Vol. 680: 223–246, 2021
https://doi.org/10.3354/meps13934

MARINE ECOLOGY PROGRESS SERIES
Mar Ecol Prog Ser

Published December 9

Contribution to the Theme Section 'Advancing dynamic modelling of marine populations and ecosystems'

Climate change, marine resources and a small Chilean community: making the connections

Sonja M. van Leeuwen[1,2,*], Hugo Salgado[3], Jennifer L. Bailey[4], Jonathan Beecham[2], Jose L. Iriarte[5,6,7], Luz García-García[2,8], Robert Thorpe[2]

[1]NIOZ Royal Netherlands Institute for Sea Research, Department of Coastal Systems, 1790 AB Den Burg (Texel), The Netherlands
[2]Centre for Environment, Fisheries and Aquaculture Science (Cefas), Lowestoft NR33 0HT, UK
[3]Universidad de Talca, School of Business, Talca, 3465548 Chile
[4]Norwegian University of Science and Technology, Department of Sociology and Political Science, 7491 Trondheim, Norway
[5]Instituto de Acuicultura, Universidad Austral de Chile, Puerto Montt, Chile
[6]Centro de Investigación Dinámica de Ecosistemas Marinos de Altas Latitudes- IDEAL, Universidad Austral de Chile, Punta Arenas, Chile
[7]COPAS-Sur Austral, Centro de Investigación Oceanográfica en el Pacífico Sur-Oriental (COPAS), Universidad de Concepción, Concepción, Chile
[8]*Present address:* Spanish Oceanographic Institute, 15001 A Coruña, Spain

ABSTRACT: Climate change is affecting large-scale oceanic processes. How and when these changes will impact those reliant on marine resources is not yet clear. Here we use end-to-end modeling to track the impacts of expected changes through the marine ecosystem on a specific, small community: Cochamó, in the Gulf of Ancud wider area, Chile. This area is important for Chilean fisheries and aquaculture, with Cochamó reliant on both lower and upper trophic level marine resources. We applied the GOTM-ERSEM-BFM coupled hydro-biogeochemical water-column model to gauge lower-trophic level marine ecological community response to bottom-up stressors (climate change, ocean acidification), coupled to an existing Ecopath with Ecosim model for the area, which included top-down stressors (fishing). Social scientists also used participatory modeling (Systems Thinking and Bayesian Belief Networking) to identify key resources for Cochamó residents and to assess the community's vulnerability to possible changes in key resources. Modeling results suggest that flagellate phytoplankton abundance will increase at the cost of other species (particularly diatoms), resulting in a greater risk of harmful algae blooms. Both climate change and acidification slightly increased primary production in the model. Higher trophic level results indicate that some targeted pelagic resources will decline (while benthic ones may benefit), but that these effects might be mitigated by strong fisheries management efforts. Participatory modeling suggests that Cochamó inhabitants anticipate marine ecosystem changes but are divided about possible adaptation strategies. For climate change impact quantification, detailed experimental studies are recommended based on the dominant threats identified here, with specific local species.

KEY WORDS: Climate change · Fishing · Ecosystem services · Gulf of Ancud · Patagonian fjords

1. INTRODUCTION

Marine ecosystems provide a range of benefits or services to human communities. These include provisioning services (such as fish as food source), regulating services (such as the regulation of climate, water or disease), supporting services (such as photosynthesis or nutrient cycling) and cultural services (such as spiritual, aesthetic, educational or recreational aspects of life) (Reid et al. 2005). But these systems

*Corresponding author: sonja.van.leeuwen@nioz.nl

Publisher: Inter-Research · www.int-res.com

are experiencing a range of pressures that can affect their structure and functioning, and such changes may in turn affect the marine ecosystem services on which human communities rely (Barange et al. 2010, Malone et al. 2016). One source of stress — climate change — affects large-scale oceanic processes, and the mechanism, extent and timing of its effects on a specific area or ecosystem service are seldom clear. Local conditions can generate distinctive reactions, and there are diverse pathways by which stressors can affect resources upon which human communities directly or indirectly rely. All of these issues make connecting large scale oceanic processes to local resources a formidable task (Barange et al. 2010, Rose et al. 2010, Hyder et al. 2016).

The present article relates work done to connect large-scale oceanic processes to the resources relied upon by a single community. We also explore the vulnerability of that community to prospective changes in its marine resource base. This work requires an understanding of the effects of climate change on physical ocean processes and their interaction with other ocean stressors, and their combined effects on the lower-trophic food web. These effects must then be tracked through the food web to higher trophic levels and ultimately to their effect on resources in a specific location. To this end, we adapted a hydro-biogeochemical water-column model (here GOTM-ERESM-BFM) to the area and coupled it to an existing, local food web model (Ecopath with Ecosim, EwE). The combined model was then used to simulate the ecosystem responses up to year 2100 under different scenarios, representing single and mixed oceanic stressors. The model simulates the systemic effects of changes, from the hydrodynamics, chemical composition and plankton level to the fish abundance in the Gulf of Ancud, Chile. It connects key global processes (e.g. changing precipitation patterns, rising surface water temperatures and pH changes) to the regional ecosystem that in turn affects the highly localized ecosystem. The residents of Cochamó are directly affected by all these spatial scales.

Understanding how the marine resource base may change is only the first step in understanding how such changes may affect a given human community. Much depends on the vulnerability of the community to such changes. Here, we apply Turner et al.'s (2003) definition of vulnerability as a function of the community's exposure, sensitivity and adaptive capacity. The Turner et al. (2003) framework recognizes that communities are embedded in larger socio-ecological contexts and that vulnerability must be understood as a function of these as well. However, vulnerability is also strongly affected by how local people perceive their situation (Brown & Westaway 2011, Maass et al. 2016, Siders 2019). To explore the vulnerability of the community of Cochamó, Chile, we used participatory modeling (Systems Thinking and Bayesian Belief Networks). These methodologies capture the participants' perceptions of the most important threats they believe they face and the key factors that will affect their exposure and sensitivity to change and their adaptive capacity.

The present work is only a first step in the effort to connect changes in the abiotic properties of a marine system through the trophic levels (including human impacts) to the community reliant on its services. Our results help identify which stressors are important drivers of change in the overall ecosystem and the impact ranges that can be expected. Our research goal is to quantify the future ecosystem envelope for a specific community, so that further studies can focus on specific experiments with regard to the locally important species and available industries. Thus, for a real translation to the specific needs of a local community (e.g. prospects of specific fishery activities) this type of work should be followed by detailed studies of the local species of interest and the impact the identified (combined) stressors have on them. Community-based participatory modeling provides a preliminary view of Cochamó's concerns and resources (local and regional), but extensive and comprehensive socio-economic research is required for a more complete understanding of the vulnerability of Cochamó and the soundness of its inhabitants' longer-term plans. This work was part of the EU-funded OCEAN CERTAIN project (https://cordis.europa.eu/project/id/603773).

2. METHODS

2.1. Study areas: Chilean Patagonia and the community of Cochamó

2.1.1. Environment

The Patagonian coast of Chile (41–56° S), including the Regions of Los Lagos, Aysén and Magallanes, is marked by a distinctive fjord system. The local marine system is near-permanently stratified: the Andes mountain range generates high annual rainfall causing a continuous freshwater streamflow input into the fjords, rich in silicic acid and dissolved carbons (Iriarte 2018). The local circulation is driven by the interaction between this surface layer of fresher water above a layer of the Sub-Antarctic Water (SAAW). As a result, the Patagonian fjords experience a haline buoyancy-driven circulation (Strub et al. 2019, Saldías et al. 2019). The freshwater from melting glaciers, precipitation and river runoff shows a marked seasonal freshening signal in coastal Patagonia (Saldías et al. 2019). The Pacific SAAW comes from the Antarctic and is particularly rich in dissolved nutrients, especially phosphates and nitrates (Iriarte et al. 2007). Due to the permanent stratification, there is reduced mixing of these 2 water masses, and organisms requiring light and essential nutrients (i.e. nitrate, phosphate and silicate) can only thrive at the interface of these water masses. The system has been suggested to be highly variable on a seasonal basis, where carbon fluxes are related to multivorous trophic webs (González et al. 2010). In spring, grazing pressure from zooplankton on microphytoplankton (largely diatoms) results in the relative dominance of the classical food web (phytoplankton, zooplankton, filter feeders, fishes). Conversely, in winter, zooplankton grazing (mainly on nanoplankton) results in a relative dominance of the microbial loop (phytoplankton, bacterioplankton, microzooplankton, macrozooplankton), with lower carbon export than found in spring (González et al. 2010).

The Reloncaví Basin (Reloncaví Fjord and Reloncaví Seno) and the Gulf of Ancud (see Fig. 1) are characterized by a high discharge of freshwater from the main river (Puelo River, mean streamflow: 600 $m^3 s^{-1}$), causing permanent stratification (González et al. 2010, León-Muñoz et al. 2018). Several smaller rivers also contribute to the stratification, including the Cochamó, Petrohué, Blanco and Canutillar. The estuarine surface layer varies between 1 and 30 m depth and displays salinity values ranging from 10 (Reloncaví Fjord) to 31 (Gulf of Ancud), with high concentrations of silicic acid and organic materials. The Puelo River (discharging into the sub-basin Seno de Reloncaví) shows high riverine discharge in austral winter and spring, with lower volumes in the austral summer and autumn (see Fig. S1a in Supplement 2 at www.int-res.com/articles/suppl/m680p223_supp.pdf). The oceanic water below the brackish layer consists here of Modified Subantarctic Water (MSAAW, coming in from the Pacific), which is characterized by a relative constant salinity of ~31–34 and relatively low oxygen (3–6 ml l^{-1}) but is still rich in phosphate and nitrate (González et al. 2010, Castillo et al. 2016).

In the Inner Sea of Chiloé, where the Gulf of Ancud is located, net primary production (netPP) estimates are highly seasonal, with high values up to 4 g C m^{-2} d^{-1} during summer and low values in winter (<0.5 g C m^{-2} d^{-1}) (Iriarte et al. 2007). In general, primary productivity in the Inner Sea of Chiloé, including Reloncaví system (Fjord and Seno) and Gulf of Ancud, has been indicated to be nitrate limited (Iriarte et al. 2013), with diatoms accounting for almost 90% of the total primary production, especially in austral spring and summer months. Small phytoplankton size classes (pico- and nanoplankton) better at nutrient uptake in low-nutrient conditions dominate the winter period (June–August) (González et al. 2010, Pavés et al. 2013).

2.1.2. Human community

The Gulf of Ancud, located roughly at 41° S, is an important area for Chilean fisheries and aquaculture. The Los Lagos region, which encompasses both the Gulf and the Seno de Reloncaví, is dominated by a metropolitan area (Puerto Montt), but is also populated by many much smaller communities. One of these is the community of Cochamó, which has a rural character with a total area of 3911 km^2, about 4000 inhabitants and a small town center. It is located in Reloncaví Fjord, at the point of entry the Cochamó Valley which is known as the 'Yosemite of South America'. Cochamó residents harvest a mixture of brackish and marine molluscs and fishes from Reloncaví Fjord and the near coastal parts of the Seno de Reloncaví (Fig. 1). They are, however, especially reliant on the collection of mussel seeds from the natural environment which they supply to the growing mussel mariculture industry (Figueroa & Dresdner 2016). In the time period preceding the workshop (held on the 22nd of July 2015), mussel seed harvesters had noticed changes in the environmental conditions of the fjord, and many in the community have questions about what their future strategy should be (project workshops). The community has long relied upon marine resources, mainly fishing and more recently also employment in the commercial aquaculture industry. After catch declines in the 2000s and the crash in Chilean salmon aquaculture in the area in 2007–2009 (caused by the infectious Salmon Anemia virus, Bachmann-Vargas et al. 2021), a part of the community turned to mussel seed cultivation. In recent years the area has also become a popular new tourist destination for trekking, rock climbing and kayaking (https://www.chile.travel/en/where-to-go/macrozone/the-south-its-lakes-and-volcanoes/, https://chiletourism.travel/en/where-to-go/patagonia/patagonia-de-rios-y-lagos/tour/cochamo.html). Although the community hosts some tourist fishing, most tourism in the community is not

