Journal of
Marine Science and Engineering

MDPI

Article

Ria de Alvor Suitability for Aquaculture: Future Challenges

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Abstract: A large number of estuarine systems provide favorable conditions for aquaculture, including high nutrient content, sheltered waters, and favorable water temperatures. In this context, the main objective of this work is to identify the most suitable areas within the Ria de Alvor for bivalve and fish aquaculture production considering present and future conditions in a climate change context. A suitability index was developed based on the results of an annual simulation with the Delft3D model and the thresholds and optimal values of development of each species were analyzed. Generally, results suggest that the most suitable areas for aquaculture were located along the axis of the lagoon's main channel, although seasonal variability was presented depending on the species. During winter and autumn, bivalves (oysters and mussels) are more susceptible to environmental conditions than fish. Conversely, spring presents the most favorable environmental conditions for the production of all species considered. Future projections indicate a general decrease in aquaculture suitability, particularly during winter for both bivalve species and during summer for Mussels, mostly due to the predicted increase in water temperature.

Keywords: bivalve; fish; suitability index; climate change; Delft3D

Citation: Picado, A.; Pereira, H.; Sousa, M.C.; Dias, J.M. Ria de Alvor Suitability for Aquaculture: Future Challenges. *J. Mar. Sci. Eng.* **2023**, *11*, 1009. https://doi.org/10.3390/jmse11051009

Academic Editors: Bahareh Kamranzad and Eugen Rusu

Received: 11 April 2023
Revised: 26 April 2023
Accepted: 4 May 2023
Published: 8 May 2023

1. Introduction

Coastal systems at the land–ocean interface are highly dynamic and valuable, containing a variety of biological and physical resources. They support a diversity of human activities, including leisure and tourism, fisheries, and aquaculture [1]. However, due to human occupation, population growth, and economic development, coastal systems are frequently under pressure, leading to significant degradation of their natural resources and ecosystem services [1]. Additionally, coastal systems face a broad suite of impacts from climate change (sea level rise, increase in water temperature, higher frequency of extreme weather events, ocean acidification, harmful algal blooms, eutrophication, and hypoxia, among others) [2,3].

Since the beginning of the 20th century, coastal aquaculture has experienced significant development worldwide [4], leading to environmental impacts and new challenges in the management of coastal areas [5]. Since coastal systems offer ideal conditions for aquaculture, including a reliable supply of seawater, favorable water temperatures, and nutrient-rich waters for bivalves, environmental changes can have significant effects on the development and growth of farmed species [6].

Several studies were performed to understand the implication of climate change on aquaculture production. In a review, Maulu et al. [7] summarized the main elements of climate change and their effects on aquaculture, which include rising water temperature, ocean acidification, changes in rainfall/precipitation patterns, sea level rise, changes in sea surface salinity, and higher frequency of extreme climatic events [8,9]. Both positive and negative effects of environmental factors on aquaculture were identified by the authors. For instance, rising water temperatures can initially enhance the physiological rates of aquatic organisms and boost growth and productivity. However, if the water temperature continues to rise beyond a certain threshold, it can lead to physiological stress, disease outbreaks, and even mortality [7,10]. Similarly, Maulu et al. [7] found that other environmental factors, such as dissolved oxygen (DO) levels, pH, salinity, and nutrient availability, can also have both beneficial and detrimental effects on aquaculture depending on their concentrations and duration of exposure. In another study, Steeves et al. [9] analyzed the performance of two bivalve mollusks (oysters—*Crassotrea virginica* and mussels—*Mytilus edulis*) under past, present, and future climate conditions in the Scotian Shelf and Gulf of Saint Lawrence. Results suggest that warming ocean temperatures will cause an increase in the growth rates of both species, with oysters generally outperforming mussels since their tolerance to higher temperature is greater.

Considering two environmental factors, Rato et al. [11] studied the combined effect of water temperature and salinity changes on the mortality and feeding behavior of the European clam (*Ruditapes decussatus*). Results indicate that abrupt reductions in salinity and sharp increases in water temperature will lead to high mortality.

In Portugal, aquaculture has undergone significant expansion in recent years, with a particular focus on fish and bivalve production in estuaries and coastal lagoons. The central and southern regions of the country are especially active in this regard, with numerous aquaculture units [5,12,13]. Among the fish species farmed in Portugal are sea bass (*Dicentrarchus labrax*), sea bream (*Sparus aurata*), and rainbow trout (*Oncorhynchus mykiss*). Bivalve mollusks such as clams (*Ruditapes decussatus*), oysters (*Crassostrea gigas*, *Magallana gigas*, *Crassostrea angulate*, and *Magallana angulata*), and mussels (*Mytilus* spp.) are also widely produced [14].

The Ria de Alvor (Figure 1) is a coastal lagoon located in the southern region of Portugal, which has high importance in terms of aquaculture exploration. However, unlike other estuarine systems in Portugal [13,15,16], the Ria de Alvor has not been yet the subject of any studies to assess the potential impacts of climate change on this ecosystem and their impact on the viability of aquaculture in this region. However, Mateus et al. [17] examined the main characteristics and challenges of the Ria de Alvor, emphasizing the need for additional studies on this and other minor estuaries and lagoons.

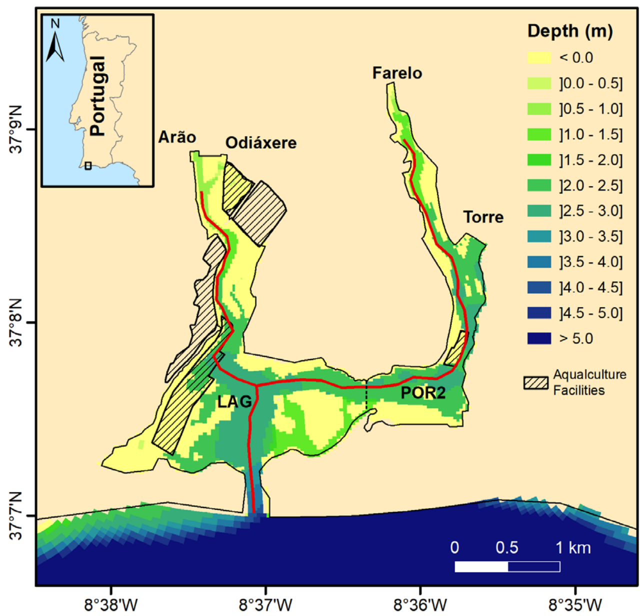

Figure 1. Bathymetry of the study area with the main freshwater sources (Arão, Odiáxere, Farelo, and Torre) and aquaculture facilities. The two bivalve production zones are also identified (LAG and POR2).

In this context, the present work aims to provide useful information on the suitability of the Ria de Alvor as a location for aquaculture exploitation, as well as to assess the impact that climate change will have on future production. Therefore, a numerical model previously developed and capable of simulating the main biophysical characteristics of the Ria de Alvor is used to assess its potential for bivalve and fish aquaculture under present and future conditions. The findings of this study can be used to guide future management and conservation efforts aimed at ensuring the long-term viability of aquaculture in a region that is threatened by climate change impacts.

