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Pacific oyster (*Crassostrea gigas*) growth modelling and indicators for offshore aquaculture in Europe under climate change uncertainty

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15 Abstract

Aquaculture development in Europe, while critical to the European Union (EU) Blue Growth 16 strategy, has stagnated over the past decades due largely to high competition for space in the 17 nearshore coastal zone among potential uses and the lack of clear priorities, policy, and 18 planning at EU and national scales. Broad Marine Spatial Planning, including the designation 19 of Allocated Zones for Aquaculture, requires spatial data at the corresponding broad spatial 20 scale, which has not been readily available, as well as model projections to assess potential 21 impacts of climate change. Here, daily chlorophyll-a, water temperature, salinity, and current 22 23 speed outputs from a marine ecosystem model encompassing the coastal North East Atlantic, the North Sea, and the Mediterranean Sea (the pan-European POLCOMS-ERSEM model 24 25 configuration) are used to drive a Dynamic Energy Budget growth model of Pacific oyster (Crassostrea gigas). Areas broadly suitable for growth were identified using threshold 26 tolerance range masking applied using the model variables mentioned above, as well as 27 bathymetry data. Oyster growth time series were transformed into simplified indicators that 28 are meaningful to the industry (e.g., time to market weight) and mapped. In addition to early-29 century indicator maps, modelling and mapping were also carried out for two contrasting late-30 century climate change projections, following representative concentration pathways 4.5 and 31 8.5. Areas found to have good ovster growth potential now and into the future were further 32 assessed in terms of their climate robustness (i.e., where oyster growth predictions are 33 34 comparable between different future climate scenarios). Several areas within Europe were highlighted as priority areas for the development of offshore Pacific oyster cultivation, 35 36 including coastal waters along the French Atlantic, the southern North Sea, and western 37 Scotland and Ireland. A large potential growth hot spot was also identified along northwestern 38 Africa, associated with a cool, productive upwelling coastal zone. The framework proposed here offers a flexible approach to include a large range of ecological input data, climate and 39 40 ecosystem model scenarios, aquaculture-related models, species of interest, indicator types, and tolerance thresholds. Such information is suggested to be included in more extensive 41 spatial assessments and planning, along with further socioeconomic and environmental data. 42

44 Keywords

45 bivalve; Pacific oyster; Dynamic Energy Budget (DEB); Marine Spatial Planning (MSP);

- 46 offshore aquaculture; site selection, climate change
- 47

48 Highlights

- 49 Aquaculture-relevant oyster growth indicators modelled and mapped across Europe
- 50 Large-scale hot spots highlighted as potential zones for industry development
- 51 Contrasted climate change scenarios considered to assess future uncertainty
- 52

53 **1. Introduction**

A diverse marine aquaculture sector has been linked with achieving a more sustainable food 54 55 system, with both environmental and human health benefits when best practices and appropriate site selection are applied (Schubel and Thompson, 2019). Although Europe is one 56 of the largest markets for seafood globally, it remains highly dependent upon international 57 sources to meet demand. Over 60% of seafood consumed by European Union member states 58 are supplied by non-European imports (STECF, 2018). At the same time, the proportion of 59 European seafood supplied by aquaculture remains much lower than ratios observed 60 internationally, at approximately 20% compared with over 50%, and with much lower growth 61 rates (FAO, 2018; STECF, 2018). Throughout Europe, a major bottleneck in issuing new 62 licenses has constrained the aquaculture industry for over a decade. This results in large part 63 64 from the lack of clear prioritization, planning, and management, as well as the high level of 65 competition for space in the already-overcrowded coastal zones (Hofherr et al., 2015). For Europe to achieve its desired "Blue Growth" strategy, of which aquaculture development is a 66 key component (European Commission, 2017), such issues need to be addressed. 67

68 Offshore cultivation has been cited as potentially having the means to overcome space 69 limitations in nearshore areas in Europe and around the world (European Commission, 2017; Gentry et al., 2017). Technological advances (Buck and Langan, 2017; Landmann et al. 70 2019), as well as experimental results (e.g., Pogoda et al., 2011; 2012; 2013), indicate the 71 increasing feasibility of cultivating various species in the offshore realm, which in most cases 72 73 is exposed to strong waves, high current velocities, and strong winds, among other challenges. The potential to combine aquaculture with, for example, offshore wind energy generation in 74 coproduction scenarios (Buck et al., 2008; Jansen et al., 2016; Buck and Langan, 2017; Buck 75 et al., 2018) and within multi-species facilities offshore, including integrated multi-trophic 76 aquaculture (Troell et al., 2009; Korzen et al., 2016; Buck and Langan, 2017), further adds to 77 78 the appeal with respect to dual purpose investments or leveraging existing resources. Furthermore, recent studies point to a suite of additional benefits of offshore aquaculture, 79 80 ranging from reduced pathogen and pollutant exposure (Buck et al., 2005; Pernet et al., 2018) to greater production and carrying capacity (Di Trapani et al., 2014). 81

Pacific oyster (Crassostrea gigas) has been considered for offshore farming in several 82 European countries (e.g., France (Palmer et al., 2020; Glize et al., 2010; Mille et al., 2008), 83 Germany (Buck and Langan, 2017; Pogoda et al., 2011; Buck et al., 2006), and the UK 84 (Ferreira et al., 2009)). Although offshore cultivation remains experimental at these sites, 85 results to date have been promising, with a growth rate often outpacing that in nearby coastal 86 farms. At several French Atlantic sites, C. gigas growth was found to be more than 15% and 87 88 as much as 100% higher offshore than at a reference intertidal site, varying between animal ploidy and life stage (i.e., spat versus adults) considered (Mille et al., 2008; Glize et al., 89 2010). Likewise, similar or higher survival rates and oyster quality indices (ratio of flesh to 90 total animal weight) have also been documented from oysters grown in offshore cages in 91 92 Germany (Pogoda et al., 2011; Buck et al., 2020), in France (Glize et al., 2010), as well as in New Zealand (Heasman et al., under review). Despite such promise, substantial investments 93 would be required to install and maintain infrastructure, as well as for ongoing operations, and 94 the offshore environment remains largely uncharted territory from an aquaculture industry 95 96 perspective (Gentry et al., 2017).

