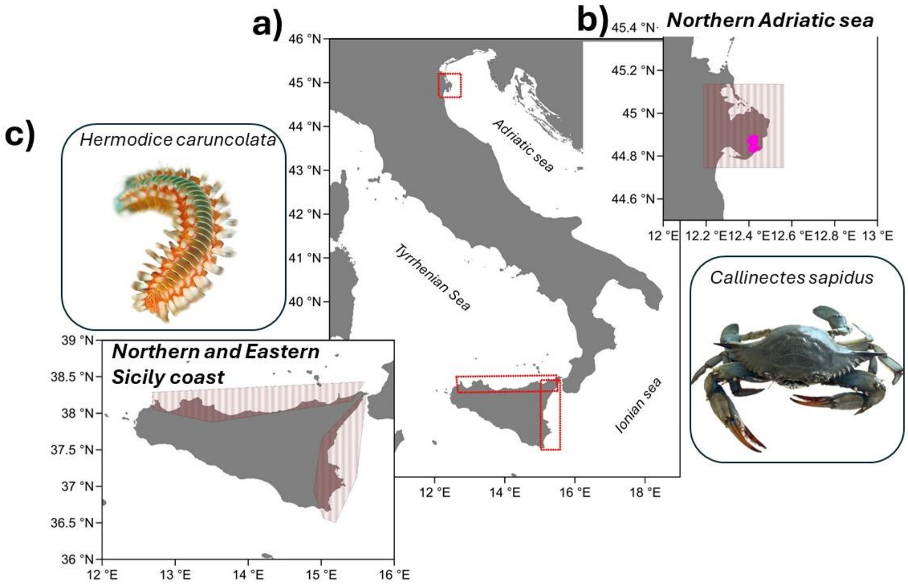


Figure 1*:* Map of Italy (a) the red boxes highlighted the two study areas: the Po river delta (b), the magenta area representing the Canarin and Scardovari lagoons and the Sicily island (c) with the red boxes in panel b

https://doi.org/10.5194/sp-2024-16
Preprint. Discussion started: 20 September 2024

and c representing the areas used for computing the SST field . The species *C. sapidus* and *H. carunculata* are also indicated in small images.

2.1.2 Sicily

Sicily Island is situated at the convergence of the eastern and western basins of the Mediterranean Sea, influenced by both the relatively cooler Atlantic waters and the warmer Levantine waters (Figure 1) . Specifically, the eastern coast of Sicily (Ionian Sea) is significantly affected by quasi-decadal reversals of the Northern Ionian Gyre, driven by the mechanisms of the Bimodal Oscillating System in the Ionian Sea (Gačić et al., 2021; Menna et al., 2022). The distribution of water masses is altered by bringing warm and salty Levantine water during the cyclonic phase (counterclockwise) and transporting cooler Atlantic waters during the anticyclonic phase (clockwise). This dynamic influences marine ecosystems, favoring the presence of Levantine species during the cyclonic phase and vice versa (Civitarese et al., 2023). In comparison, the northern coast of Sicily (Tyrrhenian Sea) experiences less salty and relatively cooler Atlantic waters entering through the Sardinia Channel (Vetrano et al., 2010), while the southern coast of Sicily is characterized by cold waters due to a semi-permanent upwelling (Raffa et al., 2017).

2.2 Biological characteristics of the two species

2.2.1 *Callinectes sapidus*

The Atlantic blue crab *C. sapidus* Rathbun, 1896 is a species native from the western coasts of the Atlantic Ocean, naturally distributed from Nova Scotia to northern Argentina (Millikin and Williams, 1984). It was first recorded in Europe in 1901 and in the Mediterranean since 1947 (Mancinelli et al. 2021). The first record in Italian waters dates back to 1949 in the Venice Lagoon and ballast water is considered the most likely reason (Nehring, 2011). In Mediterranean waters, *C. sapidus* is recognized as one of the top 100 most invasive alien species (Zenetos et al.,2005; Streftaris and Zenetos, 2006; Katsanevakis et al., 2018) and is present in at least seven of the nine South-European Marine Ecoregion (Mancinelli et al., 2017a,b). Over the last decade, this crab has rapidly expanded its range in new ecosystems throughout the Mediterranean, such as the European Atlantic waters of Portugal, France, Belgium and Germany, but also in Italian waters (Tiralongo et al., 2021; Bardelli et al., 2023). This eurythermal and euryhaline species is a voracious predator characterized by aggressive behavior, high fecundity, excellent swimming ability and high fertility (Millikin and Williams, 1984; Streftaris and Zenetos, 2006), inhabiting lagoons, estuaries and other coastal environments. In marine waters, this species lives mainly on soft substrates between 1 and 90 m deep. Its life cycle is very complex and involves different environments depending on sex and ontogenetic stage: adults can reach a relatively large size, with a carapace up to 25 cm wide in males and 18 cm in females (Millikin and Williams, 1984), and reside in lagoons and estuaries where males tend to settle and molt. After copulation, oviparous females move to the sea where they lay their eggs; juveniles return to transitional environments and, after rapid growth, reach maturity in the second year of life (Millikin and Williams, 1984; Taylor et al., 2021). Although several studies have been carried out on this species, the impacts/interactions of *C. sapidus* on native species and Mediterranean aquatic ecosystems are still poorly understood and require further investigation (Mancinelli et al. 2017; Clavero et al. 2022).

https://doi.org/10.5194/sp-2024-16
Preprint. Discussion started: 20 September 2024

2.2.2 *Hermodice carunculata*

The thermophilic amphinomid *H. carunculata* (Pallas, 1766), commonly known as bearded fireworm, is a large predator/scavenger polychaetae first described in the West Indies. This species shows an amphi-atlantic distribution and is present in warm and temperate areas of the Caribbean Sea, Atlantic Ocean and Red Sea (Fishelson, 1971; Ahrens et al., 2013; Ramos & Schizas, 2023; Toso et al., 2024). The bearded fireworm has been reported in the Mediterranean Sea since the 1800s (Baird, 1868, Simonini et al., 2018; Toso et al., 2022), however, previous studies pointed out an increase in its abundance throughout the basin in recent years, likely due to warmer temperatures of the waters, which favor its northward expansion (Righi et al., 2020; Toso et al., 2022). As a result of its increasing expansion, *H. carunculata* can be regarded as a highly invasive species, despite being native to the Mediterranean. This may lead to detrimental effects on both the region's ecosystems and associated species, as well as on human health coastal and anthropic activities such as fishing (Figure S5) and bathing (Celona & Comparetto, 2010; Cosentino & Giacobbe, 2011; Schulze et al. 2017; Simonini et al., 2018; Righi et al. 2020; Toso et al., 2020; Tiralongo et al., 2023). The invasive nature of this polychaetae is further enhanced by its resilience to natural and anthropogenic stressors (Schulze et al. 2017) and may also become a carrier of new pathogens (Sussman et al., 2003; Schulze et al., 2017). *H. carunculata* can exceed 70 cm in length and can reach 9 years of lifespan (Simonini & Ferri, 2022). Its metameres are equipped with dorsal calcareous chaetae, which are filled with a toxin that is highly effective against predation (Kicklighter and Hay, 2006; Schulze et al., 2017; Simonini et al., 2018, 2021; Righi et al., 2021, 2022). The presence of these defensive mechanisms makes the polychaetae highly resilient to predation, with no identified species in the Mediterranean capable of effectively preying upon it (Ladd & Shantz 2016; Righi et al., 2021; Simonini et al., 2021). On the contrary, *H. carunculata* acts as a voracious predator of sessile and benthic invertebrates (Wolf and Nugues 2013; Wolf et al. 2014; Jumars et al. 2015; Barroso et al. 2016, Schulze et al., 2017; Simonini et al., 2018; Righi et al., 2020), and its ability to regenerate, promotes its expansion (Toso et al., 2024). Furthermore, this species is distinguished by a remarkable dispersal capacity, which is attributed to the production of planktotrophic and particularly long-lived larvae (Ahrens et al., 2013; Shulze et al., 2017; Toso et al., 2020). In Italian waters, the bearded fireworm is common and abundant on rocky substrates between 1 and 20 m (Righi et al., 2020; Simonini et al., 2021), but in some areas of the Mediterranean it reaches greater depths and has also been observed in association with coralligenous and pre-coralligenous bio-formations (Fishelson 1971; Righi et al., 2020).