2. Study Area

The Ria de Alvor is a mesotidal shallow coastal lagoon located on the southern coast of Portugal (Algarve region) (Figure 1). The average depth of the lagoon is 2.3 m relative to the mean sea level (excluding intertidal areas); however, to ensure navigability to the recreational and fishing port of Alvor, the navigation channel is often dredged [17,18]. Semidiurnal tide constituents are the major hydrodynamic force [18,19], with a mean spring tidal range of 2.85 m [17]. The lagoon is mildly ebb-dominant in the central area, revealing a potential to export sediments and other properties to the ocean, and it is strongly flood-dominant upstream, which means that the upstream regions are prone to accretion and property retention [18]. Additionally, the reduced freshwater inflow [18,19] associated with the tide-dominated hydrodynamic regime makes the Ria de Alvor a euhaline system (salinity range from 30 to 36) [17].

The lagoon hosts several fish aquaculture production units (Figure 1), and their exploitation tanks benefit from the natural water renewal induced by the tides. Bivalves are both cultivated in bottom beds and in tables [17,20]. According to Instituto Português do Mar e da Atmosfera (IPMA, [14]), the Ria de Alvor is divided into two bivalve production zones: one covering the central and western parts (LAG) and the other covering the eastern region (POR2) (Figure 1). Grooved carpet shell (*Ruditapes decussatus*), razor clams (*Solen marginatus*), and mussels (*Mytilus* spp.) are produced in both regions, while giant Japanese oyster (*Magalana gigas*), Portuguese oyster (*Magalana angulata*), and cockles (*Cerastoderma edule*) are only produced in the LAG zone [14]. In the latter region, sea bass (*Dicentrarchus labrax*) and gilthead sea bream (*Sparus aurata*).

The Ria de Alvor is considered a priority area of conservation, being part of the Ramsar and Natura 2020 European conservation networks [17,19], and is a significant socioeconomic resource for the western Algarve region, which is based on tourism, aquaculture, and fisheries.

Increasing pressure has been detected over recent years, mostly as a result of population expansion. Among these pressures are the increase in waste, land use changes, and nutrient inputs from agriculture and aquaculture [17].

3. Materials and Methods

3.1. Model Implementation

The present work aims to determine the most suitable regions for bivalve and fish aquaculture in the Ria de Alvor considering the present situation and a future scenario (described in Section 3.3). The target species are two bivalves, the Portuguese oyster and mussels, and one fish, the gilthead sea bream, which are among the species most cultivated in the Mediterranean area and one of the most consumed farmed fish in Portugal [4,21].

In this context, an application of the Delft3D model previously developed and calibrated by Picado et al. [18] is explored, considering the hydrodynamic (FLOW) and the water quality (WAQ) modules. A single cartesian curvilinear orthogonal grid was used, allowing a coarser resolution at the offshore open boundary (approximately 300 m) and a finer resolution inside the lagoon (between 20 and 40 m). A 2D depth-averaged approximation was considered since the Ria de Alvor is vertically homogeneous [18,19]. A time step of 30 s for the FLOW module and 5 min for WAQ was chosen to guarantee the stability and accuracy of numerical results. Bathymetry and boundary conditions are fully described in [18]. The offshore bathymetry results from the interpolation of the Digital Model Terrain, EMODnet data (resolution of 115 × 115 m), while inside the lagoon, the bathymetric data come from a survey performed with LIDAR technology. At the ocean open boundary, the model uses 13 harmonic constituents obtained from OSU TOPEX/Poseidon Global Inverse Solution [22] along with water temperature, salinity, pH, chlorophyll, nutrients, and DO concentration from the Atlantic Iberian Biscay Irish Ocean model provided by the Copernicus Marine Environment Monitoring Service (CMEMS) [23].

Regarding the freshwater input, four freshwater sources were considered (Farelo, Torre, Odiáxere, and Arão—see Figure 1) with flow and nutrients predicted by the E-hype model provided by the Swedish Meteorological and Hydrological Institute (SMHI—[24,25]). The data are only available between 1981 and 2010 and monthly climatology was therefore computed and imposed in the river boundary. The E-hype model is extensively used for river boundary conditions in estuarine/ocean system modeling [26–28] since it can provide a valid seasonal variation of the flow and nutrient concentrations. According to these data, the freshwater input in the Ria de Alvor is 2.1 (3.2) m^3/s in winter and 0.02 (0.04) m^3/s in summer at the east (west) branch. Regarding chlorophyll concentration, due to the lack of in situ and predicted continuous data, mean values from [19] were used as the river boundary condition. The atmospheric forces imposed at the air–sea interface consist of surface air temperature, relative humidity, and net solar radiation values provided by ERA5 from the European Centre for Medium-Range Weather Forecasts [29].

An annual simulation (with a spin-up period of 6 months) was performed, and a seasonal characterization of the main abiotic environmental factors (water temperature, salinity, chlorophyll concentration (Chl), DO, and pH) was also performed for the present scenario. Additionally, to characterize the current velocities in the lagoon, root mean square velocity (V_{RMS}) was also computed for neap and spring tides (since the current velocity is influenced by tides rather than by seasonal variations). V_{RMS} is used instead of average velocity since the net velocity for a tidal dominated flow is close to zero, and the ebb and flood velocities therefore have almost symmetric opposite directions [30]. V_{RMS} was computed through the following equation:

$$V_{RMS} = \left(\frac{1}{N} \sum_{i=0}^{N} V^2 \right)^{1/2} \quad (1)$$

where $V = \sqrt{u^2 + v^2}$ is the velocity modulus.

3.2. Suitability Index

A suitability index (SI) was computed to assess the local potential for aquaculture exploitation, considering the model results of an annual simulation. The SI computation is based on the methodologies presented by Picado et al. [12] and Vaz et al. [5], which consists of 5 steps:

1. Define the main environmental factors affecting bivalves and fish development.
2. Assign a weight for each environmental factor based on their influence on the success of bivalve and fish aquaculture development.
3. Identify the thresholds and optimal values of each environmental factor favorable to the production and growth of the Portuguese oyster, mussels, and gilthead sea bream.
4. Give a score between 0 and 1 to each simulated variable, considering the thresholds and optimal values.
5. Compute the SI using Equation (2).

The main environmental factors and the respective weights and ranks used in the present work are derived from Picado et al. [12] and Vaz et al. [5] and are presented in Table 1. A pairwise comparison procedure was used in which the Analytic Hierarchy Process (AHP) [31] method was applied based on its influence on the success of bivalve and fish development. Logical consistency among pairwise comparisons was guaranteed [32]. The AHP is a decision-making tool that allows for the ranking and prioritization of multiple criteria or variables based on their relative importance or weight. The assumptions used when applying the AHP method were obtained based on the available literature.

Table 1. Weights (w_i %) for bivalves and fish.

Environmental Factor	Bivalve		Fish	
	Weight (%)	Rank	Weight (%)	Rank
Bathymetry	6.7	6	4.7	4
Velocity	13.5	4	7.9	3
Water temperature	33.0	1	34.6	2
Salinity	8.1	5	4.4	5
DO concentration	16.0	3	41.5	1
Chl concentration	19.4	2	3.9	6
pH	3.3	7	3.0	7

For bivalves, maximum relative weight (33%) was assigned to water temperature since it plays an important role in determining the growth processes of filter-feeder organisms [11]. Chlorophyll, as an indicator of phytoplankton, is the main source of food and could affect bivalve development and reproduction [33], thus accounting for 19.4% of relative weight.

