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Article

Effects of Climate Crisis on Marine Ecosystem: Mass Mortality Event of the Mediterranean Mussels (*Mytilus galloprovincialis*) in the Middle Adriatic

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Abstract: The effects of the climate crisis are affecting ecosystems at different scales and magnitudes. This paper focuses on a massive Mediterranean mussel die-off observed along the middle Italian Adriatic coast in the summer of 2022. We considered the possible environmental causes of this phenomenon and carried out a climatic analysis of the last decade. We performed field surveys in different locations along a 16 Km coastal stretch (from Martinsicuro (TE) on the South, to Grottammare (AP) on the North). The study area includes two marine Sites of Community Importance under the European Natura 2000 network. The mussels die-off has interested practically all the natural mussel-beds colonizing the study area. Mussels are sessile filter-feeding organisms inhabiting the intertidal zone, therefore, are highly exposed to variations in environmental conditions such as temperature and nutrient load. We discuss the possible causes of this die-off, proposing that high temperature and the scarce availability of food acted simultaneously as stress factors, generating local unsustainable living conditions for this species.

Keywords: mussel die-off; food availability; marine heatwaves; Adriatic sea; climatic crisis; synergistic effect

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1. Introduction

The climate crisis is a global threat to species, biodiversity, and ecosystems that affects individual organisms, their interaction with other species and habitats, altering ecosystem functions and structure [1]. In this regard, the Intergovernmental Panel on Climate Change claims that the impact of recent and rapid global warming has affected weather, climate, economy and human society [2]. The impacts of the climate crisis are widespread but not uniform over time and space, as the responses of species and habitats vary according to their relative vulnerability, degree of exposure, sensitivity, and capacity to adapt [3–6]. The climate crisis affects not only the average temperature but also the duration, magnitude, and frequency of extreme events such as droughts, forest fires, and heat waves [7]. This synergy implies strong pressures on ecosystems, reducing their resilience [8].

Marine heatwaves (MHWs; anomalously warm water events) are hitting marine ecosystems at global scales, affecting local environmental dynamics, in recent decades [9]. Significant events were observed in the northern Mediterranean Sea in 2003 [10,11], in Australia (west coast) in 2011 [12], in the northwestern Atlantic Ocean in 2012 [13], in the north-eastern Pacific Ocean between 2013 and 2015 [14,15], off South East Australia in 2015/16 [16] and across Northern Australia in 2016 [17]. MHWs can generate significant impacts on ecological communities, such as the loss of kelp forests [18], coral bleaching [19], reduction of surface chlorophyll levels [14], mass mortality of marine invertebrates [20,21] and changes in distribution and structure of species and communities respectively [18,20,22].

The climate crisis is particularly intense in the Mediterranean region, due to its characteristics [23]. The Adriatic ecosystems for example are interested by the combined effect of the climate crisis and local climate variations [24]. The Adriatic Sea is a basin into which most of the rivers of northern and central Italy flow and which communicates with the Mediterranean Sea only through the Otranto channel (just 70 km wide); therefore, it could be considered an important example of a marine system strongly and dynamically influenced by both anthropic pressures led by rivers, and climate conditions [25–30]. A number of MHW events have been reported in the Adriatic Sea [31]. However, there is no report regarding the latest MHW events, nor even their potential association with mass mortality events (MMEs) of marine organisms.

The aim of this work was to analyze the potential causes and the ecological consequences of an MME of the Mediterranean mussel (*Mytilus galloprovincialis*) observed along the Piceno Adriatic coast (Marche Region, central Italy) at the end of the Summer of 2022. Specifically, we integrated a climatological analysis with observational data in order to explore the potential relationship between climatological conditions and mussel MME. It is worth mentioning that in the Mediterranean Sea, *M. galloprovincialis* is of ecological and economic importance [32–34]. As far as we know, this report is the first observation of a mussel MME within this coastal area, in which there are two marine Sites of Community Importance (SCI) and three mussel farms.