Ref. no.	Product name & type	Documentation
Copernicus products		
1	Copernicus Marine SST_MED_SST_L4_REP_OBSERVATIONS_010_021 Mediterranean Sea - High Resolution L4 Sea Surface Temperature Reprocessed	Merchant et al., (2019) https://doi.org/10.48670/moi-00173
2	Copernicus Marine MEDSEA_MULTIYEAR_PHY_006_004_E3R1 Mediterranean Sea Physics reanalysis	Escudier et al., (2021) Dataset: Escudier et al., (2020) https://doi.org/10.25423/CMCC/MEDSEA_MULTIYEAR_PHY_006_004_E3R1
Non Copernicus products		
3	Crab and clam fishery data	CONSORZIO COOPERATIVE PESCATORI DEL POLESINE Organizzazione di Produttori Soc. Coop. A r.l., Via della Sacca, 11 45018 Scardovari (RO) – ITALIA. P.IVA 00224140293
4	Questionnaire Worms Out	Link: bit.ly/3L3TWUc https://www.facebook.com/MonitoraggioVermocane
5	Questionnaire Righi et al. 2020	https://doi.org/10.12681/mms.23117 ,

Table 1: Products used in the present work. Complete references for the articles in Prod. 1, Prod. 3 and Prod. 6 are reported in the bibliography.

2.3 Temperature Datasets

To identify surface MHWs on the study areas we obtained daily SST data from the Mediterranean Sea SST Analysis L4 product of the Copernicus Marine Service, covering the period 1982-2023 (Table 1, product ref. 1). This dataset provides gap-free, optimally-interpolated, satellite-based estimates of SST, with a resolution of 0.05°x0.05°. For the

https://doi.org/10.5194/sp-2024-16
Preprint. Discussion started: 20 September 2024

analysis of subsurface temperatures in the areas of interest, daily vertical profiles of temperatures were obtained from the Mediterranean Sea Physics Reanalysis dataset spanning the period 1993-2023 (Table 1, product ref. 2), with a spatial resolution of 0.042° × 0.042°. MHWs are detected whenever SSTs exceed a daily, 40-year (1982-2023) climatological threshold for at least 5 days in a row, based on the identification framework proposed by Hobday et al. (2016).

2.4 The crab and clam fishery data

The data on clam production, waste and sales of blue crab were provided by the Scardovari and Canarin Cooperative, which has been farming this species in the Po delta for years. These are monthly values, representing the sum of the fishermen's daily harvests before they reach the market for fish sales (Table 1, ref. 3).

2.5 Questionnaire for *Hermodice carunculata*

Over the last decades, citizen participation in data collection useful for science has increased, thanks to numerous awareness-raising initiatives (Turrini et al. 2018) and has already been recognized as a valuable resource for research, biodiversity monitoring, and conservation (Lopez et al., 2019; Toivonen et al., 2019). While, in some cases, this information lacks a solid scientific basis, requiring validation by experts in the field, it offers the advantage of being gathered over broad geographical areas at a low cost (Ballard et al., 2017; Tirelli et al., 2021; Sun et al., 2021). For this reason, citizen science projects are currently increasing in several fields, especially as a tool to address environmental and conservation issues (Kullenberg et al. 2016; Turrini et al. 2018). For instance, citizen involvement is widely used in projects and initiatives related to the sighting of non-indigenous species, invasive and uncommon species, such as AlienFish project (https://www.facebook.com/alienfish), avvistAPP (https://www.avvistapp.it/), Monitoraggio Vermocane (https://www.facebook.com/MonitoraggioVermocane).
To assess the impact of the bearded fireworms on human activities, such as fishing and tourism, a questionnaire was developed and administered to fishermen and distributed as an online survey. The questionnaire consisted of 19 questions in total, of which four single-choice questions were analyzed in this study. The questions primarily addressed the frequency of the species' sightings, the abundance of specimens, and the perception of the presence of the species as a problem. These surveys were carried out within the project Worms Out, financed by the National Institute of Oceanography and Applied Geophysics and ECCSEL NatLab Italy project (Table 1, ref. 5).
Due to a current lack of scientific reports on the species, likely linked to sampling methods that failed to detect the fireworm even in known habitats, the use of this questionnaire is important for identifying and assessing the presence of this species (e.g., Fraschetti et al., 2002; Giangrande et al., 2003; Corriero et al., 2004; Mastrototaro et al., 2010), in addition to real-time data collected from maritime users. Integrating this information with traditional sources, such as scientific literature and observations, is crucial for monitoring biological invasions and studying native invader species (Azzurro et al., 2019; Giovos et al., 2019; Toivonen et al., 2019).

3. Results

https://doi.org/10.5194/sp-2024-16
Preprint. Discussion started: 20 September 2024

