Aquaculture 588 (2024) 740917

Contents lists available at ScienceDirect

Aquaculture

journal homepage: www.elsevier.com/locate/aquaculture

Marine heatwaves in the western Mediterranean: Considerations for coastal aquaculture adaptation

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ARTICLE INFO

Keywords:
Climate change
Seabream
Seabass
Marine heatwaves
Mediterranean Sea

ABSTRACT

Climate change threatens marine aquaculture, impacting fish health and farming practices through extreme events such as ocean warming and marine heatwaves. These events can compound the effects of other stressors, necessitating adaptive measures for sustainable aquaculture, such as submergible cages. We harnessed ocean reanalysis products to enhance our understanding of ocean warming and marine heatwaves in key fish farming areas in the Western Mediterranean, focusing on fish welfare thermal thresholds that inform mitigation measures. Our analyses revealed a consistent temperature increase across depths and farms over four decades, notably peaking at 0.75 °C per decade in some areas. Marine heatwaves have become three times more frequent, with nearly 50% longer durations on average compared to the 1980s. This included the most severe event experienced in 2022, with anomalies up to 4.2 °C lasting the entire summer. Fish welfare thermal thresholds exceeded the average depth of pen net systems and increased by 4.3 m per decade. Moreover, the seasonal onset of thermal thresholds shifted 5 to 6 days earlier per decade. To secure optimal conditions for seabream and seabass, net pens should be submerged to depths of around 20 m and 15 m, respectively, ideally in the second week of July. However, in shallow areas, this may not be feasible. Our findings raise concerns about the well-being of Mediterranean farmed fish, which, although adapted to current conditions, may struggle to thrive under recent and projected environmental changes. Addressing these challenges, a multi-faceted adaptative approach encompassing research, technological innovation, regulatory measures, and industry collaboration.

1. Introduction

Human-induced climate change is reshaping coastal environments across all oceans, affecting sea temperatures, dissolved oxygen, ocean currents, sea levels, acidification, and extreme events (IPCC, 2022). Ocean warming is particularly concerning, as temperature is the primary environmental factor influencing marine life, driving metabolic rates, enzyme activities, growth, reproduction, and respiration (Pham et al., 2021; Rosa et al., 2012), which poses severe challenges for sectors reliant on natural ecosystems, such as marine aquaculture (Callaway et al., 2012; Mugwanya et al., 2022). Marine environments have warmed by 0.88 °C from preindustrial times (1850–1900) to 2011–2020, with 'worst-case' scenarios predicting a 4 °C increase by the end of the century (IPCC, 2021). The Mediterranean's limited water exchange with cooler oceanic waters is exceptionally vulnerable. While global oceans warmed by 0.11 °C per decade in the last 50 years, the Mediterranean heated at 0.61 °C (Belkin, 2009; Olivier, 2002; Sakallı, 2017). In addition to gradual warming, marine heatwaves (MHWs) are abrupt and extreme spikes in sea surface temperatures that can have even more immediate and severe consequences on ecosystem services and human activities, such as coastal aquaculture. MHWs have doubled frequency since the 1980s and are expected to increase globally (IPCC, 2021). They have also been linked to an increased probability of extreme weather events like cyclones and heavy rainfall (Choi et al., 2024). Understanding these changes is crucial for adapting aquaculture practices to ensure the sustainability and resilience of the industry in the face of climate change.

Gilthead seabream (*Sparus auratus*) and European seabass (*Dicentrarchus labrax*) are central to Mediterranean aquaculture, significantly contributing to global farmed fish production (FAO, 2022). These fish are typically raised in open pen net systems across the Mediterranean, with pens often reaching depths of 20 m and in areas where water depths are at least 40 to 50 m. Consequently, farmed fish are exposed to pronounced temperature fluctuations within the generally shallow (<30 m)

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https://doi.org/10.1016/j.aquaculture.2024.740917
Received 16 November 2023; Received in revised form 14 March 2024; Accepted 3 April 2024

mixing layer (Bahamon et al., 2020), preventing them from finding thermal refuge in the more stable temperatures below the seasonal thermocline. Managing temperature fluctuations poses a significant challenge for farmers, as temperatures beyond optimal thresholds significantly impact fish feeding behaviour, growth, and stress and create a favourable environment for transmitting diseases and parasites (Cascarano et al., 2021; Rosa et al., 2012). Prolonged exposure to such high temperatures can result in exhaustion and mortality. Welfare thresholds of 25 °C and 26 °C have been proposed for seabream and seabass, respectively (Cascarano et al., 2021). Several management strategies, including submerging cages in deeper and cooler waters, have been suggested to mitigate warming effects. Submerging pen nets offer various benefits for farmed species, including protection from storms, algal and jellyfish blooms, parasite outbreaks, reduced oxygen, and biofouling (Sievers et al., 2022). While experimental trials have shown promise in the benefits of these new technologies for seabream and seabass (Maricchiolo et al., 2011), there is a need for quantitative assessments of their operational viability concerning trends in seawater temperatures and welfare and health thresholds for commonly farmed species in the Mediterranean. For example, a better understanding of the seasonal onset of welfare thresholds and changes in the depth of these isotherms can effectively inform mitigation measures such as submerging net pens. With rising sea surface temperatures and frequent marine heatwaves (MHWs) in the Mediterranean, exploring mitigation options for the region's aquaculture industry is vital to fostering sustainable blue economies (Soto et al., 2019).

In this study, we leverage ocean reanalysis products to assess ocean warming and the intensity of MHWs along the Spanish coast in the Western Mediterranean, where most Spanish fish aquaculture occurs. We focus on changes in the thermal welfare thresholds for two iconic species: the gilthead sea bream and the Mediterranean seabass. The specific objectives are as follows: 1) characterise seasonal and long-term temporal trends in seawater temperature along a latitudinal gradient in a fish farming region in the Western Mediterranean, 2) assess the trends in the intensity and duration of MHW events, 3) characterise vertical temperature profiles during the most extreme MHW event to date, with a focus on the depth of isotherms representing health and welfare thresholds for the main farmed species, and 4) evaluate long-term changes in the depth and seasonal onset of thermal thresholds to determine the feasibility of submerging farm cages to prevent temperatures from exceeding them.

