Tools for Assessment and Planning of Aquaculture Sustainability

SHORT TITLE:	**TAPAS**
COORDINATOR:	**Prof. Trevor Telfer**
ORGANISATION:	**University of STIRLING, UK**
TOPIC:	**H2020- SFS-11b-2015**
PROJECT NUMBER:	**678396**

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Contributing Authors:

Phil Wallhead, NIVA
Stefano Ciavatta, Susan Kay, PML
Stephanie Palmer, Laurent Barillé, Pierre Gernez, UN
Kostas Tsiaras, HCMR

History of changes:

Ver	Date	Changes	Author
1.0	28/02/2019	First complete draft for internal review	PW, SC, SK, SP, LB, PG, KT
2.0	27/05/2019	Final version	PW, SC, SK, SP, LB, PG, KT
3.0	13/02/2020	Final version revised	PW, SC, SK, SP, LB, PG, KT

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For other data sets referred to in this document, please contact their developers for appropriate citations.

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Contents

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Introduction

This document serves as reference for the future scenario maps produced by the decadal hindcast simulations of TAPAS regional models (i.e. “Far-fields models” in TAPAS terminology) and their documentation as Case Studies and Interactive Tools for the TAPAS toolbox (WP8). The maps and documentation herein form Deliverable 6.4 of Work Package 6 of TAPAS.

The report takes the form of a series of template which outlines the information for each of the case studies which is incorporated into the Aquaculture Toolbox in WP8.

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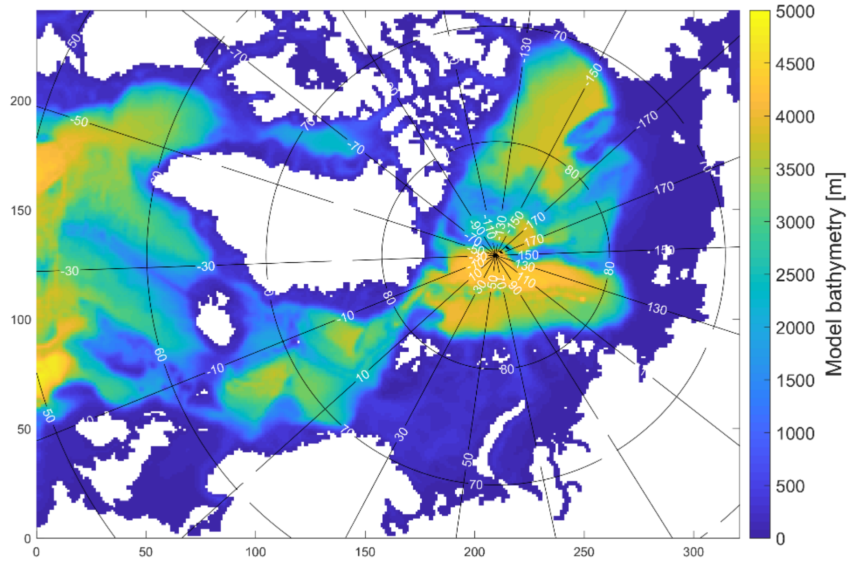
Case Study 1: Mapping regional-scale sustainability for offshore salmon and mussel aquaculture in the North Atlantic and Nordic Seas (NIVA)

	
Title:	Mapping regional-scale sustainability for offshore salmon and mussel aquaculture in the North Atlantic and Nordic Seas using the A20 ROMS-ERSEM model
Description	A 3D hydrodynamic ocean model was used to map the sustainability of salmon and blue mussel aquaculture at potential offshore sites in the North Atlantic and Nordic Seas, over the past and future 30 years.
Tool(s) applied	☒Yes Type of tool: _[guidance, interactive tool or monitoring tool]_____Guidance____ Link: _[insert link guiding people to the tool]_________ ☐ No
Who is this case study relevant for?	☒Aquaculture producers ☐Regulators ☐Certifiers ☒Spatial planners ☒Other? ___Research scientists and engineers____
Topic(s)	☐Site selection ☒Scoping ☒Spatial planning ☐Optimise production ☐Licence application ☐Production capacity assessment ☐Environment impact assessment ☐ Risk assessment

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	☐Stakeholder/community engagement ☐Early warning system ☐Ecosystem services ☐Social licence ☐Monitoring
Type of aquaculture:	☒Marine fish pens ☐Freshwater fish cages ☒Shellfish ☐Freshwater fish ponds ☐Integrated Multi-trophic aquaculture ☐Invertebrates ☐Recirculating aquaculture system ☐Seaweed ☐Other ____
Species	☒ Fish ☒Atlantic salmon (*Salmo salar*) ☐ European sea bass (*Dicentrarchus labrax*) ☐ Gilthead sea bream (*Sparus aurata*) ☐ Common carp (*Cyprinus carpio*) ☐ Rainbow trout (*Oncorhynchus mykiss*) ☐ Turbot (*Psetta maxima*) ☒Shellfish ☐ Pacific oyster (*Crassostrea gigas*) ☒ Blue mussel (*Mytilus edulis*) ☐ Mediterranean mussel (*Mytilus galloprovinicalis*) ☐ Manila clam (*Ruditapes philippinarum*) ☐ Seaweeds ☐ ____ ☐Other ____
Location	☐ Inland ☒ Atlantic Ocean ☐ Baltic Sea ☐ Mediterranean Sea ☒ Other ___Nordic Seas
Case study description [Short summary]	**What is the case study approach** We applied the A20 ROMS-ERSEM model to assess the regional-scale sustainability of offshore salmon/mussel aquaculture sites in the North Atlantic and Nordic Seas, over the past 3 decades and the next 3 decades under the RCP8.5 scenario. This analysis focuses on scoping and spatial planning for potential offshore facilities (e.g. https://www.salmar.no/en/offshore-fish-farming-a-new-era/). Sustainability of Atlantic salmon aquaculture was based on environmental windows for seawater temperature, oxygen concentration and maximum current speed (corrected for the

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	presence of the fish farm), and engineering constraints on water depth at the farm site. Sustainability of blue mussel aquaculture was based on a thermal window for favourable grow-out, a potential food supply index based on current speed and ambient particulate organic carbon, and mooring feasibility constraints on water depth (see TAPAS D6.3 for full details). These constraints were combined into sustainability indices and averaged over past and future decades to generates maps of sustainability over the North Atlantic and Nordic Seas. **What are the outputs** The model output suggests that, in lieu of administrative, technological, or logistical constraints not considered here, water depth and thermal tolerance are the primary constraints on offshore salmon aquaculture, with a secondary role played by oxygen concentration and current speed (Figure 1.1). On this basis, vast areas of the European/Nordic continental shelves would have been suitable for offshore salmon aquaculture in recent decades, if the appropriate technology had been developed (Figure 1.2). For blue mussel aquaculture, all constraints appear to be of comparable importance, and the primary driver of spatial variations in potential food supply appears to be the horizontal current speed (Figure 1.3). The combined sustainability index suggests that regions off Brittany, Northern Ireland, Scotland, the northern North Sea, the Faroe Islands, Iceland, the Norwegian coast especially in the south, and parts of the Barents Sea and western Svalbard shelf, would be suitable for offshore mussel aquaculture (again, if the technological challenges can be overcome, Figure 1.4). For both aquaculture types the overall area with potential for offshore aquaculture appears to have been stable over recent decades (Figure 1.4). In the future, under the RCP8.5 scenario, the A20 projections suggest that regional-scale sustainability will remain stable over the coming 30 years for both salmon and mussel aquaculture (Figures 1.5 and 1.6 respectively). A caveat to these results is that they represent the downscaled projections from only one driving climate model (the Norwegian Earth System Model NORESM) and this particular climate model show relatively weak warming over the next 30 years, compared to other climate models (not shown). A more rigorous analysis would consider ensemble downscaled predictions using multiple climate models. **Conclusion** This case study demonstrates how regional downscaling models can be applied to explore the sustainability of offshore salmon and mussel aquaculture. Our results suggested that large regions of the European/Nordic shelf seas could be utilized for offshore aquaculture, assuming that logistical and administrative constraints can be overcome. Our future projections based on a single climate model and a pessimistic (high-emissions) climate change scenario suggested that this potential for sustainable aquaculture will not change significantly over the next 30 years (based on environmental constraints) although a more rigorous analysis using an ensemble of climate models should be employed to provide uncertainty estimates for these projections. This type of large-scale "macro-siting" approach is useful for identifying broad regions of interest that can be further investigated using more focused models with

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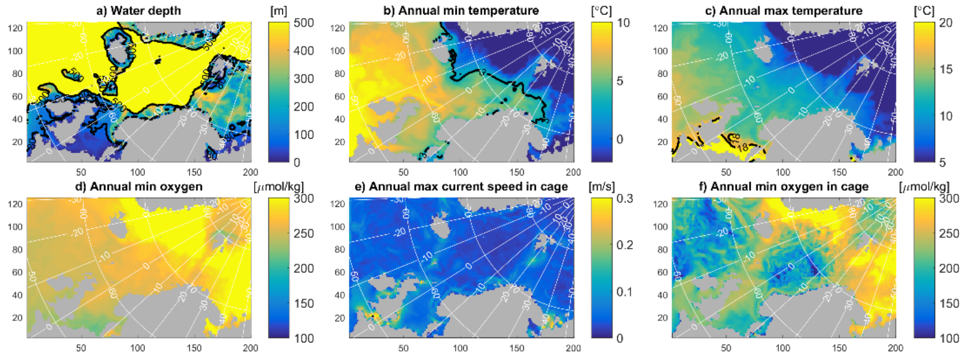
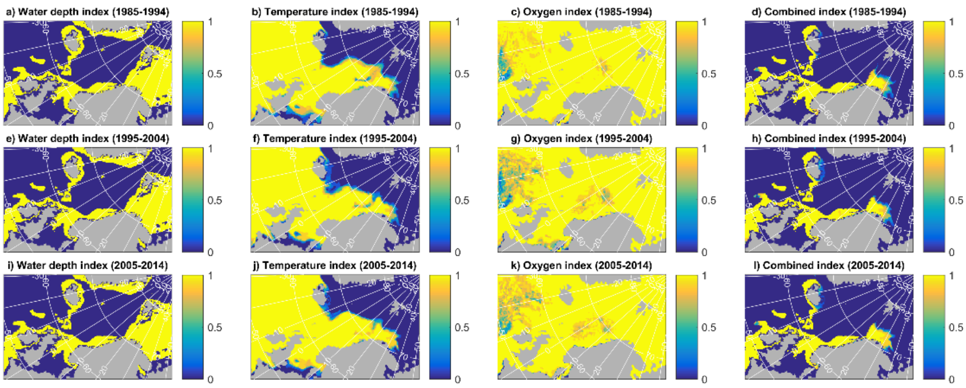
	higher spatial and process resolution but more limited geographic scope ("micro-siting", Jansen et al., 2016). It is therefore more likely useful for strategic, long-term planning of aquaculture and policy development (e.g. expansion into offshore areas as potential regions of future blue growth and sustainable exploitation).
The broader applicability	This case study demonstrates the potential utility of 3D regional ocean biogeochemical models as tools to guide large-scale and long-term aquacultural planning and policy development. While similar broad-scale "macro-siting" analyses have been performed using only observational data (e.g. Kapetsky et al., 2013; Gentry et al., 2017), the use of an ocean biogeochemical model (such as the A20 ROMS-ERSEM model used herein) has two major potential benefits: 1) The model can provide complete time series of variability at all depths and horizontal locations, not subject to gaps or sampling biases, and may thus provide more robust estimates of e.g. annual minimum oxygen concentrations; 2) The model can provide future projections, thus allowing us to investigate how different scenarios of anthropogenic change may impact conditions at a regional scale, allowing policy-makers to identify potential zones that could be used for aquaculture into the future, subject to local-scale assessment.
Relevant images or graphics	 Figure 1.1: An example of sustainability indicators for Atlantic salmon farming in the European sector of the A20 model domain during 2014. All indicators are calculated from weekly and 0-50 m averages (except for water depth). Thick black contour lines show threshold indicator values. White lines show lines of constant latitude/longitude. Axis labels show horizontal coordinates in the A20 domain (1 unit = 20 km).  Figure 1.2: Decadal sustainability indices for Atlantic salmon farming in the European sector of the A20 model domain during past decades. Top, middle, and

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bottom rows show results for decades (1985-1994), (1995-2004), and (2005-2014) respectively. White lines show lines of constant latitude/longitude.

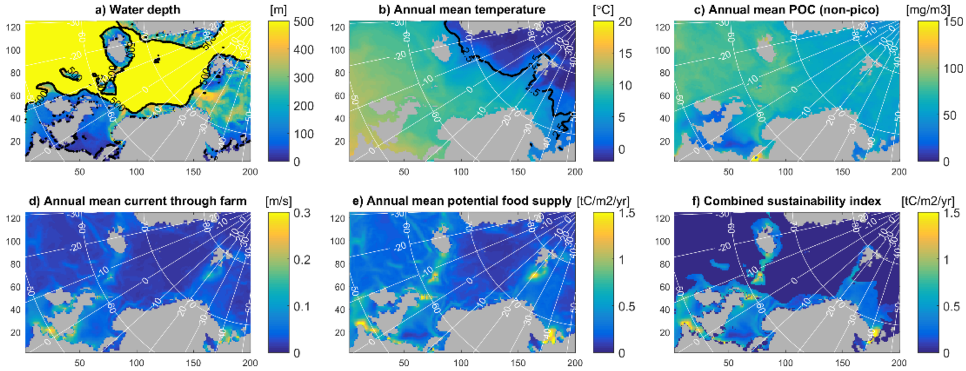

Figure 1.3: An example of sustainability indicators for blue mussel farming in the European sector of the A20 model domain during 2014. All indicators are calculated from annual and 0-50 m averages (except for water depth). Thick black contour lines show threshold indicator values. White lines show lines of constant latitude/longitude. Axis labels show horizontal coordinates in the A20 domain (1 unit = 20 km).