2. Materials and Methods

2.1. Study Area

The study area extends for about 16 km along the coast of the middle Adriatic, locally known as the Piceno coast (Figure 1). The climate has warm and moderately stormy Summer, fresh Winter with rare snowfall and mild and humid equinoctial season; the precipitation evidenced an absolute maximum in autumn and a slight secondary maximum in the month of May [35]. Summers are not usually too dry. The rainfall regime is bimodal - sublittoral adriatic and the annual rainfall and temperatures average (1997-2022), are 593 mm and 15.7°C respectively [36]. Storms from NNE to ESE characterize the wave regime of the area. The short tides have an average amplitude of 0.4-0.5 m with a maximum of around 0.75 m.

Figure 1. Sites where the massive mussel die-off was observed during summer 2022. 1: Grottammare natural reef; 2: San Benedetto del Tronto harbor; 3: San Benedetto del Tronto artificial barriers; 4: Martinsicuro artificial barriers. Photos by Google Earth.

The investigated area is characterized by shallow sandy bottoms that slowly degrade towards the open sea (medium deep of about -4.5 mt at 300 mt from the coast). Continuity solutions of this type of bottom are represented by artificial reefs (linear barriers placed to defend the coast against marine erosion) and by a natural reef of about 7 hectares, which is included in the boundaries of the SCI IT534022 "Costa del Piceno - San Nicola a mare" [37]. These hard substrates are here usually and strongly colonized by *mussel beds* (*i.e.*, *Mytilus galloprovincialis*), which perform various ecosystem functions such as the increase of the substrate three-dimensional complexity (*ecosystem engineering* function), the control of seston abundance in the water column by filtration (*control particle abundance* function), the transfer of organic matter and nutrients from the water column to the seabed through the production of biodeposits such as feces and pseudofeces (*benthic-pelagic coupling and nutrient cycling* function), the removal of waste from the water (*bioremediation* function) or being a food resource for marine organisms (*feeding* function) [34,38–40]. The observation sites insist on the following reef environments: Site 1, Grottammare, in the Marine Site of Community Importance (4761502N, 408104E) (natural reef); Site 2, San Benedetto del Tronto harbor (4756933N, 409848E) (artificial reef); Sites 3, San Benedetto del Tronto beach (4754238N, 409930E) (artificial reef); Site 4, Martinsicuro beach (4746627N, 412413E) (artificial reef) (Figure 1). All sites are characterized by a maximum depth of – 4.5 meters, which determines almost constant temperatures throughout the short water column.

Moreover, a mussel farm faces the town of San Benedetto del Tronto, about three nautical miles from the coast; two others are located just south and north of the study area.

2.2. Observations

For all observation sites, the pre and post-Summer 2022 status was detected by authors' direct observations; for site 1 the changes are also documented by photos and, since it is included in the SCI-IT534022, a detailed description of the pre-Summer 2022 condition is available [32,34]. Direct interviews with mussels' farmers were conducted to quantify the loss of productivity.

2.3. Climatic Data

In order to analyze the possible causes of the massive death of *Mytilus galloprovincialis* observed within the study area, we carried out an analysis of the available climatic data. In detail, on the basis of the ecological characteristics of this species, the climatic signal was characterized by focusing on air and sea temperature (time trend and heat waves) and precipitation/flow rivers.

Ref. [41] defines a MHW as exceeding a threshold (90th percentile relative to long-term local climatology) for at least a five-days period, with no more than two days below the threshold. In this regards, validated and analyzed meteo-marine data related to the measuring station of San Benedetto del Tronto (4756389N, 409228E) with a variable time step between 10 and 60 minutes according to the 2008 World Meteorological Organization guide [42] have been recovered from the dedicated website of marine weather observations of ISPRA [43]. This signal is homogeneous and almost continuous (except for very short recording gaps) and the data were analyzed from 1 January 2011 (data availability from June 2010). To define the data related to the SST of 30-year (period 1993-2022) with excellent approximation, and so define the 90th percentile for each day of Summer months (June, Julay, Aogust), we referred to the data of Copernicus Marine Environment Monitoring Service (CMEMS - Reprocessed (REP) Mediterranean (MED) dataset - see SST_MED_SST_L4_REP_OBSERVATIONS_010_021 product) and after nesting operation, these data were cross-referenced with the hourly data mentioned above [44].

