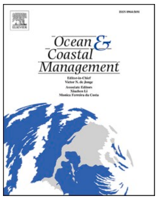
Ocean and Coastal Management 249 (2024) 106986

Contents lists available at ScienceDirect

Ocean and Coastal Management

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



A mechanistic model approach to characterize suitable regions for *Salmo salar* aquaculture in the Yellow Sea under global warming

Yu-Yang Zhang [a], Jie Wang [a], Shuang-En Yu [a], Xin Sun [a], Yue Su [a], Gianluca Sarà [b,c], Yun-Wei Dong [a,*]

[a] *Key Laboratory of Mariculture of Ministry of Education, College of Fisheries, Ocean University of China, Qingdao 266003, China*
[b] *Laboratory of Ecology, Department of Earth and Marine Sciences, University of Palermo, 90128 Palermo, Italy*
[c] *NBFC, National Biodiversity Future Center, Piazza Marina 61, 90133 Palermo, Italy*

ARTICLE INFO

Keywords:
Climate change
Dynamic energy budget
Salmo salar
Site selection
Yellow Sea cold water mass

ABSTRACT

Global warming has a profound effect on aquaculture. Salmon aquaculture, as an emerging industry in China, is particularly vulnerable to climate change. For this reason, spatial planning with mechanistic understanding is essential for mitigating and adapting to the impacts of climate change. Through the use of dynamic energy budget models for Atlantic salmon (*Salmo salar*) with fine-scale environmental data under 0 m, 20 m, 40 m, and 60 m depth, this study established a framework for identifying optimal regions for salmon aquaculture in the Yellow Sea under current and two Shared Socioeconomic Pathway scenarios (SSP1-2.6 and SSP5-8.5) in the 2050s. These results suggest that most regions in the Yellow Sea under 40 m and 60 m depth are suitable for salmon farming at both current and future scenarios, the central region of the Yellow Sea under 20 m (38°N, 123°E) is the optimal site for salmon aquaculture in China. Overall, these findings provide valuable support for aquaculture management and can help stakeholders create an effective blueprint for adaptation strategies.

1. Introduction

The production security of aquaculture is challenged by global warming, ocean acidification, sea level rise, and extreme events (Froehlich et al., 2018; Ma et al., 2021; Oyinlola et al., 2020; Stewart-Sinclair et al., 2020; Zhang et al., 2023; Zurek et al., 2022). As awareness of aquaculture's vulnerability to climate change increases, thermal threats, including warming temperatures and marine heatwaves, are receiving increased focus from both scientific and news sources (Cheung et al., 2021; Froehlich et al., 2022; Frölicher et al., 2018). How to mitigate and adapt to climate change is crucial for aquaculture, which has raised global awareness of stakeholders to focus on (FAO, 2014; Galappaththi et al., 2020; Maulu et al., 2021).

Atlantic salmon (*Salmo salar)* is one of the most productive and important marine species around the globe. The production of Atlantic salmon in 2020 was 2.7 million tonnes, which took up about 32.6 percent of marine and coastal finfish production (FAO, 2022), and the Atlantic salmon aquaculture industry has seen a rapid rise in recent years, becoming one of the most lucrative and technologically advanced industries (Chávez et al., 2019; Falconer et al., 2023). However, salmon production is detrimentally affected by thermal threats from climate change (Wade et al., 2019). These climate-change-driven shifts in water temperature exceed the thermal tolerance limits of salmon and cause mass mortality events in Newfoundland, Tasmania, and other regions (Calado et al., 2021; Meng et al., 2022). Therefore, urgent actions are needed to cope with climate change (Soto et al., 2019).

Atlantic salmon has recently been introduced to China, and the related aquaculture industry has become a promising sector in offshore aquaculture in China. However, the industry is facing great challenges due to the low upper thermal limit of the Atlantic salmon (Aas et al., 2011; Dong, 2019). The Yellow Sea cold water mass (YSCWM) is an area of 130,000 km^2 with water temperature below 10 °C in summer (Weng et al., 1988; Yu et al., 2006). The high dynamic thermal environments in YSCWM provide thermal refugia, and YSCWM has been regarded as suitable zoning for the salmon industry (Dong, 2019). Results of species distribution models also confirmed the importance of the mesoscale spatio-temporal environmental heterogeneity for *S. salar* aquaculture in this region (Yu et al., 2022). In practice, an offshore platform-based fish farming facility for culturing salmon, Deep Blue 1 (35.20°N, 122.26°E), has been deployed in this area, and the first batch of farmed salmon was

---

* Corresponding author.
E-mail address: dongyw@ouc.edu.cn (Y.-W. Dong).

https://doi.org/10.1016/j.ocecoaman.2023.106986
Received 16 August 2023; Received in revised form 29 November 2023; Accepted 12 December 2023

harvested in 2022. However, in such a heterogeneous thermal environment, warming water temperatures increase the uncertainty of the development of offshore salmon aquaculture in China. When mapping suitable offshore aquaculture areas, the effects of heat stress should be considered, which would be crucial to the success and sustainability of aquaculture with multiple approaches.

The dynamic energy budget (DEB) model is an effective and powerful mechanistic approach to quantifying functional traits of species to identify hot spots for potential development or aquaculture management (Kooijman, 2010; Montalto et al., 2015; Sarà et al., 2018). DEB model generates informative outputs that are crucial to the maintenance and restoration of the socioeconomic integrity of marine regions in the dynamic and changing environment (Baas et al., 2018; Graham et al., 2020; Mangano et al., 2019; Tan et al., 2021). Observation of the spatio-temporal variability in the performance of many aquaculture species can figure out the optimal cultivation areas of offshore aquaculture (Giacoletti et al., 2021; Sarà et al., 2012). In the present study, we provided a framework based on the DEB model as a decision support tool to inform site selection for Atlantic salmon aquaculture in the YSCWM. Areas with good growth performance were highlighted for priority consideration. These results are crucial for risk assessment, climate change mitigation and adaptation, and sustainable development of offshore aquaculture.

2. Materials and methods

2.1. DEB model

The DEB theory outlines the metabolic dynamics of an individual organism across its life cycle, with explicit connections to food availability and temperature (Sousa et al., 2010). An individual is described by three state variables: reserve, structure, maturation (juveniles)/reproduction (adults) (Table 1). Energy derived from feeding is initially allocated to reserves and then used for growth (i.e., body length/body mass), maintenance (somatic and maturity), development, and reproduction. According to DEB theory, a constant fraction κ of the mobilization energy ($\dot{p}_C$) is allocated somatic functions (somatic maintenance and growth). Maintenance has priority over growth. The rest of the energy is allocated to maturity maintenance costs and developmental/reproductive functions.

The standard DEB (stdDEB) was used in the present study as described in previous studies (Pecquerie et al., 2011; Sarà et al., 2018; Strople et al., 2018). A standard DEB model comprises three life stages: embryo (without feed and reproduce), juvenile (only feed), and adult (feed and reproduce). According to the production cycle and life cycle of *Salmo salar* (Fig. 1), our focus was directed towards comprehending the growth dynamics of salmon in the context of cage culture, the phase when salmon grow from postsmolt to adult (seawater phase, blue area in Fig. 1). The DEB model was constructed for the juvenile (postsmolt) and adult (before spawning) stages of Atlantic salmon, omitting the spawning stage of the generic DEB model format (Fig. 1). The simulated period was considered to start the day the fish (length: ~23 cm, weight: ~150 g) were released into the cages.

The model parameters were collected from Føre et al. (2016), Strople et al. (2018) and AmP procedure (DEBtool package retrieved on 08/07/2022 from http://www.bio.vu.nl/thb/deb/deblab/add_my_pet/) (Table 1). The flux equations of DEB and parameters of *S. salar* were summarized in Appendix S1 and Table 1, respectively. [], {} and a dot above the symbol (i.e., $\dot{p}_C$) indicates per unit structural volume, per unit surface area of the structural volume, and a rate/dimension per time, respectively.

The measurable length (Lw) and body mass (W) for a fish are calculated as follows:

$$L = V^{1/3}$$

$$Lw = L/\delta$$

$$W = d_v{}^{*}L^3 + (E + E_R)/e_j$$

where, L, V, and δ represent the structural length, structural volume, and shape coefficient, respectively. Where e_j is the energy content of wet reserve (J g^{-1}). d_v is the energy density of the wet structure, which equals 1 g cm^{-3} (Jusup et al., 2014; Ren et al., 2020).

Table 1
DEB parameters for *Salmo salar*.

