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Effect of climate change on the spawning season of the main harvested bivalves in Galician rias.

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ABSTRACT

Temperature and salinity play a crucial role in limiting the physiological performance of bivalves, particularly the temperature during their spawning periods. Currently, species are facing quick changes on those variables due to climate change, mainly characterized by rising temperatures. In the Rías Baixas region, located on the northwestern Iberian Peninsula, the bivalve species *Ruditapes philippinarum*, *Cerastoderma edule*, *Ruditapes decussatus*, and *Venerupis corrugata* hold significant socioeconomic importance. The majority of these species exhibit a specific water temperature range for their spawning peak periods, as indicated by the existing literature (17-19 ºC for *R. philippinarum*, 16-18 ºC for *C. edule*, 12-15 ºC for *V. corrugata* and 17-23ºC for *R. decussatus*).

Numerical models are valuable tools for assessing the potential future changes in climatic variables such as temperature and salinity. In this study, the Delft3D-Flow hydrodynamic model was employed to downscale Global and Regional Climate Models (GCMs and RCMs) in the Rías Baixas region. This downscaling process enables the calculation of bottom water temperature and salinity data with sufficient resolution to evaluate the impact of climate change on the area. The model was run for the historical period (2000-2019) and the future period (2080-2099) under the RCP8.5 scenario. A spawning predictor was utilized to calculate the percentage of time during which the bottom water temperature falls within the species-specific spawning peak temperature ranges. This spawning predictor helps identify the temporal distribution of the species' spawning peak periods of interest and allows for a comparison with historical data.

The results indicate that during the historical period, the spawning peak periods of the studied species generally align with those reported in the literature, particularly in areas relevant to aquaculture. However, projections for the end of the century under the RCP8.5 scenario suggest that the spawning peak periods for these species will occur earlier. During the months in which the spawning peak is typically taking place, the temperature could increase, reaching levels detrimental to some species' reproduction and survival by the end of the century.

Salinity changes does not appear to pose a significant issue for the aquaculture zones under the future scenario, as salinity is projected to increase in most of the cultivation areas due to the projected reduction in river discharges into the rias. Nonetheless, considering the increased frequency of extreme climate events associated with climate change, such as heavy precipitation, low salinity events combined with temperature changes could lead to reproductive disorders or mortality episodes.

KEYWORDS: Aquaculture, bivalves, climate change, salinity, spawning, temperature.

RESUMO

A temperatura xoga un papel crucial na limitación do rendemento fisiolóxico dos bivalvos, especialmente a temperatura durante os períodos de posta. Actualmente, as especies están a afrontar cambios rápidos nestas variables debido ao cambio climático, caracterizado principalmente polo aumento das temperaturas. Na rexión das Rías Baixas, no noroeste da Península Ibérica, as especies de bivalvos *Ruditapes philippinarum*, *Cerastoderma edule*, *Ruditapes decussatus* e *Venerupis corrugata* teñen unha gran importancia socioeconómica. A maioría destas especies teñen un rango específico de temperatura da auga para os seus períodos pico de posta, como indica a literatura existente (17-19 ºC para *R. philippinarum*, 16-18 ºC para *C. edule* 12-15 ºC para *V. corrugata* e 17-23ºC para *R. decussatus*).

Os modelos numéricos son ferramentas valiosas para avaliar os posibles cambios futuros en variables climáticas como a temperatura e a salinidade. Neste estudo, empregouse o modelo hidrodinámico Delft3D-Flow para facer un "downscaling" dos Modelos Climáticos Globais e Rexionais (GCMs e RCMs) na rexión das Rías Baixas. Este proceso permite obter datos de temperatura e salinidade das auga de fondo con suficiente resolución para avaliar o impacto do cambio climático na zona. O modelo executouse para o período histórico (2000-2019) e o período futuro (2080-2099) baixo o escenario RCP8.5. Utilizouse un preditor de posta para calcular a porcentaxe de tempo durante a cal a temperatura da auga do fondo está dentro dos rangos de temperatura de pico de posta específico de especie. Este preditor de posta axuda a identificar a distribución temporal dos períodos de pico de posta das especies de interese e permite unha comparación cos datos históricos.

Os resultados indican que, durante o período histórico, os períodos pico de posta das especies estudadas coinciden en xeral cos sinalados na bibliografía, sobre todo nas zonas de interese para a acuicultura. Con todo, as proxeccións para finais de século segundo o escenario RCP8.5 suxiren que os períodos álxidos de posta destas especies adiantaranse, e as elevadas temperaturas durante os meses nos que adoitan desovar poderían ter efectos adversos sobre a súa reprodución e supervivencia.

Os cambios na salinidade non parecen expor un problema significativo para as zonas de acuicultura no escenario futuro, xa que se prevé que a salinidade aumente na mayoría destas zonas debido á redución das descargas fluviais nas rías. Mais, tendo en conta o aumento na frecuencia dos fenómenos climáticos extremos asociados ao cambio climático, como as fortes precipitacións, os fenómenos de baixa salinidade combinados cos cambios de temperatura poderían provocar trastornos reprodutivos ou episodios de mortalidade.

Palabras chave: Acuicultura, bivalvos, cambio climático, posta, salinidade, temperatura.

RESUMEN

La temperatura y la salinidad desempeñan un papel crucial en la limitación del rendimiento fisiológico de los bivalvos, en particular, la temperatura durante los periodos de desove. Actualmente, las especies se enfrentan a cambios rápidos en estas variables debido al cambio climático, caracterizado principalmente por el aumento de las temperaturas. En la región de las Rías Baixas, en el noroeste de la Península Ibérica, las especies de bivalvos *Ruditapes philippinarum*, *Cerastoderma edule*, *Ruditapes decussatus* y *Venerupis corrugata* tienen una gran importancia socioeconómica. La mayoría de estas especies exhibe un rango específico de temperatura del agua para los periodos en los que se produce el mayor desove, como indica la literatura existente (17-19 ºC para *R. philippinarum*, 16-18 ºC para *C. edule*, 12-15 ºC para *V. corrugata* y 17-23ºC para *R. decussatus*).

Los modelos numéricos son herramientas valiosas para evaluar los posibles cambios que se producirán en el futuro en las variables climáticas, como la temperatura y la salinidad. En este estudio, se empleó el modelo hidrodinámico Delft3D-Flow para reducir la escala de los Modelos Climáticos Globales y Regionales (GCMs y RCMs) en la región de las Rías Baixas. Este proceso de "downscaling" permite obtener datos de temperatura y salinidad del agua de fondo con suficiente resolución para evaluar el impacto del cambio climático en la zona. El modelo se ejecutó para el periodo histórico (2000-2019) y para el periodo futuro (2080-2099) bajo el escenario RCP8.5. Se utilizó un predictor de desove para calcular el porcentaje de tiempo durante el cual la temperatura del agua del fondo se encuentra dentro de los rangos de temperatura en los que se produce el máximo desove específicos de cada especie. Este predictor de desove ayuda a identificar la distribución temporal de los periodos pico de desove de las especies de interés y permite una comparación con los datos históricos.

Los resultados indican que, durante el periodo histórico, los periodos máximos de desove de las especies objetivo coinciden en general con los señalados en la bibliografía, sobre todo en las zonas relevantes para la acuicultura. Sin embargo, las proyecciones para finales de siglo bajo el escenario RCP8.5 sugieren que los periodos pico de desove de estas especies se adelantarán, durante los meses en los que normalmente tiene lugar, la temperatura podría aumentar alcanzando valores perjudiciales para su reproducción y supervivencia.

Los cambios en la salinidad no parecen plantear un problema significativo para las zonas de acuicultura en el escenario futuro, ya que se prevé que la salinidad aumente en la mayoría estas zonas debido a la reducción de las descargas fluviales en las rías. No obstante, teniendo en cuenta la mayor frecuencia de fenómenos climáticos extremos asociados al cambio climático, como fuertes precipitaciones, los fenómenos de baja salinidad combinados con cambios de temperatura podrían provocar desordenes en la reproducción o episodios de mortalidad.

Palabras clave: Acuicultura, bivalvos, cambio climático, desove, salinidad, temperatura.

INDEX

1. Introduction

Climate change is a complex global issue that has captured the attention of the scientific community in recent decades. It can be defined as long-term alterations in the Earth's climate patterns, most notably temperature. These alterations can either be natural, such as those caused by radiative forcing, or anthropogenic (Cane *et al.*, 1997). The latter have contributed significantly to increasing the negative effects of global change in recent centuries. Examples of anthropogenic factors include nitrogen fertilization, overpopulation, and increased greenhouse gas emissions since the industrial revolution (Hansen *et al.*, 2007; Parmesan, 2006). These gases are mainly carbon dioxide, methane and nitrous oxide, produced by fossil fuels burning, which have intensified the greenhouse effect (Wuebbles & Jain, 2001). The greenhouse effect traps heat within the atmosphere, causing a gradual increase in global temperatures known as global warming (Mitchell, 1989).

The impacts of climate change are already being observed nowadays, and their consequences affect various aspects of our lives, such as the environment, the economy and human well-being (Tol, 2018). These changes have a lesser or greater extent depending on the geographical and socio-political situation (Malik *et al.,* 2012; Tol, 2018). Alterations in temperature and precipitation patterns have altered the frequency and severity of weather events and exacerbated existing environmental problems, for instance, biodiversity loss (Gregory *et al.,* 2007).

The oceans, which cover 70% of the Earth's surface (Schmitt, 1995), are home to a wealth of living marine resources (Chivian & Bernstein, 2008; Melet *et al.,* 2020) and play a vital role in climate regulation (White & Peterson, 1996). However, climate change drastically alters marine ecosystems and threatens their health and stability (Brierley & Kingsford, 2009). According to the sixth IPCC report published in 2023 is virtually certain that the upper layer of the oceans (0-700m) has increased in temperature compared to 1970 due to the human factor (Lee *et al.,* 2023).

Rising water temperatures, ocean acidification, salinity variations, melting ice caps and changing ocean circulation patterns are some devastating consequences (Doney *et al.,* 2009; Poloczanska *et al.,* 2016). In terms of marine biology, climate change drives loss of biodiversity, ecosystem degradation and temporal shifts in the life cycles and spatial distribution of species (Poloczanska *et al.,* 2016; Smale &

Wernberg, 2013; Hughes, 2000).

Climate models are important tools to help us investigate and understand the underlying mechanisms of climate change and its potential impacts. These models are mathematical and computational representations of the different components of the climate system (McFarlane, 2011). By taking advantage of fundamental laws of physics, such as thermodynamics and fluid mechanics, climate models are able to reproduce climate processes at different scales, from local variations to global trends (Feser *et al.,* 2011).

The Intergovernmental Panel on Climate Change (IPCC) has, since its inception in 1988, compiled work on human-induced changes in the climate system. In its Fith report, they define the Representative Concentration Pathway (RCP), which consists of four possible future scenarios depending on the concentration of greenhouse gases. These scenarios are labelled according to radiative forcing, from lowest to highest impact: RCP2.6, RCP4.5, RCP6 and RCP8.5 (Pachauri *et al.,* 2014). The most optimistic scenario is the RCP2.6, with a low level of radiative forcing due to drastic emission reduction; the RCP4.5 scenario is based on radiative forcing remaining stable at the end of the century; the RCP6 scenario in which radiative forcing would increase slightly, and the RCP8.5 scenario which projects high greenhouse gas emissions and consequently an increasing trend of radiative forcing (Melendez, 2021). These scenarios are used by the Coupled Model Intercomparison Project (CMIP) for global climate simulations (Nilawar & Waikar, 2019).

Climate change impacts do not affect the globe similarly (Cane *et al.,* 1997), so it is necessary to make simulations at a regional and local scale to study specific areas. Stadystic and dynamic downscaling are the techniques used to achieve that. Dynamic downscaling consists of running a regional or local model using data obtained from global projections to perform simulations at a reduced scale (Feser *et al.,* 2011; Nilawar & Waikar, 2019). This technique is used in the present work for the Rías Baixas.

The Rías Baixas are located on the northwest coast of the Iberian Peninsula in the Galician region (Spain), composed of four rias following a SW-NE direction (Varela *et al.,* 2005). Most of them have islands at the mouth that crate two inlets and protect them against incident waves (Alvarez *et al.*, 2005; Martínez *et al.*, 2011). In addition, their high productivity favoured by upwelling phenomena makes the rias an ideal environment for aquaculture, which has marked the economy, culture and society of the area (Mendez & Vilas, 2005; Martínez *et al.,* 2011; Vaz *et al.,* 2022).

Aquaculture is a growing sector globally (FAO) and also in the Region of Galicia, where the trend of annual production is positive (Figure 1), generating a profit of more than 233 Million € in 2021 (Galician Statistics Institute). Bivalve species are the most significant aquaculture species of Galicia, corresponding to 73% of the total production value, 254,716.50 tons, with an economic value of 169,645.80 €. Most of the profit appertain to the production of the *Mytilus edulis* (Lamarck, 1819), followed by *Ruditapes philippinarum* (A. Adams & Reeve, 1850), *Cerastoderma edule* (Linnaeus, 1758), *Ruditapes decussatus* (Linnaeus, 1758), and *Venerupis corrugata* (Gmelin, 1791) (Table 1, Galician Statistics Institute).

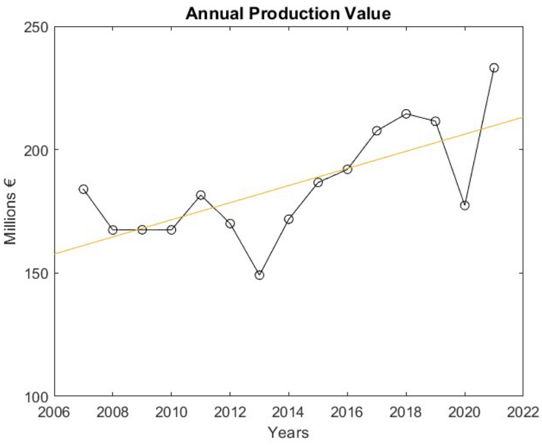

Figure 1. Annual production (Millions €) of Galician aquaculture from 2006 to 2022. Data obtained from Galician Statistics Institute.

Table 1. Collected tones (weight), annual production value (APV) in € and % of main bivalves in Galician Aquaculture. Data obtained from Galician Statistics Institute.

Species	Weight (tons)	APV (€)	APV (%)
Mytilus sp.	251,202.20	139,204,800	82.00
Ruditapes philippinarum	1458.60	16,742,900	9.86
Cerastoderma edule	836.40	4,329,400	2.55
Ruditapes decussatus	143.10	4,313,100	2.54
Venerupis corrugata	140.40	2,113,000	1.24
Crassostrea gigas	675.80	1,496,800	0.88
Ostrea edulis	257.50	1,433,200	0.84

The target species in the present work are *R. philippinarum* (Japanese clam), *C. edule* (Common cockle), *R. decussatus* (Good clam) and *V. corrugata* (Pullet carpet shell) because, in addition to being species of great socio-economic interest, their life cycle and culture method are similar. (Figure 2).