Dissolved oxygen is also vital for the growth and survival of bivalves as they rely on it for their metabolic processes [5], and a weight of 16% was therefore attributed. As current velocity plays a significant role in determining the growth processes of filter-feeder organisms (by influencing water temperature, phytoplankton, nutrient circulation, and DO dynamics [34]), a weight of 13.5% was given. A relevant but smaller weight is given to bathymetry (6.7%) and salinity (8.1%), and lower weight was assigned to pH (3.3%).

Fish culture in estuaries and lagoons, according to Lawson [35], is primarily limited by dissolved oxygen (DO) levels, and DO is therefore considered the most significant parameter with a relative weight of 41.5%, followed by water temperature, which has a weight of 34.6% due to its influence on fish breathing and growth. Other parameters such as current velocity, bathymetry, and salinity have lower weights of 7.9%, 4.7%, and 4.4%, respectively. Chlorophyll concentration and pH have weights of 3.9% and 3%, respectively.

The thresholds and optimal values for the development and growth of each species were identified and are presented in Table 2. The values were obtained through a literature review [5,12,36,37].

Table 2. Environmental thresholds for Portuguese oyster, mussels, and gilthead sea bream [5,12,36,37].

Environmental Factor	Portuguese Oyster		Mussels		Gilthead Sea Bream	
	Threshold	Optimal	Threshold	Optimal	Threshold	Optimal
Water temperature (°C)	3–35	15–25	5–30	14–20	6–33	17–26
Chl (µg/L)	>0.5	>2	>0.5	>2	0–15	2–8
Salinity	15–40	25–35	8–39	25–30	5–44	15–38
DO (mg/L)	4–10	5–8	1–10	5–7	2.7–10	7–9
pH	6.5–9.0	7.5–8.5	6.5–9	7.1–8.3	5.5–9.0	7.0–8.0
Depth (m)	0–7.0		0–10		0–30	
Velocity (m/s)	0.01–0.22		0–0.3		0.05–0.2	

Subsequently, using the results of the annual simulation (instantaneous model outputs with a temporal resolution of 30 min) performed with Delft3D and the thresholds and optimal values, a score between 0 and 1 was attributed to each variable. If variable values fell outside the threshold range, a score of 0 was attributed. If it fell within the range of the optimal thresholds, a score of 1 was attributed. If the value fell between the minimal threshold and optimal values (or maximal threshold and optimal values), a linear fit was performed to assign a score between 0 and 1.

Finally, SI was computed as the weighted geometric mean of the scored environmental factors (x_i) [5,12] through application of the following equation:

$$SI = \left(\prod_{i=1}^{n} x_i^{w_i} \right)^{\frac{1}{\sum_{i=1}^{n} w_i}} \quad (2)$$

where w_i is the weight of each environmental factor and n is the number of each variable defined in the AHP (bathymetry, velocity, water temperature, salinity, dissolved oxygen, chlorophyll concentration, and pH). The SI results were then classified into four classes: Unsuitable ($SI < 0.40$), Moderately Suitable ($0.40 \leq SI < 0.60$), Suitable ($0.60 \leq SI < 0.80$), and Highly Suitable ($0.80 \leq SI \leq 1.00$). The intervals were based on the ones presented by Vaz et al. [5].

3.3. Climate Change Scenario

To evaluate the impact of climate changes on the suitability of the Ria de Alvor for aquaculture production, a second simulation was performed considering the projections from the 6th Assessment Report (AR6) by the Intergovernmental Panel on Climate Change (IPCC) for the long-term period (2081–2100) relative to the baseline period of 1995–2014. Scenario SSP5-8.5 was considered, which is illustrative of very high greenhouse gas emissions and CO_2 annual emissions tripling by 2080. The future scenario was implemented in the numerical model by modifying the boundary conditions of air temperature (AT), mean sea level (MSL), sea surface temperature (SST), salinity, Chl, DO concentration, and pH. The average differences considered (Table 3) represent the projected changes for the south coast of Portugal. MSL, SST, AT, and pH are available in [38], and salinity, Chl, and DO were computed from an ensemble of CMIP6 models [39] considering the differences between future (2081–2100) and historical (1995–2014) periods. The main tributary inflow was considered the same as in the present period.

Table 3. Projected changes for the south coast of Portugal.

Season	AT (°C) [1]	MSL (m) [2]	SST (°C) [3]	Salinity	Chl (μg/L) [4]	DO (mg/L) [5]	pH
DJF	+3.2	+0.7	+2.1	−0.8	−0.18	−0.20	−0.40
MAM	+4.1		+2.5				
JJA	+4.7		+2.8				
SON	+4.7		+2.9				

[1] AT—atmospheric temperature; [2] MSL—mean sea level; [3] SST—sea surface temperature; [4] Chl—chlorophyll; [5] DO—dissolved oxygen.

The SI was computed for the future scenario and compared with the present situation, considering the four seasons of the year.

4. Results

4.1. Abiotic Characterization of the Ria de Alvor

The abiotic characterization of the Ria de alvor was performed based on the Delft3D model results, which provided the value of each variable in every grid point every 30 min. For current velocity, the characterization was performed for spring and neap tides (Figure 2). For other parameters, seasonal averages were computed and are represented in Figures 3 and 4.

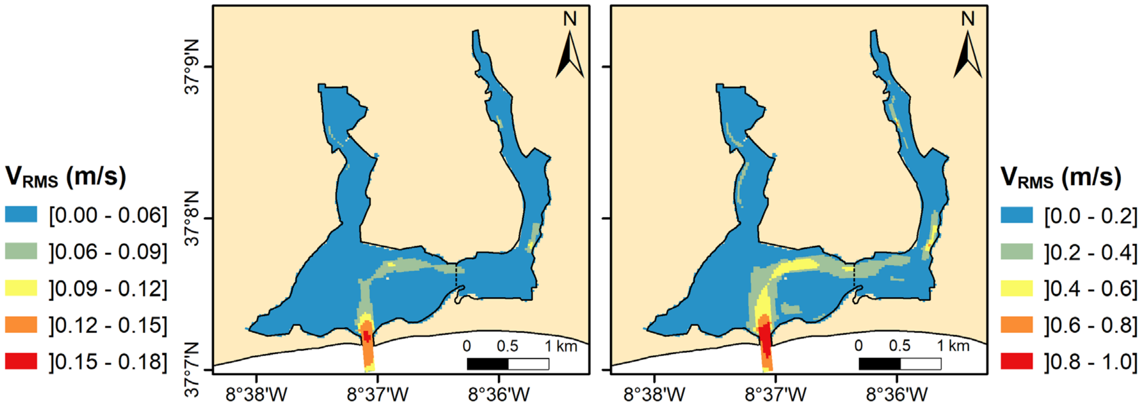

Figure 2. V_{RMS} (m/s) during a tidal cycle for neap tide (**left**) and spring tide (**right**) at the Ria de Alvor.