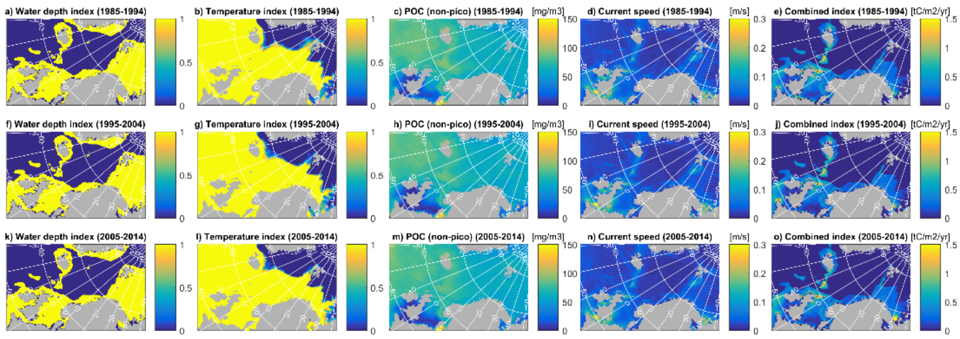

Figure 1.4: Decadal sustainability indices for blue mussel farming in the European sector of the A20 model domain in past decades. Top, middle, and bottom rows show results for decades (1985-1994), (1995-2004), and (2005-2014) respectively. White lines show lines of constant latitude/longitude.

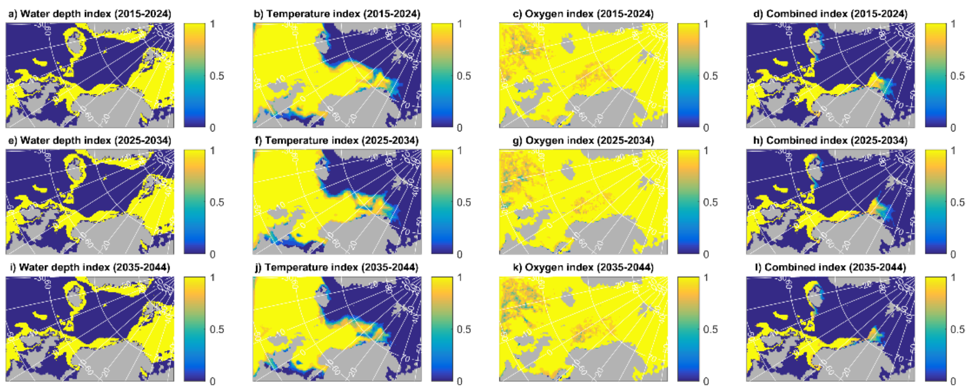

Figure 1.5: Decadal sustainability indices for Atlantic salmon farming in the European sector of the A20 model domain during future decades under the RCP8.5 scenario. Top, middle, and bottom rows show results for decades (2015-

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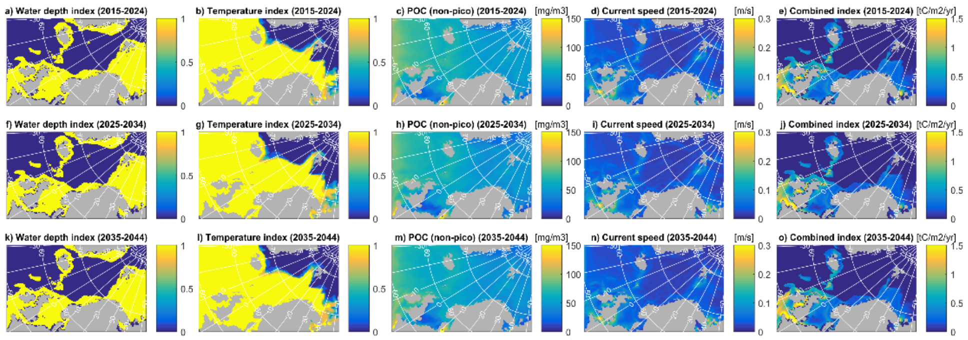
	2024), (2025-2034), and (2035-2044) respectively. White lines show lines of constant latitude/longitude.  Figure 1.6: Decadal sustainability indices for blue mussel farming in the European sector of the A20 model domain in the future under the RCP8.5 scenario. Top, middle, and bottom rows show results for decades (2015-2024), (2025-2034), and (2035-2044) respectively. White lines show lines of constant latitude/longitude.
Link to published study (if available)	
References	Gentry RR, et al. (2017) Mapping the global potential for marine aquaculture. Nat Ecol Evol 1:1317–1324. Jansen, H.M., et al. (2016). The feasibility of offshore aquaculture and its potential for multi-use in the North Sea. Aquacult Int. 24:735-756. Kapetsky, J.M., Aguilar-Manjarrez, J. & Jenness, J. (2013). A global assessment of potential for offshore mariculture development from a spatial perspective. FAO Fisheries and Aquaculture Technical Paper No. 549. Rome, FAO. 181 pp.
Contacts	[Norwegian Institute for Water Research (NIVA); Phil Wallhead; pwa@niva.no)

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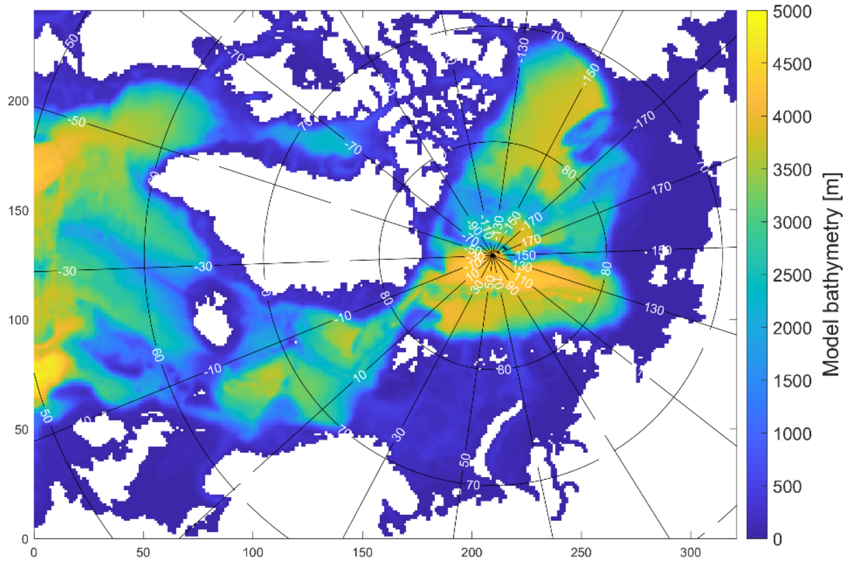
Interactive Tool 1: A20 ROMS-ERSEM (NIVA)

	
Title/name:	A20 ROMS-ERSEM
Developer:	Phil Wallhead (NIVA) based on: the ROMS physical model (Shchepetkin and McWilliams, 2005), the ERSEM biogeochemical model (Butenschon et al., 2016) adapted for the Arctic (Wallhead et al., in prep.), the FABM coupling framework (Bruggeman and Bolding, 2014), and a 20 km pan-Arctic grid (A20) developed by the Norwegian Meteorological Institute.
Description:	A20 ROMS-ERSEM predicts the 3D evolution of seawater hydrography, currents, and biogeochemistry (nutrients, oxygen, organic matter, plankton concentrations) over a pan-Arctic domain at 20 km resolution.
Who is the tool designed for?	☒ Aquaculture producers ☒ Regulators ☐ Certifiers ☒ Spatial planners ☒ Other? Research scientists and engineers.
Type of aquaculture:	☒ Marine fish cages ☐ Freshwater fish cages ☒ Shellfish ☐ Freshwater fish ponds ☐ Integrated Multi-trophic aquaculture ☐ Invertebrates ☐ Recirculating aquaculture system ☐ Seaweed ☐ Other ________________________________
Availability	☐ Available to download or access directly in the Toolbox ☒ Can be accessed via a link to external website/portal • Link: ____ ☐ Would need to be adapted for a new area

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	• Details: ____
Format of the tool:	☐ Flowchart ☐ Decision tree ☐ Guidance document ☐ Spreadsheet model ☐ Standalone computer application ☐ Computer code ☐ Multiple modelling approaches ☒ Large computer model run on supercomputers ☐ Interactive web portal ☐Other _________________
Accessibility	☐ End user has full access to the entire tool. ☐ End user has access to most of the tool and can change all of the necessary settings. ☐ End user has access to limited version of the tool and can change some of the settings. ☐End user only has access to the outputs of the tool, limited options to change settings. ☒ End user only has access to the outputs with no options to change any settings.
Spatial scale of the tool:	☒ International ☐ National ☐ Regional ☐ Waterbody or coastal scale ☐ Farm level
Specificity	☐ Tool can be used anywhere if data is available ☒ The tool can be adapted but may require additional resources to calibrate and ground-truth for new area. ☐ The approach can be adapted but would have to start from the beginning to develop the necessary components. ☐ Tools is specific to an area and cannot be adapted for another area
Cost of tool (please provide details to explain what costs are)	☒ Free to use ☐ Free to use but must register to get access ☐ Free to use but requires pay-for software (details: ☐ Single payment • Amount: _________________________________ ☐ Subscription: • Amount: __________________________________ ☒ Not available for purchase but is available as a service • Contact for further details: __________

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<table>
<tr><td>Approximate time to collect and process the input data
(please provide details to explain what takes the time)</td><td>☐ No input data required
☐ Hours
• ___________________
☐ Days
• ___________________
☐ Weeks
• ___________________
☒ Months
• The model requires input atmospheric forcings and oceanic + riverine boundary conditions that must be gathered from appropriate sources, interpolated, bias-corrected, and formatted for input into ROMS
☐ Years
• ___________________</td></tr>
<tr><td>Approximate time to use the tool
(please provide details to explain what takes the time)</td><td>☐ Hours
• ___________________
☒ Days
• If only using the model output, it should not take more than a few days to extract and collate the desired data from the output files
☒ Weeks
• For developers to rerun the model (on request as a service) a few weeks would be needed to be allowed for fine-tuning of the input parameters, scheduling of the model run on a supercomputer, and execution the model run (~5 days per decade for A20, using 1024 processors. This assumes that all necessary input data are already available (otherwise months would be required).
☐ Months
• ___________________
☐ Years
• ___________________</td></tr>
<tr><td>Purpose</td><td>☒ Site selection
☒ Scoping
☒ Spatial planning
☐ Optimise production
☐ Licence application
☒ Production capacity assessment
☐ Risk assessment
☐ Stakeholder/community engagement
☐ Early warning system
☒ Ecosystem services
☐ Social licence
☒ Monitoring</td></tr>
</table>

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Where does this fit in the licensing process? (only tick the sections that the tool actually would be used in)	☐ ☐ ☐ ☐ ☐ ☐ ☐ ☐
Technical experience required? (be specific)	☐ None ☐ May require use of guidance documents (provided in the toolbox). ☒ Some expertise • If only using model output, some expertise is required for handling model output data format (NetCDF) and, if dealing with raw model output, with the particular format of ROMS model output (e.g. vertical s-coordinate schemes) ☒ Expert • Rerunning the model requires expert technical experience (Fortran, Unix, experience with ROMS and preferably also the FABM coupling methodology)
What resources are needed to use the tool? (include details on the actual resources, e.g. specific software)	☐ Tool is standalone ☒ Software • For using model output, a NetCDF viewing program and software for reading/manipulating NetCDF output (e.g. Matlab, Python, R) is recommended, although it would also be possible to provide other formats (e.g. ascii, .xlsx) on request. For developers to rerun the model, additional software is required (Fortran/C compiler). ☒ Hardware • For rerunning the model, developers require access to (hours on) a supercomputer
What are the input data required? (include details on what needs to be collected) (add more rows as needed_	☐ None ☒ Online databases • For a hindcast run (to assess past/present-day variability) we need atmospheric reanalysis data (e.g. from ECMWF), tidal forcing data (e.g. from TPXO7.2), riverine input data (e.g. from NVE database), and oceanic boundary condition data (e.g. from SODA reanalysis and bias-corrected Earth System model output). For a future projection we need Earth System model output (e.g. from the CMIP5 portal) to define delta-changes for atmospheric, riverine, and boundary condition inputs. ☐ Experimental data • ______________________________ ☐ Fieldwork data • ______ ☐ Data from aquaculture producer

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	• ________________________________ ☐ Earth observation data • __________ ☐ Other • _______________________________
Guidance documents:	The ROMS Wiki page is a good place to start for understanding the ROMS model and raw output file formats: https://www.myroms.org/wiki/Documentation_Portal
Academic papers:	Bruggeman and Bolding 2014. A general framework for aquatic biogeochemical models. Environmental Modelling & Software Volume 61, 249–265. Butenschön, M., et al., 2016. ERSEM 15.06: a generic model for marine biogeochemistry and the ecosystem dynamics of the lower trophic levels. Geoscientific Model Development, 9(4), 1293. Shchepetkin, A. F., and J. C. McWilliams, 2005: The Regional Ocean Modeling System: A split-explicit, free-surface, topography following coordinates ocean model, Ocean Modelling, 9, 347-404.
Example of application (case study?) :	“Mapping suitability for offshore salmon and mussel aquaculture in the North Atlantic and Nordic Seas using the A20 ROMS-ERSEM model.”