Symbol	Value	Units	Description	Reference
State and Forcing variable				
E		J	Reserve energy	
V		cm^3	Structural volume	
E_H		J	Cumulated energy invested in the development	
E_R		J	Reproduction buffer energy	
T		K	Absolute temperature	
f			Scaled functional response	
c(T)			Temperature correction factor	
Parameters				
$[\dot{p}M]$	11.6	Jcm^{-3}d^{-1}	Volume-specific somatic maintenance rate	Strople et al. (2018)
$\{\dot{p}T\}$	0	Jcm^{-2}d^{-1}	Surface-specific somatic maintenance rate	Strople et al. (2018)
[EG]	5500	Jcm^{-3}	Volume-specific cost for structure	Strople et al. (2018)
$\dot{v}$	0.19	cmd^{-1}	Energy conductance	Strople et al. (2018)
K	0.9		Fraction of reserves to growth and maintenance	Strople et al. (2018)
K_R	0.95		Fraction of the reproduction buffer fixed into eggs	add my pets *
δ	0.207		Shape coefficient	Strople et al. (2018)
*l*m	120	cm	Maximum observed length	add my pets *
$\{\dot{p}_{Am}\}$	lm $[\dot{p}M]$/K	Jcm^{-2}d^{-1}	Maximum surface area-specific assimilation rate	
g	$\dot{v}$ [EG]/K$\{\dot{p}_{Am}\}$		Energy investment ratio	
$[E_m]$	$\{\dot{p}_{Am}\}/\dot{v}$	Jcm^{-3}	Maximum reserve density	
T_A	6000	K	Arrhenius temperature	Strople et al. (2018)
T_1	293	K	Reference temperature	Strople et al. (2018)
T_{AL}	160,416	K	Rate of decrease at the lower boundary	Strople et al. (2018)
T_{AH}	30,000	K	Rate of decrease at the higher boundary	Føre et al. (2016)
T_L	280	K	Lower boundary tolerance range	Strople et al. (2018)
T_H	289	K	Higher boundary tolerance range	Føre et al. (2016)

Note: add my pets *: data from add-my-pet (http://www.bio.vu.nl/thb/deb/deblab/add_my_pet/).

2.2. Forcing variable

The standard DEB model factors in two forcing variables: food density through the functional response (f; Holling 1959) and temperature through the Arrhenius theory (Kooijman, 2010). The food density is directly proportional to f following a Holling Type II response.(Kooijman, 2010)

$$f = \frac{X}{X + X_K}$$

where, X and X_K denote the food density in the environment and half saturation constant, respectively. If f = 0, the organism absorbs no energy from its surroundings. If f = 1, the steady state of energy reserve density reaches maximum. Due to the DEB model applied for

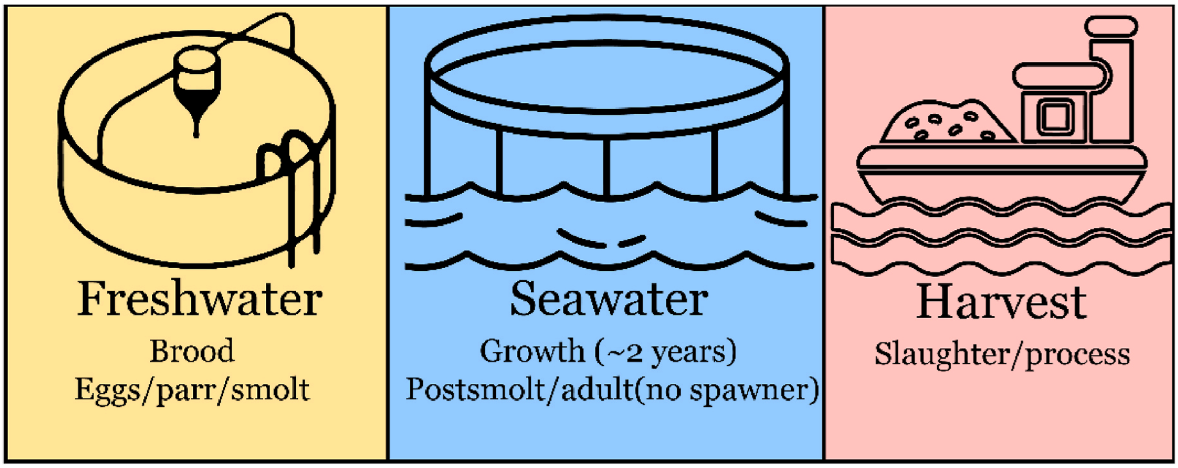


Fig. 1. Schematic representation of the production cycle of *Salmo salar*. The period covered by the blue color was regarded as the offshore aquaculture stage in China.

aquaculture salmon, rather than wild populations, food is plentiful by default, and f was set to 1.

The Arrhenius relationship (1889) (Kooijman, 2010) (Appendix S1) depicts the effect of temperature on metabolism as the flux of energy inside an organism varies according to its own metabolism and thus depends on physiological rates (Sarà et al., 2014). Daily seawater temperature at 0 m, 20 m, 40 m, and 60 m depth was used for evaluating the depth impacts on the growth performance of salmon, and in doing so we downloaded temperature daily time series from 2019 to 2020 from Copernicus Marine Service (https://marine.copernicus.eu/), with the standard regular grid at 1/12°. These simulated temperatures were validated by the observed temperature under 0 m, 20 m, and 40 m depths in Deep Blue No. 1 (Fig. S1). After validation, the water temperature dataset from 2019 to 2020 was used to simulate the growth performance of salmon under the current scenario. To assess the possible impact of global warming, the temperature at 0 m, 20 m, 40 m, and 60 m depth under two Shared Socioeconomic Pathway scenarios from 2051 to 2052 (SSP 1–2.6 and SSP 5–8.5) was downloaded from the CMIP6 website (https://esgf-node.llnl.gov/projects/cmip6/). SSP1–2.6 outlines a sustainability pathway characterized by minimal challenges for both adaptation and mitigation. In contrast, SSP5–8.5 outlines a fossil-fueled development pathway, posing significant challenges for mitigation while posing lower challenges for adaptation (Popp et al., 2017). For lacking daily water temperature data with depths under future scenarios, monthly data simulated from Alfred-Wegener-Institut für Polar-und Meeresforschung (AWI) was used in the present study. Daily water temperature was replaced by duplicate monthly water temperature based on the number of days per month.

2.3. Model validation

The DEB model was validated by two independent datasets collected from the literature on China farming aquaculture (Xu et al., 2019; Chou, 2014). The WebPlot Digitize software (https://automeris.io/WebPlotDigitizer) was used to extract the wet weight of Atlantic salmon at different months of farming from the images for model validation. The DEB model was run for the number of days observed in the original dataset. The reduced major axis (RMA) regression method was used to evaluate the agreement between observed and simulated weight (Filgueira et al., 2016; Sigourney et al., 2008), which takes into account sampling error for both the dependent and independent variables. RMA was performed by the “lmodel2” package in R (R Development Core Team, 2021).

2.4. Site selection based on growth performance

The growth rate was regarded as an indicator for selecting the suitable areas of *S. salar*. The growth rate (μ) of *S. salar* was calculated following the equation:

$$\mu = \ln((W_1 - W_0)/(t_1 - t_0))$$

where, “W” represents weight and “t” represents time. “0” and “1” refer to the start and end of a culture period of *S. salar*, respectively. The initial weight (W_0) is the mean of observed data (~150 g) of *S. salar* before cage culture in the Deep Blue 1 platform. According to the salmon industry handbook (Mowi, 2022), the commercial size of salmon was 4500 g with two-year growth cycle. Therefore, the interval time of cage culture ($t_1 - t_0$) was set to 730 (day). For identifying the suitable areas for salmon aquaculture, the grid cells in the Yellow Sea were graded to “A”, “B”, “C”, “D”, “E” and “F” according to the growth rate (μ) of salmon. The final weight (W_1) thresholds of “A”, “B”, “C”, “D”, “E” and “F” in grid cells were “>6000 g”, “5000 g–6000 g”, “4500 g–5000 g”, “4000 g–4500 g”, “3000 g–4000 g” and “<3000 g”, respectively. The grid cells where the growth rate was faster than the commercial size (4500 g; 2 years) were regarded as suitable areas (“A”, “B” and “C”) otherwise the grid cells were regarded as unsuitable areas (“D”, “E” and “F”).

3. Result

3.1. Model performance

Simulation outputs in the form of wet weight values were compared with the experimental results from the literature. There observed and simulated wet weights of *S. salar* were in great accord (Fig. 2). In the early period during cage farming, the simulated wet weight was similar to the observed postsmolt. During the interim period, the simulated fish grew less than the real fish. During the adult stage, the simulated fish grew similar or higher to the real fish. The slope of RMA regression comparing observed and simulated data points (Fig. 2b) was statistically similar to 1 ($p < 0.001$), indicating the simulation of the growth rate for the whole aquaculture period was comparable with the observed data.