2. Methods

2.1. Study region

The study area in the Western Mediterranean Sea (Spanish coast) was delimited between latitudes 37.2 and 38.65°N and longitudes 1.65°W and 0.2°E (Fig. 1). This area encompasses the Region of Murcia and the southern part of the Valencian Community, supporting the most significant proportion of finfish aquaculture in Spain (APROMAR, 2021). This area is characterised by aridity, torrential rainfall, pronounced summer drought, high evapotranspiration rates and insolation (Gil-Guirado and Pérez-Morales, 2019; Ruiz Álvarez et al., 2014). In the oceanographic context, a significant division is caused by the separation between the north and south of Cabo de Palos, which lies in a zone of divergence between oceanic currents. The Alboran current predominates in the south, while the Ligurian-Provençal current dominates in the north. Furthermore, there is a pronounced difference in bathymetry between the coast to the south and north of Cabo de Palos. The southern part exhibits a steep bathymetric profile, while the northern part features a broad and shallower continental shelf (Fig. 1). The fish farms in the area consist of groups of 10 to 20 floating circular net pens, reaching 20 m depth, located within a few hundred meters from the coastline, which is stocked with Mediterranean seabass (*Dicentrarchus labrax*), Gilthead Seabream (*Sparus aurata*) and meagre (*Argyrosomus regius*). Fish farms relatively close to each other were considered as one area (i.e. farm area A, Fig. 1). The buffer areas around the farms were used to crop the ocean reanalysis products to assess trends at the farm level, ensuring a robust spatial representation by incorporating multiple temperature data pixels. Seven fish farm areas, designated by letters from A to G, were identified as a result of this process, with 4, 2, 3, 5, 8, 2, 2, and 2 pixels, respectively (Fig. 1).

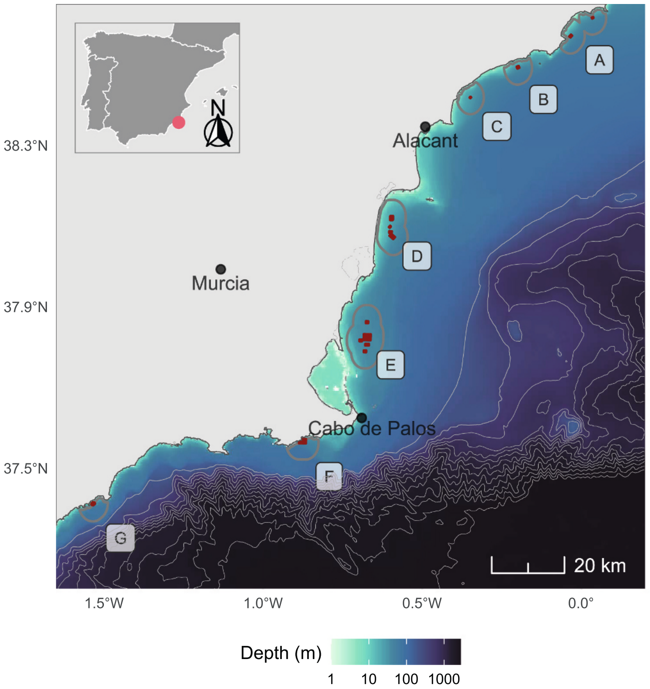

Fig. 1. The inset shows a map of the study area in the Western Mediterranean in relation to the Iberian Peninsula. Seven fish farm areas are designated with letters from A to G, arranged from North to South. The red squares denote the fish farm net pens, while the grey areas represent a 200 m buffer around the farms, from which temperature data was obtained. The white lines represent depth contours. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

2.2. Data acquisition

We obtained temperature data from the EU Copernicus Marine Service platform (https://marine.copernicus.eu/), which provides accessible, regular, and authoritative global and regional information on the physical and biogeochemical aspects of our oceans (Le Traon et al., 2019). Specifically, we acquired daily vertical profile data (0–40 m) of temperature from the Mediterranean Sea Physics Reanalyses (Escudier et al., 2021) from the *med-cmcc-tem-rean-d* dataset of the MEDSEA_MULTIYEAR_PHY_006_004 product (https://doi.org/10.25423/CMCC/MEDSEA_MULTIYEAR_PHY_006_004_E3R1), spanning from 1987 to 2020. For the period 2020–2023, we used the daily dataset cmems_mod_med_phy-tem_anfc_4.2km_P1D-m dataset from product MEDSEA_ANALYSISFORECAST_PHY_006_013-TDS (https://doi.org/10.25423/CMCC/MEDSEA_ANALYSISFORECAST_PHY_006_013_EAS7). In the daily dataset, the fields represent averages spanning 24 h, with the data centred at midday. These datasets have a spatial resolution of 0.042° × 0.042° (ca. 4 km) and provide temperature values at up to 141 unevenly spaced depths. We obtained multilevel data from these two products because no single product spans the complete long-term time series for the study area. Although there is some overlap between the two products (i.e., in 2020), we did not merge them due to discrepancies that introduced noise in the time series. Thus, the period from 1987 to 2020 was used to characterise the long-term trends in seawater temperature at different depth strata, while the most recent product was used to describe the vertical distribution of the 2022 Marine Heatwave (MHW).

Additionally, high-resolution (0.05° × 0.05°) long-term (1981–2022) sea surface temperature data was obtained from cmems_SST_MED_SST_L4_REP_OBSERVATIONS_010_021 (https://doi.org/10.48670/moi-00173) and used for the MHW analysis. We chose this product over the multilevel data as it spans the whole time series in one product and allows us to assess the long-term trend in MHW events. These are L4-level data products from Marine Copernicus, which refer to the fourth level of processing and analysis applied to oceanographic data. These products are derived from satellite observations and provide higher-level information about the marine environment. At the L4 level of processing, the raw satellite data undergoes advanced algorithms and models to derive meaningful information. This includes data calibration, quality control, interpolation, and merging multiple data sources to generate comprehensive and accurate data products. Previous validation of the Mediterranean temperature products against in-situ and satellite observations indicated an average difference of 0.65 °C (Escudier et al., 2021).

