



Modeling the impact of climate change on mussel aquaculture in a coastal upwelling system: A critical assessment

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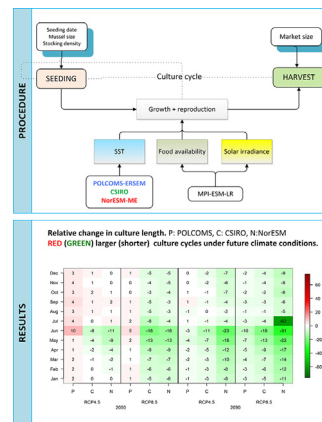
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HIGHLIGHTS

- We forecast climate change impacts on Galician mussel aquaculture.
- Bias correction is required when using ocean climate models in a coastal farm area.
- Uncertainty of SST projections is larger between models than between scenarios.
- Interaction between the farming schedule and seasonal environmental variability determine aquaculture production.
- The projected impact of climate change on mussel aquaculture is minor.

GRAPHICAL ABSTRACT



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ABSTRACT

Forecasting of climate change impacts on marine aquaculture production has become a major research task, which requires taking into account the biases and uncertainties arising from ocean climate models in coastal areas, as well as considering culture management strategies. Focusing on the suspended mussel culture in the NW Iberian coastal upwelling system, we simulated current and future mussel growth by means of a multistructural net production Dynamic Energy Budget (DEB) model. We considered two scenarios and three ocean climate models to account for climate uncertainty, and applied a bias correction to the climate models in coastal areas. Our results show that the predicted impact of climate change on mussel growth is low compared with the role of the seeding time. However, the response of mussels varied across climate models, ranging from a minor growth decline to a moderate growth increase. Therefore, this work confirms that an accurate forecasting of climate change impacts on shellfish aquaculture should take into account the variability linked to both management strategies and climate uncertainty.

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1. Introduction

Climate change is producing an unprecedented effect on the marine environment, which may have significant implications for fisheries and

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aquaculture (Barange et al., 2018; Bindoff et al., 2019; Freer et al., 2018; Handisyde et al., 2017). Aquaculture is one of the fastest growing food production sectors in the world and is now responsible for more than half of the global seafood production (FAO, 2018). Particularly, bivalve aquaculture is one of the most sustainable seafood resources (Froehlich et al., 2018). Bivalve aquaculture also provides ecosystem services such as nutrients removal in eutrophicated areas or carbon sequestration (Filgueira et al., 2019; Lindahl et al., 2005; van der Schatte Olivier et al., 2020). However, this production activity is highly dependent on the local environmental conditions and, consequently, sensitive to climate change (Barange et al., 2018; Handisyde et al., 2017). Therefore, the implementation of climate adaptation strategies is crucial to guarantee a sustainable aquaculture in the future, that is to maintain or even increase its production under climate change conditions but minimize its environmental impact (Ahmed et al., 2019). These strategies have to be supported by accurate local-scale predictions of climate related changes in key environmental factors such as seawater temperature or primary production to forecast their potential effects on bivalve aquaculture (Des et al., 2020; Falconer et al., 2020; FAO, 2018).

In bivalve aquaculture food is provided by the environment, primarily from phytoplankton primary production (Froehlich et al., 2018). In this regard, coastal upwelling areas are among the most productive marine ecosystems due to phytoplankton growth stimulation by wind-driven transport of cold and nutrient-rich waters from the deep ocean to the coast. These coastal ecosystems are optimal environments for marine bivalve aquaculture (FAO, 2018; Kämpf and Chapman, 2016; Varela et al., 2018), although since nutrient-rich upwelled waters are characterized by low pH values (Feely et al., 2008; Hernandez-Ayon et al., 2019; Mohrholz et al., 2008; Vargas et al., 2016), both the opposite effects of fertilization and ocean acidification on mussel culture should be accounted. In this sense, seawater temperature and food availability and quality do not only dictate mussel growth (Fuentes-Santos et al.,

2017; Montalto et al., 2016; Pérez-Camacho et al., 1995) but are also crucial factors in the response of bivalves to ocean acidification (Kroeker et al., 2014; Lassoued et al., 2019; Ramajo et al., 2016). In particular, the Galician rías (Fig. 1), a group of coastal inlets at the northern limit of the Canary Current Eastern Boundary Upwelling Ecosystems (EBUE), are extraordinary places for the suspended culture of the Mediterranean mussel, *Mytilus galloprovincialis*. In fact, Galician *M. galloprovincialis* mussel aquaculture, with a production ranging between 183,000 and 264,000 tones/year over the period 2007–2015, is the main aquaculture industry in Spain and produces 40% of cultured mussels in Europe (Labarta and Fernández-Reiriz, 2019). Fertilization with the well-oxygenated and relatively high pH upwelled Eastern North Atlantic Central Water (Castro et al., 2000) minimizes the impact of ocean acidification in the area for the next decades. Therefore, analyzing how climate induced changes in seawater temperature or primary production may affect Galician mussel aquaculture is crucial to evaluate the future sustainability of the sector.

Upwelling favorable coastal winds have intensified in the major (EBUEs), but have weakened in the Iberian margin of the Canary Current EBUE (Sydeman et al., 2014). Future climate projections suggest an intensification of the upwelling-favorable winds through this century at the high latitudinal range of the major EBUEs, while winds will weaken at the low latitudinal range (Rykaczewski et al., 2015). Upwelling intensification has increased and is expected to keep increasing acidification and desoxygenation in the two Pacific EBUEs (Garca-Reyes et al., 2015; Levin, 2018), but dampers acidification in the Canary Current EBUE (Lachkar, 2014). Upwelling intensification may counteract the global ocean warming trend, resulting in lower water temperature increases nearshore (Garca-Reyes et al., 2015; Varela et al., 2018). However, these global trends are affected by a large local-scale variability not captured by the available global ocean models. Therefore, climate change impacts on key factors for fisheries and aquaculture in EBUEs, such as