Adequate planning and policy, including the designation of Allocated Zones for Aquaculture 97 (AZAs) based on state-of-the-art science, have been recognized as being crucial to the success 98 and sustainability of such investments and to the aquaculture industry in general (e.g., 99 100 European Commission, 2013; Macias et al., 2019). Spatialized data, across a range of scales 101 and for various parameters, is needed to inform Marine Spatial Planning (MSP), including the identification of potential AZAs and for farm site selection therein (Lester et al., 2018; 102 Falconer et al., 2019). To assist policy and planning endeavors at the European scale, broad, 103 large-scale tools and information can provide insight for high-level planning and policy stages 104 and must complement and inform more local site-specific work. Nonetheless, there is a 105 general lack of relevant international-scale studies and data at the corresponding spatial scale 106 needed for broad, long-term policy and planning decisions (Falconer et al., 2019). 107

For sustainable decision making by the aquaculture industry, it is also crucial to consider the 108 challenges and ongoing impacts of climate change on the coastal ocean (FAO, 2018; Bindoff 109 et al., 2019). There is much uncertainty surrounding what climate change will look like where 110 and when, as well as how ecosystems and society will respond, and the numerous possible 111 related feedbacks (Moss et al., 2010; Gattuso et al., 2015; Freer et al., 2018). Satellite remote 112 sensing offers a rich, spatiotemporal component to study ecosystem processes in the ocean 113 and coastal zone, and has been usefully applied to aquaculture in several instances (e.g. 114 Radiarta and Saitoh, 2009; Thomas et al., 2011; Kapetsky et al., 2013; Thomas et al., 2016; 115 Aura et al., 2016; Brigolin et al., 2017; Snyder et al., 2017; Barillé et al., 2020; Palmer et al., 116 2020; Porporato et al., 2020). However, long-term planning and zone or site selection also 117 benefits from the consideration of what future conditions might look like, impossible through 118 the use of remote sensing data alone, and requiring the coupling of climate and ecosystem 119 models to investigate the influence of predicted future environmental changes on aquaculture-120 related indicators. Modelling that considers multiple, diverse scenarios can help us to 121 understand the potential magnitude of future climate change impacts and uncertainty (Bindoff 122 et al., 2019), in addition to providing rich spatial datasets necessary for MSP as described 123 above, and has therefore been chosen for use in this work. 124

The present study offers a framework for decision support in planning aquaculture zoning by 125 comparing the potential for offshore Pacific oyster growth across the Northeast Atlantic, 126 North Sea, and Mediterranean Sea under conditions representative of the early 21st century 127 and two contrasted end-of-century climate change scenarios. Areas characterized by good 128 growth and likely to be more stable under climate change uncertainties are highlighted for 129 priority consideration by the industry. An ecophysiological oyster growth model driven by 130 131 ecosystem model outputs was used to map growth potential in offshore areas identified to be within the bivalve's tolerance range. The use of coarse spatial resolution (0.1°) data over a 132 large, continental-scale geographic region allows the identification of broad spatial trends and 133 hot spots for industry planning and policy purposes, within which more fine-resolution, 134 detailed work could be undertaken for specific site selection. 135

136

137 **2. Materials and methods**

138 2.1 Input data: POLCOMS-ERSEM

The Proudman Oceanographic Laboratory Coastal Ocean Modelling System (POLCOMS; 139 140 Holt and James 2001) and the European Regional Seas Ecosystem Model (ERSEM; Butenschön et al., 2016) are coupled to model the three-dimensional hydrodynamic-141 biogeochemical conditions of the coastal and shelf zones of the North East Atlantic, the North 142 Sea, and the Mediterranean Sea. The former provides the physical drivers to the latter, 143 144 biogeochemical model. In addition to POLCOMS-ERSEM-modelled chlorophyll-a concentrations (chl-a) from the three largest of the four possible phytoplankton functional 145 types (picoplankton (< $2\mu m$) are not filtered by Pacific oyster and were therefore not 146 included), current speed, salinity, water temperature, and the bathymetry of the model domain 147 were also used for the selection of areas where offshore oyster aquaculture would be feasible 148 149 (see 2.2).

All POLCOMS-ERSEM data were at a 0.1° spatial and a daily temporal resolution, for the 150 151 specific years for which in situ oyster growth data were also available, and for an earlycentury (2000-2004) reference period and two contrasted climate change scenarios for a late-152 century (2090-2099) period (CERES, 2018). Future climate change scenarios considered here 153 are based on two of the Representative Concentration Pathways (RCPs) in standard use by the 154 Intergovernmental Panel on Climate Change (IPCC), RCP 4.5 and RCP 8.5, and driven using 155 the global climate Max-Planck-Institute Earth System Model, Low Resolution (MPI-ESM-156 LR). Meteorological conditions at the sea surface were taken from the 0.11° regional model 157 Rossby Centre Regional Atmospheric Model, version 4, driven by the Max-Planck-Institute 158 Earth System Model, Low Resolution (MPI-ESM-LR-RCA4) and river inputs were taken 159 from the European domain of the HYdrological Predictions for the Environment (E-HYPE), 160 also driven by MPI-ESM-LR. The model outputs were compared to satellite measurements of 161 162 sea surface temperature and chlorophyll concentration for the period 1998-2015 (CERES, 2018). Temperature outputs corresponded well with satellite observations and were 0.5-1°C 163 higher in the North Sea and western Mediterranean, less than satellite observations by a 164 similar amount elsewhere, and with Spearman correlation of greater than 0.9 in all regions. 165 Modelled chlorophyll values exceeded satellite observations by up to 2 mg m⁻³ in spring, but 166

showed good agreement in other seasons; the model captures the spatial and temporal variation of chlorophyll concentration, with Spearman correlation 0.6 overall, and 0.5 in the North Sea (CERES, 2018).

170 Under RCP 4.5, radiative forcing is projected to stabilize at 4.5 W m⁻² by ~2050, 171 corresponding to a moderate, roughly business-as-usual scenario. Under RCP 8.5, radiative 172 forcing is projected to be more extreme, exceeding 8.5 W m⁻² by 2100 (Moss et al., 2010). 173 These two scenarios were chosen to give a range of possible future climate response: RCP 8.5 174 is at the upper end of plausible carbon concentrations, while RCP 4.5 is more moderate, while 175 still showing a clear climate signal. Projected global temperature rise under RCP 4.5 is 176 approximately 2°C (IPCC 2013), in line with the goal set in the 2015 Paris Agreement.

A representative year from each of the three periods or scenarios was produced for oyster
tolerance range masking and growth modelling, described below, by taking the average of all
years for the given period/scenario.