3.2. Suitable areas under the current scenario

The growth rate was used to quantitatively assess the potential of *S. salar* aquaculture in each grid cell in the YSCWM. The growth rates of salmon were highly dynamic in different depths. There are few suitable areas for salmon farming under 0 m depth, while the other depths had an opposite trend. There are a lot of suitable areas over the commercial size

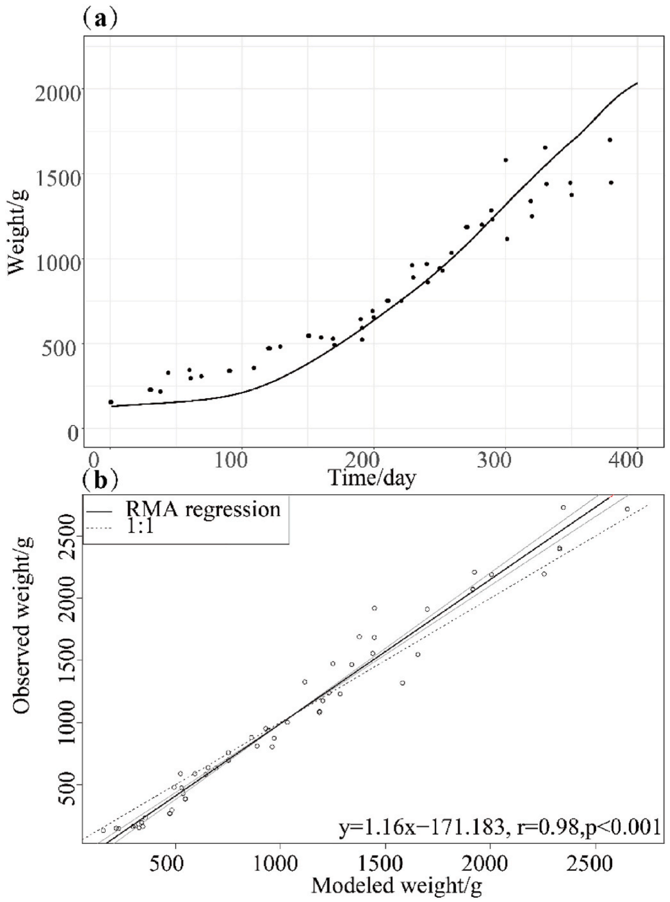


Fig. 2. (a) Simulated (black line) and observed (points) growth data represented by wet weight and time from the observed and reference dataset; (b) RMA regression for wet weight comparing observed versus modeled data points.

for salmon farming under 20 m depth, and most areas under 40 m and 60 m were suitable for salmon farming (Fig. 3).

Partial regions in the eastern center of Yellow Sea (37.5°N, 125°E) under 0 m depth could be applied for salmon farming. Suitable areas for salmon existed spatial heterogeneity under the 20 m depth. Areas located in the eastern center of the Yellow Sea (36–38°N, 124–126°E) and partial regions of the northern Yellow Sea (38°N, 122.5°E) were the most suitable areas for Atlantic salmon farming. Areas located in the northeastern of the Yellow Sea (38–39°N, 124–125°E) and most of the nearshore regions were potentially unsuitable areas for Atlantic salmon farming due to the low growth rates, which were consistent with the situation under 40 m depth.

3.3. *Suitable areas under the future scenarios*

Suitable areas for Atlantic salmon farming under 0 m and 20 m depth would shrink and most areas under 40 m and 60 m depth were suitable for salmon farming under the SSP5-8.5 scenario in the Yellow Sea, which is consistent with the situation under the SSP1-2.6 scenario (Figs. 4, 5 and S2). The suitable areas (levels: “A”, “B”, and “C”) for salmon farming under 20 m depth present a double-center structure in the eastern central region and northwest of the Yellow Sea. Areas located in the eastern center of the Yellow Sea (38°N, 125°E) and the northwest of the Yellow Sea (38°N, 123°E) will be the most suitable areas for Atlantic salmon farming in the context of global warming. The suitable areas under 20 m depth also show a trend of a northward shift in the Yellow Sea. Meanwhile, the number and distribution of suitable areas under 40 m and 60 m depth remain steady under global warming.

4. Discussion

Salmon aquaculture is a promising industry in China but facing great challenges from high water temperatures and high uncertainties from climate change, especially from the warming water and increasing extreme temperature events (Oliver et al., 2021). While it is imperative to address the impact of climate change, the reply of mitigation and adaptation of the aquaculture industry to ocean warming is relatively slow (Calado et al., 2021; Holbrook et al., 2020). The ongoing variations of heat stress in the context of climate change should be taken into consideration in the development of offshore aquaculture in China and around the globe. In the present study, a DEB model for Atlantic salmon was developed for spatial planning of salmon offshore aquaculture in the Yellow Sea. The growth performance of salmon in the Yellow Sea was also estimated under future scenarios (SSP1-2.6 and SSP5-8.5). These results provide effective information for policymaking and offshore aquaculture management.

4.1. *Importance of mesoscale environmental variations in aquaculture management*

Aquaculture zoning or site selection for specific species helps cope with climate change, especially for the emerging offshore aquaculture industry. Previous studies have confirmed that DEB models can provide useful information for stakeholders and policymakers in aquaculture, such as European seabass (*Dicentrarchus labrax*), Pacific oyster (*Crassostrea gigas*), and green-lipped mussel (*Perna viridis*) (Cheng et al., 2018; Giacoletti et al., 2021; Krupandan et al., 2022). Different from the Geographic Information Systems (GIS) based and correlative methods, the DEB modeling integrating with fine-scale environmental temperature provides a base map of biological carrying capacity for enhancing strategic decisions (Ottinger et al., 2016). This kind of mechanistic model will play a more and more important role in the future by providing invaluable support to stakeholders and decision-makers in addressing localized spatial challenges and conflicts.

Along with DEB model is now well-deployed, the importance of mesoscale environmental variations/heterogeneity on the model output was emphasized in the present study. The mapping of suitable areas for salmon farming in the Yellow Sea shows huge differences among different water depths (Fig. 5). While, aquaculture evaluation in most research, especially for those researches based on mechanistic models, was calculated based on sea surface temperature at present (Giacoletti et al., 2021; Strople et al., 2018; Zhang et al., 2023). The environmental heterogeneity in evaluating species response to climate change has been paid more and more attention by researchers (Li et al., 2021; Zellweger et al., 2020). Hence, the potential of offshore aquaculture may be underestimated without consideration of mesoscale environmental heterogeneity. The mitigation and adaptation of the aquaculture industry at the mesoscale and microscale to ocean warming should take environmental heterogeneity into consideration (Yu et al., 2022).

4.2. *Growth potential of salmon in the Yellow Sea*

Growth of Atlantic salmon exhibited high spatial heterogeneity in the Yellow Sea. Previous studies confirmed growth of the Atlantic salmon is sensitive and heavily dependent on seawater temperatures (Mowi, 2022). YSCWM, with high seasonal dynamics in water temperature, can affect salmon’s growth rate. YSCWM has three low-temperature centers, the north Yellow Sea center (38.42°N, 122.50°E), the southeast Yellow Sea center (36.50°N, 124.08°E), and the southwest Yellow Sea center (35.58°N, 122.83°E) (Yu et al., 2006). The most suitable areas for salmon aquaculture were corresponding with the surroundings of these low-temperature centers. A few suitable regions for salmon aquaculture in the southwest Yellow Sea can be attributed to the depth (Dong, 2019). Relatively shallow sea areas were more susceptible to the effects of thermal factors which led to the