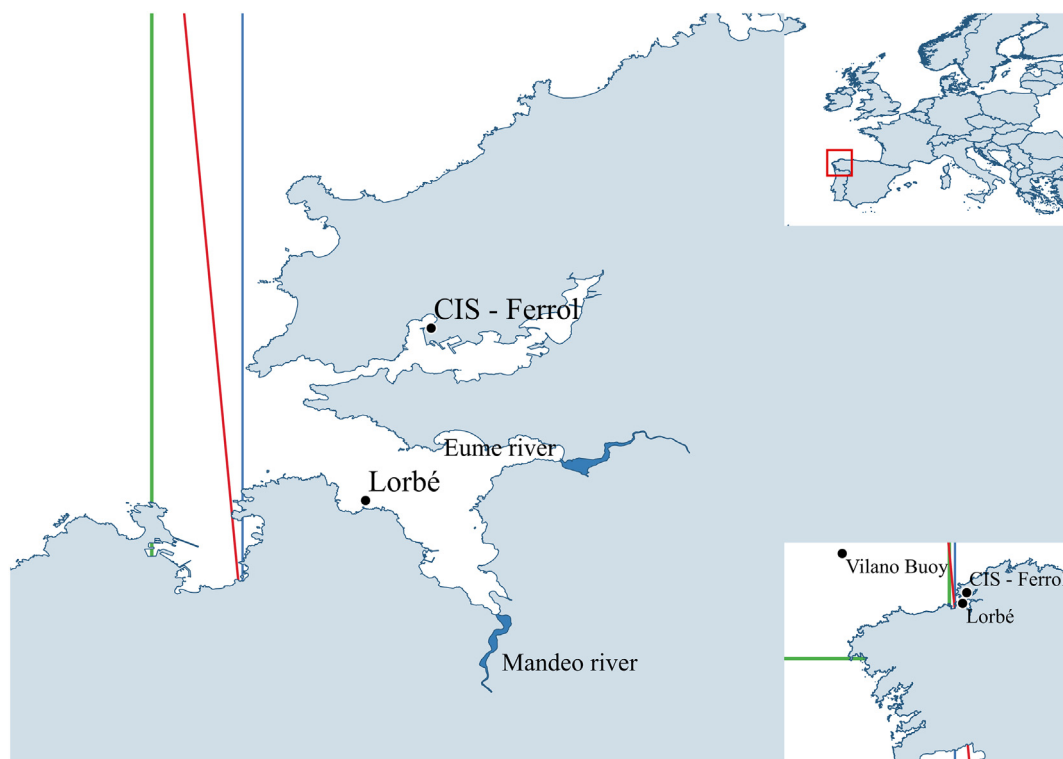


Fig. 1. Location of the study area, Ría de Ares-Betanzos (NW Iberian upwelling system). Sea surface temperature and food availability measures were conducted in Lorbé, located in the inner-southern shore. Rivers Eume and Mandeo (continental runoff), Vilano Buoy (wind regime), and CIS-Ferrol meteorological station (solar irradiance). Solid lines indicate the boundary of the POLCOMS-ERSEM (blue), CSIRO-Mk3.6.0 (green) and NorESM-ME (red) ocean model domains. The map has been generated with QGIS (QGIS Delopment Team, 2020).

seawater temperatures, the interaction between wind and stratification and their effects on primary production, remain uncertain (Barange et al., 2018; Garca-Reyes et al., 2015; Varela et al., 2018).

The assessment of climate change impacts in marine aquaculture has mainly focused on testing for the effects on the growth of cultured fish (Sarà et al., 2018; Stavrakidis-Zachou et al., 2019) and shellfish species (Cheng et al., 2018; Filgueira et al., 2016; Montalto et al., 2016). The common practice in this research field consists of using a biological model, which estimates the performance of the target organism under variable environmental conditions, in combination with a global or regional climate model, which provides future projections for the environmental drivers of the biological model (Filgueira et al., 2016; Montalto et al., 2016; Sarà et al., 2018; Stavrakidis-Zachou et al., 2019). However, this procedure suffers from some biases and uncertainties that have not been considered in these works. The bias, i.e. discrepancy between observed data and model outputs, arises from the use of global ocean climate models with coarse spatial resolution in coastal areas that fall in the boundary or even outside their spatial domain. These models cannot capture the large local environmental variability of coastal aquaculture areas and, consequently, may lead to mistaken estimations of climate change impacts on these areas (Falconer et al., 2020; Freer et al., 2018). Climate uncertainty, i.e. the variability between future climate projections, can be seen as a cascade with three main levels: scenario uncertainty, model uncertainty and internal variability (Freer et al., 2018). Scenario uncertainty stems from the different emission pathways, and it is the main source of variability in projections of ocean stressors (Frölicher et al., 2016). Model uncertainty, i.e. variability between climate models, may have a larger impact than scenario uncertainties on SST projections at high latitudes until the end of the century (Hawkins and Sutton, 2009). Internal variability, which stems from different realizations in a climate model, dominates the variability of projections at shorter timescales for pH, SST, and subsurface oxygen, but remains an important source of uncertainty for primary production towards the end of the twenty-first century (Frölicher et al., 2016).

In this context, this work aims to conduct a critical assessment of climate change impact on mussel aquaculture through the analysis of a particular case study, the suspended mussel aquaculture in the Galician rías (NW Iberian upwelling system). For this purpose, given that we are dealing with a production system, in addition to the environmental conditions, we consider the role of management strategies, such as the seeding time and harvesting target sizes, that allow farmers to adapt the culture schedule to the seasonality of the environmental conditions. Therefore, we have conducted a simulation study that compares the growth of mussels under current and future climate conditions and accounts for the interaction between culture management strategies and climate change, considering the biases and uncertainties derived from the use of coarse scale climate models to predict local climate change impacts. We first considered two emission pathways and three climate models to account for climate uncertainty. Then, we corrected the bias of each climate model. Finally, for each seeding time and harvesting size, we fed our biological model with these bias corrected climate conditions on a decadal basis to account for their interannual variability.

2. Material and methods

We simulated mussel growth under current and future climate conditions in the Ría de Ares-Betanzos, the northernmost of the Galician rías with mussel farms (Fig. 1). Different seeding dates and harvest sizes were also considered to evaluate the role of management strategies. Therefore, this simulation study is structured around three main elements: (i) the management strategies that determine the beginning and end of the simulated cultures; (ii) the multistructural net production DEB model (Fuentes-Santos et al., 2019); and (iii) the model inputs, i.e. environmental conditions driving the growth performance of mussels.

Taking into account the current aquaculture practices in Galicia, we used a shell length of 15 mm as seeding size, and simulated mussel growth using the first day of each month as seeding dates. In agreement with the current market classification in Galicia (Pérez-Camacho et al., 2013), harvesting occurs when mussels reach the minimum (50 mm) and optimal (75 mm) market shell lengths, as well as when reaching the minimum (4 g) and optimal (8 g) flesh weights. The culture length was used as a measure to compare mussel growth under the different climate and management scenarios evaluated.

The environmental inputs to the biological model were sea surface temperature (SST), food availability, and solar irradiance. Food availability is characterized in terms of the amount and quality of seston, which comprises a range of organic particles with different nutritional value and silt accessible for mussels. Total particulate matter (TPM) and organic particulate matter (POM) were used as proxies for the total and organic amount of seston, whereas the organic fraction of seston ($f = POM/TPM$) was used to characterize its quality. Food availability depends on the meteorological and hydrodynamic conditions of the embayment. In particular, food quality in the farm area can be estimated as a function of the Eume and Mandeo river discharges and coastal winds (Aguar et al., 2015). In order to account for climate change impacts on mussel growth, we ran the biological model under current and future conditions, assuming a mid-range and a high emission pathways. To account for interannual variability, we used decadal periods to represent the current conditions (2006–2015 for 2010) and the two future periods under study (2046–2055 for 2050, and 2086–2095 for 2090).

2.1. The biological model

Mussel growth has been simulated with the net production dynamic energy budget (DEB) model of Fuentes-Santos et al. (2019), which is both species and site-specific and provides accurate estimations of both shell and flesh growth. This model assumes that mussels first allocate the assimilated energy to cover the metabolic demands, and distribute the surplus, if any, between shell formation, flesh growth and reserves, part of these reserves being allocated for reproduction. The assimilation rate, i.e. the energy obtained by feeding, was determined by the ingestion rate and the absorption efficiency. The former is the product of POM and clearance rate, which measures the filtering capacity of mussels and, in low seston environments such as our study area can be estimated by an allometric relationship with shell length (Filgueira et al., 2008). The latter measures the proportion of ingested food assimilated by the organism, and can be estimated as a function of the organic fraction of seston, f (Fernández-Reiriz et al., 2007). Metabolic costs were obtained as the sum of energy consumed on respiration and excretion. Both respiration and excretion rates were estimated from their allometric relationship with shell length (Arranz et al., 2016). Finally the effect of seawater temperature on the feeding and metabolic rates involved in the energy budget was computed with the Arrhenius Law.