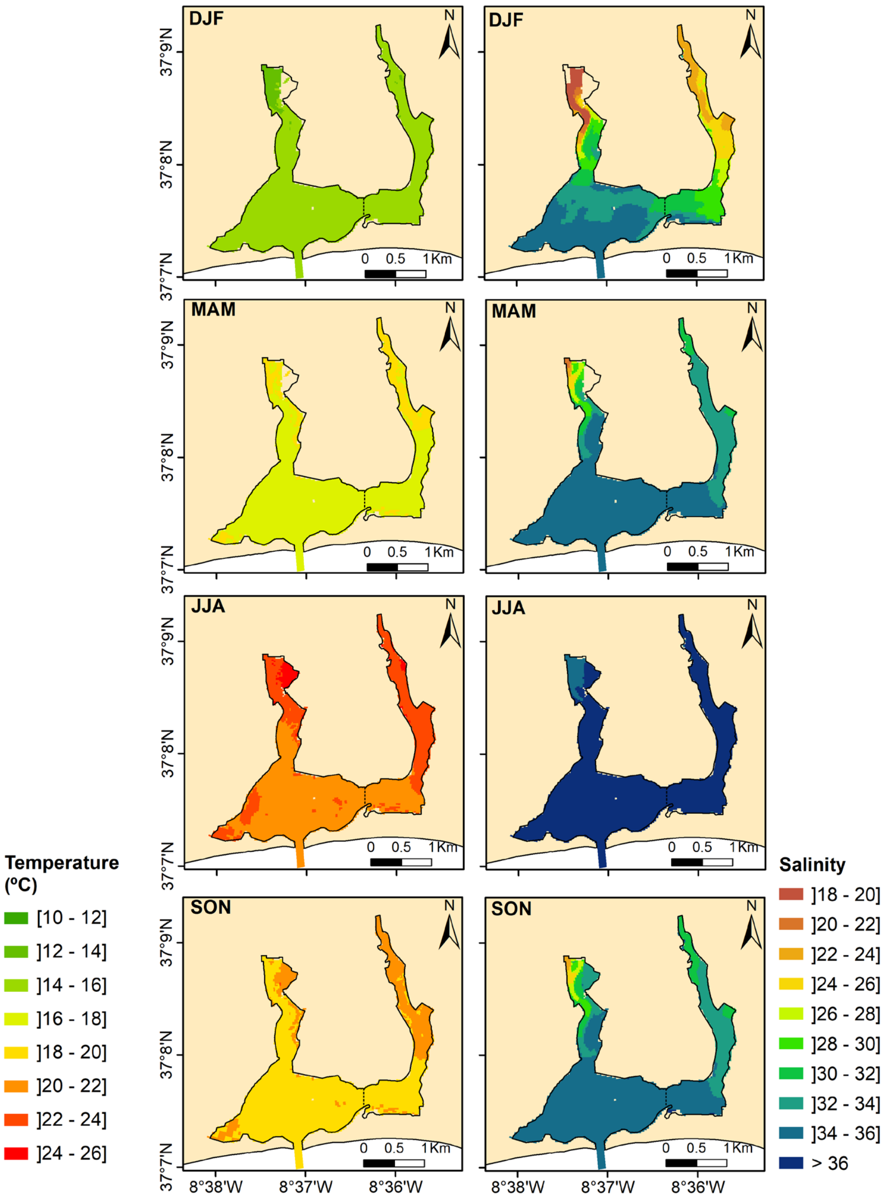

Figure 3. Seasonal distribution of water temperature (left panel) and salinity (right panel) at the Ria de Alvor.

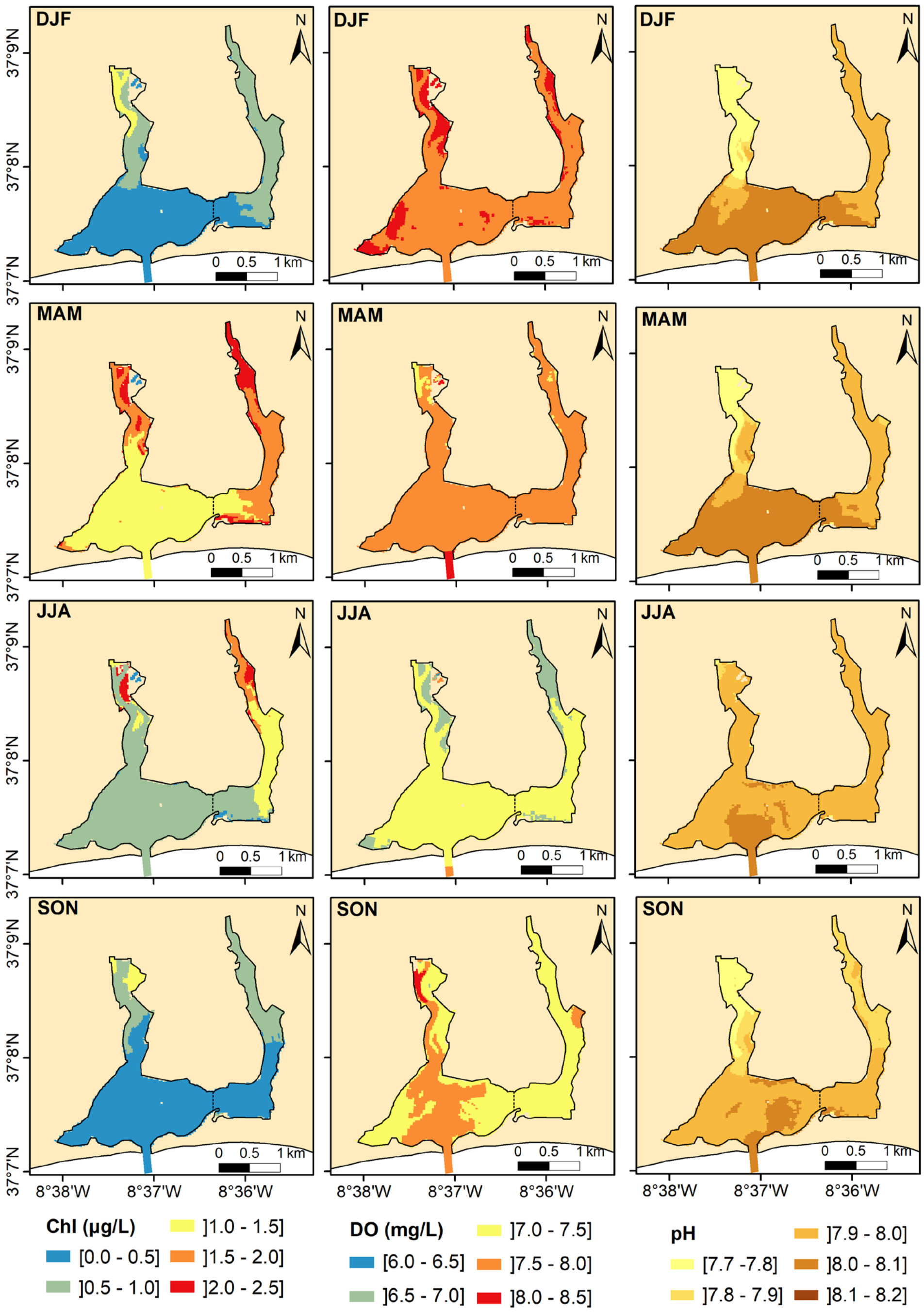

Figure 4. Seasonal distribution of Chl concentration (left panel), DO concentration (middle panel), and pH (right panel) at the Ria de Alvor.

Regarding the hydrodynamics of the Ria de Alvor, model results indicate that the current velocities are generally low and decrease upstream, varying with tidal conditions (Figure 2). Indeed, the V_{RMS} in the navigation channel ranges between 0.06 and 0.18 m/s during neap tides and between 0.2 and 1.0 m/s during spring tides, while for the rest of the lagoon, V_{RMS} is below 0.06 and 0.2 m/s for neap and spring tides, respectively.