2.3. Data analyses

All analyses were conducted using the software R version 4.3.0 (R Core Team, 2023). The gridded data was extracted and downloaded from the Motu web server using the Python library *motuclient* (https://pypi.org/project/motuclient/) accessed through RStudio (Posit, 2023) using the *reticulate* library (Ushey et al., 2023). The downloaded NetCDF files were read, processed, and spatiotemporally analysed using the R libraries *stars* (Pebesma and Bivand, 2023) and *sf* (Pebesma, 2018). Data wrangling and visualisation were conducted within the *tidyverse* library (Wickham et al., 2019). To characterise seasonal and long-term temporal trends in seawater temperature in the area, monthly average temperatures for each farm at four depths (0, 10, 20 and 30 m) were represented as time series using the *timetk* library (Dancho and Vaughan, 2023). Decomposition models were individually fitted to each farm area time series using the interquartile range method to deseasonalise the data and identify long-term trends. Annual trends in changes in sea temperature during the warmest month of the year (i.e. August) were assessed for each cell in the study area at four strata (surface, 10, 20 and 30 m) using the Sen slope method (Sen, 1968) as implemented in the R library *trend* (Pohlert, 2013). This analysis calculates the median slope (i.e., the linear rate of change) and corresponding confidence levels. The statistical significance of the estimated slopes was assessed through Mann-Kendall tests conducted using the *mk.test* function. Marine heatwaves (MHWs) were detected using the *heatwaveR* library (Schlegel and Smit, 2018) based on the MHW definition proposed by Hobday et al. (2016a). MHWs are characterised as prolonged anomalous warm events lasting over five consecutive days, with sea surface temperature (SST) surpassing a specific threshold. This threshold is derived from a fixed daily climatological baseline, identifying elevated SST values above the 90th percentile of daily variability. Consecutive events within a 3-day interval are considered as a single event. The climatological baseline was established using 30 years (1981–2011) to facilitate a seasonally varying threshold, accommodating MHW occurrences throughout the year. Four key heatwave metrics were evaluated: MHW duration, capturing the duration between event start and end dates, which can exceed a year; MHW mean intensity, representing the mean SST anomaly in degrees Celsius during an event; MHW frequency, quantifying the number of events within a given season or year; and the mean cumulative intensity per event, defined as the product of the mean intensity and the event's duration in days (°C x days). The most intense MHW detected during the study period, summer 2022, was further characterised at each farming area using vertical temperature profiles to identify the depth of the 25 °C and 26 °C isotherms representing health and welfare thresholds for farmed seabream and seabass (Cascarano et al., 2021). In addition, we assessed long-term changes in the annual maximum depth of the 25 °C and 26 °C isotherms at each farm between 1981 and 2020. We also assessed long-term changes in the seasonal onset of the isotherms by analysing the trends in the first Julian day when the isotherms reached their maximum depth each year throughout the time series. Trends in maximum isotherm depths and season onset were assessed using Sen slopes and tested using Mann-Kendall tests as described above.

3. Results

3.1. Long-term and seasonal temperature trends

The seasonally detrended time series data indicate a consistent and gradual rise in average temperatures across all depths and locations over the past four decades (Fig. 2a to 2d). Starting in 2010, there was a pronounced and abrupt temperature surge, culminating in a prominent peak in 2016. The southernmost farm location (G) displayed substantially higher temperatures than the other farm locations, particularly at a depth of 20 m (Fig. 2c). Furthermore, the four northernmost locations stood out with remarkably elevated surface temperatures (Fig. 2a). As expected, seasonality was more evident at the surface (Fig. 2e), exhibiting larger fluctuations than in deeper waters with more stable conditions (Fig. 2g and h). The seasonal variation ranged between a minimum of around 12.5 °C, consistently recorded in February across depths, and maximum temperatures in August showed a decreasing trend with depth (Fig. 2e to 2h). At the surface, the maximum temperature reached 28.8 °C (Fig. 2e), while at a depth of 30 m (Fig. 2h), it decreased to 25.8 °C. Although no distinct latitudinal patterns existed in the seasonal temperatures, the highest temperatures were observed in the southernmost location, especially at greater depths (Fig. 2h).

3.2. Spatial trends in temperature changes by depth

The analyses of annual trends in August temperatures unveiled distinctive spatial patterns of the rate of warming (Sen's slope) by depth strata (Fig. 3). At the surface, the warming rate was more consistent across the region, with a tendency to decrease with distance from the coast. Notably, the coastal areas north of Cabo de Palos, where most farms are situated, exhibited the most significant temperature increases. Over the period from 1981 to 2021, these regions experienced a substantial warming rate of up to 0.75 °C per decade (Fig. 3). Warming trends were particularly pronounced at the 20 m and 30 m in farms located North of Cabo de Palos. The decadal warming rate experienced by the farms ranged between 0.50 °C (± 0.15 S.D.) at farm E to a minimum of 0.27 °C (± 0.08 S.D.) at the northernmost farm (i.e., farm A). The warming rate experienced by farms was highest at 20 m (0.53 °C, ±0.13 S.D.) and 10 m (0.40 °C, ±0.12 S.D.) and lowest at the surface (0.25 °C, ±0.05 S.D.).

3.3. Marine heatwaves

The analysis of MHWs experienced by farms reveals significant trends over the past decades (Fig. 4). Although the mean intensity per event was relatively constant across the period, averaging 1.67 °C (range: 0.8–2.91 °C), the yearly frequency and the average duration per event substantially increased over time. This pattern translated into an overall increase in the mean cumulative intensity per event (Fig. 4). In the 1980s, there were, on average, 10.2 MHW events per year, with an average cumulative intensity of 23.9 °C x days and a duration of 13.5 days. The maximum duration observed during this decade was 42 days during an event at farm A that peaked in October 1985. Moving into the 1990s, the average number of events increased to 14.2 per year, although with a slightly lower cumulative intensity of 14.8 °C x days and shorter duration (9.8 days). The maximum duration recorded during this period was a 33-day event at farm D. The 2000s saw a further increase in events, averaging 16.1 per year. These events had a mean cumulative