When the assimilated energy cannot meet the metabolic costs, reserve energy is used to cover the deficit. When the assimilated energy is larger than the energy needed for metabolic work, the net production is distributed between growth and reserves depending on the status of the organism. The energy allocated for growth is divided between shell formation and soft tissue growth. The proportion of net production allocated for reserves increases with age (Scholten and Smaal, 1998). Part of the reserves are used for maturation in juveniles and gamete formation in adults. Spawning is triggered by an increase in solar radiation in late-winter and consist on the daily release of a fraction of gametes while enough energy is allocated in the gonads and solar irradiance is above the onset threshold (Fuentes-Santos et al., 2016).

In this work, mussel growth was simulated on a daily basis, in agreement with the temporal resolution of the environmental drivers. In each step of the model, after conversion of energy into weight, flesh weight was obtained by adding the somatic, reserves and reproduction

compounds, and shell length was estimated by an allometric relationship with shell weight (see model equations and parameters in Supporting Information S1). The model was implemented in the R statistical software (R Core Team, 2019).

2.2. Environmental conditions

We have used local measurements of the climate drivers in the Ría de Ares-Betanzos (Fig. 1) for the reference period (2006–2015). Daily values of coastal winds were provided by the Seawatch buoy of the Spanish Agency Puertos del Estado off Cape Vilano (<http://www.puertos.es>), daily values of continental runoff of rivers Eume and Mandeo (m^3/s) and global solar irradiance ($MJ/(m^2day)$) at the neighbor meteorological station CIS-Ferrol (Fig. 1) were provided by the Galician Meteorological Agency (Meteogalicia, <http://www2.meteogalicia.es>). Sea surface temperature (SST), particulate organic matter (POM) and food quality ($f = POM/TPM$) were provided by the weekly monitoring conducted by CSIC-PROINSA Mussel Lab in the cultivation area of Lorbé since 2006 (Fig. 1). Sea surface temperature was measured with a multiparameter probe YSI 556. Total (TPM) and organic (POM) particulate (mg/L) were determined gravimetrically (see details in Aguiar et al. (2015)). SST in the adjacent ocean was obtained from the NOAA Physical Sciences Laboratory (<https://www.psl.noaa.gov/data/gridded/data.noaa.oisst.v2.highres.html>), containing daily high resolution data (0.25°) obtained through a combination of satellite and in situ measurements (Reynolds et al., 2007).

To account for mid (2046 – 2055) and long-term (2086 – 2095) impacts of climate change on mussel aquaculture we have used climate projections developed within the fifth phase of the Coupled Model Intercomparison Project (CMIP5) Earth System Models (ESM's) (Taylor et al., 2012). We considered a midrange (RCP4.5) and a high (RCP8.5) emission pathways to account for scenario uncertainty. Model uncertainty on SST projections was incorporated by using three ocean CMIP5 models: the downscaled POLCOMS-ERSEM model (Butenschon et al., 2016), with a spatial resolution of 0.1° , the CSIRO-Mk3.6.0 (Gordon et al. (2002), 1.9° spatial resolution) and NorESM-ME (Iversen et al. (2013), 1° spatial resolution) global models, the three models have daily temporal scale. A regional downscaling of the NorESM-ME model (Skogen et al., 2018) was considered as candidate for this study, but discarded because it has a shorter temporal horizon (2070), lower temporal resolution (5 days), and similar spatial bias in our study area as the global NorESM-ME climate model. The POLCOMS-ERSEM model also provides climate projections for chlorophyll and organic carbon concentration, but these projections tend to overestimate chlorophyll-a concentrations during winter in the West Iberian coast (Kay et al., 2018). In view of this bias, and given that the climate models do not provide total (TPM) or organic (POM) particulate matter projections, we used the measured POM values for present and future simulations. Climate projections for food quality (f) were obtained as a function of future coastal winds and continental runoff (Aguiar et al., 2015). Solar irradiance, coastal winds and rainfall, used as a proxy for continental runoff, projections were downloaded from the regional MPI-ESM-LR-RCA4 model (Block and Mauritsen, 2013; Giorgetta et al., 2013), developed within the EURO-CORDEX project (<http://www.euro-cordex.net/>).

2.3. Data processing

The observed environmental conditions and climate model outputs were preprocessed to be used as inputs in the biological model. Annual cycles of the environmental conditions were treated as functional data (Ferraty and Vieu, 2006; Ramsay and Silverman, 2006). Functional data arise associated with continuous-time monitoring processes where the observed data are high-resolution discrete, possibly noisy, samples of smooth functions, such as the daily or weekly environmental variables or growth curves. Functional data analysis (FDA) provides the

theoretical and methodological statistical framework for this type of data. The first step in FDA is to transform the sampled functions (discrete observations) into their functional representations (curves), in this work we used Fourier basis to represent those variables with a clear seasonal pattern (SST, solar irradiance, and the organic fraction of seston (f)), and nonparametric smoothing for POM. We applied generalized cross-validation (GCV) to select the smoothing parameters in both cases (see details in Febrero-Bande and Oviedo de la Fuente (2012)).

In order to account for environmental variability, i.e. interannual variability in the environmental conditions within the same decade for each climate model and emission scenario, we used smooth bootstrap (Febrero-Bande and Oviedo de la Fuente, 2012) to generate 1000 resamples of 3-year cycles for each environmental input. FDA in this work was conducted using the *fda.usc* package (Febrero-Bande and Oviedo de la Fuente, 2012) of the R statistical software (R Core Team, 2019).

2.4. Bias correction

The mussel culture area under study is located in an embayment of $52 km^2$ which is not included in the spatial domain of any ocean climate model (Fig. 1). Therefore, we faced two sources of discrepancy between the historical climate model outputs and observed SST values during the reference period: (i) the model bias itself, i.e. differences between observed and estimated values at a given location and (ii) the spatial bias, i.e. differences between observed temperatures in the adjacent shelf (model domain) and the culture area (measurement domain). SST projections need to be corrected for both model and spatial bias, whereas we only have model bias in the coastal winds, solar irradiance, and rainfall, as the Vilano buoy and meteorological station fall within the domain of the MPI-ESM-LR-RCA4 model.

We applied a bias correction procedure analogous to the method proposed by Freer et al. (2018). This bias correction consists of adding the climate anomaly simulated by the model, i.e., the difference between projected and historical model outputs, on to a present day baseline of observed values. Let Y be the target variable (SST for instance), model anomalies for each climate scenario and period under study were computed as the difference between the decadal functional means of future, $\bar{Y}_{M,RCP}$, and historical, $\bar{Y}_{M,hist}$, annual cycles. Climate projections in the study area, (Y_{RCP}), were obtained by adding these anomalies to observed annual cycles in the reference period, Y_{hist} . We consider 2006–2015 as reference period, after checking that there is no significant increase in the observed temperatures of the adjacent shelf between the historical period of climate models (1996–2005) and the reference (2006–2015) period.

$$Y_{RCP} = Y_{obs} + (\bar{Y}_{M,RCP} - \bar{Y}_{M,hist}) = Y_{obs} + \Delta\bar{Y}_M \quad (1)$$

This procedure allowed us to correct for both model and spatial bias simultaneously, but can also be used to correct for the model bias itself when the study area falls within the model domain. It should also be noted that the climate projections obtained with this procedure reflect the interannual variability of the measured values during the reference period. Alternative bias correction procedures, which add the bias between observed and simulated historical values to the future climate projections (Falconer et al., 2020), reflect the interannual variability of the climate models.