180

181 2.2 Tolerance range-based masking of unsuitable areas

As for a number of other cultivated species (e.g., Gentry et al., 2017; Kapetsky et al., 2013), 182 tolerance thresholds and ranges of certain variables and conditions have been reported in the 183 literature, within which Pacific oyster can typically thrive. Prior to mapping growth potential 184 and related indicators, areas identified through such criteria as being unsuitable for Pacific 185 186 oyster growth were masked out and not included in further mapping. Only areas for which associated POLCOMS-ERSEM data values were within the oyster tolerance ranges of 187 chlorophyll-a, water temperature, salinity, and current speed, as well as the technical 188 bathymetry limitations for mooring infrastructure, reported in Table 1 for at least 95% of the 189 given year were retained (as per Kapetsky et al., 2013). This was done for each period (early-190 and late-century) and scenario (RCP 4.5 and 8.5) considered. An example of combining the 191 criteria for these variables to produce the overall suitability masking is provided for the early-192 century reference period in Fig. 5. 193

194Table 1. Pacific oyster tolerance thresholds and ranges, and corresponding references, for195several variables used to constrain the area suitable for cultivation, within which relative196growth potential was assessed.

0	1		
	Variable	Documented tolerance/ feasible range	Reference
	Bathymetry	< 200 m	Gentry et al. (2017)
	Chl-a	> 1 mg m ⁻³ ; > 2 μ m particles	Barillé et al. (1993)
	Current speed	Current 0.1-1 m s ⁻¹	Kapetsky et al. (2013)
	Salinity	15-45 psu	Nell & Holliday (1988)
	Water temperature	3-35°C	Bayne (2017)

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198

199 2.3 Dynamic Energy Budget (DEB) modelling

Dynamic Energy Budget (DEB) theory (Kooijman, 2010) provides a generic (i.e., nonspecies-specific) approach to mechanistically model the flow of energy through individual

organisms, from the ingestion and assimilation of food, through somatic maintenance and 202 growth, to reproduction. Here, we make use of the original parameterization for Pacific ovster 203 (Crassostrea gigas) put forth by Pouvreau et al. (2006), and further updated by Bernard et al. 204 (2011) and Thomas et al. (2016), whereby water temperature influences energy flow and 205 allocation at all stages, and food abundance further impacts ingestion according to a calibrated 206 coefficient (the half-saturation ingestion coefficient; X_k). In the offshore environments 207 considered in the current work, the oysters are always submerged in the water (i.e., 100% 208 immersion time). The impact of turbidity on oyster growth is assumed to be negligible 209 offshore (Gernez et al., 2014), and the half-saturation ingestion coefficient through which 210 high concentrations of inorganic sediment modulate ingestion, as put forth by Thomas et al. 211 (2016), X_{ky}, is therefore not included in the current modelling. A DEB model schematic can 212 be found in the supplementary information of this article (Fig. S1), and parameterization 213 214 (except for X_k) and equations are those reported in the supplementary information of Thomas et al. (2016). 215

Here, two datasets reporting the results of rare in situ offshore Pacific oyster growth 216 experiments were used to calibrate the Xk coefficient and to validate the model outputs. The 217 first dataset was compiled over two separate growing seasons (2008 and 2010) from the 218 offshore Bourgneuf Bay, France, through experiments performed by a regional aquaculture 219 organization (Syndicat Mixte pour le Développement de l'Aquaculture et de la Pêche en Pays 220 de la Loire, SMIDAP) (Glize and Guissé, 2009; Glize et al., 2010). The second, reported in 221 Pogoda et al. (2011), is from three sites and two years (2004 and 2007) in the German Bight 222 223 area of the southeastern North Sea (Fig. 1). French data for adult and spat oysters from 2010 (for which most data were available) were used in the optimization-calibration process, and 224 all other data were used to validate calibration results using the metrics of mean bias (eq. 1) 225 and absolute and relative root mean square error (RMSE; eq. 2, 3). In each, M refers to the 226 227 DEB-modelled shell length, O to the *in situ*-observed shell length, and n to the number of observations. 228

229

Mean bias =
$$\frac{1}{n} \sum_{n=1}^{n} (M - O)$$
 eq. 1
RMSE = $\sqrt{\frac{\sum_{n=1}^{n} (M - O)^2}{n}}$ eq. 2

230

231 Rel. RMSE (%) = RMSE/(max(
$$0$$
) - min(0)) × 100 eq. 3

п

232

Model outputs are dry flesh mass (DFM) and shell length, which is then transformed to total 233 weight for use in the current work using a robust empirical relationship (Palmer et al., 2020) 234 between the two variables obtained from the IFREMER in situ monitoring network, Réseau 235 d'observations conchylicoles database (RESCO; Fleury et al., 2018). Outputs were generated 236 237 for the same daily time step as the input chl-a and water temperature data, and mapped on the same spatial grid (i.e., 0.1°). For each of the three periods/scenarios, models were initialized 238 to begin on April 1 of that year, with adult DFM = 0.3 g and shell length = 5.7 cm, and spat 239 DFM = 0.05 g and shell length = 1.9 cm. 240



Figure 1. (a) Model domain and locations of offshore Pacific oyster growth data used for
Dynamic Energy Budget model calibration ((b) Bourgneuf Bay, France) and validation
(b) Bourgneuf Bay, and (c) German sites, Helgoland, Nordergründe, and Butendiek).

245

246 2.4 Oyster growth aquaculture indicators

Aquaculture industry-relevant information was then extracted from each of the adult and spat 247 oyster total weight growth curves output from the DEB modelling described above for each 248 pixel. The three-dimensional data (latitude, longitude, time) was thereby transformed into 249 two-dimensional (latitude, longitude) indicator maps for each of the periods and scenarios 250 considered. Two types of adaptable indicator are presented here as examples: (1) the date at 251 which a target weight is reached for a given production year, and (2) the total weight achieved 252 by a date of interest. Although any target weight and date of interest can be selected, we have 253 chosen to demonstrate the date at which minimum market weight for an adult Pacific oyster 254 (30 g) is achieved, the date at which spat reach size T20/T25 (14 g, a popular size for resale to 255 grow out to market weight; Palmer et al. 2020), and the total adult weight achieved by 256 December 1, which is the main European market, corresponding to the French tradition of 257 eating oysters as part of Christmas and New Year celebrations. Mapped indicators, or 258 combinations of indicators, can then be used to assess which areas have the highest growth 259 potential. 260

The modelling framework proposed here also considers the variability between late century RCP scenarios to identify climate robust zones. Porporato et al. (2020) demonstrated the interest of adding an uncertainty analysis to assess the robustness of site selection for finfish cultivation in the Mediterranean. In this work, we propose a simple metric to assess the areas where growth potential will remain consistent in the future. A stability index was calculated here as the absolute difference between indicator values for the two future scenarios normalized to the indicator value itself (eq. 4):

268 ΔX_{RCP} stability index = $|X_{RCP 8.5} - X_{RCP 4.5}| / \max(X_{RCP 8.5}, X_{RCP 4.5})$ eq. 4,

where $X_{RCP \, 8.5}$ is the resulting indicator value under the RCP 8.5 end-of-century scenario and $X_{RCP \, 4.5}$ is the value of the indicator obtained under the RCP 4.5 end-of-century scenario.

