CERES - Climate change and European aquatic RESources

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Report on the species responses to climate-related factors, and their interactions

Includes ready-to use tables

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CERES Project

CERES advances a cause-and-effect understanding of how climate change will influence Europe's most important fish and shellfish resources and the economic activities depending on them. The projects will provide the knowledge and tools needed to successfully adapt European fisheries and aquaculture sectors in marine and inland waters to anticipated climate change. We will identify and communicate risks, opportunities and uncertainties thereby enhancing the resilience and supporting the development of adaptive management and governance systems in these blue growth sectors. CERES strongly supports important European policy goals including self-sufficiency of the domestic supply of fish and shellfish.

This four-year project is designed to:

1. Provide regionally relevant short-, medium- and long-term future, high resolution projections of key environmental variables for European marine and freshwater ecosystems;

2. Integrate the resulting knowledge on changes in productivity, biology and ecology of wild and cultured animals (including key indirect / food web interactions), and 'scale up' to consequences for shellfish and fish populations, assemblages as well as their ecosystems and economic sectors;

3. Utilize innovative risk-assessment methodologies that encompass drivers of change, threats to fishery and aquaculture resources, expert knowledge, barriers to adaptation and likely consequences if mitigation measures are not put in place;

4. Anticipate responses and assist in the adaptation of aquatic food production industries to underlying biophysical changes, including developing new operating procedures, early warning methods, infrastructures, location choice, and markets;

5. Create short-, medium- and long-term projections tools for the industry as well as policy makers to more effectively promote blue growth of aquaculture and fisheries in different regions;

6. Consider market-level responses to changes (both positive and negative) in commodity availability as a result of climate change;

7. Formulate viable autonomous adaptation strategies within the industries and for policy to circumvent/prevent perceived risks or to access future opportunities;

8. Effectively communicate these findings and tools to potential end-users and relevant stakeholders.

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List of symbols and abbreviations

Note: The specific abbreviations used only in figures, are defined in the corresponding figure legend.

DoA	Description of Action
CC	Climate change
T.X.Y.	Task number, for which X is the WP number, and the Y the consecutive task of that WP.
WP	Work Package

Executive summary

This deliverable report provides details on a large, joint effort between T.2.1 (WP2, fisheries) and T.3.1 (WP3, aquaculture) to review parameter estimates needed on direct and indirect effects of climate change (CC) on fish and shellfish for biological projection modelling (T.2.2, T.2.3 and T.3.3). All datasets were transferred to modelers prior to the preparation of this report. These results also serve as inputs to vulnerability assessments (T5.3). In the case of fisheries, the indirect effect of CC on estuaries and on jellyfish-mediated impacts are reviewed, and new data generated from laboratory experiments conducted on bluefin tuna (*Thunnus thunnus*) larvae.

A desktop literature review followed by a systematic literature review and gap analysis was conducted on the effects of key abiotic factors (T, pH, O2, S) on the productivity and distribution of species important to European fisheries and aquaculture. The results indicate that most of the 642 datasets extracted from laboratory and field studies conducted in Europe stem from work in northern regions (Baltic, Barents and North Seas). The category “inland waters fisheries” included the largest number of species and datasets, followed by cyprinids and cultured rainbow trout. For marine aquaculture, over 50 datasets were devoted to Atlantic salmon. The majority of other studies on finfish was research on seabass and seabream in the Iberian Atlantic region and Mediterranean Sea. Data stemming from studies on shellfish were most abundant in the North Sea and Iberian Atlantic regions. In marine fisheries, most studies were conducted on small pelagics in northern areas (herring, sprat) and Atlantic shelf areas (anchovy, sardine). Work on demersal fish focused on cod in northern areas and hake in southern EU waters. The number of studies on large pelagics (e.g., tuna, dolphinfish) was relatively low but larger than those on squids and shrimps.

Temperature has a major influence on all aspects of the physiology and ecology of fish and shellfish, hence much (46%) of the research on abiotic factors has addressed the role of this factor, followed by O_2 (22%) and pH (16%). The responses examined were growth (41%), metabolism (29%) and mortality (25%). The amount of data was insufficient to carry out a detailed analysis of many drivers and responses or a disaggregated analysis by region or species. The results of a separate meta-analysis, however, indicated that increased temperature in summer may drive some fish and shellfish close to or beyond their thermal tolerance limit, and that it is important to include the role of season (and not merely annual means) when examining the potential impacts of warming.

There was a striking lack of information on the effect of combined stressors. This bias exists even within species that are particularly well studied such as salmon, rainbow trout and small pelagics. Species that are difficult to culture have the biggest gaps in data on most life stages. The ability to understand and model the potential effects of climate change is severely hampered by these biases, which require dedicated study in future programmes. The models used in many CERES Storylines must, therefore, largely rely on parameterizations based on data derived from work on other stocks/populations or on closely-related species from non-EU regions. Region-specific information on the responses of fish and shellfish to changes in abiotic factors is important in order to make

robust projections of climate impacts that include the potential adaptive capacity of local stocks/populations.

A review of the impacts of CC on estuarine ecosystems highlights how ecological effects may occur at individual, population and community levels, possibly affecting ecosystem-level productivity and functioning. These changes have the potential to influence marine fishery stocks that depend on estuaries for part of their life stage (as nurseries) and, at the same time, may influence the ecological status and condition of transitional water systems.

A review of the impacts of CC on jellyfish supports the view that local populations are increasing in selected areas globally as well as within some European waters. Food web impacts are likely due to the high rates of prey consumption, growth and reproduction of jellyfish as well as their wide tolerance to ecosystem changes. These rates, tolerances and responses to environmental factors are highly species- and/or population-specific. The extent of blooms and their overlap with commercial fishing operations remains unpredictable and it is challenging to project how climate change will influence impacts of jellyfish on commercial fishing.

Finally, we provide new data on the highly prices Atlantic Bluefin tuna. We found that projected changes in salinity and pH will not likely affect early stage survival. However, previous studies show that temperature will likely exert an effect on the early stages survival of this species.

Introduction

Within the structure of CERES, the initial modelling exercises (WP1) were devoted to cc scenarios delineation and physical-biogeochemical projections. The next step is to produce biological consequences o projections for fisheries (WP2) and aquaculture (WP3) species. Within this aim, this deliverable tackles a first component: providing the necessary (updated) data for the models requiring biological input of the species to be modelled. Therefore, using the information generated in the present deliverable, modelling exercises in Tasks T.2.3 (WP2) and T.3.3 (WP3) will project potential effects of CC in the productivity and distribution of selected species. The focus is to enable modelers to refine their existing tools, which may require additional processes to be incorporated (e.g. functional responses to changes in pH for shellfish models), or an improvement of existing parameterization (e.g. better depict responses to temperature fluctuations). This data provision is made in the form of ready.to-use tables. However, as specified in the DoA, data provided herein has also directly fed into WP5 to serve as a baseline for vulnerability assessments. Therefore, both direct and indirect effects of cc on species are reviewed, combining a suite of analyses that span from short literature reviews of indirect effects, to quantitative analyses of experimental data, or even generating some key new data. The deliverable is a joint effort between WP2 (fisheries) and WP3 (aquaculture), so that T.2.1 and T.3.1 are merged into this deliverable. In the case of fisheries, the indirect effect of climate change on estuaries and on jellyfish-mediated impacts are reviewed. Further, the results of the only fisheries species for which experiments were conducted, the Atlantic bluefin tuna (*Thunnus thynnus)*, are provided. The experiments conducted in aquaculture will be provided in Deliverable 3.2. Useful data for modelling purposes are also stored in tables for direct use of modellers. This data are stored at the CERES portal (see Appendix1).

Defining the Challenge

The main challenge was to collect and analyze direct as well as some indirect effects (for fisheries) of climate change on the main living aquatic resources (fish and shellfish) examined in CERES. Second, ready-to-use tables were provided to modellers to update/tune existing or newly-developed models for marine and freshwater fisheries or aquaculture species. The challenge was very demanding due to the high number of species of interest and the widely differing requirements of the various types of projection models types used in CERES.

Approach

The approaches, including both reviews and data-analysis, have involved most partners in the consortium. The main focus has been placed on compiling and transferring (to WPs and Tasks demanding it) relevant information on direct effects of climate-driven changes in physical/abiotic factors on productivity via physiology, e.g. effect of increased average temperature, acidification and hypoxia on growth, or extreme temperatures on survival.

In a first phase (first 6 months), previously compiled, extensive data sets on the physiological limits of species to multiple stressors as well as spatiotemporal abundance of species in nature were expanded using a desktop review.

The disparity of available information and formats required an alternate compilation of information based on needs of biological models tailored for priority species. This somewhat reduced list of species was agreed upon by partners in WP2 (fisheries) and WP3 (aquaculture). Only information needed for projections in T2.3 and T3.3 or as direct input to WP4 and WP5 was compiled. Biological modellers in WP2, WP3 as well as partners responsible for activities in Task .5.3 were specifically asked to supply information on the species and kinds of variables needed. Focus was placed on species considered across all aspects of the project.

Following the desktop review of existing data, a tailored search was conducted using a combined approach of partner contributions (particularly grey literature) and a systematic literature review on 33 species. The latter enabled a more sophisticated analysis of the data. The compiled data were analysed through a gap analysis in terms of available information on CC related variables (e.g., temperature, oxygen, pH, and their interaction) on distribution (latitudinal shifts etc.) or productivity (growth, reproduction, mortality). All species groups were explored in both northern and southern European regional seas except for flatfish (North Sea only). Data on the movement of fish stocks in high latitude areas (between arctic and subarctic waters) were also compiled.

Indirect effects of CC on essential habitats (e.g. estuarine nursery areas), and the effect of various impacts of jellyfish blooms on fish species, including the implications for food webs were reviewed. Targeted experiments were conducted to plug important knowledge gaps on the biology and impacts of CC on bluefin tuna early life stages. The aim was to improve the mechanistic understanding of how multiple factors (direct and direct) interact to influence vulnerable life stages.

Contribution to the project

The results from this deliverable are, together with scenarios and physical-biogeochemical projections and hindcasts provided in WP1, the fist steps towards setting the stage for analysing CC effects on EU fisheries and aquaculture. The data and knowledge supply are used to update existing models, and even help building new ones, to i) project climate change effects on the productivity and distribution of economically relevant aquatic species, and ii) enable an adaptation of fleets/production methods to the impacts to come, or identifying mitigation methods. The present deliverable contributes to tools and a list of planning options for fishing fleets based on climate-driven bioeconomic drivers (WP2, WP4), as well as farm-scale ecological and economic models to support aquaculture production scenarios for different key species (WP3 and WP4) and to analyse the environmental sustainability of different development options. The data that are not used within T.2.2, T.2.3 and T.3.3 for projecting CC effects on the biology/ecology of the selected species, will be directly used in WP5, for analysing the vulnerability of some species for which the degree of knowledge is scarce.

Dissemination and Exploitation

The results covered in this deliverable are being published in several journals. Several reviews have already been published within CERES on the effect of jellyfish on fisheries and on the indirect effect of CC on estuarine fishes. One manuscript is being prepared on the available knowledge of physiological CC effects on EU species of interest for fisheries and aquaculture, and another one on Bluefin tuna responses to varying controlled conditions. All published works are available at CERES web. Further, many communications related to this deliverable are also available at the web.

The structure of the database and the type of variables gathered have been shared with the "sister" H2020 project (funded under the same call) ClimeFish (Co-creating a decision support framework to ensure sustainable fish production in Europe under climate change).

Chapter 1. Objectives, general *development of the review process and data delivery*

We developed a review process that was tailored to the needs of the CERES project. First, a search for available databases from which data can be extracted for Tasks 2.2, 2.3, 3.3 and WPs 4 and 5 was conducted **(Chapter 2**). Then, specific data was collected, processed and made available in Chapters 3 and 4. It was divided into the analysis of **direct (Chapter 3)** and **indirect (for fisheries only) (Chapter 4)** effects of climate change, and included tables of data to be used by partners. The process was harmonised so that data from WP2 and WP3 were not only collected in a similar way but also analyzed in a comparable terms. The indirect effects for Aquaculture are presented in another deliverable (D.3.2).

Survey of existing databases

Existing databases on i) physiological responses of fish and shellfish to CC stressors and ii) databases containing long-term time series of distribution, abundance or catches, to be further explored in other tasks, were identified and tabulated. Due to the very different range of formats and data collected, and given the PM distribution among partners, we adopted a strategy of necessity-based data collection based on partner's contributions, model-based species selection and specific analyses on selected species (see further).

Direct effects analysis and compilation of tables

First, a coordinated effort between T.2.1 and T.3.1 (fisheries and aquaculture review teams) contacted the modelling teams in order to identify key variables and species to be updated/included in the models. This step was necessary to optimize the efforts in reviewing process and data provision. These requirements were summarized in one excel file for Fisheries (T.2.1) and one for Aquaculture (T.3.1). These tables were completed by partners and these, along with instructions explaining them, were put in the CERES internal portal at project month 12 for the use of modellers. The tables can be found at the CERES Teamwork platform under the name in **Appendix 1**. This was the major contribution to **Milestones 15 and 16**, delivered on time on month 12.

Due to the diversity of models and potential variables needed, a large number of variables were included in the tables: A total of 74 core variables were available for the EXPERIMENTAL table, and 53 for the FIELD table, plus 17 describing metadata (first spreadsheet in each table). A protocol with instructions to complete the tables was developed (**Appendix 2**) and distributed between the partnership together with templates for the compilation tables (month 3). For each species, four life stages were considered: egg-larvae, juvenile, adult and spawning adult. Besides the environmental factors (stressors) and biological responses, the source of the information, the reference and the contact person were annotated. Also, in the case of unpublished data from a partner, the data availability for the project was requested. To assure quality and comparability of data collected for the literature review of CERES, we used a series of inclusion criteria according to the PICO (Participants, Interventions, Comparators and Outcomes) (Bettany-Saltikov,

2012) principle for systematic reviews. Quality assessment was conducted by each participant contributing to the data compilation regarding replication (replication, appropriateness of replication, allocation of replication (randomized, haphazard, etc.) as well as other confounding factors potentially influencing data quality (**Appendix 2**).

After reviewing the quality of the collected data, it was clear that a conventional literature review was impractical. A corrective action was launched by the task leaders so that only the most relevant information was included. This involved the conduction of a **systematic literature review** on 33 key species from aquaculture and fisheries (from both marine and from inland waters, Table 1). This review was conducted by a sub-group of partners (CSIC, UHAM, IEO, DLO, UHULL) and was used for conducting a **Gap analysis** (together with the partner-collected data) and a quantitative analysis of CC-effects, in the form of a **Meta-analysis** (only on experimental data). The Gap analysis is presented in subchapter 2.1, and the meta-analysis in subchapter 2.2. Both approaches offer a picture of the current status of direct CC-induced effects on EU aquatic living resources, and more in-depth analyses are in the process of publication. Additionally, the interaction with the modellers in T.2.3 identified, amongst other needs, the necessity to compile the variability of the Von Bertalanffy growth parameters and length-weight relationships even if environmental data were not included in the published works. For that reason, a small team within PML compiled this information (Appendix 3).

Indirect effects analysis

Two exercises analysing the indirect effects of CC on aquatic living resources were conducted. First, the indirect effects of CC **on Estuaries and its associated species** was analyzed by UHULL (Subchapter 4.1). Second, the direct and indirect effects of CC on **jellyfish blooms** and the impact of the later in European fisheries/aquaculture were reviewed by CONISMA (Subchapter 4.2).

Chapter 2. Identification of Useful Databases

An initial desktop review was conducted in order to identify the types of data available. For aquaculture, onr of the main resources was the online 'WATER', which enables the exploration of suitability maps for culture of up to 35 species in Europe based on physiological and environmental constraints (Table 1). Field data available from several databases were identified as Key for the project, including those publicly available from ICES areas e.g. (DATRAS, Eggs and Larval Surveys from ICES Dataportal, or CEFAS such as DAPSTOM (Pinnegar 2014). Many of these data are available online for inferring field changes in distributions or production in relation to CC, and some have been deeply analyzed within this context (Rijnsdorp et al. 2010). From an inspection of the ICES dataportal, 16 time-series of 11 key species for CERES were detected (Fig.1).

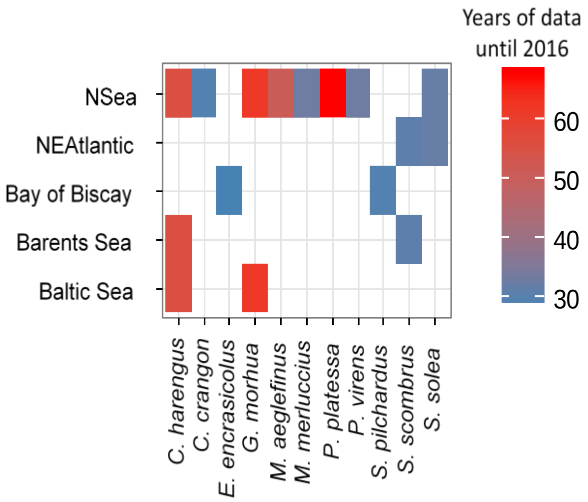


Figure 1. Example of data availability with respect to field surveys for some species of CERES

These data can be used for deriving empirical relationships in statistical models or to ground-truth or tune the hindcast outputs of models. Further, they can be explored within T.2.2. For the Mediterranean Sea, field/fisheries data availability comes mainly from the FAO GFCM portal http://www.fao.org/gfcm/data/ and includes data on production from 1970-2014 for both commercial and artisanal fisheries as well as stock assessments from 25 species. These data can be accessed generally online or upon request. Physiological databases were also consulted, some of them from EU projects (e.g. COST actions, Table 1), which provided a perspective on the amount of data available. As stated in Chapter 1, within CERES it was decided to adopt an approach of partner-participation in order to generate the available data to be used for specific modelling purposes.

Table 1 Key resources for CERES modelling studies that can be used within the frame of fisheries and aquaculture modelling

Database	Organisation	Type of Data	Area	Data frame	Main Document	Species of interest for CERES	Access
WATER	Longline Environment	integrates diverse datasets on 35 commercial species, pairing environmental and species parameters, to provide powerful analytics for aquaculture	EU waters			Rainbow trout, pike perch, Oysters, Mediterrranean mussel, meagre, manila clam, gilthead sea bream, sea bass, eel, sole, carp, salmon, Bluefin tuna	http://34.214.131.178/
COST2014	UHAM	Physiological effects of CC-related stressors such as temperature, pH or	EU waters	NA	Database	All cyprinids, small pelagics, demersal fish and cultured fish dealt with in CERES	On request
DAPSTOM	CEFAS	Stomach content from 449 cruises.	Greenland to	1864-2011	(Pinnegar 2014)	Herring, mackerel, blue	Free, online

			Spitsbergen, and Bay of Biscay to Arctic			whiting, Bluefin tuna	https://www.cefas.co.uk/cefas-data-hub/fish-stomach-records/
DATRAS	ICES	Trawl Surveys, most relevant scientific data	Baltic Sea, Skagerrak, Kattegat, North Sea, English Channel, Celtic Sea, Irish Sea, Bay of Biscay and the eastern Atlantic from the Shetlands to Gibraltar	Las 45 years		All demersal species from ICES areas	Free online, through ICES "DATA Portals". http://www.ices.dk/marine-data/data-portals/Pages/DATRAS.aspx
Arctic Legacy	CEFAS	Arctic cruises ; catch species, weight/number, length, stomach contents, plus hydrography.	Barents Sea	1930-1959	NA	Cod	On request
Tagged Fish Database	CEFAS	Information over 50 000 returns	Latitude: 62.5° to 48° Longitude: -12° to 9°	1940-2015	(Burt et al. 2006)	Over 40 species	On request
Landings database, Mediterranean	FAO	Capture production statistics	Mediterranean	1970-2015. Depending on the species		All Mediterranean species covered in CERES	http://www.fao.org/gfcm/data/

Chapter 3. Direct effects of Climate change

Sub-chapter 3.1. Gap analysis

Introduction and objectives

A Gap analysis is a technique used to determine what steps need to be taken in order to move from the current state to the desired, future state. It consists of 3 steps: 1) listing of characteristic factors of the present situation; 2) listing factors needed to achieve future objectives; and 3) highlighting the gaps that exist and need to be filled. We adopted this approach in order to identify mainly what is available at the time of CERES start and what is needed. The initial identification of needs, which we detected in a graphical analysis, was partly used to fine-tune the experiments conducted within CERES.