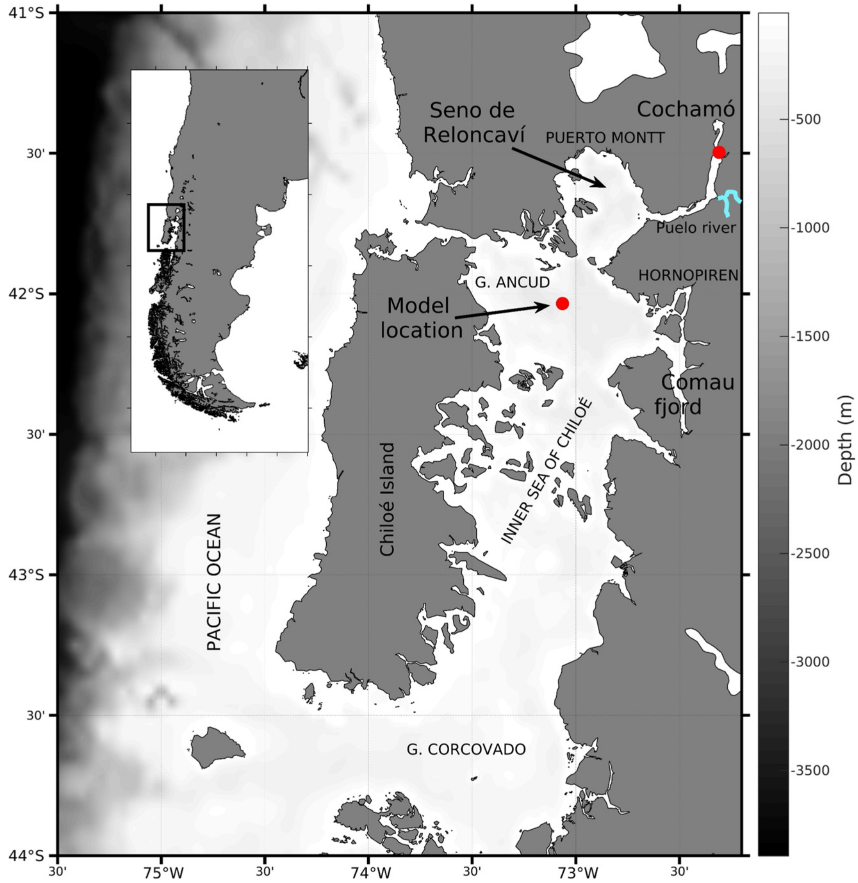

Fig. 1. Study area in a Chilean fjord system, showing the Gulf de Corcovado, Inner Sea of Chiloé and subsequent Gulf of Ancud, the Seno de Reloncaví and the adjacent Reloncaví Fjord with the Puelo river mouth. Red dots indicate the model location in the gulf and the town of Cochamó. Blue lines indicate the two main tributaries of the Puelo river and its point of entry into Reloncaví fjord

directly related to the ocean. However, ocean-related developments could affect the development of the tourism industry (by affecting water quality and the attractiveness of the community). The Los Lagos region of Chile, in which Cochamó is located, is on the whole heavily reliant on fisheries and aquaculture. With respect to the larger socio-economic setting, while Chile ranks relatively high in the Human Development Index (UNDP 2019), the Los Lagos region is one of the poorer regions of the country.

The mussel seeds that Cochamó residents harvest are from mejillón or chorito (*Mytilus chilensis*), a bivalve filter feeder (Uriarte 2008, Rivera et al. 2017). The seeds are cultivated in the fjord and sold to the growing mariculture industry located outside of the fjord in the waters of the Gulf of Ancud, Gulf de Corcovado and beyond, including the neighboring Region to the south (Aysén). Cochamó also harvests róbalo (*Eleginops maclovinus*), pejerrey (*Odontesthes regia*, Chilean silverside), jurel (*Trachurus murphyi*, Chilean jack mackerel), jibia (*Dosidicus giga*, an ommastrephid squid also known as Humboldt squid); lapa (a generic name for 13 species of keyhole limpets *Fissurella* spp. found along the Chilean coast; Herbert 1991), locos (*Concholepas concholepas*, a benthic mollusk that favors rocky substrate), and caracoles (*Trophon geversianus*, Trophon snails; a variety of marine gastropod that also favors rocky substrates).

The community of Cochamó was selected because it harvests a mix of resources typical of the smaller communities of the area (Servicio Nacional de Pesca y Acuicultura 2016), and its reliance on mussel seed cultivation relates to a major industry centered in the Los Lagos Region: Chile has become the world's leading exporter of mussels (Fernández et al. 2018). Project researchers had also established trust and the connections with respect to local community members that are necessary for work that requires stakeholder engagement.

2.2. Natural science modelling

The model location was chosen to be in the Gulf of Ancud, at 42.0° S, 73.0° W. This location coincides with Station 14 from the CIMAR cruise reported in González et al. (2010), providing much-needed observational data, and has a local water depth of 273 m. Additional reasons for choosing the model location within the Gulf of Ancud (and not Seno de Reloncaví or Reloncaví Fjord) were (1) the existence of an Ecopath model for the Inner Sea of Chiloe, (2) the location of associated mesocosm experiments within the larger project at Huinay field station in Comau Fjord (Hopwood et al. 2020) and (3) the importance of the area to Chilean fisheries in general. Simulations were performed with the GOTM-ERSEM-BFM model (GOTM, https://gotm.net/, Baretta, et al. 1995, van der Molen et al. 2013, van Leeuwen et al. 2016) coupled to the EwE model (https://ecopath.org/, Christensen et al. 2005) for the area (Pavés et al. 2013, 2014, 2015). GOTM-ERSEM-BFM is a coupled hydro-biogeochemical water-column model (1DV or 1 dimension vertical model with dimensions depth and time) that simulates the abiotic environment (vertical water movement, chemical reactions, light penetration, temperature, salinity) and the lower trophic levels of the food web (mainly plankton, bacteria and benthic organisms). Local tidal constituent data was obtained from Salinas & Castillo (2012). EwE is a food-web model representing both lower and higher trophic levels (e.g. plankton, fish, jellyfish, marine mammals) and relies on causal relationships between species. The Gulf of Ancud EwE model set-up consists of a relatively simple (parsimonious) higher tropic level food web where a variety of zooplankton species are used to feed mostly clupeids (herring and anchovy type fish), and other small pelagic species feeding into the higher trophic level species (e.g. gadoids [which represent cod and hake type fish] and Carangidae [jack mackerel]), with some non-fish predators above that (e.g. dolphins, orcas, birds, sea lions). Various jellyfish species are a side chain to the pelagic species, with limited predation. A schematic representation of the coupled model is shown in Fig. 2. More details can be found in Supplement 4, including the functional groups in ERSEM-BFM, the full list of species represented in EwE (Table S2 in Supplement 4) and species overlap (between ERSEM-BFM/EwE and the model/species of local interest), and in the listed references (for the food matrix of the EwE model see the supplement of Pavés et al. 2013). The choice of a water-column model was based on the overarching goals of the project, which focused on the vertical processes of the biological pump and the associated long-term carbon storage. It allows for many simulations within a short time frame, and so is suited to multiple-stressor interaction studies.

The models were coupled one-way upwards using the coupling library Couplerlib (Beecham et al. 2016): this introduces a management layer between the 2 models which controls the data exchange (including merging and splitting of data fields where necessary, unit conversions etc.). Simulated biomass time series of specific plankton functional groups from ERSEM-BFM were used as input into the EwE model (Fig. 2): diatoms (microphytoplankton), autotrophic nanoflagellates (ANF), ciliates (Ciliophora), heterotrophic nanoflagellates (HNF) and omnivorous and carnivorous mesozooplankton (macroflagellates). Temperature time series (top and bottom) from GOTM were also used to regulate physiological processes with EwE (mortality rates, food consumption for pelagic and benthic-oriented species, respectively). As such, bottom-up stressors like climate change and acidification affected the planktonic biomass fields (temperature affects all physiological rates in ERSEM-BFM such as ingestion, excretion, respiration and mortality), which formed the food supply at the lowest trophic levels of the EwE model. These impacts then travelled upwards within the EwE model by way of the many connections and dependencies of the simulated food web. As a result, the top-down pressure of fisheries did not affect planktonic biomass.

The simulations spanned the period 1958–2098 of which the first 20 yr were spin-up time for the model. Results are mainly presented in 30 yr averages to filter out inter-annual variation and focus on the long-term trend (see Table S1 in Supplement 1). Three stressors were applied at 2 impact levels each: climate change (CC1, CC2), ocean acidification (OA1, OA2) and fishing pressure (LF, HF). A total of 17 simulations were performed for the higher trophic levels and 7 for the lower trophic levels (Table 1). The ocean acidification (OA) and climate change (CC) stressors were both based on predicted atmospheric pCO_2 levels by the IPCC, so it would have been contradictory to have separate scenarios for acidification and climate change. For this reason, the combined scenarios considered the same levels for both stressors, but the individual stressors were maintained to gauge their separate impacts and to allow for a better understanding of the combined stressor impact. The separate acidification scenarios also aligned with mesocosm experiments within the project and can be used for further experimental studies of pH changes on specific species (e.g. pH change impact on mussel larvae survival).

Understanding how changes in the ecosystem might unfold over time requires an estimation of how key drivers may develop over time. For climate change, the scenarios RCP4.5 and RCP8.5 were applied, based on the 2014 IPCC report (IPCC 2014). The Representative Concentration Pathways (RCP) 4.5 and 8.5 meteorology (air temperature, air pressure, humidity, cloud cover, wind speed and direction) were obtained from the CMIP5 exercise (Coupled Model Intercomparison Project phase 5, Taylor et al. 2012) performed by the Cordex program (Coordinated Regional Climate Downscaling Experiment, see http://cordex.org/, spatial resolution of 0.44° or ~50 km). Comparison with ECMWF ERA-Interim meteorological forcing data showed an underestimation of summer temperatures and an overestimation of winter temperatures by Cordex (see Supplement 2). RCP 4.5 is an intermediate scenario in which greenhouse gas emissions increase by a moderate amount; RCP8.5 assumes high greenhouse gas emissions (Fig. 3).

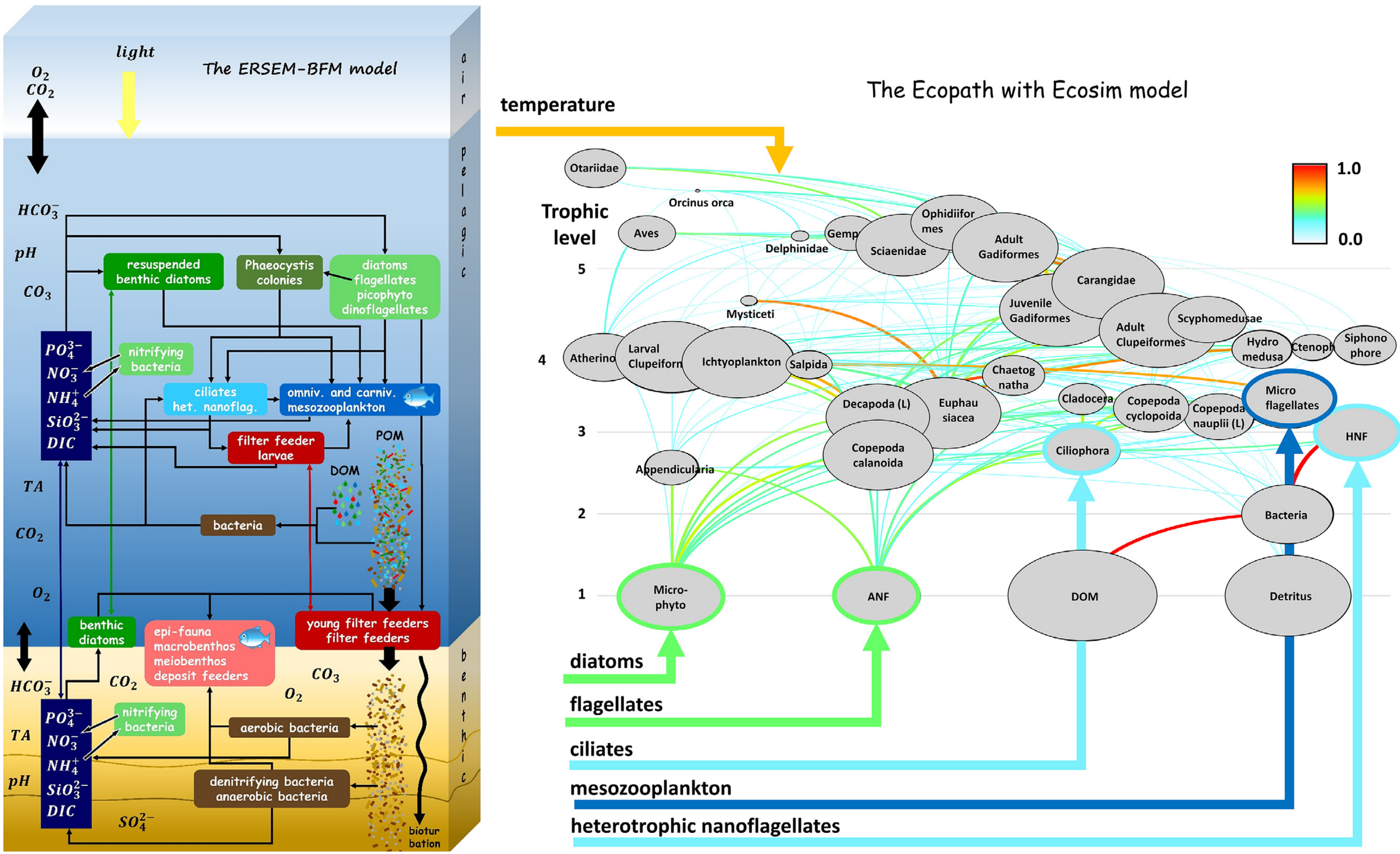

Fig. 2. The ERSEM-BFM and Ecopath with Ecosim coupled model. Note that the ERSEM-BFM model is generic (only limited parameter adjustment to account for location), but that EwE is location specific. For the species names in EwE see Table S2 in the Supplement. The scaling of EwE indicates the normalised strength of the food web connections. POM: particulate organic matter; DOM: dissolved organic matter; TA: total alkalinity