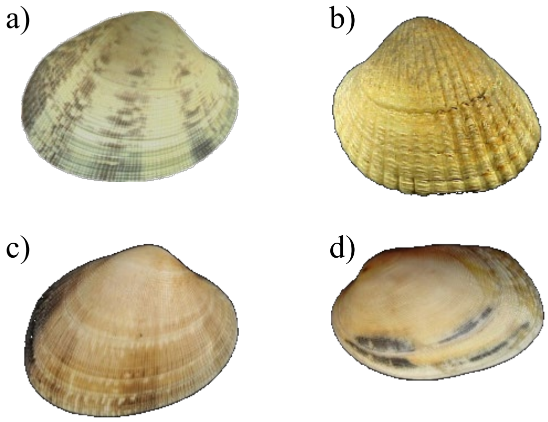

Figure 2. Species of interest; a) *Ruditapes philippinarum*, b) Cerast*oderma edule*, c) *Ruditapes decussatus*, d) *Venerupis corrugata.*

In the Rías Baixas, the after-mentioned species are obtained from small-scale artisanal harvesting. The culture process can be summarized in the sowing, rearing and harvesting (Galindo, 2022). This process starts with collecting seeds from natural areas or hatcheries and transporting them to the cultivation areas (McKindsey *et al.*, 2006). Cultivation of bivalves can occur in natural beds or designated cultivation areas protected from currents (Fürsich, 1980). Once in the cultivated area, bivalves are reared and cultivated in sand or sediments. The most traditional harvesting is performed in intertidal zones on foot and mainly by women. Harvesting in subtidal areas is carried out from fishing boats (Da Costa, 2013). The impacts that climate change may have on bivalves and their responses are species-specific (Martel *et al.*, 2022; Vázquez *et al.*, 2021; Parada *et al.*, 2012) and may have major socio-economic impacts on aquaculture (Narita *et al.*, 2012; Turley, 2011).

Bivalves are strongly influenced by temperature and salinity; thus, changes in these environmental factors can cause reduced scope for growth (Domínguez *et al.*, 2021), differences in spatial distribution (Castro-Olivares *et al.,* 2022) and mortality (Aranguren *et al.,* 2014; Des *et al.,* 2021; Parada *et al.*, 2012;). Temperature is a crucial factor driving their reproductive cycle (Domínguez *et al.,* 2021). Thus, climate change can cause temporal variations in the bivalves' reproductive cycle, such as shifts in the spawning season. Other relevant factors affecting bivalves reproduction are the photoperiod, food availability, nutrient reserves, hormonal cycles and genotype (Cáceres-Martínez & Figueras, 1998).

Changes in the reproductive cycle of bivalves would affect the bivalve community, for example, in seed harvest and, therefore, the aquaculture sector (Mladineo *et al.,* 2007). Recruitment of most commercial bivalves species is in decline; there is a notorious lack of seed clams of the right size for seeding, to recover currently unproductive areas or to enhance production in natural beds (Da Costa, 2013). For this reason, it is important to study how the variation of temperature and salinity due to climate change affects the reproductive cycle of bivalves in the Rías Baixas, especially in spawning.

The reproductive cycle encompasses the entire sequence of events from activation of the gonad through gametogenesis to spawning and subsequent recession of the gonad, differentiating a reproductive period and a rest period (Wilson & Seed, 1976). Typically, the reproductive cycle starts with gonad activation, followed by gametogenic development, maturity, spawning and a rest period. Cerviño-Otero (2011) describes gametogenic scales based on some qualitative scales of bivalves, in ascending order: sexual rest, gonadal development, advanced gametogenesis, ripe/spawning and restoration.

During sexual rest, follicles are small and scarce. This stage is characterized by the presence of residual gametes, and there is no evidence of gonadal development. The bivalves accumulate nutrients for the energetic cost of gametogenesis. Gonadal development, also known as early gametogenesis, is characterized by fully developed follicles with walls full of germ cells but only a few in the inner part. In advanced gametogenesis, vesicular cells are reduced, although some remain that is still adhered to the follicular walls. The males present germ cells in all stages of spermatogenesis, while in females, pedunculated oocytes are noticed and, in lesser amounts, ripe oocytes. At the ripe stage, germ cells fully occupy follicles, ready to be liberated into the environment. The spawning is the result of the gametes release, depending on the spawning degree of the follicles, which may be more or less empty. Once in the environment, the spermatozoids will fertilize the oocytes. Finally, the restoration stage is identified by the development of new vesicular cells. The cycle starts again in the follicles, and new germ cells can be found in the follicle walls and co-exist with remaining ripe gametes.

The life cycle of bivalves (Figure 3) passes through different phases, being the time between them specie-specific, as has been reported by several authors who had conducted experiments under laboratory conditions (Table 2). Once fertilization occurs, the embryo initiates cleavage. The following stage is a pyriform trochophore, which is able to swim. The next stage corresponds with veliger stage, which has developed two valves, a complete digestive system and a velum. This stage could happen right after the fertilized egg hatching or after the trochophore phase of the organism. In some cases, just after this stage, the hinge is curved by the formation of the umbo, giving rise to the umbonate larva. Approaching maturity, the larva develops a foot, pediveliger stage. Later the larva loses the velum, develops branchia, settles and metamorphose into a juvenile state. In this stage, the larvae change from planktonic existence to a sedentary benthic lifestyle and, with the help of their foot, begin to bury in the substrate (Da Costa *et al.*, 2013).

Table 2. Phase-to-phase time for the species of interest (days).

Species	Umbonate larva	Pediveliger	Juvenile	Reference
R. philippinarum	8	20-25	30-35	(Cerviño-Otero *et al.*, 2011)
C. edule	-	-	20-35	(Kingston, 1974)
R. decussatus	8	25-27	35-40	(Cerviño-Otero *et al.*, 2011)
V. corrugata	8	16-18	22-25	(Cerviño-Otero *et al.*, 2011)

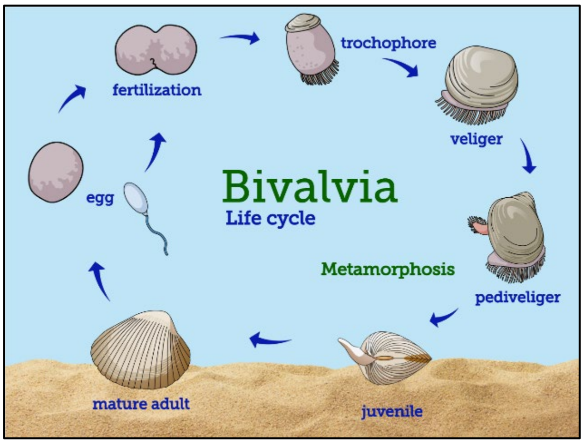

Figure 3. Esqueme of the life cycle of the bivalves of interest.

The use of climate models to study the response of bivalves to climate variations due to global change is relatively recent (Thomas & Bacher, 2018; Gourault *et al.,* 2019; Pereira *et al.,* 2023; Steeves *et al.,* 2018;). Some studies analyze the effect of climate change on different bivalve species from the Rías Baixas using climate models (Castro-Olivares *et al.,* 2022; Des *et al.,* 2020; Des *et al.,* 2021; Silva *et al.,* 2017). However, no previous work has been found that analyses the temporal variation of the spawning season of these species in the future under an RCP8.5 scenario in the Rías Baixas.

1.1. Hypothesis and objectives

This master thesis hypothesizes that ocean warming will prompt a forward in the spawning season of the bivalves *R. philippinarum, C. edule, R. decussatus* and *V. corrugata* in the Rías Baixas.

The following objectives are set to test the hypothesis:

1. Perform a downscaling of the Global Climate Models for the Rías Baixas for the historical (2000-2019) and future (2080-2099) period under the RCP8.5 scenario. The hydrodynamical module of the Delft3D model will be used to achieve this objective.
2. Analyze changes in bottom water temperature and salinity.
3. Evaluate if the projected changes in water temperature may modify the spawning period of the species of interest.

Evaluate if changes in salinity may compromise the development of the larvae and juveniles if the spawning season is forward.

2. Methodology

A bibliographic review was carried out to determine which temperature ranges favour the initialization of the spawning for the species of interest, *Ruditapes philippinarum*, *Cerastoderma edule*, *Ruditapes decussatus* and *Venerupis corrugata*, and in which months it typically occurs currently. Salinity was also taken into account to consider interactions between the spawning period and low salinity.

The Delft3D-Flow numerical model was used to downscale the climate variables of the Global Climate Models in the Rías Baixas. This allowed obtaining bottom water temperature and salinity with an appropriate resolution to assess the changes in the harvesting areas of *R. philippinarum, C. edule, R. decussatus* and *V. corrugata*. The model was run from March to June for a historical period from 2000 to 2019 and a future period from 2080 to 2099 under the RCP8.5 scenario. The model data were evaluated with the literature in order to assess the spawning period of the organisms (Figure 4).

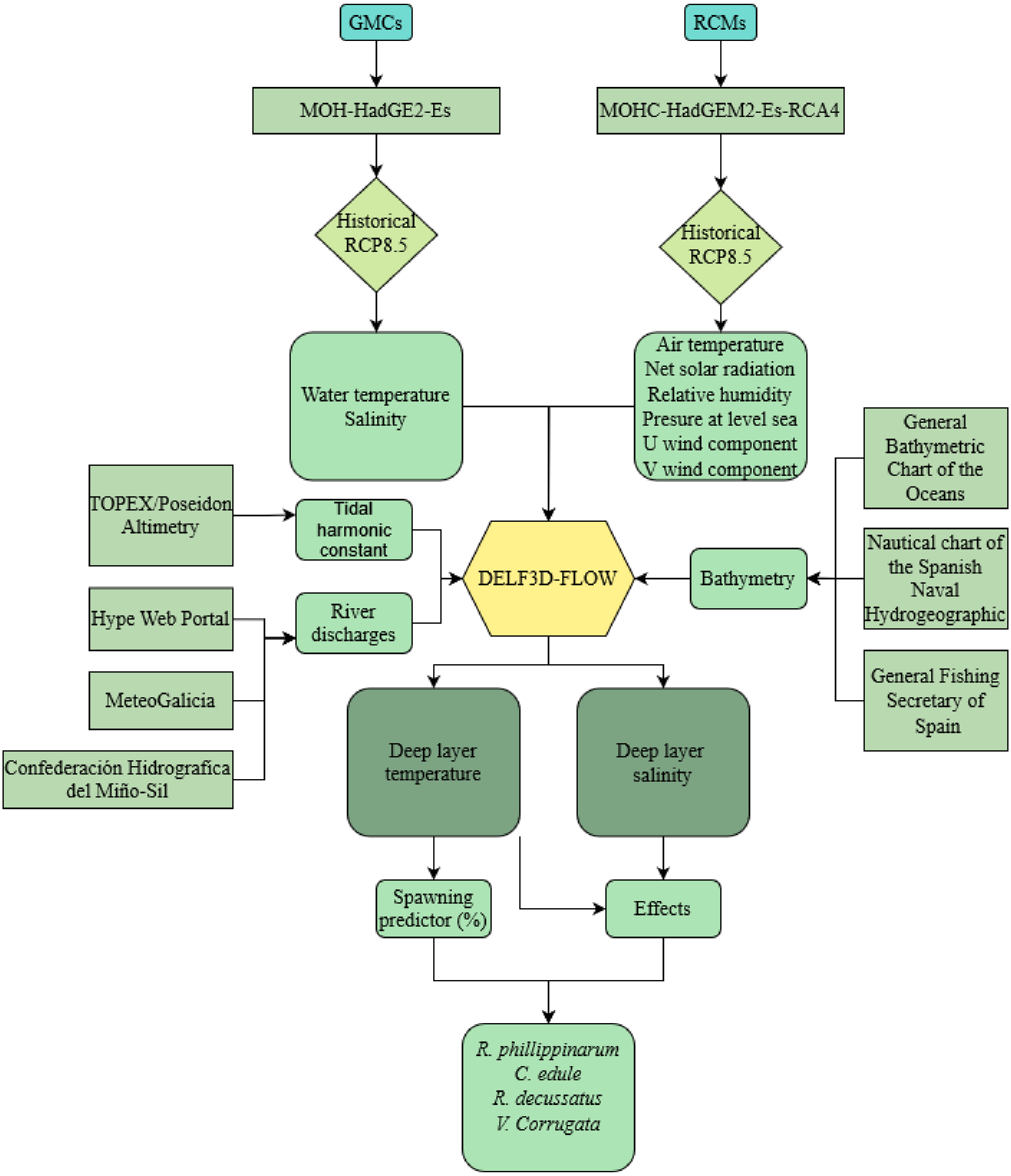

Figure 4. Data and method flow diagram.

2.1. Study Area

The study area corresponds to the Rías Baixas, located on the northwest coast of the Iberian Peninsula. The term Rías Baixas comprises four flooded incised valleys (Evans & Prego, 2003), called rias, which are from north to south: the Ría de Muros y Noia, Ría de Arousa, Ría de Pontevedra and Ría de Vigo (Figure 5). The orientation of the rias is controlled by a sub-continental basement fracture system (Morales, 2018) and is almost perpendicular to the coast, with a gently sloping seabed (Varela *et al.,* 2005).

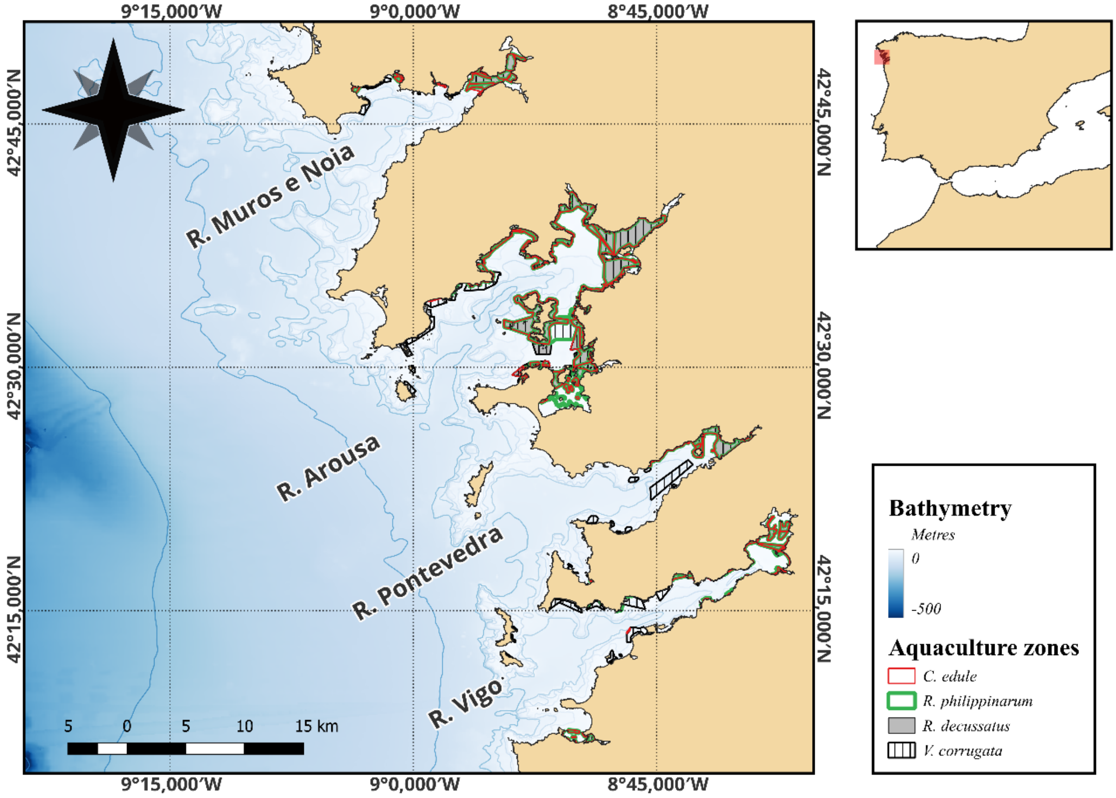

Figure 5. Map of the study area with the aquaculture zones of the species of interest. Bathymetry data was obtained from European Marine Observation and Data Network, polygons covering aquaculture zones were obtained from INTECMAR ("Instituto tecnoloxico para o control do medio mariño de galicia"). Mapping using Qgis.