Procedures

The species included in the analysis are specified in Table 2. The correspondence to the storylines (combinations of species, regions and exploitation patterns) is also specified in Tables 2 and 3.

Table 2 Species surveyed in the Gap analysis. Those for which a systematic review (only for experimental studies) was conducted are depicted with a cross. Storyline numbers are also specified (See Table 2)

Inland Waters	Systematic	Storyline	**Marine Aquaculture**	Systematic	Storyline	**Marine Fisheries**	Systematic	Storyline
Ciprinids			Finfish			Demersals		
Cyprinus carpio	x	3	*Dicentrarchus labrax*	x	13,14	*Pleuronectes platessa*	x	22
Leuciscus cephalus	x	3	*Salmo salar*	x	11	*Solea solea*	x	22
Leuciscus leuciscus	x	3	*Sparus aurata*	x	13,14	*Melanogrammus aeglefinus*	x	20
Inland Fisheries			Shellfish			*Micromesistius poutassou*		20
Abramis brama	x	4	*Ruditapes decussatus*	x	9	*Merluccius merluccius*	x	26
Alosa alosa	x	4	*Ruditapes philippinarum*	x	9	*Gadus morhua*	x	16,18,20
Alosa fallax		4	*Mytilus edulis*	x	5	*Mullus barbatus*		
Anguilla anguilla	x	4	*Mytilus galloprovincialis*	x	7	Large pelagics		
Carassius gibelio		4	*Crassostrea angulata*		6,8	*Thunnus thynnus*	x	27
Coregonus	x	4	*Crassostrea gigas*	x	6,8	*Coryphaena hippurus*	x	23
Coregonus abula		4	*Ostrea edulis*	x	6,8	Small pelagics		
Coregonus lavaretus	x	4				*Sprattus sprattus*	x	15,17,19
Coregonus lavaretus	x	4				*Clupea harengus*	x	15,17,19
Coregonus oxyrinchus	x	4				*Engraulis encrasicolus*	x	24,25
Coregonus clupeaformis		4				*Sardina Pilchardus*	x	24,25
Esox lucius	x	4				*Scomber scombrus*	x	21
Rutilus rutilus	x	4				Shrimps and squids		
Salmo trutta		4				*Parapenaeus longirostris*	x	
Sander lucioperca	x	4				*Loligo vulgaris*	x	
Sander volgensis		4						
Menydia berylina		4						
Trout culture								
Oncorhynchus mykiss	x	1,2						

Table 3 Description of the storylines that have been finally selected within the project as best examples of the combination of species, regions and exploitation regimes. The partners involved are specified.

Storyline	Partners
1. Rainbow trout NW Europe	TI-SF-LLE
2. Rainbow trout E. Mediterranean	MEU/KIL
3. Carp and associated species NE Europe	ICR, ZUT, LLE
4. Inland fisheries Europe	UHULL
5. Mussels North Sea	DTU.Aqua, DLO, LLE
6. Oysters North Sea	DLO, LLE
7. Mussels S. Atlantic coast.	SGM
8. Oysters S. Atlantic Coast	IPMA/SGM
9. Clams S.Atlantic Coast	IPMA/SGM
10. Mussels Mediterranean	CSIC
11. Salmon NE Atlantic	NUIG, VAI, LLE, IMR
12. Meagre S. Atlantic	IPMA
13. Sea bream/Sea bass W. Med and S Atlantic	IEO, IPMA, LLE
14. Sea bream /Sea bass E. Med	MEU with KIL/LLE
15. Pelagics-clupeids&osmerids in Barents and Norwegian Sea	IMR
16. Cod in Barents and Norwegian Sea	IMR
17. Pelagics-clupeids in the Baltic Sea	DTU-Aqua
18. Gadoids (cod) in the Baltic	DTU-Aqua
19. Pelagics in the North Sea-NE Atlantic	PFA
20. Gadoids, North Sea	PML, TI-SF, PFA
21. Pelagics, Mackerel, North Sea and NE Atlantic	TI-SF,PFA
22. Flatfishes, North Sea and NE Atl.	DLO (WUR), VisNED
23. Dolphinfish, W Mediterranean	CSIC
24. Pelagics-clupeids/engraulids-Bay of Biscay	IFREMER
25. Clupeids/engraulids, NW Mediterranean	CSIC
26. gadoids, E Mediterranean	HCMR
27. Bluefin tuna, NW Mediterranean	IEO

The Gap Analysis was aimed at identifying the current status of the knowledge on direct effects of CC on important species of commercial interest in the EU. For the experimental studies, two sources were combined: data from papers found during the systematic literature review following Appendix 4 and data provided by the partners following Appendix 2). Duplicated datasets were eliminated. Broad categories were re-coded for the analyses. The main factors to be explored graphically were storyline sector (Marine Aquaculture, Marine Fisheries, Inland Waters), geographical region (e.g. Barents and Norwegian Seas, Baltic Sea, etc.), storylines (See Table 3), ecological group (marine pelagic, marine demersal, shellfish, etc., see figures), species and stage (embryo (egg and non-feeding larvae), feeding larvae, juvenile, adult). In some cases, some categories were analyzed together, if the studies were conducted over a continuum of stages (e.g. measuring the effect of temperature on the growth along the non-feeding and feeding period). Abbreviations within figures are explained in the figures. All graphs are presented so that a comparison across factors and between sectors can be made. For the Field studies (mainly fisheries), graphs are presented separately.

Main results

In total, 642 independent datasets were collected either from partner's contributions or from the systematic literature review in similar proportions. This number was obtained once the duplicates were eliminated from the dataset coming from partner's contributions (Fig. 2. Around 400 datasets were almost equally split between marine aquaculture and marine fisheries, whereas approx. 250 corresponded to inland water studies. The largest number of species corresponded to inland waters and marine fisheries, with less species compiled for marine aquaculture.

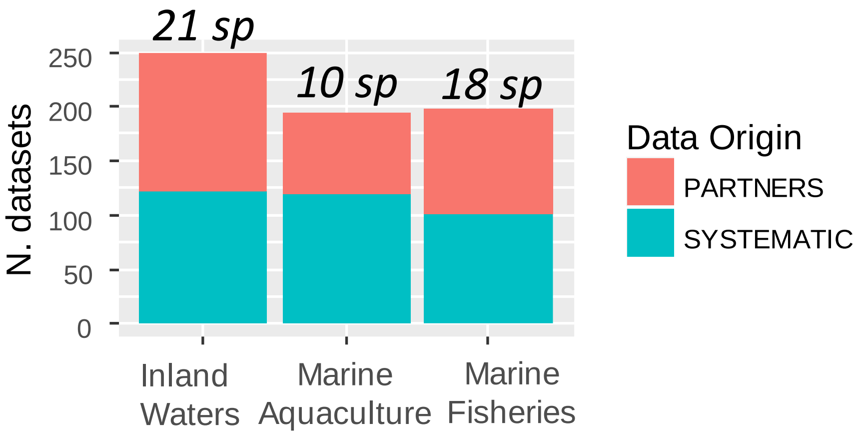


Figure 2. Distribution of the 642 independent datasets into sector groups. PARTNERS, data provided by partners through their contribution. SYSTEMATIC, data were extracted for a selected group of species using the systematic approach. The number of species (SP) in each block is indicated.

A gross division into species groups, sectors and European regions showed that most information has been generated in northern regions (Baltic Sea, Barents and Norwegian Seas, NE Atlantic Shelf and North Sea and Mediterranean Sea, inland waters - Fig. 3). Within inland waters, the general category "inland waters fisheries" registered the largest number of species and datasets studied, followed by cyprinids and rainbow trout (mostly cultured). For marine aquaculture, over 50 datasets were devoted to the study of salmon. The bulk of other studies on finfish corresponded to sea bass and sea bream in the South Atlantic and Mediterranean. Shellfish studies were abundant in the North Sea and South Atlantic EU regions. In marine fisheries most studies corresponded to small pelagic species in northern areas (herring, sprat) and mid-southern areas (anchovy, sardine). The number of studies on demersal fish was highly focused on cod in northern areas and hake in southern zones. The number of studies on large pelagics (tuna, dolphinfish) was reduced, whereas that on squids and shrimps was even more scarce.

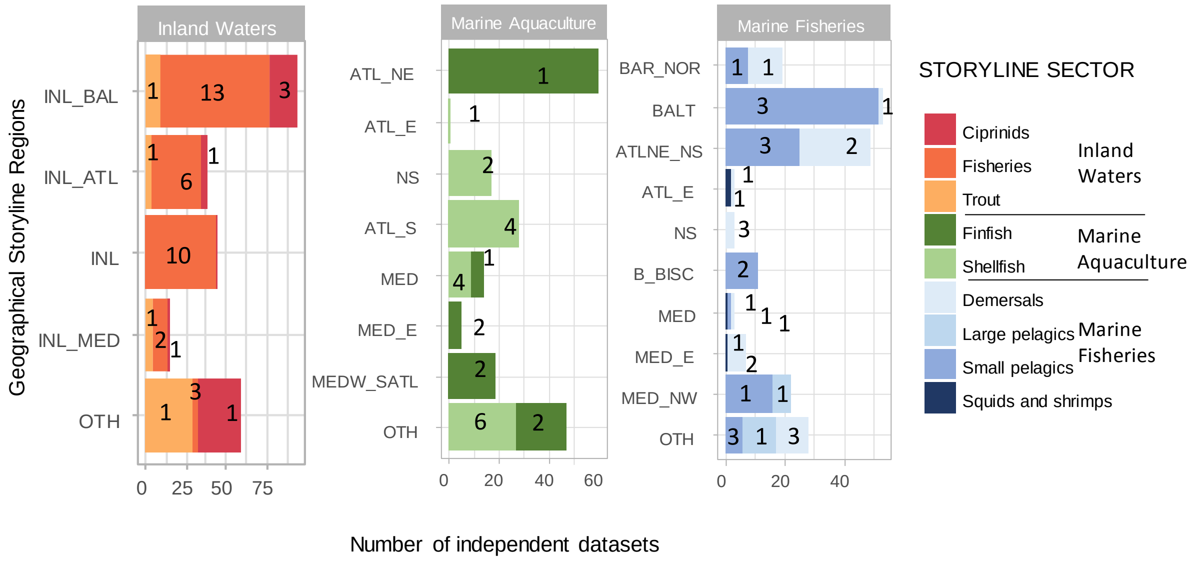


Figure 3 Number of independent datasets in D.2.1 for each broad sector (Inland waters, Marine Aquaculture and Marine Fisheries), storyline geographical region (y axis), and specific storyline sector (color bar). Numbers are species numbers. ***Regions**: BAR_NOR, Barents and Norwegian Sea; BALT, Baltic; ATL_NE, North East Atlantic; ATLNE_NS, North-East Atlantic/North Sea; ATL_E, East Atlantic; NS, North Sea; B_BISC, Bay of Biscay; ATL_S, South Atlantic; INOTH, Other Inland data; INL, European Inland Waters; MED, other Mediterranean areas; MED_E, Eastern Mediterranean; MED_NW, North-Western Mediterranean; MEDW_SATL, western Mediterranean-South Atlantic; OTH, Other regions*

A general view on the experimental studies indicates that there is a large bias in the knowledge on direct CC-related effects on fish and shellfish (Fig. 4). The vast majority of the datasets analyze the effect of a single stressor, mainly temperature, on growth and/or development. The second response in terms of analyses (driven by temperature) is physiology (usually some form of metabolic rate measurement), followed by mortality. Studies on the effects of pH, salinity or oxygen are second in number, with the main responses being growth/development, mortality and physiology. The effect of combined stressors such as pH x temperature is rarely studied. Most species categories are represented in the experimental studies of thermal impacts (Fig. 4). However, large bias exist on particular groups when other CC related drivers are examined. More importantly, many key responses are almost absent from the experimental literature, including effects on tolerance limits (for most drivers) in most groups. Details for specific analyses by storylines (species within regions) are provided later.

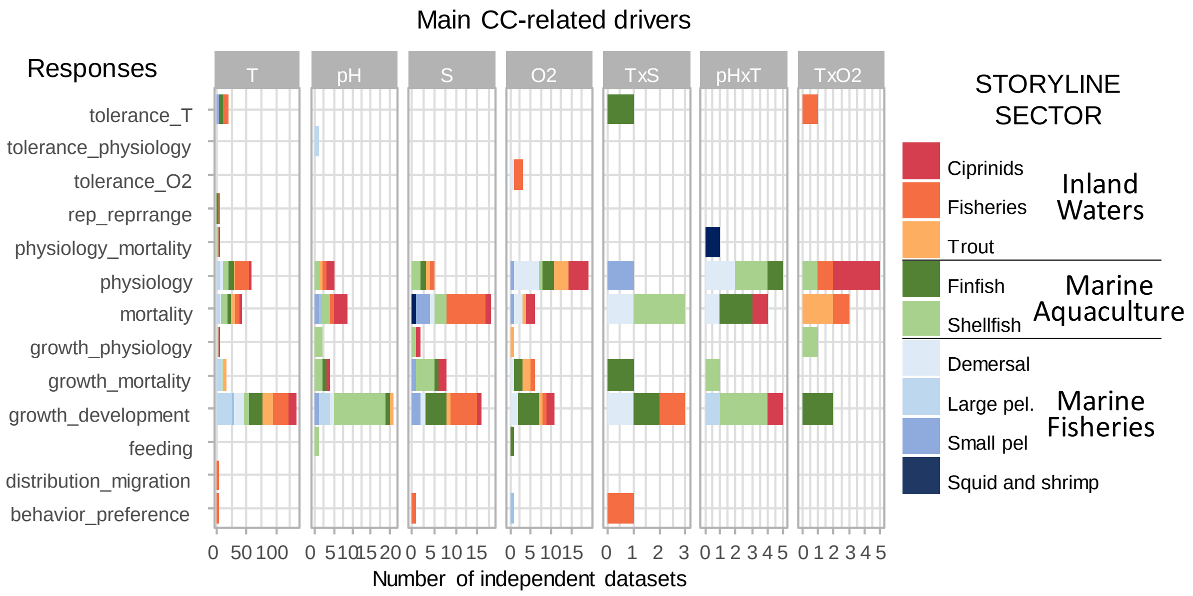


Figure 4 Experimental studies. Number of independent datasets generated in D.2.1 divided by the effect of selected drivers on responses (Y axis) for specific storyline sectors (color bar). Sectors descriptions as in Fig.2. Here, the "x" in the drivers indicates that interaction is accounted for. The response variable "physiology" embraces usually metabolic rates of different types. In the responses, the underscore symbol indicates that both responses are studied, but interaction is not considered. Specific terms needing clarification are: responses preceded by "tolerance", are tolerance measures to the respective driver. "rep_reprange" stands for studies on reproductive variables or reproductive range.

A similar analysis conducted over field studies also showed a large bias (Fig. 5). The effect of temperature on growth/development is again the most studied combination. Other responses such as distribution/migration or reproduction effects are also important. The groups involved in this analysis are mainly small pelagics and cyprinids, and few species also used in aquaculture. However, these data are less reliable as a data provision could not be properly revised and may be incomplete.

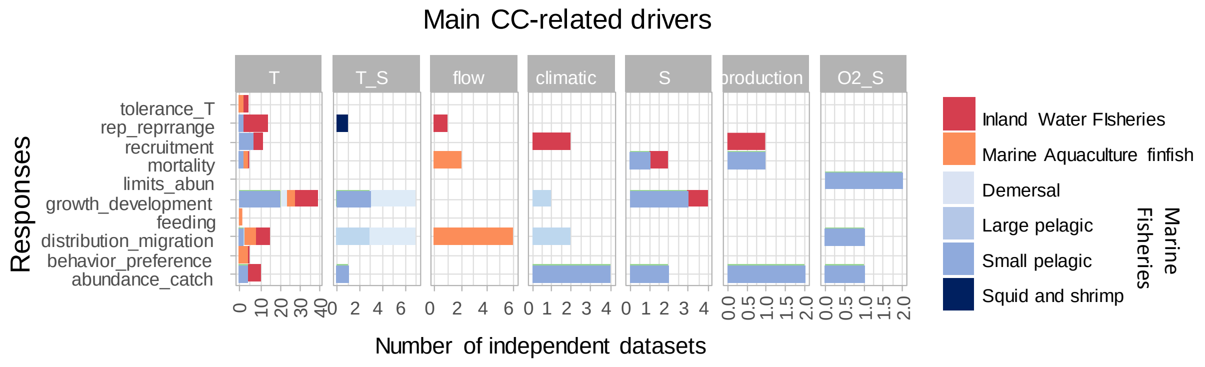


Figure 5 Field studies. Generated independent datasets from field studies in the sector of marine and inland water fisheries. In the drivers, the underscore symbol means that both drivers have been studied in the same dataset. See Fig. 3 for further explanation of the responses.

A more detailed inspection of driver vs. responses by sector showed similar patterns between inland waters and experimental studies in marine fisheries and marine aquaculture (Fig. 6). The research focus on the effect of temperature on growth and development is common across sectors. Furthermore, well-studied responses to temperature are physiology and mortality in all sectors. In marine aquaculture, pH and salinity also tend to be studied as drivers of growth, development or mortality, whereas in Inland waters and marine fisheries, oxygen effects receive a relatively higher attention compared to pH. This is probably due to the aquaculture interest for the aforementioned factors in order to maximize growth and survival.