Table 1. Scenarios applied to the GOTM-ERSEM-BFM and EwE coupled model

Scenario name	Description
Reference	Repeat of the meteorology from 1979–2008, atmospheric pCO_2 values constant from 2008 onwards
Standard fishing pressure	
CC1	Meteorological conditions from the RCP4.5 pathway (Paris agreement), atmospheric pCO_2 values constant from 2008 onwards
CC2	Meteorological conditions from the RCP8.5 pathway (business as usual), atmospheric pCO_2 values constant from 2008 onwards
OA1	Repeat of the meteorology from 1979–2008, atmospheric pCO_2 values increasing according to the RCP4.5 pathway (Paris agreement)
OA2	Repeat of the meteorology from 1979–2008, atmospheric pCO_2 values increasing according to the RCP8.5 pathway (business as usual)
CC1OA1	Meteorological conditions and atmospheric pCO_2 values according to the RCP4.5 pathway (Paris agreement)
CC2OA2	Meteorological conditions and atmospheric pCO_2 values according to the RCP8.5 pathway (business as usual)
Low fishing pressure	
LF	Low fishing pressure and repeat of the meteorology from 1979–2008, atmospheric pCO_2 values constant from 2008 onwards
CC1LF	CC1 scenario combined with low fishing pressure
CC2LF	CC2 scenario combined with low fishing pressure
CC1OA1LF	Full RCP4.5 pathway combined with low fishing pressure
CC2OA2LF	Full RCP8.5 pathway combined with low fishing pressure
High fishing pressure	
HF	High fishing pressure and repeat of the meteorology from 1979–2008, atmospheric pCO_2 values constant from 2008 onwards
CC1HF	CC1 scenario combined with high fishing pressure
CC2HF	CC2 scenario combined with high fishing pressure
CC1OA1HF	CC1OA1 scenario combined with high fishing pressure
CC2OA2HF	CC2OA2 scenario combined with high fishing pressure

Ocean acidification was simulated using the predicted atmospheric pCO_2 values for RCP4.5 and RCP8.5 directly: the model calculates CO_2 exchange between the ocean and atmosphere, and the carbonate chemistry included in the model is based on the code of Dickson & Goyet (1994). Changing pCO_2 concentrations in the air will impact on this exchange and the chemical composition of the water column, leading to changing conditions for the marine organisms.

The fisheries in the Gulf of Ancud are largely pelagic, targeting Clupeiformes (order of fish that includes herring and anchovies) and Carangidae (jack mackerel). Higher trophic level species are primarily gadoids (cod and hake type species), with a few eels, snook and drum: their predation pressure will strongly influence the stocks of mid trophic level species such as mackerel, anchovies and herring. The fishing pressure F (fraction of the average stock that is caught) due to artisanal fisheries for gadoids (long line) is 0.008 locally, for Carangidae (purse seine) 0.035 and for Clupeiformes (purse seine) 0.064 (Pavés et al. 2013, their Table 3 and Annex 3). Here, we apply low (LF) and high (HF) fishing pressure scenarios. For gadoids, the low F value was set to 0.01, with the high value set to 0.2, for Carangidae these were set to 0.03 (LF) and 0.3 (HF), while for Clupeiformes these values were 0.05 (LF) and 0.5 (HF). The low–level scenario represents values just below the current artisanal fishing pressure (as this was already low), and the high level 10 times (for line-hand and long-line fisheries) or 20 times (for gillnet and purse-seine fisheries) the low level. Note that the EwE model as described in Pavés et al. (2013) only applies to artisanal fishing pressure, resulting in relatively low values for fishing pressure in this area with high commercial fisheries interests. The fishery for Clupeiformes accounts for 81% of the fishing pressure imposed here, with gadoids and Carangidae bringing the total to 97% (Pavés et al. 2013). For the different gear types applied see Supplement 4 ('Higher trophic level model').

As described in Section 2.1.('Natural environment'), the Puelo River has a strong influence on the Gulf of Ancud hydrodynamics, as its discharge in this high precipitation region creates a layer of estuarine water over the inflowing Pacific waters (León-Muñoz et al. 2013, Castillo et al. 2016). To represent this stratification within the water-column model, salinity and temperature profiles were prescribed to which the model solution was relaxed (i.e. the numerical solution is steered towards these profiles, but they are not imposed), based on the CIMAR cruise results (González et al. 2010). As such, the profiles include contributions from other regional rivers discharging into the gulf. The salinity profiles were determined by the surface salinity (dependent on riverine discharge), the thickness of the estuarine water lens (dependent on riverine discharge, air temperature, wind speed and average winter air temperature) and the near-bed salinity (dependent on oceanic salinity levels). Temperature profiles were based on the

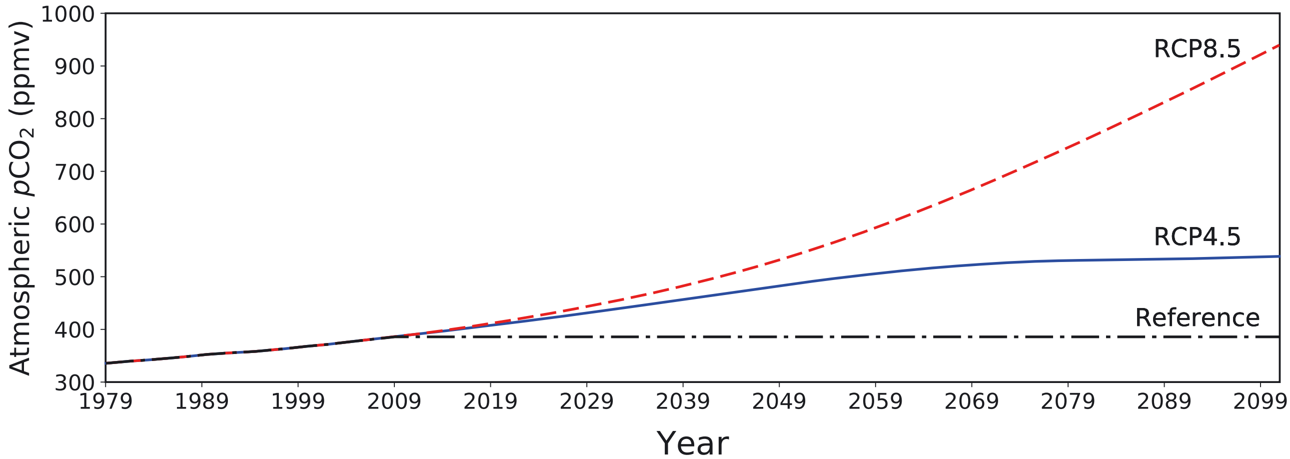

Fig. 3. The Representative Concentration Pathways that were imposed for the climate change and acidification scenarios, based on IPCC (2014). Reference: constant 2008 pCO_2 values, as used in the reference scenario. The unit ppmv stands for parts per million by volume

observed profiles in distinct seasons (winter, summer). Note that both the salinity of the oceanic layer as well as the temperature profiles only included observed seasonal dynamics and did not change under future conditions. The surface layer salinity and thickness of the estuarine water lens did change with changing future conditions, accounting for future climes and precipitation. Here, the future Puelo discharge was estimated using the normalized, averaged, seasonal signal (data available for 2003–2017) multiplied by the predicted annual precipitation (derived from the CMIP5 simulations, see Fig. S1 in Supplement 2); the area is predicted to become drier (León-Muñoz et al. 2018). However, changes to glacial melting were not included in our analysis due to lack of data, even though meltwater contributes a significant seasonal part of the run-off at present (Aguayo et al. 2019). Nutrient input from the river (mainly silicic acid and dissolved organic carbon) was related to riverine discharge and so also changed under future conditions. Note that we did not include other nutrient inputs like direct discharges from human settlements or those from aquaculture due to the chosen location (middle of Gulf of Ancud).

In order to maintain the mass balance of nutrients in the water column model, the added (riverine) nutrients were removed from the near-bed layers consisting of oceanic water (to prevent buildup of nutrients in the simulated system, i.e. mimicking the natural dispersal through horizontal advection). However, a silicate balance could not be reached; therefore, the model did not reach a true equilibrium state (i.e. the bottom layers did not contain enough silicate to allow for removal of the added riverine silicate in periods of high discharge). Also, the imposed atmospheric pCO_2 values prevented an equilibrium state in the reference simulation, as the system adjusted very slowly to the imposed, constant pCO_2 values. Although preferable from a modeling point of view (there was some buildup of silicate in the simulations), the natural system itself is likely not in equilibrium as it responds to the ever-changing Puelo River discharge.

2.3. Social science methodology

To explore the effect of changes in marine ecosystem services on Cochamó, we adopted the vulnerability analysis approach of Adger (2006), who defines vulnerability as a function of exposure (the nature and degree to which a system experiences environmental or socio-political stress), sensitivity (the degree to which a system is modified or affected by perturbations) and, adaptive capacity the ability of a system to evolve in order to accommodate environmental hazard or policy change and to expand the range of variability with which it can cope.

Cochamó relies upon a range of resources, but the project focused on 3 sectors especially reliant on marine ecosystem services: aquaculture, fishing and tourism. However, the community exists within a multi-layered socio-economic-political-ecological setting: it is affected by and affects those larger systems. Turner et al. (2003) capture this by conceptualizing the vulnerability of a 'place' situated in a 'region and world' context. This 'nested scales' perspective was implemented here by connecting local resources to the larger regional marine ecosystem and global processes (climate change) and by connecting with regional governmental agencies through an additional workshop.

Some general information about fisheries and aquaculture in Los Lagos (Region X), including Cochamó, is available from the Chilean National Fisheries and Aquaculture Service (Servicio Nacional de Pesca y Acuicultura 2016, 2017); additional information on key marine ecosystem services came from workshops, as discussed below. However, as the vulnerability analysis and other literature recognize (Turner et al. 2003, Adger 2006, Ostrom 2007), the availability of or change in resources (exposure) does not determine how communities will be affected. The sensitivity of the community to change depends in part on the other resources that can be mobilized in their social, economic and political institutional contexts (adaptive capacity). What communities do with their resources and how they respond to change also depends on how they perceive their situation and their options (Maass et al. 2016). Here, the focus was on addressing the concerns that arose from stakeholder perceptions.

To access the perceptions of members of the Cochamó community, 2 local workshops were held (morning and afternoon of 22 July 2015). The first workshop involved mostly fishers and mussel seed collectors, while the second workshop involved participants representing a broader mix of economic sectors in Cochamó. In each workshop, researchers employed the integrated approach of Systems Thinking (ST) and Bayesian Belief Networks (BBNs) as described by Richards et al. (2013) and adapted by Salgado et al. (2015). Both are forms of participatory model building that draw upon the perceptions and judgments of the participants to construct cause and effect models that include factors which the participants consider salient, and they are frequently used in data-poor environments (Haapasaari et al. 2012, Richards et al. 2013, Tiller et al. 2013). For each workshop, researchers first facilitated an ST session in which participants constructed a collective mental model of their socio-economic-political system. The ST session resulted in a complex set of nodes (variables) and causal connections, mapped during the workshop by the project facilitators. These variables and connections were subsequently entered into the software Vensim (Ventana Inc.), which preserves the workshop results, enables tracking of causal connections and generates more readable versions of the mental models. In addition, the discussion with workshop participants generated a set of narratives providing researchers with additional insights and data, as participants justified and explained their selections and reasoning. With the permission of the participants, audio recordings were made of the sessions. In the second step (BBN session facilitated by project researchers), participants identified key factors that affect their adaptive capacity. In the BBN, causality flows only one way, because the model becomes too complex if feedbacks are introduced (Kjærulff & Madsen 2008). Note that the BBN methodology was used here only to capture the belief systems of workshop participants, that is, how participants believe their socio-ecological systems work, and was not intended to capture the complexities of the natural systems in which feedback loops are important. The BNN generated a set of conditional probability tables that represented alternative scenarios. Each participant was then challenged to assess the likelihood of a given scenario given sets of values of the other variables causally linked to the scenario in question. The aim of the BBN exercise was to establish what participants see as the most important factors affecting their priority issue. The individually parameterized BBNs were then combined into a single, group-representative model. In combining these, each stakeholder's assessment was weighted equally. The follow-on sensitivity analysis shows the stakeholders' joint assessment of the probability that a particular main scenario outcome (a particular value of the parent node) will take place as the value of first- and second-level child nodes change. This allows the analyst to identify the relative importance the group awards to the individual nodes. For more details on the ST and BBN workshops, see Supplement 5.

A disadvantage of this kind of participatory modeling is that the researchers do not control what the participants choose to discuss. Therefore, the researchers held an ST/BBN workshop before the natural systems modelling started and selected several factors that they assessed to be the most important marine systemic factors related to climate change and ocean stressors: (1) the food web, (2) biological pump functions, (3) sea surface temperature (SST), (4) ocean acidification, (5) water quality, (6) water pollution and (7) algal blooms. These were briefly presented to participants at the outset of the workshop as factors that might affect the participants' resource systems. What scientists find important, however, does not always correlate with community concerns. The great advantage of the ST/BBN approach is that it allows stakeholders to tell researchers what factors most affect their decisions. It can therefore yield a more complete view of the community's adaptive capacity.