Usually, the rias are divided into three zones, the inner, middle and outer sectors, due to their hydrodynamic and sedimentological characteristics (Des *et al.*, 2021; Mendez & Vilas, 2005; Vilas & Mendez*,* 2005). The inner sector includes the shallow area of the ria, where the mouths of the main rivers are usually located; the middle sector corresponds to the central part of the ria and is distinguished by a low-energy regime (Des *et al.,* 2021). The outer sector is located at the mouth of the ria connecting it with the platform, and it is protected from the direct influence of the oceanic zone by islands that generate a north and south entrance at the mouth, except in the case of the ria de Muros e Noia (Mendez & Vilas, 2005).

The bathymetry of the area shows an approximate depth of 5-10m in the inner part that decreases continuously to depths of 45-60m in the outer part, except in the cases of the northern mouth of the Vigo and Pontevedra estuary and the northern mouth of the Arousa estuary, whose depths are 25, 15 and 5 m respectively. (Alvarez *et al*., 2005; Varela *et al.,* 2005; Vilas & Mendez*,* 2005).

Tides in the Rías Baixas are semi-diurnal, and the tidal regime is mesotidal (Morales, 2018). Typical tidal current velocities are 5cm/s for deep water and 2cm/s for shallow water (Fanjul *et al.,* 1997).

The main rivers that flow into the Rías Baixas are the Tambre in the Ría de Muros y Noia, the rivers Ulla and Umia in the Ría de Arousa, the Lerez in the Ría de Pontevedra and the Verdugo in the Ría de Vigo. These rivers present a maximum discharge during the winter months (Figure 6) controlling stratification (Sousa *et al.,* 2014), while in summer, these discharges decrease, and solar heating is the main driver for the stratification (Alvarez *et al.,* 2005).

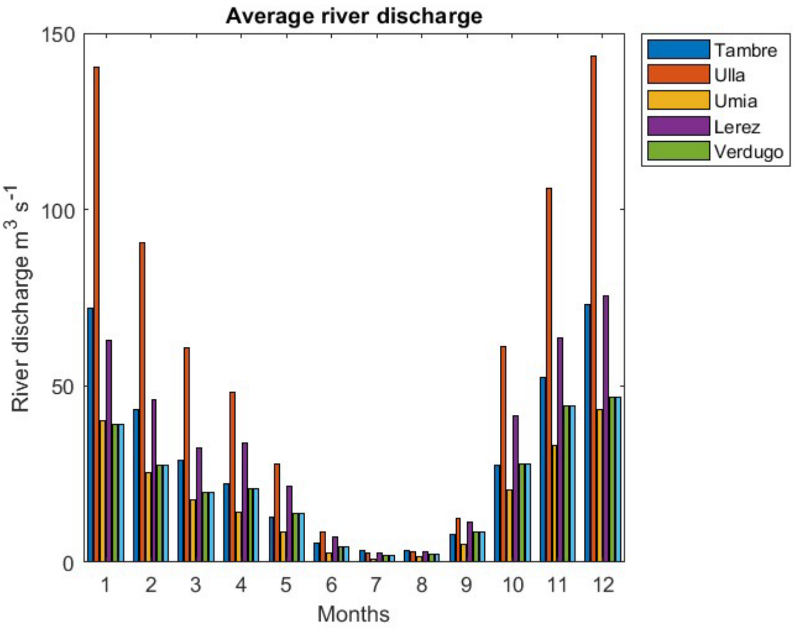

Figure 6. Monthly mean discharge of the main rivers discharging in the Rías Baixas (m^{3}s^{-1}). Data was obtained from hype climatology considering 1981 to 2011.

Mixing freshwater and seawater is generally restricted to the inner sector of the rias. Typically, the two water masses flow separately, the marine water below the fresh water, described as positive estuarine circulation (Morales, 2018). Currents velocity and wind determine the degree of mixing, generating more effective mixing in the case of stronger currents (Morales, 2018).

The region is affected by upwelling when winds blow from the north, and downwelling events, which reverses the typical circulation pattern, when the wind blows from the south (Alvarez *et al.,* 2005; Varela *et al.,* 2005). Although the upwelling season is very variable, it usually prevails from April-March to September-October, transporting important volumes of superficial water to the shelf, which is replaced by water from deep layers (Wooster *et al.,* 1976). The upwelling processes have important biological implications due to the supply of nutrients that drive the high primary productivity of the area (Fraga *et al.,* 1982).

2.2. Numerical model

The Delft3D-FLOW module (Delft3D-FLOW research version 4.04.01) was used to calculate the temperature and salinity data for the Rías Baixas. This module allows the simulation of a large number of processes, such as wind shear, wave forces, tidal forces, density-driven flows and stratification due to salinity or temperature, among others. It is a three-dimensional model whose function is to solve flow phenomena whose horizontal length and time scales are significantly larger than the vertical ones. Because of this, it is used under the shallow water hypothesis to solve the Navier-Stokes equations under the Boussinesq hypothesis (Deltares, 2014). The model solves the horizontal equations of motion, continuity, transport and turbulence (Deltares 2014). Numerical simulations were performed using a curvilinear grid, covering from 10ºW to 8.33ºW and 41.18º to 43.5ºN using 53603 grid elements. The horizontal resolution increases from the western border of the grid (2200 x 800m) to the east, reaching 220 x 140 m in the Rías Baixas and 50m x77m in the Minho River. The used time step was 0.5min, based on the Courant-Friedrichs-Lewy number. The vertical resolution comprises 16 sigma layers, representing the first and second layers 1%, the third 3%, the fourth 4%, the fifth 5%, the sixth 6% and from the seventh to the sixteenth 8% of the depth.

The bathymetry data used for the model was created with the compilation of bathymetries of the rias of Arousa and Muros e Noia, obtained from the nautical chart of the Spanish Naval Hydrographic Institute, the rias of Vigo and Pontevedra from data of the General Fishing Secretary of Spain, and those for the adjacent platform area were downloaded from the General Bathymetric Chart of the Oceans.

To reproduce the sea level, tidal harmonic components (M2, S2, N2, K2, K1, O1, P1, Q1, MsF, MM, M4, MS4, MN4), obtained from the TPXO 7.2 TOPEX/Poseidon Altimetry model (http://volkov.oce.orst.ed/tides/global.html), were introduced as astronomical forcing at the open boundary.

River discharges were obtained for the historical period from MeteoGalicia database (MeteoGalicia) and Confederación Hidrografica del Miño-Sil (Miño-Sil). For the future period, they were calculated by applying projections performed by the Hype Web portal (Hype Web Portal) to a climatology calculated based on the historical discharges. Those projections for the RCP8.5 scenario indicate a general reduction of river discharge (19.73% for March, 35.63 for April, 64.56 for May and 62.04 for June).

The "absolute flux, net solar radiation" model was used to simulate heat exchange across the free surface. This model requires relative humidity, air temperature and combined net solar radiation. The model calculates heat loss due to evaporation and convection (Deltares, 2014).

The wind components and pressure values are imposed for the flow model, varying spatially. The data source for these variables were the outputs of the regional model MOHC-HadGEM2-Es- RCA4 RCM, which were downloaded from the CORDEX project website (CORDEX).

The outputs of the global model MOHC-HadGEM2-Es, implemented within the Climate Model Program of Diagnosis and Intercomparison (CMPI5) project (https://esgfnode.llnl.gov/), were used as transport conditions (salinity and temperature) at the open oceanic boundary and as initial conditions.

Model validation was conducted by (Des *et al.*, 2019 and Des *et al.*, 2020), where more information about the model can be found. It is important to remember that climate models do not provide results corresponding to a specific date. Therefore, in order to obtain representative values of climatic conditions, it is necessary to average data over a group of years. In this study, we have considered the historical period from 2000-2019 and the future projections from 2080 to 2099 under the RCP8.5 scenario. A total of 40 tests were conducted from March 1 to June 30, although the test started 14 days ahead; those initial two weeks were considered a spin-up period. These tests were run on the Ephyslab and Deltares servers, and each test needed approximately 14 to run.

2.3. Spawning predictor.

A spawning predictor was used to assess possible changes in the period when the spawning peak may occur. This predictor considers the percentage of time that mean bottom water temperature is within the spawning ranges. The spawning temperature ranges were obtained from a bibliography review considering as primary sources those works carried out in the study area (Table 3).

Table 3. Summary of the literature review for each species.

Species	Habitat Depth/Sediment/ Burrowing depth	Gonadal cycle
R. philippinarum	1-5m depth/ Sand or mud/ <5cm	Minimum temperature to start: 8ºC. Gametogenesis: December- February Threshold spawning: 14-22ºC Spawning peak: 17-19ºC, July Salinity threshold: 20-30 PSU
C. edule	1-5m depth/ Sand or mud/ <5cm	Gametogenesis: autumn-winter Spawning period: March-October Threshold spawning: 14-25ºC Spawning peak: 16-18ºC, May Maximum larval growth: 15-20ºC Maximum temperature tolerance: 42.8ºC Salinity threshold: 15-30 PSU Optimal salinity for larvae development: 25 PSU
R. decussatus	1-5m depth/ Sand or mud/ 10cm	Normal gonadal index: 18ºC Spawning peak: 19º-23ºC Spawning peak period: April to June Salinity threshold: 20-28 PSU
V. corrugata	1-15m depth/ Sand/ 5-10cm	Optimal salinity 30-40psu Threshold spawning: 12ºC-20ºC Spawning peak: 12-15ºC, March-May Salinity threshold: 14-28 PSU

Ruditapes philippinarum inhabits sandy and muddy seabeds, where they are buried at a maximum depth of 5cm (Domínguez *et al.*, 2023). The minimum proper temperature for the reproductive cycle to begin is 8ºC, and the gametes start developing between December and February. The average temperature threshold for spawning is between 14ºC and 22ºC, considering that 22ºC all the energy obtained from food consumption is used in the reproductive cycle. Meanwhile, at temperatures of 14ºC, part of this energy can be stored as a reserve (Delgado & Pérez-Camacho, 2007a). However, in temperatures above 22ºC, gonads maturing and degenerating processes accelerate swiftly, and spawning does not occur (Toba, 1995). *Ruditapes philippinarum* usually reaches maturity in late spring, and the spawning period is in July (Spanish ministry of agriculture and fisheries) when the water temperature in estuaries is regularly about 18ºC (Delgado & Pérez-Camacho, 2007b), as well as its optimum salinity threshold (20-30 PSU, META).

Cerastoderma edule inhabits the intertidal on muddy or sandy sediments and does not usually burrow further than 5 cm in depth (Tyler-Walter, 2007). Gametogenesis begins in autumn and progresses through the winter. The spawning period is from March to October, with a spawning peak in early spring, around May (16-18ºC) (Estepa, 2006; González & Pérez-Camacho, 1984; Martínez-Castro & Vázquez, 2012). The favourable abiotic conditions for spawning entail temperatures below 25ºC; otherwise, it would not be viable (Malham *et al.*, 2012). Therefore, the spawning threshold is considered 14-25ºC, choosing 14ºC as the minimum after applying a 2ºC reduction to the temperature at which the spawning peak usually occurs based on the behaviour seen in the rest of the species. Maximum larval growth is expected between 15ºC and 20ºC (Kingston, 1974). The optimal salinity for larval rearing is 25psu (Martínez-Castro & Vázquez, 2012; Ysebaert *et al.*, 2002), and they can only withstand minimum salinities of 20 PSU (Malham *et al.*, 2012).

Ruditapes decussatus usually live on sandy sediment or mud buried at 10 cm (Morales *et al.*, 2008). Regarding gonadal development, the average normal temperature is about 18ºC, with an optimal threshold of 19-23ºC (Matias *et al.*, 2009). The spawning peak occurs between May and June (Matias *et al.*, 2013). Unlike other species, gametes are not accumulated and then released into the environment but are constantly released (Delgado & Pérez-Camacho, 2007a). Optimum threshold 18-24ºC and 20-28 PSU (META). This species finds its boundary lethal conditions above 23ºC and salinity lower than 15 PSU (Rato *et al.*, 2022).

Venerupis corrugata burrows down to 5-10cm in sandy sediment and has extended maturity and spawning periods (Morales *et al.*, 2008), from February to

July at temperatures from 12-20ºC (Cerviño-Otero, 2011), with peaks in March-May when temperatures begin to rise (12-15ºC) (Pérez-Camacho, 1978). It has the best results in scope for growth at 20ºC and larval growth at 26ºC (Albentosa *et al.*, 1994). About its optimal salinity, it has a wide range between 14-28 PSU (META). Considering lethal ranges, it is important to emphasize that temperatures above 22°C cause gradual mortality (Cerviño-Otero, 2011). Overall, large variations in salinity and low salinity values equal to or less than 20 PSU may cause oocyte deformation, large mortality events and failure in reproduction (Domínguez *et al.*, 2023; Malham *et al.*, 2012; Vázquez *et al.*, 2021).

2.4. Data Processing

All data were analyzed with the software MATLAB (R2022b). First, water temperature and salinity were extracted from the output files of the numerical model. These data had a temporal resolution of six hours, and only the data corresponding to the bottom (16th layer of the model output) was evaluated to analyze changes in the variables. Subsequently, the mean temperature and salinity were calculated for each month and the whole period for the historical and future periods. Next, the spawning peak predictor was applied to the temperature variable for each species. A series of maps were made representing the percentage of the time, with a temporal resolution of six hours, in which the water temperature of the deepest layer is within the range for each species. The species is considered to be within the spawning peak period if the percentage of time is equal to or greater than 50%.

3. Results

The results section focuses on the analysis of the effects of temperature on the spawning season, showing the results obtained by analyzing the model outputs. First, changes in monthly mean temperature are assessed. Then, the percentage of time during which the water temperature is within the optimum values for the spawning peak (spawning predictor) for each species studied is analyzed for historical and future periods. Finally, the same analysis is performed considering salinity. The study months are between March and June for the historical period (2000-2019) and the future period under the RCP8.5 scenario (2080-2099) in the background layer of the numerical model in the Rías Baixas. Figures showing the percentage of time that bottom water temperature is within the spawning period temperature range for *Ruditapes philippinarum*, *Cerastoderma edule* and *Venerupis corrugata* in the historical and future period under RCP8.5 scenario are shown in Annexe.

3.1. Water temperature

Modelled bottom water temperature (Figure 7) for the historical period ranges from 13-16ºC in March, 13-18ºC in April, 13-21ºC in May and 14-26ºC in June (Figure 7 left panels from top to bottom) while for the future period under a RCP8.5 15-18ºC in March, 16-22ºC in April, 16-26ºC in May and 16-28ºC in June (Figure 7 central panels from top to bottom). During both periods, higher temperatures are observed in shallow areas, those of interest for the present work, decreasing towards the ocean. Generally, it can be observed that the estuaries with the highest extensions of worm bottom water temperatures are the Ría de Arousa and the Ría de Vigo.

Future projections show a general increase in bottom water temperature (Figure 7, right panels). Generally, the water temperature is expected to rise more in shallow areas and in the inner part of the rias than in the middle or outer areas; those areas are the ones inhabited by the species of interest and the culture polygons (Figure 5). By months, a maximum temperature increase of approximately 3ºC in March 4.5ºC in April and 3.5ºC in May and June is expected. The rising pattern observed for June differs from the other months, as the rias experience a more pronounced impact of ocean warming throughout their entire length.