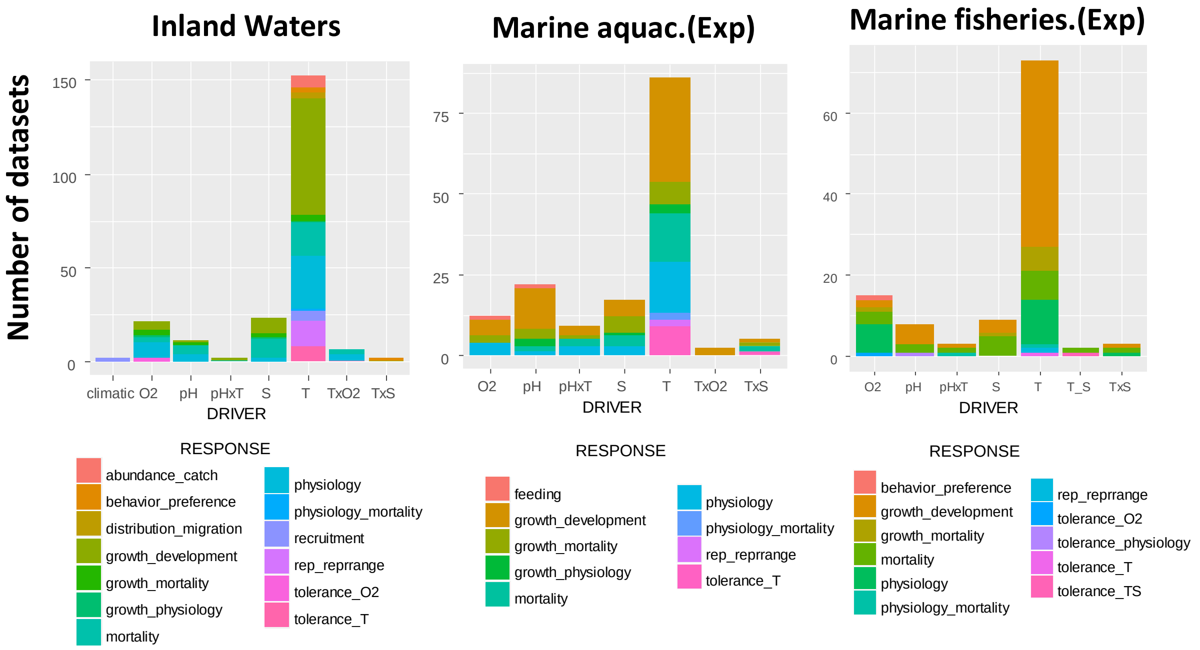


Figure 6 Number of independent datasets by sector (Inland Waters, Marine Aquaculture and Marine Fisheries), CC related DRIVER (e.g., pH) and RESPONSES measured. The responses separated by an underscore mean that both responses are measured. Only experimental studies are included for Marine aquaculture and fisheries.

Classification of experimental studies by life stage indicates marked differences between sectors. Juvenile and adult stages are most studied in inland waters and marine aquaculture, followed by either embryonic or feeding larvae. On the contrary, embryonic stages are targeted preferentially by experimental studies in marine fisheries targets (Fig. 7). Within inland waters, most studies were conducted in the inland fisheries storyline (e.g., eels, pike, several cyprinids) and rainbow trout. Marine aquaculture experimental studies concentrate on salmon (embryos and juveniles) although there is a good representation of clams (in Atlantic waters) and mussels from different regions. Additionally, a number of studies have been performed on sea bass/sea bream in the Mediterranean Sea and Atlantic waters. In marine fisheries, most studies correspond to clupeids (Baltic, NE Atlantic) or flatfishes in the North Sea/ NE Atlantic. In general, information from non-EU regions exists on storylines of interest (classified as “others” in Fig. 7) that can be of importance for modelling purposes.

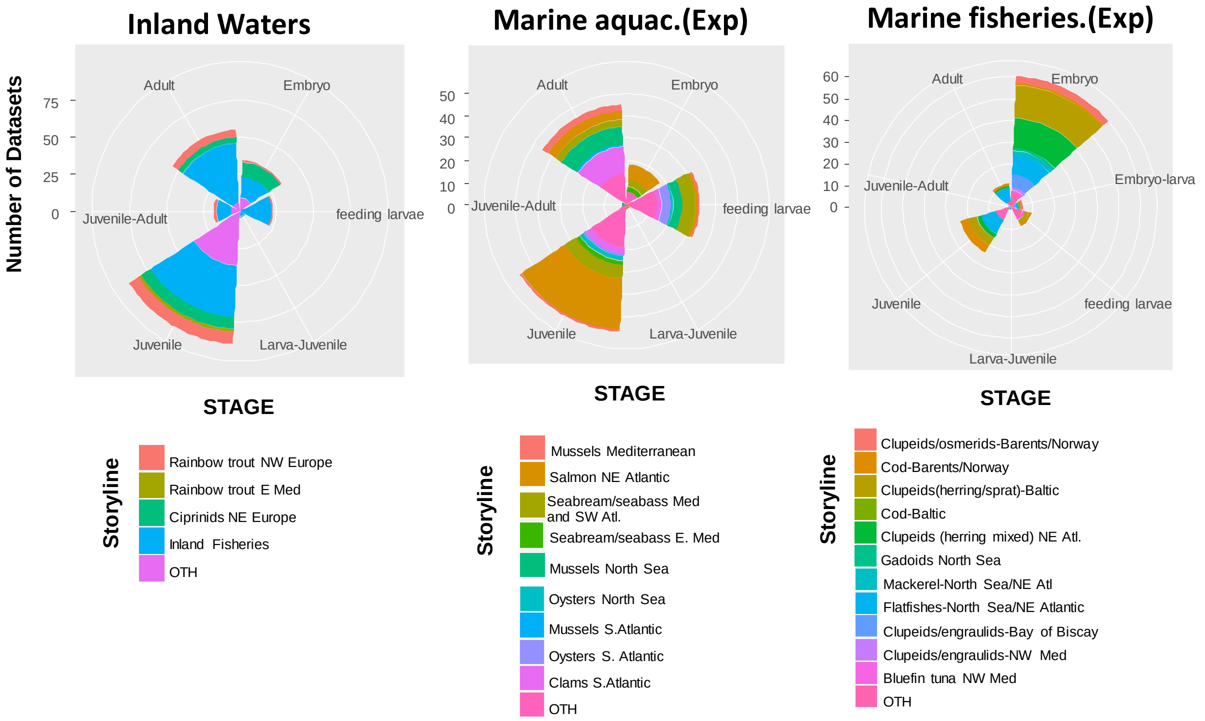


Figure 7 Number of independent datasets by sector (Inland Waters, Marine Aquaculture and Marine Fisheries), STAGE (Adults, Embryos (eggs and non-feeding larvae), feeding larvae, larvae-Juvenile (mixed in the experiments), Juveniles and Juvenile-Adults (mixed in the experiment)) and Storyline (defined in the color codes as a combination of species or group, and region. Only experimental studies are included for Marine aquaculture and fisheries. OTH, are studies from storyline species but from outside Europe.

Comparing the data available from field studies, some commonalities can be found with respect to patterns described for experimental studies (Fig. 8). Apart from the research focus on temperature, it is clear that a large number of studies is conducted in northern areas with long tradition of surveying some valued species (e.g. pelagics/gadoids in the Baltic or Barents/Norwegian seas, and also NW Mediterranean). In contrast to studies on marine fisheries derived from experiments, data from field surveys were more abundant on adults and feeding larvae. It is noteworthy that in many studies temperature and salinity are both included as drivers. Furthermore, some attention has been devoted to examine climate indices as drivers (see “climatic” in the left graph from Fig. 8).

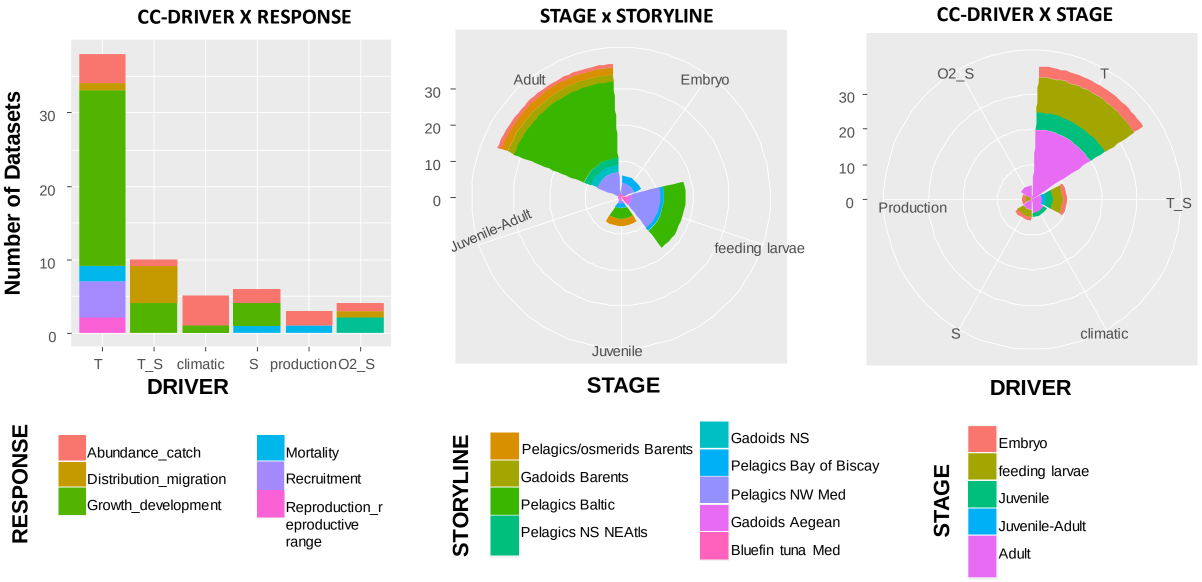


Figure 8 Number of independent datasets by exclusively for marine field studies. Explanations as in Figs. 5 and65.

Conclusions and implications

The gap analysis detected a large bias in the EU research effort on direct effects of CC on species of interest for fisheries and aquaculture. First, a clear latitudinal difference exists, with more information available in northern areas and some areas of the Mediterranean Sea, which probably results from the combination of research history and economical importance of the resource to the countries funding the research. Secondly, a large bias towards effects of temperature on growth/mortality is detected, with a scarcity of information on other single stressors. A striking lack of information on the effect of combined stressors is highlighted, fact that has been highlighted in the literature (Peck et al., 2013). By sectors, it is clear that economically important species such as salmon or rainbow trout, or small pelagics in the Baltic region, receive a lot of experimental attention (although the aforementioned bias in stressors/responses persist) whereas other species that are difficult to culture have a noticeable lack of experimental data on many of their life stages (Portner & Peck 2010; Peck et al., 2013). One immediate implication is that our ability to understand and model the potential effects of climate change is severely hampered by these biases, which should be corrected through research focused to filling in these gaps. Another implication is that, for many storylines within CERES, models will have to rely in generic approximations taken, probably, from data derived from the same or similar species from non-EU regions. It is extremely important not only to increase the needed stage-specific information on responses to cc (Rijnsdorp et al. 2009; Pörtner & Peck 2010), but the region-specific information for many species, because regional adaptations within species exist (Ojaveer & Kalejs 2005; Cozier & Hutchins 2013) and our ability to understand changes will be flawed if this information is not incorporated.Finally, it must be pointed out that the current gap analysis, while incorporating correctly experimental studies, clearly underestimates the information on field studies, which can offer valuable information on distributional shifs, phenological changes and extinction rates (e.g., Parmesan & Yohe 2003; Beare et al 2004; Rose 2005; Rijnsdorp et al. 2009; Heino et al. 2009; Phillips and Pérez-Ramírez, 2017).

Sub-chapter 3.2. A quantitative analysis on direct Climate change effects on selected fisheries and aquaculture groups: a meta-analytical approach

Introduction and objectives

Meta-analysis is an extended statistical approach for comparing outputs of multiple studies investigating a common stressor-response relationship and for generating a common effect size. In the present analysis, the effect of changes in ambient environmental conditions (temperature, pH, oxygen and salinity) versus future conditions driven by CC was compared.

Procedures

The meta-analysis was conducted following standard procedures (specified in Appendix 4), with a high degree of stringency. Forest plots were used to show how species or groups under a given stressors e.g., pH, respond with respect to the control. Plots are conducted in R following Viechtbauer (2010, 2017).

Briefly, several partners surveyed a series of selected species in Web of Science, adding to the 33 species in Table 1. An initial outcome of over 21 thousand studies published until 2018, was obtained, and a first filter through title reading was conducted. A second filter was applied using following criteria: inclusion of the relevant species, suitable explanatory variables and response variables, correct measurement of ambient treatment conditions and plausible CC affected future treatments (see thresholds in Appendix 4). An additional filter was that data derived from laboratory experiments using multiple replicates, where mean and variance were provided.

The resulting dataset, comprising pairs of measurements for growth, metabolism, mortality and development related to ambient and future environmental conditions, was collated in a specific table and is being analyzed for a future publication. For the meta-analysis a standardized effect size metric (Ln response ratio, LnRR) is calculated for each pair of treatments. Then a model is created that defines the summed up weighed effect size and the heterogeneity. The heterogeneity (I^2) varies between 0 and 100%, indicating the percentage heterogeneity that cannoy be explained by chance. In order to test the effect of the subgroups on the effect sizes, the study outcomes are aggregated by subgroups (e.g., different life stages, functional groups, seasonality). We here present some results.

Main results

The studies that matched our criteria at the current state of work (~129) included 59 studies for temperature, 21 for pH and 29 for O_2. Distinguishing between responses, 53 studies were available for growth, 38 studies for metabolism (usually oxygen consumption) and 32 studies for mortality. Only six studies considered the effect of salinity, and five studies were available on the effect on development. This precluded an exhaustive analysis of CC effects on many drivers and responses (and excluded any interaction), or a disaggregated analysis by region or species.

An interesting result is that seasonality is an important factor on the effect of temperature on mortality, when all groups are pooled (Fig.9). This suggests that increased temperature in summer may drive species close or beyond their thermal tolerance limits, and that the potential effect of thermal increases should draw attention to the seasonal component instead of annual averages.

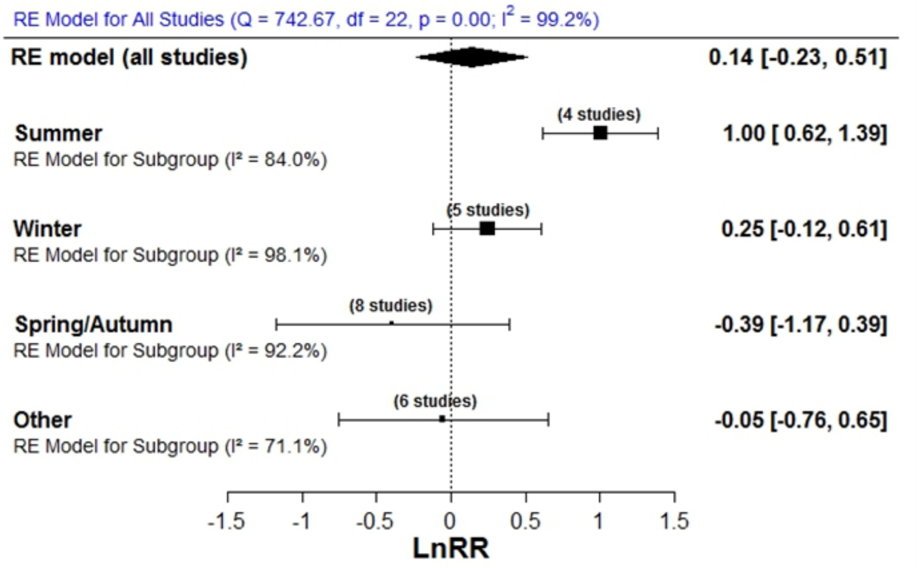


Figure 9 Summarized effects of seasonality on the response ratio for temperature-mortality. RE, random effect model. L^2 describes heterogeneity. Effect sizes and confidence intervals are shown to the right. If the error bars cross the vertical line, there is no significant effect.

The increase in temperature, the most studied effect as shown in the Gap analysis, tended to have a positive effect on the growth of demersal fish and bivalves, and a less clear or no effect in pelagic species and freshwater fish. The latter cannot, however, be taken as granted, due to the large heterogeneity in the groups (I^2 values, Fig. 10).

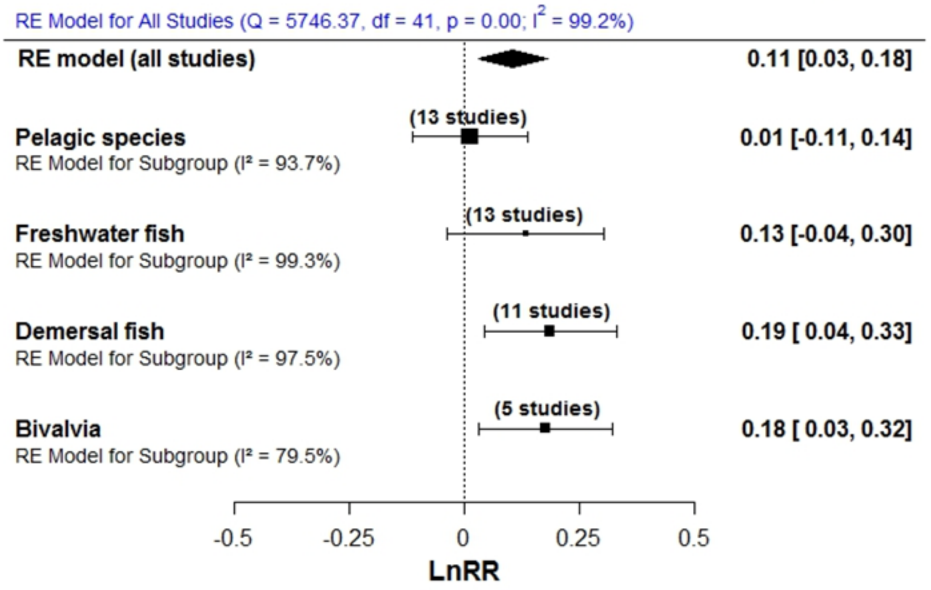


Figure 10 Summarized effect of functional group on response ratio for temperature increase on growth. Explanations as in Fig. 9

The effect of pH could not be properly analyzed due to the low number of studies, but data suggest that bivalves would suffer a significantly higher mortality under acidifying conditions (Fig. 11). This result is reasonable and is supported by additional studies demonstrating a diminished capacity to form calcareous shells under conditions of OA. The increased mortality would be paralleled by significantly decreased rates of growth (Fig. 12), also observed for the available literature data on freshwater fish. The few available data from the literature also suggest that the effect on early life stages is higher than that on older life stages (Fig. 13).

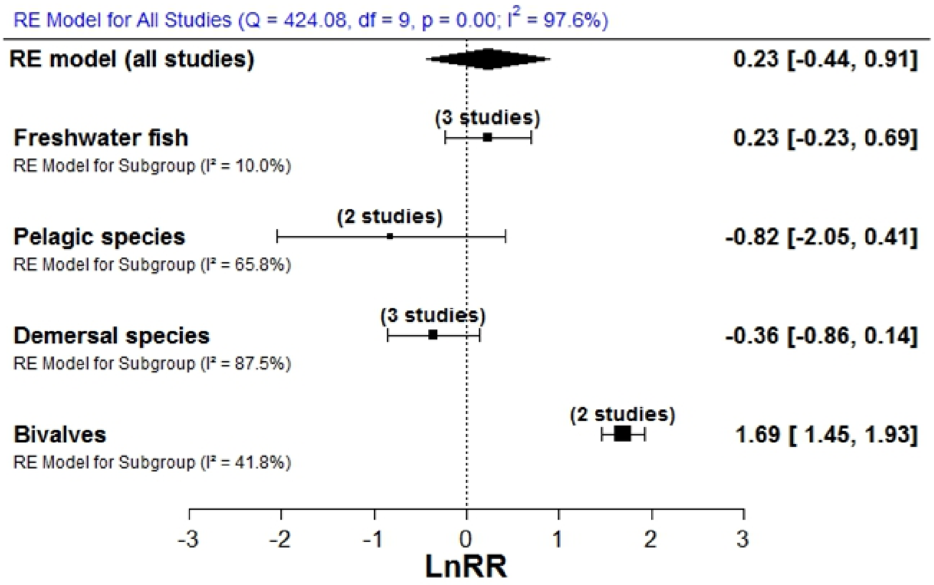


Figure 11 Summarized effect of functional group on response ratio for pH-mortality (treatment is low pH).