2.5. Statistical analysis

As detailed above, we have considered a series of climate and management scenarios to test for climate change impacts on mussel aquaculture. Thus, we need some statistical tools to summarize the

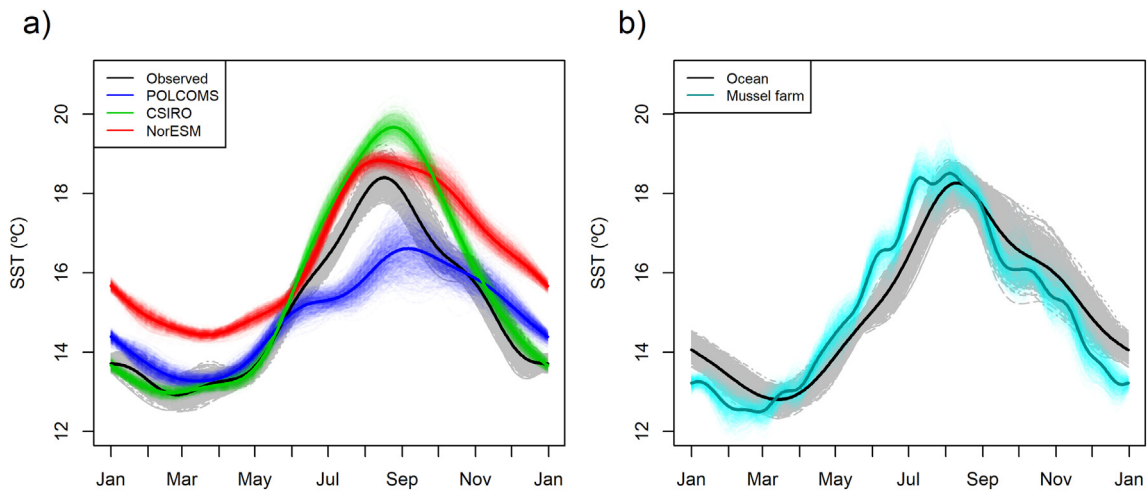


Fig. 2. Historical SST values with 95% bootstrap confidence bands. a) comparison between observed values in the adjacent ocean (black) and historical outputs for the three climate models (1996–2005). b) Comparison between observed adjacent ocean (black, 1996–2005) and Ría de Ares-Betanzos (cyan, 2006–2015).

environmental changes projected under the different scenarios, as well as the impact of those changes on mussel aquaculture.

We used functional data analysis (FDA) to summarize and compare the measured and model environmental condition during the reference period (1996–2005). We generated 95% confidence bands around the functional mean of the 10 curves representing the annual cycles of each environmental factor (SST, for instance) by smooth bootstrap (Febrero-Bande and Oviedo de la Fuente, 2012). These confidence bands characterized the annual patterns of the environmental conditions and allowed us to detect any bias in the climate models if the functional mean of the measured data did not fall within the confidence band of the model outputs. The same procedure was used to compare the environmental mid and long-term climate shifts projected by the different models and scenarios obtained.

Comparison between the effect of the different management and climate scenarios on mussel culture was done in terms of the culture length, i.e. the time between seeding and harvest. We applied kernel density estimation with plug-in bandwidth using the *ks* package (Duong, 2013) of R (R Core Team, 2019), to estimate the distribution of the 1000 simulated culture lengths obtained under the different scenarios considered in this work.

Finally, we propose a relative change index to compare the impact of the different management and climate scenarios under study on mussel culture, which is defined as follows

$$RC = 100(T_{RCP} - T_H)/T_H \quad (2)$$

where T_H and T_{RCP} denote the time to harvest under current and future climate conditions, respectively. This index provides a standardized measure of climate change impact on the culture length. Positive values, $RC > 0$, indicate that mussels will require more time to reach the target harvest size under future climate conditions, i.e. a negative impact of climate change, while negative values, $RC < 0$, indicate that culture cycles will be shorter, i.e. a positive impact of climate change.

3. Results

3.1. Environmental conditions

Figs. 2 and 3 outline the observed and modeled environmental conditions during the reference period (2006–2015). Comparison between the performance of the three climate models indicates clear differences between them (Fig. 2a). The POLCOMS-ERSEM model underestimated summer temperature, whereas the NorESM-ERSEM model overestimated SST by more than 2°C. The CSIRO model, with the lowest spatial resolution of the three models, provided the less biased simulations but overestimated SST during summer. Fig. 2b shows that, although differences between the farming area

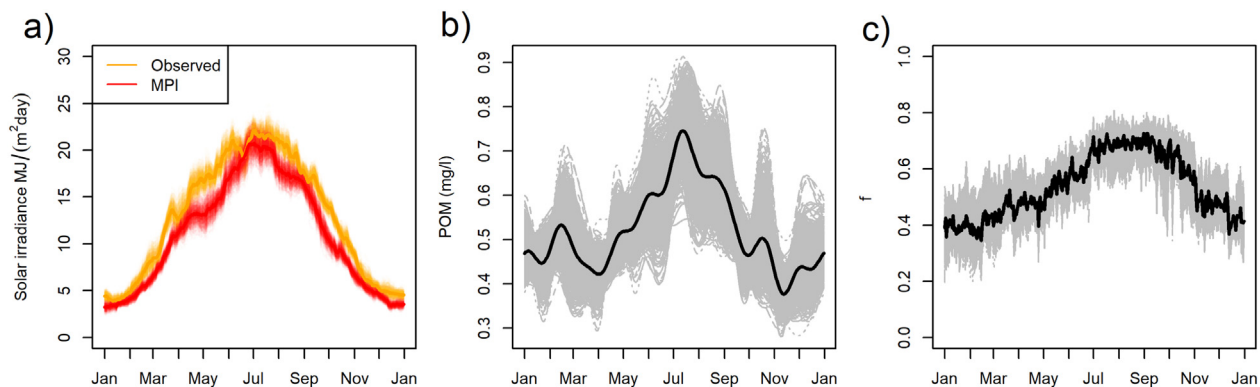


Fig. 3. a) Historical values for solar irradiance, field observations (orange) and outputs from EURO-CORDEX MPI-ESM-LR climate model (red). b) historical values for particulate organic matter. c) Historical values for food quality ($f = POM/TPM$). Mean annual cycles (thick lines) and 95% bootstrap confidence bands (shaded areas).

and the continental shelf were not large, their SST cycles during the reference period were not synchronized. Fig. 3a shows that the MPI-ESM-LR model underestimated solar irradiance in our study area. Fig. 3 also provides the reference annual cycles for particulate organic matter (POM), which did not need any bias correction, and the organic fraction of seston (f).

Fig. 4 shows the SST increase in the study areas by 2050 and 2090 projected by the two climate scenarios and the three climate models tested in this work. Comparison between climate scenarios indicated a higher temperature increase under RCP8.5. Comparison between climate models within the same period and scenario showed significant differences between them, as the respective confidence bands are not overlapped. The POLCOMS-ERSEM regional model is quite conservative, as the projected climate change impact on SST is negligible by 2050, and remains below 1.5°C by 2090 under the high emission scenario. These projections contrast with those provided by the NorESM-ME global model, which predicts that SST may increase 1–2°C in 2050 and 2–3°C in 2090 under RCP8.5.