Relative to the water temperature (Figure 3, left panel), a typical seasonal pattern is observed, with lower temperatures in winter and higher temperatures in summer. During winter, a negative gradient is observed from the mouth of the lagoon (15.7 °C) towards the upstream direction (13.5 °C and 14.5 °C at the west and east branches, respectively), reflecting the input of cold freshwater from the main tributaries. During spring, the air and water temperatures begin to rise and the volume of freshwater input decreases. As a result, a positive gradient is observed, with ~17 °C at the central region and 18 °C upstream (west and east branches). In summer, the highest water temperatures are observed, with values of 20 °C at the lagoon mouth. Due to the reduced river flow, the water temperature increases upstream, reaching 23 °C at both the west and east branches. In SON months, the mean water temperature decreases (between 19 and 20 °C).

Concerning salinity, a seasonal pattern is exhibited, with higher values during summer and lower in winter. This pattern is due to the freshwater volume input that is more significant in winter. Indeed, during DJF months (Figure 3, right panel), a typical estuarine pattern is observed, with higher salinities nearer the mouth (34) than upstream (18 and 23 at the west and east branches, respectively). During spring, the amount of rainfall decreases, leading to a reduction in the river flow into the lagoon and a subsequent increase in salinity levels (>35 at the mouth and 28 and 32 at the west and east branches) (Figure 3, right panel). In summer, the lagoon experiences the highest salinity (>36) due to the low contribution of the tributaries. In autumn, the rainfall increases and so does the freshwater input into the lagoon, leading to a salinity reduction to 35 at the mouth and 26 and 30 at the west and east branches, respectively (Figure 3, right panel).

Figure 4 presents the seasonal distribution of Chl, DO, and pH at the Ria de Alvor. DO and Chl concentrations are closely related to physical and biological processes, which are influenced by environmental factors such as water temperature, salinity, light, and nutrient availability. Indeed, during the winter, the lower water temperature and decreased nutrient availability lead to lower Chl concentrations (<0.5 μg/L in the central lagoon and >1 μg/L upstream—Figure 4, left panel) and increased oxygen levels throughout the lagoon (>7.9 mg/L) (Figure 4, middle panel). For spring (MAM months), the Chl levels are higher as a result of the increased sunlight that provides more energy for photosynthesis, promoting the growth of phytoplankton and other small organisms [40]. This can lead to an increase in oxygen production through photosynthesis, resulting in high DO levels in the water column (>7.9 mg/L).

During summer and autumn months, the warmer water temperature results in lower oxygen levels throughout the lagoon (7.2 mg/L in both branches and 7.5 mg/L in the central region). Summer Chl concentrations are approximately 0.6 μg/L in the central area and >1 μg/L in the west and east branches. For autumn, Chl is <0.5 μg/L in the central area, increasing upstream to >0.5 μg/L.

The pH levels exhibit seasonal variations (Figure 4, right panel), with lower values during summer and autumn months coinciding with lower levels of DO. In winter and spring, the pH ranges between 8.04 at the central region and 7.33 (7.92) at the west (east) branch, which is due to the influence of freshwater discharge. During summer, the gradient is almost imperceptible, with pH values of approximately 8.00 at the lagoon mouth and slightly decreased values of 7.97 upstream (both branches), due to the low freshwater input. Regarding autumn, values of 7.99 are found in the central lagoon and 7.63 (7.87) upstream.

Regarding the future simulation, results are not shown since the majority of the differences are homogeneous for the entire lagoon. For water temperature, results show that changes imposed on the ocean boundary (Table 2) lead to an increase of the same magnitude throughout the lagoon, suggesting that this is relatively homogeneous in terms of its response to changes in water temperature. Concerning salinity, differences are mainly observed upstream at both the west and east branches, where salinity levels increase for all seasons except for summer. In contrast, the central area of the lagoon exhibits a decrease in salinity, ranging from 0.4 to 0.8 across all seasons, as imposed in the ocean boundary. Specifically, during winter, salinity increases by approximately 4 and 1 in the west and east branches, respectively. In spring, the western branch experiences a salinity increase of approximately 2, while no significant differences are observed in the eastern branch. Throughout summer, a uniform decrease in salinity levels, ranging from 0.7 to 0.8, is observed across the entire lagoon, which is indicative of the low influence of freshwater during the summer, reinforcing the importance of marine forces in lagoon dynamics. Finally, during SON months, a slight salinity decrease is observed in the central region, while upstream regions experience a salinity increase (2 and 0.08 for the west and east branches, respectively). Sea level rise induces penetration of the lagoon by a greater volume of ocean water at each tidal cycle, and salinity consequently increases upstream, particularly in seasons with a greater inflow of fresh water where typical salinity gradients are more evident.

The changes in biogeochemical variables observed in the Ria de Alvor are consistent with those applied in the ocean boundary conditions. Specifically, a decrease of around 0.4 in pH and 0.18 and 0.20 µg/L in Chl and DO concentrations was observed throughout the entire lagoon.

4.2. Ria de Alvor Suitability Index

The SI for the Portuguese oyster, mussels, and gilthead sea bream was computed for winter, spring, summer, and autumn and is represented in Figure 5. Results suggest that, generally, the suitable areas for the exploitation of both bivalves and fish species in this study are located along the axis of the lagoon's main channel. However, the suitability of the Ria de Alvor for aquaculture production varies seasonally and locally.