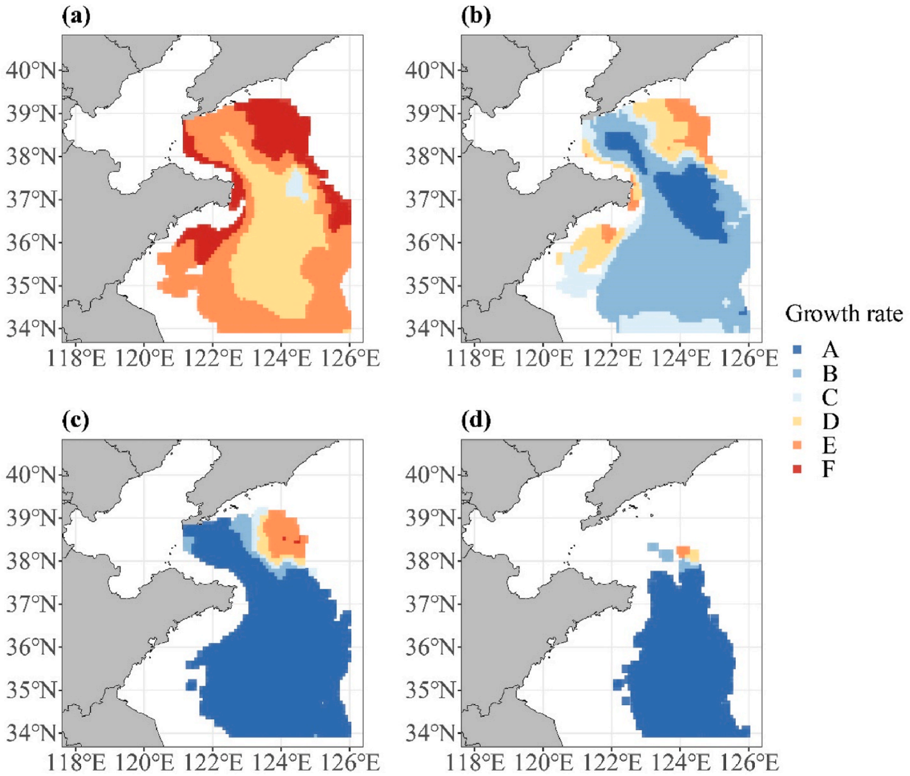


Fig. 3. The growth rate of *Salmo salar* under 0 m (a), 20 m (b), 40 m (c), and 60 m (d) in the Yellow Sea at the current scenario from 2019 to 2020. The growth rate thresholds (based on final weight) of A, B, C, D, E, and F were ">6000 g", "5000 g–6000 g", "4500 g–5000 g", "4000 g–4500 g", "3000 g–4000 g", and "<3000 g", respectively.

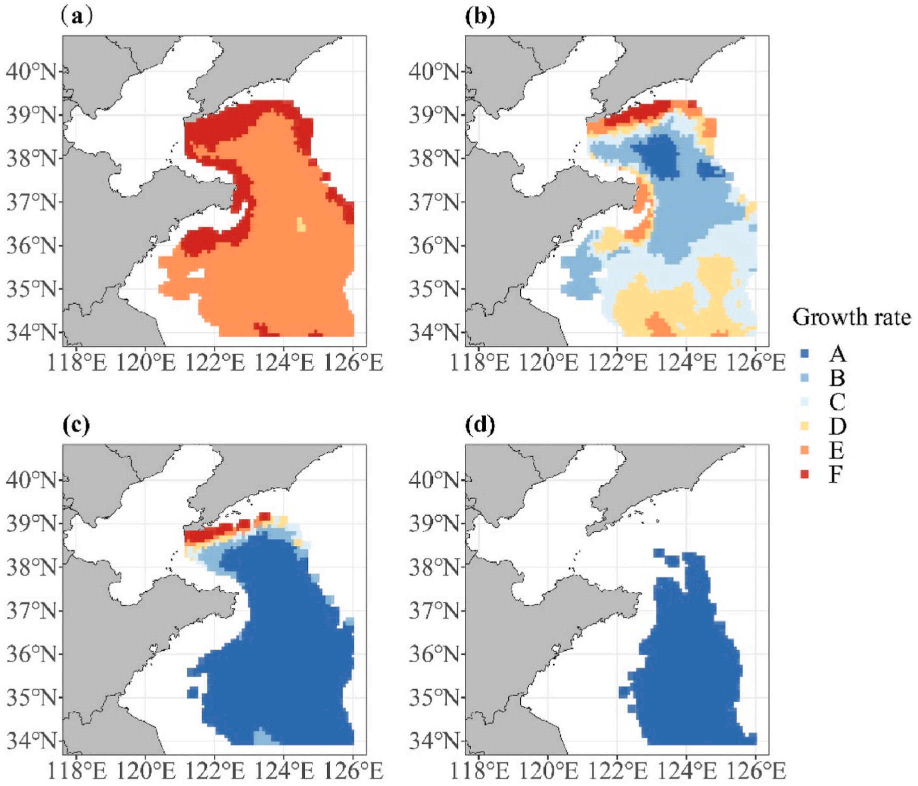


Fig. 4. The growth rate of *Salmo salar* under 0 m (a), 20 m (b), 40 m (c), and 60 m (d) in the Yellow Sea at the Shared Socioeconomic Pathway scenario (SSP5-8.5) from 2051 to 2052. The growth rate thresholds (based on final weight) of A, B, C, D, E, and F were ">6000 g", "5000 g–6000 g", "4500 g–5000 g", "4000 g–4500 g", "3000 g–4000 g", and "<3000 g", respectively.

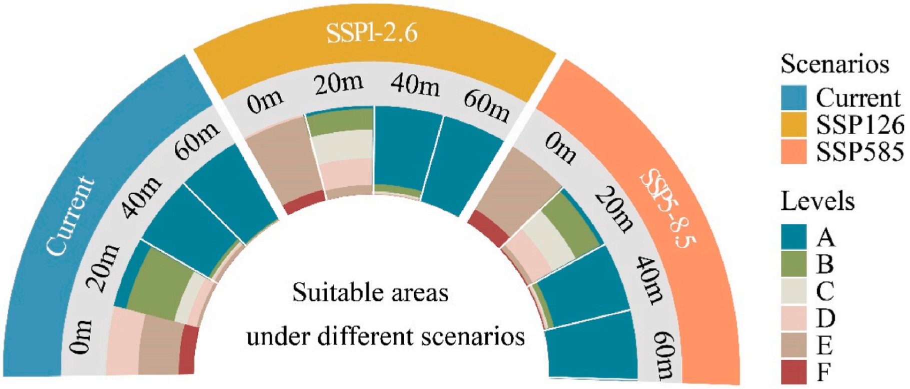


Fig. 5. The proportion of grid cells with different growth rates of *Salmo salar* in the Yellow Sea. Light blue, yellow, and tangerine colors represented the current, SSP1-2.6, and SSP5-8.5 scenarios, respectively. 0 m, 20 m, 40 m, and 60 m in the grey cubes represented water layers with depths in the Yellow Sea. The bottom bar represents the proportion of the respective growth rates. The thresholds (based on final weight) of blue (A), green (B), grey (C), light red (D), brown (E), and dark red (F) were ">6000 g", "5000 g–6000 g", "4500 g–5000 g", "4000 g–4500 g", "3000 g–4000 g", and "<3000 g", respectively.

southwest Yellow Sea center existing for a relatively short time. However, submerging the net cage into deep cold water is a feasible approach to culture the salmonids in this region.

Global warming will lead to a northward shift of suitable areas for salmon farming in the Yellow Sea. Although the sector still offers a promising future, the distribution of these suitable areas will shift northward, displaying a double-center pattern in the eastern central region and the northwestern region of the Yellow Sea (Fig. 4). Moreover, the number of most suitable areas is expected to increase with warming water temperatures. There is a great seasonal variation in the water temperature in the Yellow Sea, with temperatures in the northern YSCWM lower than 4 °C, even dropping to 1 °C in winter. On the other hand, after the vertical mixing of water in autumn, there is a large area with temperatures higher than 18 °C in the southern YSCWM (Li et al., 2016). The thermal range for the growth of Atlantic salmon is between 4 and 6 °C to 19–22.5 °C (Calado et al., 2021), and temperatures beyond 18 °C can negatively influence salmon production (Gamperl et al., 2020). As such, salmon cultured in the northern YSCWM are exposed to low-temperature stress, while salmon cultured in the southern YSCWM are exposed to a short period of high-temperature stress in autumn. The increasing temperature within the thermal tolerance boundaries of cultured species may shorten cultivation time, increase growth rate, and boost production (Elliott and Elliott, 2010; Klinger et al., 2017; Mangano et al., 2019; Meng et al., 2022). Therefore, warming water temperatures in winter in the northern YSCWM may help salmon escape from the cold stress and enhance the growth performance while warming temperatures in autumn in the southern YSCWM could make it too warm to grow optimally. In conclusion, long-term ocean warming in the Yellow Sea has both positive and negative effects on the salmon industry, yet still offers great potential for salmon aquaculture in the context of global warming.