3.1 Northern Adriatic

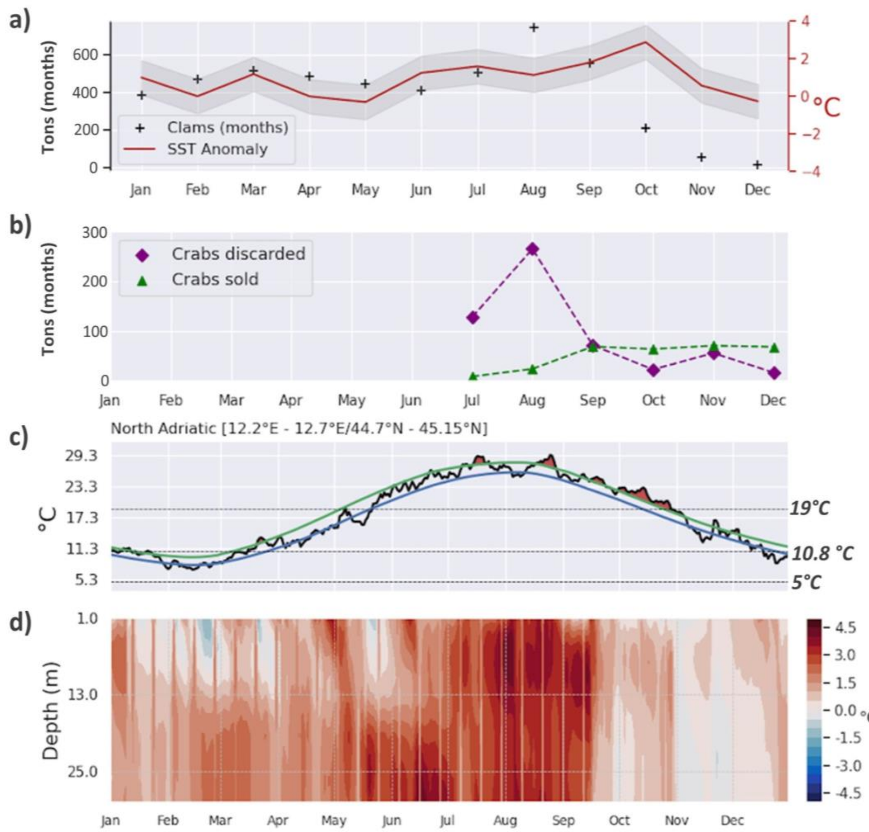
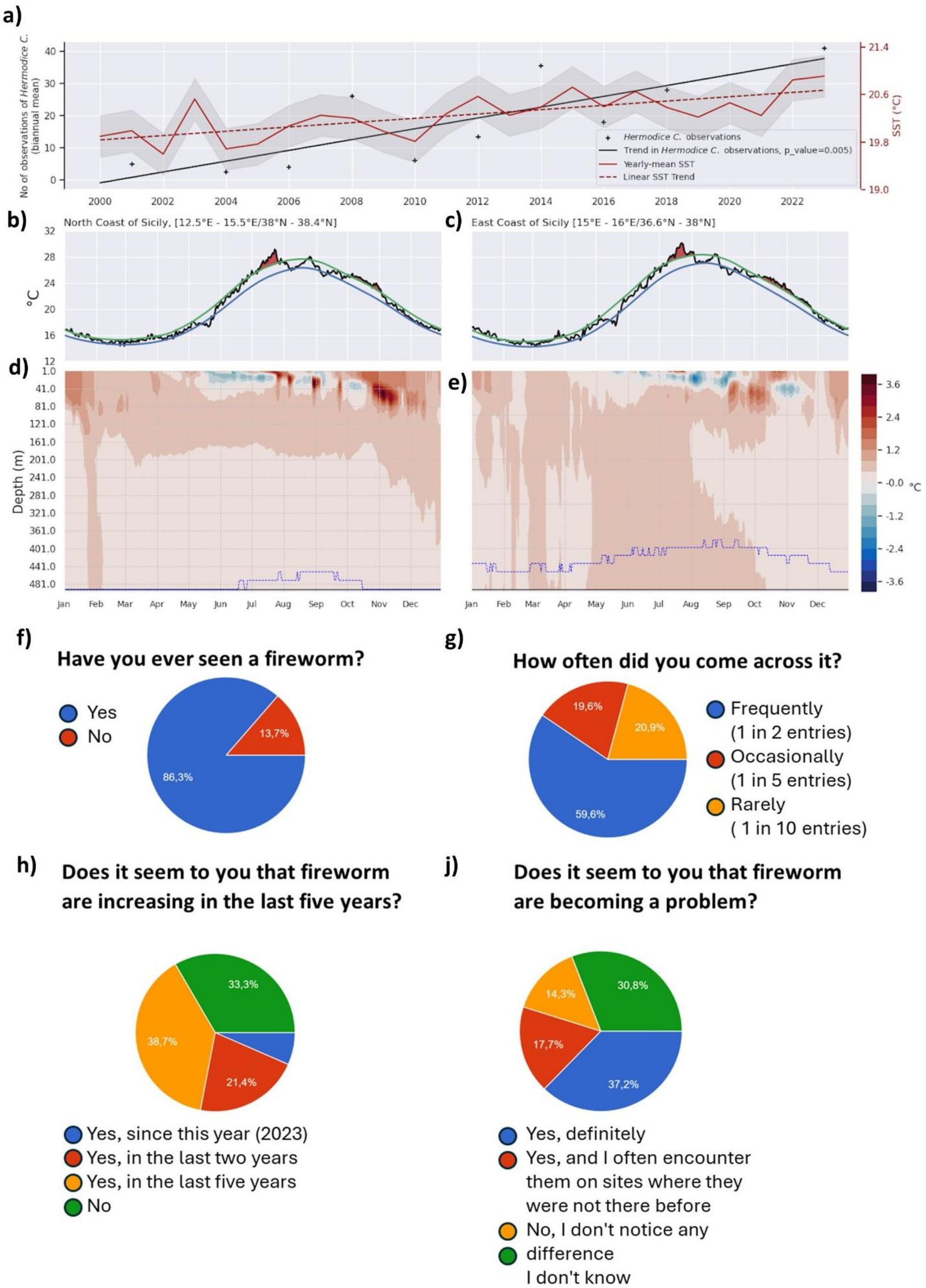


Figure 2: Northern Adriatic study area: a) Time series of daily, spatially-averaged SST anomalies of 2023 relative to the period 1993-2016 (red line), and monthly evolution of sold clams (black cross). b) Monthly evolution of sold (green triangles) and discharged (purple diamonds) blue crabs during 2023. c) Time series of daily, spatially-averaged SST during 2023 (black), smoothed SST climatology (blue) and 90th percentile threshold of SST (green) based on the 1982-2023 period. MHWs are indicated in red and identified using the Hobday et al. (2016) definition. The three dashed lines represent the temperature thresholds for winter dormancy (5°C), reproductive activity (10.8°C) and larval development (19°C) of blue crab. d) Vertical profile of temperature anomalies during 2023, relative to the period 1993-2016, spatially-averaged at each depth. Temperature data were obtained from Copernicus Marine Service (Table 1, product ref. 1, 2), Clams and Crab data were obtained from the Consorzio Cooperative Pescatori del Polesine (Table 1, product ref. 3).

During the first half of 2023, clam production in the area was about 400 tons per month, reaching a production peak in August (800 tons), before drastically declining from September through December (Figure 2a). In contrast, crab sales began during the summer months, with the highest discard observed in August 2023, totaling 300 tons. Towards the end of 2023, crab discard levels were comparable to sales (Figure 2b). Throughout 2023, the North Adriatic study area was also characterized by particularly high SSTs with six MHWs observed (Figure 2c and d): The first event occurred during March, lasted for 5 days and had a moderate intensity, while the rest of the events occurred during the summer and autumn seasons. The most intense MHW was observed at the end of August 2023, characterized by temperatures over 3°C higher than normal and 11 days duration (Table S1). The longest event was observed in October, persisting for 36 days with a strong intensity (>2.6°C). The high temperatures of 2023 affected the entire water column as well, with the most intense subsurface temperature anomalies (>4°C) seen between 4m and 15m depth during the summer season (Figure 2d). This indicates a significant rise in subsurface temperatures in the area, given that typical deviations from the 1993-2016 mean range between 0.8°C and 1.2°C (Figure S1). Regarding the potential cumulative temperature effects on the blue crab's life cycle, while the SST during 2023 has not been below the winter dormancy threshold (5°C), it has exceeded the reproductive activity (10.8°C) and larval development (19°C) temperatures, by 300 and 170 days, respectively (dashed lines in Figure 2c).

https://doi.org/10.5194/sp-2024-16
Preprint. Discussion started: 20 September 2024

234 **3.2 Sicily**



235 **Figure 3: a) Yearly-averaged time series and linear trend of SST (red), spatially-averaged over the Northern**
236 **coast of Sicily and yearly records of H. carunculata (black cross) with their linear trend, based on Righi et al.**

https://doi.org/10.5194/sp-2024-16
Preprint. Discussion started: 20 September 2024

(2019) and our questionnaire for the period 2000-2023 (Table 1, product ref. 4 and 5). Daily and spatially-averaged SST time series during 2023 (black), smoothed SST climatology (blue) and 90th percentile threshold of SST (green) based on the 1982-2023 period, for the Northern (b) and Eastern (c) coast of Sicily. MHW are indicated in red and identified using the Hobday et al. (2016) definition. Vertical profile of spatially-averaged temperature anomalies during 2023, relative to the climatological period of 1993-2016 for the Northern (d) and Eastern (e) coast of Sicily. The climatological depth of 14 °C isotherm is displayed in blue dashed line whereas the depth of the 14 °C isotherm during 2023 in solid black. d) Main results of the Worms out questionnaire (Table 1, product ref. 4). Temperature data were obtained from Copernicus Marine Service (Table 1, product ref. 1, 2).