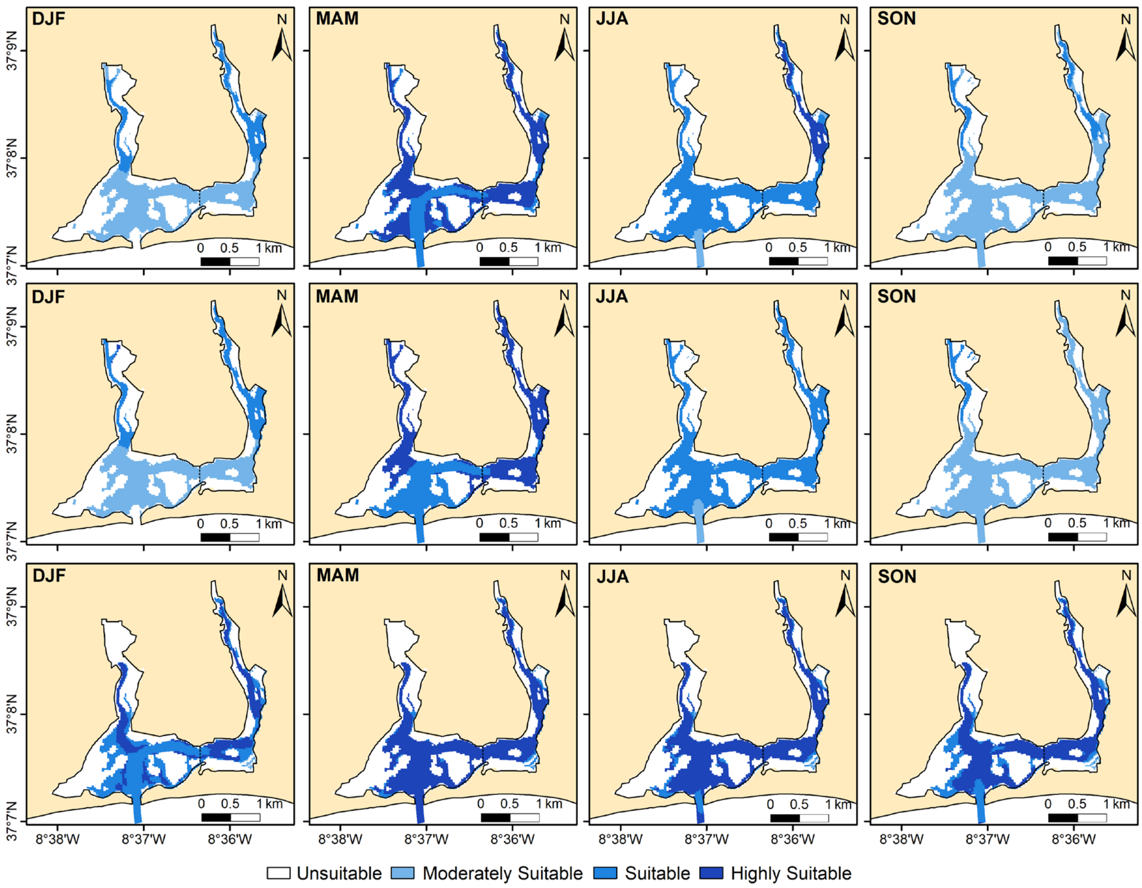

Figure 5. Ria de Alvor suitability index under present conditions for the Portuguese oyster (top panel), mussels (middle panel), and gilthead sea bream (bottom panel): Unsuitable ($SI < 0.40$); Moderately Suitable ($0.40 \leq SI < 0.60$); Suitable ($0.60 \leq SI < 0.80$); Highly Suitable ($0.80 \leq SI \leq 1.00$).

Indeed, during winter, the central region was found to be moderately suitable for Portuguese oyster and mussels cultivation, with the upstream regions deemed to be suitable. Regarding gilthead sea bream production, during winter, the Ria de Alvor is considered suitable along the navigation channel and highly suitable upstream.

The spring season presents the most favorable environmental conditions for all species considered. Indeed, the entire lagoon is highly suitable for the production of all the species under analysis, with the exception of the navigation channel that belongs to the Suitable category for both Portuguese oyster and mussels (Figure 5, top and middle panels). The suitability of the Ria de Alvor for the production of both bivalves decreases during summer when compared with spring, revealing conditions belonging to the Suitable category, except in the eastern branch where conditions for Portuguese oyster belong to the Highly Suitable category. For gilthead sea bream, the environmental conditions observed during summer are optimal, as lagoon conditions fall into the Highly Suitable category. In autumn, the environmental conditions in the Ria de Alvor are moderately suitable for Portuguese oyster and mussels cultivation, while for the gilthead sea bream conditions belong to the Highly Suitable category. For all seasons, the far end of the western branch is considered unsuitable for gilthead sea bream due to bathymetry constraints.

In order to understand the implications of climate-induced changes in the suitability of the Ria de Alvor for the exploitation of Portuguese oyster, mussels, and gilthead sea bream, the respective SI was computed for present and future conditions and is represented throughout the axis of the west and east branches (red lines in Figure 1) in Figures 6–8.

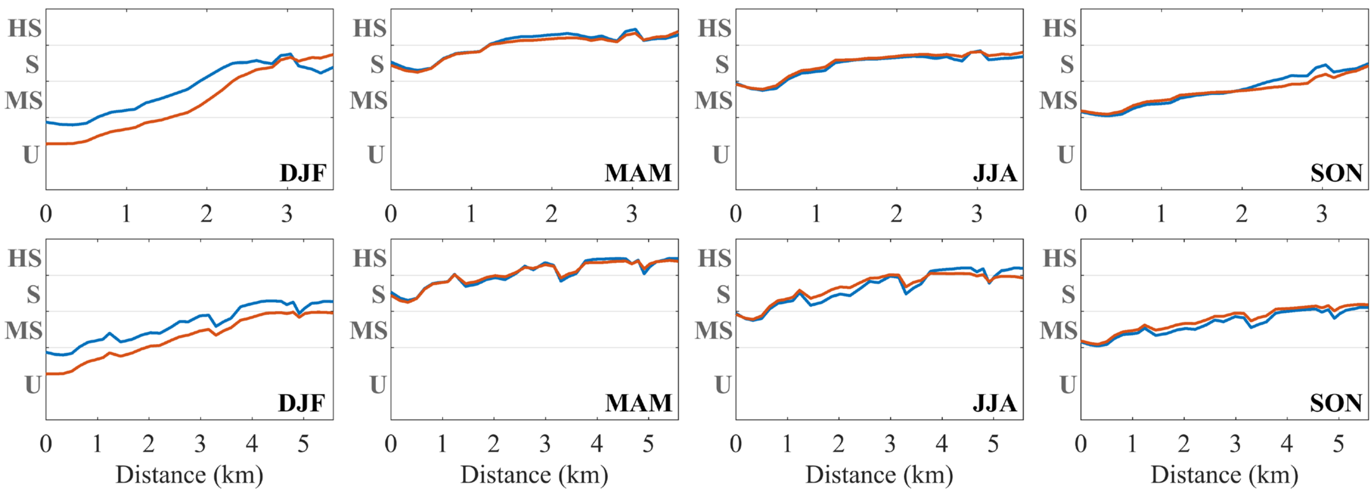

Figure 6. Ria de Alvor suitability index for the Portuguese oyster throughout the axis of the west (top panel) and east (bottom panel) branches (red lines in Figure 1). The *x*-axis is the distance from the mouth of the lagoon and the *y*-axis represents the *SI* classes (U—Unsuitable, MS—Moderately Suitable, S—Suitable, and HS—Highly Suitable). Blue and orange lines stand for the present and future scenarios, respectively.

Based on the present analysis, it has been generally observed that both bivalves analyzed show greater susceptibility to environmental changes during the winter season. Specifically, this study has revealed that during winter, the suitability of the Ria de Alvor for Portuguese oyster and mussels production is projected to decline for the entire lagoon, except for the upstream western branch region where suitability is expected to slightly increase. Indeed, during winter, results suggest that the environmental conditions for both bivalve species in the central area (from the lagoon mouth until ~2 km) are projected to decline from a Moderately Suitable categorization to an Unsuitable categorization. Additionally, in the eastern branch from 4 km upstream, suitability for both Portuguese oyster and mussels is anticipated to decrease in the future from the Suitable classification to the Moderately Suitable classification. For gilthead sea bream, no significant changes in production suitability for the Ria de Alvor are observed.