Although salmon offshore aquaculture in the Yellow Sea is feasible under current and SSP scenarios, the destructiveness of extreme events cannot be ignored (Smith et al., 2021, 2022). The suitable areas for salmon farming based on the DEB model only considered the ongoing effect of global warming but ignored the short-term impacts of extreme temperature events (weeks/days). The Yellow Sea experienced unprecedented marine heatwaves (MHWs) from 2016 to 2018 (Gao et al., 2020). With increasing MHWs (IPCC, 2022), climate change will likely dramatically increase the risk and uncertainty of offshore aquaculture in the Yellow Sea. In addition, the distribution of MHWs in the Yellow Sea shows high geographical variations, with trends of MHWs in the east-central of the Yellow Sea decreasing in frequency and days from 1982 to 2018, indicating consequently fewer risks of heatwaves (Yao et al., 2020). To avoid uncertainty from climate change, areas located in the east-central Yellow Sea should be given priority for site selection (Meng et al., 2022). Thermal sensitivity analysis of specific species prior to spatial planning will also be useful for the management of offshore aquaculture (Ma et al., 2021).

4.3. Perspectives and recommendations

(1) In the present study, we provide base maps for decision support in site selection for Atlantic salmon aquaculture based on their potential growth using the DEB model. However, the decision should take into account several social, economic, and ecological impacts, such as labor, transportation costs, current, and risks from farmed fish escaping (Aguilar-Manjarrez et al., 2017; Chávez et al., 2019; Gomez-Uchida et al., 2018; Krupandan et al., 2022). Moreover, fish escaping, including genetic risks and the spread of diseases and parasites, pose one of the most significant challenges for ensuring environmental sustainability in aquaculture (Atalah and Sanchez-Jerez, 2020), and should be considered in offshore aquaculture. Furthermore, it is also noteworthy that extreme events, such as marine heatwaves and storm activity, can be devastating for aquaculture. Offshore aquaculture may be susceptible to severe weather, with disease outbreaks and poorer growth performances correlated with heatwaves (Calado et al., 2021) and large-scale fish escaping correlated with storm events (Jensen et al., 2010). Therefore, the physical capabilities of the farmed fish species and other potential factors must be fully understood in the site selection. Notably, consistency of other management should be taken into consideration for avoiding conflicts, such as privatization of waterways, fisheries livelihoods, and ecological preservation management (Carneiro, 2011; Primavera, 2006). Integrating multiple functional layers into spatial planning will be of great benefit in this regard.

(2) Breeding programs have been identified as a crucial and effective biotechnological solution to enable salmon to adapt to climate change (Calado et al., 2021). The northern Yellow Sea has experienced cold stress in winter, while the southern region has been affected by short-term heat stress in autumn. As such, both the cold- and heat-tolerance strain selection of the species depending on the farm's location should be taken into account. Furthermore, genomic approaches and precision breeding should be employed to adequately address rapidly changing conditions (Liu et al., 2022).

(3) Environmental monitoring is essential for salmon aquaculture, as it is heavily dependent on the environment, such as temperature, dissolved oxygen, and currents (Vikeså et al., 2017). Aquaculture

has experienced significant changes in the context of climate change except for temperature (Dong et al., 2023): 1) Oxygen loss: The global ocean is experiencing a substantial decline in oxygen levels at a rate loss of 961 ± 429 Tmol per decade since 1960 (Schmidtko et al., 2017). Reductions ranging from 1% to 7% are anticipated in the global ocean's oxygen inventory in the next century (Keeling et al., 2010), and coming with the emergence of hypoxia and anoxia zoning; 2) Ocean acidification (pH): Compared to the pH level of 8.2 during the Industrial Revolution, the global surface ocean pH has decreased by approximately 0.1, now standing at around 8.1. By the year 2100, there is a potential for further decline in the range of 0.1–0.4 in pH units (Garcia-Soto et al., 2021); 3) Eutrophication: Eutrophication is projected to continually increase in the 21st century due to changes in precipitation (Sinha et al., 2017; Wang et al., 2021). In addition, the co-occurrence and interaction of multiple biological factors have been regarded as a significant threat to the sustainable development of aquaculture (Reid et al., 2019). Biological factors of YSCWM under climate change bring uncertainty to offshore aquaculture operations, so real-time environmental monitoring of farms is essential for stakeholders to effectively manage the risks posed by climate change. To further reduce these risks, monitoring and warning systems that can predict marine heatwaves in advance should be developed (De et al., 2022; Spillman et al., 2015).

(4) Atlantic salmon is a non-native species in the Yellow Sea, and the model stationarity should be tested in the future (Monaco et al., 2019). The offshore cage, Deep Blue 1 (35.20°N, 122.26°E), has been deployed for salmon production recently, and we have not enough experimental data. In the future, we will test the model stationarity of Atlantic salmon in this region using both environmental data and growth data generated from Deep Blue 1 for better spatial management.

(5) Fish welfare in submerged cages should be considered, and related technical issues need to be addressed. There is a lack of comprehensive research focus on the impacts of submerged culture on fish. Especially for salmon, with open swim bladders, submerged cages aquaculture for salmon becomes a more complex process because they require air access for swim bladder refilling and buoyancy maintaining (Korsøen et al., 2012). The oxygen needs of farmed fish may have been resolved by air domes or other artificial oxygen supply methods (Oppedal et al., 2020). However, ensuring salmon live in their preferred conditions is key for optimal growth in sea-cages (Oppedal et al., 2011), farming submerged fish under ideal environmental conditions remains a challenge for fish welfare and production (Sievers et al., 2022).

5. Conclusion

Offshore salmon aquaculture in the Yellow Sea is facing great uncertainty from climate change. In the present study, we provided a biological base map of the salmon industry in the Yellow Sea with the consideration of the risks of global warming. Our results indicated that due to the spatial heterogeneity of temperature, offshore salmon farming is feasible in some regions of the Yellow Sea, implying it has great potential for the development of salmon aquaculture. Based on models of temperature-mediated growth (DEB model), the center of the Yellow Sea (38°N, 123°E) is deemed to be the optimal region for the offshore salmon industry. It is important to note that this preliminary base map is only a starting point for site selection (based on a single factor: temperature) and further consideration of multiple factors is necessary for the spatial management of offshore aquaculture.

CRediT authorship contribution statement

Yu-Yang Zhang: Conceptualization, Data curation, Methodology, Software, Writing – original draft, Writing – review & editing. **Jie Wang:** Software, Writing – review & editing. **Xin Sun:** Data curation, Methodology. **Yue Su:** Data curation, Methodology. **Gianluca Sarà:** Conceptualization, Writing – review & editing. **Yun-Wei Dong:** Conceptualization, Funding acquisition, Writing – original draft, Writing – review & editing.

Declaration of competing interest

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

Data availability

Data will be made available on request.

Acknowledgements

The authors thank the editor and anonymous reviewers for their constructive comments that improve the present study. This study is supported by the National Natural Science Foundation of China (U1906206) and the Fundamental Research Funds for the Central Universities.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ocecoaman.2023.106986.

References

Aas, Øystein, Einum, Sigurd, Klemetsen, Anders, Skurdal, Jostein, 2011. Atlantic Salmon Ecology. Wiley-blackwell in press, New Jersey, United States.

Aguilar-Manjarrez, Jose, Soto, Doris, Brummett, Randall, 2017. Aquaculture Zoning, Site Selection and Area Management under the Ecosystem Approach to Aquaculture. A Handbook. FAO, Rome, Italy. http://www.fao.org/documents/card/en/c/4c777b3a-6afc-4475-bfc2-a51646471b0d/.

Atalah, J., Sanchez-Jerez, P., 2020. Global assessment of ecological risks associated with farmed fish escapes. Glob. Ecol. Conserv. 21, e00842 https://doi.org/10.1016/j.gecco.2019.e00842.

Baas, Jan, Augustine, Starrlight, Marques, Gonçalo M., Dorne, Jean Lou, 2018. Dynamic energy budget models in ecological risk assessment: from principles to applications. Sci. Total Environ. 628–629, 249–260. https://doi.org/10.1016/j.scitotenv.2018.02.058.

Calado, Ricardo, Mota, Vasco C., Madeira, Diana, Leal, Miguel C., 2021. Summer is coming! tackling ocean warming in atlantic salmon cage farming. Animals 11 (6), 1–18. https://doi.org/10.3390/ani11061800.

Carneiro, Gonçalo, 2011. Marine management for human development: a review of two decades of scholarly evidence. Mar. Pol. 35 (3), 351–362. https://doi.org/10.1016/j.marpol.2010.10.015.

Chávez, Carlos, Dresdner, Jorge, Figueroa, Yanina, Quiroga, Miguel, 2019. Main issues and challenges for sustainable development of salmon farming in Chile: a socio-economic perspective. Rev. Aquacult. 11 (2), 403–421. https://doi.org/10.1111/raq.12338.