In the two coastal regions of northern and eastern Sicily SST remained above climatological values throughout 2023 (Figure 3b,c): Eastern Sicily experienced three MHWs that lasted approximately 60 days in total (Table S1). The most intense event occurred in July, persisting for 21 days and the longest one during October, lasting for 30 days. On average, the northern coast of Sicily, experienced slightly longer MHWs: The first event occurred in March, lasted for 5 days and had an intensity of 1.4°C. The most intense MHW (>2.5°C) was observed between July-August, lasting for 25 days, while the longest event (49 days) occurred during autumn with an intensity of 1.6°C. Relative to the 1993-2016 period, temperatures throughout the water column in both regions were warmer than normal, by approximately 1.2*°C* - 4*°C*, and more so in the northern coast of Sicily. The upper 80 meters of the water column exhibit the highest temperature anomalies (>2°C) throughout the year, especially during autumn months (>2.5 °C) in both areas. However, during some days of the summer period, subsurface layers between 10 and 50 meters depth exhibit negative (up to -2 °C) temperature anomalies (Figure 3d,e), with temperatures dropping below 14 degrees only at greater depths. Typically, subsurface temperatures deviate approximately 0.8 - 2°C from the 1993-2016 mean, with the highest values observed in the upper 20-80 m depth between June-November (Figure S1). The progressive temperature increase of around 0.03 °C/year observed along the Northern coast of Sicily appears to correspond with a rising trend in *Hermodice carunculata* records over the last 20 years, predominantly during 2007-2008, 2014-2015 and 2023, when the highest number of observations were recorded (Figure 3a). This increasing trend is also supported by the results of our proposed questionnaire, revealing a significant increase in the frequency of sightings in recent years compared to 2018, particularly during recreational activities. Specifically, the results of the questionnaire demonstrate that the presence of this species is increasingly recognised as a growing issue, particularly as *H. carunculata* is observed in areas where it has not been seen before (Figure 3 h and j).

4. Discussion and conclusions

The two study areas of the Mediterranean Sea experienced multiple, prolonged and strong surface MHWs throughout 2023, with temperature anomalies during the events ranging between 1.6°C - 2.6 °C in the East and North coasts of Sicily and between 2 - 3 °C in the Northern Adriatic coast. These events are associated with a general warming tendency, indicated in the Northern Adriatic by the elevated monthly temperature anomalies almost throughout the year (especially during the summer), and by a 0.03 °C/year trend particularly evident in the SST along the coast of

https://doi.org/10.5194/sp-2024-16
Preprint. Discussion started: 20 September 2024

Northern Sicily for the period 2000-2023. Compared to the study areas in Sicily, the Northern Adriatic exhibited a slightly stronger warming throughout the water column, likely due to its shallower depth. However, lower than normal subsurface temperatures were observed in the upper 40 m of the two study areas in Sicily, during certain periods in summer and autumn. This feature is likely associated with a stronger upper ocean stratification during those periods and a displacement of the thermocline (see Figure S2,S3), resulting in cooler temperatures nearer to the surface, similar to Pirro et al. (2024). Overall, significant warming was observed in all study areas during 2023, which apparently affected the abundance of the two invasive species examined here, *Hermodice carunculata* and *Callinectes sapidus*. In particular, there was a notable increase in the monthly biomass of crabs in the Northern Adriatic peaking in the summer months, similar to an increase in the annual records of *H. carunculata* along the coasts of Sicily. These trends appear to correlate well with the observed temperature rise in both regions.

Global warming and biological invasions in marine systems are interconnected, although the extent of their interactions and the role of climate change as a driver remain a subject of debate. The impacts of climate change and biological invasions differ throughout the invasion process and are influenced by species-specific responses to warming (Cinar et al., 2014, Joyce et al., 2024). These responses affect the distribution, demographics, and life histories of invasive species. For marine invertebrates with intricate life cycles, the effects of climate warming are particularly pronounced during critical stages such as larval development, reproductive activity, or winter dormancy (Alter et al., 2024). Nevertheless, fishing practices (e.g. cleaning nets, discarding) should also be taken into account because they can greatly contribute to the dispersion of marine invertebrates or can create favorable conditions to their settlement or survival. Our observations with *H. caruncolata* indicate that discarding fish and cleaning nets after fishing in coastal areas provide ample food resources for this species . Furthermore, releasing egg-filled *C. sapidus* females into the lagoon (i.e. under these conditions the crabs cannot be sold on the market) has led to a significant increase in crab larvae within the lagoon. These examples illustrate how inadequate management practices can unintentionally enhance the spread of invasive species

4.1 *Callinectes sapidus*

For non-indigenous as well as for native marine invertebrates with complex life cycles, the impact of climate warming may intensify during crucial phases of their life cycle (Libralato et al., 2015) such as larval development, reproductive activity or winter dormancy (dashed line in Figure 2c). The Atlantic blue crabs, specifically, have a complex, biphasic life cycle consisting of marine planktonic larvae (zoea) followed by benthic post larvae (megalopa), with juveniles and adults residing in estuaries, lagoons, and other coastal habitats (Lipcius et al. 2007). Winter dormancy and reproductive activity in adults, as well as egg maturation, zoea and megalopa development in the early stages of the life cycle are all crucially related with temperature minima (Schneider et al. 2024; Brylawsky and Miller 2006; Rogers et al. 2022). In addition, higher temperatures can induce a faster metamorphosis in *C. sapidus* from zoea to megalopa, reducing predation risk and promoting survival. The observed increase in the Northern Adriatic SSTs has likely triggered a positive feedback in the phenology of larval and adult blue crabs, ultimately leading to higher survival and reproduction rates, reflecting the anomalous demographic increase. This scenario has also been proposed for other invasive crabs such as *Hemigrapsus takanoi* (van den Brink et al. 2012). In this context, rising temperatures may have enhanced the invasiveness of *C. sapidus* in regions where the species has long been established but until recently only

https://doi.org/10.5194/sp-2024-16
Preprint. Discussion started: 20 September 2024

occurred in low numbers, as exemplified by the case of the Po River estuary. The proliferation of the blue crab in the Po river delta has significantly disrupted the clams production (Figure S4), and under current conditions no resurgence of clams populations is expected in 2024. Additionally, the costs of removing crabs discarded by fishery further exacerbates the damage to the clam industry (Figure S4).