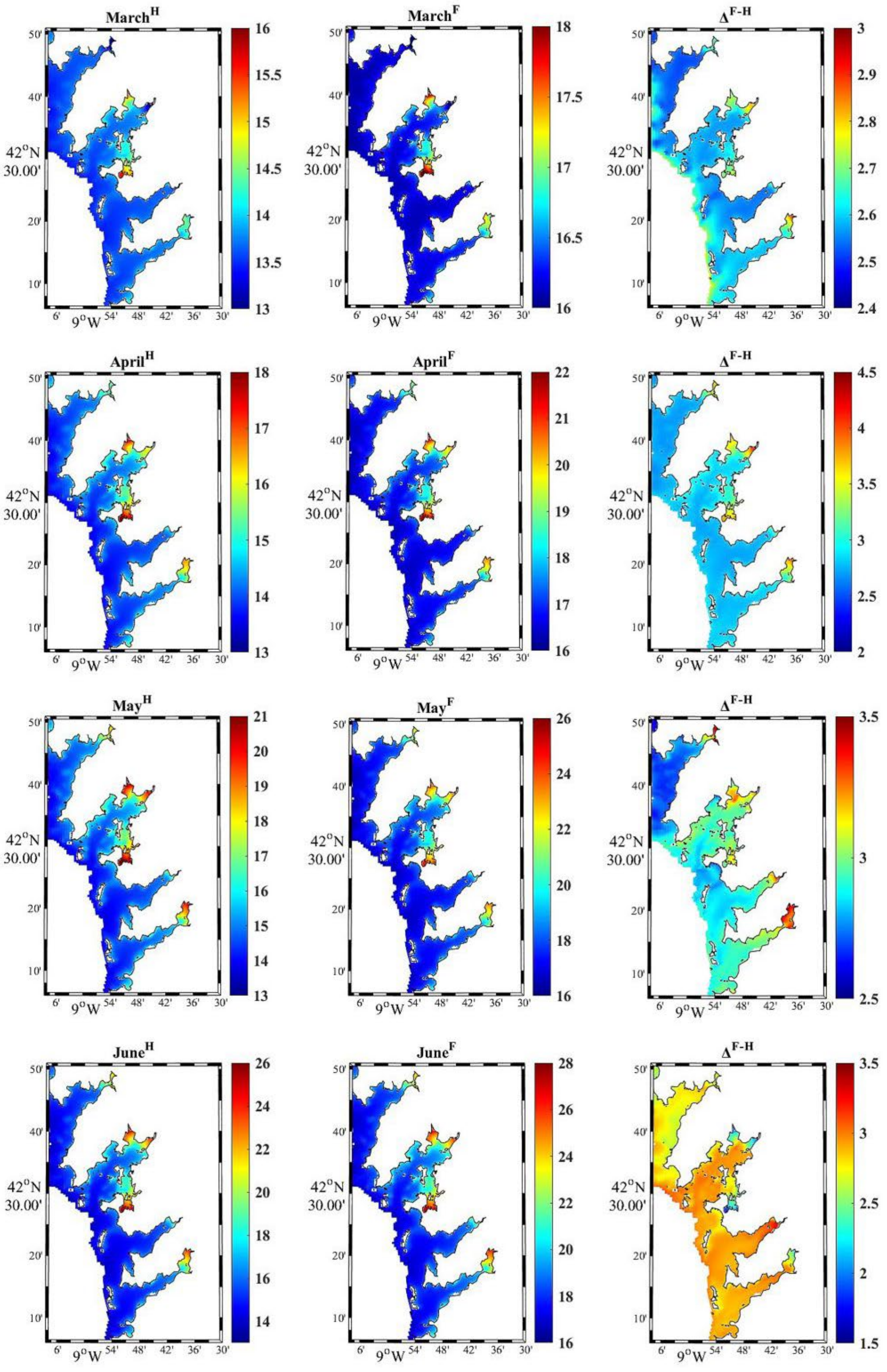

Figure 7. Mean bottom water temperature (ºC) in the Rías Baixas from March to June for historical (H, 2000-2019, left panels), future under RCP8.5 scenario (F, 2080-2099, central panels) and its variation (Future-Historical, right panel) from March to June. Colourbar varies from figure to figure.

3.1.1. Ruditapes philippinarum

Following the literature, the optimal peak spawning temperature for *R. philippinarum* was set between 17 and 19ºC, although spawning may occur between 14 and 22ºC.

The numerical results for the historical period (Figure 8) show that this range is reached in April, some shallow areas in the inner part of the Ría de Arousa and the Ría de Vigo reach the optimal range 60% of the time. May is in which the water temperature is within the optimal range to a great extent, reaching 80% of the time in internal zones of the Rías of Muros e Noia, Arousa and Vigo, with a slight percentage of time in the inner part of the Pontevedra estuary. Finally, in June, some areas are within the optimal range 100% of the time; however, temperature begins to be unfavourable in some shallower areas of the cultivation polygons. Although temperatures in the range of 17-19ºC are not found in some of the areas of interest in May and June for the Rías of Muros e Noia, Arousa and Vigo, the average temperature is within the spawning threshold (14-22ºC), results not show.

Under future projections (Figure 9), optimal peak spawning temperature is reached in March in some areas of the Rías of Arousa and Vigo. However, the water temperature may overpass the upper limit in May and June. Considering only the temperature, it means that an earlier spawning peak of *R. philippinarum* is projected. It could generally occur in the four rias from April in some cultivation banks of the Rías of Arousa and Vigo from March. Spawning in June could be negatively affected by high temperatures that may overpass the upper limit of the spawning threshold (22ºC).

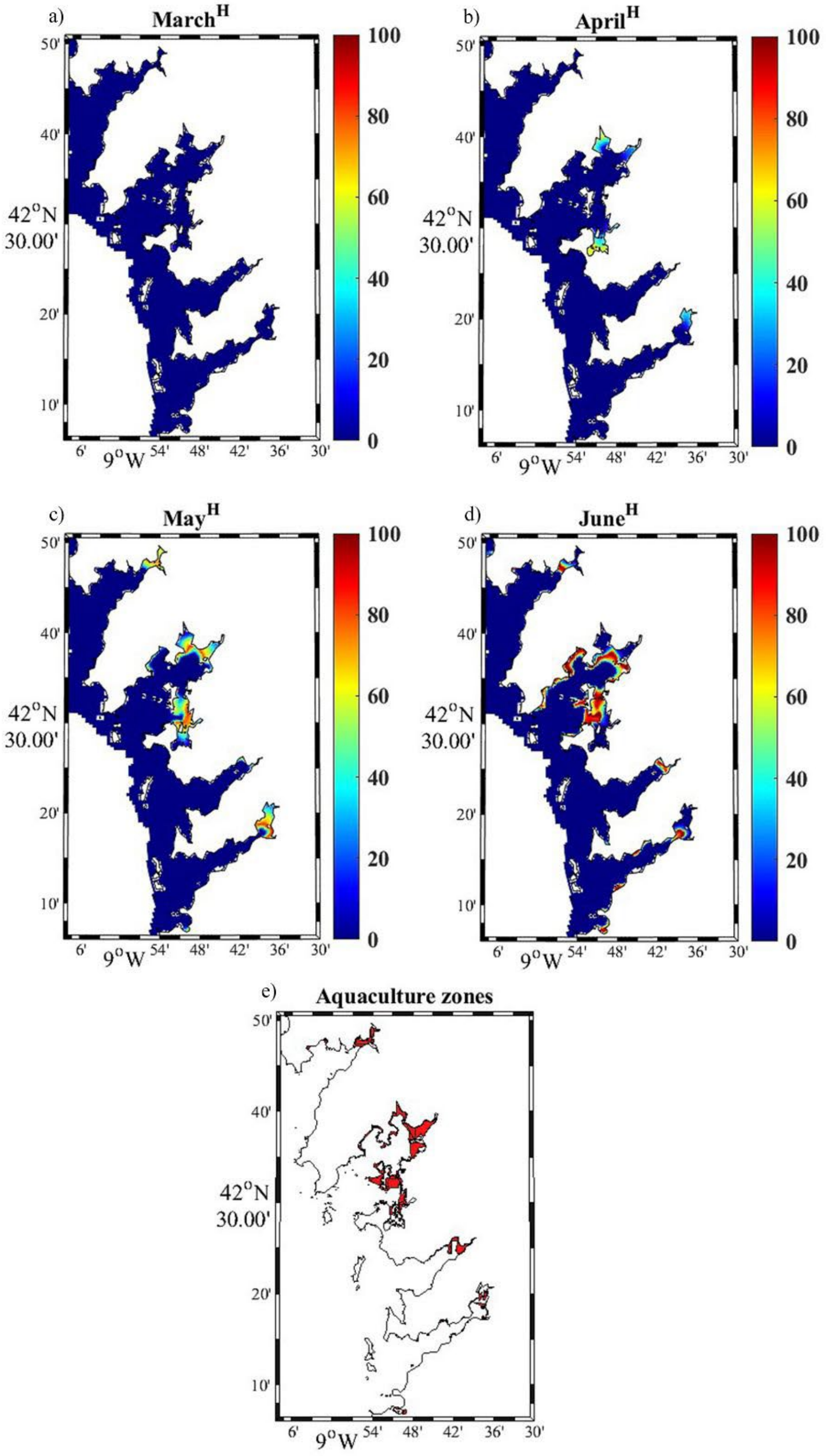

Figure 8. Monthly *Ruditapes philippinarum* spawning predictor (%) in the Rías Baixas from March to June (a-d) for the historical period (2000-2019). (e) Areas of current harvesting.

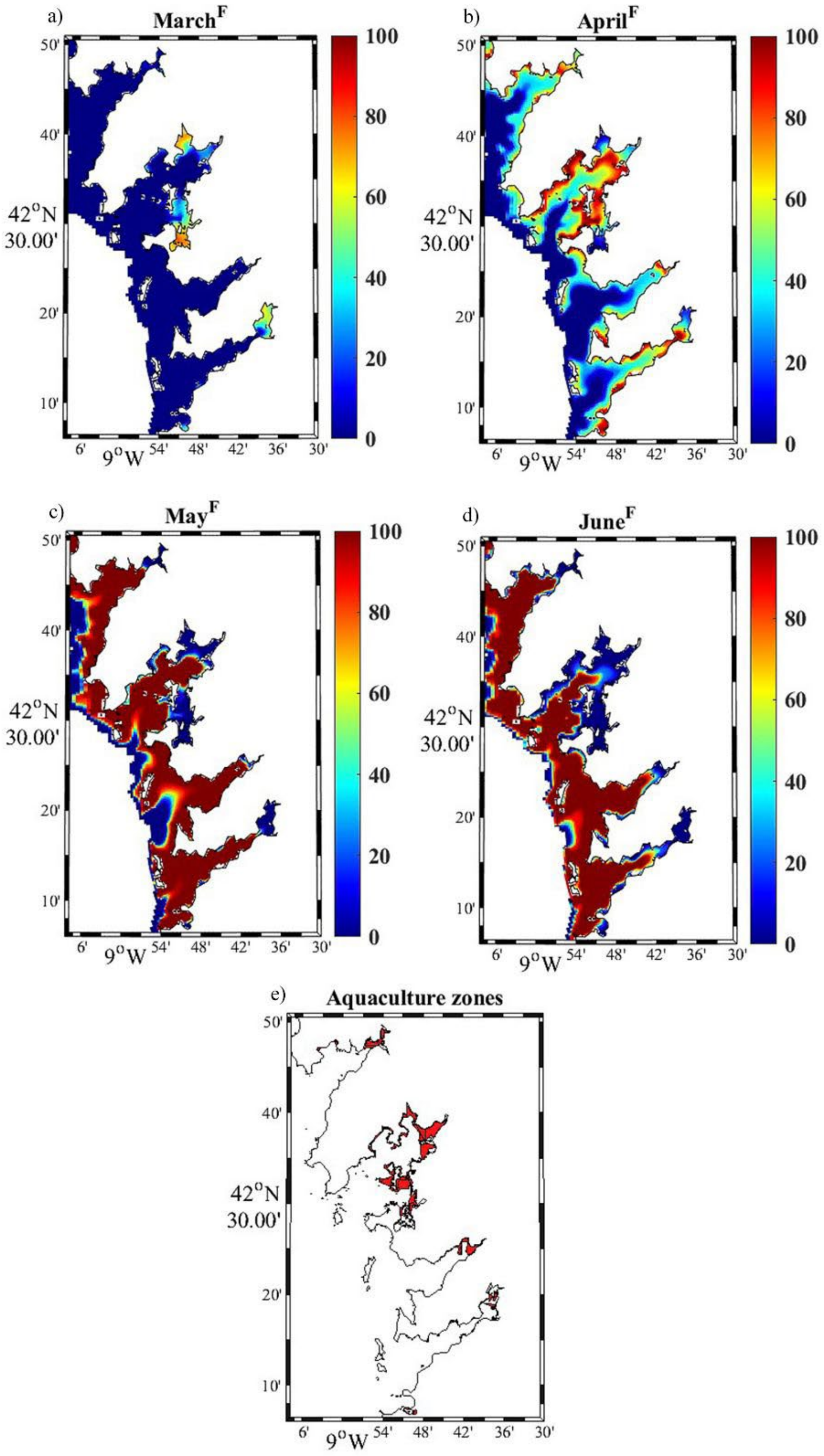

Figure 9. Monthly *Ruditapes philippinarum* spawning predictor (%) in the Rías Baixas from March to June (a-d) for the future period under RCP8.5 scenario (2080-2099). (e) Areas of current harvesting.

3.1.2. Cerastoderma edule

In the case of *C.* edule, the literature indicates that the optimal peak spawning temperature ranges from 16-18ºC, although spawning may happen up to 25ºC.

During the historical period (Figure 10), bottom water temperature is within the spawning peak temperature from April, at least 50% of the time at shallow areas of the inner part of the Ría de Arousa and the Ría de Vigo. May is when a higher extension of the cultivation areas is a greater percentage of time within the optimal range, between 80% and 100% of the time. June is close to 100% in central and outer coastal areas.

By the end of the century, under scenario RCP8.5 (Figure 11), the spawning peak could get ahead to March and April, when the water temperature in the culture areas is within the optimal range between the 80 and 100% of the time. In May and June, the projected temperature exceeds the optimum range in the cultivation areas, although suitable areas are observed in deeper areas, out of the depth range of *C. edule*.