Biological impacts of MHWs can vary greatly and appear to be context and target species dependent [9]. Therefore, based on both the results of [45] who observed that mussel mortality was 80% and 30% for a stay of 15 days at 30°C and of 30 days at 28°C respectively, and of [46] who found

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that the distribution of *M. galloprovincialis* is defined by an extreme SST around 29-30°C, we paid particular attention to the MHWs in which the SST cross up 30°C.

Finally, we analyzed the flows of the main rivers flowing along the western coast of the upper Adriatic Sea and the available data about the organic load.

3. Results

3.1. Climatic Data Analysis

The historical series relating to thermal parameters for water and air, for a total of more than 1.2 mln of numerical data (period 2011-2022), was analyzed in detail. A rather significant thermal increase of the sea surface temperature (SST), quantifiable at about 0.37°C and therefore in line with the indications deriving from the 17th Report on the climate in Italy of the "Higher Institute for Environmental Protection and Research" [47], highlights these data. The air temperature recorded in San Benedetto del Tronto during the same period evidenced an increase of about 1.08°C. In order to analyze the occurrence of MHW during Summer months (June, July, August) in the study area, Figure 2 shows number and amplitude of these events in the period 2011 - 2022.

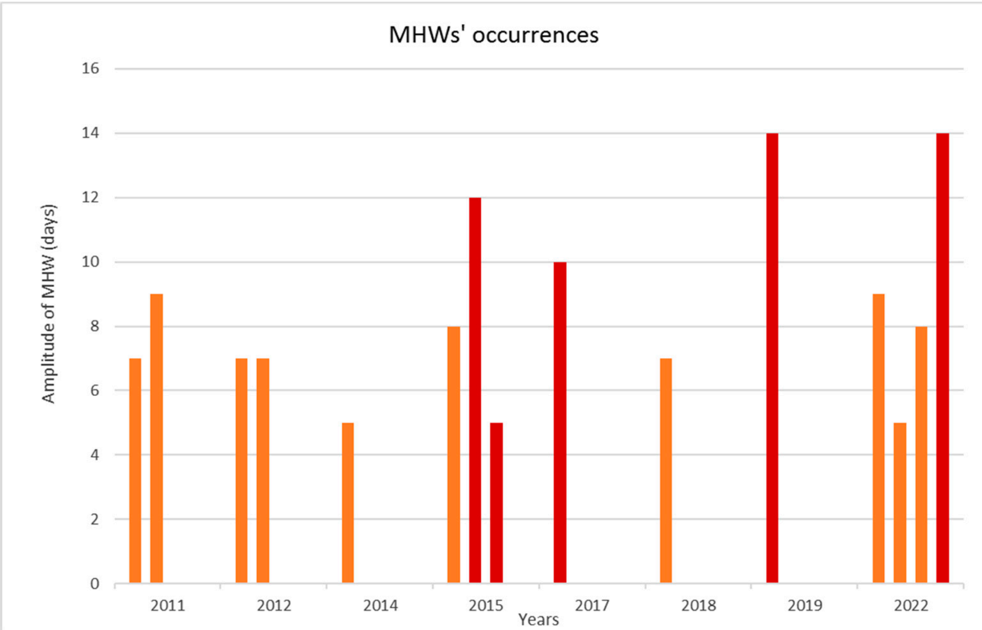

Figure 2. MHWs occurred in the study area in the period 2011 - 2022; in red the MHWs in which the temperature crossed up 30°C. In 2013, 2016, 2020 and 2021 years no MHWs were detected.

In the considered climatological series (period 2011 - 2022) the year 2022 was the year in which both the number of MHWs occurred (4) and the annual chronic heat stress of organisms (ACHSO) [48] (34 days of MHW) were the highest for the period. Of the four MHWs detected, one was exceeding the 30°C threshold for 10 days out of 14 (on the remaining 4 days the temperature was between 29.5 and 29.9°C) and the maximum temperature detected in this year was 30.6°C on the 6th of August.

Summer 2015 was the second one in terms of MHW's number (3) and of ACHSO (25 days). The longest and most intense MHW was observed in 2019 when the 90th percentile was exceeded for 14 consecutive days, and the temperature exceeded 30°C for 3 days of these. The highest absolute temperature values for the 2011 - 2022 period was recorded in the summer of 2017, and precisely on the 6th of August, with 31.2°C. Only one 10-day MHW occurred this summer, with temperatures greater than or equal to 30°C. Finally, also in the Summer 2019 was recorded a 14-day MHW in which the temperature was greater than 30°C for 3 days and between 27.8 and 29.7°C for the remaining 11 days.