Cheng, Martin C.F., Tan, Alicia L.S., Rinaldi, Alessandro, Giacoletti, Antonio, Sarà, Gianluca, Williams, Gray A., 2018. Predicting effective aquaculture in subtropical waters: a dynamic energy budget model for the green lipped mussel, *Perna viridis*. Aquaculture 495, 749–756. https://doi.org/10.1016/j.aquaculture.2018.04.008.

Cheung, William W.L., Frölicher, Thomas L., Lam, Vicky W.Y., Oyinlola, Muhammed A., Reygondeau, Gabriel, Rashid Sumaila, U., Tai, Travis C., Teh, Lydia C.L., Wabnitz, Colette C.C., 2021. Marine high temperature extremes amplify the impacts of climate change on fish and fisheries. Sci. Adv. 7 (40), 1–16. https://doi.org/10.1126/sciadv.abh0895.

Chou, Denggao, 2014. Effects of light environment factors on the growth performance and gonadal development of Atlantic salmon (*Salmo salar* L.) in recirculating aquaculture systems. Univ. Chin. Acad. Sci.

De, Burgh-Day, Catherine, O., Spillman, Claire M., Smith, Grant, Stevens, Craig L., 2022. Forecasting extreme marine heat events in key aquaculture regions around New Zealand. J. South. Hemisphere Earth Syst. Sci 72 (1), 58–72. https://doi.org/10.1071/ES21012.

Dong, Shuanglin, 2019. Researching progresses and prospects in large Salmo- nidae farming in cold water mass of Yellow Sea. Periodic. Ocean Univ. China 49, 1–6.

Dong, Shuang-lin, Tian, Xiang-li, Gao, Qin-feng, Dong, Yun-wei, 2023. Aquaculture Ecology. Springer. https://doi.org/10.1007/978-981-19-5486-3.

Elliott, J.M., Elliott, J.A., 2010. Temperature requirements of Atlantic salmon Salmo salar, brown trout *Salmo trutta* and Arctic charr *Salvelinus alpinus*: predicting the effects of climate change. J. Fish. Biol. 77 (8), 1793–1817. https://doi.org/10.1111/j.1095-8649.2010.02762.x.

Falconer, Lynne, Cutajar, Karl, Krupandan, Amalia, Capuzzo, Elisa, Corner, Richard A., Ellis, Tim, Jeffery, Keith, Mikkelsen, Eirik, Moore, Heather, O'Beirn, Francis X., O'Donohoe, Pauline, Ruane, Neil M., Shilland, Robyn, Tett, Paul, Telfer, Trevor C., 2023. Planning and licensing for marine aquaculture. Rev. Aquacult. 15, 1374–1404. https://doi.org/10.1111/raq.12783.

FAO, 2014. Climate Change Adaptation in Fisheries and Aquaculture. Rome, Italy.

FAO, 2022. The State of World Fisheries and Aquaculture 2022. Towards Blue Transformation. Rome, Italy. https://doi.org/10.4060/cc0461en.

Filgueira, R., Chapman, J.M., Suski, C.D., Cooke, S.J., 2016. The influence of watershed land use cover on stream fish diversity and size-at-age of a generalist fish. Ecol. Indicat. 60, 248–257. https://doi.org/10.1016/j.ecolind.2015.06.006.

Føre, Martin, Alver, Morten, Alfredsen, Jo Arve, Marafioti, Giancarlo, et al., 2016. Modelling growth performance and feeding behaviour of Atlantic salmon (*Salmo salar* L.) in commercial-size aquaculture net pens: model details and validation through full-scale experiments. Aquaculture 464, 268–278. https://doi.org/10.1016/j.aquaculture.2016.06.045.

Froehlich, Halley E., Gentry, Rebecca R., Halpern, Benjamin S., 2018. Global change in marine aquaculture production potential under climate change. Nat. Ecol. Evol. 2 (11), 1745–1750. https://doi.org/10.1038/s41559-018-0669-1.

Froehlich, Halley E., Koehn, J Zachary, Holsman, Kirstin K., Halpern, Benjamin S., 2022. Emerging trends in science and news of climate change threats to and adaptation of aquaculture. Aquaculture 549, 737812. https://doi.org/10.1016/j.aquaculture.2021.737812.

Frölicher, Thomas L., Fischer, Erich M., Gruber, Nicolas, 2018. Marine heatwaves under global warming. Nature 560 (7718), 360–364. https://doi.org/10.1038/s41586-018-0383-9.

Galappaththi, Eranga K., Ichien, Stephanie T., Hyman, Amanda A., Aubrac, Charlotte J., Ford, James D., 2020. Climate change adaptation in aquaculture. Rev. Aquacult. 12 (4), 2160–2176. https://doi.org/10.1111/raq.12427.

Gamperl, Anthony K., Ajiboye, Olufemi O., Zanuzzo, Fábio S., Sandrelli, Rebbecah M., Peroni, Ellen de Fátima C., Beemelmanns, Anne, 2020. The impacts of increasing temperature and moderate hypoxia on the production characteristics, cardiac morphology and haematology of Atlantic Salmon (*Salmo salar*). Aquaculture 519, 734874. https://doi.org/10.1016/j.aquaculture.2019.734874.

Gao, Guandong, Marin, Maxime, Feng, Ming, Yin, Baoshu, Yang, Dezhou, Feng, Xingru, Ding, Yang, Song, Dehai, 2020. Drivers of marine heatwaves in the east China sea and the South Yellow Sea in three consecutive summers during 2016–2018. J. Geophys. Res. Ocean 125 (8), 1–19. https://doi.org/10.1029/2020JC016518.

Garcia-Soto, C., Cheng, L., Caesar, L., Schmidtko, S., Jewett, E.B., Cheripka, A., Rigor, I., Caballero, A., Chiba, S., Báez, J.C., Zielinski, T., Abraham, J.P., 2021. An overview of ocean climate change indicators: sea Surface temperature, ocean heat content, ocean pH, dissolved oxygen concentration, arctic sea ice extent, thickness and volume, sea level and Strength of the AMOC (atlantic meridional overturning circula. Front. Mar. Sci. 8 https://doi.org/10.3389/fmars.2021.642372.

Gomez-Uchida, D., Sepúlveda, M., Ernst, B., Contador, T.A., Neira, S., Harrod, C., 2018. Chile's salmon escape demands action. Science 361, 857–858. https://doi.org/10.1126/science.aau7973.

Giacoletti, A., Lucido, G.D., Mangano, M.C., Sarà, G., 2021. Functional trait-based layers - an aquaculture siting tool for the Mediterranean Sea. Aquaculture 532, 736081. https://doi.org/10.1016/j.aquaculture.2020.736081.

Graham, Philip, Falconer, Lynne, Telfer, Trevor, Mossone, Paolo, Viale, Iolanda, Carboni, Stefano, 2020. A modelling approach to classify the suitability of shallow Mediterranean lagoons for pacific oyster, *Crassostrea gigas* (Thunberg, 1793) farming. Ocean Coast Manag. 192 (November 2019), 105234 https://doi.org/10.1016/j.ocecoaman.2020.105234.

Holbrook, Neil J., Alex, Sen Gupta, Oliver, Eric C.J., Hobday, Alistair J., Benthuysen, Jessica A., Scannell, Hillary A., Smale, Dan A., Wernberg, Thomas, 2020. Keeping pace with marine heatwaves. Nat. Rev. Earth Environ. 1 (9), 482–493. https://doi.org/10.1038/s43017-020-0068-4.

Holling, C.S., 1959. Some characteristics of simple types of predation and parasitism. Can. Entomol. 91, 385–398.

IPCC, 2022. Climate change 2022: impacts, adaptation and vulnerability. In: Climate Change and Land: an IPCC Special Report on Climate Change, Desertification, Land Degradation, Sustainable Land Management, Food Security, and Greenhouse Gas Fluxes in Terrestrial Ecosystems.

Jensen, Dempster, T., Thorstad, E.B., Uglem, I., Fredheim, A., 2010. Escapes of fishes from Norwegian sea-cage aquaculture: causes, consequences and prevention. Aquac. Environ. Interact 1 (1), 71–83. https://doi.org/10.3354/aei00008.

Jusup, Marko, Klanjšček, Tin, Matsuda, Hiroyuki, 2014. Simple measurements reveal the feeding history, the onset of reproduction, and energy conversion efficiencies in captive bluefin tuna. J. Sea Res. 94, 144–155. https://doi.org/10.1016/j.seares.2014.09.002.

Keeling, R.F., Körtzinger, A., Gruber, N., 2010. Ocean deoxygenation in a warming world. Ann. Rev. Mar. Sci 2, 199–229. https://doi.org/10.1146/annurev.marine.010908.163855.