We used five classes to map the variability in future oyster growth: 0.00 - 0.05 (very stable), 0.05 - 0.10 (stable), 0.10 - 0.15 (medium stability), 0.15 - 0.20 (low stability), and > 0.20 (very low stability). The most "climate robust" areas were those with stability index values of between 0.00 and 0.10, corresponding to both high and consistent growth projections in light of the uncertainties inherently associated with climate prediction and ecosystem modelling. This chosen threshold value could be adjusted by the user depending on their needs and the indicator in question.

278 Future stability was determined for areas already exhibiting good growth potential for the early-century reference period. In the current example, for total adult oyster weight attained 279 by December 1, this means that future growth variability was only determined for areas where 280 adults reach at least the 30 g minimum market weight in the 2000-2004 reference period. A 281 framework for decision-making based on current and future oyster growth indicators is 282 proposed in Figure 2. The first step considers whether an area corresponds to good growth 283 (according to user-defined criteria depending on the indicator) under current environmental 284 conditions. The second step identifies areas for which growth either remains good or 285 improves relative to current conditions in at least one of the future scenarios. The last step 286 uses the stability index (eq. 4) to identify areas that are similar under the two distinct climate 287 288 change scenarios. These can be given further priority in selecting zones for industry development (Fig. 2). 289

290



Figure 2. Schematic of decision-making framework incorporating maps of current and future oyster growth indicators to identify climate-robust hot spots as potential AZAs. As an example, criteria based on one indicator, the adult weight attained by December 1st, are shown at each step.

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In addition to maps of current and future growth potential for the full study area, the future
growth potential of several example areas within the Biscay Bay on the French Atlantic coast
is compared statistically with current growth potential through ANOVA (by rank when
normality and equal variance assumptions fail) and subsequent Tukey (or Mann-Whitney, if
following Kruskall-Wallis ANOVA by rank) pairwise comparison.

303

304

305 3. Results

306 3.1 Biogeochemical climate change scenarios

The future changes in chl-a and water temperature predicted by the model POLCOMS-ERSEM in the two climate change scenarios are presented in Figures 3 and 4 respectively. Both RCP 4.5 and 8.5 scenarios consistently predict an overall warming trend, which is nonetheless higher under the more extreme RCP 8.5 scenario. Furthermore, in areas currently

- characterized by warmer waters (e.g., lower latitudes; the Mediterranean Sea; Fig. 3a), we seegreater warming, particularly under RCP 8.5 (Fig. 3c).
- 313 Chl-a concentration is, unsurprisingly, generally higher in the near-coastal areas, with certain

regions standing out as being exceptionally productive in this sense (e.g., off the coasts of

315 Western Sahara and Mauritania in Africa; Fig. 4a). Unlike the consistent trend observed for

316 water temperature, however, whereas mean annual chl-a concentration is projected to increase

- under climate change in some areas, it is also projected to decrease over large regions of the
- study area, notably from the Bay of Biscay on the French Atlantic coast northward (Fig. 4b,
- c). Furthermore, the change in the mean annual chl-a is not always greater under the more
 extreme RCP 8.5 scenario than under the RCP 4.5 scenario. Rather, for some areas (e.g., the
- west coast of Portugal) the area or magnitude of increasing chl-a is greater under RCP 4.5
- than under RCP 8.5, and *vice versa* (e.g., the coasts of Western Sahara and Mauritania and the
- 323 Mediterranean).



Figure 3. (a) Mean annual water temperature (°C) for the early-century reference period, 2000-2004, and changes in mean annual water temperature (°C) under the emissions scenarios (b) RCP 4.5 and (c) 8.5 by late-century (2090-2099). The white areas are outside the model domain.



Figure 4. (a) Mean annual chlorophyll-a (mg m⁻³) for the early-century reference period, 2000-2004, and changes in mean annual chlorophyll-a (mg m⁻³) under the emissions scenarios (b) RCP 4.5 and (c) 8.5 by late-century (2090-2099). The white areas are outside the model domain.

336

337 3.2 Delimitation of tolerance range

338 The results of the binary, threshold-based masking of unsuitable area for the early-century 339 reference period are presented in Figure 5. Very similar results were also obtained and used for each of the two late-century climate change scenarios. Although water temperature (3-340 35°C; Bayne, 2017) and salinity (15-45 psu; Nell & Holliday, 1988) were also considered, 341 these were not found to limit the suitable area in terms of Pacific oyster tolerance ranges for 342 any of the periods or scenarios considered here. Further narrowing the salinity range to 25-40 343 psu was likewise not found to limit the suitable area. We see that, although current speed is 344 the primary limiting factor for much of the study area (Fig. 5c), bathymetry (Fig. 5a) and chl-a 345 concentration (Fig. 5b) ranges also serve to limit some areas. This is notably the case in the 346 Mediterranean Sea, with bathymetry alone found to further limit the potential of offshore 347 Pacific oyster cultivation along the north coast of Spain and northern and western Portugal at 348 the coarse spatial resolution of the data used in this exercise. Areas where conditions fall 349 within all tolerance ranges are highlighted in the cumulative constraint mask (Fig. 5d). 350 Within these areas, the growth potential was simulated and mapped by using the DEB model. 351

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Figure 5. Ranges within which Pacific oyster cultivation is considered to be suitable (in red), based on (a) bathymetry, (b) chlorophyll-a, and (c) current speed masks used to define (d) the overall suitable area for Pacific oyster cultivation and within which DEB modelling was carried out, for the early-century reference period.

360 3.3 Dynamic Energy Budget (DEB) calibration and validation

361 Only one parameter of the DEB model was required to be tuned. The half-saturation coefficient (X_k) was determined through the regression-based optimization using data on 362 offshore adult and spat growth in Bourgneuf Bay, France, in 2010. The resulting value was 363 found to reasonably model adult and spat oyster growth observed in situ for a separate year 364 (2008) in Bourgneuf Bay, as well as that measured in situ at three German sites in 2004 and 365 2007 (Pogoda et al. 2011), across the full in situ size range (Fig. 6). Shell length 366 measurements ranged from less than 3 to almost 10 cm, corresponding to total weights 367 ranging between approximately 2 and 75 g. Note that in situ measurements from the start of 368 the growing seasons were used to initialize the DEB model, and so are not included in Fig. 6. 369



370

Figure 6. (a) Calibration and (b) validation of the DEB half-saturation coefficient
(X_k).