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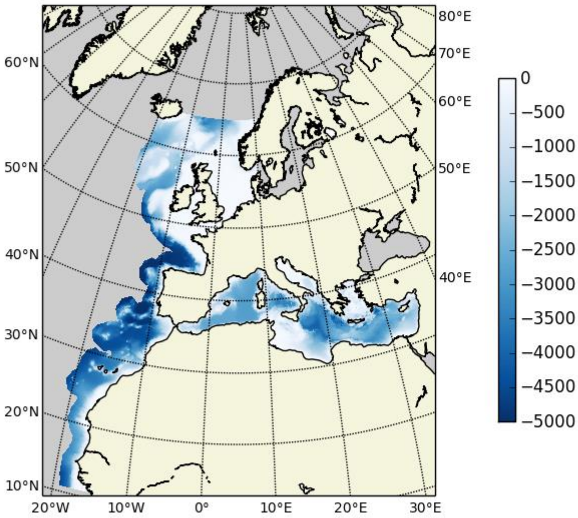
Case Study 2: Assessing future suitability for aquaculture across Europe, based on projections from a POLCOMS-ERSEM model (PML)

	Model domain and bathymetry (m) 
Title:	Assessing future suitability for aquaculture across Europe, based on projections from a POLCOMS-ERSEM model.
Description	A 3D hydrodynamic-biogeochemical ocean model was used to map change in projected environmental conditions for European seas over the 21st century
Tool(s) applied	☒Yes Type of tool: model output dataset • Link: : https://climate.copernicus.eu/climate-data-store Note: the dataset is due to be ingested into the Climate Data Store soon. In the meantime it can be accessed on request to Susan Kay, suka@pml.ac.uk. ☐ No
Who is this case study relevant for?	☒Aquaculture producers ☐Regulators ☐Certifiers ☒Spatial planners ☒Other? ___Research scientists and engineers____
Topic(s)	☒Site selection ☒Scoping ☒Spatial planning ☒Optimise production ☐Licence application ☒Production capacity assessment ☐Environment impact assessment ☐ Risk assessment ☐Stakeholder/community engagement

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	☐Early warning system ☒Ecosystem services ☐Social licence ☐Monitoring
Type of aquaculture:	☒Marine fish pens ☐Freshwater fish cages ☒Shellfish ☐Freshwater fish ponds ☐Integrated Multi-trophic aquaculture ☐Invertebrates ☐Recirculating aquaculture system ☐Seaweed ☐Other ____
Species	☒ Fish ☒Atlantic salmon (*Salmo salar*) ☒ European sea bass (*Dicentrarchus labrax*) ☒ Gilthead sea bream (*Sparus aurata*) ☐ Common carp (*Cyprinus carpio*) ☐ Rainbow trout (*Oncorhynchus mykiss*) ☒ Turbot (*Psetta maxima*) ☒Shellfish ☒ Pacific oyster (*Crassostrea gigas*) ☒ Blue mussel (*Mytilus edulis*) ☒ Mediterranean mussel (*Mytilus galloprovinicalis*) ☒ Manila clam (*Ruditapes philippinarum*) ☐ Seaweeds ☐ ____ ☐Other ____
Location	☐ Inland ☒ Atlantic Ocean ☐ Baltic Sea ☒ Mediterranean Sea ☒ Other North Sea
Case study description [Short summary]	**What is the case study approach** We applied the POLCOMS-ERSEM model to produce projections of the change in physical and biogeochemical conditions in the North East Atlantic and Mediterranean across the 21st century (2006-2099). A range of environmental indicators are available as 3d variables, including temperature, salinity, chlorophyll, primary production, nutrients, pH, oxygen, phytoplankton and zooplankton biomass and total organic carbon. Some of these have been used to give maps of change and the full dataset is available via the Copernicus Climate Data Store, enabling users to focus on the variables and regions that interest them.

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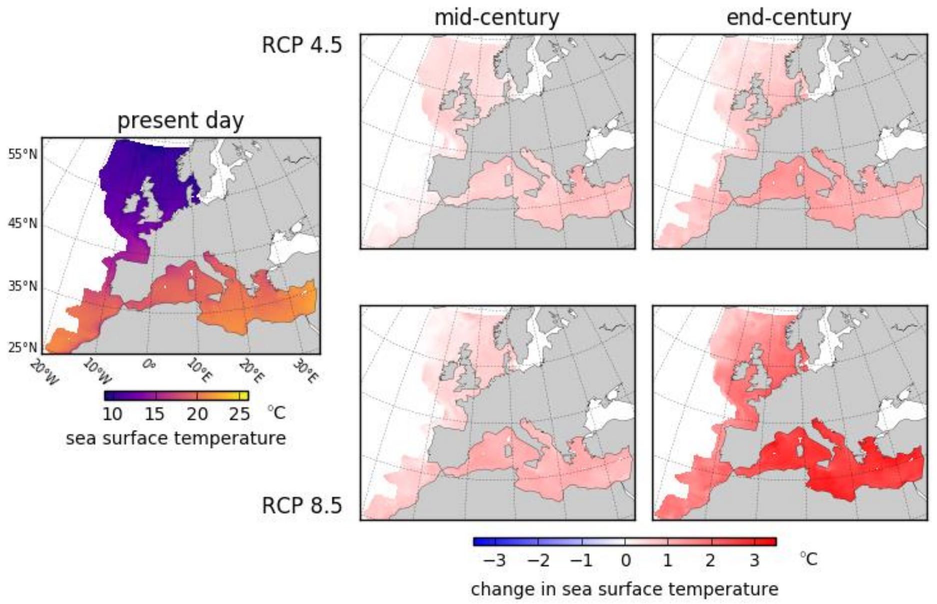
	What are the outputs A dataset consisting of change in conditions relevant to aquaculture planning; maps produced from that dataset. **Conclusion** This dataset and maps will assist with identifying where climate change will lead to regions becoming more or less suited to aquaculture of various species. It is intended as a flexible tool to use as it is, or as input to more specialised models, as is exemplified by the case studies from HCMR and the University of Nantes.
The broader applicability	This is a non-specific tool, with wide applicability
Relevant images or graphics	 Figure 1. Modelled sea surface temperature at the start of the 21st century and projected change for mid and end-century under RCP 4.5 (top) and RCP 8.5 (bottom). The present day plot shows the mean for 2006-2016; the change plots show the difference between the future period (2046-2055 or 2086-2095) and 2006-2016.

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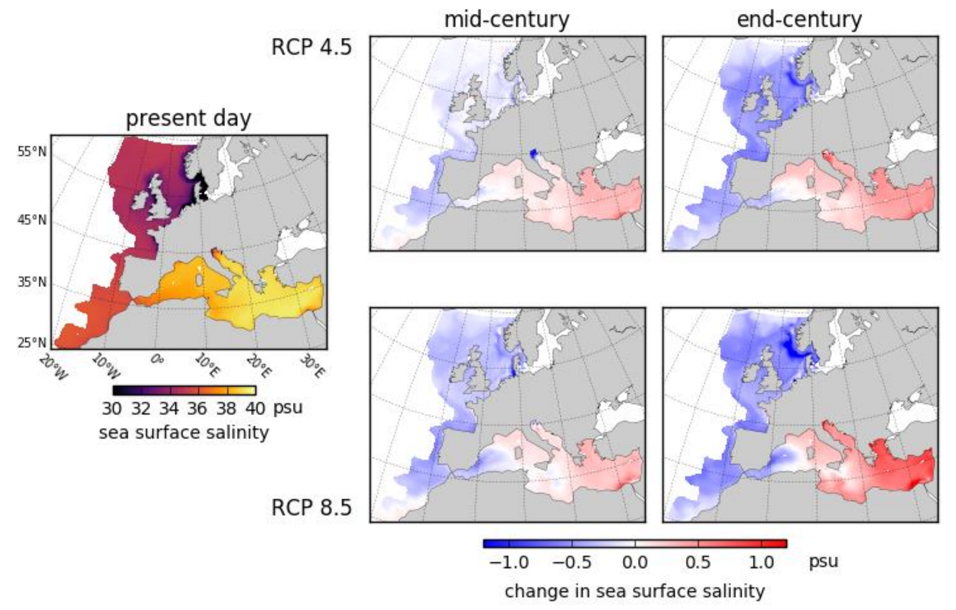

Figure 2. Modelled sea surface salinity at the start of the 20th century and projected change for mid and end-century under RCP 4.5 (top) and RCP 8.5 (bottom). The present day plot shows the mean for 2006-2016; the change plots show the difference between the future period (2046-2055 or 2086-2095) and 2006-2016.

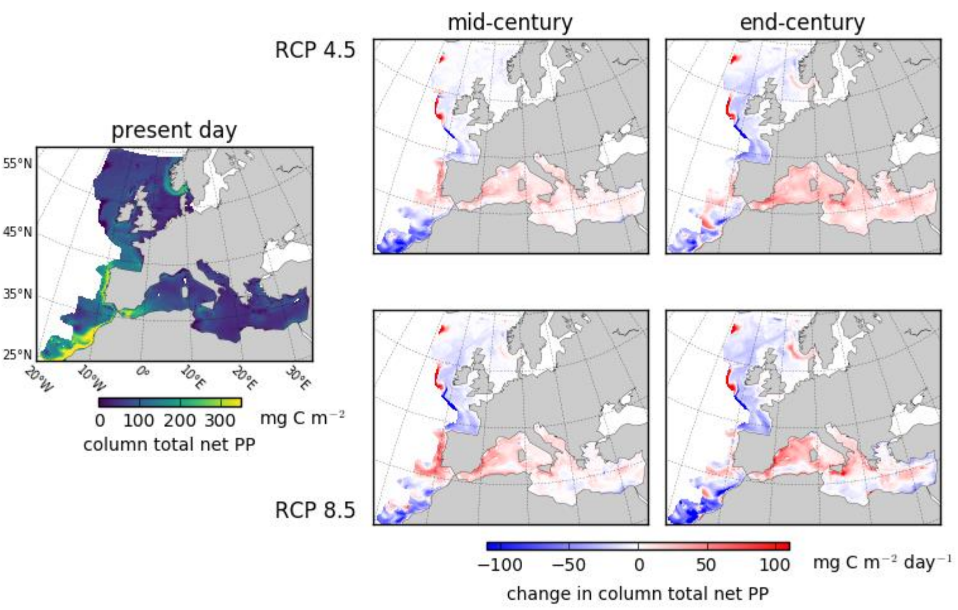

Figure 3. Modelled net primary production at the start of the 20th century and projected change for mid and end-century under RCP 4.5 (top) and RCP 8.5 (bottom). The present day plot shows the mean for 2006-2016; the change plots show the difference between the future period (2046-2055 or 2086-2095) and 2006-2016.

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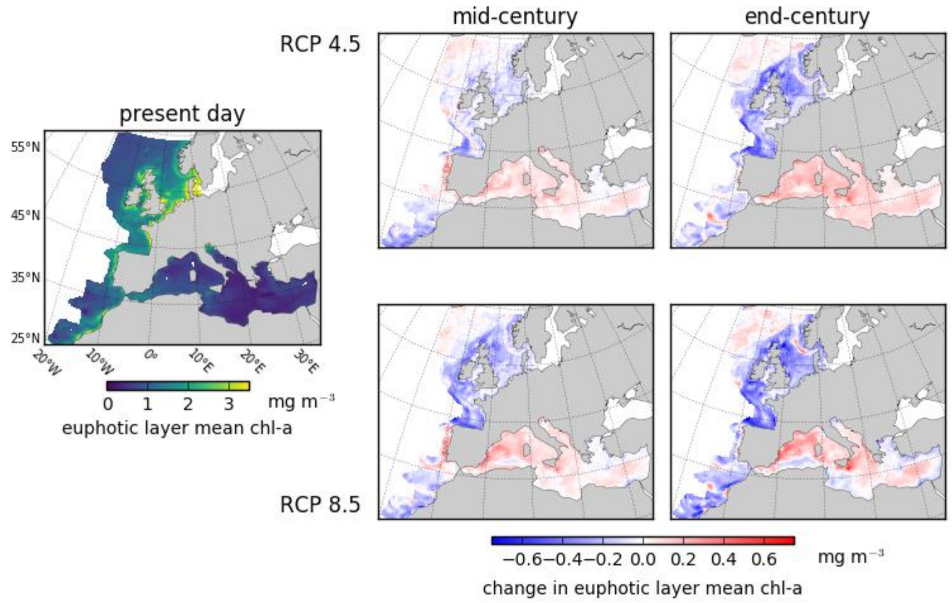

Figure 4. Modelled mean chlorophyll-a concentration for the euphotic layer at the start of the 20th century and projected change for mid and end-century under RCP 4.5 (top) and RCP 8.5 (bottom). The present day plot shows the mean for 2006-2016; the change plots show the difference between the future period (2046-2055 or 2086-2095) and 2006-2016.

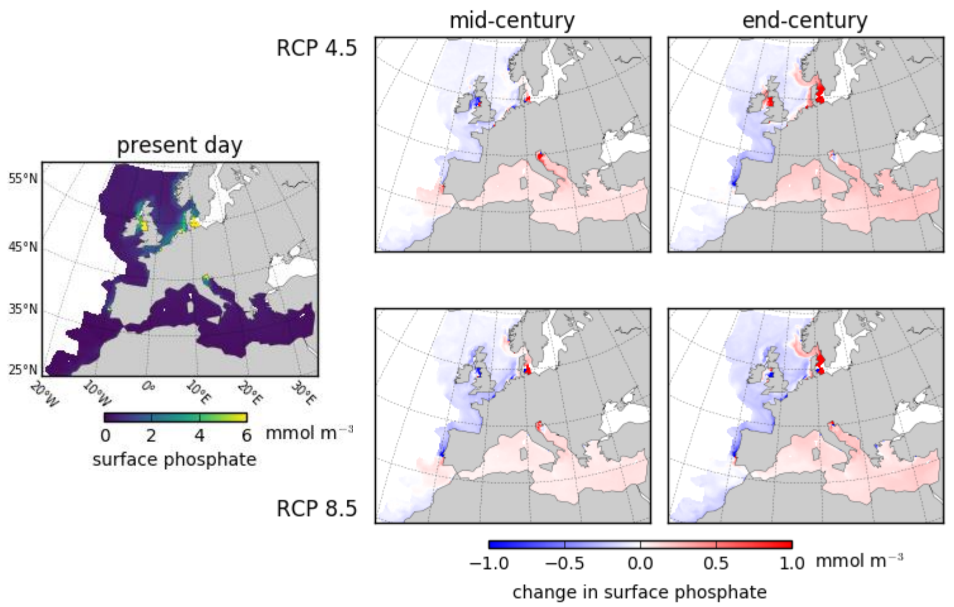

Figure 5. Modelled dissolved phosphate for the surface layer at the start of the 20th century and projected change for mid and end-century under RCP 4.5 (top) and RCP 8.5 (bottom). The present day plot shows the mean for 2006-2016; the change plots show the difference between the future period (2046-2055 or 2086-2095) and 2006-2016.

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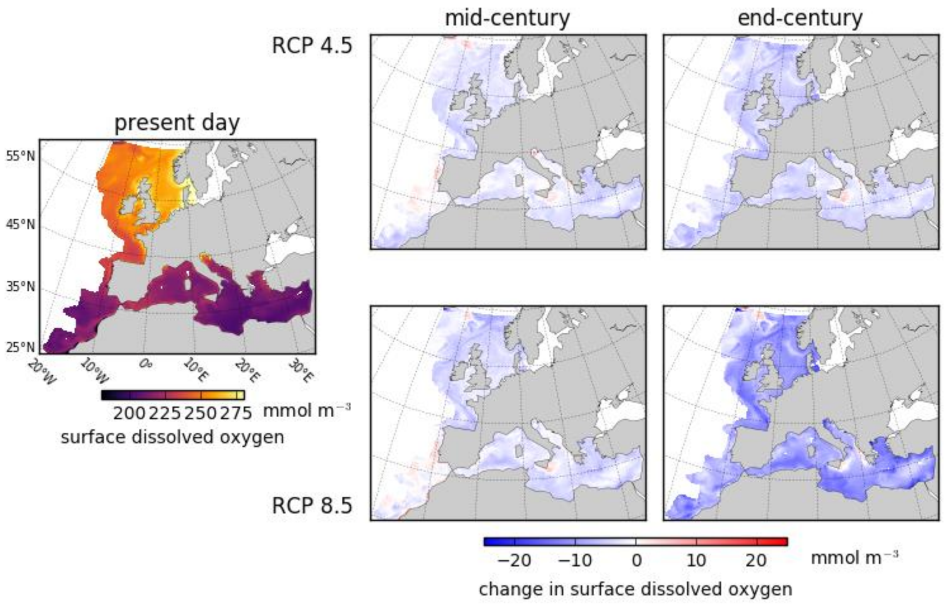

Figure 6. Modelled dissolved oxygen concentration for the surface layer at the start of the 20th century and projected change for mid and end-century under RCP 4.5 (top) and RCP 8.5 (bottom). The present day plot shows the mean for 2006-2016; the change plots show the difference between the future period (2046-2055 or 2086-2095) and 2006-2016.