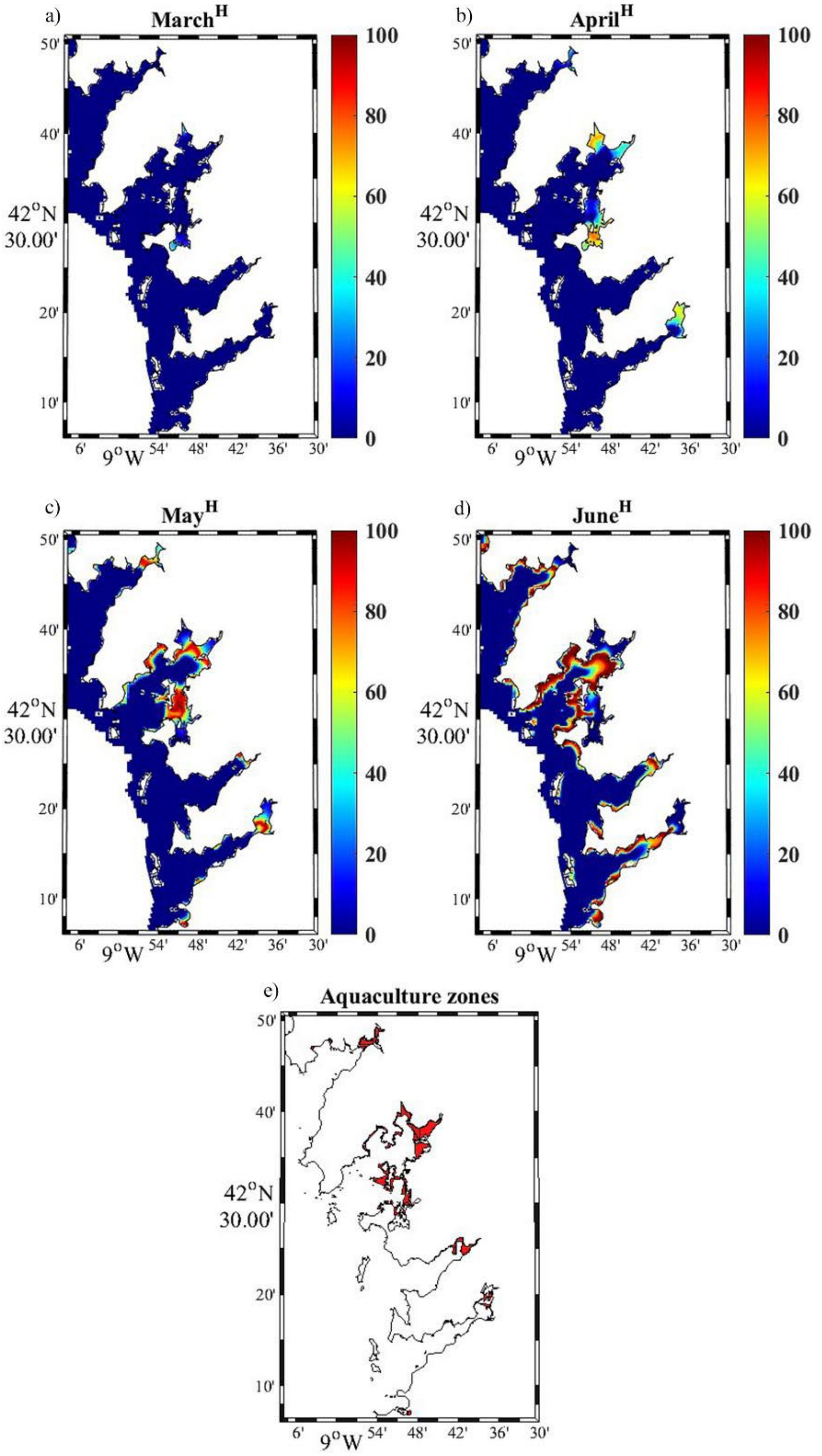

Figure 10. Monthly *Cerastoderma edule* spawning predictor (%) in the Rías Baixas from March to June (a-d) for the historical period (2000-2019). (e) Areas of current harvesting.

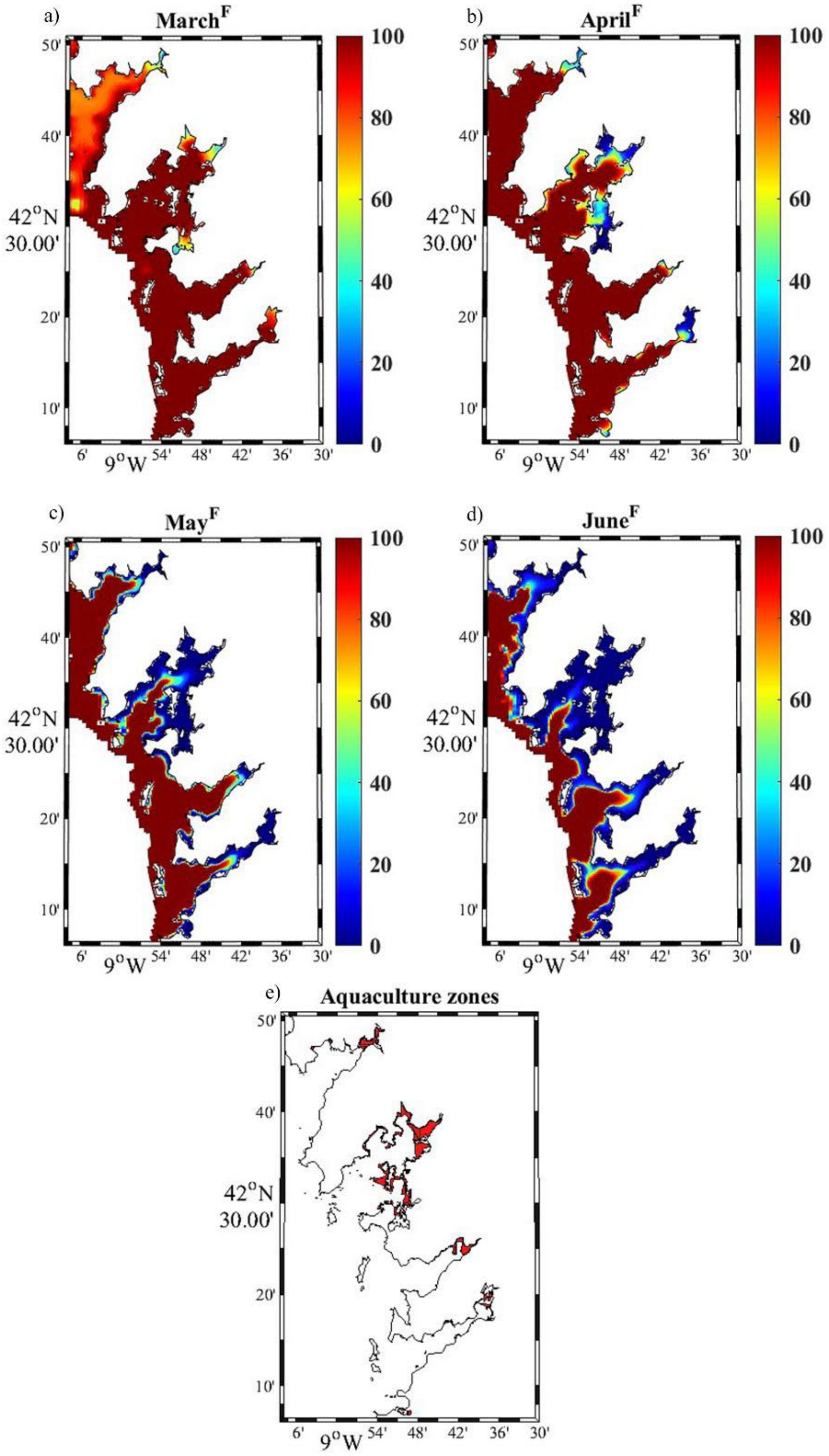

Figure 11. Monthly *Cerastoderma edule* spawning predictor (%) in the Rías Baixas from March to June (a-d) for the future period under RCP8.5 scenario (2080-2099). (e) Areas of current harvesting.

3.1.3. Ruditapes decussatus

Following the literature, the optimal peak spawning temperature for *R. decussatus* was set between 19 and 23ºC.

During the historical period (Figure 12), bottom water temperature is likely to begin within the spawning peak range in May in the internal areas of the Rías of Arousa and Vigo, with values over 60% of the time. A higher percentage of time is observed in June, when suitable spawning conditions are observed in most cultivation areas.

The data for the future period (Figure 13) shows an earlier spawning peak in April, with values over 60% of the time, reaching 80% in the inner areas of Ría de Arousa and Ría de Vigo. May is the month in which the temperature is optimal in most of the culture banks, while in June, the conditions worsen in the shallower areas, observing a displacement towards deeper areas. In the case of *R. decussatus*, the spawning peak could be brought forward one month.

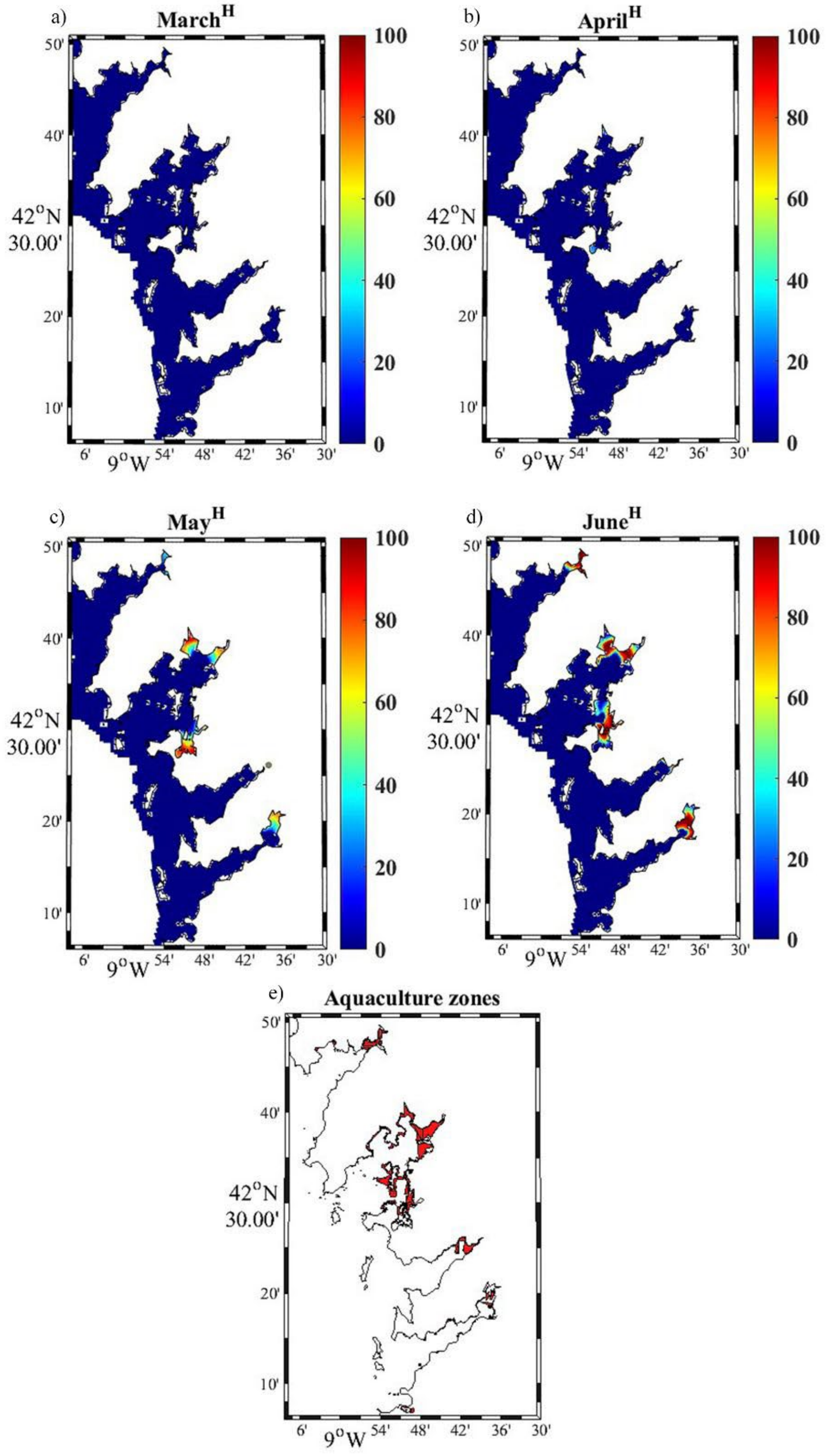

Figure 12. Monthly *Ruditapes decussatus* spawning predictor (%) in the Rías Baixas from March to June (a-d) for the historical period (2000-2019). (e) Areas of current harvesting.

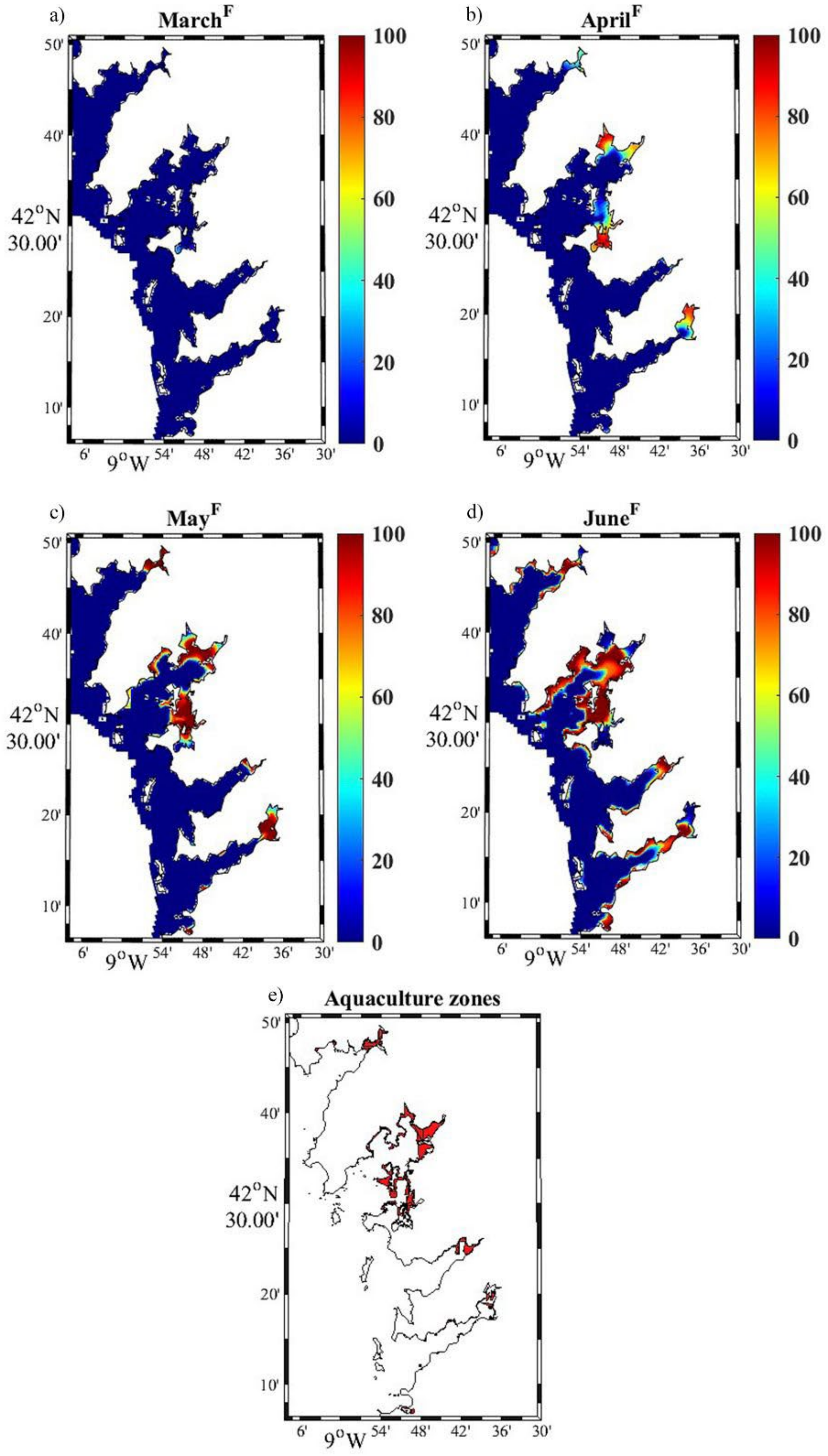

Figure 13. Monthly *Ruditapes decussatus* spawning predictor (%) in the Rías Baixas from March to June (a-d) for the future period under RCP8.5 scenario (2080-2099). (e) Areas of current harvesting.