The status of the sea waters of the study area depends not only on the conditions at the mesoscale (basin of Tronto and Aso rivers) but especially on what happens in the upper Adriatic basin, where the main Italian rivers (in terms of water flow: Po, Adige, and Brenta) flow their freshwater; indeed, a dominant sea current from north to south, runs along the Italian Adriatic coast, transporting southward the runoff.

Analyzing the data of the above-cited ISPRA Report [47], it is possible to observe that the flow rates of the aforementioned rivers and especially the rainfall that occurred in the catchment areas of the Po and the Adige were extremely low even in the first half of the year, due to a long phase of climatic drought, extended temporally from December 2021 and lasted until July 2022; moreover, this phase was also characterized by a strong nivometric deficit on the Alpine and Apennine mountains. The negative anomalies related to the first 6 months of the 2021-22 meteorological years were about 55% in the regions of Piemonte and Valle d'Aosta and about 50% in Lombardy and Tridentine Venice (in northern Italy).

The Po River reached the absolute minimum of the last 200 years during 2022, with a flow of 104 mc/sec on the 24th of July (hydrometric station of Ferrara-Pontelagoscuro) (Figure 3); other exceptional dry periods for the Po River were in June 2022 with a range of 303 mc/sec, in June 2006 with 320 mc/sec, in June 2005 with 444 mc/sec and in June 2003 with 521 mc/sec [49].

As a consequence of all this, from January to August 2022, in the mid-Adriatic Sea (South of the Po river's mouth) the chlorophyll-a was always much lower than the average of the period [50].

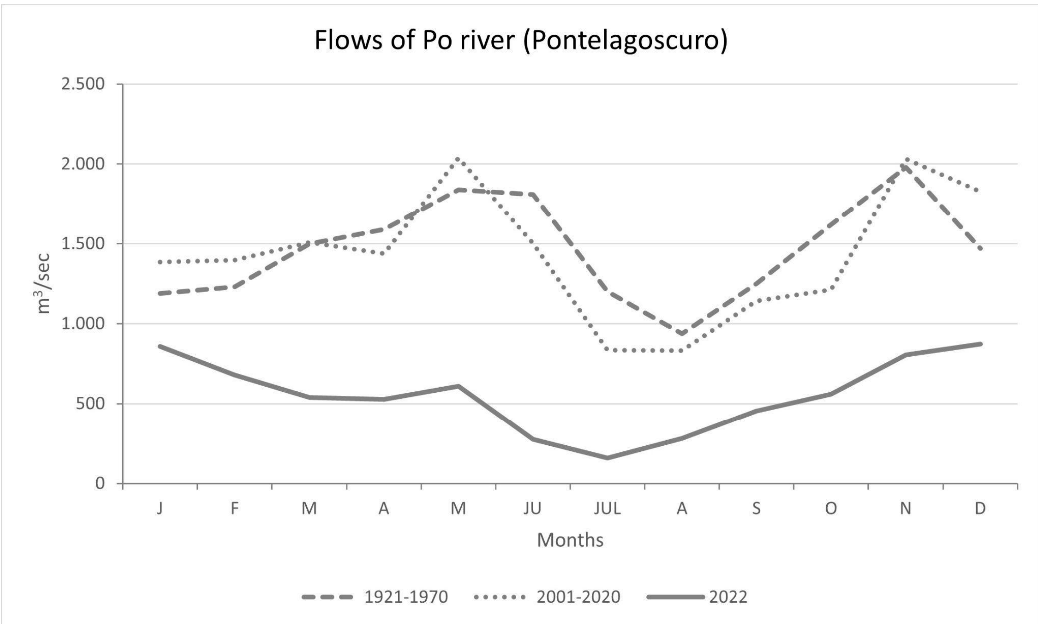

Figure 3. Flow river comparison between the year 2022 and two previous periods, at Pontelagoscuro (FE) station (data source [49]).