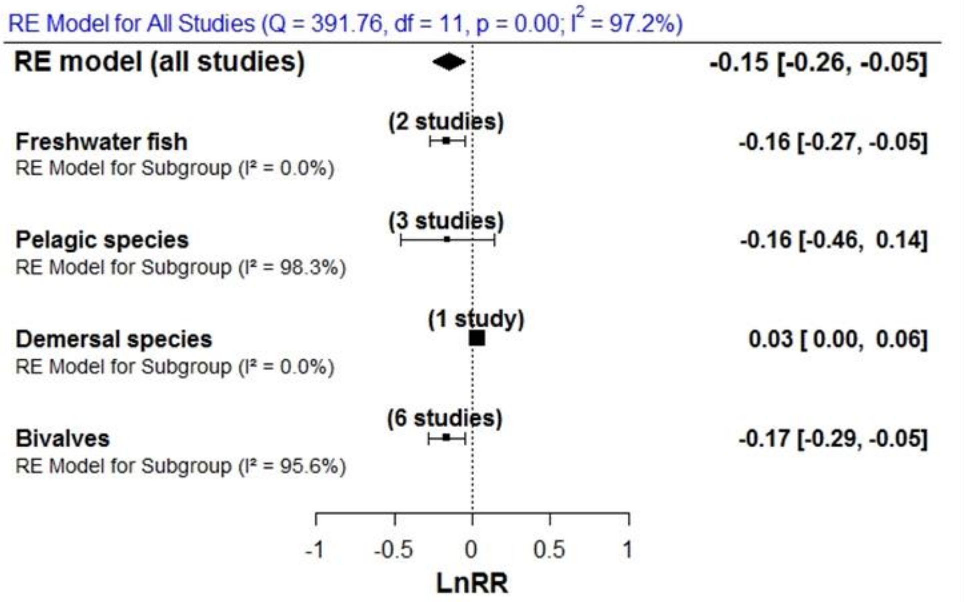


Figure 12 Summarized effects for grouped species: response ratio for pH (stressor) on growth

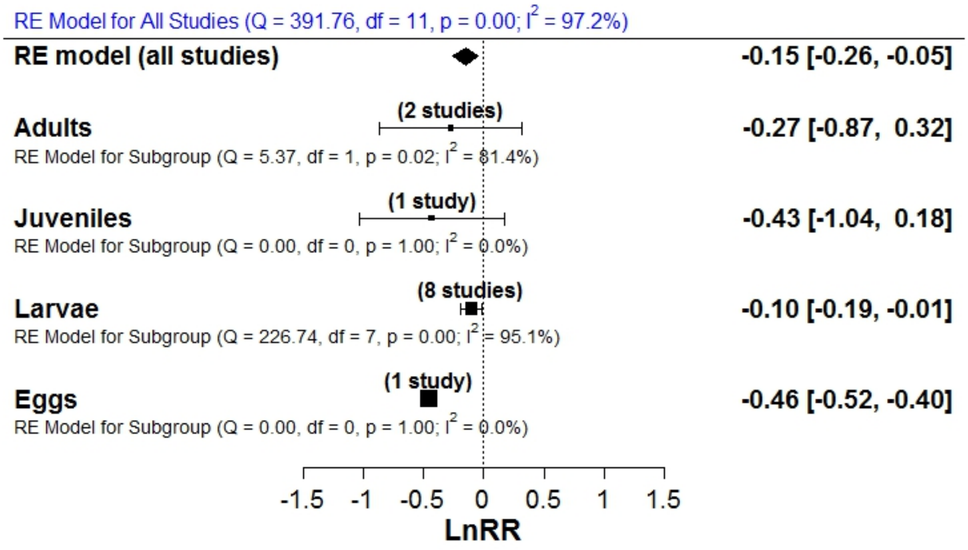


Figure 13 Summarized effect of functional group (life stage) on response ratio for pH (stressor) on growth

Conclusions and implications

The meta analysis results suggest a different effects of CC related stressors on species groups and life stages, with the most reliable results being reflected in the positive effect of CC-related increases in temperature on the growth for some species, but an increase in mortality when these thermal effects occur in summer. Negative effects of pH on growth are suggested for bivalves, and for early stages of combined groups. Overall, the heterogeneity in our analysis is high, and more research is needed across regions and life stages in order to provide further conclusions.

Sub-chapter 3.3. Experiments on Bluefin tuna

Introduction, objectives and procedures

Although the experiments for aquaculture species are delivered within WP3, one experiment was conducted on a key fisheries target (Atlantic bluefin tuna) and these results are presented here. This experiments was specifically designed to cover the existing gaps on the highly priced Atlantic bluefin tun*a*. The eastern Atlantic stock of bluefin tuna spawns in the Mediterranean Sea, and the Balearic Islands region is a key reproductive zone to ensure larval survival (Reglero et al. 2018). The aim of these experiments, conducted by IEO, was to test the effects of pH and salinity on larval survival. Previous work had already been conducted on the effect of temperature on egg survival and larval growth.

Fertilized Atlantic bluefin tuna eggs were collected from spontaneous spawning in captive broodstock fish maintained in sea cages since the summer 2016. Natural fertilized eggs were collected and transported to the experimental facilities at the Spanish Institute of Oceanography in Mazarrón (Spain), arriving around 1 hour later, when the eggs were in the 4–16 cell phase. For the salinity experiment, the eggs were distributed among 300 ml flasks with 50 eggs each at controlled salinity between 27-49 with 5 replicates for salinities of 27, 30, 33, 36, 37, 38, 39, 40, 43, 46 and 49, all at a constant pH of 8. For the pH experiment, the eggs were distributed among 300 ml flasks with 50 eggs each at controlled pH between 7.3-8, with 5 replicates for pHs of 7.3, 7.5, 7.7 and 8, all at a constant salinity of 38. Salinities or pHs remained constant throughout the experiment in each replicate. The experiments lasted for 44 hours. When all the eggs were hatched, the larvae were counted, identifying normal and abnormal larvae to calculate the hatching rate (rate of normal larvae with regard to total inoculated eggs).

Main results and conclusions

The results from the salinity treatment suggested a bell-shaped curve, with higher hatching percentages at intermediate salinities and lower percentage hatch at the extreme salinities. Hatching rates were always above 50% (Fig. 14, top). There were no significant differences for the pH treatment and survival were above 80% in all cases (Fig. 14, bottom). In present environmental conditions, both salinity and temperature are the two main variables related to the distribution of Atlantic Bluefin tuna larvae. The range of temperature in which larvae occur in the field is tightly related to the minimum temperature tolerance for eggs and larvae (19°C) and the optimal hatching rate for eggs (around 24°C). The experiments show the salinity at which larvae occur in the field (37-38) cannot be related to a physiological effect on larval survival at hatching since the extreme salinities at which an effect on hatching was observed was too extreme compared to projections for the Mediterranean. The same was observed for pH. Therefore, growth and survival relationships with temperature will be used in the climatic projections to estimate both larval distribution and survival, whereas salinity and pH will not be used since the range of values expected in the physical projections are unlikely to exert any effect on larval physiology.

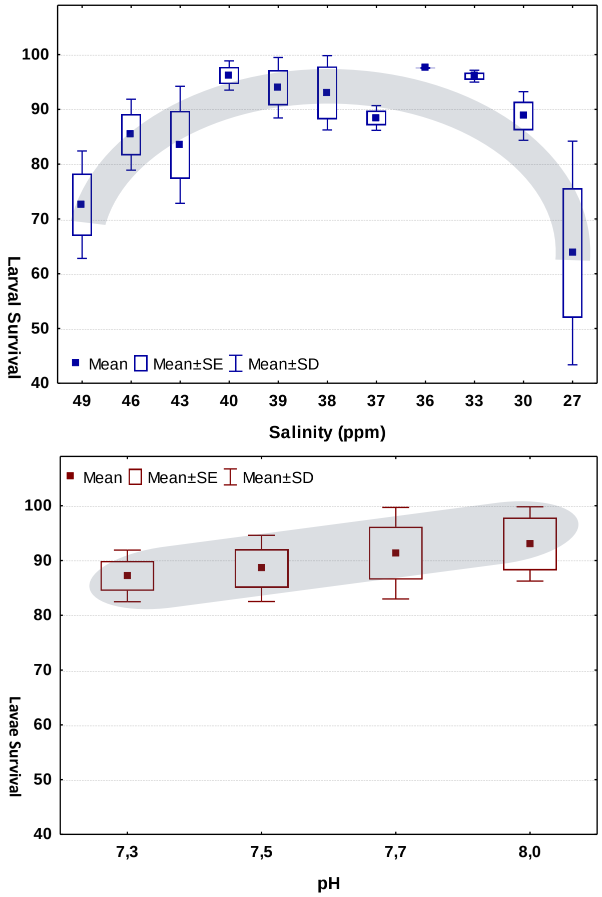


Figure 14 Main results of the laboratory experiments performed with Atlantic bluefin tuna. Relationship between larval survival and salinity (top) or pH (bottom)

Sub-chapter 3.4. Use of direct effects data within CERES

The data collection has been an iterative activity during the first 12 months, by which modellers initially expressed their data/equations needs for updating/tuning the models. After that, the uptake of these data was checked on month 18 (Fig.18). Whereas some of the data were directly used in complex models, some other data was re-analyzed to derive empirical equations.

The Atlantis model was updated using data generated in this deliverable by IMR, DTU and UHAM. Projection models based on physiological models (DEBs) coupled to spatial individual-based models (IBM-DEB) were parametrized by IFREMER using data generated in this deliverable. New parameter values for some species were supplied to SS DEBM models run by PML, and freshwater AQUATOX model also used collected data within D.2.1. In the Mediterrranean, several spatial distribution models have been built by CSIC and HCMR for pelagic and demersal species using the data collected within this activity.

A list of variables that can be potentially useful for WP5 vulnerability analyses was also generated and transferred to T.5.3.

Chapter 4. Review of Indirect effects of Climate change on EU fisheries

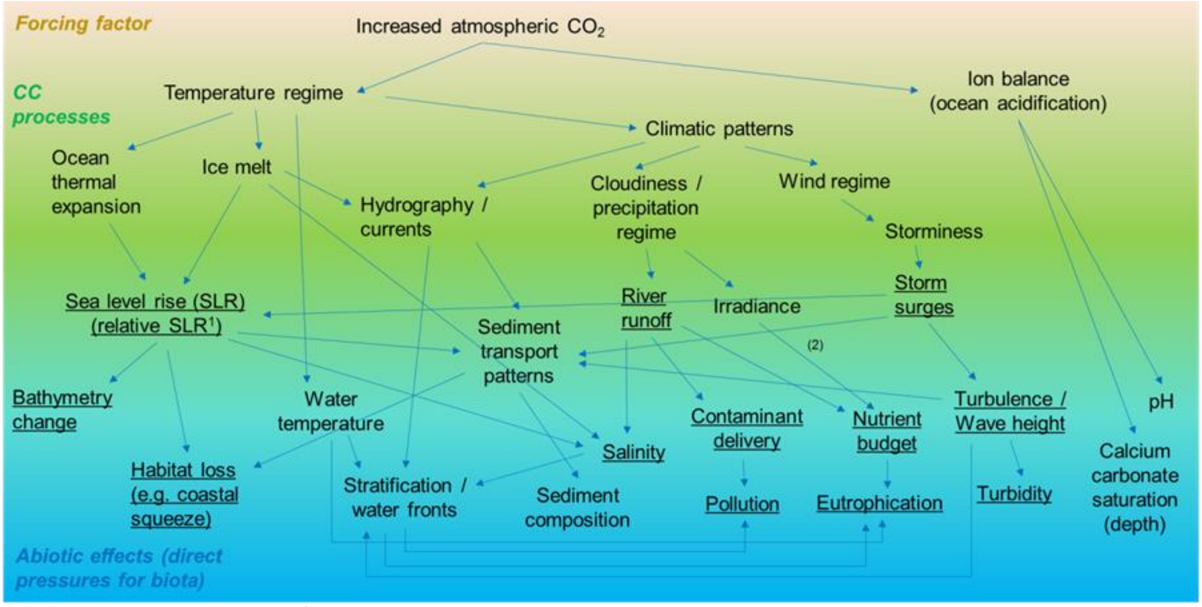
Sub-chapter 4.1. Indirect effects of climate change on fish through effects on estuarine habitats (UHULL)

Introduction, objective and procedures

Estuarine ecosystems may play an important role in supporting marine and inland fisheries, particularly for those marine species that use estuarine habitats during critical stages of their life cycle (marine migrants, e.g. sole, plaice, cod, herring) or for those migratory (diadromous) fish using estuaries as pathways for their spawning migrations (e.g. catadromous species as eel, anadromous species as salmon) (Franco et al., 2008; Potter et al., 2011). Being at the interface between aquatic and terrestrial ecosystems, and between marine and freshwater systems, estuaries may be particularly affected by climate change (CC), with consequent changes in the physical, geomorphological and biogeochemical environment. These changes may alter the functioning of estuaries as essential habitats (namely juvenile habitats / nurseries) for marine fishes as well as the connectivity between the marine and freshwater realms, thus affecting indirectly marine and inland fisheries. Although these effects cannot be directly included in the predictive models developed for marine fish stocks, as they originate and operate outside the strictly marine spatial domain, it is important to take them into account as they may contribute to the unexplained, residual variability and uncertainty of these models. As such, a literature review was undertaken by UHULL in order to integrate WP2 results with findings on how climate-induced changes in estuaries may indirectly affect fishes while using the estuarine environment. The full report can be found in Appendix 5, whereas here we summarize the main findings and figures.

Main results and conclusions

Climate-induced alterations of temperature, hydrological regime, saline intrusion, water quality and habitat availability in transitional waters are likely to affect fish use of estuaries. Abiotic changes may solicit physiological and behavioural responses in fish, altering the performance of individuals at different life stages or from different populations, influencing dispersal and recruitment and affecting species interactions within communities. Ecological effects may occur at individual, population and community levels, possibly affecting the productivity and functioning of aquatic ecosystems (Figure 15). These changes have the potential to influence marine fishery stocks that depend on estuaries for part of their life stage (as nurseries) and at the same time may influence the ecological status and condition of transitional water systems.



[1] Including effect of vertical land movement; [2] Effect mediated by biotic processes (primary production)

Figure 15 Primary drivers and processes of marine global climate change and resulting effects on physico-chemical properties of the marine environment. Elements underlined indicate CC factors and effects that are relevant only to estuarine habitats, whereas those not underlined are relevant to both estuarine and marine environments.

Temperature has a major influence on all aspects of the physiology and ecology of fishes hence much of the research on climate-induced changes has addressed the role of this factor. Temperature changes may affect egg and larval development and hatching, activity and metabolism, immune function, swimming performance and behaviour, foraging rate, growth, maturation, prey availability, predation risk and mortality. Phenology of crucial events such as spawning and migration might be affected, as well as the reproductive and recruitment success, population viability and productivity and species distribution range (via invasions and local extinctions) (Fig. 16). Research showed that many of the species that may be affected include fish using transitional waters for most or all of their life cycle, hence leading to potential changes to the composition, diversity, abundance and habitat use of estuarine fish assemblages.

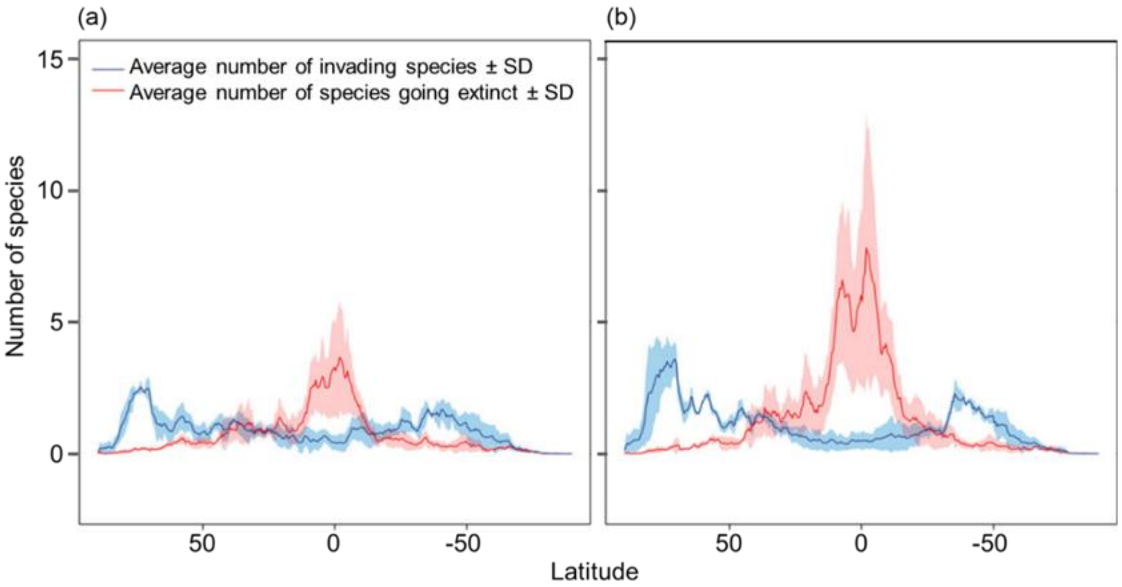


Figure 16 Mean total number of species predicted to invade and go locally extinct at different latitudes between 2000 and 2050 under climate change scenarios (a) RCP 2.6 and (b) RCP 8.5 (IPCC, 2013). The shaded area represents confidence intervals at 1 standard deviation (SD) (from Jones and Cheung, 2015).

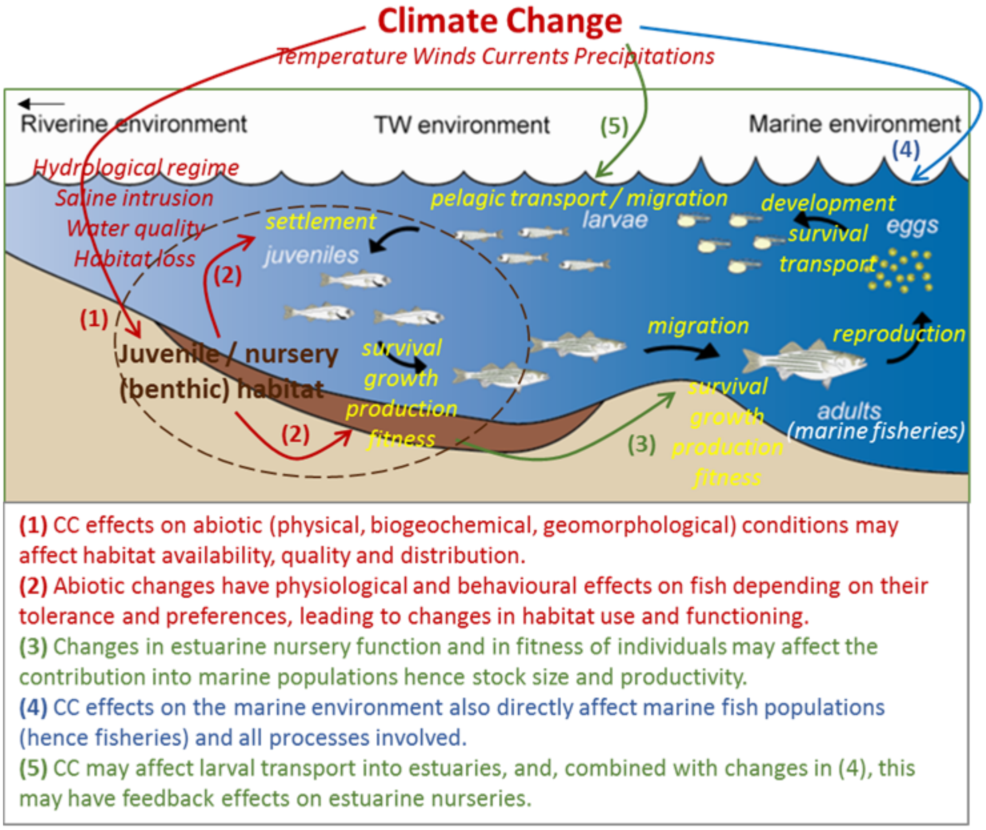
Climate-induced shifts in hydrological and salinity conditions may result in transitional waters following the reduction in river runoff and river discharge, increase of intrusion of marine waters (with alteration of the estuarine salinity gradient) and increase of the frequency of drought events. Research showed how these factors may affect the suitability of estuarine habitats as nursery grounds for marine migrant species, leading to changes in the recruitment success, production, abundance, diversity, and functional structure of estuarine fish assemblages. Migrations of diadromous species through the estuary may also be affected by the loss of suitable riverine habitats induced by the alteration of hydrological regime.