373

374 3.4 Oyster growth indicator mapping

375 *Current spatial trends and hot spots*

Within the suitable area determined through tolerance range masking (Fig. 5), oyster growth 376 potential was found to be highly variable for each of the three indicators. Total adult weight 377 obtained for the main European market (i.e., December 1, Fig. 7), shows many areas of low 378 growth (in red) where only ~6 g were gained over the entire growing season (from the initial 379 total weight of 14 g on April 1), and end-of-season weight remains below the market 380 minimum (i.e., 30 g). A number of areas, especially close to the coast, mapped in orange, 381 yellow, or green, were found to achieve minimum market weight under current (i.e., early-382 century reference period) conditions, with several along the French Atlantic coast of the 383 Biscay Bay (Fig. 7d), as well as off western Africa (Fig. 7e). These areas resulted in hot spots 384 of exceptional growth, with large oysters (46 - 65 g, corresponding to the French caliber 4;385 Palmer et al. 2020) growing from the initial 14 g spat within a single season. The two other 386

indicators determined the date on which a target total weight was achieved (i.e., 30 g for adults (Fig. S2) and 14 g for spat (Fig. S3)). For both of these, the mapped area of the indicator is less than the total suitable area and less than the area mapped for adult weight on December 1, because the target weight will not be reached everywhere (e.g., the red areas of Fig. 7 are < 30 g by the end of the growing season). However, where the target weights are achieved, similar growth hot spots are identified, notably in western France and Africa.



Figure 7. Pacific oyster total adult weight obtained by Dec. 1 (from an initial weight of 14 g on April 1) for the early-century reference period, for the full model domain (a) and indicated close-ups: (b) the United Kingdom, (b) the southeastern North Sea, (c) the Bay of Biscay, and (d) the west coast of Western Sahara and Mauritania.

399

400 *Climate robust zones*

Future growth potential was also considered by mapping the indicators for each of the climate 401 change scenarios, to assess where investments to the industry and related policy decisions 402 might be the most sustainable, as well as have the most impact currently. Figure 8 shows the 403 example of adult growth (total weight by Dec. 1) for several potential zones off western 404 France, near areas where Pacific oyster is currently cultivated, and compares current growth 405 and spatial variability (Fig. 8a) with those under RCP 4.5 (Fig. 8b) and RCP 8.5 (Fig. 8c). An 406 area of relatively poor and decreasing growth potential is observed in South Brittany (Fig. 407 8d). ANOVA and Tukey pairwise comparisons indicate decreasing growth potential under 408 both future climate scenarios compared with current conditions in this area (Tukey p < 0.001409 for both RCP 4.5 and RCP 8.5. This contrasts with an area of moderate and stable growth in 410 coastal waters close to the Loire Estuary (Fig. 8e). Kruskall-Wallis ANOVA by ranks 411 indicates no significant difference between current and future scenarios there (p = 0.122). 412 Another area with very good growth potential is observed in the coastal waters south of the 413 Gironde Estuary (Fig. 8f). Here, the growth potential was projected to remain reasonable in 414 both scenarios, with marketable product achieved within the average projected future season, 415 despite the potential decrease under both future RCP scenarios compared to the reference 416 417 period.



Figure 8. Pacific oyster total adult weight obtained by December 1 (from an initial 419 weight of 14 g on April 1) in the Bay of Biscay for (a) the early-century reference 420 period and (b, c) two future climate change scenarios considered (RCPs 4.5, 8.5). 421 (d-f) Data from each period and scenario have been extracted from three potential 422 zones of interest along the coast to consider spatial (within-box) and between-423 scenario (between-box) variability: (d) South Brittany, (e) coastal waters close to 424 the Loire Estuary, and (f) coastal waters south of the Gironde Estuary. Grey 425 dashed lines indicate minimum market weight (30 g) and Calibre 4 total weight 426 (45 g) for the French market (Palmer et al. 2020). Boxes sharing a common 427 superscript are not statistically different (Tukey p < 0.05). 428

Such information can also be considered and mapped in terms of a decision-making 430 framework, such as that proposed in Figure 2. After determining areas where the user-431 defined criteria of "good" growth potential is currently achieved (the 30 g minimum 432 market weight is applied in this example), areas where this is also achieved in the future 433 for at least one of the climate change scenarios were identified, and further refined to 434 areas where "good" growth potential was consistent between climate change scenarios 435 (i.e., ΔX_{RCP} , as defined in eq. 4). These areas are mapped for our example indicator 436 (adult weight on December 1) in Figure 9, and include the Loire Estuary area identified 437 in Fig. 8e discussed above, with most climate-robust (i.e., most consistent future 438 conditions, also characterized by good current and future growth potential) in green, and 439 indicate the interest of certain areas from a climate change perspective. This further 440 constrains areas to be targeted for investment, such as off the coasts of Scotland, 441 Ireland, Germany, Denmark, France, and western Africa (Fig. 9). These areas are fewer 442 and smaller than the current areas of good growth potential in Figure 7, as growth 443 potential decreases under at least one climate change scenarios for many areas. 444 Similarly, the most "climate robust" areas (lowest ΔX_{RCP}) highlighted in Figure 9 are 445 not necessarily those with the highest current growth potential highlighted in Figure 7, 446 since this is instead an indicator of future change and stability between climate 447 scenarios (i.e., off the coast of Germany in Figs. 7c and 9c versus off the coast of 448 western Africa in Figs. 7e and 9e). It is therefore recommended to include both of these 449 respective absolute and relative indicators in policy and investment considerations. 450





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Figure 9. ΔX_{RCP} stability index results for future oyster growth (total adult weight by Dec. 1) between two climate change scenarios considered (RCP 4.5 and 8.5) (difference normalized to the maximum absolute total weight between the two scenarios). More climate-robust areas are considered to be those with lower future, between-scenario normalized variability. These areas are shown in green, and have normalized variability of less than 0.1.