In addition, considering the hottest summers of the considered period, during the 2017 year, there was a slightly lower negative anomaly of winter and spring precipitation than in 2022 but the hydrological data of the flows of the Po river in Spring and Summer were characterized by values much higher than those of 2022. Regarding the summer 2015, we observed that the first half of the year was characterized by rainfall around the average of the last thirty years, with moderate snowfall in the sectors of the central and eastern Alps and alpine river flows were significantly higher than in 2022. Thanks to both winter snowfalls in line with seasonal averages and abundant rainfall in the months of May and April, the flow of the Po river showed in 2019 year no significant minimums, always remaining above 900 m3/sec until the end of the Spring and reaching an absolute minimum of 620 m3/sec in the third ten days of July [49].

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3.2. Field Observation of Mussel MME

In the present study, we recorded a massive absence of Mediterranean mussel beds on rocky substrates that were almost completely covered before the summer 2022 (Figure 4). This phenomenon affected both intertidal and subtidal zones and was observed after the heat wave series hit the central Adriatic coast in June-August 2022 period, when four MHWs occurred, water temperatures reached 30.6°C, and remained above 30°C for 10 days during the last MHW (25th July - 7th August). The drop in mussel production recorded in the farms located in front of the study area three nautical miles from the coast, after Summer 2022 was around 30%.

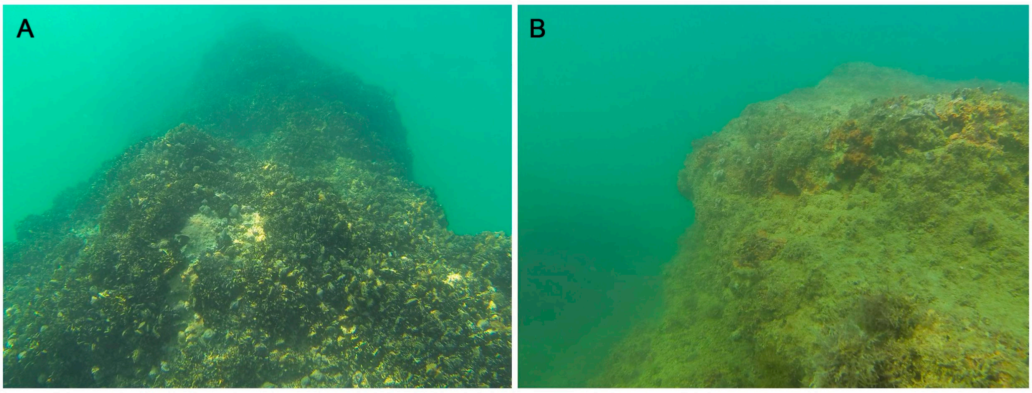

Figure 4. Pre and post Summer 2022 coverage of the mussel beds in Site 1; A, September 2020 (this photo was not taken immediately before Summer 2022, but it is well representative of this period), B October 2022.

4. Discussion

4.1. Climatic Data

The air thermal increase of about 1.08°C recorded in San Benedetto del Tronto harbor station, during the 2011-2022 timespan, is confirmed by the data recorded in the nearby harbors of Ancona and Ortona, respectively 1.27°C and 1.22 °C. At meso-scale level we can observe a strong acceleration of climate forcing. The increase of 0.37°C of the SST, in the same period, is comparable to the data acquired from satellite observations within the Copernicus Marine Environment Monitoring Service (CMEMS) project - Mediterranean SST [51] and with those acquired directly in the Croatian surface waters of the Central Adriatic Sea [23]. These authors highlighted two fundamental points: *i*) contrary to what happened in the previous 20 years, the period after 2005 would be characterized by a constant increasing thermometric trend (about 0.04ºC/year) without cooling or breaking phases, *ii*) there is a change in the width of the seasonal cycle, characterized by a sharp increase in the uptrend of SST in summer (about 0.056°C/year), and a slowdown in winter (~0.029°C/ year). The increase in SST on the eastern coast of the Adriatic Sea, with a total increase exceeding 1°C between 1979 to 2015, was also shown by [52] and [53]. The seasonal variability changes could affect the SST trend during solstice seasons - with summers warmer than the winters - and could amplify the effects of the sea heat waves in terms of frequency, magnitude, and duration, with negative impacts on marine ecosystems as a consequence.