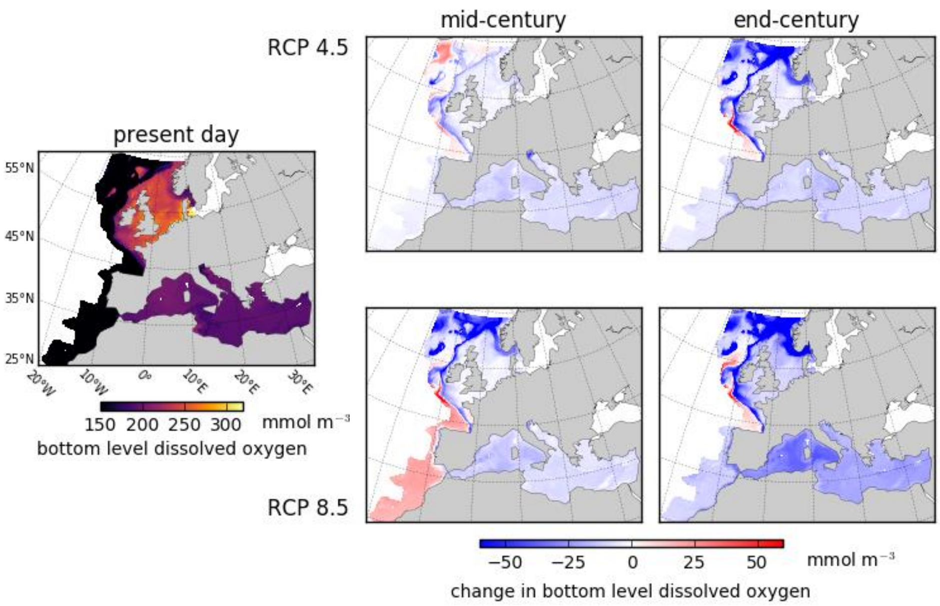

Figure 7. Modelled dissolved oxygen concentration for the bottom layer at the start of the 20th century and projected change for mid and end-century under RCP 4.5 (top) and RCP 8.5 (bottom). The present day plot shows the mean for 2006-2016; the change plots show the difference between the future period (2046-2055 or 2086-2095) and 2006-2016.

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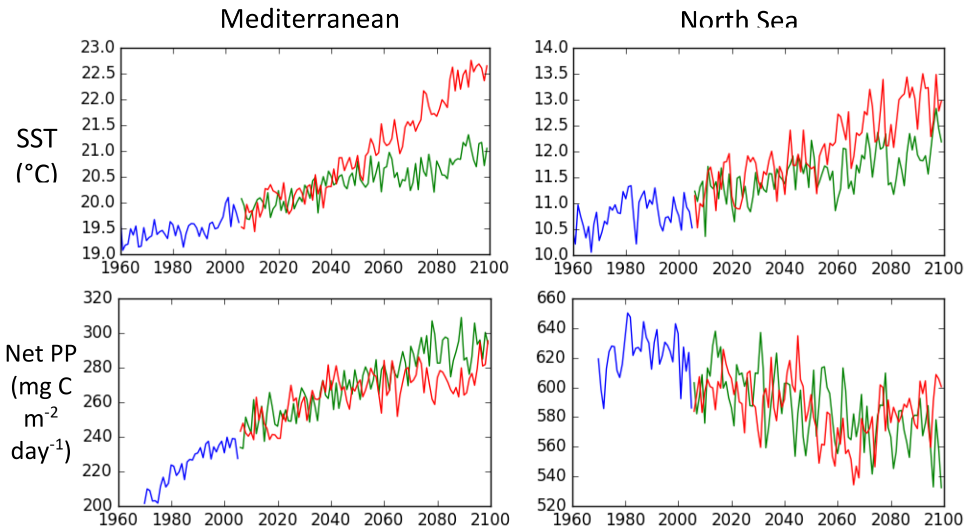

Figure 8. Sample time series created from the dataset: projected annual average sea surface temperature (top) and column total net primary production (bottom) for the Mediterranean (left) and North Sea (right). Blue shows the historical period, green the projection under RCP 4.5 and red under RCP 8.5.

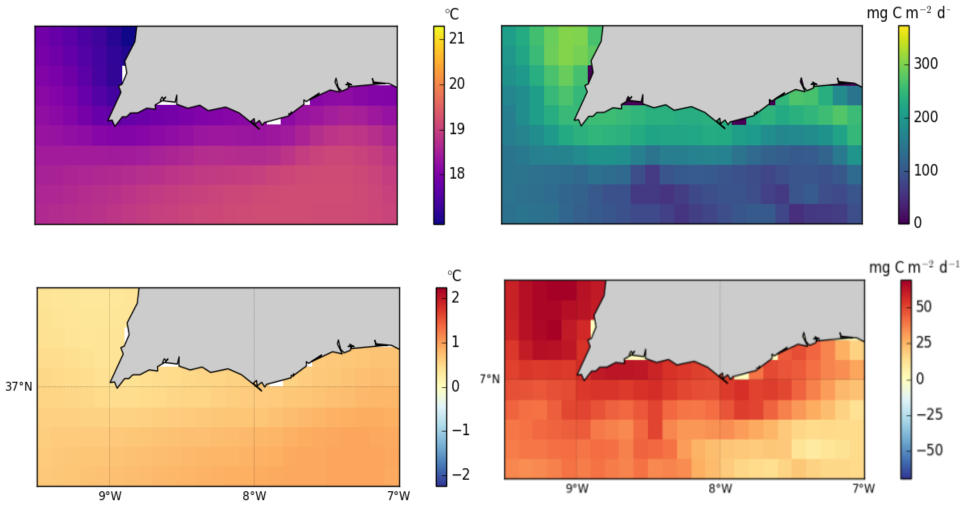

Figure 9. Sample regional plots to illustrate the available resolution; in this case southern Portugal is shown. The top row shows present day conditions for sea surface temperature (left) and column total net primary production (left); the bottom row shows the difference at the end of the century under RCP 8.5.

Link to published study (if available)	
References	
Contacts	Plymouth Marine Laboratory (PML): Susan Kay (suka@pml.ac.uk)

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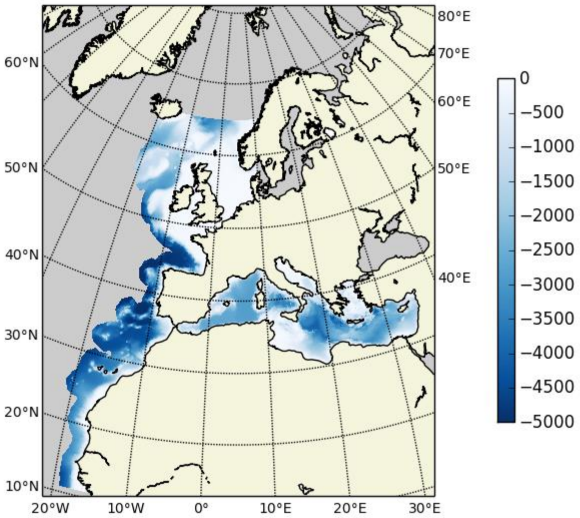
Interactive Tool 2: POLCOMS-ERSEM model outputs for Europe (PML)

Model domain and bathymetry (m)



Title/name:	POLCOMS-ERSEM model outputs for Europe
Developer:	Susan Kay (PML) based on outputs from the POLCOMS physical model (Holt and James 2001) coupled to the ERSEM biogeochemical model (Butenschön et al., 2016) and run for a domain created by combining elements of the Global Coastal Ocean Modelling System (Holt et al., 2009)
Description:	This POLCOMS-ERSEM system predicts the 3D evolution of seawater hydrography, currents, and biogeochemistry (nutrients, oxygen, organic matter, plankton concentrations) over a pan-European domain at a resolution of 0.1° (approximately 11 km).
Who is the tool designed for?	☒ Aquaculture producers ☒ Regulators ☐ Certifiers ☒ Spatial planners ☒ Other? Research scientists and engineers.
Type of aquaculture:	☒ Marine fish cages ☐ Freshwater fish cages ☒ Shellfish ☐ Freshwater fish ponds ☐ Integrated Multi-trophic aquaculture ☐ Invertebrates ☐ Recirculating aquaculture system ☐ Seaweed ☐ Other ____________________
Availability	☐ Available to download or access directly in the Toolbox ☒ Can be accessed via a link to external website/portal • Link: https://climate.copernicus.eu/climate-data-store. Note: the dataset is not on the Climate Data Store yet. This will happen by October 2019 at the latest, probably sooner, and in the meantime the model outputs are available from Susan Kay, suka@pml.ac.uk ☐ Would need to be adapted for a new area • Details: ____

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Format of the tool:	☐ Flowchart ☐ Decision tree ☐ Guidance document ☐ Spreadsheet model ☐ Standalone computer application ☐ Computer code ☐ Multiple modelling approaches ☐ Large computer model run on supercomputers ☐ Interactive web portal ☒Other A set of outputs from a large computer model run on a supercomputer
Accessibility	☐ End user has full access to the entire tool. ☐ End user has access to most of the tool and can change all of the necessary settings. ☐ End user has access to limited version of the tool and can change some of the settings. ☐End user only has access to the outputs of the tool, limited options to change settings. ☒ End user only has access to the outputs with no options to change any settings.
Spatial scale of the tool:	☒ International ☐ National ☐ Regional ☐ Waterbody or coastal scale ☐ Farm level
Specificity	☐ Tool can be used anywhere if data is available ☐ The tool can be adapted but may require additional resources to calibrate and ground-truth for new area. ☐ The approach can be adapted but would have to start from the beginning to develop the necessary components. ☒ Tools is specific to an area and cannot be adapted for another area
Cost of tool (please provide details to explain what costs are)	☒ Free to use ☐ Free to use but must register to get access ☐ Free to use but requires pay-for software (details: ☐ Single payment • Amount: ________________________________ ☐ Subscription: • Amount: ____ ☐ Not available for purchase but is available as a service • Contact for further details: _____________
Approximate time to collect and	☒ No input data required ☐ Hours

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process the input data (please provide details to explain what takes the time)	• ____________________ ☐ Days • ____________________ ☐ Weeks • ____________________ ☐ Months • ____________________ ☐ Years • ____________________
Approximate time to use the tool (please provide details to explain what takes the time)	☒ Hours • The dataset is quick to acquire from the Copernicus CDS, and there are online tools to help with analysis. Total time would be hours or days, depending on the level of the user's experience and the amount and type of information required. ☒ Days • ____________________ ☐ Weeks • ____________________ ☐ Months • ____________________ ☐ Years • ____________________
Purpose	☒ Site selection ☒ Scoping ☒ Spatial planning ☐ Optimise production ☐ Licence application ☒ Production capacity assessment ☐ Risk assessment ☐ Stakeholder/community engagement ☐ Early warning system ☒ Ecosystem services ☐ Social licence ☐ Monitoring
Where does this fit in the licensing process? (only tick the sections that the tool actually would be used in)	☐ ☐ ☐ ☐ ☐ ☐ ☐ ☐

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Technical experience required? (be specific)	☐ None ☐ May require use of guidance documents (provided in the toolbox). ☒ Some expertise • Some expertise is required for handling model output data format (NetCDF) and using the CDS tools for data analysis ☐ Expert •
What resources are needed to use the tool? (include details on the actual resources, e.g. specific software)	☒ The dataset can be used without additional software, using the tools available in the Climate Data Store ☒ Software • For using downloaded model output, a NetCDF viewing program and software for reading/manipulating NetCDF output (e.g. Matlab, Python, R) is required. ☐ Hardware • For rerunning the model, developers require access to (hours on) a supercomputer
What are the input data required? (include details on what needs to be collected) (add more rows as needed_	☒ None ☐ Online databases ☐ Experimental data • ______________________________ ☐ Fieldwork data • ______ ☐ Data from aquaculture producer • ________________________________ ☐ Earth observation data • ___________ ☐ Other • _______________________________
Guidance documents:	See the documentation on the Copernicus Climate Data Store.
Academic papers:	Butenschön, M., Clark, J., Aldridge, J.N., Allen, J.I., Artioli, Y., Blackford, J., Bruggeman, J., Cazenave, P., Ciavatta, S., Kay, S., Lessin, G., van Leeuwen, S., van der Molen, J., de Mora, L., Polimene, L., Sailley, S., Stephens, N., Torres, R., 2016. ERSEM 15.06: a generic model for marine biogeochemistry and the ecosystem dynamics of the lower trophic levels. Geosci Model Dev 9, 1293–1339. https://doi.org/10.5194/gmd-9-1293-2016 Holt, J., Harle, J., Proctor, R., Michel, S., Ashworth, M., Batstone, C., Allen, I., Holmes, R., Smyth, T., Haines, K., Bretherton, D., Smith, G., 2009. Modelling the Global Coastal Ocean. Philos. Trans. R. Soc. Math. Phys. Eng. Sci. 367, 939–951. https://doi.org/10.1098/rsta.2008.0210 Holt, J.T., James, I.D., 2001. An s coordinate density evolving model of the northwest European continental shelf 1, Model description and density structure. J. Geophys. Res. 106, 14015–14,034. https://doi.org/10.1029/2000JC000304

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Example of application (case study?) :	"Assessing future suitability for aquaculture across Europe, based on projections from a POLCOMS-ERSEM model"

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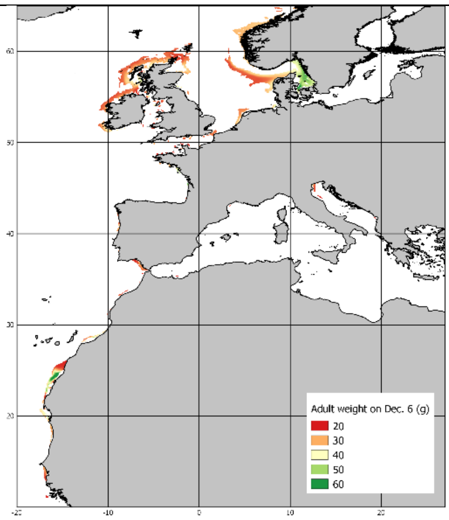
Case Study 3: POLCOMS-ERSEM driven Dynamic Energy Budget (DEB) modelling of Pacific oyster growth in the offshore environment: indicators, regional comparison & selection (UN)