Through sea level rise, climate change has the potential to modify the estuarine topography thus altering the availability, configuration and location of intertidal habitats. These may have an important role as nursery and feeding ground for fish, hence the loss of these habitats (e.g., due to coastal squeeze) may decrease the capacity of estuaries to support life-history diversity, with potential long-term effects on the viability of estuarine-dependent fish populations.

Estuarine environments may be highly susceptible to climate-induced water acidification. The potential for this factor to affect habitat selection, feeding predator avoidance behaviour, spawning and migration behaviour, mate choice and reproductive behaviour has been demonstrated for several fish species, including species that are commonly found in estuaries. As a result, shifts in fish community structure may in occur in transitional waters as a consequence of reduced pH levels.

Climate change may indirectly alter other abiotic conditions in estuaries, leading for example to reductions of dissolved oxygen concentration, changes in ocean circulation and in dilution and residence time of dissolved nutrients and pollutants. These changes have the potential to influence many aspects of the ecology of fish, including habitat use, reproductive success, growth, predation risk, thus negatively affecting the carrying capacity of estuarine ecosystems.

The links between CC factors, consequent abiotic changes in estuaries and their potential relevance to fish in estuaries and to marine fisheries, as depending on the factors described above, have been summarised in a conceptual model as reported in Fig. 17. Consideration has also been given to assumptions and confounding factors in establishing a cause-effect relationship between climate-induced changes in estuaries and changes in marine fisheries. These are mainly associated with the exogenous/wide scale nature of CC pressures (with effects acting simultaneously on the estuarine and the marine environment, hence possibly leading to difficulties in disentangling direct and indirect effects on the marine fisheries) and with the inter-dependence between estuaries and the marine environment, where estuarine use by fish may also be influenced by feedback effects of changes in the marine environment and stocks (e.g. changes in reproductive success, stock distribution, larval transport within the estuary etc).



(1) CC effects on abiotic (physical, biogeochemical, geomorphological) conditions may affect habitat availability, quality and distribution.
(2) Abiotic changes have physiological and behavioural effects on fish depending on their tolerance and preferences, leading to changes in habitat use and functioning.
(3) Changes in estuarine nursery function and in fitness of individuals may affect the contribution into marine populations hence stock size and productivity.
(4) CC effects on the marine environment also directly affect marine fish populations (hence fisheries) and all processes involved.
(5) CC may affect larval transport into estuaries, and, combined with changes in (4), this may have feedback effects on estuarine nurseries.

Figure 17 Life cycle of marine migrant fishes using estuaries as nurseries (dashed circle identifies nursery habitat within an estuary). In yellow are the main processes involved. Also shown are main links between CC pressures, direct and indirect effects in estuaries (red), in the marine environment (blue) and on connectivity between the two systems (green). Symbols for diagrams courtesy of the Integration and Application Network (iam.umces.edu/symbols), University of Maryland Centre for Environmental Science.

Sub-chapter 4.2. Effects of climate change on jellyfish blooms and European fisheries (CONISMA)

Introduction, objectives and main results.

Despite the lack of scientific consensus in identifying the global trends in (and controlling mechanism(s) of) jellyfish blooms, recent analyses of jellyfish population dynamics suggest that these organisms are increasing in different worldwide areas, including Mediterranean coastal zones (Brotz and Pauly 2012; Condon et al. 2013). Massive proliferations of these gelatinous organisms are likely to have ecological effects such as altering food web structure and trophodynamics due to their high rates of prey consumption, growth and reproduction, and their wide tolerance to abiotic factors such as low dissolved oxygen. Moreover, these blooms will impact many human activities such as tourism, fishing activities, coastal industrial plants and net pen aquaculture (Purcell et al. 2007; Richardson et al. 2009; Palmieri et al. 2014; Bosch-Belmar et al. 2017).

Interference with fishing operations is one of the most frequently reported incident occurring with jellyfish blooms, having severe economic consequences for the sector since large catches of jellyfish can rip fishing nets, ruin the quality of the catch and increase fishing time and costs (Richardson et al. 2009; Palmieri et al. 2014). Such problems apparently are more widespread than reported in the literature, since encounters between jellyfish blooms and fishing activities are hardly forecasted and complex to study, only reported when the economic losses due to the interaction are high and repeated over time. Fisheries from Japanese Sea are those most affected by jellyfish blooms, when for e.g. in 2003-2004 increasing densities of *Aurelia* sp. and *Nemopilema* jellyfish in important fishing areas resulted in significant economic losses at 17 Japanese prefectures (Uye and Ueta 2004; Kawahara et al. 2006).

In the Mediterranean and North European Seas problems with jellyfish blooms have also been reported, being fishing net clogging and catch damage and reduction the most frequently documented impacts. The main involved species in these events were *Pelagia noctiluca* (Mariottini et al. 2008; Bernard et al. 2011), *Rhizostoma pulmo* (Purcell et al. 2007; Fuentes et al. 2011; Nastav et al. 2013) and Aurelia sp.(Purcell et al. 2007) for central and western Mediterranean coast; *Rhopilema nomadica* (Lotan et al. 1994; Öztürk and İşinibilir 2010) in the eastern Mediterranean area and the ctenophore *Mnemiopsis leidyi* with reported incidences in different Mediterranean areas (Kideys 1994; Shiganova 1998; Purcell et al. 2007). On the other hand, jellyfish impacting fishing operation in northern Europe were *Aurelia aurita* and *Cyanea capillata* (Lynam et al. 2005), as well as the hydromedusae *Periphylla periphylla* in some Norwegian fiords (Tiller et al. 2016) (see table CONISMA (link in Appendix 1) for more info).

In literature is possible to find many studies on jellyfish clearance and feeding rates performed to investigate the potential predatory pressure exerted by gelatinous zooplankton in an ecosystem (Olesen 1995; Purcell and Arai 2001; Titelman and Hansson 2006; Pereira et al. 2014). Jellyfish could also impact fisheries indirectly reducing natural fish stocks, either by predation on fish eggs and larvae or by competing with planktivorous fish and fish larvae for available zooplankton prey. When jellyfish occupy a trophic level similar to that of small pelagic fish, they have the potential (given their substantial biomass) of competing with these species, especially in years with low ecosystem productivity (Brodeur et al. 2008). Moreover, some marine human activities such as intensive fishing operations could open up and facilitate ecological space for jellyfish (Richardson et al. 2009), as for example happened in the northern Benguela upwelling system (Namibia), where intense fishing decimated sardine stocks, and the system passed to be dominated by jellyfish such as *Chrysaora* (Flynn and Gibbons 2007); or the well-known case of the ctenophore *Mnemiopsis leidyi* in the Black Sea (Shiganova 1998).

Separately or in combination, different anthropogenic and climatic stressors have been suggested as potential causes of increasing jellyfish densities: overfishing by removing jellyfish predators and competitors; the proliferation of artificial hard substrates, providing suitable habitats for jellyfish- producing polyps; ocean warming, boosting higher jellyfish reproduction rates and wider distribution areas; and eutrophication, leading to higher availability of nutrients and plankton food sources for these gelatinous organisms. Moreover, other factors such as ocean acidification or low dissolved oxygen have been proposed as potentially beneficial for jellyfish with respect to fish or other marine organisms (Purcell et al. 2007; Boero et al. 2016).

In the recent years, several studies focus on the effect of a wide range of environmental factors on jellyfish occurrence, abundance, physiology and life cycles have been performed. Temperature, salinity, pH, chlorophyll a, eutrophication and water turbidity, hypoxia and low dissolved oxygen, river flow and rainfall, oceanic water inflow and phenomenon such as the North Atlantic Oscillation (NAO) were recorded as the most studied factors; and *Aurelia* spp., *P. noctiluca* and *M. leidyi* were the most frequently involved jellyfish species (See references in table CONISMA, link in Appendix 1).

Most majority of the published literature suggests that temperature and salinity were positively related with densities, growth and reproduction of the three aforementioned species, except for some studies from the North Sea and the south of Baltic Sea where a negative relation between temperature and Aurelia sp. and *M. leidyi* densities was found.

Moreover, habitat eutrophication has been positively related with jellyfish density and predation success; and other stressful conditions such as low dissolved oxygen overall resulted in jellyfish survival and increasing reproduction rates.

Up to now, the effect of ocean acidification on jellyfish has been poorly studied, but few papers showed that *Aurelia* sp. presented high tolerance and survival to low pH, reduced statoliths and increasing asexual reproduction and ephyra growth in some cases.

Presence of river flow was negatively related with the occurrence and abundance of *Aurelia* sp., *Rhizostoma pulmo* and *Pelagia noctiluca*, while the influence of NAO in northern Europe varied geographically. A negative relation between NAO and *Aurelia* densities was found in the Southern North Sea (west of Denmark and East of Scotland); while in Northern Scotland this relationship was positive.

Conclusions

Effects of climatic and environmental factors on jellyfish blooms are diverse and may change within genera, which have from polar to equatorial representatives and sometimes within species, as with the invasive ctenophore *M. leidyi*. At the same time, the sudden and unpredictable nature of jellyfish blooms hinders the implementation of preventive measures against their negative effects on different marine human activities, becoming a substantial problem with high economic losses. Because of this, further investigations are required to better understand jellyfish blooms dynamics and factors influencing their spatial distribution and life cycles in the current and forecasted future scenarios.

Sub-chapter 4.3. Use of indirect effects data within CERES

For the study of indirect effects in estuarine systems (UHULL), data has been used for of ad-hoc analyses to answer some specific questions related to cc. Although these effects cannot be directly included in the predictive models developed for marine fish stocks, as they originate and operate outside the strictly marine spatial domain, it is important to take them into account as they may contribute to the unexplained, residual variability and uncertainty of these models. Besides the interpretative value of the literature review conducted for estuaries, an added value is in how this information will be used in risk analysis, vulnerability and mitigation (WP5). Effects of CC on certain species that depend on estuaries will be informed by this literature review, and mitigation/adaptation measures proposed accordingly, all embedded within the stakeholders consultation process.

As for Estuarine stidies, the effect of jellyfish blooms cannot be adequately incorporated into the future projections. Most information on direct effects of jellyfish will be generated in D.3.2 results of experiments (impacts of jellyfish in aquaculture). However, the observations stemming from the current literature review suggest that increased eutrophication and altered salinity and temperature tend to correlate with certain jellyfish outbursts in certain regions, with direct effects on fisheries, can be used in WP5 risk analysis schemes.

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Appendix 1

A) Link to the tables in the CERES intraweb. Data will be made public before the end of the project

- Name: "20_02_2017_compiled_data_fisheries_CERES.xls"

  Description: Excel file containing three spreadsheets: one explaining the meaning of each variable, one containing the table with experimental data collected by the partners "EXPERIMENTAL" and one containing the data derived from field studies "FIELD"

- Name: "Monster Table Task 3_1 Pedro Domingues FINAL 070417.xlsx"

  Description: Description: Excel file containing two spreadsheets: one explaining the meaning of each variable, one containing the table with experimental data collected by the partners "EXPERIMENTAL".

- Name: "Meta_analysis_table"
  Description: Data used to conduct the meta-analysis: the access to this table is protected until a publicacion has been derived.
- Name: "CONISMA_Jellyfish & fisheries_26_01_2017.xls"
  Description: Excel file containing all data used for the review on the indirect effects of jellyfish

Appendix 2

A) Instructions for data collection by partners within CERES task 2.1/T.3.1

B) Inclusion criteria instructed to partners in order to ensure quality and comparability of the data in the tables.

A) Instructions for data collection by partners within CERES task 2.1/T.3.1 (CSIC-UHAM)

The excel file sent to you is composed by three (for fisheries) or two (aquaculture) spreadsheets. The first spreadsheet just lists vertically the requested variables, so you can look at them easily. Only two sheets (EXPERIMENTAL_table (fisheries) and FIELD_table) should be compiled for your species and area.

1) Objective of the tables

The table aims at collecting information between CC-related stressors and aquatic organisms productivity and physiology. The table is expected to compile the information on PUBLISHED or UNPUBLISHED data (essential focus on grey literature) that SPECIFICALLY TESTS THE EFFECTS OF A RANGE OF CC-RELATED FACTORS ON RESPONSE VARIABLES. This is crucial: **we do not intend to collect any information on, for example, a**

paper describing growth rates at one given temperature. We will only focus at works testing, for example, a suite of temperatures, or pH ranges, or O_2, or combination of factors.

Only in the cases where a lack of information is evident, and where that information is needed by the modelers, it can be discussed the possibility of deriving empirical relationships. **You should indicate that at the appropriate cells.** As several partners are working with the same species, it is likely that by joining available data all partners working with that species will benefit from the joint effort.

It is also the objective of the task to conduct a meta-analysis that can end up in a publication. The meta-analysis would enable, for example, exploring potential differences in reaction norms of a given species across latitudinal ranges, which is invaluable for the project. See for example the figure below from Pörtner & Peck (2010).

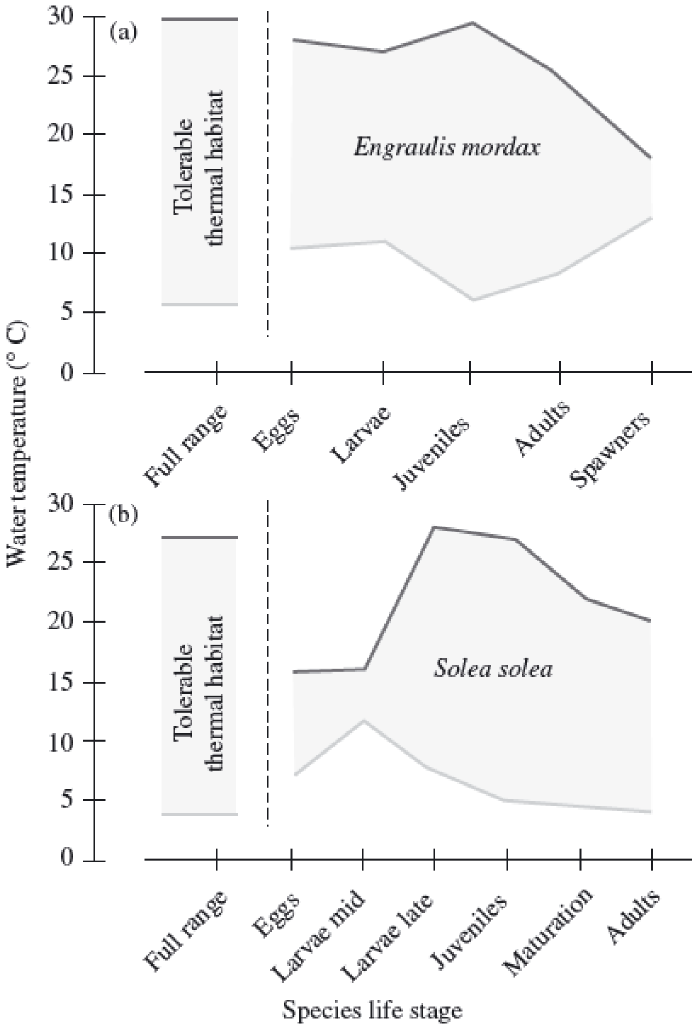


FIG. 2. Ontogenetic changes in thermal habitats or tolerance for *Engraulis mordax* in the California current (from Brewer, 1976) and *Solea solea* in the North Sea (from Rijnsdorp *et al*., 2009). In both cases, the earliest life stages were more sensitive (had a more narrow range in thermal tolerance) than later larvae and early juveniles that can exploit the largest range in thermal habitats compared to earlier or later (adult) life stages. In the *S. solea* example, maturation refers to the body size at which fish become sexually mature (first enter the adult stage) and does not refer to adult fish that are in spawning condition (displayed for *E. mordax* data).

For this, we have included a column in the table where the partner has to specify if they agree that the data provided are used for the meta-analysis. Also, a protocol was attached for the inclusion of grey literature data in the table (see below)

2) Organization of the tables

The tables are organized so that each of them (experimental and field data tables) includes all species groups as described in the Document of Work. All relevant columns have comments inserted, clarifying what they mean. Initially, there are a series of columns describing generalities of the data included. It is very important to fill in the **"effect being compiled"** cell, as well as who is collecting the data and if you consent to use the data for meta-analysis. For each combination of species/area, we include FIVE LIFE STAGES for fish, and 4 for mollusks. For the fish, the reason to include "spawning adult" as a different life stage will enable to collect the information on changes in distribution of spawning areas only. **Of course most cells will be blank for a given study, that is not a problem.** The tables are designed so that you can include in the same way both studies dealing with only one effect or with interacting effects. Of course, it is possible that some works cannot be fit into these tables. Then just add a column at the end.

3) Expectations

The partners devoting PM to these tasks are asked to contribute to the table by providing data, preferably grey literature, on the effects of CC-related stressors on fish and shellfish production and distribution variables. If the partners are currently using relationships of, say, T and larval growth, they are expected to insert what data they are using, so that the team can look for the newest information. **If they need some specific information and they cannot get it, please specify it in the appropriate cell by "NEEDED".** This will help identifying potential experiments or the need for deriving empirical relationships. IF the partners themselves are going to conduct empirical relationships within CERES, **please write "CERES" in the corresponding cell**

B) Inclusion criteria instructed to partners in order to ensure quality and comparability of the data in the tables.

To assure quality and comparability of data collected for the literature review of CERES, the following inclusion criteria according to the **PICO** (Participants, Interventions, Comparators and Outcomes) principle for systematic reviews were taken into account:

- relevant populations
    - all naturally occurring or aquaculture species
    - no genetically modified species

- relevant interventions
    - treatment conditions in experimental studies should be of reasonable stability, thus it is extremely important to state the range of the environmental factors (e.g. temperature, salinity, pH/pCO_2, O2). Variability within one treatment should not exceed
      ± 0.5°C for temperature
      ± 0.5 ppt for salinity
      ± 0.05 pH units/ 10% of pCO_2 applied
      ± 0.5 kPa for oxygen

- relevant comparators
    - true control treatment in experimental studies are obligatory (only data from sources where a relationship between a CC-related stressor and the impact on potential organismal traits/parameter, such as growth or abundance, is revealed (e.g. an experiment where different temperatures are tested with regard to the effect on larval growth of trout) should be recorded. But not the data of studies in which a trait/parameter is

    measured at one single temperature. The latter should only be collected if there are no data on stressors effects and some empirical relationships have to be derived from the literature by compiling different studies.)