4.2 *Hermodice carunculata*

Over the last 20 years, the increased presence and bathymetric expansion of *H. carunculata* has coincided with a general rise in coastal water temperatures of Sicily (Pisano et al., 2020; Tiralongo et al., 2023; Kubin et al., 2024), which became particularly evident during 2023 (Figure 3a). Numerous studies suggest that water temperature is a critical environmental factor contributing to the proliferation of fireworms (Righi et al. 2020). *H. carunculata*, being a thermophilic species, is frequently observed in shallow waters during summer months, which is consistent with its occurrence in subtropical and tropical regions (Schulze et al., 2017; Encarnação et al., 2019). Righi et al. (2020) observed a progressive expansion of *H. carunculata* across Sicily, suggesting temperature as a key driver of species range shifts, by facilitating settlement and dispersion (Stachowicz et al., 2002; Samperio-Ramos et al., 2015). The ongoing warming trend in the Mediterranean Sea indicates that this species is likely to continue expanding along the north-western Mediterranean coast (Righi et al. 2020). This expansion is anticipated to further disrupt benthic habitats, alter community composition, and affect the abundance of other species, similar to impacts observed with other annelids (Berke et al., 2010; Pires et al., 2015). To address the scarcity of scientific reports, we integrated real-time observations with the findings of Righi et al. (2020) and recent data from 2023. Our results corroborate the ongoing expansion and economic repercussions of *H. carunculata* on fishing activities, as documented by Righi et al. (2020) ((Tiralongo et al., 2023). Questionnaire responses further support this expansion, revealing a notable rise in sightings over the past five years.

One of the most significant and measurable impacts of *H. carunculata* is on the fishing economy, although comprehensive documentation of these effects has only recently emerged (Tiralongo et al., 2023). This species, inflicts both direct and indirect damage to fishing operations (Figure S5). Direct damage includes severing secondary lines attached to hooks, either through the worm's teeth or by concealing itself among rocks after consuming the bait. The need to minimize the impact of *H. carunculata* on target species forces fishermen to reduce the soaking time of the gear used, thereby decreasing catch rates (Simonini et al., 2021; Tiralongo, 2020). Aside from impeding fishing efficiency, *H. carunculata* can be hazardous to human health. It contains toxic compounds known as carunculins (Righi et al., 2022), which can cause severe stings upon contact, posing health risks to tourists in coastal areas and to fishermen primarily during net cleaning (Tiralongo et al., 2023). Significant economic losses in the fishing industry can be also caused by the scavenging activities of *H. carunculata*. Damage inflicted by the worms to fish catch leads to a decreases of its market value of affected fish, rendering them less attractive to consumers. The economic impact is estimated at approximately 7.32 euros per kilogram of damaged fish, leading to substantial annual losses given the total weight of commercially valuable catches (Tiralongo et al., 2023). Thus, *H. carunculata* not only poses a severe threat to marine biodiversity but also undermines the economic stability of local fisheries. This vulnerability highlights

https://doi.org/10.5194/sp-2024-16
Preprint. Discussion started: 20 September 2024

the urgent need for effective mitigation strategies to address the induced impacts of climate change on fisheries, tourism and coastal economies.

4.3 Implication for human life and solutions for stakeholder

The ongoing invasion of the Atlantic blue crab provides an opportunity to evaluate strategies and measures to contain the dispersion of invasive species while mitigating their ecological impact. This situation also provides the opportunity to exploit these invasive species for both food and non-food uses, as their economic value has already been recognized internationally. Several studies have demonstrated that overharvesting plays an important role in the control of invasive species (Mancinelli et al., 2017), as evidenced by the examples of blue crabs harvesting (which support an important fishery) along the coasts of US (Hines, 2007, Kennedy et al., 2007; Bunnell et al., 2010); accordingly, control policies should aim at similar marketing strategies. Despite the introduction of the Atlantic blue crab to the Italian market, it is not yet widely consumed, complicating efforts to eradicate it. Effective management strategies should therefore include cultural incorporation of this species. For example, the Italian government has initiated efforts to promote the blue crab including its presentation at the 2024 G7 summit and the dissemination of promotional online content . However, to increase its consumption, targeted events and campaigns should be organized to inform the public, akin to successful approaches used for other species. Additionally, the extraction of chitosan and astaxanthin from crab shells may support the ongoing shellfish market, while providing valuable compounds with diverse applications in pharmaceutical, biomedical, cosmetic, agricultural, and biotechnological fields (Ambati et al., 2014; see also Demir et al., 2016, Baron et al., 2017 for recent examples on *C. sapidus*).

The increasing frequency of *H. carunculata* sightings highlights the need for effective management strategies to mitigate its proliferation . As an efficient scavenger and opportunistic consumer that can also feed on carrions, *H. carunculata* has been also found in high abundance beneath aquaculture net cages and at sites with high anthropic pressure and organic enrichment, such as artisanal fishery ports (Heilskov et al., 2006, Riera et al., 2014; Righi et al., 2020). As an efficient scavenger and predatory generalist, and due to its capacity to tolerate captivity, the bearded fireworm presents potential applications for the disposal of waste from the production and processing of marine products. Current research within biorefineries projects explores its use in processing mollusc waste, specifically expired mussels from retailers, for shell recovery and valorization (Simonini et al., 2024). . Preliminary results show that *H. carunculata* consumes mussel meat at high rates, leaving the shells almost completely clean. The high efficiency of *H. carunculata* in selectively removing meat from shells, coupled with the ability to maintain them at high densities without substrate, could prove useful for valorizing waste shells, while clean shells can be used as a source of "green" calcium carbonate (Seesanong et al., 2023). Developing practical applications for this invasive species could also support removal interventions from areas where *H. carunculata* is becoming a pest (Simonini et al. 2024).

Thus, management and control costs in invaded habitats may ultimately yield profits for local populations, while the effects of the invader may be greatly reduced, even enhancing the ecosystem goods and services provided by coastal habitats. Collaborative efforts are essential for formulating adaptive measures to safeguard both marine ecosystems and the livelihoods of communities along the Mediterranean coasts. Through interdisciplinary cooperation and

https://doi.org/10.5194/sp-2024-16
Preprint. Discussion started: 20 September 2024

proactive management strategies, it is possible to mitigate the adverse effects of climate change and invasive species proliferation, ensuring the long-term sustainability of Mediterranean marine environments and the well-being of coastal communities.

5. References

Ahrens, J. B., Borda, E., Barroso, R., Paiva, P. C., Campbell, A. M., Wolf, A., ... & Schulze, A.. The curious case of *Hermodice carunculata* (Annelida: Amphinomidae): evidence for genetic homogeneity throughout the Atlantic Ocean and adjacent basins. *Molecular Ecology*, *22*(8), 2280-2291, 2013.

Alter, K., Jacquemont, J., Claudet, J., Lattuca, M.E., Barrantes, M.E., et al.. Hidden impacts of ocean warming and acidification on biological response of marine animals revealed through meta-analysis. Nature Communication, 15, 2885. https://doi.org/10.1038/s41467-024-47064-3, 2024.

Ambati, R. R., Phang, S. M., Ravi, S., Aswathanarayana, R. G.. Astaxanthin: sources, extraction, stability, biological activities and its commercial applications - A review. Mar. Drugs 12, 128-152, 2014

Azzurro, E., Sbragaglia, V., Cerri, J., Bariche, M., Bolognini, L., Ben Souissi, J., ... & Moschella, P.. 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, 2019.

Ballard, H. L., Dixon, C. G., & Harris, E. M.. Youth-focused citizen science: Examining the role of environmental science learning and agency for conservation. Biological Conservation, 208, 65-75, 2017

Bardelli, R., Mancinelli, G., Mazzola, A., & Vizzini, S.. The Atlantic blue crab *Callinectes sapidus* spreading in the Tyrrhenian sea: Evidence of an established population in the Stagnone di Marsala (Sicily, southern Italy). *NAŠE MORE: znanstveni časopis za more i pomorstvo*, *70*(3 Special issue), 177-183, 2023.