To understand the larger socio-political context of the community, a third workshop was held in Valparaíso, Chile, on 28 August 2015, where the relevant regional offices of the national administrative and fisheries management bodies are located. Ten people representing different government agencies attended, with seven staying to complete the BBN session. The agencies represented were: the Undersecretariat of Fishing and Aquaculture (SUBPESCA), the National Service for Fishing (SERNAPESCA, in charge of fisheries and aquaculture enforcement) and the Ministry of the Environment (MMA, in charge of the National Strategy and Action Plan for Climate Change). Consultants working with these agencies on related projects also attended.

3. RESULTS

The model configuration for the Gulf of Ancud, as described in Section 2.2., was forced with the different stressor scenarios as listed in Table 1. Future riverine discharge and meteorological conditions were predicted from CMIP5 (regional downscaling experiment for South America, model location extracted from CMIP5 results through interpolation) and used as input (Figs. S1 & S2 in Supplement 2). These predictions show a decrease in riverine discharge (Fig. S1) due to a decline in precipitation. An increase in air temperature of around 3°C by 2100 is observed under the RCP8.5 scenario (CC2) (Fig. S2b). Further changes include a slight decrease in humidity under CC2 by the end of the 21st century accompanied by a decrease in wind speed, though both changes are relatively small (Fig. S2d,f). Overall, the main changes in this region will be increased air temperatures and decreased precipitation.

3.1. Response of the physical and chemical system

Rising air temperatures lead to rising sea surface temperature (SST, Fig. 4a), with a 6% increase to an average of 12.1 °C by 2100 under the RCP8.5 scenario (CC2). Stratification strength decreases under future conditions (Fig. 4b), allowing for more mixing between top and bottom waters and easier break-up of stratification. Here, two opposing effects are at play. Firstly, the increased air temperatures will enhance stratification (as the temperature of the top layer increases accordingly, but the temperature of the oceanic bottom layer does not change). Secondly, the reduction in precipitation will reduce the Puelo River discharge and so decrease stratification (as the estuarine water lens will become more shallow and more saline). Depending on the dominant process, the strength of the stratification may increase or decrease temporarily (Fig. 4b), though in the end the governing effect is that of the reduced estuarine water lens, reducing the strength of stratification. Thus, the model indicates that in the future it will be easier for strong wind events to overturn the stratification and mix the different layers (allowing for temporary easy access to all nutrients for the biota within the euphotic zone). The meteorological prediction indicates a decrease in averaged wind speed (Fig. S2f), but this does not necessarily mean a decrease in storm events that could remix the water column.

The pH values (Fig. 4c) show that the system is not in equilibrium in the reference state, i.e. under the current conditions. Here, there are also two competing effects: increased CO_2 emissions to the atmosphere promote CO_2 uptake by surface seawater, which in turn raises pCO_2 in seawater, increasing acidification (lowering the pH compared to the reference simulation). Climate change effects cause a slight decrease of the same flux (as DIC and total alkalinity [TA] concentrations are affected by changes in chemical and biological processes), increasing pH with respect to the reference state. The buildup of silicate in the model (due to the occasional extremely high riverine discharge) influences the carbonate system and adds to the increase in pH observed in the reference simulation. Note that these results are 30 yr averages: CO_2 take up from or export to the atmosphere by the marine environment is usually a seasonal process, with uptake of CO_2 in some seasons and release in others. Reloncaví Fjord had an annual air–water CO_2 flux of 0.716 ± 2.48 mol m^{-2} yr^{-1} in 2015 (Vergara-Jara et al. 2019) and thus acted as a low emission system; the model captures this system dynamic, as pH values slowly increase over time in the reference situation. The annual cycle is mainly governed by seasonal changes in biological processes that enhance the shift from a CO_2 sink in late spring and summer, caused by high primary production rates (and thus carbon fixation), to a CO_2 source during the winter season, (mainly) caused by high community respiration due to allochthonous organic carbon inputs (Vergara-Jara et al. 2019). Oxygen values (Fig. 4d) show a near 8% decline under the RCP8.5 scenario compared to the reference state. Note that oxygen levels decline due to the isolation of the bottom layer in all scenarios.

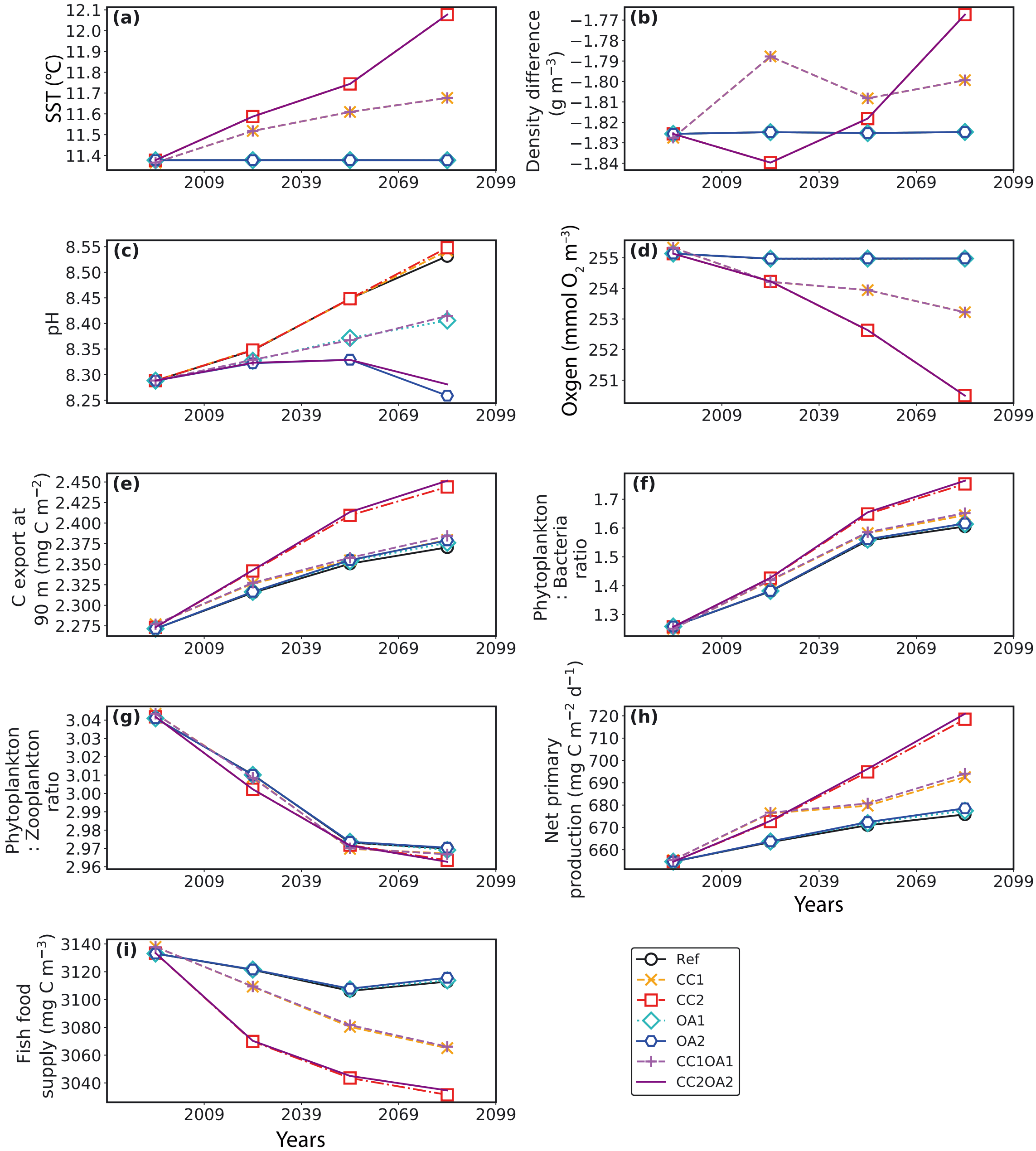

Fig. 4. Physical results in 30 yr averaged time blocks for all scenarios for the Gulf of Ancud: (a) sea surface temperature, (b) density difference between the top and near-bed layer, indicating strength of stratification, (c) depth-averaged pH, (d) depth-averaged oxygen levels, (e) carbon export at 90 m depth, (f) depth-integrated phytoplankton biomass to bacteria biomass ratio, (g) depth-integrated phytoplankton to zooplankton ratio, (h) net primary production and (i) depth-averaged fish food supply. See Table 1 for details on the different scenarios

3.2. Response of the lower trophic levels

Both primary production and carbon export to the deep increase in the Gulf of Ancud due to climate change effects (Fig. 4e,h). At the same time the system shifts to a slightly less microbial one (Fig. 4f), with zooplankton increasing relative to phytoplankton (Fig. 4g). Primary production increases in the model (Fig. 4h) in all scenarios, while biomass for phyto- and zooplankton and pelagic bacteria decreases under climate change pressures (Fig. 5a). Primary production in the simulations increases under future climate scenarios due to (1) increased turnover rates (metabolic processes are faster under

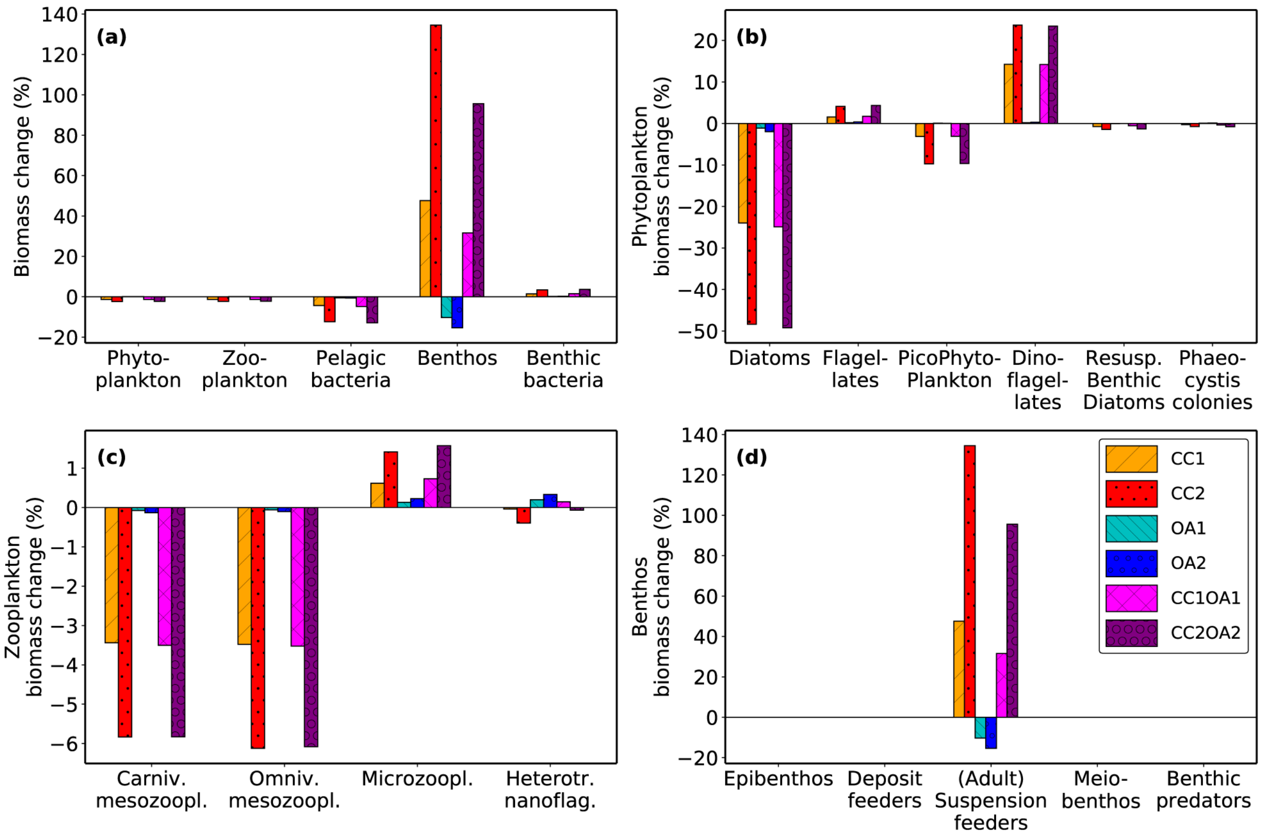

Fig. 5. Predicted percentage changes in biomass for all scenarios for (a) all main biomass groups, (b) phytoplankton functional groups, (c) zooplankton functional groups and (d) benthic functional groups. For a definition of the scenario acronyms see Table 1

higher temperatures) and thus increased use of recycled nutrients, (2) more access to nutrients due to decreased stratification, (3) a slight increase in the underwater light values (results not shown) due to decreased riverine DOC transport and (4) longer growing seasons due to increased temperatures (results not shown). At the same time, phytoplankton biomass decreases due to increased grazing (Fig. 4g) and faster nutrient cycling, meaning that less phytoplankton is needed to cycle the same amount of nutrients. The fact that phytoplankton biomass decreases despite the increase in nutrient availability indicates that the increase in nutrient access is not enough to offset the effect of faster recycling and increased grazing. In general, the primary production results (Fig. 4h) follow the changes in stratification (Fig. 4b) for the CC1 scenario, indicating that the dominant process is the reduction in stratification, increasing nutrient availability in the top layer and thus allowing for additional primary production. For the CC2 scenarios, the net primary production does not follow the density difference pattern, so that the dominant mechanism is probably the increased remineralization of nutrients by bacteria, leading to increased primary production using regenerated nutrients. Due to the decline in biomass in the pelagic functional groups, the amount of plankton biomass eaten by fish declines (Fig. 4i), even for the reference simulation (constant atmospheric pCO2 and a repeated current climate). Again, this is probably caused by adjustment of the system to the 2008 pCO_2 values, and associated changes in the marine chemistry. Here, the different climate scenarios have a negative impact on fish food due to the decrease in phytoplankton biomass, resulting in a 3% decline in fish food supply over the simulated period (except for the acidification-only scenarios).