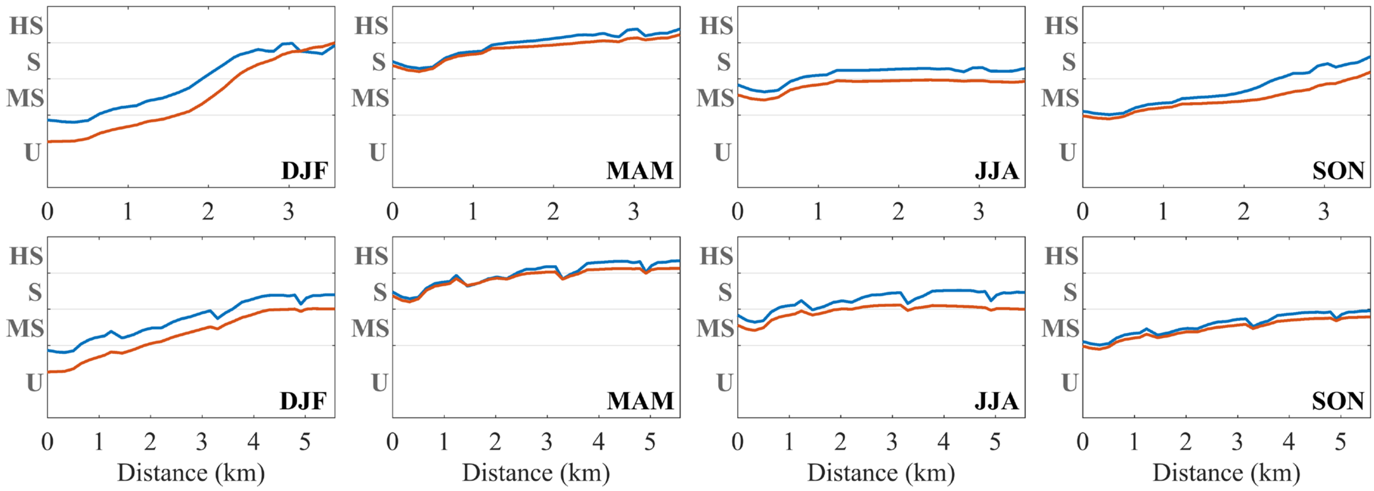

Figure 7. Ria de Alvor suitability index for mussels throughout the axis of the west (top panel) and east (bottom panel) branches (red lines in Figure 1). The *x*-axis is the distance from the mouth of the lagoon and the *y*-axis represents the *SI* classes (U—Unsuitable, MS—Moderately Suitable, S—Suitable, and HS—Highly Suitable). Blue and orange lines stand for the present and future scenarios, respectively.

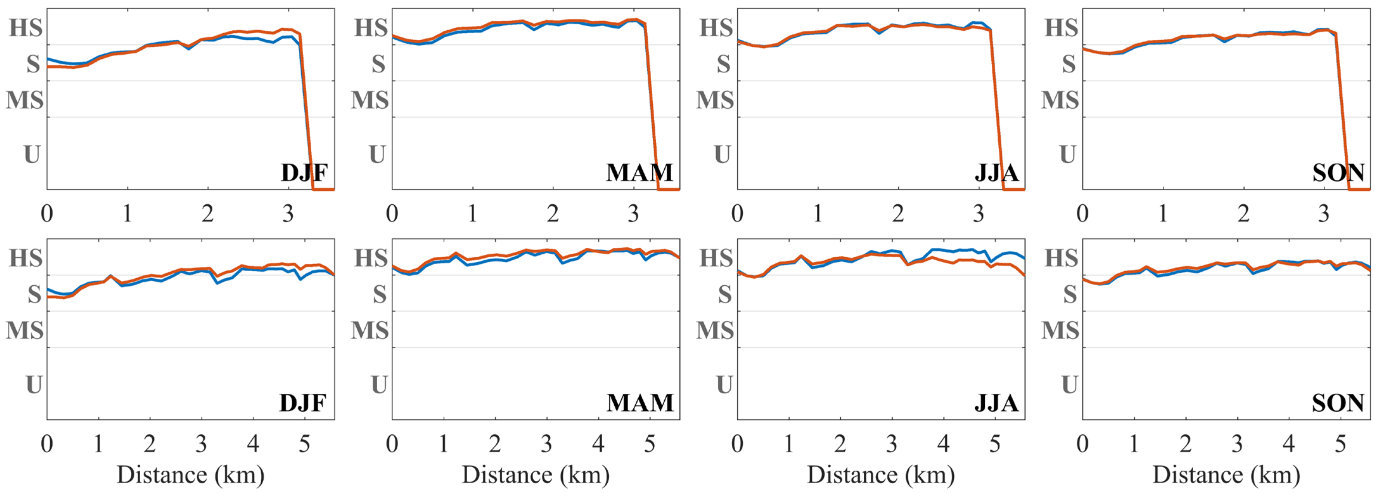

Figure 8. Ria de Alvor suitability index for gilthead sea bream throughout the axis of the west (top panel) and east (bottom panel) branches (red lines in Figure 1). The *x*-axis is the distance from the mouth of the lagoon and the *y*-axis represents the *SI* classes (U—Unsuitable, MS—Moderately Suitable, S—Suitable, and HS—Highly Suitable). Blue and orange lines stand for the present and future scenarios, respectively.

Based on the findings of the present work for the remaining seasons, it appears that for the Portuguese oyster and gilthead sea bream, the anticipated environmental changes are not expected to have any adverse effects on the suitability of aquaculture production in the lagoon. Conversely, in some specific locations, the suitability for production of these species will increase slightly, but not enough to change the categorization of the lagoon (e.g., during autumn at the eastern branch). Regarding mussels, suitability for the production of this species is predicted to decrease during all seasons, with special importance during summer, when suitability decreases from the Suitable to Moderately Suitable category in the central area and western branch.

5. Discussion

The present work intends to contribute to the identification of the most suitable regions for sustainable bivalve (Portuguese oysters and mussels) and fish (gilthead sea bream) aquaculture production in the Ria de Alvor. Additionally, this study seeks to evaluate the impact of climate change on the suitability of these areas for aquaculture exploitation. The strategy developed and implemented involves the use of a modeling tool (Delft3D) to simulate the abiotic environmental conditions of the Ria de Alvor for winter, spring, summer, and autumn, integrating this information with the tolerance thresholds and optimal values of bivalve and fish growth and development.

It is essential to identify highly effective and productive locations for aquaculture to ensure both environmental sustainability and economic growth [41]. It is noteworthy that the present analysis only considers natural factors, omitting human activities and land use. For instance, despite occasional suitability assessments, the installation of aquaculture facilities in the navigation channel is not advisable due to the traffic of recreational, sports, tourism, and fishing boating. Moreover, it should be noted that the existence of aquaculture facilities in the region, which can alter environmental conditions [42,43], was not considered for suitability calculation. Indeed, in a recent study, Brito et al. [13] studied the impact of increasing oyster production in the Sado Estuary and concluded that increasing oyster production caused changes in the chlorophyll-a (decrease), nutrient (increase), and dissolved oxygen (decrease) concentrations near the farm regions.

According to the results for the Ria de Alvor, the suitable areas for aquaculture production are located along the axis of the lagoon's main channel. Indeed, the low depth and low current velocities in the marginal zones of the channels make them unsuitable areas for aquaculture [5]. Moreover, the suitability of the Ria de Alvor for aquaculture production can vary depending on the seasonal environmental conditions. Indeed, during winter, the Ria de Alvor exhibits moderately suitable conditions in the central region for Portuguese Oyster and mussels. This finding is attributed to both water temperature and Chl concentration (Figures 3 and 4), which, on average, fall below the optimal values required for the development of both bivalve species (Figure 5).

Chlorophyll, as an indicator of phytoplankton, is the main source of food, reducing chemical feeding (process of adding specific nutrients and other essential compounds to the water in a controlled manner) and production costs [5] and ensuring sustainable practices. Although gilthead sea bream has similar water temperature and Chl concentration thresholds to Portuguese oysters and mussels, the central region of the Ria de Alvor is considered a suitable location during winter. The difference can be explained by the different weights attributed to Chl concentration, namely 19.4% and 3.9% for bivalves and fishes, respectively. The upstream areas of the Ria de Alvor are prone to aquaculture of all species (conditions in the Suitable category for bivalves and Highly Suitable category for fish) during winter because of the high chlorophyll availability near freshwater sources. The availability of this food source not only simplifies farming techniques but also reduces feed costs [41]. Moreover, it has been shown to have potential environmental benefits [44,45].