Klinger, Dane H., Levin, Simon A., Watson, James R., 2017. The growth of finfish in global openocean aquaculture under climate change. Proc. R. Soc. B: Biol. Sci. 284 (1864) https://doi.org/10.1098/rspb.2017.0834.

Kooijman, S.A.L.M., 2010. Dynamic Energy Budget Theory for Metabolic Organisation Dynamic, vol. 4. Cambridge University press, Cambridge. Issue 1.

Korsøen, Øyvind J., Dempster, Tim, Oppedal, Frode, Kristiansen, Tore S., 2012. Individual variation in swimming depth and growth in Atlantic salmon (*Salmo salar* L.) subjected to submergence in sea-cages. Aquaculture 334–337, 142–151. https://doi.org/10.1016/j.aquaculture.2011.12.031.

Krupandan, Amalia Grace, Gernez, Pierre, Palmer, Stephanie, Thomas, Yoann, Barillé, Laurent, 2022. Exploring South African Pacific oyster mariculture potential through combined Earth observation and bioenergetics modelling. Aquac. Rep. 24, 101155 https://doi.org/10.1016/j.aqrep.2022.101155.

Li, Guangxue, Qiao, Lulu, Dong, Ping, Ma, Yanyan, Xu, Jishang, Liu, Shidong, Liu, Yong, Li, Jianchao, Li, Pin, Ding, Dong, Wang, Nan, Dada Olusegun, A., Liu, Ling, 2016. Hydrodynamic condition and suspended sediment diffusion in the Yellow Sea and east China sea. J. Geophys. Res. Ocean 121 (5), 3010–3028. https://doi.org/10.1002/2015JC011442.

Li, Xiaoxu, Tan, Yue, Sun, Yongxu, Wang, Jie, Dong, Yun wei, 2021. Microhabitat temperature variation combines with physiological variation to enhance thermal resilience of the intertidal mussel *Mytilisepta virgata*. Funct. Ecol. 35, 2497–2507. https://doi.org/10.1111/1365-2435.13885.

Liu, Junyu, Peng, Wenzhu, Yu, Feng, Shen, Yawei, Yu, Wenchao, Lu, Yisha, Lin, Weihong, Zhou, Muzhi, Huang, Zekun, Luo, Xuan, You, Weiwei, Ke, Caihuan, 2022. Genomic selection applications can improve the environmental performance of aquatics: a case study on the heat tolerance of abalone. Evol. Appl. 992–1001. https://doi.org/10.1111/eva.13388.

Ma, Chao Yi, Zhu, Xiao Lu, Liao, Ming Ling, Dong, Shuang Lin, Dong, Yun Wei, 2021. Heat sensitivity of mariculture species in China. ICES J. Mar. Sci. 78 (8), 2922–2930. https://doi.org/10.1093/icesjms/fsab168.

Mangano, M. Cristina, Giacoletti, Antonio, Sarà, Gianluca, 2019. Dynamic Energy Budget provides mechanistic derived quantities to implement the ecosystem based management approach. J. Sea Res. 143, 272–279. https://doi.org/10.1016/j.seares.2018.05.009.

Monaco, C.J., Porporato, E.M.D., Lathlean, J.A., Tagliarolo, M., Sarà, G., McQuaid, C.D., 2019. Predicting the performance of cosmopolitan species: dynamic energy budget model skill drops across large spatial scales. Mar. Biol. 166, 1–13. https://doi.org/10.1007/s00227-018-3462-4.

Maulu, Sahya, Hasimuna, Oliver J., Haambiya, Lloyd H., Monde, Concillia, Musuka, Confred G., Makorwa, Timothy H., Munganga, Brian P., Phiri, Kanyembo J., Nsekanabo, Jean Da Mascene, 2021. Climate change effects on aquaculture production: sustainability implications, mitigation, and adaptations. Front. Sustain. Food Syst. 5 (March), 609097 https://doi.org/10.3389/fsufs.2021.609097.

Meng, Hangyu, Hayashida, Hakase, Norazmi-Lokman, Nor Hakim, Strutton, Peter G., 2022. Benefits and detrimental effects of ocean warming for Tasmanian salmon aquaculture. Continent. Shelf Res. 246 (August), 104829 https://doi.org/10.1016/j.csr.2022.104829.

Montalto, V., Rinaldi, A., Sarà, G., 2015. Life history traits to predict biogeographic species distributions in bivalves. Sci. Nat. 102 (9) https://doi.org/10.1007/s00114-015-1313-4.

Mowi, 2022. Salmon Farming Industry Handbook.

Oliver, Eric C.J., Benthuysen, Jessica A., Darmaraki, Sofia, Donat, Markus G., Hobday, Alistair J., Holbrook, Neil J., Schlegel, Robert W., Sen Gupta, Alex, 2021. Marine heatwaves. Ann. Rev. Mar. Sci 13, 313–342. https://doi.org/10.1146/annurev-marine-032720-095144.

Oppedal, F., Folkedal, O., Stien, L.H., Vågseth, T., Fosse, J.O., Dempster, T., Warren-Myers, F., 2020. Atlantic salmon cope in submerged cages when given access to an air dome that enables fish to maintain neutral buoyancy. Aquaculture 525, 735286. https://doi.org/10.1016/j.aquaculture.2020.735286.

Oppedal, Frode, Dempster, Tim, Stien, Lars H., 2011. Environmental drivers of Atlantic salmon behaviour in sea-cages: a review. Aquaculture 311 (1–4), 1–18. https://doi.org/10.1016/j.aquaculture.2010.11.020.

Ottinger, Marco, Clauss, Kersten, Kuenzer, Claudia, 2016. Aquaculture: relevance, distribution, impacts and spatial assessments - a review. Ocean Coast Manag. 119, 244–266. https://doi.org/10.1016/j.ocecoaman.2015.10.015.

Oyinlola, Muhammed A., Reygondeau, Gabriel, Wabnitz, Colette C.C., Cheung, William W.L., 2020. Projecting global mariculture diversity under climate change. Global Change Biol. 26 (4), 2134–2148. https://doi.org/10.1111/gcb.14974.

Pecquerie, Laure, Johnson, Leah R., Kooijman, Sebastiaan A.L.M., Nisbet, Roger M., 2011. Analyzing variations in life-history traits of Pacific salmon in the context of Dynamic Energy Budget (DEB) theory. J. Sea Res. 66 (4), 424–433. https://doi.org/10.1016/j.seares.2011.07.005.

Popp, A., Calvin, K., Fujimori, S., Havlik, P., Humpenöder, F., Stehfest, E., Bodirsky, B.L., Dietrich, J.P., Doelmann, J.C., Gusti, M., Hasegawa, T., Kyle, P., Obersteiner, M., Tabeau, A., Takahashi, K., Valin, H., Waldhoff, S., Weindl, I., Wise, M., Kriegler, E., Lotze-Campen, H., Fricko, O., Riahi, K., Vuuren, D.P., 2017. Land use futures in the shared socio-economic pathways. Global Environ. Change 42, 331–345. https://doi.org/10.1016/j.gloenvcha.2016.10.002.

Primavera, J.H., 2006. Overcoming the impacts of aquaculture on the coastal zone. Ocean Coast Manag. 49 (9–10), 531–545. https://doi.org/10.1016/j.ocecoaman.2006.06.018.

R Development Core Team, 2021. R: A Language and Environment for Statistical Computing. R Foundation for Statistical Computing, Vienna, Austria.

Reid, Gregor K., Gurney-Smith, Helen J., Marcogliese, David J., Knowler, Duncan, Benfey, Tillmann, Garber, Amber F., Forster, Ian, Chopin, Thierry, Brewer-Dalton, Kathy, Moccia, Richard D., Flaherty, Mark, Smith, Caitlin T., De Silva, Sena, 2019. Climate change and aquaculture: considering biological response and resources. Aquac. Environ. Interact. 11, 569–602. https://www.jstor.org/stable/26920865.

Ren, Jeffrey S., Jin, Xianshi, Yang, Tao, Kooijman, Sebastiaan A.L.M., Shan, Xiujuan, 2020. A dynamic energy budget model for small yellow croaker *Larimichthys polyactis*: parameterisation and application in its main geographic distribution waters. Ecol. Model. 427, 109051 https://doi.org/10.1016/j.ecolmodel.2020.109051.

Sarà, G., Reid, G.K., Rinaldi, A., Palmeri, V., Troell, M., Kooijman, S.A.L.M., 2012. Growth and reproductive simulation of candidate shellfish species at fish cages in the Southern Mediterranean: dynamic Energy Budget (DEB) modelling for integrated multi-trophic aquaculture. Aquaculture 324 (325), 259–266. https://doi.org/10.1016/j.aquaculture.2011.10.042.