The 2022 MHWs resulted from the high air temperatures recorded at the end of June along the middle and upper Adriatic Italian coast. The month of July has been indeed the hottest of the last 50 years [54]. These sea heat waves confirm a trend of increasing temperatures in the Mediterranean basin in the last twenty years [31].

The reduced river runoff is another crucial aspect that characterized the Central Adriatic waters during 2022. The Po River is the largest Italian river and the main contributor to the nutrient load in the central northern Adriatic waters [26]. In Summer, the typical flow of the Po River falls below the range of 550 and 700 mc/sec. Interestingly, the slowest flow (*i.e.* 104 mc/sec) was recorded exactly in

July 2022 [49]. In 2022, the fluvial regime of the Po River (Figure 3) and, simultaneously, of the Adige, Piave and Brenta rivers, which are normally of the nivo-glacial type, showed a typical Mediterranean regime, with a slight maximum in winter and a slight recovery in the flow rate in May. This regime was due to the rapid melting of the very scarce residual snowpack present on the Alpine chain, and a strong summarizing minimum in summer.

4.2. Mussels MME

The disappearance of the mussels bed observed in the study area is not attributable to phenomena of illegal fishing (Figure 5), as it is widespread throughout the investigated area and is totalitarian in the observation sites (both intertidal and subtidal zones).

Figure 5. Effects of illegal mussel removal resulting in localized holes in the dense cover of mussels (photo of Grottammare Site1, June 2020); note the difference with respect Figure 4, photo B, in which the absence of mussels is total.

Here the main marine predators of the mussels are *Sparus aurata*, *Rapana venosa* and *Murix* sp.; although ecosystem alterations are attributed to *R. venosa* [55], due to the times and ways of the observed massive mussel death, predation must be excluded as a possible cause.

Neither polluting events nor Harmful Algal Blooms (HABs) were recorded during and before Summer 2022 [56]; similarly, in this period no pathologies were detected by farmers in mussels, during the analysis required by law for their marketing.

Our findings align with previous studies demonstrating that HMWs correlate with MMEs in the Mediterranean Sea [21,57]. However, there is still limited knowledge of this association in the Adriatic Sea area. In the Northwestern Mediterranean Sea, mortality incidence between 20% and 100% was registered according to MHW duration ranging from 25 to 50 days [58]. This finding suggests that the level of mortality associated to MHWs is highly variable, and demonstrates the need to consider further factors in analyzing the relationship between heat stress and MMEs, like the ecological memory of the previous exposures to MHWs over the same geographic areas [59], and potential species or populations-related differences [60,61]. For instance, benthic organisms colonizing intertidal zones, such as *M. galloprovincialis*, are exposed to a variety of harsh marine and terrestrial conditions that could affect their survival. Indeed Ref. [62] demonstrated that the Mediterranean mussel exposed to a low food load and high temperatures (30ºC) had a survival of 33%, while individuals exposed to the same thermal conditions but with a high food load had a survival of 57%.

Previous experimental studies focusing on measuring the death levels of *M. galloprovincialis* in response to increasing temperature showed that individuals exposed to 30ºC reached a 80% mortality rate after 10 days of exposure, peaking at 100% on the 12th day [45]. Indeed, Ref. [63] suggests that natural populations of Mediterranean mussels already live in conditions close to their thermal acclimation limits, considering that 24–25°C is identified as the upper limit for optimal physiological processes.

Physiological parameters that may contribute to increased animal stress include the heart rate. Ref. [64] observed that increasing temperatures promote the rise of heartbeats until a certain critical temperature, after which the heart rate drops. Therefore, the effects of the climate crisis are challenging their physiological limits, making these bivalves particularly vulnerable to extreme thermal variations, especially considering that rocky intertidal coasts are habitats extremely variable and thermally stressful [65].

Another aspect to consider for both natural and farmed mussel populations is the status of the byssus. Byssal threads are composed of extracellular proteinaceous (collagenous) fibers and are synthesized along the mussel's foot starting from a mussel foot protein [66]. The byssus' role includes preventing dislodgement of the bivalve in harsh hydrodynamic conditions, resisting mobile competitors, and competing for space [67]. Environmental conditions like the warming of waters and ocean acidification may alter byssal production processes causing a reduction in strength, stiffness, and extension [68,69]. Ref. [70] further demonstrated that in *Mytilus coruscus* the expression of mussel foot protein genes are affected by elevated temperature, making the byssus susceptible to ocean warming and leading to a risk of dislodgement at high sea temperature (up to 27°C). Similarly, Ref. [71] found that the attachment strength of *M. galloprovincialis* was negatively correlated with sea surface temperature.