Biologically, there are winners and losers in the lower trophic levels, with the benthic system profiting from the imposed changes (Fig. 5a) at the expense of the pelagic system. More nutrients are available to autotrophic nanoflagellates as the larger diatom species decline with the decrease in available river-borne silicate, strengthening the flagellate–microzooplankton carbon pathway to higher trophic levels at the expense of the diatom–mesozooplankton pathway. This causes an increase in microzooplankton which leads to a grazing-induced decline of pelagic bacteria. Thus, under climate change forcings, the system slowly shifts from the slower diatom carbon pathway to the faster flagellate carbon pathway. Benthic groups consisted purely of filter feeders (due to the hard rock substrate in the region), which benefit from climate change effects (increased export of organic material to the bed; Fig. 4e), moderated by acidification impacts. Here, the relative change is large mainly due to the small initial biomass of the benthic groups, as 237 m depth is too deep for species such as mussels and oysters in the model. However, the impacts are an indication of the direction of change for shallower areas with more complex benthic systems. Thus, both climate change and acidification have distinct impacts on the local system.

3.3. Response of the higher trophic levels

Here, we consider the impact on the main commercial species. Note that the fishing pressure represents the efforts of 4 small scale fisheries in the area, as reported by Pavés et al. (2013). It does not include commercial fisheries for these species, and so the applied fishing pressure does not represent the actual fishing pressure in the area which has led to overexploitation of stocks (Subpesca 2019).

The effect of acidification on fish biomass is negligible (Fig. 6), with the OA1 and OA2 lines being almost identical to the reference line in the results for gadoids (the top line represents the OA2 scenario, obscuring the OA1 and Reference results) and the CC1OA1 and CC2OA2 lines practically identical to (and overlaying) the CC1 and CC2 lines, respectively. The decline observed in gadoid stock biomass in the reference simulation is roughly 20% between 2008 and 2098. Note that the initial decline (1958–1978) is an artefact of the spin-up period required by the combined model. The period 1979–2008 (light blue area) shows stabilizing biomass values representing the current period. For Clupeiformes, the graph is distorted by the wide smoothing applied for this short-lived species (see Fig. S5 in Supplement 4 for the unsmoothed biomass results). The reference simulation decline over the period 2009–2099 is ~13% for this species, while for jack mackerel it is ~50%. This is due to the adjustment of the carbonate system to the imposed constant atmospheric $p\text{CO}_2$ values and the decline in fish food observed in the reference simulation of lower trophic levels (Fig. 4i).

The scenario-induced decline of gadoids and Clupeiformes (with respect to the reference simulation) is due to the applied fishing pressure, reduced food supply (Fig. 4i) and the increased SST (Fig. 4a). The latter causes more stress in species with a limited temperature range (such as gadoids and Clupeiformes) and less in more temperature-tolerant species (like Carangidae) (Serpetti et al. 2017). For jack mackerel (Fig. 6e,f), a strong decline is also observed, but mainly for the CC1 scenario: the species benefits from a reduction in competition and predation at higher fishing pressure. Climatic effects on jack mackerel are small and show only slight decreases in biomass with increasing temperatures.

The impact of fishing is visible in the reference period, when all other stressors are equal. For gadoids, biomass is halved if high fishing pressure is applied, compared to the low (approx. current) fishing pressure. Clupeiformes lose a third of the biomass under the HF scenario (compared to LF). There is a noticeable effect of climate change on stock biomass under exploitation: a decline of between 5% for low exploitation of cod and hake species under CC1 and 15% under the more stressful high exploitation (compared to the reference situation; Fig. 6a,b). For herring and anchovies (Fig. 6c,d), the maximum extra decline (compared to the reference simulation) is around 10% (showing that the decline in gadoid stocks is closely matched to the underlying decline in herring stock biomass). However, the simulated data is much noisier in the short-lived Clupeiform stocks. Jack mackerel react strongly to fishing pressure as well, with high pressure being more beneficial for this species (in terms of having higher biomass). Thus, fishing pressure is the main stressor affecting stock biomass in the modelled results.

The reference simulation indicates a stabilization of stocks by 2040–2060 (LF) or 2060–2080 (HF), except for jack mackerel. However, additional pressure from the high impact climate scenario (CC2) indicates that stabilization may not occur within this century under high exploitation rates for gadoids and Clupeiformes. Note that although the Clupeiformes population (short-lived species) stabilizes within about 60 yr, the gadoid stock biomass (much longer-lived species) is much less stable, especially when the net growth rate is low under heavy fishing. The high F-values used (0.5 for herring and 0.2 for gadoids) are at the limit of sustainability (i.e. the fish stocks still stabilize, albeit slowly).

Conversely, jack mackerel (Carangidae) both compete with and are eaten by gadoids. Increased fishing for cod and hake-type species (even when accompanied by fishing for Clupeiformes and Carangidae) therefore led to increases in the biomass of these stocks. Overall, climate change is less impor-

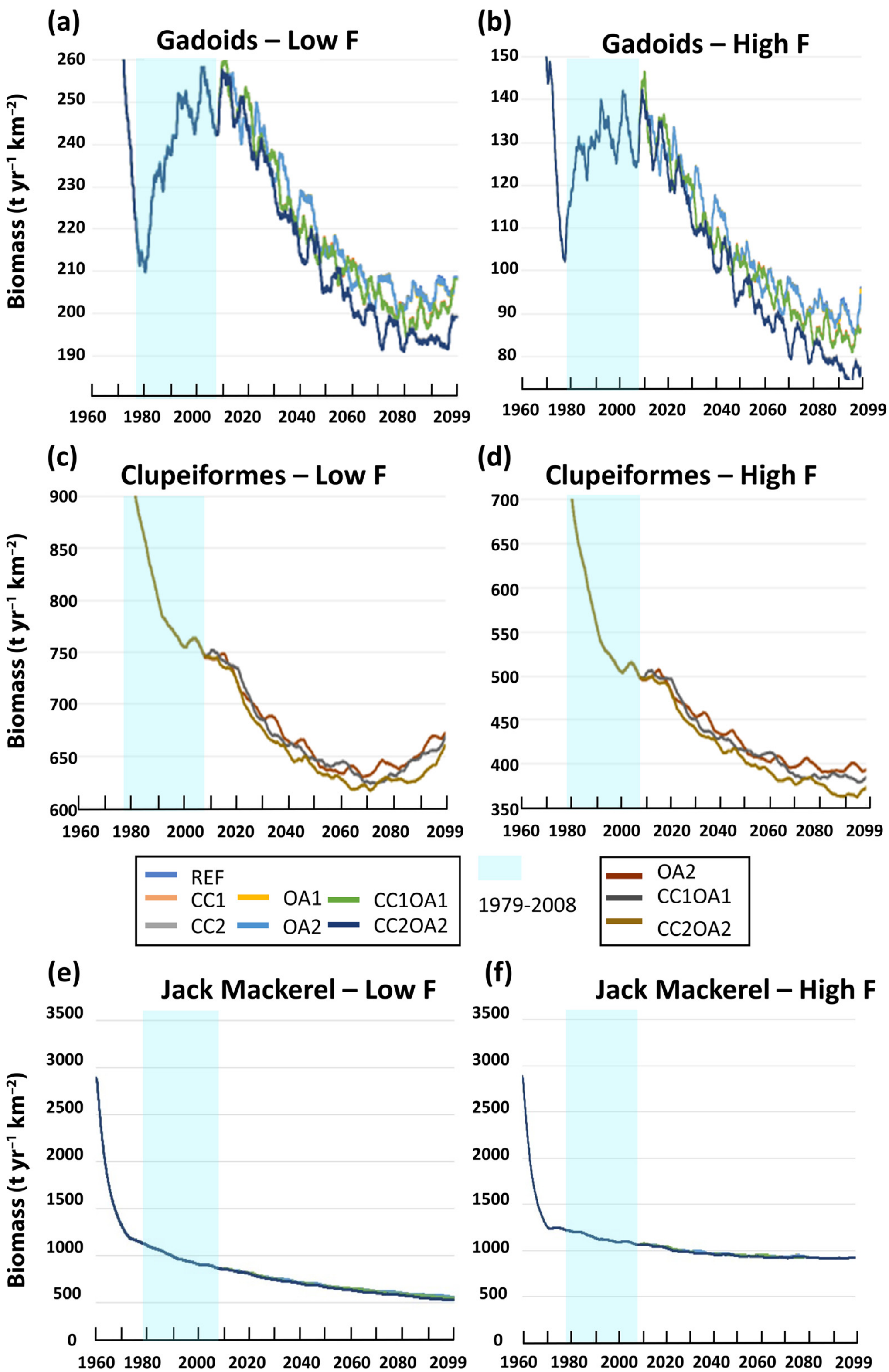

Fig. 6. (a,b) Projected gadoid (cod, hake, etc.) stock biomass under (a) low (F = 0.01) and (b) high (F = 0.2) fishing pressure. (c,d) Smoothed Clupeiformes (herring, anchovies, etc.) biomass under (c) low (F = 0.05) and (d) high (F = 0.5) fishing scenarios. (e,f) Unsmoothed Jack mackerel biomass under (e) low (F = 0.03) and (f) high (F = 0.3) fishing pressure. The light blue area indicates the reference period of 1979–2008. The large initial adjustment on coupling is visible in the left part of the plotted lines. For an explanation of the scenarios, see Table 1. Note that for reasons of clarity we only display the scenarios OA2, CC1OA1 and CC2OA2 in figures (c) and (d) with a separate legend; this is due to the high smoothing applied to the short-lived Clupeiformes

tant than fishing pressure for the overall wellbeing of the Patagonia fish stocks as simulated here. Climatic effects include a decline in fish food species, increased water temperatures and a shifting balance in species, which leads to an additional decline in Clupeiformes and gadoid stock biomass. Overall, arrow worms (Chaetognatha), Salpida, Hydromedusea and comb jellies (Ctenophora) increase in biomass under climate change effects, with higher fishing pressure resulting in even higher biomass (results not shown), as for jack mackerel. Cusk-eels/pearlfishes, neotropical silversides and drums/croakers all show initial increases in biomass with subsequent declines, with their peak dependent on fishing pressure and gadoid and each other's biomass levels (results not shown), indicating shifting carbon pathways in the higher trophic levels. The model results indicate that the time until stock stabilization depends on the fishing pressure employed and differs per species.

3.4. Cochamó community

The workshops with various stakeholders in the region revealed a local community that has been highly dependent on the marine resources of the fjord and perceives itself as highly affected by changes in the larger marine ecosystem with which the Reloncaví Fjord is connected. Before the year 2000, Cochamó relied primarily on artisanal fishing and small-scale farming and existed in relative isolation from much of the national economy. The rise of salmon and trout aquaculture in Los Lagos, with its epicenter in the Gulf of Ancud (Salgado et al. 2015, Iizuka & Sanlungo 2016), and the expansion of local and larger-scale fishing in the area coincided with declines in species important to Cochamó's economy. The community was drawn into the economic sphere of the aquaculture industry as older fishermen found jobs in the industry and younger people left for the booming regional center of Puerto Montt. The regional crisis of the aquaculture industry from 2007 to 2009, however, led first to a dramatic drop in aquaculture production and then to the movement of the industry to new areas further south. These events left Cochamó in need of a new source of livelihood, with options related to marine resources being limited.

In these circumstances, some members of the community turned to the cultivation of mussel seed. At the time of the workshop, the mussel seed collectors were, however, concerned about the future of their business. They had noted a decline in the productivity of seed production in recent years and speculated that several factors might account for this. Changes in the amount of freshwater run-off and changes in sea-level were perceived to be altering the tide and currents of the fjord, resulting in the need to place their collectors in deeper waters, which in turn required new technology and gear and was increasing their costs. The concerns of the mussel seed collectors relating to environmental factors merged with those of the others who relied on marine resources: alien and invasive species, changes in SST, the results of a large volcanic eruption, changes in freshwater run-off, and changes in sea level. They also perceived that the general economic development of the area was having a negative effect on marine systems: increased pollution into the fjord was especially problematic because of the low rate of water exchange in the fjord. The discussion also uncovered governance issues. Workshop participants blamed weak regulation and enforcement of the aquaculture industry for poor environmental conditions, while a slow and inflexible permit system was hindering the relocation of mussel seed collection.

In the BBN session, the participants of the first workshop (those directly reliant upon marine resources) selected 'the productivity of mussel seed collectors' as their priority issue. They collectively decided that seed mortality, the quality of seeds and the productivity of natural stocks were most likely to determine that productivity. The drivers that were believed to affect these factors are listed in Table 2a. Of these factors, the participants thought that the productivity of natural stocks was the most important (seed spawning of natural stocks). The factors of the second-level child node that were most important were: oxygen in the water, temperature and the renewal rate of natural stocks. Asked to rate the probability of the preferred state of each variable occurring, these participants were more optimistic than initial discussions had suggested: for example, they collectively assessed the probability that the productivity of natural stocks would be adequate in the near future as >70%, that there would be low seed mortality as >67% and that the quality of seeds would be adequate as >67%.