	 *Total adult C. gigas weight (g) in time for the main December market, within food, temperature, salinity, bathymetric, and current speed constraints, for the early-century reference period (2000-04).*
Title:	POLCOMS-ERSEM driven Dynamic Energy Budget (DEB) modelling of Pacific oyster growth in the offshore environment: indicators, regional comparison & selection
Description	DEB-modelled Pacific oyster growth throughout western Europe and north-western Africa, based on POLCOMS-ERSEM modelled environmental data (SST, chlorophyll-a), for an early-century reference period (2000-04) and two late-century future scenarios (2090-99; RCP 4.5, 8.5), digested into industry-relevant indicators for regional comparison and selection by aquaculture producers and planners, considering constraints relevant to larger industrial producers, as well as smaller farmers.
Tool(s) applied	☒Yes Type of tool: interactive tool (netCDF file of mapped growth time series for each scenario) Link: _ ☐ No
Who is this case study relevant for?	☒Aquaculture producers ☐Regulators ☐Certifiers ☒Spatial planners ☐Other? ______________________________
Topic(s)	☒Site selection ☒Scoping ☒Spatial planning ☐Optimise production

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	☐Licence application ☐Production capacity assessment ☐Environment impact assessment ☐ Risk assessment ☒Stakeholder/community engagement ☐Early warning system ☐Ecosystem services ☐Social licence ☐Monitoring
Type of aquaculture:	☐Marine fish pens ☐Freshwater fish cages ☒Shellfish ☐Freshwater fish ponds ☐Integrated Multi-trophic aquaculture ☐Invertebrates ☐Recirculating aquaculture system ☐Seaweed ☐Other ____
Species	☐ Fish ☐Atlantic salmon (*Salmo salar*) ☐ European sea bass (*Dicentrarchus labrax*) ☐ Gilthead sea bream (*Sparus aurata*) ☐ Common carp (*Cyprinus carpio*) ☐ Rainbow trout (*Oncorhynchus mykiss*) ☐ Turbot (*Psetta maxima*) ☒Shellfish ☒ Pacific oyster (*Crassostrea gigas*) ☐ Blue mussel (*Mytilus edulis*) ☐ Mediterranean mussel (*Mytilus galloprovinicalis*) ☐ Manila clam (*Ruditapes philippinarum*) ☐ Seaweeds ☐ ____ ☐Other ____
Location	☐ Inland ☒ Atlantic Ocean ☐ Baltic Sea ☒ Mediterranean Sea ☒ Other _North Sea____
Case study description [Short summary]	**What is the case study approach?** Dynamic Energy Budget (DEB) modelling of offshore Pacific oyster (*Crassostrea gigas*) growth was carried out at the regional scale using surface layer water temperature and chlorophyll-a data (phytoplankton excluding picoplankton) outputs from POLCOMS-ERSEM modelling (see the "Interactive Tool 2: POLCOMS-

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	ERSEM model outputs for Europe (PML)" section of this report), and applied to the western North Atlantic (including the North Sea), extending south to the Mediterranean and to north-western Africa. In addition to an early-century reference period, from 2000-2004, input data for two late-century future scenarios for the period 2090-2099, based on representative concentration pathway (RCP) 4.5, corresponding to a peak in greenhouse gas emissions at approximately 2040 and subsequent decline, and RCP 8.5, associated with continuously increasing emissions over the next century, were also used in growth modelling. Spatial "hotspots" and changes in projected oyster growth over time under the different scenarios were considered in combination with chlorophyll-a, temperature, salinity, current speed, and bathymetric thresholds within which production is feasible, to identify areas that may sustain or increase in productivity in the future, as well as areas of existing cultivation that may become less productive or inappropriate. Differences between results from the early-century reference period and future RCP 4.5 and RCP 8.5 scenarios are intended to inform climate-adaptive aquaculture planning and policy. Daily time-step growth data were further digested into industry-relevant growth-related indicators (e.g., time to achieve minimum market weight) to aid in the interpretation of this tool by producers and planners alike, with spat, grow-out, and fattening/finishing scenarios considered. Scales relevant to the technology accessible by both larger-scale industrial producers and smaller-scale farmers were considered and compared. **What are the outputs** Outputs are maps of modelled oyster growth (shell length, transformed allometrically to total weight, and dry flesh mass) at the same temporal and spatial resolution as the input data for the simulated period (i.e., daily time-step between March 1 and December 6, and 0.1° respectively; Fig. 1). Spawning events are also modelled and the timing of their occurrence can be mapped.

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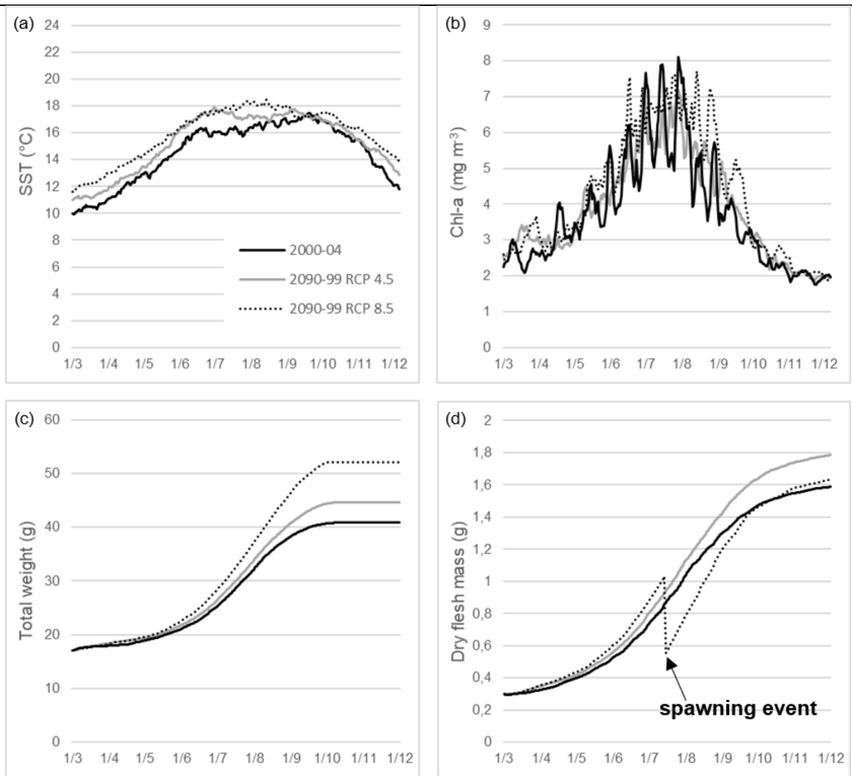

Fig. 1. Examples of POLCOMS-ERSEM input data, SST (a) and chl-a (b), and resulting DEB modelled oyster growth, total weight (c) and dry flesh mass (d), for an average growing season (March 1 – December 6) of the three scenarios/periods considered (early-century reference (2000-04) and late-century under various climate change scenarios (2090-99; RCPs 4.5 and 8.5), extracted for a single pixel near Bourgneuf Bay, France (Fig. 3).

From an industry standpoint, most criteria of interest are related to total weight, which underlies the definition of oyster calibre and therefore demand and price, as well as Quality Index, which is a measure of oyster fullness (ratio of flesh to total weight). Several example indicators were therefore defined and implemented as a function of these. Key market timings and market weight thresholds were identified through consultation of producers and professionals from one of the main oyster-producing regions in France and examples of these are integrated into indicators mapped for the early-century reference period in Fig. 2: (a) days until the smallest spat size reach target sale size (T25; approximately 18g); (b) days until minimum adult market size (30g) is reached; (c) weight (g) obtained by adults for the (main) December market; and (d) Quality Index (drained flesh weight/total weight (%)) obtained by adults for the (main) December market. Indicators are relevant to specialization in the production of various life stages (spat production, growing adults, and fattening/finishing), and could easily be adapted to other user-defined criteria (e.g., the timing the weight of a certain calibre of oyster is achieved; growth for secondary summer market or another target date), by altering threshold values or dates.

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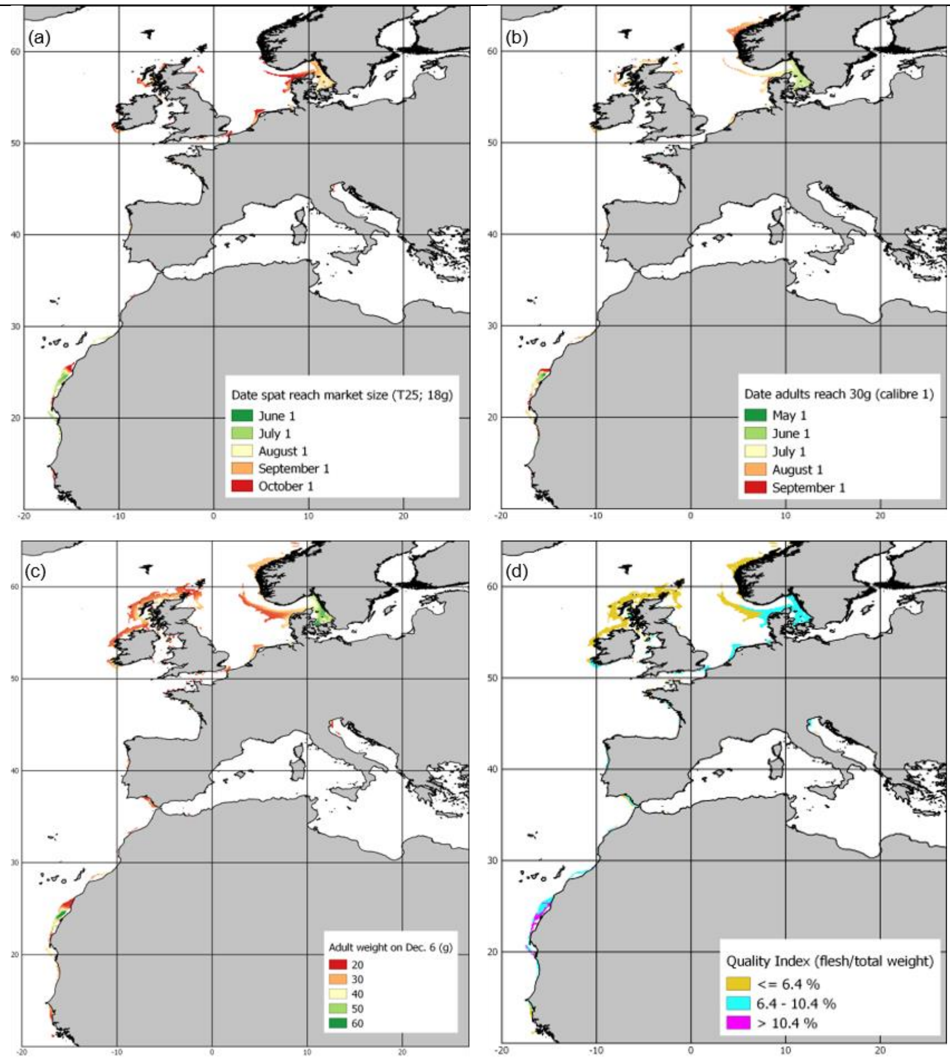

Fig. 2. Examples of mapped Pacific oyster growth indicators, defined according to industry standards and requirements, and within 95% confidence interval threshold-defined food (>1 mg m^{-3}), temperature (1.8-35°C), salinity (5-45 psu), bathymetric (<200 m), and current speed (0.1-1 m s^{-1}) constraints, for the early-century (2000-04) reference period; (a) date T6-T8 spat reach target market size to sell to other producers (size T25; approximately 18g); (b) date adult minimum market size (30g; calibre 1) is reached; (c) weight (g) obtained for the (main) December market; and (d) Quality Index (drained flesh weight/total weight (%)) obtained for the (main) December market. Growth simulation runs from March 1 through December 6. Indicator maps and raw modelled growth data are also available for the two future scenarios (2090-99; RCP 4.5 and 8.5).

Values of mapped indicators can then be used to quantitatively compare selected locations or regions of interest (ROIs), and changes for a given ROI over time or under difference climate scenarios. For example, Fig. 3 presents mapped adult oyster weight obtained in the Bay of Biscay (a-c) and the North Sea (d-f) for the main December market, for the early-century reference and two future scenarios, after areas where conditions fall outside of the tolerated or feasible food (chl-a), temperature, salinity, current speed, and bathymetric ranges were excluded. Several offshore areas are highlighted as having the potential for sufficient growth.

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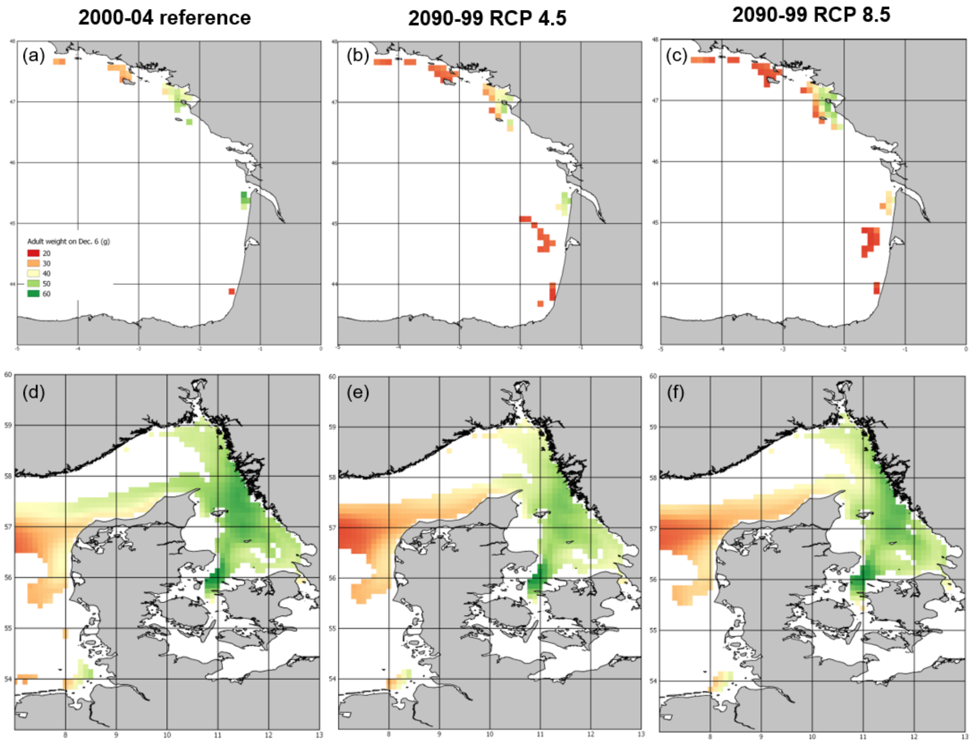

Fig. 3. Total adult *C. gigas* weight (g) in time for the main December market, within food, temperature, salinity, bathymetric, and current speed constraints, for the western Bay of Biscay (a-c) and western North Sea (d-f), under conditions associated with the early-century reference period and two late-century scenarios.