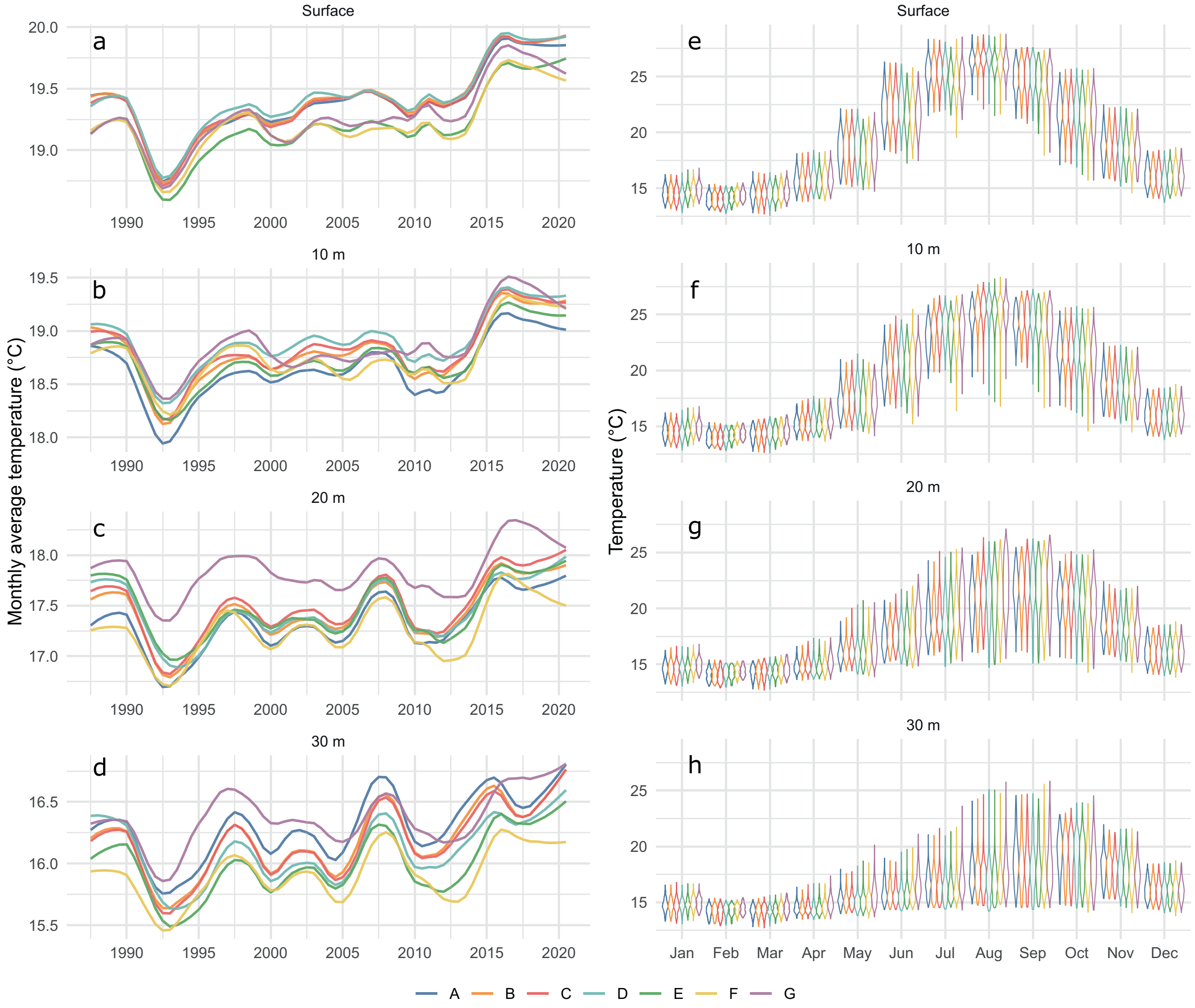

Fig. 2. Seasonally detrended yearly average temperature (a, b, c, and d) and violin plots of monthly water temperature (e, f, g, and h) at the surface 10 m, 20 m, and 30 m depth at each fish farming area (A - G) in the study area in the Western Mediterranean. Trends are based on ocean reanalysis products from the EU Copernicus Marine Service platform.

intensity of 18.5 °C x days and an average duration of 10.8 days. The maximum duration observed during this decade was 40 days experienced by farm B (Fig. 4B). The following decade (2010s) experienced a substantial rise in the number of events, with an average of 32.1 per year, and the mean cumulative intensity per event reached 26.0 °C x days. The mean duration was longer during this period, with an average of 21.2 days and a maximum of 78 days experienced by farm A. In the most recent decade, the 2020s, the average number of marine heatwave events per year remained high, with approximately 31.3 events. These events were characterised by a high mean cumulative intensity per event (41.2 °C x days), a mean intensity of 1.60 °C, and a substantially longer average duration of 19.6 days. The maximum duration observed during this decade was a remarkable 87 days recorded between 04 July and 28 September at farm F, implying that temperature was over the historic 90th percentile for most of the summer.

The MHW events recorded during the summer of 2022 represent the most intense events ever recorded in the region and were further analysed by inspecting the vertical profiles during the summer for each farm (Fig. 5). The mean duration of these events across farms was 76.6 days, with a mean intensity of 2.4 °C and maximums of up to 4.2 °C, translating into temperatures over 29 °C recorded in mid-August at farms D and E (Fig. 5). The vertical profiles revealed that the 25 °C isotherm, considered the welfare thermal threshold for seabream, reached an average depth of 13.3 m and a maximum of 26.4 m. In contrast, the 26 °C isotherm, considered the welfare thermal threshold for seabass, reached an average depth of 11.3 m and a maximum of 19.9 m (Fig. 5).

The maximum depth of the 25 °C and 26 °C isotherm across farms was 20.2 m (± 9.7 S.D.) and 14.2 m (± 9.6 S.D.), respectively (Fig. 6A). There was a latitudinal gradient in the maximum depth of the 25 °C isotherm, being shallower in the northern farms (16.5 m ± 5.1 at farm A) and deeper in the southern farms (23.4 ± 7.3 m at farm G). There were no significant long-term trends in the maximum depth of the 25 °C isotherm ($p > 0.05$, Fig. 6A), except G, which significantly increased on average by 3.0 m per decade ($p < 0.05$, Fig. 6A). In contrast, there was a long-term increase in the maximum of the 26 °C isotherm for all farms, increasing up to 5.2 m in farm G ($p < 0.05$, Fig. 6A). However, this trend was not significant for farms A, D and F ($p > 0.05$, Fig. 6A).