One further consequence of the increased ocean warming is decreased marine productivity [72]. Ref. [73] have suggested that depending on the timing of phytoplankton blooms, marine bivalves may face periods of limited food availability and elevated temperatures, especially in the high intertidal zone. These authors indeed recorded a decrease in the enzyme kinetics with a controlled increase of water temperature in the Mediterranean mussels in anoxia or normoxia conditions. Interestingly, the authors found that severe environmental conditions can be buffered by food availability.

Our observations also show that during the Summer of 2022, the study area experienced a dry period (*i.e.* strong nivometric deficit in winter, low rainfall in springer, and an absolute minimum of rivers' flow in springer and summer), which resulted in a low concentration of nutrients released into the sea by rivers. 2019, 2017 and especially 2015 were also hot years but only in the half part of 2022 was observed a very lower organic load (chl-a). Differently from previous years, when the productivity was almost constant, local mussel farmers recorded a reduction of 30% after Summer 2022. Although the environmental conditions (e.g., temperature, depth, currents) are different between the coastal zone (study area) and the three-mile zone (location of the farms), the decrease in productivity which occurred in the same period as the observed mussel death, is nevertheless a significant fact; especially considering that farmers have recently implemented procedures to reduce the heat waves' damage.

We thus hypothesize that the mussel MME observed in our study could be due to a vicious cycle of heat stressors (*i.e.* MHWs and ACHSO) which increased the metabolic rate, and to the low nutrient availability, which did not meet the metabolic demand. Indeed, critical heatwaves with temperatures above 30ºC also occurred in the summer seasons of 2015, 2017 and 2019. However, the Po River runoffs during the spring and summer of these years were characterized by values much higher than those of 2022, and as consequence, neither MME nor mussel bed reduction were observed in the same study area, during our monthly surveys.

5. Conclusions

Based on our field observation in the study area, climatic data analysis, and also considering previous findings on *M. galloprovincialis'* tolerance under certain stress conditions, we suggest that the MMEs observed in Summer 2022 was likely due to prolonged anomalously warm water combined with reduced nutrient supply. These findings clearly indicate that the Adriatic Sea is undergoing an evident acceleration of climate change impact, whose socio-ecological implications need to be addressed.

Probably, *M. galloprovincialis* from our study area lives in a defined range of summer temperatures and food availability; the knowledge of the climatic conditions that led to the observed massive die-off can represent an important contribution both to the monitoring of ecosystems and the management of mussel farms. The consequences of this stressor combination (*i.e.,* MHW, ACHSO and low nutrient load) on mussel farms are extremely different to what is possible to observe in natural settlements because the good farming practices adopted by farmers (*e.g.,* anticipating the sale of the product before the hottest periods and using fine knit socks (even in cotton)), can reduce the damage in certain periods allowing production to resume. On the contrary, climate crisis-driven alterations of natural habitats can be dramatic and require a longer time to restore, with the risk that once altered, natural habitat can reassemble itself with components and structures different from the initial condition.

Considering that these extreme climatological events will probably intensify [74], our preliminary analysis stresses the need for adopting specific mitigation and restoration measures in order to improve the management of marine natural ecosystems and fisheries.

Author Contributions: Conceptualization, L.B. and F.A.P.; formal analysis, L.B., M.F.; investigation, L.B., M.C. and P.C.; methodology, L.B., M.C., M.F. and P.C.; software, L.B. and M.F.; Data Curation, L.B., M.C.; supervision, L.B. and F.A.P.; visualization, L.B. and P.C.; Writing – Original Draft Preparation, L.B., M.C., P.C. and F.A.P.; writing-review and editing, L.B., M.C. and F.A.P. All authors have read and agreed to the published version of the manuscript.

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Data Availability Statement: The data presented in this study are available on request from the corresponding author. The data are not publicly available as they are partly owned by local governments.

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Conflicts of Interest: The authors declare no conflict of interest.

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