- relevant outcomes
    - all parameters stated in the excel template for which data is available

Appendix 3

Summary of fisheries t-tests of growth index (phi') and length mass relationship slope (b) (PML).

Data were taken from Fishbase for 11 species of fish: anchovy, cod, dolphinfish, haddock, hake, herring, mackerel, sardine, sole, sprat and Atlantic bluefin tuna. The growth indices (Φ') and slopes of length mass relationships (b).

Table A3.1: Abbreviations used in text and tables.

NWA	Western part of the North Atlantic Ocean
NEA	Eastern part of the North Atlantic Ocean
SM	Southern Mediterranean (Tunisia, Sicily, Libya)
WM	Western Mediterranean (anything west of Italy)
EM	Eastern Mediterranean (includes Aegean sea)
NNA	Northern part of the North Atlantic Ocean
UK	UK waters
NEP	Eastern part of the North Pacific Ocean
NP	Northern part of the North Pacific Ocean
(***)	p-value of order of 10^{-4} or lower
(**)	p-value of order of 10^{-3}
(*)	p-value of order of 10^{-2} lower than 0.04
(°)	p-value ≈ 0.05
1	p-value non-significant

Overall, fewer significant differences were found in fish length-mass relationships than in their growth indices. It should however be noted that they present smaller datasets, which may affect the preciseness of the tests, and meant larger areas were grouped together.

Anchovy growth was significantly different between NEA – Black Sea and NEA – Mediterranean (***), and somewhat significant between the Black Sea and the Mediterranean (°). No significance was found between the Adriatic Sea and other areas. More differences were found in the length-mass relationships: a high significance was found between the Black Sea and the Adriatic, Black Sea and NEA, and the EM and the NEA (***). Also significant were the differences between Adriatic Sea-EM, Black Sea-EM, and Black sea-WM (*).

Many significant differences were found in the growth rate of cod depending on their habitat area (Table 2). Cod coming from the Baltic Sea, NNA, North Sea, Norwegian Sea and the North West Atlantic are shown to all differ in their growth index, except between NNA and the Baltic Sea. No differences were significant in their length-mass relationships.

Table A3.2: Significance results of the t-tests for cod growth.

	Baltic Sea	NNA	North Sea	Norwegian Sea
NNA	1	-	-	-
North Sea	***	***	-	-
Norwegian	***	**	**	-
NWA	*	***	***	***

The growth of dolphinfish was found to be significantly different between Mediterranean – Caribbean, NEP-Caribbean, NEP- Mediterranean, NEP- NP, and Mediterranean-NP (** and ***). A lower significance (*) was found between Caribbean-NWA and NP-NWA. Significant differences between length-mass relationships were also found (*) between the Mediterranean and the Gulf of Mexico, as well as the Pacific.

A significant difference in the growth of haddock was found between the North Sea and NWA (**). The data set was, however, too small to look at differences in their length-mass relationships.

Hake growth differed significantly between EM and the Irish Sea (***), Adriatic Sea (*), the Scottish waters (*), NEA (***), and WM (**). Significant differences were also found between the Irish Sea and Adriatic Sea, SM, WM (***) and NEA (*), and between Adriatic Sea-NEA (**), NEA-SM (*), Scottish waters-SM (*) and Scottish waters-WM (p=0.5). Meanwhile, the length-mass relationship of hake from Eastern Mediterranean differed from all other areas: the Adriatic Sea (*), NEA (*), North Sea (**), and WM (**).

Herring from the Baltic Sea differed significantly in their growth index from all other areas (Celtic Sea, Irish Sea, North Sea, Norwegian Sea, NWA, Scottish waters), except the Barents Sea. The Barents Sea herring did not different significantly from other areas; however, there were only 3 data points for that population. On the other hand, the only significant difference in herring's length-mass relationship was between the Irish Sea and Scottish waters (***).

Mackerel growth in NWA was found to be significantly different to most areas: the Mediterranean, NNA and the North Sea (*), but not NEA. However, differences in length-mass relationship of mackerel were found between the Adriatic Sea and Mediterranean (*), NEA (*), and UK waters (**).

The only significance for the sardine's growth index was between populations in the NEA and WM (*). No significance was found in the differences between length-mass relationships.

Significant differences were found between the growth indexes of sole in Eastern Mediterranean and the Adriatic Sea (**), NEA (*), North Sea (*), and Western Mediterranean (**), and also between the North and Adriatic Seas (*). The only difference in length-mass relationship of sole that was found to be significance was between NEA and WM (**).

Significant differences were found in sprat growth between Black Sea-NEA (*), Black Sea-North Sea (***), Mediterranean-North Sea (*), and Black Sea-Baltic Sea (*). The length-mass relationship of sprat in the Black Sea was found to be significantly different to that of sprat from the North Sea (**) and UK waters (**). A somewhat significant difference was also found between Baltic Sea-UK waters (°).

A significant difference was found in the growth of Bluefin tuna between the NEA and the WP (*), and a slight significance between the Mediterranean and WP (°). However, Bluefin tuna length-mass relationships were all found to be similar.

Appendix 4

Systematic literature review protocol (Meta-analysis) for experimental studies.

This protocol was conducted by a sub-group of partners in order to achieve a coherent analysis of the experimental studies, besides what each partner could contribute in terms of grey literature.

Research question

The main objective of the meta-analysis was to describe / sum up our knowledge about climate change effects on several responses of 33 commercially relevant marine/aquaculture species. To answer this, we collected data on several drivers and responses from experimental studies in a systematic way (see below), which were then analysed using accepted methods.

Data acquisition

Below we detail the protocol applied by each contributor to collect the data to be analyzed

- Data bases used
  - Web of Science (the only common one to all partners involved)

- Search terms:

(„latin species name“ OR “common species name1” OR “common species name2”) AND (temperature OR climate change OR climat* shift OR acidi* OR pH OR oxygen OR hypox* OR hypercapn* OR O2 OR salinity OR freshening OR stress* OR thermal) AND (tolera* OR limit* OR critic* OR lethal OR threshold* OR growth OR weight OR mass OR diameter OR develop* OR mortality OR surviv* OR metaboli* OR respir* OR oxygen consumption OR prefer* OR thermal window OR aerobic scope OR metabolic scope OR sensitivity) NOT (chem* OR enginee* OR technology)

- Check alternative nomenclature (incl. common names) in fish base (section synonyms or common names) for species of interest and include them into the search term (e.g. common species name 2)

<u>Working steps</u>

1. Create excel sheet for each species in which details of search are noted down: Copy paste the search window from Web of Science and note down the number of hits.

(save/download citation list from Web of Science). This excel will have to be sent for quality check.

2. Scan results of search (title & abstract) for papers that might be relevant. Create list in excel sheet with potentially relevant papers (separate lists for each species).
3. Go through potentially relevant papers (from list) in detail, check relevance according to inclusion criteria, note down reason for exclusion of papers in list. It is important to know why we excluded some initially selected papers.
4. Extract data and add it to meta-analysis excel table provided.

➔ In case there are papers which you want to include, but that did not turn up in your search, please clearly mark them, so that the process of papers inclusion stays transparent.

Inclusion criteria

- Consider studies that turn up in the search according to the following inclusion criteria:
    a. *Subject studied*: plaice, sole, cod, haddock, mackerel, herring, sprat, anchovy, hake, red mullet, sardine, dolphinfish, Bluefin tuna, shrimp, squid, salmon, eel, pikeperch, shad, coregonids, cyprinids (carp), seabass, seabream, rainbow trout, oyster, mussel, clam (all life stages)
    b. *Control treatment: ambient temperature (we assumed the median treatment to be the temperature control), pH (we followed the author's "ambient conditions" (7.9 - 8.21 or lowest µatm treatment for CO2 in sea water, for freshwater we used 7.0-7.8 as a control), oxygen (not yet defined), salinity conditions (excluded due to scarcity of data).*

       CC effect treatment: non-ambient temperature (2-5°C warmer than control), pH (up to 0.6 less than control for sea water, up to 1.5 less in fresh water), oxygen (not yet defined) or salinity conditions (excluded due to scarcity of data)
    c. *Response*: Growth/size (mass, length, diameter, VBG parameters, weight-length relationships), developmental rate, mortality/survival, metabolic rate (SMR, RMR, SDA, MMR, AS), aerobic metabolic scope, optimal/critical/lethal/preferred treatment conditions (including limits, thresholds, ranges). See excel.
    d. *Comparator*: True control treatment in experimental studies are obligatory. Only data from sources where a relationship between a CC-related stressor and the impact on potential organismal traits/parameter, such as growth, is revealed (e.g. an experiment where different temperatures are tested with regard to the effect on larval growth of trout) should be recorded. But not the data of studies in which a trait/parameter is measured at one single temperature. The latter should only be collected if there are no data on stressors effects and some empirical relationships have to be derived from the literature by compiling different studies.

       An exception are optimal/critical/lethal/preferred treatment conditions including limits, thresholds, ranges, as these can be reported in isolation, without a comparator.

e. *Type of study*: Any primary studies with appropriate comparators and variance measures (number of true replicates (n!), standard deviation of the mean (SD)). If standard error (SE) instead of SD is reported, calculate SD from SE and n ($SD = SE * \sqrt(n)$). The meta-analysis cannot be conducted without the variance measures.

- Consideration of the following issues of non-independence:
  - Multiple experiments within one study:
    Choose single experiment per study (aggregate measures of outcome per study, if not possible, chose result with largest sample size)
  - Multiple measures of outcome: Choose single most important measure (deal with in final table stage)
  - Multiple treatments with common control: derive new variance for several common experimental designs
  - Repeated measures: Use single time point (final measurement) and use effect metric that assesses change over time (for example assuming a linear response if feasible)
  - Factor to be considered as confounding moderators in later analysis: multiple studies from same author/group, phylogenetic distance

Cross-check search protocol before start of search:

A search on a small subset of data was conducted by everyone involved in the literature review to make sure inclusion criteria lead to same results. The results were checked for consistence and the inclusion criteria adjusted if necessary.

Cross-check search term:
("common sole") AND (temperature OR climate change OR climat* shift OR acidi* OR pH OR oxygen OR hypox* OR hypercapn* OR O2 OR salinity OR freshening OR stress* OR thermal) AND (tolera* OR limit* OR critic* OR lethal OR threshold* OR growth OR weight OR mass OR diameter OR develop* OR mortality OR surviv* OR metaboli* OR respir* OR oxygen consumption OR prefer* OR thermal window OR aerobic scope OR metabolic scope OR sensitivity) NOT (chem* OR enginee* OR technology)

The above term is a shortened version for the cross check. In the true search, the following species names have to be included in the first parenthesis: "dover sole" OR "black sole" OR "Solea vulgaris" OR "pleuronectes solea" OR "Solea solea"

(51 results in Web of Science)

Analyses

The analyses were conducted using the package “meta” from R (Viechtbauer 2010). The selection criteria after the initial search included Target species, relevant explanatory variables and response variables, suitable measures of ambient and treatment effects, data must belong to experiments, mean and variance must be provided, and true replicates must also be identified.

The LnResponseRatio (LnRR) for each pair of treatments was calculated, and a model defining summed up weighed effect size created following Harvey et al. (2013).

We used the random effect model (RE), which assumes a variability in the treatment effects (whereas Fixed Effect Model (FE) assumes an overall common effect). The model estimates the mean of all effect distributions, and is weighted for both within-study and between-study variation (tau2, theta2). It is similar to FE model but with wider confidence intervals, thus more stringent. The RE gives relatively more weight to smaller studies. The effect metric, LnRR, is given by

$$L = \ln(R) = \ln(\bar{X}_E) - \ln(\bar{X}_C)$$

where E is effect and C is control, both referred to their mean values. This is considered as accurate with small sample sizes, as was the case, and is often used in ecology. The variance (V) is given by

$$V_{lnR} = S^2_{pooled}\left(\frac{1}{n_1(\bar{X}_1)^2} + \frac{1}{n_2(\bar{X}_2)^2}\right),$$

Where S2 pooled is the standard deviation.

All graphs are presented using standard forest plots (Viechtbauer, 2010, 2017)

Appendix 5

Indirect effects of climate change on fish through effects on estuarine habitats.Anita Franco and Mike Elliott. Institute of Estuarine and Coastal Studies, University of Hull, Hull, UK

*Abstract:*Climate-induced alterations of temperature, hydrological regime, saline intrusion, water quality and habitat availability in transitional waters are likely to affect fish use of estuaries. Abiotic changes may solicit physiological and behavioural responses in fish, altering the performance of individuals at different life stages or from different populations, influencing dispersal and recruitment and affecting species interactions within communities. Ecological effects may occur at individual, population and community levels, possibly affecting the productivity and functioning of aquatic ecosystems. These changes have the potential to influence marine fishery stocks that depend on estuaries for part of their life stage (as nurseries) and at the same time may influence the ecological status and condition of transitional water systems. The possible indirect effects of climate-induced changes on fish in estuaries has been reviewed here.

Temperature has a major influence on all aspects of the physiology and ecology of fishes hence much of the research on climate-induced changes has addressed the role of this factor. Temperature changes may affect egg and larval development and hatching, activity and metabolism, immune function, swimming performance and behaviour, foraging rate, growth, maturation, prey availability, predation risk and mortality. Phenology of crucial events such as spawning and migration might be affected, as well as the reproductive and recruitment success, population viability and productivity and species distribution range (via invasions and local extinctions). Research showed that many of the species that may be affected include fish using transitional waters for most or all of their life cycle, hence leading to potential changes to the composition, diversity, abundance and habitat use of estuarine fish assemblages.

Climate-induced shifts in hydrological and salinity conditions may result in transitional waters following the reduction in river runoff and river discharge, increase of intrusion of marine waters (with alteration of the estuarine salinity gradient) and increase of the frequency of drought events. Research showed how these factors may affect the suitability of estuarine habitats as nursery grounds for marine migrant species, leading to changes in the recruitment success, production, abundance, diversity, and functional structure of estuarine fish assemblages. Migrations of diadromous species through the estuary may also be affected by the loss of suitable riverine habitats induced by the alteration of hydrological regime.

Through sea level rise, climate change has the potential to modify the estuarine topography thus altering the availability, configuration and location of intertidal habitats. These may have an important role as nursery and feeding ground for fish, hence the loss of these habitats (e.g., due to coastal squeeze) may decrease the capacity of estuaries to support life-history diversity, with potential long-term effects on the viability of estuarine-dependent fish populations.

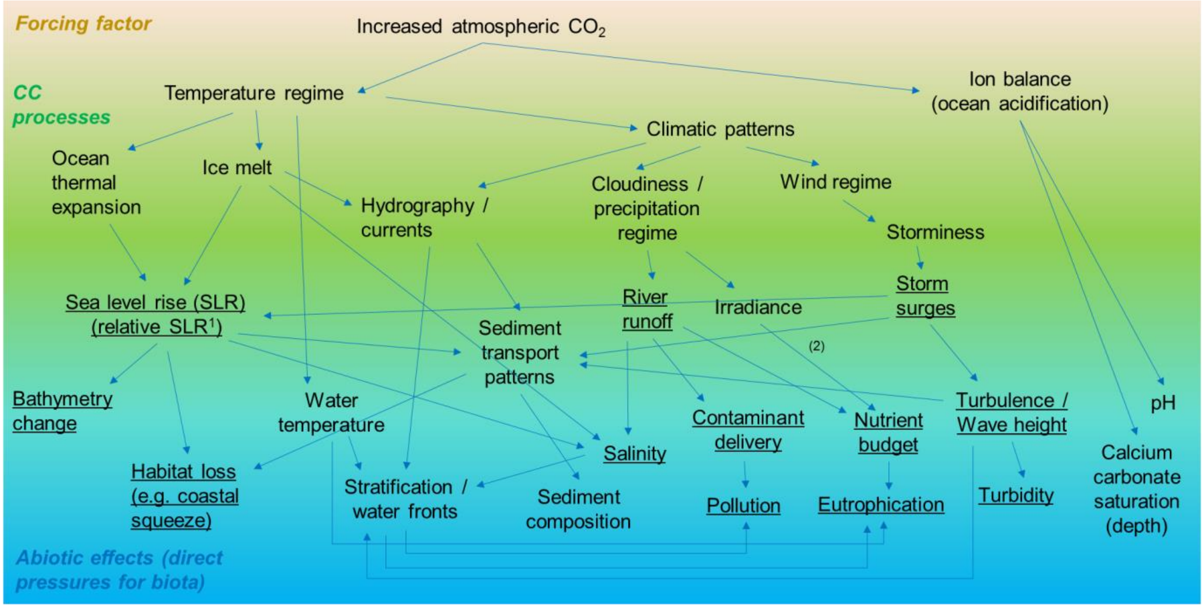
Estuarine environments may be highly susceptible to climate-induced water acidification. The potential for this factor to affect habitat selection, feeding predator avoidance behaviour, spawning and migration behaviour, mate choice and reproductive behaviour has been demonstrated for several fish species, including species that are commonly found in estuaries. As a result, shifts in fish community structure may in occur in transitional waters as a consequence of reduced pH levels.

Climate change may indirectly alter other abiotic conditions in estuaries, leading for example to reductions of dissolved oxygen concentration, changes in ocean circulation and in dilution and residence time of dissolved nutrients and pollutants. These changes have the potential to influence many aspects of the ecology of fish, including habitat use, reproductive success, growth, predation risk, thus negatively affecting the carrying capacity of estuarine ecosystems.

Key words: Temperature, salinity, hydrological regime, habitat loss, acidification, individual performance, recruitment success, phenology, population viability, estuarine production, fish community structure.

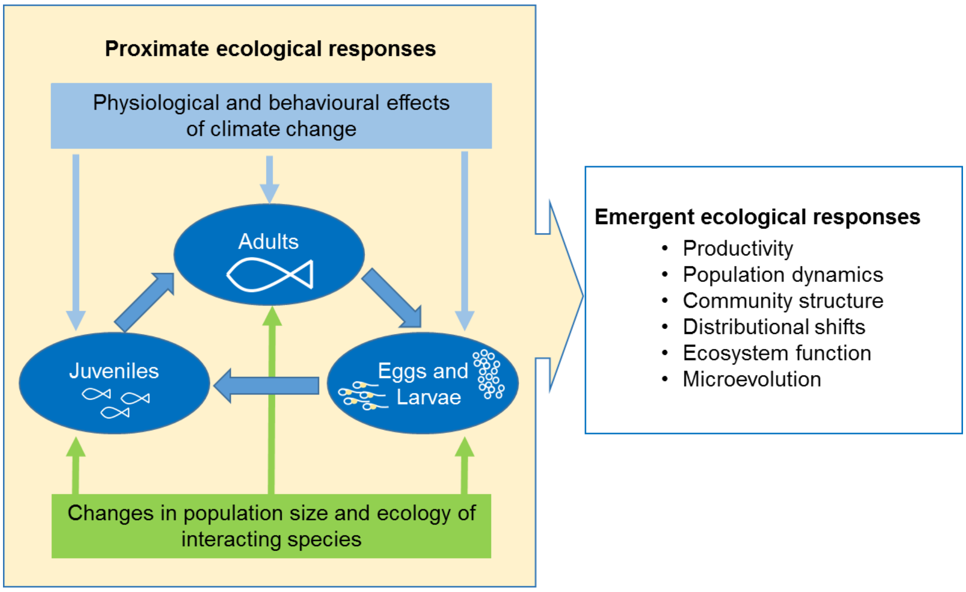
Introduction: Estuarine ecosystems may play an important role in supporting marine and inland fisheries, particularly for those marine species that use estuarine habitats during critical stages of their life cycle (marine migrants, e.g. sole, plaice, cod, herring) or for those migratory (diadromous) fish using estuaries as pathways for their spawning migrations (e.g. catadromous species as eel, anadromous species as salmon) (Franco et al., 2008; Potter et al., 2011). Being at the interface between aquatic and terrestrial ecosystems, and between marine and freshwater systems, estuaries may be particularly affected by climate change (CC), with consequent changes in the physical, geomorphological and biogeochemical environment. These changes may alter the functioning of estuaries as essential habitats (namely juvenile habitats / nurseries) for marine fishes as well as the connectivity between the marine and freshwater realms, thus affecting indirectly marine and inland fisheries. Although these effects cannot be directly included in the predictive models developed for marine fish stocks, as they originate and operate outside the strictly marine spatial domain, it is important to take them into account as they may contribute to the unexplained, residual variability and uncertainty of these models. As such, a literature review was undertaken by UHULL in order to integrate WP2 results with findings on how climate-induced changes in estuaries may indirectly affect fishes while using the estuarine environment.