The time series of fish welfare thresholds revealed a significant decline in the seasonal onset of both thermal thresholds across farms,

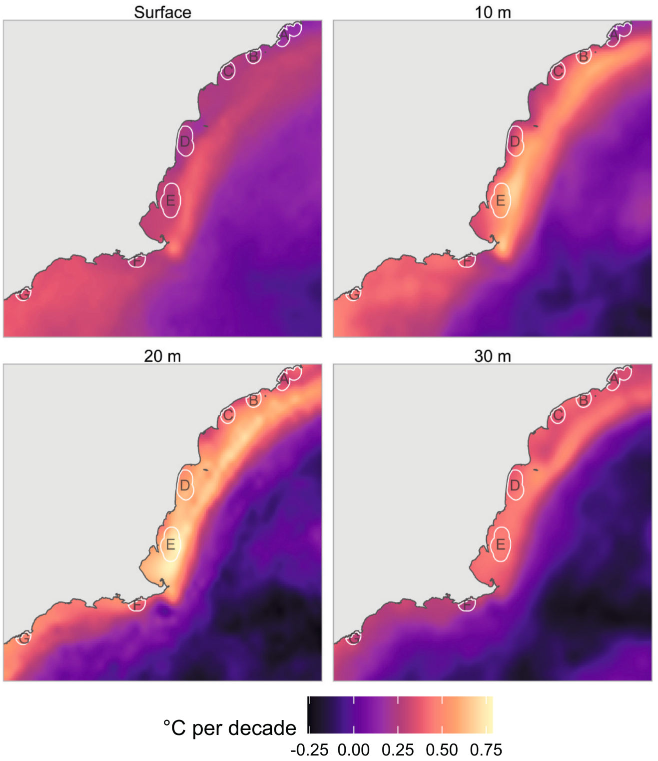

Fig. 3. Decadal temperature trend based on Sen's slopes of August average sea temperatures at the surface, 10 m, 20 m and 30 m depths for the study region in the Western Mediterranean for 1987–2020 based on ocean reanalysis products data obtained from the EU Copernicus Marine Service platform. The grey areas represent a 200 m buffer around fish farms.

except for the 26 °C threshold at farm F (Fig. 6B). On average, the onset of the 25 °C and 26 °C isotherm was on day 192 (July 11th) and day 204 (July 23rd), respectively (Fig. 6B). The onset was approximately a week earlier on the northern farms than on the southernmost farms. The seasonal onset declined by 6.2 days per decade (±1 S·D) for the 25 °C threshold and by 5.4 days per decade (±1 S·D) for the 26 °C threshold (Fig. 6B). The three southernmost farms recorded the most rapid declines in the seasonal onset of the 25 °C isotherm, up to seven days earlier per decade (Fig. 6B). For the 26 °C threshold, farms C and D experienced faster changes, with onset 6.8 and 6.4 days earlier per decade, respectively (Fig. 6B).

4. Discussion

Our results showed a consistent and gradual rise in average temperatures across all depths and farm locations over the past four decades. There was significant variability in relation to oceanographic and oceanic conditions; notably, farms to the north of Cabo de Palos have experienced substantial temperature increases. These increases are estimated to be as high as 0.75 °C per decade, which aligns with or exceeds the findings of previous studies on surface waters in the Mediterranean (Belkin, 2009; Darmaraki et al., 2019; Olivier, 2002; Pisano et al., 2020; Sakallı, 2017). Interestingly, our study revealed that this trend was more pronounced at a depth of 20 m than at the surface and deeper levels. This may be attributed to the disconnection from air-sea exchanges, which help retain heat content long-term and are aided by low-frequency variability, especially in the absence of strong mixing (Darmaraki et al., 2019). This warming has been accompanied by a significant increase in the duration and intensity of MHWs across farm locations. On average, MHWs have become three times more frequent and have lasted 50% longer in recent years (i.e. 2000s) compared to the 1980s. These findings are consistent with earlier studies highlighting similar trends in the Mediterranean region (Ciappa, 2022; Darmaraki et al., 2019; Martínez et al., 2023). Based on these studies and our own results, it is evident that the historical warming trend contributes to an increase in both the frequency and intensity of these events, which is particularly noticeable when analysing the data for MHWs after detrending (Ciappa, 2022; Martínez et al., 2023). Moreover, we described the most intense MHW recorded to date experienced during the entire 2022 summer, which produced anomalies up to 4 °C, which greatly exceeded previous MHWs detected in this and previous studies (Ciappa, 2022; Darmaraki et al., 2019; Martínez et al., 2023). The thermal thresholds for fish welfare of the most farmed species in the region consistently exceeded the average depth of the pen net systems (i.e., 20 m). These thresholds often extended to depths of up to 40 m. We observed an increase in the maximum depth of the welfare isotherm, especially at the southernmost farms, where it expanded by 4.3 m per decade. Additionally, there was a significant decline in the seasonal onset, occurring on average 5 to 6 days earlier per decade. These findings underscore the potential challenges faced by the most farmed fish

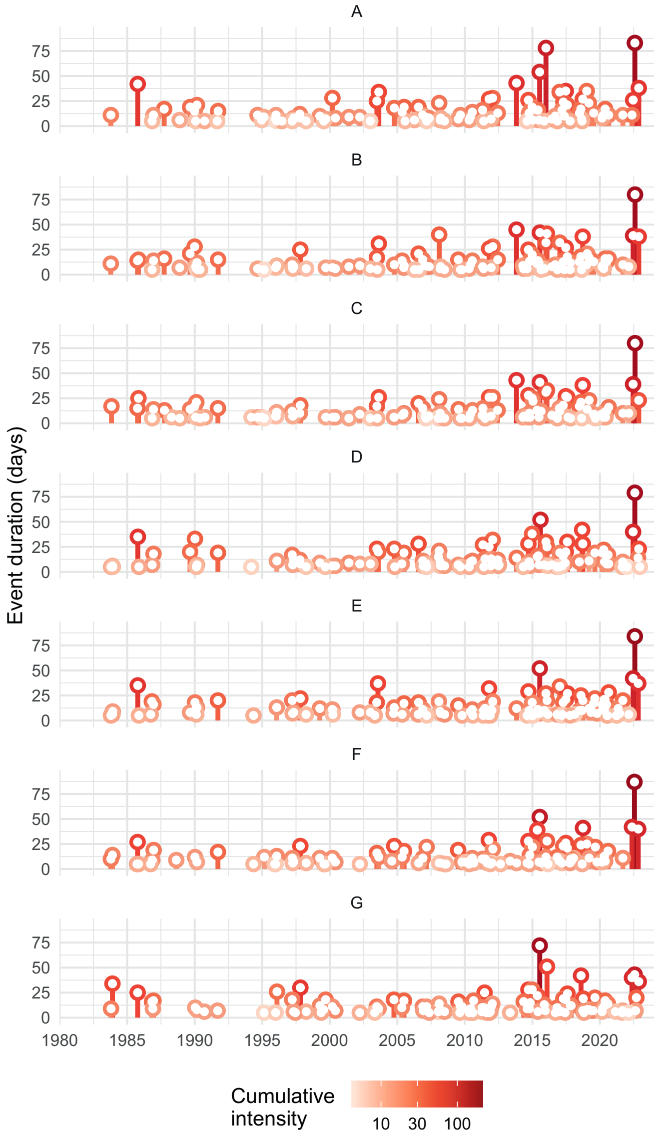

Fig. 4. Duration, in days, of marine heatwaves (MHWs) observed at each fish farm area (A - G) from 1983 to 2022. The colour scale represents the cumulative intensity of each MHW event. MHW is based on the definition proposed by Hobday et al. (2016a) and calculated using ocean reanalysis products from the EU Copernicus Marine Service platform.