Baron, R. D., Pérez, L. L., Salcedo, J. M., Córdoba, L. P., Sobral, P. J. d. A.. Production and characterization of films based on blends of chitosan from blue crab (*Callinectes sapidus*) waste and pectin from Orange (*Citrus sinensis* Osbeck) peel. Int. J. Biol. Macromol. 98, 676-683, 2017.

Barroso, R., Almeida, D., Contins, M., Filgueiras, D., & Dias, R.. *Hermodice carunculata* (Pallas, 1766) (Polychaeta: Amphinomidae) preying on starfishes. Marine Biodiversity, 46, 333-334, 2016.

Berke, S.K., Mahon, A.R., Lima, F.P., Halanych, K.M., Wethey, D.S. et al., Range shifts and species diversity in marine ecosystem engineers: patterns and predictions for European sedimentary habitats. Global Ecology and Biogeography, 19 (2), 223-232, 2010.

Bordignon, F., Zomeño, C., Xiccato, G., Birolo, M., Pascual, A., & Trocino, A.. Effect of emersion time on growth, mortality and quality of Pacific oysters (Crassostrea gigas, Thunberg 1973) reared in a suspended system in a lagoon in Northern Italy. Aquaculture, 528, 735481, 2020.

Brylawski, B. J. & Miller, T. J. Temperature-dependent growth of the blue crab (*Callinectes sapidus*): a molt process approach. Can. J. Fish. Aquat. Sci. 63, 1298-1308, doi:10.1139/f06-011, 2006.

Bunnell, D. B., Lipton, D. W., Miller, T. J.. The bioeconomic impact of different management regulations on the Chesapeake Bay blue crab fishery. N. Am. J. Fish Manage. 30, 1505-1521, 2010.

Celona, A., & Comparetto, G.. Prime osservazioni sulla predazione opportunistica del "vermocane" *Hermodice carunculata* (Pallas, 1766), ai danni della piccola pesca artigianale nelle acque di Lampedusa (Is. Pelagie). Annales, Series Historia Naturalis, 20, 15-20, 2010.

Çinar, M. E., Arianoutsou, M., Zenetos, A., & Golani, D.. Impacts of invasive alien marine species on ecosystem services and biodiversity: a pan-European review. Aquatic Invasions, 9(4), 391-423, 2014.

Civitarese, G., Gačić, M., Batistić, M., Bensi, M., Cardin, V., Dulčić, J., . & Menna, M.. The BiOS mechanism: history, theory, implications. Progress in Oceanography, 103056, 2023.

https://doi.org/10.5194/sp-2024-16
Preprint. Discussion started: 20 September 2024

STATE OF THE PLANET Discussions

Clavero M, Franch N, Bernardo R, López V, Abelló P, Mancinelli G.. Severe, rapid, and widespread impacts of an Atlantic blue crab invasion. Marine Pollution Bulletin, 176, 113479, 2022.

Coll, M., Piroddi, C., Steenbeek, J., Kaschner, K., Ben Rais Lasram, F., Aguzzi, J., ... & Voultsiadou, E.. The biodiversity of the Mediterranean Sea: estimates, patterns, and threats. *PloS one*, *5*(8), e11842, 2010.

Copernicus: 2023 is the hottest year on record, with global temperatures close to the 1.5°C limit. (n.d.). Copernicus. https://climate.copernicus.eu/copernicus-2023-hottest-year-record, 2023.

Corriero, G., Gherardi, M., Giangrande, A., Longo, C., Mercurio, M. et al.. Inventory and distribution of hard bottom fauna from the marine protected area of Porto Cesareo (Ionian Sea): Porifera and Polychaeta. Italian Journal of Zoology, 71, 237-245, 2004.

Cosentino, A., & Giacobbe, S.. The new potential invader *Linopherus canariensis* (Polychaeta: Amphinomidae) in a Mediterranean coastal lake: Colonization dynamics and morphological remarks. Marine Pollution Bulletin, 62(2), 236-245, 2011.

Darmaraki, S., Somot, S., Sevault, F., Nabat, P., Cabos Narvaez, W. D., Cavicchia, L., ... & Sein, D. V.. Future evolution of marine heatwaves in the Mediterranean Sea. Climate Dynamics, 53, 1371-1392, 2019.

Demir, D., Öfkeli, F., Ceylan, S., Bölgen, N.. Extraction and characterization of chitin and chitosan from blue crab and synthesis of chitosan cryogel scaffolds. J. Turkish Chem. Soc. Sect. Chem. 3, 131-144, 2016.

Donati F., Fabbro E. "La molluschicoltura nelle lagune del Delta del Po veneto. Aspetti socio - economici". Relazione tecnica, 2010.

Encarnação, J., Morais, P., Baptista, V., Cruz, J., & Teodósio, M. A.. New Evidence of Marine Fauna Tropicalization off the Southwestern Iberian Peninsula, 2019.

EU Copernicus Marine Service Product: Mediterranean Sea Surface Temperature time series and trend from Observations Reprocessing, Mercator Ocean International [data set], (2022a) https://doi.org/10.48670/moi-00268

EU Copernicus Marine Service Product: Global Ocean Sea Surface Temperature time series and trend from Observations Reprocessing, Mercator Ocean International [data set], (2022b) https://doi.org/10.48670/moi-00242

Fishelson, L.. Ecology and distribution of the benthic fauna in the shallow waters of the Red Sea. Marine Biology, 10(2), 113-133, 1971.

Franzoi, P., Facca, C., Redolfi Bristol, S., Boschiero, M., Matteo, Z., & Scapin, L.. Application of the Habitat Fish Biological Index (HFBI) for the assessment of the ecological status of Po Delta lagoons (Italy). Italian Journal Of Freshwater Ichthyology, 9, 91-106, 2023.

Fraschetti, S., Giangrande, A., Terlizzi, A., Miglietta, M., Del- la Tommasa, L. et al.. Spatiotemporal variation of hydroids and polychaetes associated with *Cystoseira amentacea* (Fucales: Phaeophyceae). Marine Biology, 140 (5),949-958, 2002.

Gačić, M., Ursella, L., Kovačević, V., Menna, M., Malačič, V., Bensi, M., ... & Rubino, A.. Impact of dense-water flow over a sloping bottom on open-sea circulation: laboratory experiments and an Ionian Sea (Mediterranean) example. *Ocean Science*, *17*(4), 975-996, 2021.

Giakoumi, S., Katsanevakis, S., Albano, P. G., Azzurro, E., Cardoso, A. C., Cebrian, E., ... & Sghaier, Y. R.. Management priorities for marine invasive species. Science of the total environment, 688, 976-982, 2019.

Giangrande, A., Delos, A.L., Fraschetti, S., Musco, L., Licciano M. et al.. Polychaetes assemblages along a rocky shore on the South Adriatic coast (Mediterranean Sea): patterns of spatial distribution. Marine Biology, 143, 1109-1116, 2003.

Giovos, I., Kleitou, P., Poursanidis, D., Batjakas, I., Bernardi, G. et al.. Citizen-science for monitoring marine invasions and stimulating public engagement: a case project from the eastern Mediterranean. Biological Invasions 21, 3707-3721, 2019.

Guinaldo, T., Voldoire, A., Waldman, R., Saux Picart, S., & Roquet, H.. Response of the sea surface temperature to heatwaves during the France 2022 meteorological summer. Ocean Science, 19(3), 629-647, 2023.

Heilskov, A. C., Alperin, M., & Holmer, M.. Benthic fauna bio-irrigation effects on nutrient regeneration in fish farm sediments. Journal of Experimental Marine Biology and Ecology, 339(2), 204-225, 2006.