According to the analysis conducted, spring is the most suitable season for aquaculture production of the three species under investigation (categorized herein as Suitable and Highly Suitable). This is likely due to the optimal combination of water temperature, salinity, and biogeochemical variables (pH, DO, and Chl concentration) that promote the growth and survival of bivalves and fish. Indeed, during spring, water temperature (on average between 17 and 18 °C) and Chl levels (>1 μg/L), which are among the most important factors for bivalve and fish production [41], are within the optimal range for all three species. Additionally, it is during this season that phytoplankton blooms tend to occur due to the combination of increased sunlight, warmer water temperatures, and higher nutrient availability [46], which can provide a food source for aquaculture organisms. However, it is important to note that an increased amount of phytoplankton can have negative impacts on aquatic ecosystems, such as oxygen depletion and the enhancement of planktonic processes due to eutrophication [42,43]. At the Ria de Alvor, no relationship between phytoplankton and nutrients has been established [19], and according to the model results (Figure 4), the average DO levels for the spring season are between 7.7 and 8 mg/L, which suggests that there may not be significant oxygen depletion caused by the increase in phytoplankton. Moreover, the low residence time and ebb dominance of the central region [18] results in the efficient exchange of water with the ocean [17–19].

Regarding the summer season, the suitability of the Ria de Alvor decreases for both Portuguese oyster and mussels (from the Suitable/Highly Suitable category in spring to the Suitable category in summer), which is due to the high salinity levels observed (>36). The optimal upper limit considered for salinity is 35 for the Portuguese oyster and 30 for mussels. Additionally, the lower levels of Chl concentration (0.6 μg/L in the central area and higher than 1 μg/L upstream) observed during summer reduce the suitability of the lagoon to aquaculture exploitation. Otherwise, since the optimal salinity range is 15 to 38 for gilthead sea bream, salinity is not considered a limiting factor for the aquaculture of this species. During fall, Chl concentration seems to be the limiting factor for exploitation of the bivalves considered. As such, the central region offers moderately suitable conditions for their development and growth since, during autumn, Chl concentrations in the Ria de Alvor are below 0.5 μg/L (Figure 4). The Chl concentration does not have an impact on the suitability of the Ria de Alvor for gilthead sea bream production, as their weight is low (3.9, Table 1). According to the results, the pH levels in the Ria de Alvor do not have a significant impact on the suitability of the lagoon for aquaculture exploitation, as the pH levels in the lagoon are consistently within the optimal range for the species analyzed and do not fluctuate significantly during the year (Figure 4).

Since the suitable areas for aquaculture production are located along the axis of the lagoon's main channel, to understand the impact of climate changes in the suitability of the Ria de Alvor, the SI was represented throughout the main channel axis for both present and future scenarios. Results suggest that induced climate changes will affect the studied species differently. Specifically, during winter, the central area may become unsuitable for Portuguese oyster and mussels production due to the predicted decrease in Chl concentration. The present concentration levels are already below the optimal range, and they are expected to reduce by a further 0.2 μg/L in the future, which would fall below the species threshold. The suitability index for gilthead sea bream does not show a significant decrease in response to the decline in Chl concentration, as this variable has a lower weight in the index calculation.

For the other seasons, slight changes are predicted in the suitability of the Ria de Alvor for aquaculture exploitation, with opposed effects according to the species analyzed. Indeed, for summer and autumn, the predicted water temperature increase led to average values higher than the optimal range for mussels (14–20 °C), and the suitability for production of this species in the Ria de Alvor therefore declined. For the Portuguese oyster, a slight increase in the suitability index is observed for autumn, since optimal values (15–25 °C) are higher than for mussels; however, this increase is not enough to change the categorization from that of Moderately Suitable. These results support a recent study carried out in the Rías Baixas [47], which revealed that the rise in water temperature would benefit the establishment of the Pacific oyster in the future. Unlike the Portuguese oyster, Pacific oysters prefer a higher temperature range (20–28 °C), making the temperature increase favorable for their settlement. However, the methodology adopted by the authors only accounts for water temperature in the evaluation of suitability, considering the region to be suitable when the daily mean water temperature is above 18 °C for at least 15 consecutive days. The study disregarded important variables such as the availability of phytoplankton. Additionally, it is essential to consider that the Rías Baixas (northwest coast of the Iberian Peninsula) are strongly influenced by upwelling events [48,49] that bring cold water from the bottom layers to the surface, and the impact of the increase in water temperature would therefore be different than in the southern coast of Portugal, where upwelling is less effective [49].

The projected changes in other environmental factors of the Ria de Alvor are not expected to have negative impacts on its suitability for aquaculture exploitation. For instance, although an increase of 4 in salinity is projected for winter in the upstream western branch (due to the increase in mean sea level), this region is influenced by two tributaries, which prevent salinity from reaching critical values. Furthermore, all the species analyzed in the study are able to tolerate high salinity levels (optimal maximum values are 35, 30, and 38 for the Portuguese oyster, mussels, and gilthead sea bream, respectively). However, when exposed to stressful conditions, such as severe variations in water temperature and salinity, bivalves usually close the valves as a mechanism of protection [50], reduce feeding activity, and therefore slow growth and respiration rates, consequently altering oxygen consumption [50,51]. Additionally, for gilthead sea bream, variations in water temperature and salinity can affect their growth and development. For example, high water temperatures have been found to increase the metabolic rate and feeding activity of fish, which can lead to faster growth rates. On the other hand, salinity has been shown to have a more complex effect, with both high and low salinity levels leading to reduced growth rates and poorer feed conversion [52].

6. Conclusions

The present work aimed to identify the most suitable regions throughout the Ria de Alvor for the aquaculture exploitation of two bivalve species (Portuguese oyster and mussels) and one fish (gilthead sea bream) under present and future conditions in a climate change context. Generally, results suggest that the suitability of the Ria de Alvor for the production of these species varies with location and season. For the present, during winter, both bivalve species analyzed were revealed to be highly vulnerable due to the lower concentration of Chl and low water temperature. Future projections indicate that decreasing Chl concentration and increasing water temperature are the major factors threatening bivalve production in the Ria de Alvor, decreasing the suitability of the Ria de Alvor for bivalve aquaculture exploitation. Conversely, the environmental conditions of the Ria de Alvor are optimal for the growth and development of gilthead sea bream, and induced climate change impacts are unlikely to affect suitability for this species.

Author Contributions: Conceptualization, A.P., H.P., M.C.S. and J.M.D.; methodology, A.P., H.P. and J.M.D.; software, A.P. and H.P.; formal analysis, A.P.; investigation, A.P.; resources, J.M.D.; writing—original draft preparation, A.P.; writing—review and editing, A.P., M.C.S., H.P. and J.M.D. All authors have read and agreed to the published version of the manuscript.

Funding: Thanks are due to FCT/MCTES for the financial support provided to CESAM (UIDP/50017 /2020 + UIDB/50017/2020 + LA/P/0094/2020) through national funds. H. Pereira was funded by a PhD grant from FCT (SFRH/BD/138755/2018).

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Data sharing is not applicable to this article.

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

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