Highlighted areas can then be examined in terms of the spatial and temporal variability, as presented in Fig. 4. Areas where end-of-season weight is consistently high across the spatial window, and into the future as well as under different climate scenarios (i.e., climate robust) would be considered better choices to investigate.

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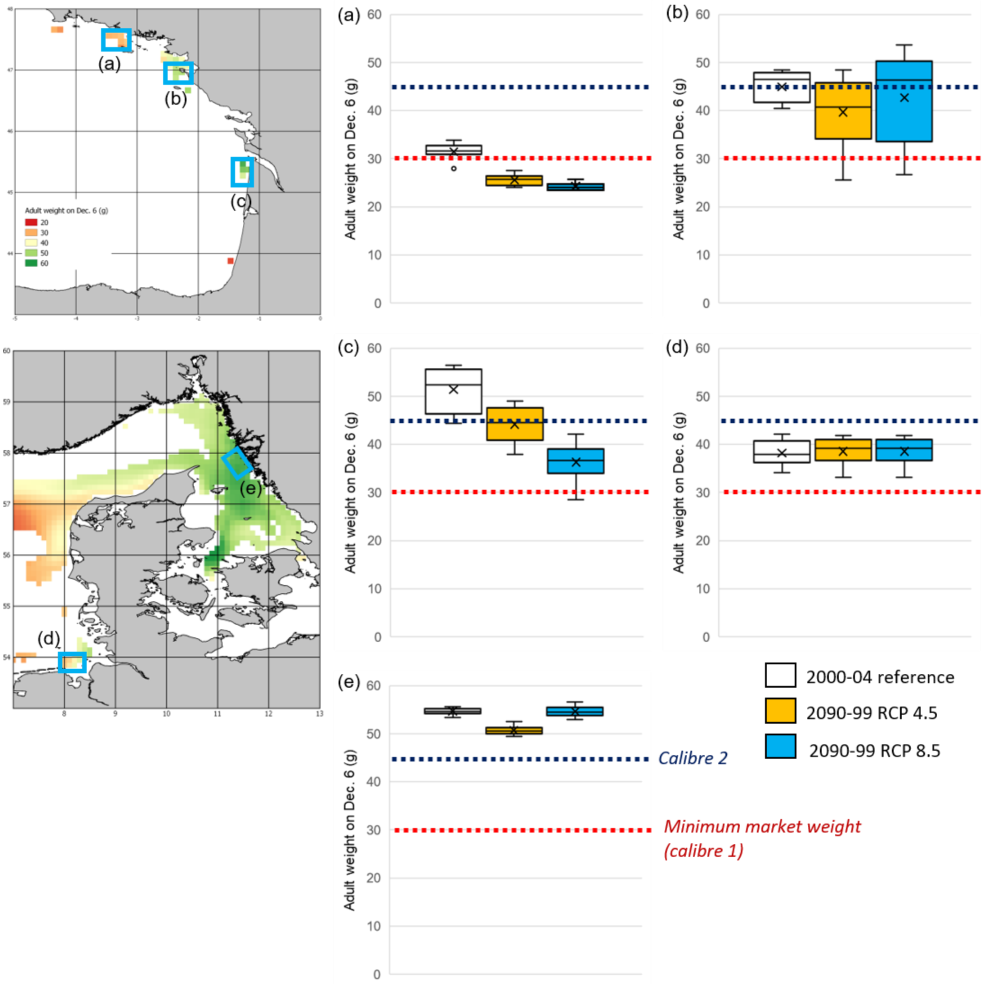

Fig. 4. Variable growth within several hypothetical leasing zones in the French Bay of Biscay and western North Sea regions; (a) south Brittany; (b) Pays de la Loire; and (c) Aquitaine oyster-producing regions of France; (d) the German Bight portion of the Wadden Sea; and (e) the Swedish Kattegat. In the box plots, different coloured boxes indicate the different periods and scenarios for each site, with longer boxes indicative of more spatial variability in growth.

Conclusion

The approach described here provides a large, macro-scale perspective toward identifying areas within which future offshore oyster farms could be situated, in terms of various constraints and focusing on growth potential. Through quantitative mapping and analysis, areas warranting further investigation on a finer spatial scale are highlighted. Areas for which growth is expected to be more robust under variable climate conditions are also highlighted and should be paid special attention in planning and development, as should emerging areas, where oyster cultivation may not currently be present, but may be feasible and worthy of investment now and/or into the future. Such quantitative mapping of potential growth and related indicators can be included as part of more comprehensive spatial multi-criteria evaluation (SMCE) to further explore and integrate the social,

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	economic, environmental, and biological suitability of a given site or area in aquaculture site selection and planning.
The broader applicability	The use of POLCOMS-ERSEM data to drive regional-scale DEB modelling here, as well as to constrain potential sites for Pacific oyster aquaculture based on temperature, food, salinity, current speed and bathymetry thresholds, has allowed its application to western Europe and north western Africa. Potential “hot spots” warranting further investigation were able to be highlighted, as were broad spatial and temporal patterns at the scales investigated and under variable climate scenarios possible over the coming century. Such information is intended to support climate-adaptive long-term and large-scale scoping, decisions and planning in the aquaculture industry and related fields. Although applied here for Pacific oyster, DEB theory has also been used to investigate the growth of other species under variable environmental conditions, and a similar exercise could foreseeably be used to model growth-related indicators other species of interest; for example, blue mussel (*Mytilus edulis*), Mediterranean mussel (*Mytilus galloprovincialis*), and great scallop (*Pecten maximus*). *In situ* growth data, when possible, should be used to provide some corroboration of model results. Likewise, based on current industry standards and preferences, and in consultation with industry professionals, we have selected and mapped a suite of growth-related indicators to enhance the relevance of the model output data, but growth data could also be transformed into other user-defined indicators, using the mapped time series provided here.
Link to published study (if available)	
References	Ciavatta, S., Kay, S., Saux-Picart, S., Butenschön, M., & Allen, J. I. (2016). Decadal reanalysis of biogeochemical indicators and fluxes in the North West European shelf-sea ecosystem. Journal of Geophysical Research: Oceans, 121(3), 1824-1845. Ciavatta, et al. (2018). Assimilation of ocean-color plankton functional types to improve marine ecosystem simulations. Journal of Geophysical Research: Oceans, 123(2), 834-854. Gentry RR, et al. (2017) Mapping the global potential for marine aquaculture. Nat Ecol Evol 1:1317–1324. Kapetsky, J.M., Aguilar-Manjarrez, J. & Jenness, J. (2013). A global assessment of potential for offshore mariculture development from a spatial perspective. FAO Fisheries and Aquaculture Technical Paper No. 549. Rome, FAO. 181 pp. Kay, S., & Butenschön, M. (2018). Projections of change in key ecosystem indicators for planning and management of marine protected areas: An example study for European seas. Estuarine, Coastal and Shelf Science, 201, 172-184. Thomas, Y., et al. (2016). Global change and climate-driven invasion of the Pacific oyster (Crassostrea gigas) along European coasts: a bioenergetics modelling approach. Journal of Biogeography, 43(3), 568-579.
Contacts	[University of Nantes; Stephanie Palmer; stephanie.palmer@univ-nantes.fr)

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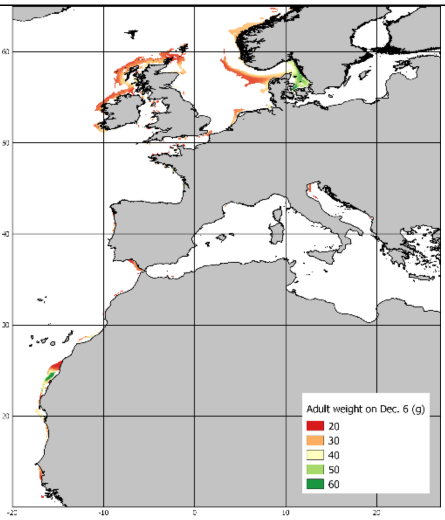
Interactive Tool 3: POLCOMS-ERSEM/DEB-modelled Pacific oyster growth for the offshore environment (UN)

	 *Total adult C. gigas weight (g) in time for the main December market, within food, temperature, salinity, bathymetric, and current speed constraints, for the early-century reference period (2000-04).*
Title/name:	POLCOMS-ERSEM driven Dynamic Energy Budget (DEB)-modelled Pacific oyster growth for the offshore environment
Developer:	Stephanie Palmer, Laurent Barillé, Pierre Gernez (UN): adaptation of spatialized DEB model of Thomas et al. (2016) and selection and mapping of industry-relevant growth indicators of interest; Susan Kay, Stefano Ciavatta (PML): modeling of hydrodynamic biogeochemical (POLCOMS, ERSEM) input data for select future climate scenarios.
Description:	DEB modelling of Pacific oyster growth in the offshore environment throughout western Europe and northwestern Africa, based on POLCOMS-ERSEM-modelled environmental data (SST, chlorophyll-a) for current and two future scenarios (RCP 4.5, 8.5). The tool is a netCDF file of representative daily growth simulated for each of the three scenarios.
Who is the tool designed for?	☒ Aquaculture producers ☐ Regulators ☐ Certifiers ☒ Spatial planners ☐ Other? ____________________
Type of aquaculture:	☐ Marine fish cages ☐ Freshwater fish cages ☒ Shellfish ☐ Freshwater fish ponds ☐ Integrated Multi-trophic aquaculture ☐ Invertebrates ☐ Recirculating aquaculture system

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	☐ Seaweed ☐ Other ____________________
Availability	☒ Available to download or access directly in the Toolbox ☐ Can be accessed via a link to external website/portal • Link: _____[Insert link that will be used in toolbox]_____________ ☐ Would need to be adapted for a new area • Details: ____
Format of the tool:	☐ Flowchart ☐ Decision tree ☐ Guidance document ☐ Spreadsheet model ☐ Standalone computer application ☐ Computer code ☐ Multiple modelling approaches ☐ Large computer model run on supercomputers ☐ Interactive web portal ☒Other __[time series of Pacific oyster growth maps for various climate scenarios]______________
Accessibility	☒ End user has full access to the entire tool. ☐ End user has access to most of the tool and can change all of the necessary settings. ☐ End user has access to limited version of the tool and can change some of the settings. ☐End user only has access to the outputs of the tool, limited options to change settings. ☐ End user only has access to the outputs with no options to change any settings.
Spatial scale of the tool:	☒ International ☐ National ☐ Regional ☐ Waterbody or coastal scale ☐ Farm level
Specificity	☐ Tool can be used anywhere if data is available ☐ The tool can be adapted but may require additional resources to calibrate and ground-truth for new area. ☒ The approach can be adapted but would have to start from the beginning to develop the necessary components. ☐ Tools is specific to an area and cannot be adapted for another area
Cost of tool	☒ Free to use ☐ Free to use but must register to get access ☐ Free to use but requires pay-for software (details:

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(please provide details to explain what costs are)	☐ Single payment • Amount: ______________________________ ☐ Subscription: • Amount: ____ ☐ Not available for purchase but is available as a service • Contact for further details: ____________
Approximate time to collect and process the input data (please provide details to explain what takes the time)	☒ No input data required ☐ Hours • _________________ ☐ Days • _________________ ☐ Weeks • _________________ ☐ Months • _________________ ☐ Years • _________________
Approximate time to use the tool (please provide details to explain what takes the time)	☒ Hours • Simulated growth on a daily time-step is provided; user can make use of pre-defined and pre-mapped indicators, or define and process data using their own (i.e., adjust timings or weight thresholds of interest) ☐ Days • _________________ ☐ Weeks • _________________ ☐ Months • _________________ ☐ Years • _________________
Purpose	☒ Site selection ☒ Scoping ☒ Spatial planning ☐ Optimise production ☐ Licence application ☐ Production capacity assessment ☐ Risk assessment ☒ Stakeholder/community engagement ☐ Early warning system ☐ Ecosystem services ☐ Social licence ☐ Monitoring

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Where does this fit in the licensing process? (only tick the sections that the tool actually would be used in)	☐ ☐ ☐ ☐ ☐ ☐ ☐ ☐
Technical experience required? (be specific)	☐ None ☒ May require use of guidance documents (provided in the toolbox). ☒ Some expertise • Some expertise is required for handling data format (NetCDF)__ ☐ Expert • ____________________________
What resources are needed to use the tool? (include details on the actual resources, e.g. specific software)	☐ Tool is standalone ☒ Software • A NetCDF viewing program and software for reading/manipulating NetCDF output (e.g. SNAP, Matlab, Python, R) is recommended _____________________ ☐ Hardware • _________________________
What are the input data required? (include details on what needs to be collected) (add more rows as needed_	☒ None ☐ Online databases • ____________ ☐ Experimental data • ____________________________ ☐ Fieldwork data • ______ ☐ Data from aquaculture producer • ______________________________ ☐ Earth observation data • __________ ☐ Other • _____________________________
Guidance documents:	The DEB wiki contains more extensive description of DEB theory and tools, and provides links to additional resources and research in the community, including for other species: http://www.debtheory.org/wiki/index.php?title=Main_Page
Academic papers:	Ciavatta, S., Kay, S., Saux-Picart, S., Butenschön, M., & Allen, J. I. (2016). Decadal reanalysis of biogeochemical indicators and fluxes in the North West European shelf-sea ecosystem. Journal of Geophysical Research: Oceans, 121(3), 1824-1845.