Hines, A. H.. Ecology of Juvenile and Adult Blue Crabs, in: Kennedy, V.S., Cronin, L.E. (Eds.), The Blue Crab: *Callinectes sapidus*. Maryland Sea Grant College, pp. 565-654, 2007.

Hobday, A. J. et al.. A hierarchical approach to defining marine heatwaves. *Prog Oceanogr* 141, 227-238, doi:10.1016/j.pocean.2015.12.014, 2016.

Joyce, P.W.S., Tong, C.B., Yip, Y.L., Falkenberg, L.J.. Marine heatwaves as drivers of biological and ecological change: implication of current research patterns and future opportunities. Marine Biology, 171(20), https://doi.org/10.1007/s00227-023-04340-y, 2024.

Jumars, P. A., Dorgan, K. M., & Lindsay, S. M.. Diet of worms emended: an update of polychaetae feeding guilds. Annual review of marine science, 7, 497-520, 2015.

Katsanevakis, S., Rilov, G., & Edelist, D.. Impacts of marine invasive alien species on European fisheries and aquaculture–plague or boon?. CIESM Monograph, 50, 125-132, 2018.

Kennedy, V. S., Oesterling, M., Van Engel, W. A.. History of Blue Crab Fisheries on the US Atlantic and Gulf Coasts, in: Kennedy, V.S., Cronin, L.E. (Eds.), The Blue Crab: *Callinectes sapidus*. Maryland Sea Grant College, pp. 655-710, 2007.

Kicklighter, C. E., & Hay, M. E.. Integrating prey defensive traits: contrasts of marine worms from temperate and tropical habitats. Ecological Monographs, 76(2), 195-215, 2006.

Kubin, E., Menna, M., Mauri, E., Notarstefano, G., Mieruch, S., & Poulain, P. M.. Heat content and temperature trends in the Mediterranean Sea as derived from Argo float data. Frontiers in Marine Science, 10, 1271638, 2023.

Kullenberg, C., & Kasperowski, D.. What is citizen science?–A scientometric meta-analysis. PloS one, 11(1), e0147152, 2016.

Ladd, M. C., & Shantz, A. A.. Novel enemies–previously unknown predators of the bearded fireworm. Frontiers in Ecology and the Environment, 14(6), 342-343, 2016.

Libralato, S., Caccin, A., & Pranovi, F.. Modeling species invasions using thermal and trophic niche dynamics under climate change. Frontiers in Marine Science, 2, 29, 2015.

Lipcius, R. N., Eggleston, D. B., Heck, K. L., Seitz, R. D. & Van Montfrans, J.. in The Blue Crab: *Callinectes sapidus* (eds V. S. Kennedy & L. E. Cronin) 535-564 (Maryland Sea Grant College, 2007), 2007.

Lopez, B.E., Magliocca, N.R., Crooks, A.T.. Challenges and Opportunities of Social Media Data for Socio-Environmental Systems Research. Land, 8 (7), 107, 2019.

Maicu, F., De Pascalis, F., Ferrarin, C., & Umgiesser, G.. Hydrodynamics of the Po River-Delta-Sea System. Journal of Geophysical Research: Oceans, 123(9), 6349-6372, 2018.

Mancinelli, G., Alujević, K., Guerra, M. T., Raho, D., Zotti, M., Vizzini, S.. Spatial and seasonal trophic flexibility of the Atlantic blue crab *Callinectes sapidus* in invaded coastal systems of the Apulia region (SE Italy): a stable isotope analysis. Estuar. Coast. Shelf Sci. in press, DOI: 10.1016/j.ecss.2017.1003.1013, 2017a.

Mancinelli, G., Chainho, P., Cilenti, L., Falco, S., Kapiris, K., Katselis, G., Ribeiro, F.. The Atlantic blue crab *Callinectes sapidus* in southern European coastal waters: Distribution, impact and prospective invasion management strategies. Marine Pollution Bulletin 119: 5–11, 2017b.

Mancinelli G, Bardelli R, Zenetos A.. A global occurrence database of the Atlantic blue crab *Callinectes sapidus*. Scientific Data, 8, 111, 2021.

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

Mastrototaro, F., d'Onghia, G., Corriero, G., Matarrese, A., Maiorano, P. et al.,. Biodiversity of the white coral bank off Cape Santa Maria di Leuca (Mediterranean Sea): An update. Deep Sea Research Part II: Topical Studies in Oceanography, 57 (5-6), 412-430, 2010.

Menna, M., Gačić, M., Martellucci, R., Notarstefano, G., Fedele, G., Mauri, E., ... & Poulain, P. M.. Climatic, Decadal, and Interannual Variability in the Upper Layer of the Mediterranean Sea Using Remotely Sensed and In-Situ Data. Remote Sensing, 14(6), 1322, 2022.

Millikin, M. R., Williams, A. B.. Synopsis of biological data on blue crab, *Callinectes sapidus* Rathbun. FAO Fisheries Synopsis 38, 1984.

Mistri, M., Ceccherelli, V.U.. Growth and secondary production of the Mediterranean gorgonian *Paramuri-ceaclavata*. Marine Ecology-Progress Series, 103, 291-291, 1994.

Nehring, S.. Invasion History and Success of the American Blue Crab *Callinectes sapidus* in European and Adjacent Waters, in: Galil, B.S., Clark, P.F., Carlton, J.T. (Eds.), In the Wrong Place - Alien Marine Crustaceans: Distribution, Biology and Impacts. Invading Nature - Springer Series in Invasion Ecology. Springer Netherlands, pp. 607-624, 2011.

Pallas, P. S.. Miscellanea zoologica: quibus novae imprimis atque obscurae animalium species describuntur et observationibus iconibusque illustrantur. apud Sam. et Joan. Luchtmans. 1778.

Pastor, F., Valiente, J. A., & Palau, J. L.. Sea surface temperature in the Mediterranean: Trends and spatial patterns (1982–2016). Meteorology and climatology of the Mediterranean and Black Seas, 297-309, 2019.

Pires, A., Martins, R., Magalhães, L., Soares, A.M.V.M., Figueira, E. et al.. Expansion of lugworms towards south-ern European habitats and their identification using combined ecological, morphological and genetic approaches. Marine Ecology Progress Series, 533, 177-190, 2015.

Pirro A., Martellucci R., Gallo A., Kubin E., Mauri E., Juza M., Notarstefano G., Pacciaroni M., Bussani A., Menna M. (2024) Subsurface warming derived by Argo floats during the 2022 Mediterranean marine heatwave. 2024, *in* Ocean State Report 8, State of the Planet. (accepted), 2022.

Pisano, A., Marullo, S., Artale, V., Falcini, F., Yang, C., Leonelli, F. E., ... & Buongiorno Nardelli, B.. New evidence of Mediterranean climate change and variability from sea surface temperature observations. Remote Sensing, 12(1), 132, 2020.

Raffa, F., Ludeno, G., Patti, B., Soldovieri, F., Mazzola, S., & Serafino, F.. X-band wave radar for coastal upwelling detection off the southern coast of Sicily. Journal of Atmospheric and Oceanic Technology, 34(1), 21-31, 2017.

Ramos, M. A. C., & Schizas, N. V.. Population structure of the fireworm *Hermodice carunculata* in the wider Caribbean, Atlantic and Mediterranean Sea. Journal of the Marine Biological Association of the United Kingdom, 103, e14, 2023.