Fig. 5 suggests that climate change may have a minor impact on solar irradiance (top) and food quality (bottom). The MPI-ESM-LR model predicts a decrease in solar irradiance during summer, except for RCP8.5 in 2090, and a slight increase during spring and autumn. Climate projections predict a 5% increase in organic content of seston during early autumn, and a decrease from November onward, which may reach the 10% by 2090 (Fig. 5 (bottom)).

3.2. Effect of climate change on mussel culture

Table 1 and Fig. 6 show the time needed to reach the optimal shell length ($L=75$ mm) and flesh weight ($FW=8$ g) during the reference period by seeding date. See results for the minimum target sizes in the Supporting Information S2 (Table s2 and Fig. S2). Mussels seeded in winter (January, February) needed from 7 to 8 months to reach the optimal market sizes, whereas mussels seeded in summer and early autumn (July–October) may require a year to reach the target sizes. The culture length of mussels seeded in spring (April–June) had bimodal distribution and showed large differences between harvesting criteria. Mussels reached the optimal length in 5 months, but they may need more than a year to reach the target flesh weight (Fig. 6). These differences are linked with the effect of the environmental variability on mussel growth. On one hand, interannual variability in the seasonal pattern of SST and food availability may determine whether mussels reach the target size prior to the temperature and seston reduction during winter. On the other hand, the differences between the target L and FW are linked with the mismatch between shell and soft tissue growth. The former is asymptotic and reduces or stops during winter unfavorable conditions, whereas the latter decreases during spawning and under unfavorable conditions.

As expected in view of the model uncertainty observed in SST projections (Fig. 4), the estimated impact of climate change on mussel growth depends on the climate model used to run the simulations.

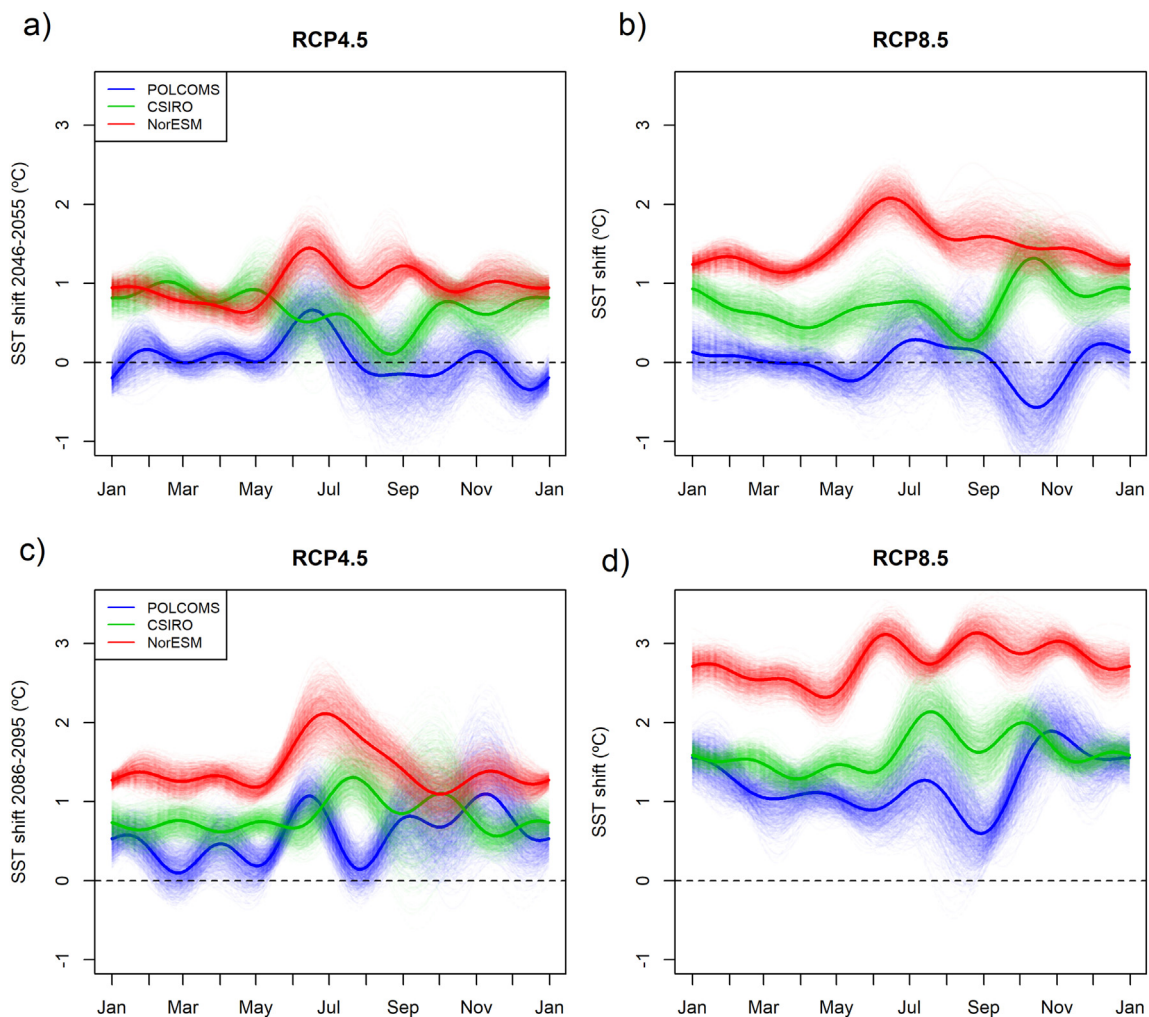


Fig. 4. SST change by 2050 (top) and 2090 (bottom) with respect to the historical period (1996–2005) predicted by the three climate models under RCP4.5 (a,c) and RCP8.5 (b,d). Mean annual cycles (thick lines) and 95% bootstrap confidence bands (shaded areas).