The second workshop (representatives of various economic sectors in Cochamó) led to a discussion more focused on the further development of the tourism sector. Because participants anticipated moving into new economic activities as old-standbys were perceived to be in decline, this group addressed more specifically the adaptive capacity of the community. Interestingly, this group displayed somewhat less confidence about the future than did the first group.

Table 2. Bayesian Belief Network (BBN) trees based on researcher-facilitated workshops with Cochamó residents and other stakeholders to identify the threats they perceive for the community (see Section 3.4. for details). Parent node (**bold**); First level child nodes (*italic*); Second level child nodes (plain text)

(a) BBN Tree 1. Productivity of mussel seed collectors (Members of the Cochamó fishers' cooperative)								
Mussel seed mortality			*Productivity of natural stocks*			*Quality of seeds*		
Oxygen in water	Food for seeds	Sea surface temperature	Reproduction capacity	Renewal rate of natural stock	Availability of plankton (as food for mussels)	Pollution from aquaculture	Food availability for seeds	Water pollution
(b) BBN Tree 2. Tourism development in Cochamó (Diverse Cochamó participants)								
Hotel capacity			*Advertising Cochamó as a tourist destination*			*Touristic offers*		
Tourism promotion funds	Ease of access to public funds	Entrepreneurial capacity	Information	Community tourism web page	Touristic services	Support of the local authorities	Organization of the community	Tourism capacity building
(c) Vulnerability of local communities (Regional and national governmental representatives and associated consultants)								
Sustainability			*Interdisciplinary research*			*Governance*		
Resilience	Productive activity in line with carrying capacity	Whether carrying capacity was known	Funding	Approach	Capacity	Legal framework	User participation	Institutions

The initial ST session led to a wide-ranging discussion of a variety of environmental changes that participants had already noticed, many of which they attributed to climate change: warmer air temperatures, increased variability in crop yields and impacts on honeybees. The session facilitator had to coax participants back to a discussion of the marine system and related economic activities. As was the case with the first group, many attributed significant negative environmental effects on the marine ecosystem to the aquaculture industry (from e.g. chemicals and antibiotics, waste disposal problems and diseases in aquaculture facilities). They anticipated that climate change would further affect the few remaining fish species of importance to them (róbalo, pejerry, jurel) and did not believe there was much future in aquaculture and mussel seed collection. This is why they turned to tourism as their priority issue.

In the BBN sessions, the participants' priority issue was building a sustainable tourism industry based primarily on land-based activities, and their discussions focused primarily on what would be required to attract tourists who would bring economic benefits to the community (Table 2b). In summary, while they believed that the area held great potential and that the community had the necessary entrepreneurship, they also thought that the community lacked the necessary facilities (such as hotels and attractions) and needed to advertise more effectively. These factors in turn required support from local and regional authorities, but also a highly organized community. On the whole, participants considered it generally unlikely (probability of <50%) that support from local authorities would become available to develop tourist attractions (touristic offers) and roughly equally unlikely that the community would be sufficiently cohesive to achieve their goal (<49%). They did, however, find it more likely (>66% chance) that funds to promote tourism would be available.

In the third workshop, representatives of the state's regional management authorities discussed the likely impacts of climate change on local ecosystems at great length. In the BBN session, however, they were most concerned with what they called the vulnerability of local communities (Table 2c). Because the focus here is on the local stakeholders, we only present a few points related to the perceptions of these officials and consultants. First, they recognized that the vulnerability of a community like Cochamó is affected by the state of natural systems (the ST discussion) and respect for the carrying capacity of the ecosystem (BBN session) but found other factors very important in determining what such a community would make of its situation. For example, basic research was required to establish the carrying capacity of the area, a first step in making sure that economic activities did not cross carrying-capacity boundaries. For this, sufficient funding would be required for the highly interdisciplinary research that would be needed. Secondly, they recognized that governance was critical. Of the factors that would most affect governance, these officials and consultants put the most weight on the involvement of user groups in management. Notably, these workshop participants did not address the availability of regional resources that local people might use to finance a shift into tourism or invest in the exploitation of new marine resources.

The workshops accordingly revealed many factors affecting natural systems that stakeholders (both local and regional officials and consultants) found of interest. Given that stakeholders appeared somewhat divided on the future of their mussel seed farming and the health of their marine resources, additional insights on how climate change and other ocean stressors might affect these can be useful. Food web issues were of most direct importance with respect to the lower trophic levels (availability of food for mussels and mussel seed) but also in a limited way to the availability of key harvested resources (and their food supply). Stakeholders also expressed concern about the impact of water temperatures, freshwater run-off into the fjord, changes in the chemical composition of the fjord, sea level changes and changes in tides and currents. However, local participants did not show much concern for acidification, one of the original drivers used to start the ST sessions. Only regional officials, managers and consultants were concerned with this factor. Finally, general water quality was also selected as being of broad general importance to all marine-resource based economic activities.

4. DISCUSSION

4.1. Research findings

We have applied end-to-end modeling for the Chilean Gulf of Ancud and the small community of Cochamó (located on the Reloncaví Fjord, which feeds into the Seno de Reloncaví, which in turn is connected to the gulf), in an attempt to link bottom-up and top-down changes in a larger-scale marine ecosystem to a local community reliant upon marine resources. We applied detailed water-column modelling of the physical, chemical and biological systems and stakeholder adaptive capacity to link future changes in the natural system to their impact upon the small community of Cochamó, considering its reliance on specific marine resources. Our study looks at what information can be provided to Cochamó to aid them in planning a sustainable economic future despite gaps in the knowledge base.

Our simulated results for the gulf predict an increase in sea surface temperature by 0.7 °C and a decrease in depth-averaged oxygen concentrations of 8% by 2100 under the worst-case scenario (RCP8.5 climate and acidification impacts: CC2OA2 scenario, Fig. 4), aligning with the worries expressed by the local population (Table 2a). The predicted decrease in oxygen concentration is due to the increased water temperatures (warmer waters can hold less oxygen) and the increased turn-over of nutrients, as bacterial remineralization uses oxygen. Surface mixed layer salinity is predicted to increase with 0.25 PSU under the CC2 scenario, due to decreased precipitation and riverine discharge. Maximum pH values would increase by 0.23 units if current pressures are maintained (reference, periods 1979–2008 and 2069–2098), due to the CO_2-emitting nature of the system. Acidification impacts modify this increase to 0.1 (CC1OA1) or actually decrease the maximum pH by 0.02 (CC2OA2). These changes, representing 30 yr averages calculated for the central gulf, can be applied to more specific locations within the wider system given local measurements. Daily simulated maximums (minimums) include 18.57 (6.05) °C, 32.02 (28.43) PSU and 8.68 (8.16) for temperature, salinity and pH of the surface layer, respectively. Changes in near-bed oxygen values would require a fully advective model, as hypoxic areas can be very local. Both climate change and acidification seem to have a distinct impact on biomass distribution of the different species. Net primary production is expected to increase even though plankton biomass decreases. At the same time, the reduction in Puelo River discharge will decrease the amount of nutrients coming into the system, particularly for silicates, and this limits diatom growth. Diatoms lose the competition for the spring bloom nutrients increasingly to flagellates, with the carbon flow to higher trophic levels thus shifting from the diatom–mesozooplankton pathway to the flagellate–microzooplankton one. The latter process is faster in transporting carbon up the food chain and leads to increased grazing on bacteria by the microzooplankton. As a result, a species shift in the phyto- and zooplankton can be expected, as well as an improved underwater light climate, providing more opportunities for nuisance and/or harmful algal species.

Simulated carbon export below 90 m also increased, benefitting the benthic community. The additional export is essentially new carbon locked into organic compounds by the increased primary production, using regenerated and some newly accessible nutrients. This process allows carbon (taken up from the atmosphere) to be transported to greater depths, where some will be sequestered long-term. But most carbon will accumulate near and on the bed, feeding a benthic system that has no direct access to sunlight. Thus, the benthic food supply increases while the fish food supply decreases (less plankton biomass), marking a shift towards a more benthic-oriented system. Based on our modeling results, we conclude that the benthic system (including mussels, sea snails and limpets) in general will benefit from the expected physical and chemical changes, but that area- and species-specific studies are needed to quantify the effect for the community of Cochamó.

For Patagonian fish stocks, the modeling indicated that climate change is less important than fishing pressure for the stock biomass response in this area. Acidification had no discernable direct impact at all on higher trophic level biomass. However, the simulations all showed an initial decline in gadoids (cod and hake type species), Carangidae (jack mackerel) and Clupeiformes (herring and anchovy type species) as a result of fishing pressure combined with a reduction in the planktonic food supply, even under the reference conditions. A shift in biomass between species on both lower and higher trophic levels was found, affecting dominant carbon pathways. Increased fishing of gadoids showed an increase in mackerel biomass, as predation and competition for this commercial species was reduced. Local species of interest such as cusk-eels and pearlfishes, neotropical silversides and drums and croakers all showed varying timing of an initial stock maximum followed by declines in the long term, driven by the changes in food web interactions and the main carbon pathways (i.e. Clupeiformes–gadoids). The picture of 50–80 yr of change will be complicated by socioeconomic changes and the pressure for increased exploitation to compensate for overexploited offshore stocks in the area.

4.2. Appropriateness

The chosen model location (Gulf of Ancud) does not coincide with the area fished by the Cochamó fishermen (Reloncaví Fjord, coastal parts of Seno de Reloncaví; see Section 2.2. for the reasons). González et al. (2010) present observational evidence from a CIMAR cruise spanning the entire length of the system, starting at the Gulf of Corcovado, through the Inner Sea of Chiloé and the Gulf of Ancud to the Seno de Reloncaví and into Reloncaví Fjord. They found clear differences between the Gulf of Ancud (Stations 16 & 14), Seno de Reloncaví (Stations 8 & 3) and Reloncaví Fjord (Stations 5–7). The Gulf of Ancud and the Seno are ~300 m deep, while Reloncaví Fjord has a depth of around 200 m. The fjord displays strong stratification due to the Puelo River discharge, as well as high silicic acid levels at the surface, combined with high levels of nitrate and orthophosphate in the bottom layer. There is a seaward gradient of nutrients throughout the entire system (decreasing strongly towards the Pacific) and dissolved oxygen (increasing towards the Pacific; González et al. 2010). Austral summer results show the fjord is nitrogen limited, while the gulf is less so due to less strong stratification. The temperature of the top mixed layer is relatively constant throughout the system, while salinity slowly increases with distance from the fjord. Nevertheless, the top layer of estuarine waters is clearly visible in the observations from the fjord through to the Gulf of Ancud, with a relatively constant thickness. Thus, the dominant physical mechanisms in the gulf and the fjord are similar, and the results of this work for the gulf area can be interpreted for the fjord system, where Cochamó residents fish. As the fjord experiences stronger stratification, the exchange of nutrients between the top and bottom layers is more limited than in the gulf, as shown by the nitrate depletion in the fjord in austral summer (González et al. 2010). This is partly offset by direct sources of nutrient input in the more coastal area (aquaculture, human settlements). Due to the lack of advective processes, the simulated system was also nitrate-limited in summer, and so the modelled biological response for the gulf is similar to that expected for Reloncaví Fjord. Note that we applied a water column model, and as such did not take into account horizontal processes such as advection of nutrients and area avoidance by organisms. In the northern section of the Patagonian fjords and channels, salmon farms are presumably the main anthropogenic source of inorganic nutrients. Cage salmon farms release the inorganic nutrients ammonium (NH_4) and phosphate (PO_4) into the surrounding surface water, as well as a high amount of organic matter, mainly directly below and in the immediate vicinity of the farm (Olsen et al. 2014, Quiñones et al. 2019). Previous results have shown a positive biomass response to nutrient loading of the microautotroph, microheterotroph and mesoheterotroph functional groups, dominated by microphytoplankton, ciliates and copepods, respectively (Olsen et al. 2014, 2017). Effects of aquaculture in the area were excluded, as the chosen model location is in the central gulf. Hernández-Miranda et al. (2021) show local impact of aquaculture on environmental quality, with the highest impacts directly next to the coastal salmon farms. Bravo et al. (2020) show significant regional downstream connectivity between aquaculture farms in the Inner Sea of Chiloé. These farms, located around the entire coastline of the area including the Seno de Reloncaví and Reloncaví Fjord, form significant local nutrient inputs. But surface mixed layer nutrient concentrations in the central gulf do not show elevated levels compared to those in the central seno and fjord (González et al. 2010), indicating that aquaculture impact in the central areas is limited.

The reported shift towards a more benthic-oriented system is equally applicable to the seno as to the gulf, both of which have similar depths (~300 m). The fjord is characterized by depths of around 200 m, and the local community relies on benthic species which are harvested in areas much shallower than this. In such shallower areas the benthic system forms a much more integral part of the local ecosystem. Whether the simulated shift towards a more benthic system would benefit the local benthic species of interest (locos, limpets, mollusks and Trophon top shell) remains to be seen, but it is likely if the system is not disturbed too much (e.g. no overfishing of a particular species).