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	Ciavatta, et al. (2018). Assimilation of ocean-color plankton functional types to improve marine ecosystem simulations. Journal of Geophysical Research: Oceans, 123(2), 834-854. Kay, S., & Butenschön, M. (2018). Projections of change in key ecosystem indicators for planning and management of marine protected areas: An example study for European seas. Estuarine, Coastal and Shelf Science, 201, 172-184. Thomas, Y., et al. (2016). Global change and climate-driven invasion of the Pacific oyster (*Crassostrea gigas*) along European coasts: a bioenergetics modelling approach. Journal of Biogeography, 43(3), 568-579.
Example of application (case study?):	POLCOMS-ERSEM driven Dynamic Energy Budget (DEB) modelling of Pacific oyster growth in the offshore environment: indicators, regional comparison & selection

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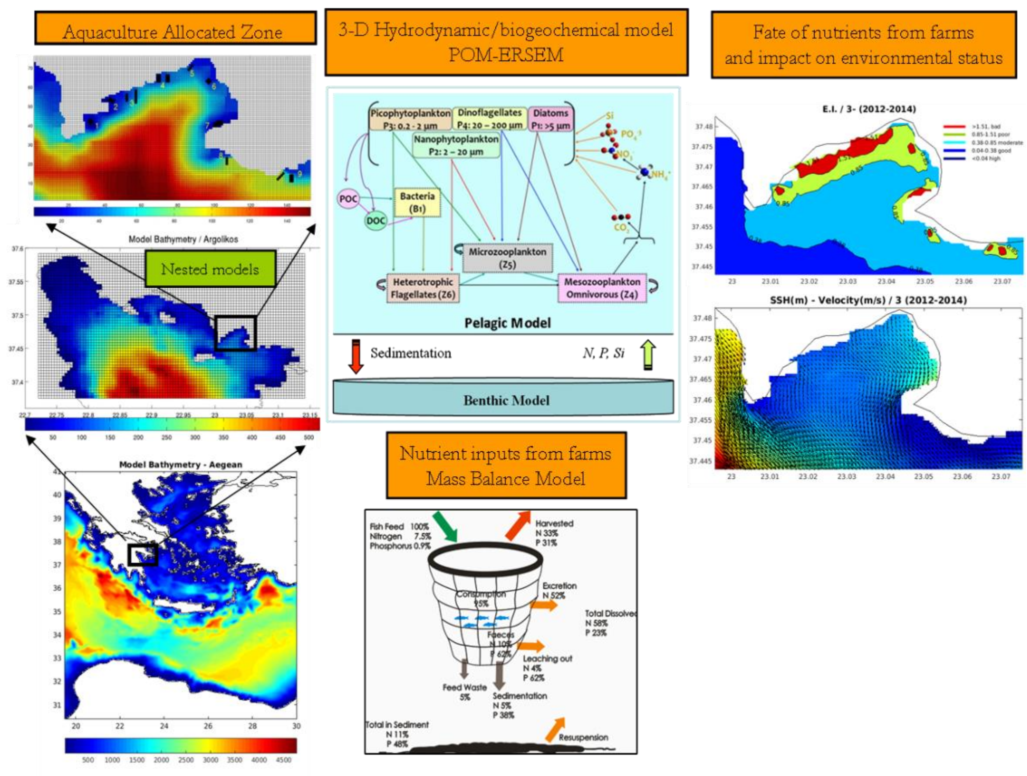
Case Study 4: Aquaculture Integrated Model (AIM) (HCMR)



Title:	Aquaculture Integrated Model (AIM)
Description	A 3-D coupled hydrodynamic/biogeochemical model is used to examine the impact of aquaculture wastes on the environmental status of the area under different scenarios (fish production, changing climate).
Tool(s) applied	☐Yes Type of tool: Guidance and partly interactive tool _______ Link: Other case studies are available in Ecological Modeling Tool in the link of Lifewatch Greece Portal (https://portal.lifewatchgreece.eu/). ☐ No
Who is this case study relevant for?	☐Aquaculture producers ☐Regulators ☐Certifiers ☐Spatial planners ☐Other? ____Research_______________________________________
Topic(s)	☐Site selection ☐Scoping ☐Spatial planning ☐Optimise production ☐Licence application ☐Production capacity assessment

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	☐Environment impact assessment ☐ Risk assessment ☐Stakeholder/community engagement ☐Early warning system ☐Ecosystem services ☐Social licence ☐Monitoring
Type of aquaculture	☐Marine fish pens ☐Freshwater fish cages ☐Shellfish ☐Freshwater fish ponds ☐Integrated Multi-trophic aquaculture ☐Invertebrates ☐Recirculating aquaculture system ☐Seaweed ☐Other ____
Species	☐ Fish ☐Atlantic salmon (*Salmo salar*) ☐ European sea bass (*Dicentrarchus labrax*) ☐ Gilthead sea bream (*Sparus aurata*) ☐ Common carp (*Cyprinus carpio*) ☐ Rainbow trout (*Oncorhynchus mykiss*) ☐ Turbot (*Psetta maxima*) ☐Shellfish ☐ Pacific oyster (*Crassostrea gigas*) ☐ Blue mussel (*Mytilus edulis*) ☐ Mediterranean mussel (*Mytilus galloprovinicalis*) ☐ Manila clam (*Ruditapes philippinarum*) ☐ Seaweeds ☐ ____ ☐Other ____
Location	☐ Inland ☐ Atlantic Ocean ☐ Baltic Sea ☐ Mediterranean Sea ☐ Other ____

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Case study description [Short summary]	**What is the case study approach** The Aquaculture Integrated Model (AIM, Tsagaraki et al., 2011; Petihakis et al., 2012) was used in an Aquaculture Allocated Zone (AAZ) (Argolikos gulf, Greece) to examine the fate of seabass/seabream aquaculture wastes under different scenarios (e.g. fish production, changing climate) and assess their potential impacts on the surrounding ecosystem, in terms of good environmental status. The modelling tool consists of a high resolution 3-D coupled hydrodynamic/biogeochemical model, with a mass balance model (Tsapakis et al., 2006), being used to calculate nutrient inputs from the fish cages, based on fish feed data. A series of nested models is used to consistently downscale the hydrodynamics and biogeochemistry from the coarser resolution (~few kilometres) model of the wider area to the high resolution model (~few tens of meters) of the fish farm area. The model was validated against available satellite (Chl-a) and collected in situ (Chl-a, nutrients, mesozooplankton) data. The tool has been implemented within WP5 (see D5.3) in a hindcast simulation to assess the present (2012-2014) environmental impact of the fish farms in the AAZ and to investigate the system carrying capacity through additional scenarios adopting an increased fish production. The tool was also implemented within WP6 to investigate the potential changes in the AAZ environmental status due to climate changing conditions (i.e. increase of temperature/stratification etc), under future scenarios (RCP4.5 and RCP8.5) for 2030-2050 and 2080-2100 time windows. For these future climate simulations, the model was forced with SMHI climatic atmospheric forcing, while open boundary conditions (temperature, salinity, inorganic nutrients) were obtained from PML Mediterranean basin scale future climate simulations (Kay and Butenschon, 2018), adopting an “anomaly”approach (i.e. multiply .the open boundary conditions of hindcast simulation with a changing factor= future/present, obtained from PML boundary conditions). **What are the outputs** The model produces maps of near surface currents, Chl-a and dissolved inorganic nutrients (phosphate, nitrate, ammonium, silicate) that can be used to calculate environmental indicators (i.e. Environmental Index E.I.; Primpas et al., 2010) describing the environmental status in the area and assess the AAZ carrying capacity. The environmental conditions in the AAZ were found “good” during winter well mixed period and “moderate” to “poor” during summer more stratified periods (see Figure 1). The environmental conditions in the vicinity of different fish farms were found to be correlated to the fish farm production and the predominant current speed, with some fish farms presenting relatively better environmental conditions, despite their high fish production due to the stronger prevailing currents that result in the more efficient off-shore dispersion of fish farm wastes. A scenario simulation, adopting a double fish production was performed, investigating the carrying capacity of the AAZ. An additional increased production scenario was also performed, distributing this increase based on the environmental index variability, thus allocating more production increase in fish farms characterized by better conditions. In this case the deterioration

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	of conditions in fish farms was more balanced, avoiding extremes (i.e. fish farms #3, #4; see Figure 2). Future climate conditions were mostly characterised by an increase of temperature (from +0.4 ^{o}C in 2030-rcp4.5 to +2 ^{o}C in 2080-rcp8.5), resulting in a slight decrease of plankton biomass due to increased metabolism (Figure 3) and an increase of open sea dissolved inorganic nutrients (obtained from the basin scale model). Changes in the environmental status under future climate conditions were relatively small, as compared to present conditions (see Figure 4 & 5) and were related to the combined effect of increased open boundary dissolved inorganic nutrients, the plankton increased metabolism and the effect of changing stratification on the dispersion of aquaculture wastes. **Conclusion** As demonstrated by model outputs, the AIM tool was used to examine the ecosystem effects of fish farm wastes in an aquaculture allocated zone and assess the environmental impact in terms of good environmental status. By means of scenario simulations, the modelling tool was used to evaluate the effect of increasing fish production and assess how much this can be increased without adversely affecting the ecosystem. Moreover, the model was used to evaluate the long-term potential impact of climate changing conditions (temperature, stratification etc) on the environmental status in the aquaculture zone, even though climate change predictions are characterized by significant uncertainty on such local scale. Currently in Greece, aquaculture licensing is mainly based on Environmental Impact Assessment (EIA) studies that usually consider only some limited data in the vicinity of the fish farms (e.g. nutrients, currents) and typically do not ensure a coherent view of the whole ecosystem. AIM simulates the effect of aquaculture wastes, offering a low cost solution, as compared with systematic in situ monitoring, for the evaluation of the environmental status in the surrounding areas. The use of a comprehensive biogeochemical model, such as ERSEM allows investigating the complex food web response, triggered by the nutrient inputs. The high resolution (~50m) of the hydrodynamic model and its progressive downscale through nesting with coarser models allows a realistic simulation of circulation, which is crucial for the correct dispersion of aquaculture effluents. More importantly, the tool can be used by means of scenario (e.g. farm location, production etc) simulations as a management tool for the efficient spatial planning and licensing of new farms or the increase of production for existing farms, considering the area carrying capacity and the overall effect on the ecosystem.
The broader applicability	The modelling system can be relatively easily adapted for other areas. The main prerequisite for the initial model setup is a relatively high resolution bathymetry of the area and initial fields for the hydrodynamic (temperature, salinity) and biogeochemical (dissolved inorganic nutrients) models that are usually obtained from coarser sub-

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basin scale models (e.g. Aegean) and/or existing climatologies. In addition, fish feed data are also required to calculate fish farm wastes. The main limitation of the modelling system is that it is computationally demanding, due to the very high resolution of the near-field model. Therefore, overall the use of AIM as a management tool requires some effort and expertise (scientific for the model output interpretation and technical for the model implementation), but future plans include the dynamic model implementation through a web application that will make this tool more user-friendly.

Other case studies are available in Ecological Modeling Tool in the link of Lifewatch Greece Portal (https://portal.lifewatchgreece.eu/).
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<tr><td>Relevant images or graphics</td><td>

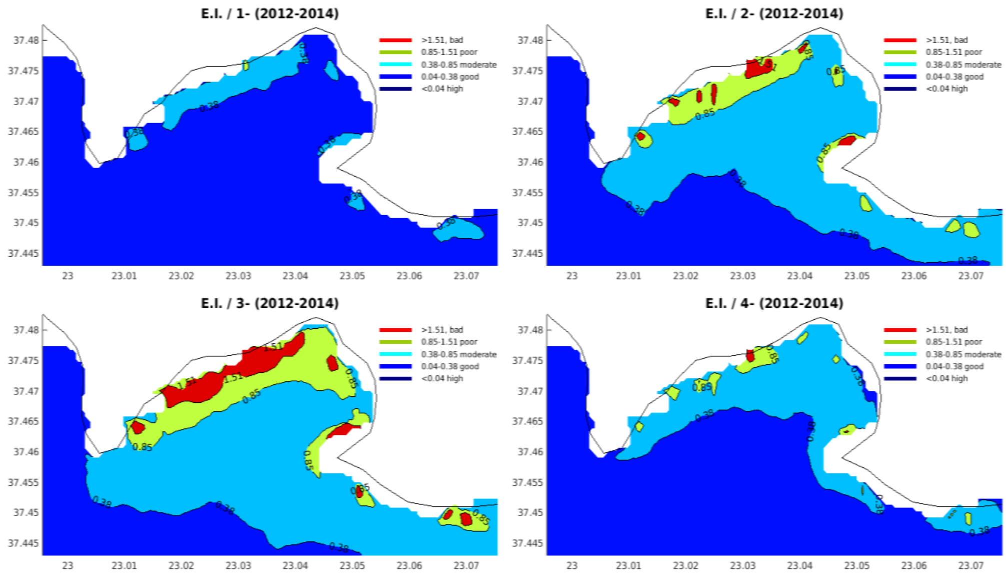

Figure 1: Seasonal variability (1=winter, 2=spring, 3=summer, 4=autumn) of simulated Environmental Index (E.I) over 2012-2014 period.

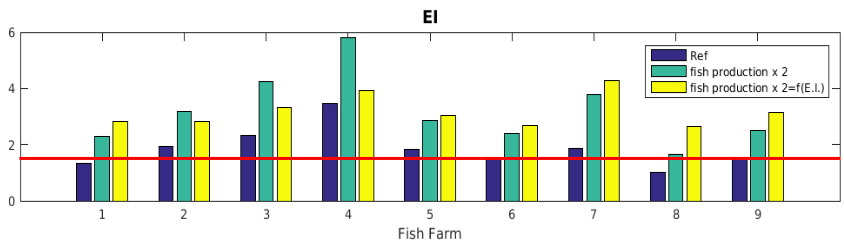

Figure 2: Mean 2013 summer simulated E.I. index in the vicinity of the fish farms with Reference fish production, double fish production and double fish production “optimally” distributed in different fish farms taking into account of E.I variabiliry. The red line indicates the threshold identifying “bad” environmental conditions E.I (1.51) index.
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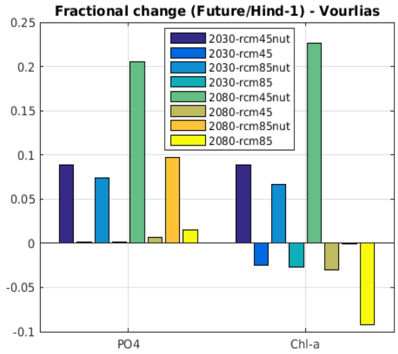

Figure 3: Mean summer fractional change (Future/present-1) of simulated average phosphate and Chl-a under future climate scenarios (2030-2050 & 2080-2100 rcp4.5 and rcp8.5), adopting (temperature, salinity and dissolved inorganic nutrients, e.g. 2030-rcp45nut) or just (temperature, salinity) in the boundary conditions from the basin scale model. The decrease of Chl-a in the second series of experiments is related to the increased metabolism, resulted from temperature increase.