Sarà, G., Rinaldi, A., Montalto, V., 2014. Thinking beyond organism energy use: a trait-based bioenergetic mechanistic approach for predictions of life history traits in marine organisms. Mar. Ecol. 35, 506–515. https://doi.org/10.1111/maec.12106.

Sarà, Gianluca, Gouhier, Tarik C., Brigolin, Daniele, Porporato, Erika M.D., Mangano, Maria Cristina, Mirto, Simone, Mazzola, Antonio, Pastres, Roberto, 2018. Predicting shifting sustainability trade-offs in marine finfish aquaculture under climate change. Global Change Biol. 24 (8), 3654–3665. https://doi.org/10.1111/gcb.14296.

Schmidtko, S., Stramma, L., Visbeck, M., 2017. Decline in global oceanic oxygen content during the past five decades. Nature 542, 335–339. https://doi.org/10.1038/nature21399.

Sievers, Michael, Korsøen, Øyvind, Warren-Myers, Fletcher, Oppedal, Frode, Macaulay, Georgia, Folkedal, Ole, Dempster, Tim, 2022. Submerged cage aquaculture of marine fish: a review of the biological challenges and opportunities. Rev. Aquacult. 14 (1), 106–119. https://doi.org/10.1111/raq.12587.

Sigourney, D.B., Letcher, B.H., Obedzinski, M., Cunjak, R.A., 2008. Size-independent growth in fishes: patterns, models and metrics. J. Fish. Biol. 72 (10), 2435–2455. https://doi.org/10.1111/j.1095-8649.2008.01830.x.

Sinha, E., Michalak, A.M., Balaji, V., 2017. Eutrophication will increase during the 21st century as a result of precipitation changes. Science 357, 1–5. https://doi.org/10.1126/science.aan2409.

Smith, Kathryn E., Burrows, Michael T., Hobday, Alistair J., Gupta, Alex Sen, Moore, Pippa J., Thomsen, Mads, Wernberg, Thomas, Smale, Dan A., 2021. Socioeconomic impacts of marine heatwaves: global issues and opportunities. Science 374 (6566). https://doi.org/10.1126/science.abj3593.

Smith, Kathryn E., Burrows, Michael T., Hobday, Alistair J., King, Nathan G., Moore, Pippa J., Gupta, Sen, Alex, Thomsen, Mads S., Wernberg, Thomas, Smale, Dan A., 2022. Biological impacts of marine heatwaves. Ann. Rev. Mar. Sci 1–27. https://doi.org/10.1146/annurev-marine-032122-121437.

Soto, Doris, León-Muñoz, Jorge, Dresdner, Jorge, Luengo, Carol, Tapia, Fabián, J., Garreaud, René, 2019. Salmon farming vulnerability to climate change in southern Chile: understanding the biophysical, socioeconomic and governance links. Rev. Aquacult. 11 (2), 354–374. https://doi.org/10.1111/raq.12336.

Sousa, Tânia, Domingos, Tiago, Poggiale, J.C., Kooijman, S.A.L.M., 2010. Dynamic energy budget theory restores coherence in biology. Philos. Trans. R. Soc. B: Biol. Sci. 365 (1557), 3413–3428. https://doi.org/10.1098/rstb.2010.0166.

Spillman, C.M., Hartog, J.R., Hobday, A.J., Hudson, D., 2015. Predicting environmental drivers for prawn aquaculture production to aid improved farm management. Aquaculture 447, 56–65. https://doi.org/10.1016/j.aquaculture.2015.02.008.

Stewart-Sinclair, Phoebe, J., Last, Kim S., Payne, Ben L., Wilding, Thomas A., 2020. A global assessment of the vulnerability of shellfish aquaculture to climate change and ocean acidification. Ecol. Evol. 10 (7), 3518–3534. https://doi.org/10.3389/fsufs.2021.609097.

Strople, Leah C., Filgueira, Ramón, Hatcher, Bruce G., Denny, Shelley, Bordeleau, Xavier, Whoriskey, Frederick G., Crossin, Glenn T., 2018. The effect of environmental conditions on Atlantic salmon smolts' (*Salmo salar*) bioenergetic requirements and migration through an inland sea. Environ. Biol. Fish. 101 (10), 1467–1482. https://doi.org/10.1007/s10641-018-0792-5.

Tan, Alicia Lee Sian, Cheng, Martin Chun Fai, Giacoletti, Antonio, Chung, Jing Xiang, Liew, Juneng, Sarà, Gianluca, Williams, Gray A., 2021. Integrating mechanistic models and climate change projections to predict invasion of the mussel, *Mytilopsis sallei*, along the southern China coast. Sci. Total Environ. 762, 143097 https://doi.org/10.1016/j.scitotenv.2020.143097.

Vikeså, Vibeke, Nankervis, Leo, Hevrøy, Ernst Morten, 2017. Appetite, metabolism and growth regulation in Atlantic salmon (*Salmo salar* L.) exposed to hypoxia at elevated seawater temperature. Aquacult. Res. 48 (8), 4086–4101. https://doi.org/10.1111/are.13229.

Wade, Nicholas M., Clark, Timothy D., Maynard, Ben T., Atherton, Stuart, Wilkinson, Ryan J., Smullen, Richard P., Taylor, Richard S., 2019. Effects of an unprecedented summer heatwave on the growth performance, flesh colour and plasma biochemistry of marine cage-farmed Atlantic salmon (*Salmo salar*). J. Therm. Biol. 80, 64–74. https://doi.org/10.1016/j.jtherbio.2018.12.021.

Wang, Y., Liu, D., Xiao, W., Zhou, P., Tian, C., Zhang, C., Du, J., Guo, H., Wang, B., 2021. Coastal eutrophication in China: trend, sources, and ecological effects. Harmful Algae 107, 102058. https://doi.org/10.1016/j.hal.2021.102058.

Weng, Xuechuan, Yiken, Zhang, Congmin, Wang, Qilong, Zhang, 1988. The variational characteristics of the Yellow Sea cold water mass. Oceanol. Limnol. Sinica 4, 368–379.

Xu, Shihong, Wang, Yanfeng, Liu, Qinghua, et al., 2019. Study on the growth and gonadal development of Atlantic salmon under recirculating aquaculture. Mar. Sci. 43 (11), 97–102.

Yao, Yulong, Wang, Junjie, Yin, Jianjun, Zou, Xinqing, 2020. Marine Heatwaves in China's marginal seas and adjacent offshore waters: past, present, and future. J. Geophys. Res. Ocean 125 (3), 1–16. https://doi.org/10.1029/2019JC015801.

Yu, Shuangen, Dong, Shuanglin, Zhang, Zhixin, Zhang, Yuyang, Sarà, Gianluca, Wang, Jie, Dong, Yunwei, 2022. Mapping the potential for offshore aquaculture of salmonids in the Yellow Sea. Mar. Life Sci. Technol., 0123456789 https://doi.org/10.1007/s42995-022-00141-2.

Yu, Fei, Zhang, Zhixin, Diao, Xinyuan, Gou, Jingsong, Tang, Yuxiang, 2006. Analysis of evolution of the huanghai Sea cold water mass and its relationship with adjacent water masses. Acta Oceanol. Sin. 28, 26–34.

Zellweger, F., de Frenne, P., Lenoir, J., Vangansbeke, P., Verheyen, K., Bernhardt-Römermann, M., Baeten, L., Hédl, R., Berki, I., Brunet, J., van Calster, H., Chudomelová, M., Decocq, G., Dirnböck, T., Durak, T., Heinken, T., Jaroszewicz, B., Kopecký, M., Máliš, F., Macek, M., Malicki, M., Naaf, T., Nagel, T.A., Ortmann-Ajkai, A., Petřík, P., Pielech, R., Reczynska, K., Schmidt, W., Standovár, T., Swierkosz, K., Teleki, B., Vild, O., Wulf, M., Coomes, D., 2020. Forest microclimate dynamics drive plant responses to warming. Science 368, 772–775. https://doi.org/10.1126/science.aba6880.

Zhang, Yu Yang, Yu, Shuang En, Wang, Wen Lei, Yang, Li En, Lu, Qin Qin, Xie, Chao Tian, Liu, Tao, Dong, Yun Wei, 2023. Temperature sensitivity of marine macroalgae for aquaculture in China. Aquaculture 567, 739262. https://doi.org/10.1016/j.aquaculture.2023.739262.

Zurek, Monika, Hebinck, Aniek, Selomane, Odirilwe, 2022. Climate change and the urgency to transform food systems. Science 376 (6600), 1416–1421. https://doi.org/10.1126/science.abo2364.