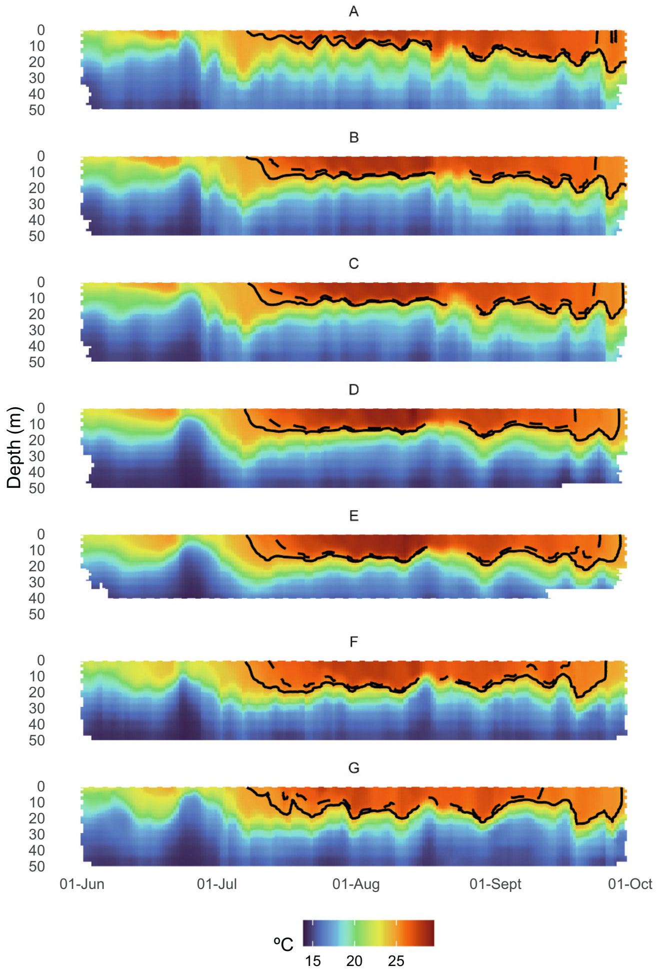

Fig. 5. Vertical sea temperature profiles for each fish farm area (A – G) in the study region in the Western Mediterranean during the marine heatwave recorded in the summer of 2022. The dashed and solid lines represent the 25 °C and 26 °C isotherms, respectively.

species in the Mediterranean, namely seabream and seabass. These species have adapted to current conditions but may not thrive under the conditions experienced in recent years and those projected for the future (Stavrakidis-Zachou et al., 2022). While forecasting was outside the scope of our study, multiple studies have projected a consistent rise in the frequency, intensity and duration of MHWs globally and in our study region (Hobday et al., 2016b; Spillman and Hobday, 2014; Spillman et al., 2021), aligning with the historical trends detected by our study. Seasonal and long-term forecasts are readily available online, such as those provided by the European Centre for Medium-Range Weather Forecasts (https://www.ecmwf.int/en/forecasts). The aquaculture and fishing industry are already using decision support tools that integrate seasonal forecasts (e.g. de Burgh-Day et al., 2022; Hobday et al., 2016b). These approaches could prove crucial for the industry's adaptation to climate change by helping farmer adapt their activities and mitigate the risk of adverse conditions.

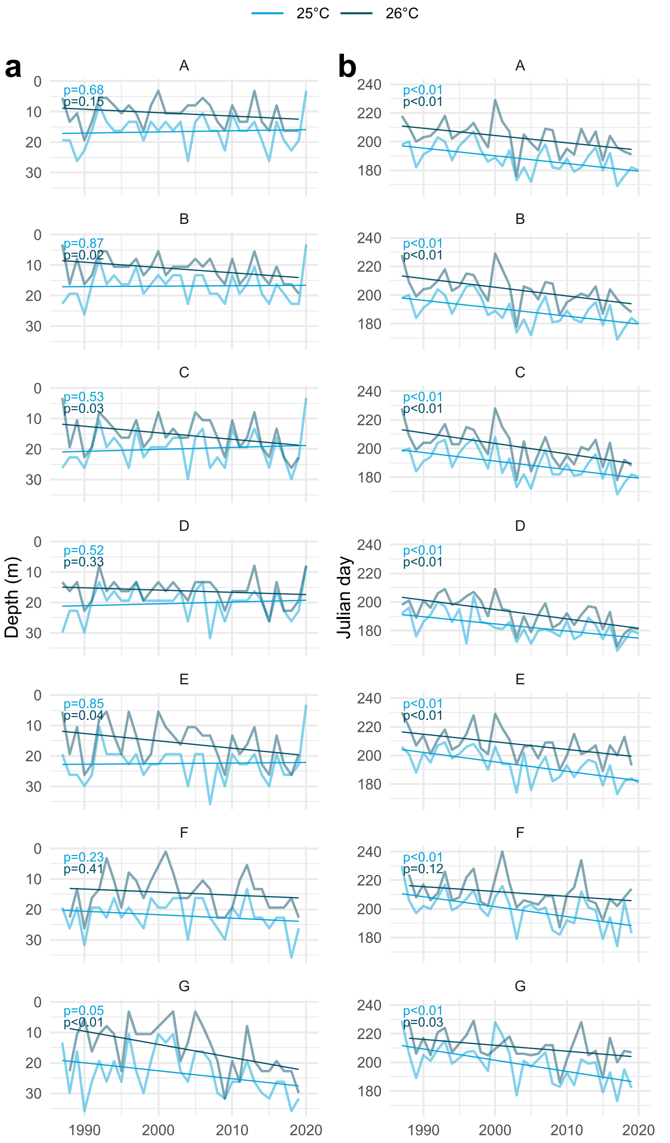

Fig. 6. Depth in meters (a) and Julian day for the seasonal onset (b) of the 25 and 26 °C isotherm at each fish farm area (A - G) in the study region in the Western Mediterranean between 1987 and 2021 based on ocean reanalysis products obtained from the EU Copernicus Marine Service platform.