The fishing pressure we applied to the higher trophic levels only represents artisanal fisheries, resulting in low pressure values. Thus, any conclusions from our work regarding fisheries management apply to the local, inshore fisheries only. The offshore fisheries, often operated by large companies with more available funds than the local community, are expected to have a large impact on fish biomass within the Gulf of Ancud. As such, the simulated results are also more applicable to the Seno de Reloncaví and the associated fjord than to the central gulf.

4.3. Model uncertainties

The Patagonian system was simulated with a 1-way upwards coupled water column model, representing all trophic levels. Thus, horizontal processes were neglected, resulting in a system that was not in equilibrium in the reference state. This influenced results, as depth-integrated silicate concentrations increased within the reference simulation, causing an additional increase in pH. However, the model correctly simulated the CO_2 emissions-character of the local system, including the increase in pH with changing air–sea fluxes. Fisheries impacts on plankton biomass were not included due to technical issues. This can affect the results presented here, as variability of zooplankton grazing was limited in the lower trophic level model, affecting phytoplankton biomass levels and thus primary production. However, as the lower trophic level model (ERSEM-BFM) included dynamic grazing pressure (Supplement 4), these effects would have been minor. The project timeframe (4 yr) also prevented some connections from being made: due to the large amount of work involved, the natural and socio-economic work packages ran simultaneously, and results from the workshops were not yet available when modelling choices had to be made. Habitat shifts were also not included: as waters warm, some species might avoid higher temperatures by heading towards the Pacific or to deeper areas. This is a potential problem for the local community, as adjustment to gears can be expensive.

Regardless of which models are applied, there are uncertainties included in end-to-end modelling. Apart from specific causes of uncertainty mentioned above and in Supplement 4, the applied models include parametric uncertainties (e.g. many parameters were derived under lab conditions) and process parametrization uncertainty. The latter can be seen in the lower trophic level model (where temperature is included in all biological processes, whereas pH is mainly included in chemical processes) and the higher trophic level model (which does not include seasonal processes like recruitment beyond parameterization). This driver-inclusion difference affects the impact certain drivers can have on the system, with climate stressors tending to dominate over other oceanic pressures due to our better understanding of their impact. Then there are additional uncertainties related to the applied forcings, e.g. the CMIP5 meteorological forcing applied here is the result of a down-scaling experiment by 1 model, not an ensemble of different global meteorological model results. The Puelo River is the largest in the area, yet there are more rivers as well as direct run-off and melting glaciers, which are not accounted for in the forcing. Overall, the results presented here are an indication of expected change in the area and for the local community, using the best available data.

Further studies are needed to quantify predicted changes for the local community given their specific species of interest. These studies should relate to both the impact of acidification and of climate warming. The former may affect mussel seed production and survival, as these are critical life stages of which little is known and which are thus not included in our model beyond simple reproduction. Climate warming may lead to the replacement of a species with a narrow temperature range by one with a broader and/or higher range, which can have a minimal effect on the system (if both species perform the same ecosystem function) while having profound economic consequences (if the species have very different economic values). Recent research on Mediterranean mussels indicates that both development of the shell and the transition from the first to the second larval stage are sensitive to low pH values (Kapsenberg et al. 2018). Note that the omission of rapid glacial melting (from Andean glaciers or fjord marine-terminating glaciers) may influence our results in the short-term future: if the local glacial melt accelerates due to climate change, the estuarine freshwater lens is expected to thicken initially, decreasing oceanic nutrient supply to the euphotic zone and bringing in more silicates for diatom blooms. However, the observed increased occurrence of harmful algae blooms (HABs) in the area supports our long-term model study findings.

4.4. Implications

This situation of increased occurrences of HABs has already been observed specifically in the Reloncaví system, where a major flagellate bloom outbreak occurred during the 2016 summer months (León-Muñoz et al. 2018, Mardones et al. 2021). The harmful algae bloom was explained by the synergy of climatic, hydrological and oceanographic anomalies such as solar radiation (high), wind (reduced), sea surface temperature (warmer) and precipitation-river streamflows (reduced) affecting the surface stratification of the area. In particular, strong stratification (allowing for deep chlorophyll maximum [DCM] formation) followed by weakened stratification (causing higher surface salinities and a shallowing of the DCM) was deemed favourable for the observed HAB species (Mardones et al. 2021). With reduced freshwater input along the Patagonian fjords (as predicted due to climate change; Aguayo et al. 2019), the supply of silicic acid to the productive zone below the brackish layer might be reduced, increasing the N:Si ratio, which could shift the phytoplankton community more in favour of dinoflagellates or other non-silicified species. Thus, more frequent flagellate or dinoflagellate outbreaks may be expected during summer and autumn months, when less freshwater streamflow is predicted to occur in the Inner Sea of Chiloé (Aguayo et al. 2019). Our results support this prediction over longer time scales. As such, relevant worries by the community (Table 2) seem justified. The increased water clarity which facilitates HAB occurrence can however be beneficial to the growing tourist industry. Threats might come from the increase in HABs but also from other factors related to climate change — such as changes in weather and precipitation, river flow and the melting of glaciers. Such changes could eventually affect tourism not directly reliant on marine resources, such as hiking and camping. Future success in tourism will also be affected by competition from other localities and by a host of climate and socio-economic factors that affect national and international tourism patterns (Scott et al. 2016). However, such patterns are far beyond the scope of the current project.

Concerning the local species of interest, the increasing pH values we found could safeguard the mussel seed industry, though further research using the local species is recommended. Good management of the artisanal fisheries has the potential to maintain the local ecosystem services that the local community relies upon. Note that a food web model such as the one applied here incorporates the most important carbon pathways up through the trophic levels. It may well be that a particular local resource valued highly by the community does not have an equally important biological role in the ecosystem, limiting the model's ability to predict changes to its stock biomass (e.g. jibia, the Humboldt squid). Thus, to quantify impacts more directly for Cochamó's fishermen, more specialized studies are recommended. These can build on the general model results already performed for this marine system and local community, focusing on the overall dominant threats identified within the project work and the predicted impact ranges. The results also indicate that jack mackerel benefits from fishing on gadoids, which are not targeted currently by the Cochamó fishing community.

Overall, Cochamó, a small community dominated by artisanal rather than industrial fishers, is more likely to be affected by changes in the marine system and by the strategies of other fishers and communities, rather than to cause systemic change itself. It does not at present land gadoids in any appreciable number but does take some pelagic fishes (including jack mackerel). The community has already responded to the significant presence of salmon aquaculture farming by shifting to mussel seed extraction, suggesting that this community, while not a particularly wealthy one, has demonstrated the capacity to adapt to changing conditions in the past. The modelling findings suggest that the large-scale processes studied here are unlikely to have a major direct impact on mussel seed extraction or on the industrial enterprises cultivating mussels to which the villagers sell their seeds. However, significant fluctuations in mussel seed productivity have occurred in the past, for example between 2011 and 2013, when it declined by >50% (Figueroa 2015). Previous studies (Figueroa & Dresdner 2016, Fernández et al. 2018) suggest that mussel seed productivity is largely determined by environmental factors (biotic and abiotic), particularly HABs (Fernández et al. 2018). This in turn suggests that short-term, more immediate environmental factors are at work here, including those connected to the aquaculture industry — as workshop participants have suggested. Responding to less dramatic, long-term, incremental change may require some adjustments in mussel seed farming; making these may require more flexibility in governance. The new regulations introduced in 2019 (Ley de Mitildos, https://www.subpesca.cl/portal/615/articles-105996_documento.pdf) may help in this regard, as these facilitate (amongst other things) non-salmonid operation relocations and seasonal harvest extensions. The pelagic species Cochamó residents fish all show declining stock biomass in the long term, though this might be mitigated by good management. More detailed, experimental research on specific species is recommended. Marine protected areas are recognized to be effective tools in restoring marine ecosystem diversity and ecosystem services and could be useful in this context. Sala et al. (2021) estimate that Chile has 20% of its exclusive economic zone in the top 10% priority areas for global marine biodiversity conservation. Their suggested multi-objective prioritization of areas for strongly enforced marine protected areas would benefit ecosystem services such as carbon storage, food provisioning and biodiversity conservation, with the Patagonian fjords marked for the possibility of all 3 benefits. Conflicts with the large-scale fishing industry might thus be avoided, which would benefit small communities such as Cochamó.

The 3 workshops we conducted showed that there are mixed interests in the community and that the aspiration of some to expand the tourism industry could be perceived to conflict with the desire of others to continue exploitation of mussel seeds or more traditional resources in the Reloncaví Fjord. Participants in both community workshops believed that pollution from land-based development was having a negative impact on the local marine ecosystem, but the second workshop suggested that a group within the community wants to expand investment in facilities to attract tourists, which could contribute to the pollution problem. Given that stakeholders appeared somewhat divided on the future of their mussel seed farming and the health of their marine resources, additional insights on how climate change and other ocean stressors might affect these can be useful. The division in the community may explain the pessimism in the second group that the community will be cohesive enough to make the transition to a more tourist-based economy. This brings up an important unexplored issue in this work: the role women are playing in the adaptation of the community. Women are seldom fishers, but their contributions are essential in making a fishing community thrive. In addition to bringing in new sources of income, a new industry such as tourism could transform the community by opening up new opportunities for women. This kind of change could increase tensions in a community or revitalize it, as women turn away from unpaid fishing-supporting roles to generating additional income (Yodanis 2000).

The workshops made it very clear that villagers are concerned about their marine resources and that they are aware of the possibility that climate change may affect them. But it was also clear that they ranked other threats to their marine livelihood more highly. The explosive growth and subsequent crisis (2007–2009) of the large salmon aquaculture industry in the area (in the fjord and the gulf) had a great impact. The growth of the industry transformed the region, including Cochamó, economically and socially by integrating it into the national economy, including the siphoning off of fishers to that more lucrative and monetized economy. The cultivation of mussel seeds was a response to the changing economic as well as environmental conditions. Our findings show that acidification impacts related to climate change are expected to increase the local pH, which will benefit shell-building organisms such as mussels, though effects of increased temperatures on mussel seed remain unknown. At the same time, better fisheries management has the potential to offset some of the negative effects of climate change impacts and may increase some local stocks of interest in the short-term. So options for the local community remain open, and with their demonstrated capacity for adaption the issue comes down to regulations allowing for potential changes in their marine-based activities. The recently introduced Ley de Mitildos is an example of what is possible here and provides hope for the future.

5. CONCLUSIONS

While uncertainties remain (see Section 4.3), given the difficulties encountered in creating an end-to-end model for this location and the compromises that had to be made, the modeling results presented here suggest that acidification is unlikely to be a major problem in the immediate future in the larger-scale system; major changes in the lower trophic level are not anticipated, and both climate change and acidification impacts are predicted to increase primary production according to the simulation results. The model was unable to simulate acidification effects on the actual shell-building of organisms, and benthic results are tenuous due to the permanently stratified conditions and lack of advective processes in the applied modelling. However, pH increases under the different scenarios, and the results indicate a shift towards a more benthic-oriented system, with increased carbon export to the deep, which should benefit benthic species in general. At the same time, a shift to a less bacterial system was observed within the pelagic zone, as zooplankton grazing became a more dominant aspect of the system. With the decline of river-borne silicates the diatom–mesozooplankton carbon pathway shifted towards a flagellate–microzooplankton (ciliates) pathway in austral spring and summer months. Fish stocks showed a strong impact of fishing pressure, with less direct impact from climate change effects, but also responded to changes in the food supply for forage fish due to climatic changes. The recovery time of fish stocks was strongly controlled by fishing pressure, indicating that the major threat here can potentially be controlled by good management. Such governance may present a challenge in Chile, where most stocks are overfished. Additional research on the direct impact of acidification on mussel seeds and benthic species of local economic interest are recommended, and the findings reported here can be used to define these additional experiments.

The OCEAN CERTAIN project advanced knowledge of the impact of climate change and other stressors on a local marine ecosystem. It also contributed to understanding what impact these stressors will have on specific Cochamó marine resources: the social science identified the concerns of the community, and the natural science estimated the impact range. Our findings provide the groundwork for particularly detailed experimental studies on the response of the specific species of interest to the identified threats. Our work also demonstrates the possibilities of linking large scale processes to the needs of small communities, and the work required for it, allowing for detailed social and economic impact studies in rural areas facing environmental changes on a regional scale.

Acknowledgements. This research was supported by the European Commission, Horizon 2020 Framework Programme OCEAN CERTAIN (grant no. 603773). The climate change and freshwater input views for Patagonian fjords are part of the framework of the research program 'Productivity in a Changing Ocean' of ANID-FONDAP IDEAL 15150003.