459 **4. Discussion**

460 4.1 Spatial trends and areas of interest identified

461 Several broad zones of European and northwestern African waters have been identified as having significant Pacific oyster aquaculture potential, now and into the future under different 462 climate change scenarios, through the use of modelled growth indicators. These allowed us to 463 recognize areas where offshore aquaculture zones, and eventually farms, may be best situated 464 to optimize oyster growth. Generally, across the model domain, water temperature follows a 465 latitudinal gradient, decreasing poleward (Fig. 3a). Chl-a, on the other hand, follows a more 466 near- to offshore gradient, with higher concentrations typically observed nearer the coastline 467 (Fig. 4a). The influence of these parameters on oyster growth potential is clear in the similar 468 spatial patterns observed between, for example Fig. 4a and Fig. 7a. 469

Within the total model domain (i.e., Fig. 7a), the area off northwestern Africa (Fig. 7e) stands 470 out in particular. This corresponds to a large upwelling area that is part of the Canary 471 Upwelling Current, flowing southward from the Iberian Peninsula to Senegal, whereby north-472 easterly winds move the warmer surface waters further offshore to be replaced by cooler, 473 deeper, more nutrient rich waters (Pelegrí and Benazzouz, 2015). Indeed, following only the 474 Benguela Current (from southern South Africa to Angola), the Canary Upwelling Current is 475 476 the second most productive system in the world (Demarcq and Somoue, 2015). Superimposed upon the general latitudinal water temperature gradient observed in Figure 3a, we see waters 477 approximately 1-3°C cooler in this zone (annual mean), similar to temperatures typically 478 observed 15-20° further north, as well as higher chl-a concentration (Fig. 4a), corresponding 479 to the enhanced productivity enabled by these very nutrient-rich upwelling waters. 480

This corresponds to the general spatial trends in productivity and magnitude of chl-a 481 concentrations observed here by others over the past decades (Demarcq and Somoue, 2015). 482 Furthermore, we see both climate change scenarios corresponding to further increases in 483 annual mean chl-a relative to the early-century reference period (Fig. 4b,c), with even more 484 productive conditions under more extreme climate change (i.e., RCP 8.5). It is therefore 485 unsurprising to see this area also highlighted as an area of exceptional potential in the future, 486 and several large areas (totalling > 6000 km^2) where this is expected to be the case under both 487 climate change scenarios considered are highlighted (in green) as relatively climate robust in 488 Fig. 9a,e. 489

Several European areas were also found to have a high and climate-robust growth potential 490 (Fig. 7b-d), although this is somewhat lower compared with that of the northwestern African 491 hot spot, due to the combined influence of overall lower temperatures and chl-a 492 concentrations. In Figure 7a-d, a dominant latitudinal gradient in oyster growth potential was 493 494 also mapped, similar to general trends in water temperature, with less rapid growth observed to the northwest of Scotland and Ireland (Fig. 7b) and in the North Sea (Fig. 7c) than in the 495 more southerly Biscay Bay (Fig. 7d). However, although lower, many of these more northerly 496 areas also achieve minimum market weight (30 g) within the single growing season 497 considered here (Figs. 9, S2). Relative to the current status quo of nearshore Pacific oyster 498 cultivation, this should be regarded as exceptionally good growth. 499

500 Typically, for example near the calibration-validation site of Bourgneuf Bay, France, adult 501 grow-out from spat of a similar size will take at least two (and up to four) growing seasons in

the nearshore intertidal environment where oyster farms are currently located (note that these 502 areas cannot be observed at the spatial resolution of this work), due to particular challenges 503 encountered there (i.e., much higher turbidity; substantially lower immersion time; Palmer et 504 al., 2020). Although the nearshore-offshore difference in growth rates will certainly be less 505 substantial in areas where these factors are not as contrasted from one setting to the other (i.e., 506 nearshore oyster cultivation in fjords or lochs where tidal gradients and inorganic turbidity are 507 lower), and further experimental results are needed to evaluate this, faster growth may be a 508 primary incentive to moving cultivation offshore. This is in addition to existing space 509 constraints already highlighted as a barrier to European aquaculture expansion nearer shore 510 (Hofherr et al., 2015). 511

These more northern case sites are also characterized by more climate-robust good growth 512 potential in the future (Fig. 9), whereby growth between the two scenarios is more similar. 513 However, this indicator should be interpreted while also taking into account the absolute 514 growth under the different climate change scenarios. Given the definition of the climate-515 robustness indicator, there may be good projected growth (e.g., 30 g) under one scenario, and 516 exceptional growth (e.g., 90 g) under the other, which leads to less stable results (i.e., 0.67) 517 than simply good growth (i.e., 30 g) under both scenarios (i.e., 0.0). This highlights the need 518 to combine more than one indicator for a fuller picture in effective decision-making. 519

520

521 4.2 Advantages and limitations of the modelling approach and data used

The advantage of combining dynamic, ecophysiological growth modelling with the binary 522 tolerance range threshold approach employed elsewhere (e.g., Gentry et al. 2017; Kapetsy et 523 al., 2013) is clear in terms of the additional information and insight provided. Within areas 524 identified to fall within the Pacific oyster tolerance range for a number of variables (Fig. 5d), 525 there is a great deal of variability in oyster growth potential. Such an approach has also been 526 used to identify suitable areas for finfish cultivation in the Mediterranean (Porporato et al., 527 528 2020) and North Africa (Brigolin et al., 2015) and for shellfish cultivation in the Adriatic (Brigolin et al., 2017) and western France (Thomas et al., 2011, 2016; Barillé et al., 2020), 529 where good modelled growth is considered with other advantageous factors in more thorough 530 spatial multi-criteria evaluation. 531

Under the same DEB model initialization (i.e., oyster size, start and end dates) and 532 parameterization, total adult weight at the end of the growing season ranges from < 20 g to >533 60 g across the full model domain (Fig. 7a), and ranges by as much as 50 g over as little a 534 distance as 100 km, notably off the coast of northwestern Africa (Fig. 7e), but also by as 535 much as 20 g over the same distance along the French Atlantic (Fig. 7d) and western Scottish 536 coast (Fig. 7b), and even by as much as 10-15 g over just 30 km for parts of all of the areas of 537 interest (Fig. 7). Without this information to further optimize aquaculture zoning and site 538 selection, we would simply know that Pacific oyster aquaculture should be feasible across this 539 area (Fig. 5). 540

541 While the coarse spatial resolution of the input data (0.1°) is an inherent limitation of such 542 broad scale studies, it makes it possible to provide general assessment of trends and scenarios 543 using a cohesive approach and methodology at multi-national scale, to support decision-544 making and planning, and identify hot spots for potential development or further

consideration (Falconer et al., 2019). However, the inability of studies at such large scales to 545 account for environmental heterogeneity on finer spatial and temporal scales, documented as 546 being important to organismal physiology, is a notable limitation and highlights the need for 547 complementary studies across scales (Helmuth et al., 2014). In many instances, anomalies and 548 extreme events (for example in water temperature), as well as the dynamic and heterogeneous 549 nature of the "ocean weather" (Bates et al., 2018), which could substantially affect growth, 550 reproduction, and mortality of Pacific oyster and many other species, may not be detected 551 when using such coarse input data. Instead, the signal is averaged out over the larger spatial 552 and temporal timestep and extremes are dampened. Although the offshore environment 553 investigated here is expected to be much less sensitive and heterogeneous compared with the 554 highly variable nearer-shore and intertidal environments (i.e. Gernez et al., 2017; Choi et al., 555 2019), the importance of local climatic and non-climatic stressors should not be neglected in 556 557 site selection and should be included in the finer-scale site selection activities recommended to follow broad zoning initiatives. 558