Our findings highlight significant local-scale variability in climate risk, impacting aquaculture sites in distinct ways. This variability becomes particularly apparent when considering notable shifts in coastal morphology, as exemplified in Cabo de Palos. The variations in water temperature patterns we have elucidated are primarily driven by geographical factors, including bathymetry and oceanographic components, notably mesoscale thermohaline currents (López Mengual et al., 2021). For instance, the warming of ocean surface temperatures was particularly noticeable in farms in shallow areas north of Cabo de Palos. In contrast, the increase in the maximum depth of the welfare thresholds was more pronounced on farms located in the deeper southern areas of Cabo de Palos. Cabo de Palos is a region characterised by the divergence of ocean currents, with the Alboran current dominating to the south and the Ligurian-Provencal current to the north. These shifts originate from thermohaline processes and exhibit seasonal variability influenced by westerly or easterly winds, which affect the currents and the water masses they transport (Gutiérrez Ortega et al., 2009). Furthermore, there is a drastic difference in bathymetry between the north and south of Cabo de Palos. An extensive shallow continental platform characterises the former, while the latter features a steep shelf with abrupt changes in depth of over 1000 m (Fig. 1). For example, the formation of internal waves can propagate away and break elsewhere, resulting in further vertical mixing. This is important because it may reduce vertical thermal stratification, and vertical mixing is affected by bathymetry in coastal areas (Valle-Levinson and Wilson, 1994). Despite climate change manifesting through various oceanographic patterns and processes at the examined scale, it ultimately implies that warming oceans are significantly reducing suitable farming areas in the region.

Understanding the significance of regional mesoscale oceanographic and bathymetric conditions is paramount when assessing the far-reaching impacts of ocean warming and MHWs on coastal ecosystems and aquaculture sites.

Since fish are ectothermic, meaning their internal body temperature varies with the surrounding environment, temperature plays a crucial role in regulating their metabolism. This, in turn, influences physiological functions like breathing, digestion, reproduction, and feeding. Additionally, fish exhibit specific thermal preferences, encompassing lower and upper tolerance limits and optimal temperatures for growth. Essentially, each species has its comfort zone, which could be affected by the above-described thermal instability, affecting aquaculture productivity (Rosa et al., 2012). During the 2022 Marine Heatwave (MHW), recorded temperatures soared from over 25 °C to a peak of 29 °C for several weeks, most likely causing severe thermal stress on seabream and seabass (Pörtner and Knust, 2007). This stress triggers a transition from aerobic to anaerobic metabolism (Madeira et al., 2013) and activates protective mechanisms such as heat shock proteins (Iwama et al., 1998). Additionally, considering the impact of rising temperatures and MHWs, as evidenced by our study, on the prevalence and emergence of pathogens and parasites is crucial. In their comprehensive review, Cascarano et al. (2021) examined the potential consequences of temperature increases on prevalent diseases affecting gilthead seabream and European seabass, including those caused by *Vibrio* spp., *Photobacterium damselae* and *Tenacibaculum maritimum*. While most pathogens may adapt or expand their geographical ranges due to higher temperatures, farmed fish species are less tolerant and cannot move, with gilthead seabream exhibiting lower thermal resilience than European seabass. When farmed fish are thermally stressed, they become immunocompromised and more susceptible to disease (Scharsack and Franke, 2022). Furthermore, elevated temperatures can foster the proliferation of parasites, such as *Sparicotyle chrysophrii* (Monogenea: Polyopisthocotylea), which poses a significant threat to fish aquaculture in Mediterranean cages, especially gilthead seabream (Mladineo et al., 2021). This parasite leads to substantial mortality rates, resulting in considerable economic losses for aquaculture companies and necessitating the use of highly toxic substances like formaldehyde for treatment (Toksen et al., 2010). In rapidly increasing sea temperatures, pathogens, particularly viruses and bacteria, gain a competitive advantage over their vertebrate hosts. Their genomic and metabolic adaptability allows them to swiftly acclimate to new environmental conditions, potentially giving rise to more severe epizootic outbreaks (Cascarano et al., 2021). Thus, under current and future environmental conditions, disease management and implementation of stringent biosecurity measures will become increasingly crucial for future-proofing the industry.

Climate change adaptation involves adjusting to current or anticipated climate conditions and their impacts. This involves modifying processes, practices, and structures to reduce potential harm or take advantage of opportunities resulting from climate change (Galappaththi et al., 2020; Soto et al., 2019). With recent increases in sea surface temperatures and the rising frequency of extreme weather events in the Mediterranean (Belkin, 2009; Darmaraki et al., 2019; Olivier, 2002; Sakallı, 2017), exploring adaptation and mitigation options for Mediterranean finfish aquaculture is becoming increasingly important to promote sustainable blue economies. One promising avenue that holds great potential is the use of submerged cages (Sievers et al., 2022). These innovative structures offer an appealing alternative by mitigating the risks associated with extreme weather conditions, thereby fortifying the industry's resilience. With their ability to provide thermal stability, elevate fish survival rates, and minimise environmental repercussions, submerged cages emerge as a compelling solution to address the ongoing challenges of climate change in marine aquaculture. For example, our quantitative assessment of the depth and seasonal onset of welfare thresholds indicates that it would be necessary to submerge net pens to a depth of approximately 20 m and 15 m to avoid unfavourable conditions for seabream and seabass, respectively. Our seasonal onset estimations indicate that this management practice should be implemented in the second week of July; however, at current warming rates, this could occur as early as the first week of June by mid-century. Nevertheless, the feasibility of submerging cages in relatively shallow areas, such as those north of Cabo de Palos, is limited due to the estimated depth of the isotherm reaching near the seabed, rendering this option impossible. In this context, it is crucial to consider this management option in conjunction with adequate spatial planning (Dempster and Sanchez-Jerez, 2008), especially when developing offshore sites where deeper water does not pose a constraint for submersible cages.