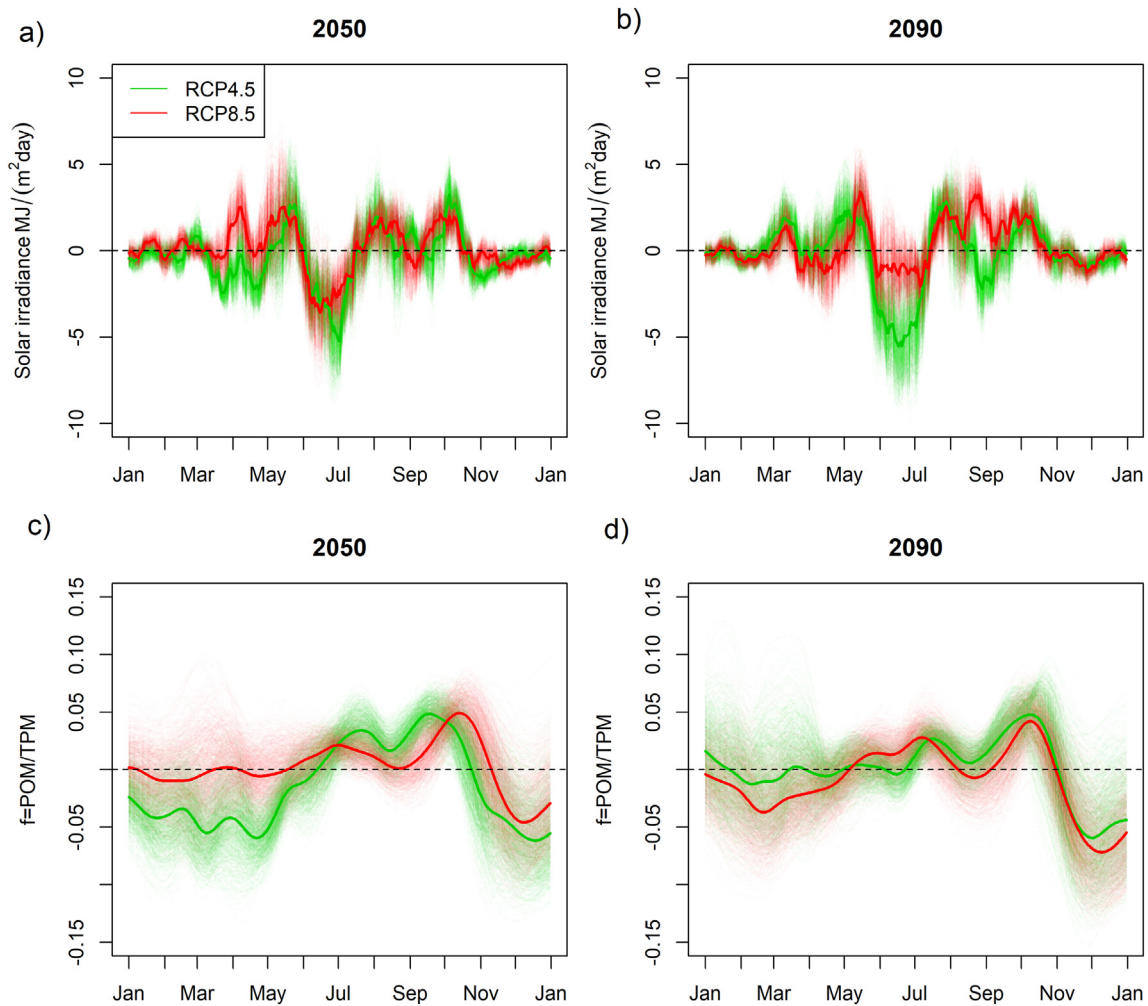


Fig. 5. Predicted change in solar irradiance (top) and organic fraction of seston (bottom) by 2050 (a,c) and 2090 (b,d) with respect to the observed values in the reference period (Fig. 3). Mean annual cycles (thick lines) and 95% bootstrap confidence bands (shaded areas).

The SST increase predicted by the CSIRO and NorESM-ME models will fasten shell and flesh growth during the 21st century, whereas no significant changes on the growth curves are expected under the POLCOMS-ERSEM climate projections (see Figs. S3–S8 in Supporting Information S2).

Fig. 7, which provides the mid and long-term relative change indexes by emission pathway, climate model, and seeding time,

Table 1

Time (days) to reach the optimal shell length ($L=75$ mm) and flesh weight ($FW=8$ g) by seeding time during the reference period (2006 – 2015). Mean, median and percentiles obtained with $B=1000$ realizations of the climate conditions.

Seeding time	Time to $L=75$ mm				Time to $FW=8$ g			
	Mean	Median	$P_{2.5}$	$P_{9.75}$	Mean	Median	$P_{2.5}$	$P_{9.75}$
Jan	230	230	212	252	241	241	214	287
Feb	202	201	183	226	218	218	187	295
Mar	180	179	160	207	222	222	165	358
Apr	158	157	136	186	273	273	143	390
May	149	145	116	200	335	335	133	378
Jun	198	147	103	369	347	347	333	364
Jul	346	350	306	383	349	349	333	368
Aug	359	357	332	395	342	342	326	362
Sep	347	344	322	390	327	327	311	350
Oct	323	320	298	362	308	308	293	332
Nov	300	298	275	339	294	294	272	318
Dec	268	266	244	305	273	273	244	305

shows similar trends for the target L and FW , except for those months with bimodal distribution in the culture length (April–June, Fig. 6). The predicted shifts vary across seeding times and climate models. The POLCOMS-ERSEM model predicted a slight increase of the culture length in all the culture cycles by 2050. This negative impact decreased, or even turned into positive under RCP8.5 by 2090. Using the CSIRO and NorESM-ME models reported shorter culture lengths for the two RCPs and decades under study for mussels seeded in winter (January–March). According to these models, the culture cycles starting from July to December may suffer a minor increase by 2050 under RCP4.5, whereas minor reductions are obtained under RCP8.5 and by 2090 under both emission scenarios. Larger shifts were obtained for mussels seeded in spring (April–June), with a bimodal or heavy-tailed culture length distribution (Fig. 6). For instance, the expected shifts in the time required by mussels seeded in April to reach the optimal shell length is similar to that observed for the cultures starting in winter (Fig. 7a), whereas we obtain a large reduction (42 – 57%) in the time to reach the target flesh weight (Fig. 7b). The predicted warming changes the bimodal distribution of the culture length increasing the chance of reaching the target size before winter and, consequently reducing the culture length up to 6 months (see Fig. S9). Climate change may also increase the chance to reach the target shell length for mussels seeded in June (see Fig. S10), but may have a minor negative impact on the time to reach the optimal weight (<5%).