3.1.4. Venerupis corrugata

Following the literature, the optimal peak spawning temperature for *V. corrugata* was set between 12 and 15ºC.

In the case of *V. corrugata,* the most suitable water temperature conditions for spawning are observed in March for the historical period (Figure 14a). In April, temperature exceeds the maximum threshold in the shallowest areas and is overpassed in May and June in all the cultivation polygons. The results for the future period (Figure 15) show that the peak spawning season does not occur in any of the analyzed months.

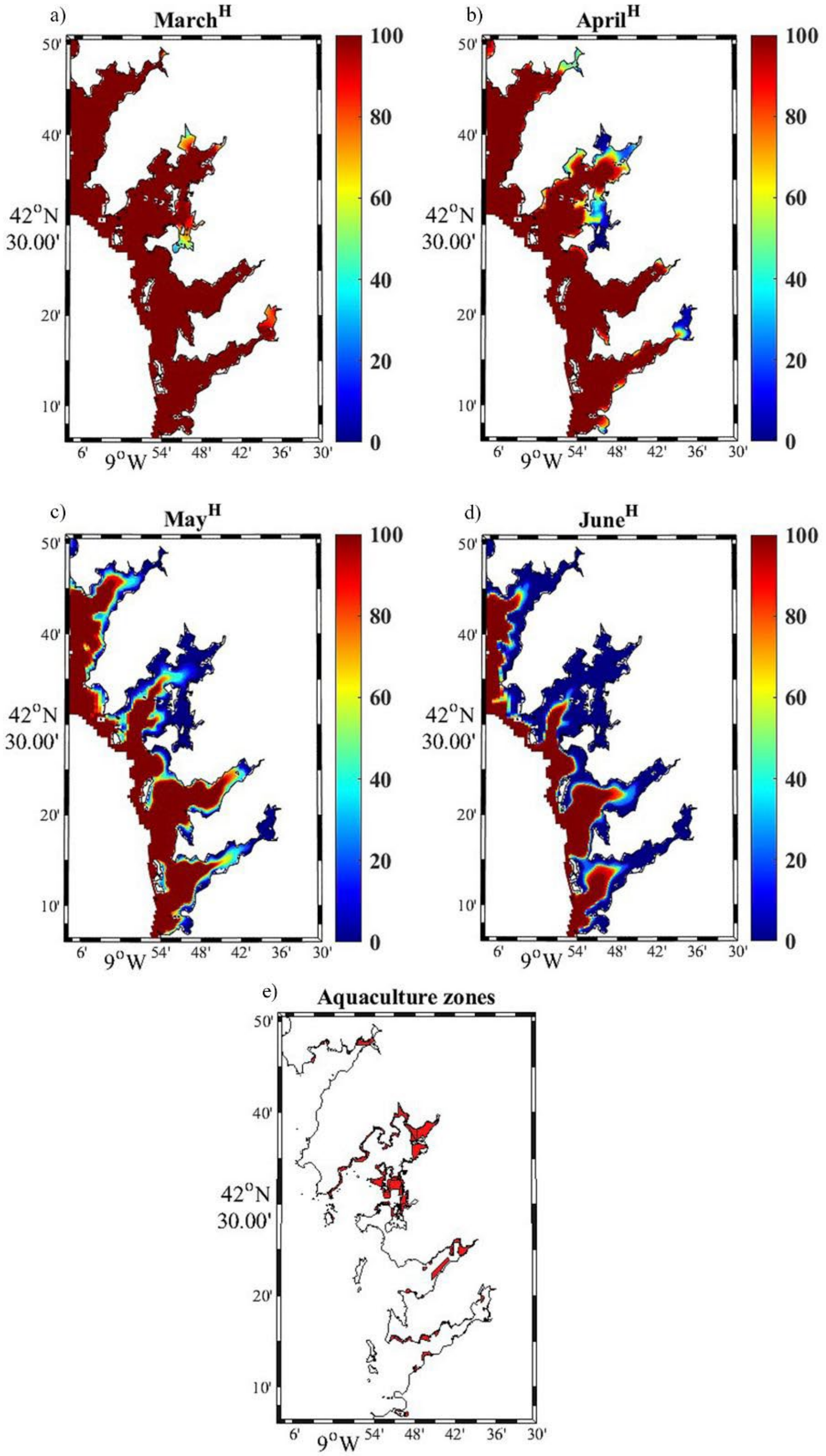

Figure 14. Monthly *Venerupis corrugata* spawning predictor (%) in the Rías Baixas from March to June (a-d) for the historical period (2000-2019). (e) Areas of current harvesting.

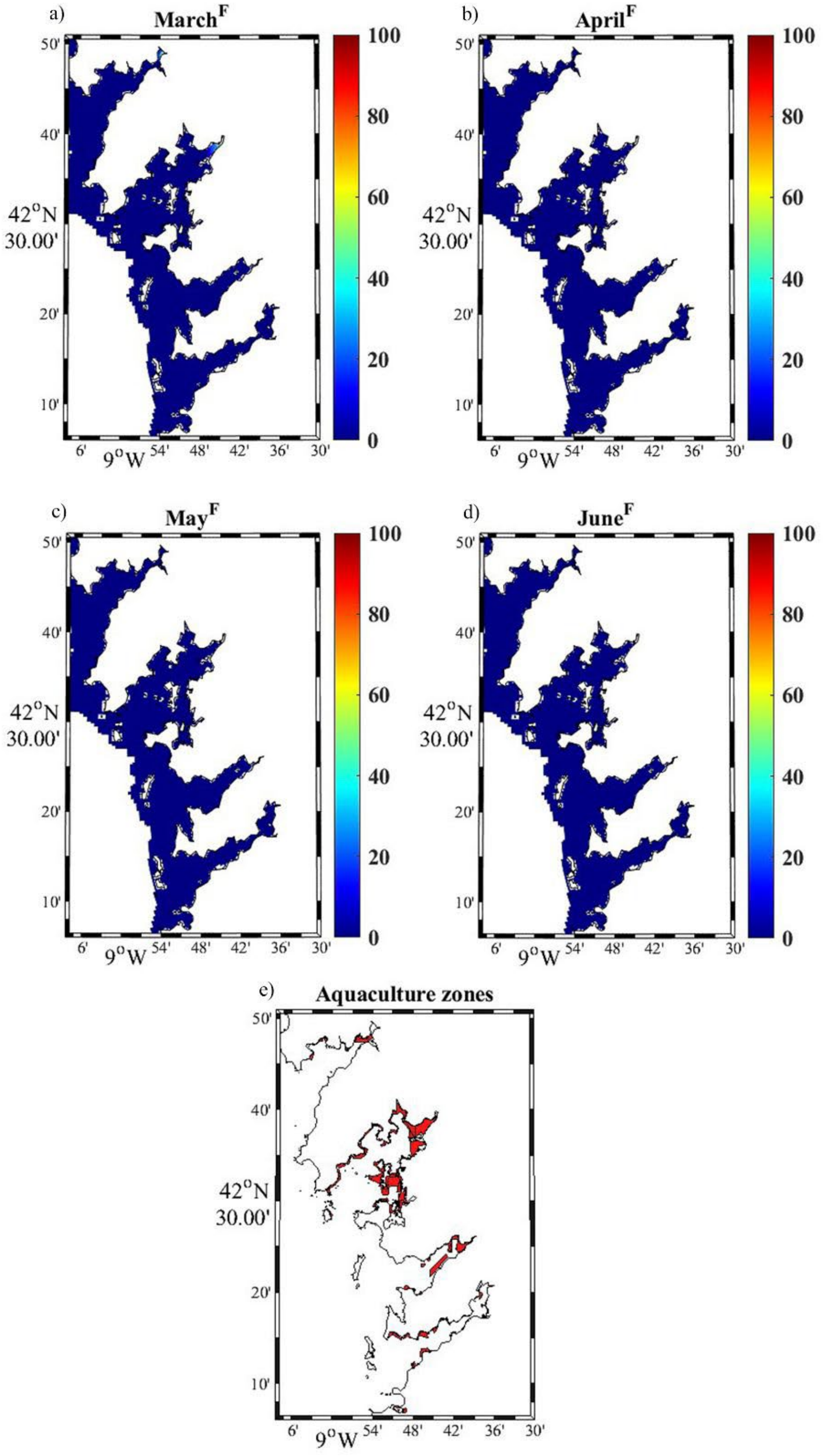

Figure 15. Monthly *Venerupis corrugata* spawning predictor (%) in the Rías Baixas from March to June (a-d) for the future period under RCP8.5 scenario (2080-2099). (e) Areas of current harvesting.

3.2. Salinity

Generally, modelled salinity projects a decrease in the areas most influenced by oceanic conditions and an increase in those affected by river discharges, with a maximum increase of approximately 2 PSU in March, 4 PSU in April, 6 PSU in May and 3 PSU in June. During the historical period, salinity in the cultivation areas fluctuates within the optimal range for *V. corrugata* (14-28 PSU) and *C. edule* (15-30 PSU) threshold, whereas for *R. philippinarum (*20-30 PSU*)* and *R.decussatus* (20-28 PSU) is slightly lower. The projected increase in salinity in those areas may favour those species.

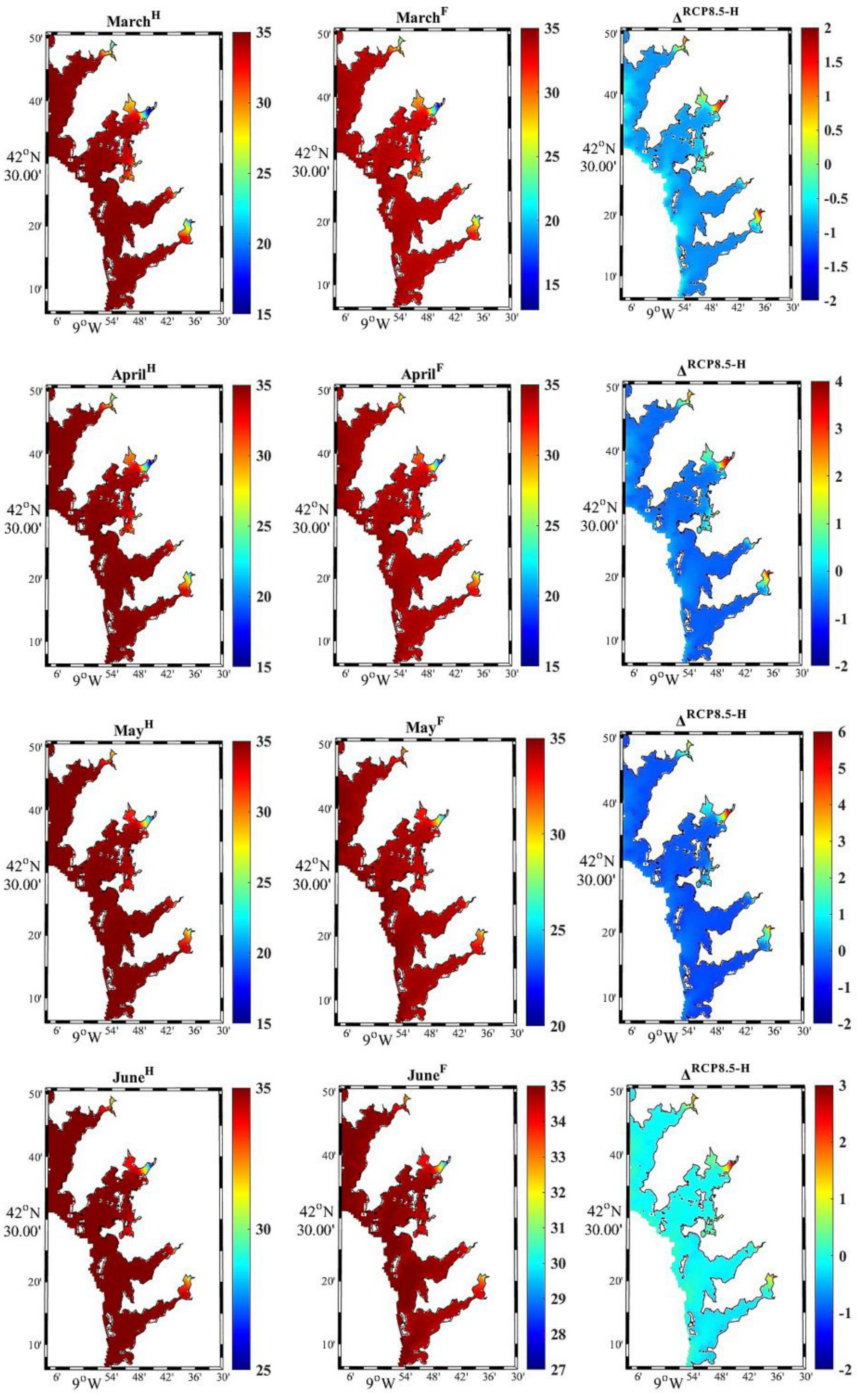

Figure 16. Mean bottom salinity (PSU) in the Rías Baixas from March to June for historical (H, 2000-2019, left panels), future under RCP8.5 scenario (F, 2080-2099, central panels) and its variation (Future-Historic, right panel) from March to June. Colourbar varies from figure to figure.

4. Discussion

The successful reproduction of species plays a vital role in their survival. However, the process of reproduction itself imposes physiological stress on individuals (Garmendia *et al.*, 2010). Consequently, any additional external stress experienced during the reproductive period can have a profound impact. This is because individuals must allocate a significant amount of energy towards meeting maintenance costs (Cáceres-Martinez & Figueras, 1998), leaving limited energy available for growth, storage, and reproduction. The imposition of exogenous stressors during this critical period can have dramatic consequences, affecting the ability of organisms to survive and reproduce successfully.

Comparison between the historical spawning peak predictor and predicted one under an RCP8.5 scenario allows, alongside the average temperature and salinity variation, to determine how the increase in temperature due to climate change could affect the species of interest *Ruditapes philippinarum*, *Cerastoderma edule*, *Ruditapes decussatus* y *Venerupis corrugata* in Rías Baixas. As temperature is one of the main climatic factors that regulate bivalves reproduction (Domínguez *et al.,* 2021) and the most affected by ocean warming, this is it has been selected for this study as spawning predictor. The spawning period comprises an extensive range, encompassing *R. philippinarum* from December to February, *C. edule* from March to October, *R.decussatus* continuously spawning and *V. corrugata* from February to July. However, a noticeable peak spawning occurs in July, May, April-June and March-May, respectively (Tabla 3). Simultaneously with these spawning peaks, the upwelling season begins in Rías Baixas, causing an increase in nutrient concentration in the environment. These upwelled nutrients supply the bivalve communities with feeding content needed to recover from the consumed energy during the spawning and improve the larvae survival possibilities (Holland, 1978).

Bottom water temperature variation shows a general rising in the area of study when compared to the historical data, being the inner side of the Rías, where cultivation of the bivalves of interest takes place, is the most affected, as has been stated in previous studies (Castro-Olivares *et al.* 2022; Silva *et al.*, 2017).