Optimal spatial planning and site selection for aquaculture facilities involves a delicate trade-off. It entails locating areas conducive to optimal fish growth, such as those with good water quality, adequate flow, and sufficient depth, while simultaneously minimising potential impacts on vulnerable marine ecosystems and conflicts with other coastal users (Sanchez-Jerez et al., 2016). Given the context of ocean warming, stable environmental conditions and reduced susceptibility to extreme weather events become imperative. The EU Directive 2014/89/EU mandates that member states conduct maritime spatial planning. This is a crucial factor to be integrated into the planning process to ensure the effective management of maritime activities, including aquaculture, and the sustainable utilisation of coastal and marine resources. It establishes a framework for informed and transparent decision-making considering climate change risks. One potential avenue currently being exploited is offshore aquaculture, which provides a mitigation solution for the more extreme summer temperatures experienced in inshore areas (López Mengual et al., 2021). Fish farms are already moving to offshore waters as inshore temperatures are no longer suitable for farming cold-water species in many world regions (Broekhuizen et al., 2021; Daalder, 2022; Rosa et al., 2012). However, offshore aquaculture in exposed areas introduces new operational and logistics challenges (Galparsoro et al., 2020). Thus, careful consideration of site selection, sustainable planning, and the exploration of innovative approaches like offshore aquaculture are essential steps towards adapting to ocean warming and ensuring the long-term viability of marine aquaculture.

Diversifying farmed species can also help tackle warming and animal welfare challenges. Some Mediterranean species, like meagre (*Argyrosomus regius*), thrive at temperatures up to 29 °C and can withstand up to 34 °C (Stavrakidis-Zachou et al., 2021). Another emergent species in the region with greater temperature tolerance and faster growth than seabass and seabream is the greater amberjack *Seriola dumerili* (Navarro-Guillén et al., 2022). Our study revealed that these species are better suited to current and projected warming and extreme MHWs. Moreover, warming waters offer opportunities for farming new, warmer water species (Callaway et al., 2012). However, caution is vital due to the potential impacts of introducing non-native species for farming. Another mitigation option is developing strains of fish that are better adapted to local conditions, including higher water temperatures, which can enhance aquaculture resilience. Selective breeding programs can help create more robust stocks (Soto et al., 2019). Currently, most European aquaculture production originates from various selective breeding programmes that perform family selection (Janssen et al., 2017), and these are expected to shift from growth performance to thermal tolerance. The move to land-based recirculation aquaculture systems (RAS) represents another potential avenue in the aquaculture industry to mitigate the impacts of climate change. RAS offer several advantages, including water efficiency, reduced environmental impact, and precise control over environmental conditions. However, they come with challenges, such as high initial investment costs and the need for technical expertise. In addition to RAS, another alternative involves harnessing technological advancements like mobile aquaculture, which has been proposed to enhance resilience against ocean warming (Yu et al., 2023). This system, designed for mobility, enables precise control of water conditions to optimise fish growth, including avoiding temperature extremes. While several promising technological and scientific advancements are available to address the challenges of climate change and ocean warming in aquaculture, it is essential to note that many of these solutions are still in development and necessitate substantial investments in research and development.

Climate change poses a significant challenge to the marine aquaculture industry (Klinger et al., 2017; Mugwanya et al., 2022; Rosa et al., 2012). Extreme events triggered by climate change, including ocean warming and MHWs, harm fish health, welfare, and farming practices (Callaway et al., 2012; Rosa et al., 2012). These events can amplify the adverse impacts of multiple stressors, leading to intensified consequences (Sánchez-Jerez et al., 2022; Sarà et al., 2022). Considering this precarious backdrop, it becomes imperative to devise adaptive measures to ensure the viability and sustainability of marine aquaculture while judiciously identifying suitable areas for fish farming that account for present conditions and future scenarios (Soto et al., 2019). Therefore, the convergence of adverse factors, comprising limited space resources, environmental degradation, high aquaculture density, and recurrent disease outbreaks, has imposed substantial limitations on nearshore aquaculture. These challenges are compounded by the influence of climate change, as emphasised by the results of this study, revealing a decreasing availability of suitable conditions for fish farming. Addressing the challenges posed by increasing sea surface temperatures and extreme weather events in the Mediterranean demands a multi-faceted approach. This approach should encompass scientific research, technological innovation, regulatory measures, and industry collaboration. Sustainable finfish aquaculture practices play a pivotal role in safeguarding the environment and ensuring the long-term viability of the region's blue economy and global food security. Adaptation plans are being developed at national and European levels to tackle climate change in marine aquaculture. These planned activities hold significant potential to contribute to the success of the United Nations' Sustainable Development Goals (SDGs), particularly SDG 13 (Combat climate change and its impacts urgently) and SDG 14 (Sustainably use and conserve oceans, seas, and marine resources for development). Our findings provide valuable quantitative data for climate change adaptation measures and risk assessment models. This data aids in the strategic spatial planning of coastal environments. Additionally, real-time ocean monitoring can be the foundation for a valuable early warning system. In this regard, we have demonstrated that leveraging ocean reanalysis products provided by the Copernicus EU platform can play a crucial role in promoting the sustainable management of marine farms within aquaculture.

CRediT authorship contribution statement

Javier Atalah: Funding acquisition, Formal analysis, Data curation, Conceptualization, Investigation, Methodology, Software, Validation, Visualization, Writing – original draft, Writing – review & editing. **Sofia Ibañez:** Formal analysis, Writing – original draft, Writing – review & editing. **Laura Aixalà:** Conceptualization, Formal analysis, Writing – original draft. **Xavier Barber:** Conceptualization, Funding acquisition, Investigation, Methodology, Project administration, Writing – original draft, Writing – review & editing. **Pablo Sánchez-Jerez:** Methodology, Project administration, Supervision, Writing – original draft, Writing – review & editing, Conceptualization, Formal analysis, Funding acquisition, Investigation.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data and code used for the analyses are available at https://github.com/jatalah/MODESTA

Acknowledgements

Research reported in this publication was supported by a Maria Zambrano Grant awarded to JA, financed by the Spanish Government through the European Union NextGenerationEU fund. This study forms part of the ThinkInAzul programme (https://thinkinazul.es/) and it was supported by MCIN with funding from the European Union NextGenerationEU (PRTR-C17·I1) and Generalitat Valenciana (THINKINAZUL/2021/044-TOWARDS and THINKINAZUL/2021/021-MODESTA).

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