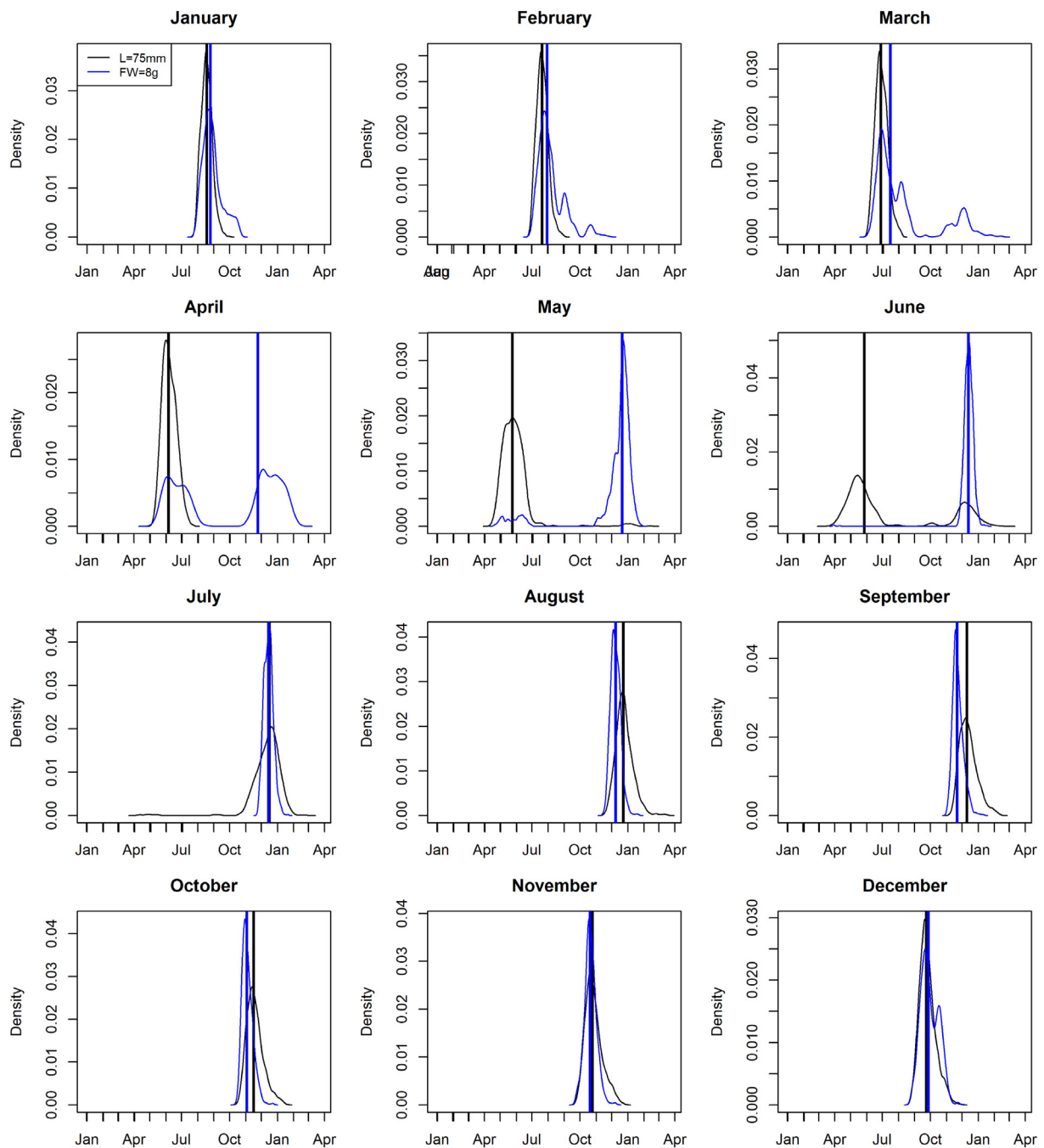


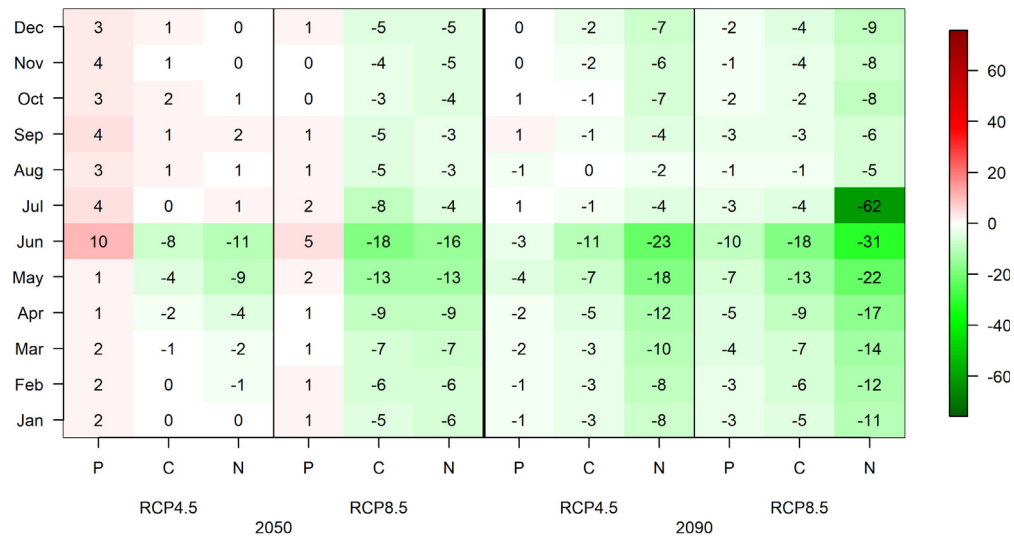
Fig. 6. Kernel density estimator and median (vertical lines) of the harvesting time by seeding month and target commercial size under observed environmental conditions. Optimal shell length (black) and flesh weight (blue).

4. Discussion

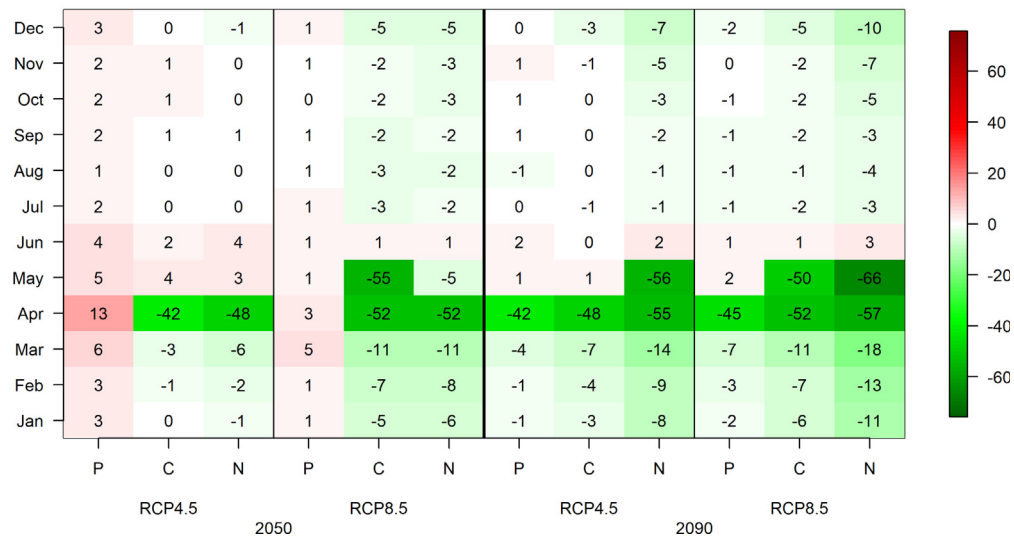
The assessment of climate change impacts on shellfish aquaculture has become a major concern over the last decade, given the major role of aquaculture as food production system and its strong dependence on the environmental conditions in the farming area (FAO, 2018). This task should be conducted with caution and demands taking into account the biases and uncertainties that arise when, i) coarse scale ocean climate models are used to forecast future climate conditions in coastal areas, ii) the interannual variability of the environmental conditions overlaps with long-term trends, and iii) the effect of management strategies interact with climate change. Focusing on the suspended culture of the mussel *M. galloprovincialis* in the Galician rías, this work

provides a critical assessment on how these factors can affect the predicted response of shellfish aquaculture to climate change. Here, following Freer et al. (2018), we have considered two sources of uncertainty in future climate data, namely scenario and model uncertainty, as well as the bias of climate models during the reference period. Recent works considered scenario uncertainty, but none of them accounts for model uncertainty (Figueira et al., 2016; Montalto et al., 2016; Sarà et al., 2018; Stavrakidis-Zachou et al., 2019). On the other hand, model bias has been addressed by Falconer et al. (2020). To the best of our knowledge, this is the first work that considers model bias and the two components of climate uncertainty.

The three ocean climate models used in this work provided biased estimations of SST during the reference period. These discrepancies



(a) Relative change in the time required to reach the target shell length $L = 75$ mm.



(b) Relative change in the time required to reach the target flesh weight $FW = 8$ g.