Our results show that ocean warming in the area will range from 2.5ºC to 4ºC by the end of the century. These values agree with the increase of 3ºC projected by Silva *et al*. (2017).

Through the historical period, the model was able to predict the peak spawning period for *R. decussatus*, *C. edule*, and *V. corrugata* in cultured areas. However, for *R. philippinarum*, verifying the alignment of the spawning peak period with the available literature was impossible because the model was not run for July.

In a future scenario, the spawning predictor proposed in this work indicates that the spawning peak may come ahead. Model outputs by the end of the century showed a general increase in bottom temperatures above the spawning limits of the species, reaching temperatures of up to 26ºC in the shallower areas close to the river's mouth. Those conditions may be reached in months in which this peak occurs in the historical period and might be detrimental to the spawning of the species or even to the species themselves, potentially reducing their scope for growth, reducing their burial ability or even causing mortality events (Aranguren *et al*., 2014; Domínguez *et al.*, 2021). Climate change is also linked with increased occurrence and intensity of anomalous events such as heat waves and precipitation. These high temperatures and the heat waves effect can cause gonadal resorption and a reduction in the burial of *C. edule, V. corrugata* and *R decussatus* (Vázquez *et al.*, 2021). Although it is known, the adaptation ability of these species to dim temperature changes (Domínguez *et al.*, 2021) and the closure of valves during low salinity episodes to avoid mineral losses from the mantle and reduce their physiological activity (Pteiro *et al.*, 2018). Besides this strategy, upwelling events might buffer the temperature increases because of the cold, nutrient-rich water reaching the surface (Bograd *et al*., 2022). Some authors have stated that wind force might intensify, increasing upwelling phenomena in poleward areas (García-Reyes *et al*., 2015) such as the Rías Baixas. Nevertheless, the increase in stratification led by ocean warming might counteract the increase in the upwelling index (Sousa *et al*., 2020), reducing its cooling capability.

As for the mean salinity, it can be seen that it is expected an increase in the salinity in the areas affected by the river discharges. It is due to the projection of a reduction in river discharge for each month studied, calculated by averaging all the river discharge results from all the global models that make up the hype web portal under this scenario. Since those are climatological results, it does not mean that the areas will not be affected by salinity drops caused by extreme precipitation events, which could negatively affect the analyzed species, even to a greater extent, if their spawning is brought forward. Domínguez *et a1.* (2020) set forth how the targeted species of this study can be damaged by low salinity events within a few days, *R. decussatus* and *V. corrugata* being the most affected, even though they can recover after the stressor ceases. Conversely, Parada *et al.* (2012) and Pteiro *et al.* (2018) stated that exposure to moderate salinities of 15 PSU over a few days can cause mortality.

The salinity results show that the Ria de Arousa has less salinity than the rest of the Rías. This can be explained by the fact that the Arousa estuary has two rivers that flow into it, one of them the Ulla, which is the river that transports the larger volume of fresh water to the estuaries (Figure 6). This ria supports the largest production of the species, and salinity drops might negatively affect the sector (Des *et al*. 2021).

According to the results, compared to the literature (Vázquez *et al.*, 2021), the variation in salinity is so tiny that, *a priori*, it should not cause problems in the reproduction of the species of interest. Nevertheless, we must take into account that if the spawning period is brought forward due to the increase in temperatures, it is more likely to coincide with low salinity events – that are likely to occur - could lead to alterations of the gonadal cycle, as well as suspension or mortality of species.

In the specific case of *R. decussatus*, model results show a temperature higher than 23ºC in its cultivation areas in May and July. This should not be a problem for *R. decussatus* because it is the most temperature stress-tolerant of the species of interest. However, previous studies (Rato *et al.*, 2022) show that temperatures above 23ºC in conjunction with low salinity events may cause mortality of *R. decussatus.* Salinity results display an increase within the cultivation areas that could dim this effect. Nevertheless, the enhancement of extreme precipitation events could result in the simultaneous interaction o flow salinity and high temperatures leading to the death of the communities.

Recognizing the significance of climate variability and extreme events, and their interplay with other stressors, is crucial in comprehending how ecosystems respond to long-term climate change. It also helps predict regional-scale economic, societal, and ecological implications. As various species react differently to climate change, it becomes apparent that ecosystems undergo reorganization and experience shifts in their functions, ultimately influencing the benefits they provide to humanity (Poloczanska *et al.*, 2016).

Halting or reversing global warming within the next 100 years, possibly even longer, will be extremely challenging. As a result, it becomes essential to adopt additional strategies to mitigate the potential detrimental impacts of climate change on coastal marine systems. Significant scientific advancements have been made, and they will play a crucial role in achieving current and future conservation and management objectives. However, there are several key areas that still require further investigation. Alongside temperature, it is imperative to thoroughly examine the implications of climate-related variables such as CO_2 and pH. These factors must be more comprehensively considered to gain a deeper understanding of their effects and to develop effective measures for conservation and management in coastal marine systems.

As far as aquaculture is concerned, measures, such as management plans (Dominguez *et al.*, 2023), must be implemented to avoid the negative economic effects that the impact of global change on bivalves may have. More studies are needed on how climate change impacts affect bivalves of socio-economic interest in the Rías Baixas in order to assess the joint effects of different impacts.

5. Summary and conclusions

The main objective of this master's thesis is to investigate the potential impacts of climate change, specifically the increase in bottom water temperature, on the peak spawning period of economically important aquaculture species, *Ruditapes philippinarum*, *Cerastoderma edule*, *Ruditapes decussatus*, and *Venerupis corrugata*, in the Rías Baixas. To achieve this goal, the hydrodynamics of these rias during March and June were simulated for both the historical period (2000-2019) and the future period (2080-2099) using the Delft3D-Flow numerical model and considering the RCP8.5 scenario. Thorough literature review, a spawning predictor was defined and used to analyze model outputs. This predictor considers the percentage of time when the bottom water temperature falls within the optimal range for peak spawning.

The initial hypothesis proposed in this study has been confirmed, since model outputs suggest that the peak spawning periods for *R. philippinarum*, *C. edule*, *R. decussatus*, and *V. corrugata* could be brought forward by the end of the century.

The following conclusions can be drawn from this research:

- In general, the peak spawning period for all the studied species might be brought forwared under future scenarios.
- In the inner zones of the rias, ocean warming might have a negative impact on the spawning period of the target species due to exceeding the average spawning temperature. The optimal range for their spawning and proper growth might also be overpassed in some cases.
- Based on the model results, changes in salinity might not have a relevant effect on spawning.
- The combination of extreme precipitation events and the projected rising temperature could lead to potential mortality or spawning damage, such as gamete deformation.
- These impacts will affect the aquaculture areas of the target species unless emissions are reduced to avoid reaching the RCP8.5 scenario. It is essential to implement management plans to mitigate the effects of climate change on the aquaculture sector.

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Annexe

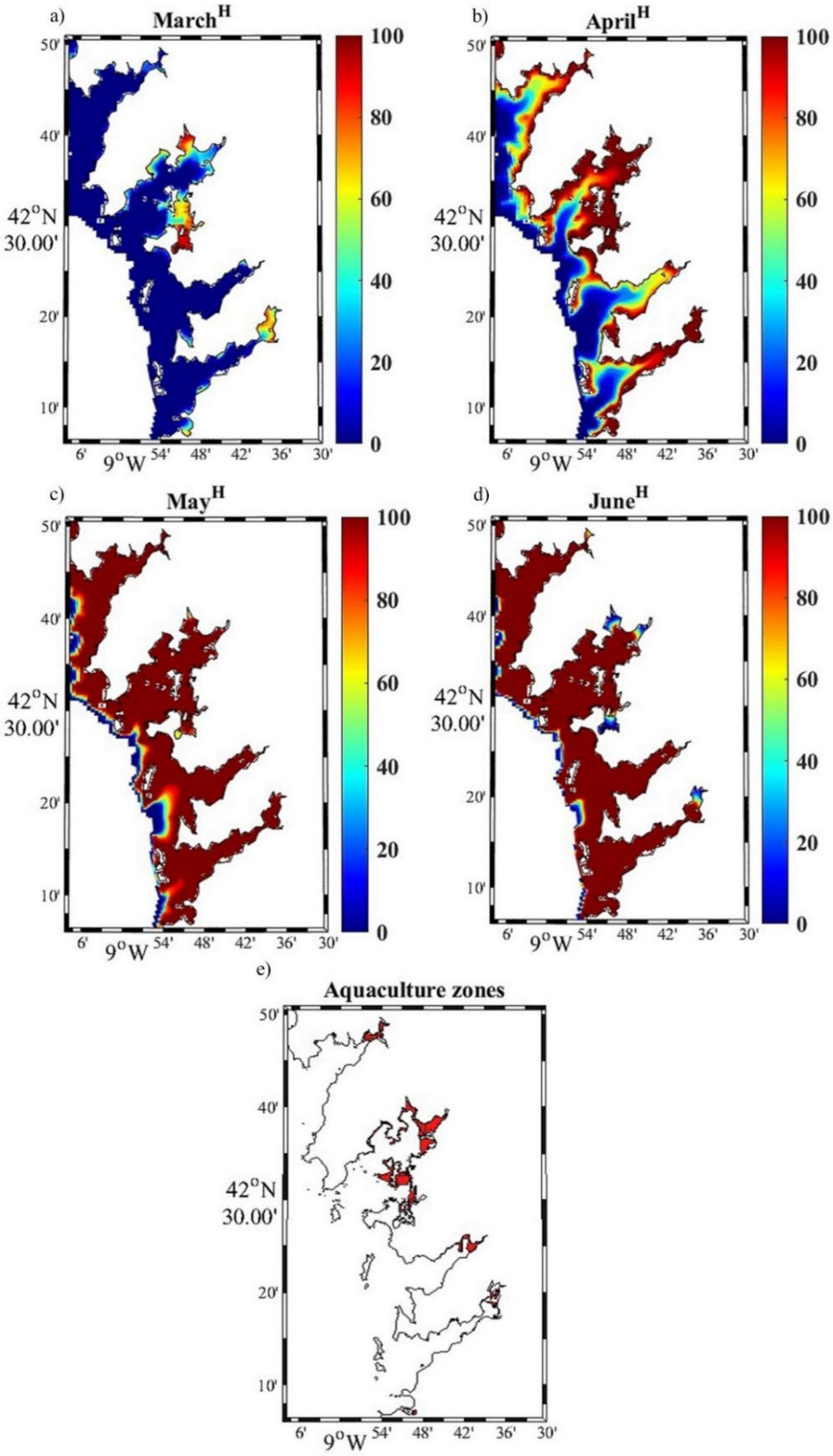

Figure A1. Monthly *Ruditapes philippinarum* percentage of time at which water temperature is within spawning threshold (%) in the Rías Baixas from March to June (a-d) for the historical period (2000-2019). (e) Areas of current harvesting.

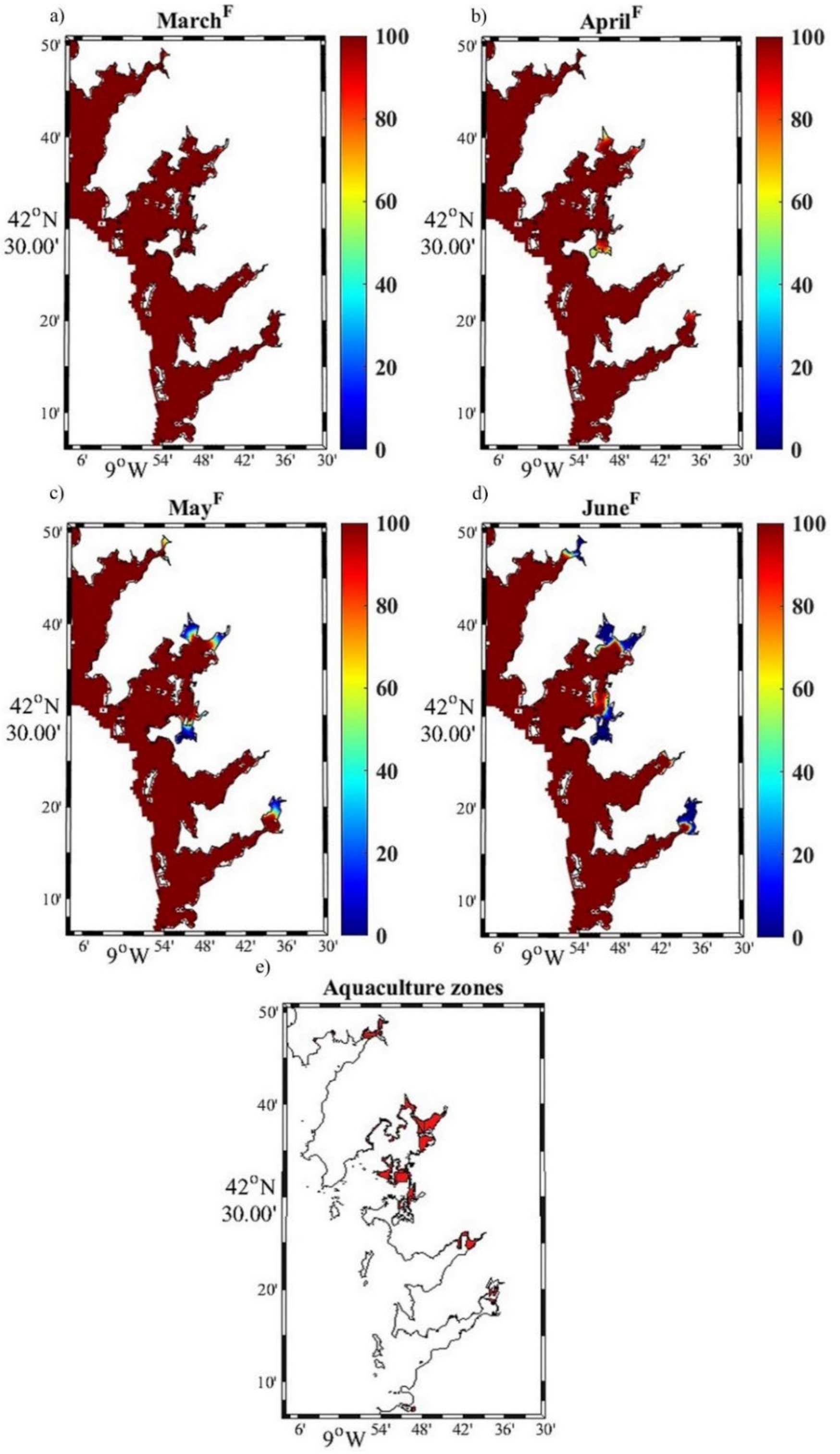

Figure A2. Monthly *Ruditapes philippinarum* percentage of time at which water temperature is within spawning threshold (%) in the Rías Baixas from March to June (a-d) for the future period under RCP8.5 scenario (2080-2099). (e) Areas of current harvesting.