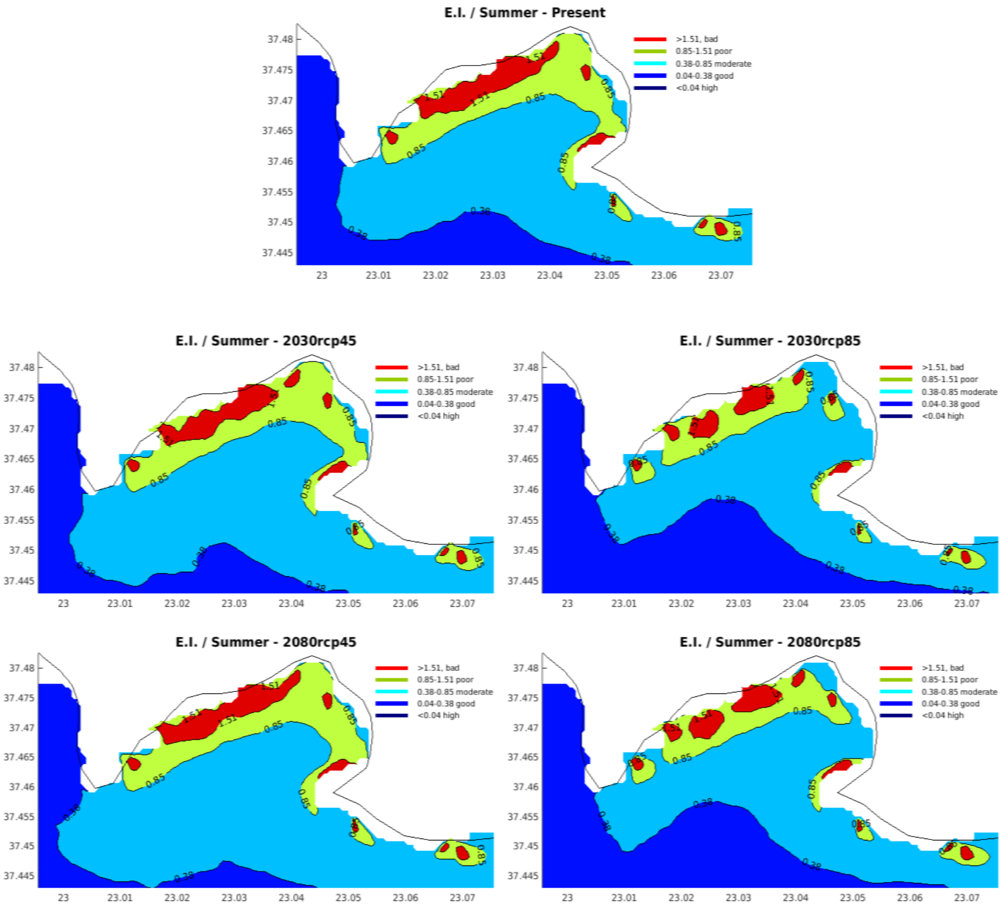

Figure 4: Mean summer simulated Environmental Index (E.I.), under present and future climate (2030-2050 & 2080-2100 rcp4.5 and rcp8.5) conditions.

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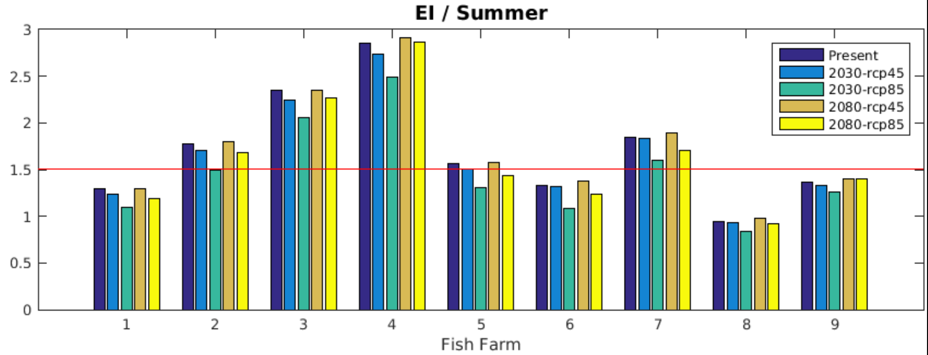

Figure 5: Mean summer Environmental Index (E.I.) in the vicinity of fish farms, under present and future climate (2030-2050 & 2080-2100 rcp4.5 and rcp8.5) conditions.
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<td>Link to published study (if available)</td>
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Kay, S., Butenschon, M., 2018. Projections of change in key ecosystem indicators for planning and management of marine protected areas: An example study for European seas. Estuarine, Coastal and Shelf Science, 201, 172-184.
Petihakis, G., Tsiaras, K., Traintafyllou, G., Korres, Tsagaraki, T.M., Tsapakis, M., Vavillis, P., Pollani, A. and Frangoulis, C. 2012. Application of a complex ecosystem model to evaluate effects of finfish culture in Pagasitikos Gulf, Greece. Journal of Marine Systems, 94, S65-S77.
Primpas, I., Tsirtsis, G., Karydis, M., & Kokkoris, G. D. 2010. Principal component analysis: Development of a multivariate index for assessing eutrophication according to the European water framework directive. Ecological Indicators, 10, 178–183.
Tsagaraki, T.M., Petihakis, G., Tsiaras, K., Triantafyllou, G., Tsapakis, M., Korres, G., Kakagiannis, G., Frangoulis, C. and Karakassis. 2011. Beyond the cage: ecosystem modelling for impact evaluation in aquaculture. Ecological Modelling, 222(14): 2512-2523.
Tsapakis, M., Pitta, P., Karakassis, I., 2006. Nutrients and fine particulate matter released from sea bass (Dicentrachus labrax) farming. Aquat. Living Resour. 19, 69–75.
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<tr>
<td>Contacts</td>
<td>[institution; person (optional); email]
Hellenic Centre for Marine Research (HCMR), Kostas Tsiaras, ktsiaras@hcmr.gr</td>
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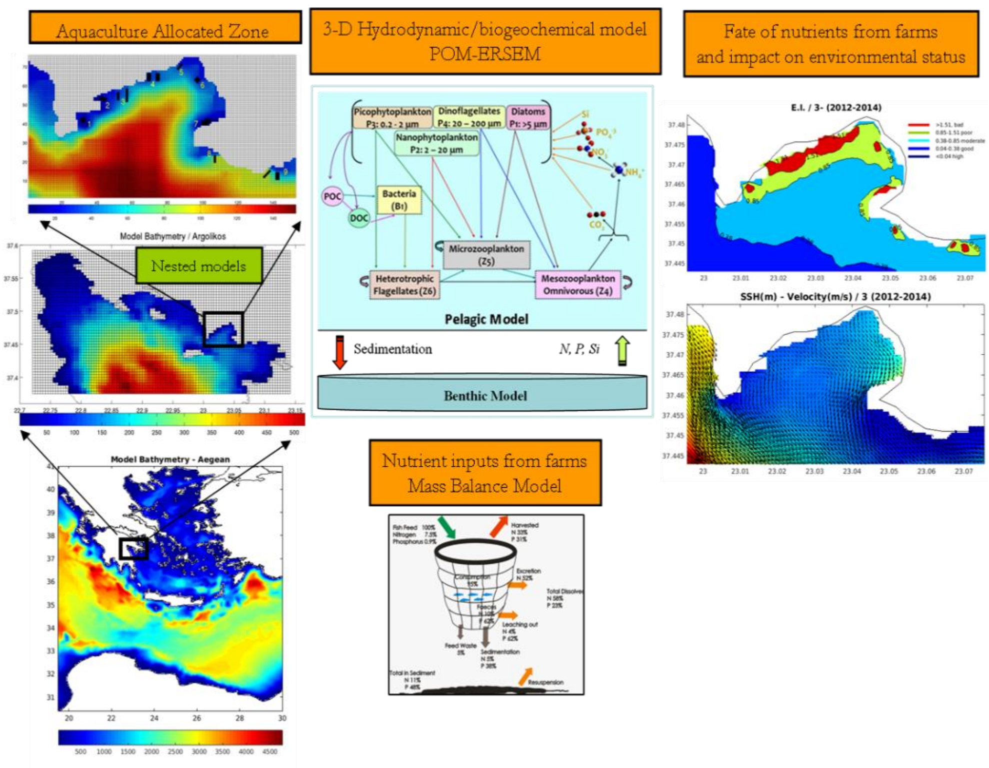
Interactive Tool 4: Aquaculture Integrated Model (AIM) (HCMR)



Title/name:	Aquaculture Integrated Model (AIM)
Developer:	Hellenic Centre for Marine Research (HCMR)
Description:	A 3-D coupled hydrodynamic/biogeochemical model is used to examine the impact of aquaculture wastes on the environmental status of the area under different scenarios (fish production, changing climate).
Who is the tool designed for?	☐ Aquaculture producers ☐ Regulators ☐ Certifiers ☐ Spatial planners ☐ Other? Research
Type of aquaculture:	☐ Marine fish cages ☐ Freshwater fish cages ☐ Shellfish ☐ Freshwater fish ponds ☐ Integrated Multi-trophic aquaculture ☐ Invertebrates ☐ Recirculating aquaculture system ☐ Seaweed ☐ Other ____________________
Availability	☐ Available to download or access directly in the Toolbox ☐ Can be accessed via a link to external website/portal • Link: __________________

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	☐ Would need to be adapted for a new area • The modelling system can be relatively easily adapted for other areas. The main prerequisite for the initial model setup is a relatively high resolution bathymetry of the area and initial fields for the hydrodynamic (temperature, salinity) and biogeochemical (dissolved inorganic nutrients) models that are usually obtained from coarser sub-basin scale models (e.g. Aegean) and/or existing climatologies. In addition, fish feed data are also required to calculate fish farm wastes. The main limitation of the modelling system is that it is computationally demanding, due to the very high resolution of the near-field model. Therefore, the tool application requires some effort and expertise (scientific for the model output interpretation and technical for the model implementation). Future plans include the dynamic model implementation through a web application that will make this tool more user-friendly.
Format of the tool:	☐ Flowchart ☐ Decision tree ☐ Guidance document ☐ Spreadsheet model ☐ Standalone computer application ☐ Computer code ☐ Multiple modelling approaches ☐ Large computer model run on supercomputers ☐ Interactive web portal ☐Other _________________
Accessibility	☐ End user has full access to the entire tool. ☐ End user has access to most of the tool and can change all of the necessary settings. ☐ End user has access to limited version of the tool and can change some of the settings. ☐End user only has access to the outputs of the tool, limited options to change settings. ☐ End user only has access to the outputs with no options to change any settings.
Spatial scale of the tool:	☐ International ☐ National ☐ Regional ☐ Waterbody or coastal scale ☐ Farm level
Specificity	☐ Tool can be used anywhere if data is available ☐ The tool can be adapted but may require additional resources to calibrate and ground-truth for new area. ☐ The approach can be adapted but would have to start from the beginning to develop the necessary components.

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	☐ Tools is specific to an area and cannot be adapted for another area
Cost of tool (please provide details to explain what costs are)	☐ Free to use ☐ Free to use but must register to get access ☐ Free to use but requires pay-for software (details: ☐ Single payment • Amount: ______________________________ ☐ Subscription: • Amount: ____ ☐ Not available for purchase but is available as a service • Contact for further details: • George Triantafyllou, gt@hcmr.gr, Hellenic Centre for Marine Research
Approximate time to collect and process the input data (please provide details to explain what takes the time)	☐ No input data required ☐ Hours • _________________ ☐ Days • _________________ ☐ Weeks • collect necessary data (bathymetry, temperature, salinity, dissolved inorganic nutrients) for the initial model setup from available sources (databases, model outputs etc) and customize for the specific application. Collect available historical data (satellite, in situ) for model validation ☐ Months • To collect and analyze in situ data for model validation ☐ Years • _________________
Approximate time to use the tool (please provide details to explain what takes the time)	☐ Hours • _________________ ☐ Days • _________________ ☐ Weeks • _________________ ☐ Months • Initial model setup, customization, testing and validation • _________________ ☐ Years • _________________
Purpose	☐ Site selection ☐ Scoping ☐ Spatial planning ☐ Optimise production ☐ Licence application ☐ Production capacity assessment

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	☐ Risk assessment ☐ Stakeholder/community engagement ☐ Early warning system ☐ Ecosystem services ☐ Social licence ☐ Monitoring
Technical experience required? (be specific)	☐ None ☐ May require use of guidance documents (provided in the toolbox). ☐ Some expertise Some technical (computer) and scientific expertise is needed in order to apply the tool (run model simulations) and interpret the model outputs. • ___________________________ ☐ Expert • _____________________________
What resources are needed to use the tool? (include details on the actual resources, e.g. specific software)	☐ Tool is standalone ☐ Software Fortran programming language to compile the code • _________________________ ☐ Hardware Computer server to run the model • __________________________
What are the input data required? (include details on what needs to be collected) (add more rows as needed_	☐ None ☐ Online databases • High resolution bathymetry of the area (e.g. Naval service database) • Available historic in-situ data for model validation (e.g. SeaDataNet) ☐ Experimental data • _____________________________ ☐ Fieldwork data • In situ data for model validation (If possible) ☐ Data from aquaculture producer • Fish farm fish feed data_______________________________ ☐ Earth observation data • Available satellite (Chl-a, SST, altimetry) for model validation__________ ☐ Other • ______________________________
Guidance documents:	

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Academic papers:	Petihakis, G., Tsiaras, K., Traintafyllou, G., Korres, Tsagaraki, T.M., Tsapakis, M., Vavillis, P., Pollani, A. and Frangoulis, C. 2012. Application of a complex ecosystem model to evaluate effects of finfish culture in Pagasitikos Gulf, Greece. Journal of Marine Systems, 94, S65-S77. Tsagaraki, T.M., Petihakis, G., Tsiaras, K., Triantafyllou, G., Tsapakis, M., Korres, G., Kakagiannis, G., Frangoulis, C. and Karakassis. 2011. Beyond the cage: ecosystem modelling for impact evaluation in aquaculture. *Ecological Modelling*, 222(14): 2512-2523.
Example of application (case study?) :	Pagasitikos gulf (Petihakis et al., 2012) Cyprus (Tsagaraki et al, 2011)

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