Fig. 7. Relative impact of climate change on the culture cycle, measured in terms of time required to reach the target shell length (7) and flesh weight (8) by seeding time (rows), climate model (P: POLCOMS-ERSEM, C: CSIRO, N: NoreESM), emission pathway (RCP4.5 and RCP8.5) and decade (2050 and 2090). Positive (negative) impact of climate change in green (red)

between observed data and climate model outputs support the use of a bias correction procedure. Echoing Falconer et al. (2020), we argue that biased climate models can over or underestimate the impact of climate change on mussel growth and, consequently, lead to the recommendation of inappropriate adaptation measures. The bias correction used in this work, which follows the proposal of Freer et al. (2018), reflects the interannual variability observed in the reference period, allowing us to reproduce both the mean behavior and environmental variability of the farm area, complementing the bias corrector by Falconer et al. (2020) which reflects the variability of the climate model. However, downscaled higher resolution models are required to obtain accurate

SST projections in areas such as the upwelling system under study, where climate change effects differ from those expected in the adjacent ocean (Garca-Reyes et al., 2015).

The results of this work highlight the important role of management strategies, such as the seeding time or the target harvesting size. The culture length depends on the seeding time, as a consequence of the dependence of this aquaculture system on the seasonal variability of SST, food availability and solar irradiance that drive the growth and reproduction of mussels (Fuentes-Santos et al., 2016, 2017). We have also seen that the interannual variability of the environmental conditions can affect the success of the seeding schedule. In particular, given the

negative impact of low SST and food shortage on mussel growth (Fuentes-Santos et al., 2017; Pérez-Camacho et al., 1995), mussels seeded in spring and early summer, which can be harvested in less than 6 months in years with warm autumns, may need more than 1 year to reach the target sizes in years with lower SST and food availability during autumn and winter.

This work shows that both scenario and model uncertainty cause large variability in the predicted response of mussel growth to climate change. Culture length predictions based upon different climate models ranged from the minor negative impact obtained with the conservative POLCOMS-ERSEM model, which predicts slower mussel growth, to a minor or moderately positive impact, i.e. faster growth, predicted by the CSIRO and NorESM-ME models. Although, as expected, we observed a larger impact of climate change on mussel aquaculture at the end of the century for the high emissions pathway, model uncertainty dominated the variability in the predicted responses. These results highlight that an accurate analysis of climate change impacts on suspended mussels aquaculture requires taking into account model uncertainty. Indeed, the subjective selection of a single climate model can provide biased predictions and mislead the design of adaptation plans. In agreement with our results, Freer et al. (2018) pointed out that the selection of the climate data must be made carefully, and warned about the risk of using a single model or emission scenario as input for an ecological prediction.

In view of the mild climate related changes predicted for food quality and solar irradiance, we can consider SST as the main driver of the projected shifts in mussel aquaculture production, although the different impact on shell and soft tissue growth may be attributed to an extension of the spawning period because of the projected increase in solar irradiance during spring and autumn (Fuentes-Santos et al., 2016). The largest growth rates were obtained with the NorESM-ME model under the high emission pathway, which forecasts a 2 – 3°C SST increase by 2090 but maintains SST values within the optimal thermal range of *Mytilus galloprovincialis* (11.61 – 23.31, Montalto et al. (2016)). This temperature increase in combination with the minor changes predicted for food quality enhances mussel growth, especially during the cold season. The maximum SST values during summer (>23°C) approach the upper limit of the optimal thermal range, above which the metabolic and physiological performance of mussels decreases reducing their growth rates, but below thermal stress conditions that, in combination with other stressors, such as food restrictions or hypoxia, may compromise their survival (Anestis et al., 2007; Artigaud et al., 2014; Jansen et al., 2009). In contrast with our findings, Des et al. (2020), who predicted water temperature and stratification during summer in the NW Iberian upwelling system and assumed thermal stress conditions above 20°C, concluded that the expected SST increase during the 21st century shall have a dramatically negative impact on mussel aquaculture production in the Galician rías.

It should be noted that the results of this work are subjected to the current availability and quality of observed and projected environmental data. Accurate local-scale climate change projections for primary production in our area are not available, so we could not evaluate the response of mussels to future shifts in food availability. Upwelling has been indirectly considered through the use of coastal winds as driver for food quality. Wind regimes in combination with continental runoff also affect the timing and extension of harmful algal blooms (Alvarez-Salgado et al., 2008), and larval settlement cycles in the Galician rías (Fuentes-Santos et al., 2016; Peteiro et al., 2011). Recent studies predict an enhancement of upwelling favorable winds in this area during summer over the 21st century (Alvarez et al., 2017; Sousa et al., 2017, 2020). These studies focus on a particular season, but further research is required to test for climate related changes on coastal winds over the whole year. In addition, future wind trends are highly depended on the climate model (Feser et al., 2015; Ruosteenoja et al., 2019; Stocker et al., 2013), thus model uncertainty should also be considered in the analysis of future wind patterns.

Ocean Acidification has been identified as a major threat for calcifying marine organisms, such as mussels. OA increases homeostasis and calcification costs, with the subsequent impact on shell strength, mussel growth and survival (Parker et al., 2013). The predicted OA over this century ranges from a mean decline in pH levels of 0.3 – 0.4 units under the RCP4.5 midrange emission pathway to a 0.6 units decline under the RCP8.5 high emission pathway (Bindoff et al., 2019). Considering these projections, the pH and carbonate saturation levels by year 2100 will be within the estimated tolerance ranges for mussels in alkaline and nutrient rich environments, such as the Galician rías (Fernández-Reiriz et al., 2012). Therefore, OA has not been considered in this work. Notice that the explicit partitioning of energy between flesh growth and shell formation in our biological model (Fuentes-Santos et al., 2019) would allow the incorporation of OA effects on mussel growth when required.

5. Conclusion

This work tests climate change impact on mussel aquaculture by studying mussel growth performance under current and future climate conditions. We used two emission scenarios and three climate models to account for climate uncertainty, and applied a bias correction procedure to reduce the discrepancy between measured and model data during the reference period. We have seen that management strategies, such as the seeding time and harvesting target size, and environmental variability play an important role in the growth performance of mussels. Indeed, culture cycles starting in late summer and autumn can last twice than those starting from January to March. Comparison between the climate models highlights that model uncertainty can dominate the variability of SST projections and, consequently, the predicted climate change impact on mussel growth varies across climate models, ranging from the minor negative impact predicted by the POLCOMS-ERSEM model to the moderate positive impact obtained with the CSIRO and NorESM-ME models. These results alert against the use of a single model to test for climate change impacts on aquaculture production.

Finally, we have identified some knowledge gaps that should be addressed for a proper estimation of climate change impacts on mussel aquaculture. On one hand, higher resolution regional scale climate models accounting for the ocean-land interactions in coastal areas are required to forecast future trends in key environmental factors, such as SST, coastal winds, food availability and pH. On the other hand, this approach focuses on mussel growth, but a proper estimation of climate change impact on suspended mussel aquaculture should also test for climate related changes on seed availability and harmful algal blooms, which affect management decisions such as the seeding and harvesting schedule, the presence of predators in the farming areas or the occurrence of extreme weather events. Further research is required to incorporate all these issues to the assessment of climate change impacts on mussel aquaculture.

CRedit authorship contribution statement

Isabel Fuentes-Santos: Conceptualization, Investigation, Methodology, Software, Formal analysis, Writing – original draft. **Uxío Labarta:** Conceptualization, Writing – original draft, Supervision, Funding acquisition. **María José Fernández-Reiriz:** Writing – review & editing, Funding acquisition. **Susan Kay:** Data curation, Writing – review & editing. **Solfrid Sætre Hjøllø:** Data curation, Writing – review & editing. **X. Antón Alvarez-Salgado:** Conceptualization, Writing – original draft, Supervision, Funding acquisition, Project administration.

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.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.scitotenv.2021.145020>.

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