559 The reliability of such modelling results is also limited by the availability of in situ data for calibration and validation. As offshore aquaculture remains relatively novel and experimental, 560 in situ data are likewise rare, as has been noted elsewhere and for other species (e.g., Brigolin 561 et al., 2017). In our case, we were fortunate to have two spatially disparate sites for DEB 562 model calibration and validation, representing two oyster-producing zones in Europe (the 563 French Atlantic and German North Sea) and substantial latitudinal and longitudinal gradients, 564 as well as from four different years. Although at an even greater spatial distance, Monaco et 565 al. (2019) reported the inability to predict Mediterranean mussel (Mytilus galloprovincialis) 566 growth at a South African site using calibration parameterization from a native Mediterranean 567 site. Such inability was speculated to be due to unaccounted for differences in environmental 568 variables and phenotypic plasticity. The inclusion of additional environmental parameters 569 (e.g., suspended particulate matter; Thomas et al. (2016)) and other approaches to address 570 issues of environmental variability over large spatial scales have been proposed elsewhere 571 572 (Thomas and Bacher, 2018; Alunno-Bruscia et al., 2011).

Validation results (Fig. 6) here were found to be satisfactory across both sites and multiple years. However, *in situ* data remain relatively sparse given the coverage of the model domain. Despite this limitation, our results demonstrated the added value of the methodology and framework applied in revealing general trends and hot spots. Further *in situ* data acquisition is recommended to support and complement modelling studies allowing fuller spatial coverage at all scales. Our work can help to justify and optimize the investment in carrying out additional field studies, through the identification of promising potential zones.

580 Many facets of the methodology and approach presented are flexible, in that they could be applied using other models, for other species, different production stages (e.g., spat and adult 581 582 cultivation demonstrated here), or different indicators (whether new ones, or by simply adjusting the weight and/or timing thresholds for the indicators demonstrated here) and 583 584 definitions of resulting "good" potential and zones (e.g., Figs. 2, 9). Multiple indicators and selection criteria could be combined to assess the sensitivity thereof, as well as to strengthen 585 the support for highlighted areas. Likewise, any spatiotemporal input data of choice could 586 foreseeably be used, provided that its appropriateness is demonstrated via successful growth 587 model validation. 588

This is especially important in using modelled data to drive models (as in the current case, 589 where climate model data are used to drive ecological models, the output of which is used to 590 drive oyster growth modelling), as error propagates at each stage. Notably, many other 591 climate change models and scenarios are available, including models that better take internal 592 climate variability into account (Freer et al., 2018; Thomas et al., 2018). Here, the purpose 593 was to show results from two contrasting future projections, as the greatest unknown in 594 current climate change predictions is the pace of anthropogenic greenhouse gases emissions 595 rather than modelling uncertainties (Thomas et al., 2018). While this gets at some of the 596 uncertainty in future climate change, and demonstrates a framework to include this in 597 choosing AZAs, it is by no means intended to be an exhaustive or complete assessment. 598 However, as mentioned above, different input data based on other climate scenarios and/or 599 models, as well as other ecological models, could be used as of interest. This would also give 600 601 more understanding of the uncertainty in the model results. The source model used here (MPI-ESM-LR) gives a lower projected rise than some other global climate models and so greater 602 future change than projected here could be possible. 603

604

4.3 Additional considerations in establishing Allocated Zones for Aquaculture

A number of biogeochemical and physical variables output from the POLCOMS-ERSEM 606 ecosystem model were used here to delineate and highlight areas that should be given priority 607 consideration for offshore Pacific oyster aquaculture, as well as to indicate areas not likely to 608 be suitable, successful, or sustainable in this respect. Although framed here within Pacific 609 ovster tolerance ranges and growth modelling, the considered variables (chl-a, water 610 temperature, salinity, current speed, bathymetric depth) are broadly relevant to many farmed, 611 as well as unfarmed species, in addition to underlying countless ecological processes in the 612 marine environment. However, many other variables and factors that were beyond the scope 613 of this work and were not explicitly considered here are known or expected to also be 614 important determinants of Pacific oyster and other aquaculture potential at a given location. 615

Some factors are known to currently preclude the installation of offshore infrastructure in 616 some locations that might otherwise be productive (e.g., wave height, which may impact 617 organism growth potential as well as accessibility of offshore structures to undertake 618 operations and maintenance (Buck and Langan, 2017)). Some are likely to intensify in some 619 locations or generally under climate change conditions (e.g., frequency of storms (Feser et al., 620 2015), ocean acidification (Kroeker et al., 2010; Barton et al., 2012), frequency of wintertime 621 seawater temperature anomalies (Thomas et al., 2018), and drop in pH levels (Law et al. 622 2018), as well as the cumulative effects of combinations of these parameters). These stressors 623 will have a direct impact on the potential for offshore as well as nearshore aquaculture into 624 the future. Others (e.g., storm surges (Vousdoukas et al., 2016) and sea level rise (Grinsted et 625 al., 2015)) may not be as detrimental to infrastructure and cultivation in the offshore 626 environment itself, but may be important to consider in terms of their projected increasing 627 impact on the coast and related damage to infrastructure necessary to support offshore 628 629 production there (e.g., ports; grading, packing, and distribution facilities). Likewise, 630 interaction between and among climatic and non-climatic stressors, and potential adaptation and acclimatization may be substantial (Helmuth et al., 2014). 631

As different species are expected and documented to respond differently to the impacts of 632 climate change (e.g., Filgueira et al., 2018; Steeves et al., 2018; Thomas and Bacher, 2018), 633 this should also be considered in selecting species to farm. For the Atlantic Canadian site 634 investigated by Steeves et al. (2018), although the growth of both species was found to be 635 enhanced overall, the greater thermal tolerance of the eastern oyster, Crassotrea virginica, 636 allowed it to outperform the blue mussel, *Mytilus edulis*. Modelling by Filgueira et al. (2018) 637 found similar results favouring C. virginica over M. edulis in warming scenarios, and also 638 suggests that bivalve aquaculture may enhance ecological resilience under some climate 639 change scenarios and coastal geomorphologies (e.g., bays with large rivers). Likewise, the 640 negative environmental impacts accruing from the aquaculture of different species are also 641 not expected to be uniform in space and time under different climate scenarios and for 642 different species. This has been demonstrated for the Mediterranean seabass, Dicentrarchus 643 labrax, in the Mediterranean and Black seas in terms of organic loading as well as animal 644 growth, whereby the trade-off between fish growth and farm pollution was found to become 645 increasingly difficult to optimize under their modelled climate change scenarios (Sarà et al., 646 2018). In the Mediterranean, the growth, mortality, and phenology of three different 647 commercial mussel species has been forecasted to respond variably and non-linearly by 648 species and site in response to modelled warming (Montalto et al., 2016). Pacific oyster 649 results from the northeast Atlantic suggest that climate change has a positive impact on oyster 650 growth and reproduction (due to chl-a and SST increase; Thomas et al., 2016) and that 651 phytoplankton dynamics, more than temperature directly, underlie modelled climate-driven 652 phenological shifts in this species in terms of spawning event timing (Gourault et al., 2019). 653 On the other hand, warming is also likely to result in a higher risk of adult oyster mortality 654 655 due to an increase in the occurrences of positive wintertime temperature anomalies (Thomas et al., 2018). This highlights the need for modelling across trophic levels, and to consider 656 657 seasonal dynamics and interannual climate variability in addition to more binary tolerance 658 ranges.