LITERATURE CITED

Adger WN (2006) Vulnerability. Glob Environ Change 16: 268–281

Aguayo R, León-Muñoz J, Vargas-Baecheler J, Montecinos A and others (2019) The glass half-empty: Climate change drives lower freshwater input in the coastal system of the Chilean Northern Patagonia. Clim Change 155:417–435

Bachmann-Vargas P, van Koppen CSA, Lamers M (2021) Re-framing salmon aquaculture in the aftermath of the ISAV crisis in Chile. Mar Policy 124:104358

Barange M, Field JG, Harris RP, Hofmann EE, Perry RI, Werner F (eds) (2010) Marine ecosystems and global change. Oxford University Press, Oxford

Baretta JW, Ebenhöh W, Ruardij P (1995) The European regional seas ecosystem model, a complex marine ecosystem model. Neth J Sea Res 33:233–246

Beecham J, Bruggeman J, Aldridge J, Mackinson S (2016) *Couplerlib*: a metadata-driven library for the integration of multiple models of higher and lower trophic level marine systems with inexact functional group matching. Geosci Model Dev 9:947–964

Bravo F, Sidhu JPS, Bernal P, Bustamante RH and others (2020) Hydrodynamic connectivity, water temperature, and salinity are major drivers of piscirickettsiosis prevalence and transmission among salmonid farms in Chile. Aquacult Environ Interact 12:263–279

Brown K, Westaway E (2011) Agency, capacity, and resilience to environmental change: lessons from human development, well-being, and disasters. Annu Rev Environ Resour 36:321–342

Castillo MI, Cifuentes U, Pizarro O, Djurfeldt L, Caceres M (2016) Seasonal hydrography and surface outflow in a fjord with a deep sill: the Reloncaví fjord, Chile. Ocean Sci 12:533–544

Christensen VC, Walters CJ, Pauly D (2005) Ecopath with Ecosim: a user's guide. November 2005 edn. Fisheries Centre, University of British Columbia, Vancouver, BC. https://www.researchgate.net/profile/Villy-Christensen/publication/267193103_Ecopath_with_Ecosim_A_User's_Guide/links/553775c40cf2058efdeabe99/Ecopath-with-Ecosim-A-Users-Guide.pdf

Dickson AG, Goyet C (1994) Handbook of methods for the analysis of the various parameters of the carbon dioxide system in sea water. Version 2 (No. ORNL/CDIAC-74). Oak Ridge National Laboratory, Oak Ridge, TN, https://www.osti.gov/servlets/purl/10107773

Fernández FJ, Ponce RD, Vásquez-Lavin F, Figueroa Y, Gelcich S, Dresdner J (2018) Exploring typologies of artisanal mussel seed producers in southern Chile. Ocean Coast Manage 158:24–31

Figueroa Y (2015) Factores determinantes en la oferta de colectores de semilla de chorito (*Mytilus chilensis*) producidos en Áreas de Manejo y Explotación de Recursos Bentónicos, en la Región de los Lagos, Chile. Magister en Economía thesis, Universidad de Concepción. http://repositorio.udec.cl/bitstream/11594/1916/1/Tesis_Factores_determinantes_en_la_oferta_de_colectores.Image.Marked.pdf

Figueroa Y, Dresdner J (2016) Are mussel seed producers responsive to economic incentives? Empirical evidence from the Benthic Resource Management Areas in Chile. Aquac Econ Manag 20:283–311

González HE, Calderon MJ, Castro L, Clement A and others (2010) Primary production and plankton dynamics in the Reloncaví Fjord and the Interior Sea of Chiloé, Northern Patagonia, Chile. Mar Ecol Prog Ser 402:13–30

Haapasaari P, Mãntyiemi S, Kuikka S (2012) Baltic herring fisheries management: stakeholder views to frame the problem. Ecol Soc 17:36

Herbert DG (1991) Foraminiferivory in a *Puncturella* (Gastropoda: Fissurellidae). J Molluscan Stud 57:127–140

Hernández-Miranda E, Estrada R, Strange P, Veas R, Krautz MC, Quiñones RA (2021) Macrofauna community patterns in a Chiloe Island channel used intensely for aquaculture: the ecological status of its benthic environment. Rev Chil Hist Nat 94:1

Hopwood MJ, Sanchez N, Polyviou D, Leiknes Ø and others (2020) Experiment design and bacterial abundance control extracellular H_2O_2 concentrations during four series of mesocosm experiments. Biogeosciences 17:1309–1326

Hyder K, Rossberg AG, Allen JI, Austen MC and others (2016) Making modelling count — increasing the contribution of shelf-seas community and ecosystem models to policy development and management. Mar Policy 61: 293–302

Iizuka M, Zanlungo JP (2016) Environmental collapse and institutional restructuring: the sanitary crisis in the Chilean salmon industry. In: Hosono A, Iizuka M, Katz J (eds) Chile's salmon industry. Springer, Tokyo, p 109–135

IPCC (Intergovernmental Panel on Climate Change) (2014) Climate change 2014: synthesis report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. IPCC, Geneva. www.ipcc.ch/site/assets/uploads/2018/02/SYR_AR5_FINAL_full.pdf

Iriarte JL (2018) Natural and human influences on marine processes in Patagonian subantarctic coastal waters. Front Mar Sci 5:360

Iriarte JL, González HE, Liu KK, Rivas C, Valenzuela C (2007) Spatial and temporal variability of chlorophyll and primary productivity in surface waters of southern Chile (41.5°–43° S). Estuar Coast Shelf Sci 74:471–480

Iriarte JL, Pantoja S, González HE, Silva G and others (2013) Assessing the micro-phytoplankton response to nitrate in Comau Fjord (42° S) in Patagonia (Chile), using a microcosms approach. Environ Monit Assess 185:5055–5070

Kapsenberg L, Miglioli A, Bitter MC, Tambutté E, Dumollard R, Gattuso JP (2018) Ocean pH fluctuations affect mussel larvae at key developmental transitions. Proc R Soc B 285:20182381

Kjærulff UB, Madsen AL (2008) Bayesian networks and influence diagrams: a guide to construction and analysis. Springer, New York, NY

León-Muñoz J, Marcé R, Iriarte JL (2013) Influence of hydrological regime of an Andean river on salinity, temperature and oxygen in a Patagonia fjord, Chile. NZ J Freshw Mar Res 47:515–528

León-Muñoz J, Urbina MA, Garreaud R, Iriarte JL (2018) Hydroclimatic conditions trigger record harmful algal bloom in western Patagonia. Sci Rep 8:1330

Maass M, Balvanera P, Bourgeron P, Equihua M and others (2016) Changes in biodiversity and trade-offs among ecosystem services, stakeholders, and components of well-being: the contribution of the International Long-Term Ecological Research network (ILTER) to Programme on Ecosystem Change and Society (PECS). Ecol Soc 21:31

Malone T, Azzaro M, Bode A, Brown E and others (2016) Chapter 6. Primary production, cycling of nutrients, surface layer and plankton. In: United Nations (ed) The first global integrated marine assessment, World Ocean Assessment I. Cambridge University Press, Cambridge, p 119–148

Mardones JI, Paredes J, Godoy M, Suarez R and others (2021) Disentangling the environmental processes responsible for the world's largest farmed fish-killing harmful algal bloom: Chile, 2016. Sci Total Environ 766:144383

Olsen LM, Hernández KL, Ardelan MV, Iriarte JL and others (2014) Responses in the microbial food web to increased rates of nutrient supply in a southern Chilean fjord: possible implications of cage aquaculture. Aquacult Environ Interact 6:11–27

Olsen LM, Hernández KL, Ardelan MV, Iriarte JL, Bizsel KC, Olsen Y (2017) Responses in bacterial community structure to waste nutrients from aquaculture: an *in situ* microcosm experiment in a Chilean fjord. Aquacult Environ Interact 9:21–32

Ostrom E (2007) A diagnostic approach for going beyond panaceas. Proc Natl Acad Sci USA 104:15181–15187

Pavés HJ, González HE, Christensen V (2013) Structure and functioning of two pelagic communities in the North Chilean Patagonian coastal system. Hydrobiologia 717: 85–108

Pavés HJ, González HE, Christensen V (2014) Trophic impact and keystone species in two pelagic communities in the North Chilean Patagonian coastal system. In: Steenbeek J, Piroddi C, Coll M, Heymans JJ, Villasante S, Christensen V (eds) Ecopath 30 years conference proceedings: extended abstracts. Fisheries Centre, University of British Columbia, Vancouver, BC, p 178–179

Pavés HJ, González HE, Castro L, Iriarte JL (2015) Carbon flows through the pelagic sub-food web in two basins of the Chilean Patagonian coastal ecosystem: the significance of coastal–ocean connection on ecosystem parameters. Estuaries Coasts 38:179–191

Quiñones RA, Fuentes M, Montes RM, Soto D, León-Muñoz J (2019) Environmental issues in Chilean salmon farming: a review. Rev Aquacult 11:375–402

Reid WV, Mooney HA, Cropper A, Capistrano D and others (2005) Ecosystems and human well-being: Synthesis. Island Press, Washington, DC

Richards R, Sanó M, Roiko A, Carter RW, Bussey M, Matthews J, Smith TF (2013) Bayesian belief modeling of climate change impacts for informing regional adaptation options. Environ Model Softw 44:113–121

Rivera A, Unibazo J, León P, Vásquez-Lavín F, Ponce R, Mansur L, Gelcich S (2017) Stakeholder perceptions of enhancement opportunities in the Chilean small and medium scale mussel aquaculture industry. Aquaculture 479:423–431

Rose KA, Allen JI, Artioli Y, Barange M and others (2010) End-to-end models for the analysis of marine ecosystems: challenges, issues, and next steps. Mar Coast Fish 2:115–130

Sala E, Mayorga J, Bradley D, Cabral RB and others (2021) Protecting the global ocean for biodiversity, food and climate. Nature 592(7854):397–402
Saldías GS, Sobarzo M, Quiñones R (2019) Freshwater structure and its seasonal variability off western Patagonia. Prog Oceanogr 174:143–153
Salgado H, Bailey J, Tiller R, Ellis J (2015) Stakeholder perceptions of the impacts from salmon aquaculture in the Chilean Patagonia. Ocean Coast Manage 118:189–204
Salinas S, Castillo M (2012) Caracterización de las corrientes mareales y submareales en canal Desertores (42° 42′ S; 72° 50′ W). Cienc Tecnol Mar 35:5–18
Scott D, Hall CM, Gössling S (2016) A review of the IPCC Fifth Assessment and implications for tourism sector climate resilience and decarbonization. J Sustain Tour 24:8–30
Serpetti N, Baudron AR, Burrows MT, Payne BL, Helaouët P, Fernandes PG, Heymans JJ (2017) Impact of ocean warming on sustainable fisheries management informs the Ecosystem Approach to Fisheries. Sci Rep 7:13438
Servicio Nacional de Pesca y Acuicultura (2016) Estadísticas: Anuarios Estadísticos, Desembarque Artesanal por Regíon. Sernapesca, Santiago, http://www.sernapesca.cl/informes/estadisticas
Servicio Nacional de Pesca y Acuicultura (2017) Anuario Estadísticos. Sernapesca, Santiago, http://www.sernapesca.cl/informes/estadisticas
Siders AR (2019) Adaptive capacity to climate change: a synthesis of concepts, methods, and findings in a fragmented field. Wiley Interdiscip Rev Clim Change 10:e573
Strub PT, James C, Montecino V, Rutllant JA, Blanco JL (2019) Ocean circulation along the southern Chile transition region (38°–46° S): mean, seasonal and interannual variability, with a focus on 2014–2016. Prog Oceanogr 172:159–198
Subpesca (2019) Especies hidrobiológicas. www.subpesca.cl/portal/616/w3-propertyname-510.html (accessed 7 January 2020)
Taylor KE, Stouffer RJ, Meehl GA (2012) An overview of CMIP5 and the experiment design. Bull Am Meteorol Soc 93:485–498
Tiller R, Gentry R, Richards R (2013) Stakeholder driven future scenarios as an element of interdisciplinary management tools; the case of future offshore aquaculture development and the potential effects on fishermen in Santa Barbara, California. Ocean Coast Manage 73:127–135
Turner BL II, Kasperson RE, Matson PA, McCarthy JJ and others (2003) A framework for vulnerability analysis in sustainability science. Proc Natl Acad Sci USA 100:8074–8079
UNDP (United Nations Development Programme) (2019) Human Development Report 2019. UNDP, New York, NY. http://hdr.undp.org/sites/default/files/hdr2019.pdf
Uriarte I (2008) Estado actual del cultivo de moluscos bivalvos en Chile. In: Lovatelli A, Farías A, Uriarte I (eds) Estado actual del cultivo y manejo de moluscos bivalvos y su proyección futura: factores que afectan su sustentabilidad en América Latina. FAO Actas de Pesca y Acuicultura 12. FAO, Rome, p 61–75
van der Molen J, Aldridge JN, Coughlan C, Parker ER, Stephens D, Ruardij P (2013) Modelling marine ecosystem response to climate change and trawling in the North Sea. Biogeochemistry 113:213–236
van Leeuwen SM, Le Quesne WF, Parker ER (2016) Potential future fisheries yields in shelf waters: a model study of the effects of climate change and ocean acidification. Biogeosciences 13:441–454
Vergara-Jara MJ, DeGrandpre MD, Torres R, Beatty CM, Cuevas LA, Alarcón E, Iriarte JL (2019) Seasonal changes in carbonate saturation state and air-sea CO_2 fluxes during an annual cycle in a stratified-temperate fjord (Reloncaví Fjord, Chilean Patagonia). J Geophys Res Biogeosci 124:2851–2865
Yodanis CL (2000) Constructing gender and occupational segregation: a study of women and work in fishing communities. Qual Sociol 23:267–290

Editorial responsibility: Ingrid van Putten, Hobart, Tasmania, Australia
Reviewed by: C. Margaret Bulman, F. Javier Bravo and 1 anonymous referee

Submitted: January 29, 2021
Accepted: October 13, 2021
Proofs received from author(s): December 6, 2021