Fish experience climate through temperature, winds, currents and precipitations (Ottersen 2001, 2010). In transitional waters, additional climate effects on fish populations and communities would also likely act through alterations in the estuarine habitat availability and suitability as affected by changes in the hydrological regime, saline intrusion, water quality and habitat loss (Scavia *et al.*, 2002; Roessig *et al.*, 2004; Graham and Harrod, 2009; Gillanders *et al.*, 2011; James *et al.*, 2013) (Appendix 5 Figure 1). These factors may affect the ecology of fish at individual, population and community level through physiological and behavioural effects and by altering the inter-specific interaction dynamics within communities. This leads to emergent ecological responses (e.g., changes in species distribution, community structure; Appendix 5 Figure 2) which can indirectly affect marine fish stocks by influencing their life stages while in estuaries. These effects are reviewed in detail in this report, with particular attention to marine species and life stages depending on estuarine habitats for part of their life cycle (e.g. juveniles using estuarine habitats as nurseries).



¹ Including effect of vertical land movement; ² Effect mediated by biotic processes (primary production)

Appendix 5 Figure 1. Primary drivers and processes of marine global climate change and resulting effects on physico-chemical properties of the marine environment. Elements underlined indicate CC factors and effects that are relevant only to estuarine habitats, whereas those not underlined are relevant to both estuarine and marine environments.

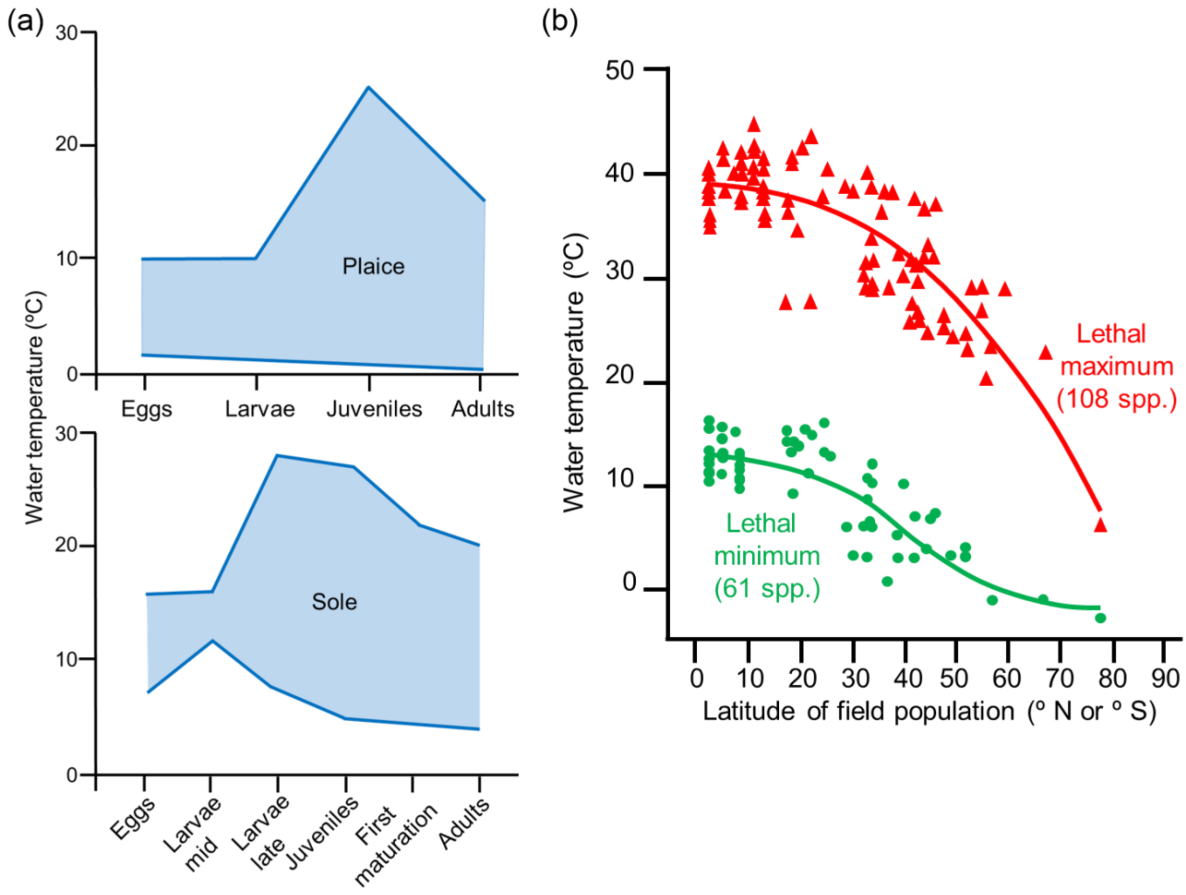


Appendix 5 Figure 2. Conceptual diagram of potential ecological responses of fish to climate change (modified from Graham and Harrod, 2009).

Temperature change

Temperature has a major influence on the ecology and physiology of fishes, hence the bulk of research on the likely effects of climate change on fish has concentrated on the role of this factor (Graham and Harrod, 2009). Furthermore, effects of temperature changes are likely to be enhanced in the shallow waters of coastal and transitional areas (Pörtner and Peck, 2010).

Temperature changes may affect almost all aspects of fish physiology and ecology, including egg and larval development and hatching, activity, oxygen demand, swimming performance, distribution, growth, maturation, immune function, seasonal timing (phenology) of crucial events such as spawning and migration, foraging rate, production, reproductive and recruitment success, prey availability, predation risk and mortality (Graham and Harrod, 2009 and references therein). The effects can vary between species or even between different life stages of an individual species, according to the variability in their thermal tolerance range (Figure 3). Early life stages (eggs and larvae) are the most sensitive to temperature changes, due to their narrower thermal tolerance window compared to juveniles and adults (e.g., plaice (*Pleuronectes platessa*) in the Northeast Atlantic, Freitas *et al.*, 2010; common sole (*Solea solea*) in the North Sea, Rijnsdorp *et al.*, 2009). Thermal tolerance ranges vary also within and among fish species depending on the latitude of the field population, with wider ranges being generally observed in fishes inhabiting mid-latitudes compared with fish at high and low latitudes, reflecting their adaptation to larger seasonal thermal fluctuations (Pörtner and Peck, 2010).



Appendix 5 Figure 3. Change of temperature tolerance range in marine fish species (a) by life stage (modified from Rijnsdorp *et al.*, 2009 and Freitas *et al.*, 2010) and (b) latitude of the species and/or population (modified from Pörtner and Peck, 2010).

The association between temperature changes and reproductive phenology has been observed, for example in populations of common sole in the North Sea, Irish Sea and English Channel (Fincham *et al.*, 2013). Significant results were obtained also for resident species in transitional waters, as in the case of the grass goby (*Zosterisessor ophiocephalus*) in the Venice lagoon, Italy (Zucchetta *et al.*, 2012). Such shifts in the timing of spawning with the warming sea temperature may affect the match-mismatch dynamics between the timing of larval development and the availability of planktonic food (Cushing, 1990).

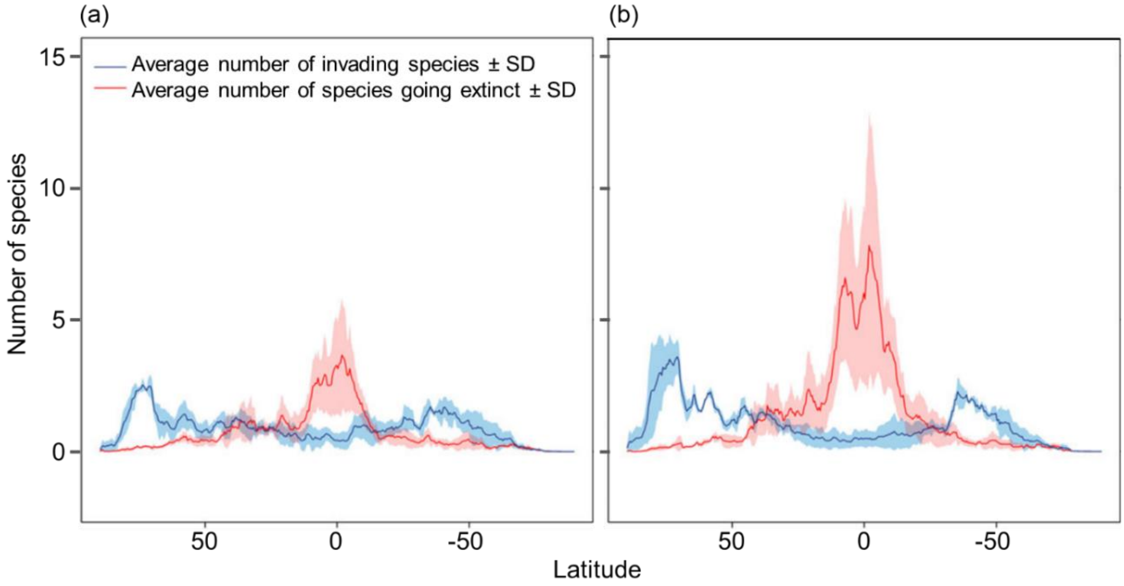
Temperature changes may affect also population viability and productivity of fish species using transitional waters during their life cycle or part of it. This could be mediated by behavioural effects, for example through impairment of antipredator behavioural performance at higher temperature as observed in juveniles of European sea bass (*Dicentrarchus labrax*) (Malavasi *et al.*, 2013). In species with multiple spawning throughout the year, higher temperature may have differential impact on different young-of-the-year cohorts. Vinagre *et al.* (2013) reported potential benefits for earlier 0+ cohorts of Senegalese sole (*Solea senegalensis*) compared with higher mortality in later 0+ cohorts. Life stages of a same species may also respond to temperature increase in different ways; for example estuary perch (*Percalates colonorum*) showed faster growth at younger ages in years characterized by warm temperatures, this being the result of factors associated with physiological sensitivity or ontogenetic diet change (Morrongiello *et al.*, 2014). Also changes in the connectivity between marine spawning sites and estuarine nursery areas may play a role in affecting recruitment success (Pörtner and Peck, 2010), this latter factor being the principal cause of fluctuations in fish stocks productivity (Garrod, 1983).

Effects of temperature on recruitment success are considered as particularly relevant to the large-scale geographical distribution and productivity of fish stocks (Graham and Harrod, 2009; Pörtner and Peck, 2010). In addition, as fish are thermal conformers (Brill *et al.*, 1994), thermoregulation occurs through active migration into waters that meet the fish physiological optima (Magnuson and Destasio, 1997). Through these effects, climate change may determine shifts in the geographical distribution of fish species, as observed in the North Atlantic where the rate of immigration of southern species of marine fish has been related to the warming of the water over the last 40 years (Stebbing *et al.*, 2002). Such effects are generally more evident where the northern and southern boundaries of the geographic range of species occur compared with populations at the centre of their distribution (Graham and Harrod, 2009; Pörtner and Peck, 2010). The degree and sign with which climate variability affects stocks at the edge of their range is not geographically uniform (Genner *et al.*, 2004). For example, cod (*Gadus morhua*) in the North Atlantic showed a positive correlation between North Atlantic Oscillation index and recruitment at the southern boundary while a negative correlation was recorded at the northern boundary of the species distribution (Brander and Mohn, 2004).

The effect recorded in an area may vary with the species, possibly leading to northward or southward shifts in the distribution range of different marine species in the same area (Perry *et al.*, 2005). Evidence of a northward shift in the species distribution was given also for several typical estuarine species (completing part or all of their life cycle in transitional waters) in European tidal estuaries along the northeast Atlantic seaboard over the last 30 years (Nicolas *et al.*, 2011). These shifts were consistent with the assumption of a northward migration or extension of estuarine nursery grounds of marine migrant species in response to global warming, although the combination with local-scale processes could not be excluded (Nicolas *et al.*, 2011). In conditions where this northward shift is strongly constrained by geographical boundaries (e.g., in partially enclosed seas as the Adriatic Sea; Pranovi *et al.*, 2013) or by the availability of suitable habitats (e.g., in the North Sea; Rutterford *et al.*, 2015), the water temperature increase might result in the latitudinal squeeze of the fish distribution range, and, eventually, in the loss of cold species from the wider ecoregion.

Through these effects, climate change may alter the available pool of species that can make up the estuarine fish assemblage, thus potentially affecting the taxonomic composition and species relative abundance in transitional water areas. The direction and magnitude of such changes would be site-specific, due to the geographical constraints mentioned above. For example, climatic variability was found to have a principal controlling influence on fish fauna in the Thames Estuary, UK, by affecting the community structure, the growth of many resident juveniles and the abundance of many of the dominant fish species using the estuary as a nursery area (Attrill and Power, 2002). Although the North Atlantic Oscillation (NAO) was the main factor responsible for such variability, the effects on growth and abundance were ascribed mostly to the opportunistic use of available thermal habitat in the estuary. This led to the increase in the population size of southern species as for example European sea bass and sprat (*Sprattus sprattus*) and the decrease in the population of flatfishes and of northern species such as herring (*Clupea harengus*) during high NAO years (Attrill and Power, 2002).

The water warming might result also in the increase of the overall fish species diversity, particularly at high latitudes in the Northern hemisphere and low latitudes in the Southern hemisphere. In this areas, Jones and Cheung (2015) predicted a net dominance of invasion of species (from lower or higher latitudes, respectively) over local extinctions under different climate change scenarios (Appendix 5 Figure 4). A significant increase in the number of fish species has been recorded in the North Sea, and ascribed to the higher species richness generally associated with assemblages at lower latitudes (Hiddink and Ter Hofstede, 2008). Amongst the marine species that showed the wider expansion in range were also species that have been reported to undertake seasonal migrations to estuarine and lagoon areas as for example anchovy (*Engraulis encrasicolus*) and striped red mullet (*Mullus surmuletus*) (Franco *et al.*, 2008; Potter *et al.*, 2013). Therefore, their contribution to the diversity of estuarine fish assemblages at northern latitudes is expected to significantly increase with global warming. A signal of such climate effect was highlighted in the Thames Estuary, where an increase of diversity in the estuarine fish assemblage was observed during wet, warm winters (high NAO index) (Attrill and Power, 2002). This was partly explained by the significant increase in the number of rare species, mostly species with a southern distribution such as for example gurnards, anchovy, wrasse, and weeverfish (Attrill and Power, 2002).



Appendix 5 Figure 4. Mean total number of species predicted to invade and go locally extinct at different latitudes between 2000 and 2050 under climate change scenarios (a) RCP 2.6 and (b) RCP 8.5 (IPCC, 2013). The shaded area represents confidence intervals at 1 standard deviation (SD) (from Jones and Cheung, 2015).

The use of estuaries as pathways of migration for diadromous species may also be affected by increased water temperature through the exacerbation of deleterious effects of other environmental conditions such as eutrophication or reduced levels of dissolved oxygen. These effects would be particularly evident on those species that are sensitive to such conditions as for example salmonids (family Salmonidae), shads (*Alosa* spp.) (Crisp, 1996; Maes *et al.*, 2008). This might potentially affect (negatively) the abundance of diadromous species and therefore the condition of Natura 2000 sites where such species are a reason for the site designation.

Hydrodynamic regime (incl. salinity gradient)

Changes in abundance and frequency of precipitations under future climate conditions have the potential to affect estuarine fish assemblages through changes in the hydrological regime and conditions, and through the alteration of the balance between marine and fresh waters in estuarine systems (Struyf *et al.*, 2004).

Chaalali *et al.* (2013) provided evidence of how past climate induced shifts in estuarine hydrological and salinity conditions have had an effect on estuarine fish species in the Gironde Estuary, France. Together with the warming of estuarine waters, an increase in the intrusion of marine waters was observed in the estuary in 1987 as a consequence of a decreases river discharge and river runoff. This was considered as the main responsible for the observed changes in the abundance of fish species using the system as a nursery ground (Pasquaud *et al.*, 2012; Chaalali *et al.* 2013). Such changes resulted for example in an increased use of the estuary by small marine pelagic fish (e.g., sprat, anchovy), whereas opposite trends were observed for flounder and catadromous species such as smelt (*Osmerus eperlanus*) (Pronier and Rochard, 1998; Pasquaud *et al.*, 2012; Chaalali *et al.* 2013).

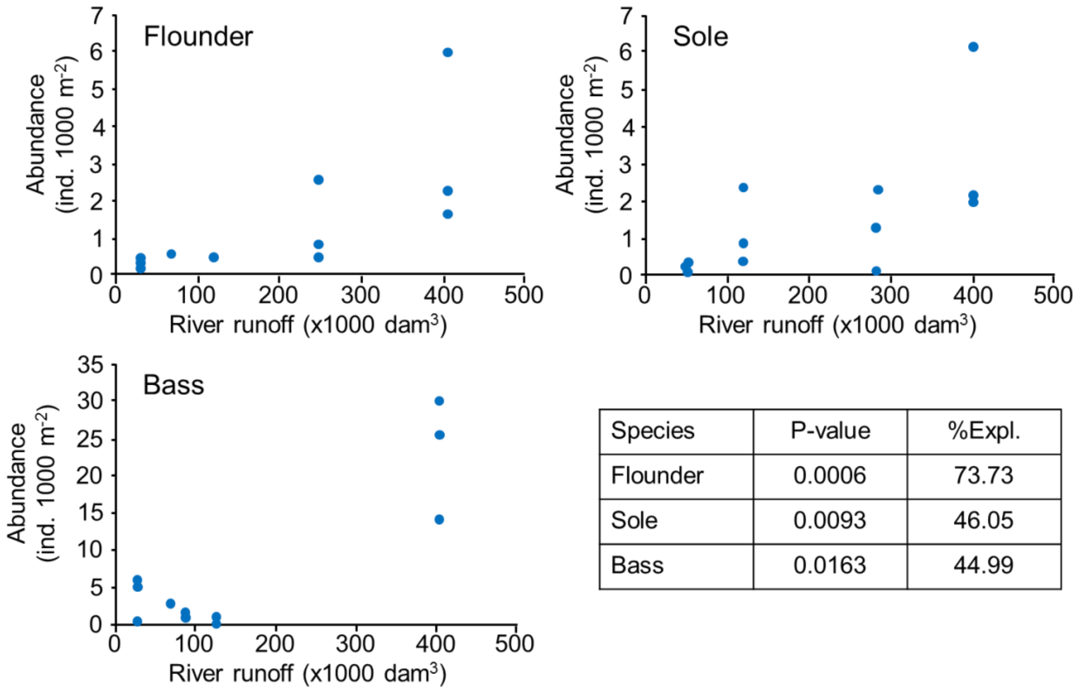
The salinity gradient has been identified as a major influence on the settlement and distribution of flounder larvae and juveniles in transitional waters, this factor acting as an external cue for the migratory behaviour in flatfish larvae from marine spawning areas towards estuarine nurseries (Bos and Thiel, 2006; Zucchetta *et al.*, 2010). Alterations of such gradient have therefore the potential to change the suitability of estuarine nursery habitats for these marine migrant species, thus leading to changes in their use of the estuary with possible consequences for the connectivity with adult marine stocks.