Riera, R., Pérez, O., Rodríguez, M., Ramos, E., & Monterroso, Ó.. Are assemblages of the fireworm *Hermodice carunculata* enhanced in sediments beneath offshore fish cages?. Acta Oceanologica Sinica, 33(4), 108-111, 2014.

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

Righi, S., Savioli, M., Prevedelli, D., Simonini, R., & Malferrari, D.. Unraveling the ultrastructure and mineralogical composition of fireworm stinging bristles. *Zoology*, 144, 125851, 2021.

Righi, S., Forti, L., Simonini, R., Ferrari, V., Prevedelli, D., & Mucci, A.. Novel Natural Compounds and Their Anatomical Distribution in the Stinging Fireworm *Hermodice carunculata* (Annelida). *Marine Drugs*, 20(9), 585, 2022.

Rogers, T. L., Gouhier, T. C. & Kimbro, D. L.. Distinct temperature stressors acting on multiple ontogenetic stages influence the biogeography of Atlantic blue crabs. Mar. Ecol. Prog. Ser. 690, 97-111, doi:10.3354/meps14039, 2022.

Samperio-Ramos, G., Olsen, Y. S., Tomas, F., Marbà, N.. Ecophysiological responses of three Mediterranean invasive seaweeds (*Acrothamnion preissii*, *Lophocladia lallemandii* and *Caulerpa cylindracea*) to experimental warming. Marine pollution bulletin, 96 (1-2), 418-423, 2015.

Schneider, A. K., Fabrizio, M. C. & Lipcius, R. N.. Reproductive phenology of the Chesapeake Bay blue crab population in a changing climate. Front. Ecol. Evol. 11, 1304021, doi:10.3389/fevo.2023.1304021, 2024.

https://doi.org/10.5194/sp-2024-16
Preprint. Discussion started: 20 September 2024

Schulze, A., Grimes, C. J., & Rudek, T. E.. 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, 2017.

Seesanong, S., Seangarun, C., Boonchom, B., Laohavisuti, N., Thompho, S., Boonmee, W., ... & Rungrojchaipon, P. . Bio-green synthesis of calcium acetate from oyster shell waste at low cost and reducing the emission of greenhouse gases. Sustainable Environment Research, 33(1), 26, 2023.

Simonini, R., Maletti, I., Righi, S., Fai, S., & Prevedelli, D.. 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, 2018.

Simonini, R., Prevedelli, D., Righi, S.. Esemplari mediterranei del verme di fuoco *Hermodice carunculata* (Annelida) catalogati nelle raccolte zoologiche di musei europei. Atti della Società dei Naturalisti e Matematici di Modena, 150, 2019.

Simonini, R., Righi, S., Zanetti, F., Fai, S., Prevedelli D.. Development and catch efficiency of an attracting device to collect and monitor the invasive fireworm *Hermodice carunculata* in the Mediterranean Sea. Mediterranean Marine Science, *22*(3), 706-714, 2021.

Simonini, R., & Ferri, A.. Prime stime della longevità del verme di fuoco *Hermodice carunculata* (Annelida) dedotte grazie al contributo dei fotografi subacquei alla scienza partecipata. Atti della Società dei Naturalisti e Matematici di Modena, 153, 2022.

Simonini, R., Ferri, A., Righi, S., Cenni, E., Ferrari, V., Sabia, C., ... & Prevedelli, D.. Potenziali applicazioni biotecnologiche dei policheti *Halla parthenopeia* (Oenonidae) e *Hermodice carunculata* (Amphinomidae) . Biologia Marina Mediterranea, 28(1), 27-30, 2024.

Stachowicz, J.J., Terwin, J.R., Whitlatch, R.B., Osman, R.W.,. Linking climate change and biological invasions: ocean warming facilitates nonindigenous species invasions. Proceedings of the National Academy of Sciences, 99 (24), 15497-15500, 2002.

Streftaris, N., Zenetos, A.. Alien marine species in the Mediterranean - the 100 'Worst Invasives' and their impact. Mediterr. Mar. Sci. 7, 87-117, 2006.

Sun, C. C., Hurst, J. E., & Fuller, A. K.. Citizen science data collection for integrated wildlife population analyses. Frontiers in Ecology and Evolution, 9, 682124, 2021.

Sussman, M., Loya, Y., Fine, M., & Rosenberg, E.. 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, 2003.

Taylor, D. L., & Fehon, M. M.. Blue Crab (*Callinectes sapidus*) Population structure in Southern New England tidal rivers: Patterns of shallow-water, unvegetated habitat use and quality. Estuaries and Coasts, 44(5), 1320-1343, 2021.

Tiralongo, F., Crocetta, F., Riginella, E., Lillo, A. O., Tondo, E., Macali, A., ... & Azzurro, E.. Snapshot of rare, exotic and overlooked fish species in the Italian seas: A citizen science survey. Journal of Sea Research, 164, 101930, 2020.

Tiralongo, F., Villani, G., Arciprete, R., Mancini, E.. Filling the gap on Italian records of an invasive species: first records of the Blue Crab, *Callinectes sapidus* Rathbun, 1896 (Decapoda: Brachyura: Portunidae), in Latium and Campania (Tyrrhenian Sea). Acta Adriatica, 61(2), 99-104. https://doi.org/10.32582/aa.62.1.8, 2021.

Tiralongo, F., Marino, S.Ignoto, S., Martellucci, R., Lombardo, B.M., Mancini, E., Scacco, U.. Impact of *Hermodice carunculata* (Pallas, 1766) (Polychaeta: Amphinomidae) on artisanal fishery: A case study from the Mediterranean Sea. Marine Environmental Research, 192, 106227. https://doi.org/10.1016/j.marenvres.2023.106227, 2023.

Tirelli, V., Goruppi, A., Riccamboni, R., & Tempesta, M.. Citizens' Eyes on Mnemiopsis: How to Multiply Sightings with a Click!. Diversity, 13(6), 224, 2021.

Toivonen, T., Heikinheimo, V., Fink, C., Hausmann, A., Hiippala, T. et al.. Social media data for conservation science: A methodological overview. Biological Conservation, 233, 298-315, 2019.

https://doi.org/10.5194/sp-2024-16
Preprint. Discussion started: 20 September 2024

Toso, A., Boulamail, S., Lago, N., Pierri, C., Piraino, S., & Giangrande, A.. 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, 2020.

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

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

Turrini, T., Dörler, D., Richter, A., Heigl, F., & Bonn, A.. The threefold potential of environmental citizen science-Generating knowledge, creating learning opportunities and enabling civic participation. Biological Conservation, 225, 176-186, 2018.

van Beukering, P., Brouwer, R., Schep, S., Wolfs, E., Brander, L., Ebanks-Petrie, G., & Austin, T.. The impact of invasive species on tourism. Wolfs Company, 2014.

Vetrano, A., Napolitano, E., Iacono, R., Schroeder, K., Gasparini, G. P.. Tyrrhenian Sea circulation and water mass fluxes in spring 2004: Observations and model results. Journal of Geophysical Research: Oceans, 115(C6), 2010.

Wolf, A. T., & Nugues, M. M.. Predation on coral settlers by the corallivorous fireworm *Hermodice carunculata*. Coral Reefs, 32(1), 227-231, 2013.

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

Zenetos, A., Çinar, M. E., Pancucci-Papadopoulou, M. A., Harmelin, J. G., Furnari, G., Andaloro, F., Bellou, N., Streftaris, N., Zibrowius, H.. Annotated list of marine alien species in the Mediterranean with records of the worst invasive species. Mediterr. Mar. Sci. 6, 63-118, 2005.