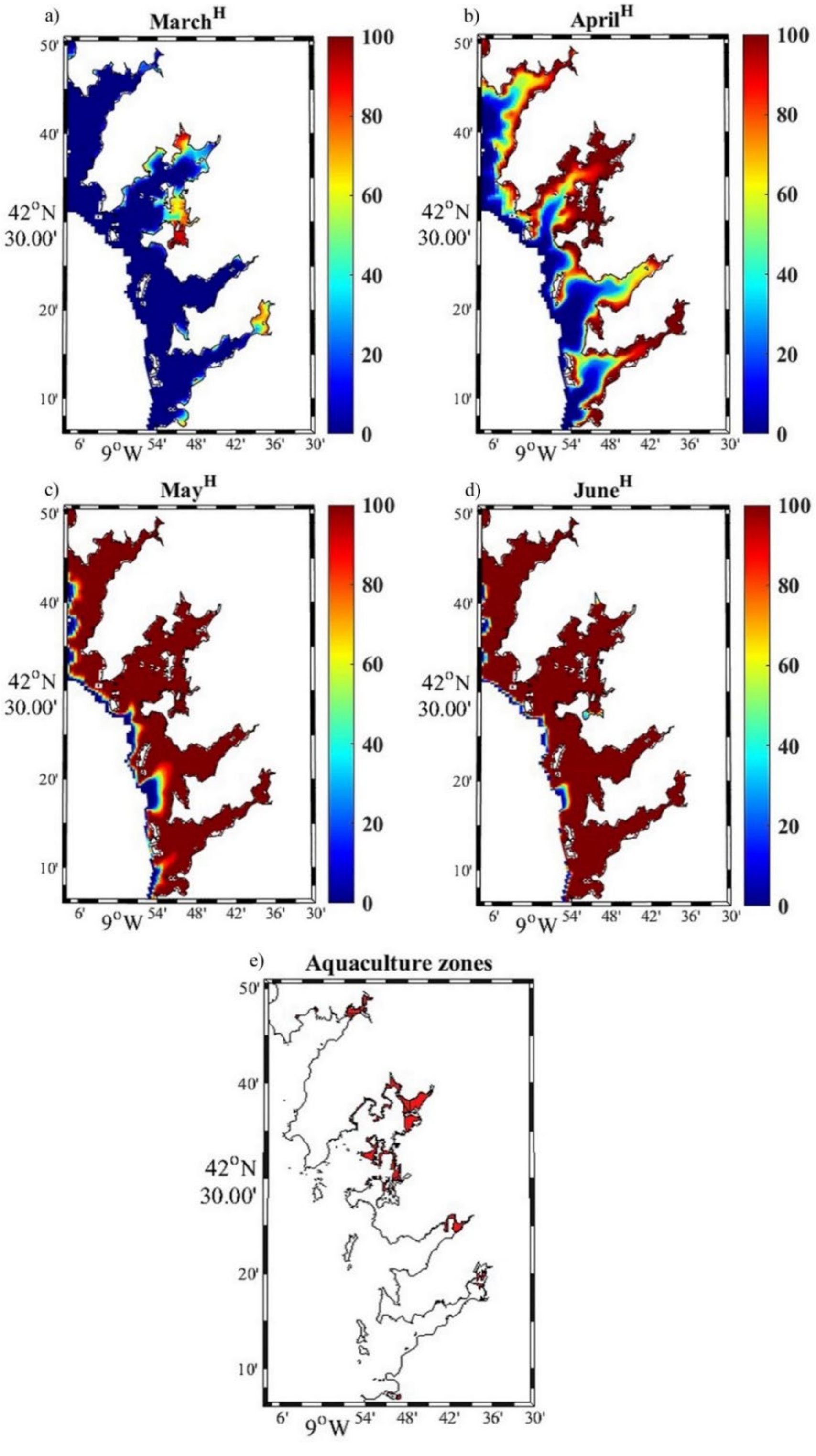

Figure A3. Monthly *Cerastoderma edule* percentage of time at which water temperature is within spawning threshold (%) in the Rías Baixas from March to June (a-d) for the historical period (2000-2019). (e) Areas of current harvesting.

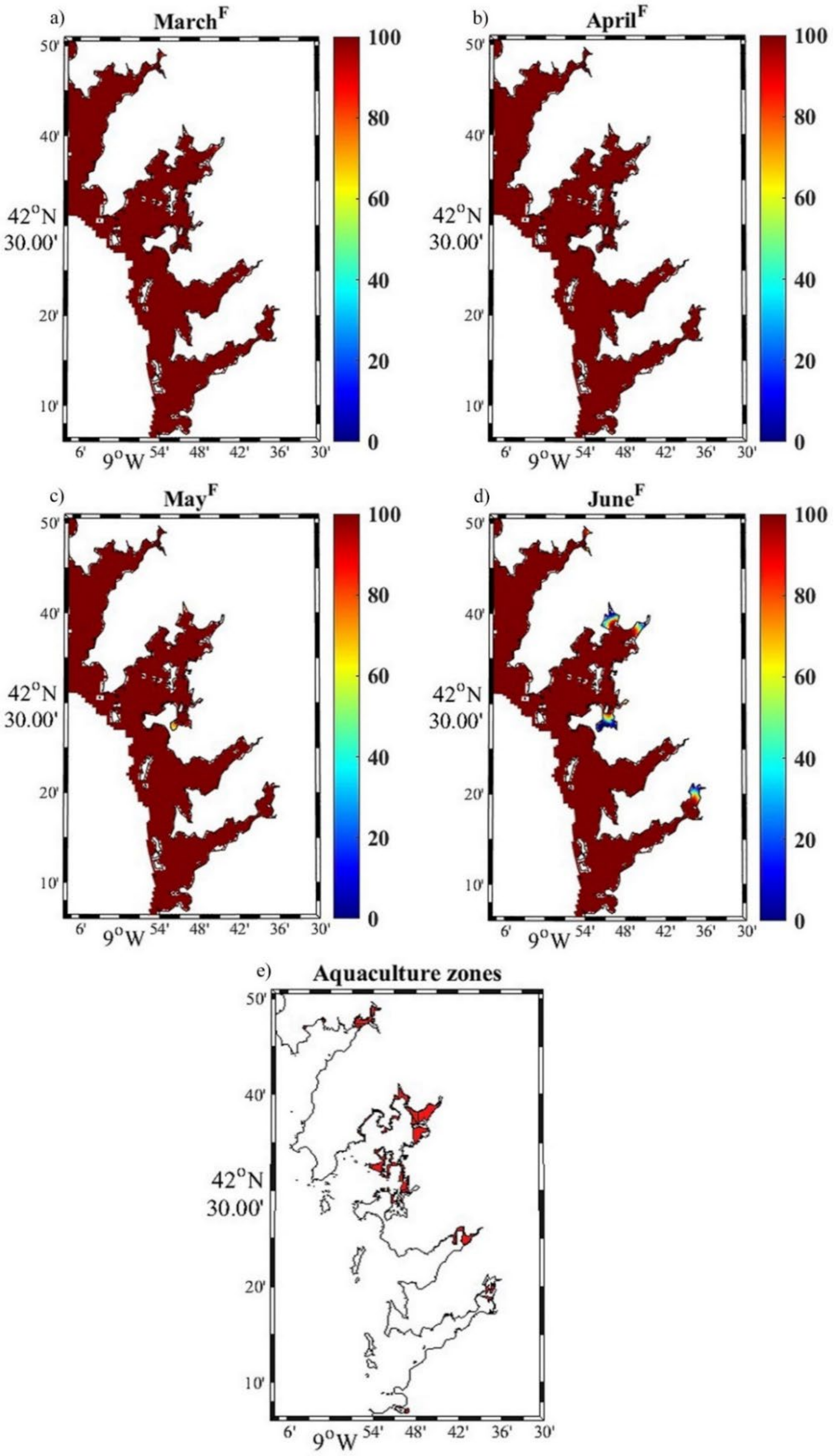

Figure A4. Monthly *Cerastoderma edule* percentage of time at which water temperature is within spawning threshold (%) in the Rías Baixas from March to June (a-d) for the future period under RCP8.5 scenario (2080-2099). (e) Areas of current harvesting.

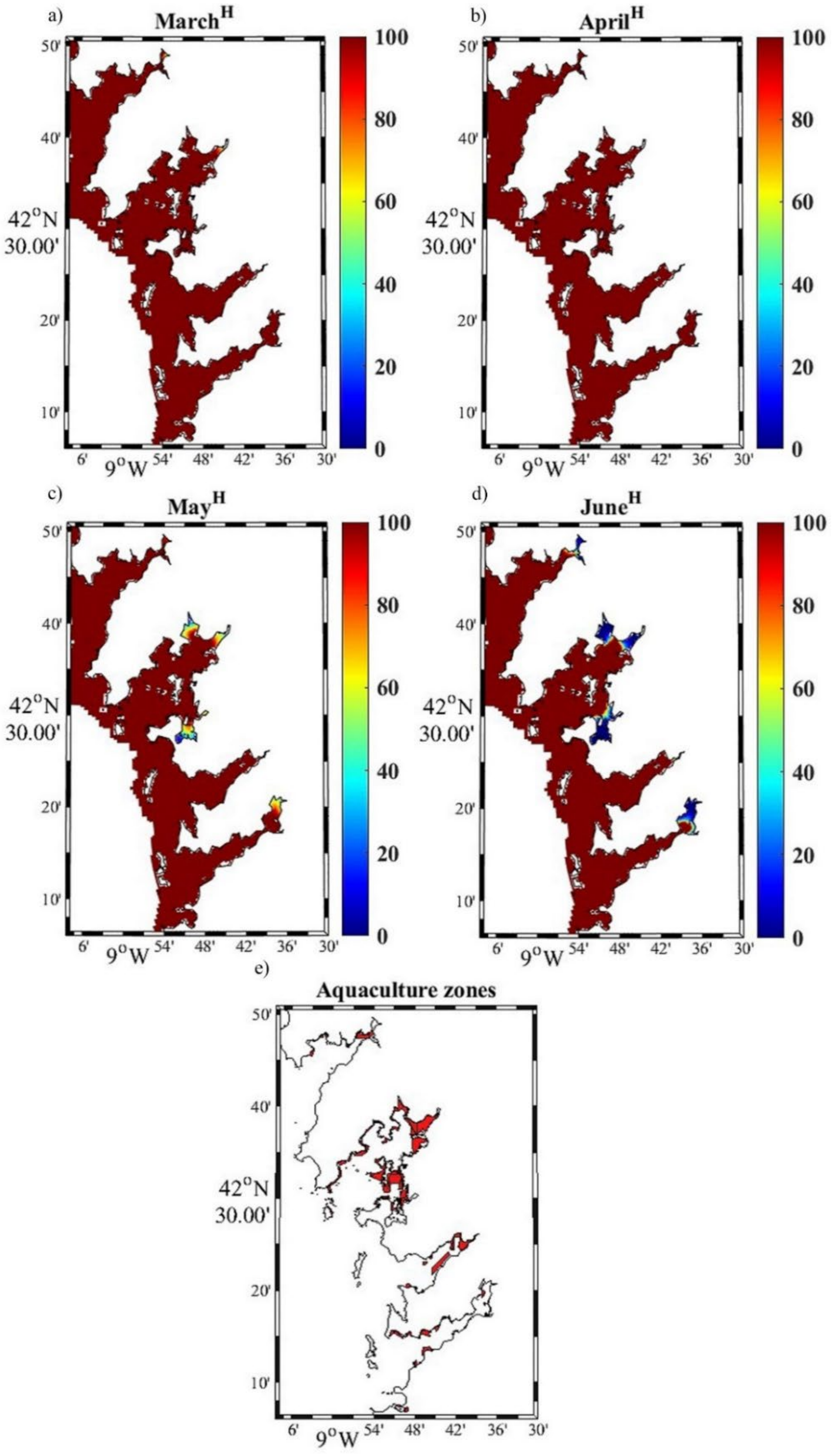

Figure A5. Monthly *Venerupis corrugata* percentage of time at which water temperature is within spawning threshold (%) in the Rías Baixas from March to June (a-d) for the historical period (2000-2019). (e) Areas of current harvesting.

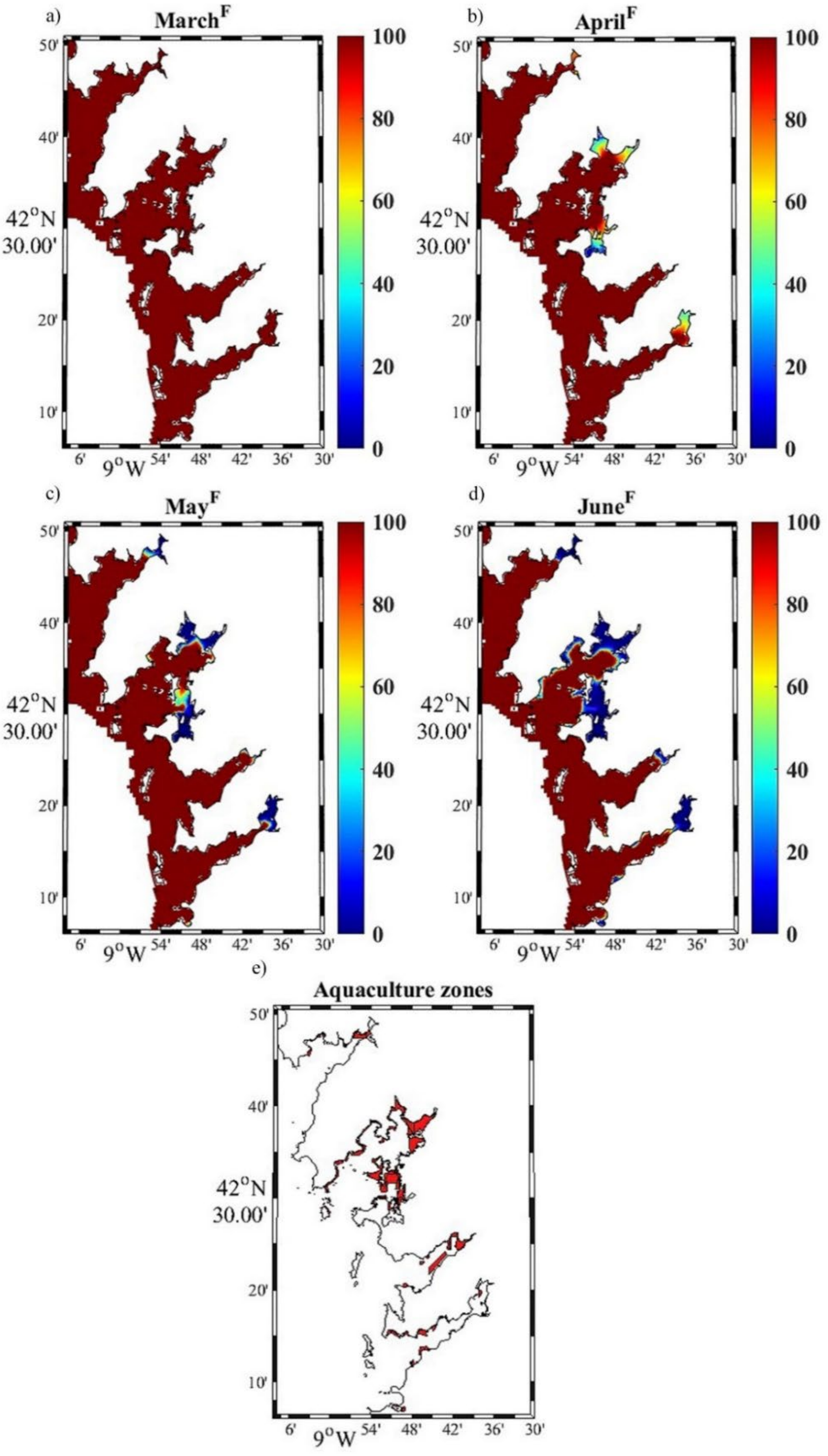

Figure A6. Monthly *Venerupis corrugata* percentage of time at which water temperature is within spawning threshold (%) in the Rías Baixas from March to June (a-d) for the future period under RCP8.5 scenario (2080-2099). (e) Areas of current harvesting.