Increases in salinity have also the potential to reduce species richness and diversity of estuarine fish assemblages, with freshwater and diadromous species becoming less abundant, as observed in Australian estuaries (Zampatti *et al.*, 2010). Changes in salinity have been predicted also as a major driver of fish biodiversity in the Baltic Sea, an estuarine ecosystem where waters are expected to become warmer and fresher as a consequence of climate change (Mackenzie *et al.*, 2007). As a consequence of such conditions, a partial contraction of the distribution of marine-tolerant species is expected, whereas habitats of freshwater species will likely expand (Mackenzie *et al.*, 2007).

Significant effects of climate-induced alteration of hydrological regimes have been predicted also for salmonids in the south-east of England (Graham and Harrod, 2009; and references therein). These changes are mostly ascribed to a loss of suitable riverine habitat due to reduced runoff, low water flow, higher water temperatures and lower water oxygenation (Graham and Harrod, 2009). However, the resulting effect on both upstream and downstream migrations of these anadromous species would have consequences for the use of estuarine areas as well (Solomon and Sambrook, 2004; Graham and Harrod, 2009). On a wider scale, such alterations are likely to contribute also to a range contraction in the species distribution, with the loss of southern populations and the northward distribution of salmonid species predicted as a result of changing temperature, rainfall and river runoff (Graham and Harrod, 2009).

Fish assemblages in transitional waters are likely to be significantly affected also by the increase in the frequency of extreme drought events as predicted in future climate scenarios. The reduced river runoff during extreme drought events have proved to significantly affect the structure of estuarine fish assemblages, the recruitment and production of marine migrant and estuarine resident species, particularly in estuaries at lower latitudes (Martinho *et al.*, 2007, 2009; Dolbeth *et al.*, 2008; Nyitrai *et al.*, 2013; Boucek and Rehage, 2014) (Appendix 5 Figure 5). A depletion of freshwater species, a decrease in abundance of the estuarine residents and an increase in marine stragglers have been associated with such events (Martinho *et al.*, 2007; Nyitrai *et al.*, 2013). A significant reduction in the estuarine production has been also recorded in driest years, with possible implications for the nursery role of such habitats (in terms of export of secondary production to marine stocks; Dolbeth *et al.*, 2008). The effect of freshwater inflow on the recruitment success has been also reported for certain estuarine-dependent fish, with high freshwater inflows acting as spawning cues for adults and potentially providing favourable conditions for larvae (e.g., estuary perch; Morrongiello *et al.*, 2014).

Through the above described effects, climate change has the potential to affect all the metrics measuring the structure and abundance of fish communities in transitional waters, by affecting the abundance distribution across species and guilds. Furthermore, the effect on the use of estuaries by fish species and on their geographical distribution is likely to influence the future conservation status of Natura 2000 sites where these species are relevant features for the site designation (as it is often the case for salmonid fish).



Species	P-value	%Expl.
Flounder	0.0006	73.73
Sole	0.0093	46.05
Bass	0.0163	44.99

Appendix 5 Figure 5. Relationship between abundance of 0-group individuals of flounder, sole and bass and river runoff (during the third month prior to the period of estuarine colonisation) in the Mondego Estuary, Portugal. Significance (P-value) and percentage of the deviance explained (%Expl.) by river runoff within the gamma-based GLM fitted to the abundance data and environmental variables (modified from Martinho *et al.*, 2009).

Habitat change/loss

The loss of intertidal habitats (including tidal flats and saltmarshes) is an extreme pressure in estuarine areas, as a consequence of the cumulative impacts of a range of anthropogenic pressures (Colclough *et al.*, 2010). Through sea level rise, climate change has the potential to modify the estuarine topography thus further altering the availability, configuration, and location of habitats, particularly where the habitat high water mark is residing against hard defence structure such as a sea wall (through coastal squeeze; Pontee, 2013).

Estuarine intertidal habitats may have an important role as nursery and feeding grounds for fish, particularly at juvenile stage (Laffaille *et al.*, 2000; Paterson and Whitfield, 2000; Elliott and Hemingway, 2002; Franco *et al.*, 2006; Rountree and Able, 2007). Therefore, the loss of these habitats may have important implications for the structure and functioning of fish assemblages in transitional waters, and for the marine fish stocks that depend on these habitats for their function of nursery. Limitations on the availability of estuarine nursery habitats may act as a bottleneck for population size and productivity (Pörtner and Peck, 2010). This is particularly true for those broadcast marine spawning species where the size of populations is determined by the size and availability of spawning and nursery habitats (e.g., flatfishes; Rijnsdorp *et al.*, 1992; Gibson, 1994). Effects of climate change on estuarine habitat loss have been indicated also as critical to the long-term survival potential of some rearing salmonids for which estuarine marsh habitats have an important role as foraging and refuge areas (Koski, 2009; Flitcroft *et al.*, 2013). Similarly, the vulnerability of other highly productive estuarine nursery habitats to climate change (e.g., seagrass) might significantly affect the survival and recruitment of young fish in transitional waters, hence the viability of fish populations in these systems and at sea (Jones, 2014).

The loss of such important habitats, the consequent change in the estuarine habitat mosaic and possible reduction in habitat diversity are likely to lead to a decrease in the capacity of estuaries to support life-history diversity (Flitcroft *et al.*, 2013). However, positive effects on fish nursery production have been also predicted as a result of the habitat fragmentation possibly induced by sea level rise (Fulford *et al.*, 2014). Therefore, although variable, changes may be expected on the composition and abundance of fish assemblages in estuarine systems, as mediated by the effects on single species populations. If habitat changes result in a reduction in the nursery potential of estuarine areas, this might also lead to a reduced use by marine migrant species, with consequent possible alterations in the connectivity with and viability of marine adult stocks at sea.

Water acidification

Consequent to climate change, in the second half of this century the surface ocean will experience CO_2 levels that are known to significantly impair the behaviour of some marine fishes (Leduc *et al.*, 2013). A higher susceptibility of estuarine environments to reduced pH can be expected, because they are shallower, less saline and have lower alkalinity compared to marine waters and are also likely to have additional sources of CO_2 such as via freshwater input (Miller *et al.*, 2009).

Studies on both freshwater and marine fishes have demonstrated the potential for water acidification (even with relatively small changes in pH) to affect habitat selection, feeding predator avoidance behaviour, as well as spawning and migration behaviour (e.g., in salmonids), or mate choice and reproductive behaviour (as observed in species that are commonly found also in estuaries, such as pipefish and sticklebacks) (Leduc *et al.*, 2013 and references therein). Due to the variable sensitivity of different species to acidification, shifts in community structure would probably occur, favouring more tolerant species. Such shifts would be likely affected also by indirect effects on prey-predator relationships (e.g., shifts in prey preference by predators, variable prey tolerance), although the potential for genetic adaptation of fishes on an evolutionary perspective cannot be excluded (Leduc *et al.*, 2013).

Other effects and synergies

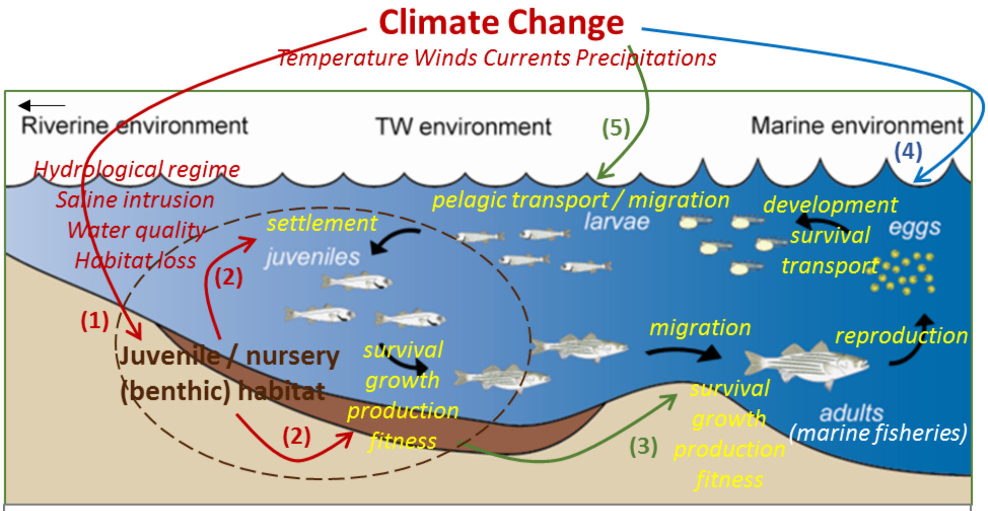
As mentioned before, climate-induced changes described in the previous sections might also affect fish fauna in transitional waters indirectly by exacerbating environmental conditions to which fish species may be sensitive. For example, reductions of dissolved oxygen concentrations might occur following the warming of waters, coupled also with the higher oxygen demand at higher temperature (due to higher metabolic rates). These conditions have the potential to influence many aspects of the ecology of fish, including habitat use, reproductive success, growth and predation risk, thus negatively affecting the carrying capacity of aquatic systems (Graham and Harrod, 2009).

Effects on wind intensity and patterns, and ocean circulations will have the potential to affect the connectivity between estuarine and marine habitats. By affecting the fish larval transport from spawning grounds to estuarine nurseries, this might have consequences on the fish use and species composition in these latter environments.

Also, increased residence times in transitional waters would likely reduce the dilution of dissolved nutrients and pollutants and increase the time to flush then from the system (Struyf *et al.*, 2004). This might affect the estuarine fauna through an increased risk and frequency of algal blooms and consequent low oxygen conditions and greater exposure to pollutants (Graham and Harrod, 2009).

Indirect effects on marine fisheries – a conceptual model

The links between CC factors, consequent abiotic changes in estuaries and their potential relevance to fish in estuaries and to marine fisheries, as depending on the factors described above, have been summarised in a conceptual model as reported in Appendix 5 Figure 6 and in Appendix 5 Annex 1. Consideration has also been given to assumptions and confounding factors in establishing a cause-effect relationship between climate-induced changes in estuaries and changes in marine fisheries. These are mainly associated with the exogenous/wide scale nature of CC pressures (with effects acting simultaneously on the estuarine and the marine environment, hence possibly leading to difficulties in disentangling direct and indirect effects on the marine fisheries) and with the inter-dependence between estuaries and the marine environment, where estuarine use by fish may also be influenced by feedback effects of changes in the marine environment and stocks (e.g. changes in reproductive success, stock distribution, larval transport within the estuary etc) (Appendix 5 Appendix 5-Figure).



(1) CC effects on abiotic (physical, biogeochemical, geomorphological) conditions may affect habitat availability, quality and distribution.

(2) Abiotic changes have physiological and behavioural effects on fish depending on their tolerance and preferences, leading to changes in habitat use and functioning.

(3) Changes in estuarine nursery function and in fitness of individuals may affect the contribution into marine populations hence stock size and productivity.

(4) CC effects on the marine environment also directly affect marine fish populations (hence fisheries) and all processes involved.

(5) CC may affect larval transport into estuaries, and, combined with changes in (4), this may have feedback effects on estuarine nurseries.

Appendix 5-Figure 6. Life cycle of marine migrant fishes using estuaries as nurseries (dashed circle identifies nursery habitat within an estuary). In yellow are the main processes involved. Also shown are main links between CC pressures, direct and indirect effects in estuaries (red), in the marine environment (blue) and on connectivity between the two systems (green). Symbols for diagrams courtesy of the Integration and Application Network (iam.umces.edu/symbols), University of Maryland Centre for Environmental Science.

Appendix 5 Annex1 . Summary table of climate-induced changes (CC) in estuaries, their relevance to fish using estuaries and consequently to marine fisheries. Assumptions and possible confounding factors in the cause-effect relationship between CC effect in estuaries and effects on marine stocks are also identified.

CC factors relevant to estuaries	Main climate-induced (abiotic) changes in estuaries	Relevance to fish in estuaries	Relevance to marine fisheries	Assumptions	Possible confounding factors (in determining cause-effect relationship between CC effects in estuaries and effects on marine stocks)
Sea level rise (relative-) (SLR)	Coastal squeeze - intertidal habitat loss	Loss of nursery and feeding habitats (area) may affect overall estuarine production (through loss of highly productive habitats) *(note: production is intended in terms of secondary production associated with the biomass of marine migrant juvenile fish)*	(1) Reduced recruitment into marine fish populations (estuarine-dependent fishery species) and possibly reduced fitness of recruits/adults (survival, growth, size, fecundity etc.) leading to changes in marine stocks (size, reproduction, standing stock etc.)	(1) Marine population (hence fishery stock) depends on estuarine nursery for recruitment (2) Changes in the estuary are of enough magnitude to have significant effect on overall estuarine production within the timescale relevant to recruitment patterns into marine populations	(1) Habitat loss in estuaries due to other (endogenic, chronic or diffuse) pressures (land claim, dredging, anthropic developments, etc.) - disentangling the two effects may be difficult (effect of other pressures may also act at a faster rate than CC, hence with higher effects of higher magnitude on the short/medium term) (2) Marine stocks also affected by pressures acting directly on the stock in the marine environment, including CC and other pressures (e.g. fishery) - disentangling the indirect effects associated with estuarine changes from direct effects on the marine stock may be difficult (3) Changes in marine stocks (in relation to CC or other pressures) affecting reproductive success, larval fitness, transport into estuarine areas may have effect on estuarine production (via effects on larval supply and pre-settlement processes hence on initial density and condition (e.g. size) of juveniles in estuarine nursery) with feedback effect on its contribution to marine populations themselves
	Habitat change - bathymetry	Change in suitability of estuarine habitats as nursery areas may affect juvenile fish	(1) as above	(1) and (2) as above	(4) Bathymetric changes in estuaries due to other pressures (e.g. dredging activities, hydro-morphological changes consequent

CC factors relevant to estuaries	Main climate-induced (abiotic) changes in estuaries	Relevance to fish in estuaries	Relevance to marine fisheries	Assumptions	Possible confounding factors (in determining cause-effect relationship between CC effects in estuaries and effects on marine stocks)
		survival and growth hence production of these habitats, contributing to effect on overall estuarine production)			to anthropic developments) (2) and (3) as above
	Salinity gradient - longitudinal shift and extent (habitat change)	Change in distribution and suitability of nursery and feeding habitats may affect juvenile fish survival and growth hence production of these habitats, contributing to effect on overall estuarine production)	(1) as above	(1) and (2) as above	(5) Salinity gradient changes in estuaries due to other pressures (e.g. anthropic developments (e.g. barriers, dykes) altering hydrodynamics and connectivity) (2) and (3) as above
Global warming	Temperature regime (warming)	Physiological changes induced by change in temperature may affect juvenile fish survival, metabolism, growth etc. hence production of estuarine nursery habitats, contributing to effect on overall estuarine production	(1) as above	(1) and (2) as above	(2) as above (3) as above, with also indirect effects on estuarine nursery via alteration to interspecific interactions (e.g. latitudinal shifts associated with changes in temperature regime leading to local introduction/extinction of key prey, predators, pathogens; phenological changes affecting match-mismatch with food resources production)
River run-off	Salinity gradient - longitudinal shift and extent (habitat change)	*see SLR*	*see SLR*	*see SLR*	*see SLR*

CC factors relevant to estuaries	Main climate-induced (abiotic) changes in estuaries	Relevance to fish in estuaries	Relevance to marine fisheries	Assumptions	Possible confounding factors (in determining cause-effect relationship between CC effects in estuaries and effects on marine stocks)
	Water quality - contaminant delivery / pollution	Physiological changes resulting from juvenile fish response to change in habitat quality (water & sediment contamination) may affect juvenile fish survival, metabolism, growth etc. hence production of estuarine nursery habitats, contributing to effect on overall estuarine production	(1) as above (2) Bioaccumulation with effects potentially transferred/enhanced through the food web hence possible effect other stocks/species	(1) and (2) as above	(6) Habitat contamination in estuaries due to other (endogenic) pressures (e.g. chronic or diffuse pollution associated with anthropogenic activities, discharges) (2) as above (3) as above, with also indirect effects on estuarine nursery via increased sensitivity to contamination (associated with lower fitness of immigrating larvae/juveniles)
	Water quality - nutrient budget / eutrophication / water oxygenation	Mostly relevant in terms of decreased water oxygenation affecting habitat quality and use/availability (fish avoidance), with consequent effect on juvenile fish survival, metabolism, growth etc. hence production of estuarine nursery habitats and of estuary as a whole	(1) as above	(1) and (2) as above	(7) Nutrient inputs (and associated consequences) in estuaries due to other (endogenic) pressures (e.g. agricultural runoff, urban discharges) (2) and (3) as above
	Exhacerbating SLR effects	see SLR	(1) as above	(1) and (2) as above	*see SLR*

CC factors relevant to estuaries	Main climate-induced (abiotic) changes in estuaries	Relevance to fish in estuaries	Relevance to marine fisheries	Assumptions	Possible confounding factors (in determining cause-effect relationship between CC effects in estuaries and effects on marine stocks)
Storminess / storm surges	Changes to turbulence and wave height affecting sediment transport patterns, hence bathymetry and seabed morphology	see SLR - bathymetry Turbulence may also alter larval/juvenile settlement in nursery habitats (displacement and transport to unsuitable habiats or outside the estuary) with consequent effect on juvenile fish survival hence production of estuarine nursery habitats and of estuary as a whole	(1) as above	(1) and (2) as above	*see SLR - bathymetry*
	Water quality - Turbidity	Increased turbidity may affect fish survival (e.g. gills clogging), particularly where species are not adapted to high background levels	(1) as above	(1) and (2) as above	(8) Changes in turbidity in estuaries due to other (endogenic) pressures (e.g. dredging activities), albeit likely to be more localised and shorter-term compared to climate induced ones (2) and (3) as above
Hydrography / currents	Altered direction/intensity of currents between estuary and marine area	Changes in connectivity between the marine reproductive areas and the estuarine nursery areas through changes in larval transport into estuaries, with effects on overall estuarine production	(1) as above	(1) and (2) as above (3) Changes in the current pattern significantly affect input of larvae and effect on nurseries is large enough to affect overall estuarine production within the timescale relevant to recruitment patterns into	(9) Changes in connectivity between marine reproductive areas and estuarine nurseries due to other (endogenic) pressures (e.g. morphological alterations (barriers, dykes, dredging) altering estuarine morpho-hydrodynamics and conseuquent transport and settlement of larvae into estuaries) (2) and (3) as above

CC factors relevant to estuaries	Main climate-induced (abiotic) changes in estuaries	Relevance to fish in estuaries	Relevance to marine fisheries	Assumptions	Possible confounding factors (in determining cause-effect relationship between CC effects in estuaries and effects on marine stocks)
				marine populations	

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