659 Further variables to consider relate more to alternative and conflicting uses of the space from a socioeconomic perspective, notably related to capture fisheries, the existence of other 660 industries (e.g., windfarms; oil and gas platforms), transportation and militarized zones, and 661 environmentally protected areas (Barillé et al., 2020; Porporato et al., 2020). The presence of 662 663 sufficient coastal infrastructure to support offshore aquaculture (e.g., harbours or ports within 664 a reasonable distance) is another crucial consideration. Some of these will result in the absolute preclusion of aquaculture from some areas (i.e., marine protected areas, or if there is 665 not a port within, for example, 25 nm (Kapetsky et al., 2013), offshore aquaculture cannot be 666 considered), whereas others will need to be considered in terms of finding a balance with 667 aquaculture (e.g., fishing type (Barillé et al., 2020)). 668

Existing examples of spatial multi-criteria evaluation (SMCE) and multi-criteria decision 669 670 analysis (MCDA) offer frameworks for how a multitude of variables of different types can be integrated to further improve information provided for planning and policy, as well as site 671 selection (Falconer et al., 2019). Whereas most assess conditions for a current or recent 672 scenario, the consideration of future climate change uncertainty, via the inclusion of different 673 RCP scenarios in the stability index proposed here, represents a novel adaptation of such a 674 SMCE approach, and is key to supporting sustainable decision-making for long-term industry 675 investments and development. 676

Although it is likely that not all data that would be beneficial to include are available at the 677 appropriate spatial resolution and broad spatial coverage demonstrated here (Falconer et al., 678 2019), such data could be added upon considering specific identified hot spots at the smaller 679 regional scale to further assess a proposed AZA, or at the even smaller local scale, as part of 680 the farm site selection step. In this work, our aim is to demonstrate the added benefit and 681 utility of using such a dynamic, growth modelling-based approach to identify areas of interest 682 from a biological perspective, and we recommend the integration of such results and 683 indicators as produced here into a fuller SMCE or MCDA. 684

In addition to considering the biological potential of a cultured species of interest (i.e., Pacific 685 oyster here) along with factors likely to restrict potential areas for aquaculture, areas where 686 687 additional benefit may be possible should also be sought out. Co-production with other sectors, notably energy, can also be targeted as a means to make dual use of shared 688 infrastructure. Co-production of shellfish with offshore wind energy has received a great deal 689 of attention, and, albeit less-so, co-production with active or decommissioned offshore oil and 690 gas platforms has also been noted, with a few small-scale demonstration projects having taken 691 place (Buck and Langan, 2017). Although each of these activities is complex and 692 controversial in its own right, the idea is that existing physical infrastructure, as well as 693 processes related to site selection and permitting, might be leveraged to the benefit of new, 694 related aquaculture developments (Buck and Langan, 2017). Likewise, this would represent a 695 more efficient use of space in the marine environment, which, even offshore, is limited and 696 multiple potential uses must be balanced. 697

Areas where the biological potential is high for several potential species could likewise be 698 prioritized in the designation of general AZAs within economic exclusive zones of a country. 699 This has been done to a certain extent using a binary thresholding approach (e.g., Gentry et 700 al., 2017), but could be improved upon by making use of DEB modelling of other shellfish or 701 finfish of interest. In fact, such parameterization has already been undertaken for a suite of 702 relevant species (e.g., blue mussel (Mytilus edulis; Filgueira et al., 2011), Mediterranean 703 mussel (Mytilus galloprovincialis; Sarà et al., 2012), great scallop (Pecten maximus; Gourault 704 705 et al., 2019), European seabass (Dicentrarchus labrax; Stavrakidis-Zachou et al., 2019), and white and gilthead seabream (Diplodus sargus and Sparus aurata; Serpa et al., 2013)), noting 706 707 that, of course, not all species will be of interest or feasible for all countries.

Such areas of added benefit, where different species or different commodities have the potential to be produced, should be identified and included positively in MSP activities, such as SMCE or MCDA. As discussed in Palmer et al. (2020), issues of Pacific oyster carrying capacity and stocking density were not considered here, and are implicitly excluded from the *in situ* datasets upon which modelled results are based. If farms were established offshore, with inherently greater numbers of farming structures, growth potential and carrying capacity would be expected to be affected, and the environmental impact would need to be considered.

715

716 **5.** Conclusions

717 Several large (> 1000 km²) areas have been highlighted as current hot spots for offshore
718 Pacific oyster cultivation across Europe and northwestern Africa. These are found to be
719 associated with continued good production into the coming century under distinct climate

change scenarios according to the input data, model results, and framework presented here. 720 Pacific ovster and/or other bivalve cultivation is already practiced in the more nearshore 721 environment for several highlighted regions, including the intertidal zone of the French 722 Atlantic, the southern North Sea, southwestern Ireland, and lochs of western Scotland, 723 indicating the promise for facilitated industry and expertise transfer to the offshore 724 environment in these areas. A large area off the coasts of Western Sahara and Mauritania is 725 also highlighted, corresponding to a major upwelling zone, which could indicate a promising 726 new industry for this region. Such climate-robust areas of exceptional Pacific oyster growth 727 are recommended for prioritization in subsequent zoning or higher-resolution site selection. A 728 suite of flexible indicators and a framework to integrate results into decision making have 729 been demonstrated, which may be adapted to the specific decision-making need or to uptake 730 similar modelling results for other species of interest. 731

732

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744 Author contributions

SP, PG, LB, and SC designed the study. SC and SK generated POLCOMS-ERSEM data, and
SP generated the DEB outputs. PG and LB contributed to *in situ* data collection and
compilation. SP, SC, and SK contributed to data analysis. SP, PG, LB, SC, SK, and BB
contributed to data interpretation. SP wrote the manuscript. All authors contributed to writing
and revision and gave their approval to the manuscript final version.

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