Supplement 1. Scenario time periods

Table S1: subdivision of the simulation period into 30-year blocks.

Period	Name	Description
1958–1978	Spin-up time	Necessary spin up time for the benthic system
1979–2008	Current conditions	Reflecting the state on which the current economic use of the resources is based
2009–2038	Future block 1	Immediate future prediction
2039–2068	Future block 2	Intermediate future prediction
2069–2098	Future block 3	Long-term future prediction

Note that the reference simulation applied the 1979-2008 meteorology repeated 3 times to create a stable 30-year average baseline.

Supplement 2. Predicted environmental changes

Riverine discharge

Here the estimated non-marine changes for the region are shown. Figure S1a shows the average annual signal (based on observational data) for the Puelo river, while Figure S1b shows the estimated annual discharge up to 2100. The latter is based on predicted annual rainfall (CMIP5, Cordex) times the normalized seasonal signal. Thus, Puelo river discharge varies with the different climate predictions.

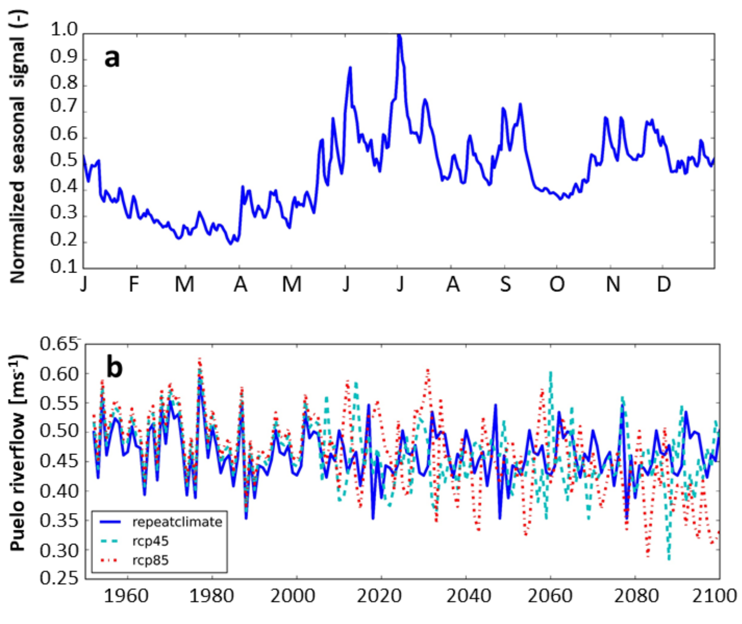

Figure S1: Puelo river information: a) the averaged seasonal signal of the Puelo discharge over the data period 2003-2017 (normalized), b) the estimated annual discharge. Note that the Puelo river is located in the southern hemisphere, so that winter is June, July, August and summer is December, January, February.

Meteorological changes

Figure S2 shows the predicted meteorological changes for the Gulf of Ancud as predicted by the CMIP5 (Taylor et al. 2012) regional downscaling experiment for South America (ww.cordex.org). The South American experiment was performed by Euromediterranean Centre on Climate Change (CMCC) with a spatial resolution of 0.44 degrees or ~ 50 km. The South American experiment within CORDEX corresponds to the ensemble run r1i1p1 run of the Rossby Centre regional atmospheric model (RCA4 v3) run by the Swedish meteorological and Hydrological Institute (SMHI) using as driving model the MPI-ESM-LR CMIP5 simulations carried out by the Max Planck Institute for Meteorology.

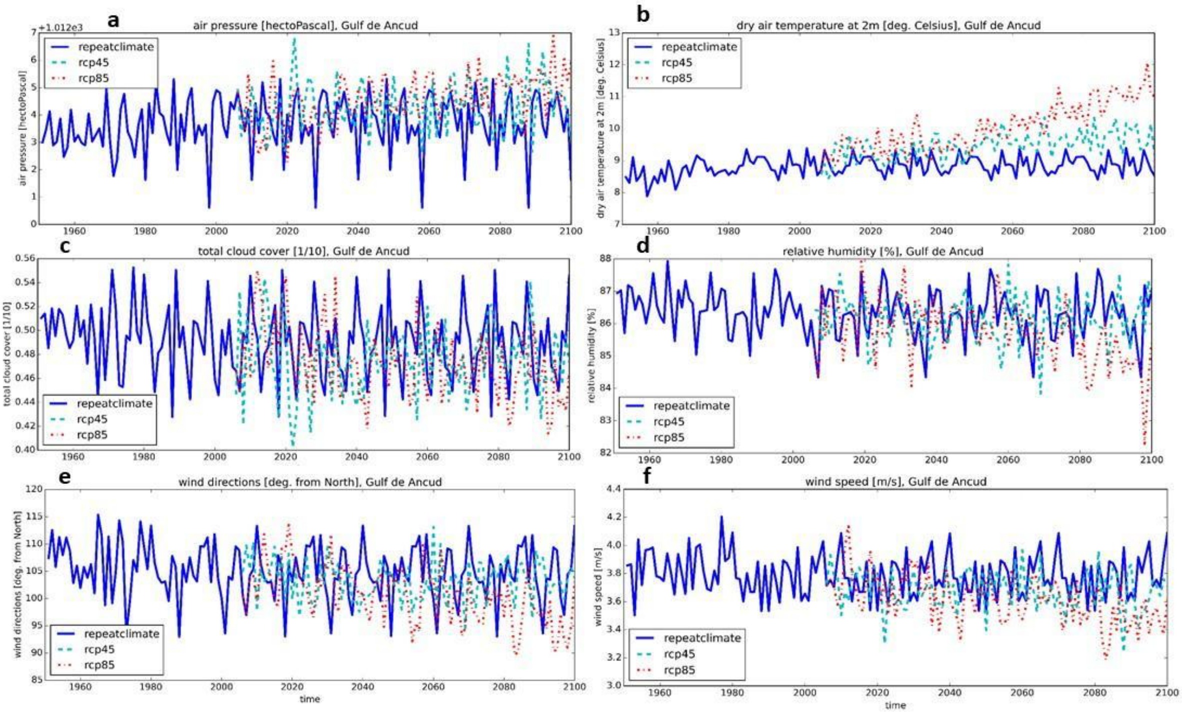

Figure S2: climatological conditions compared to the reference conditions (repeat of 1979-2008 climate) for the location [-42.0° N, -73.0° E] in the Gulf of Ancud: a) air pressure, b) air temperature, c) cloud cover, d) relative humidity, e) wind direction and f) wind speed.

Cordex results were compared to ECMWF ERA-Interim meteorology for the same location (Figure S3), showing an underestimation of summer and overestimation of winter temperatures by the Cordex experiment. Wind speeds were generally lower as well. Note that the ERA-Interim forcing was used only for a separate validation simulation, and that all scenarios applied the Cordex predicted meteorology.

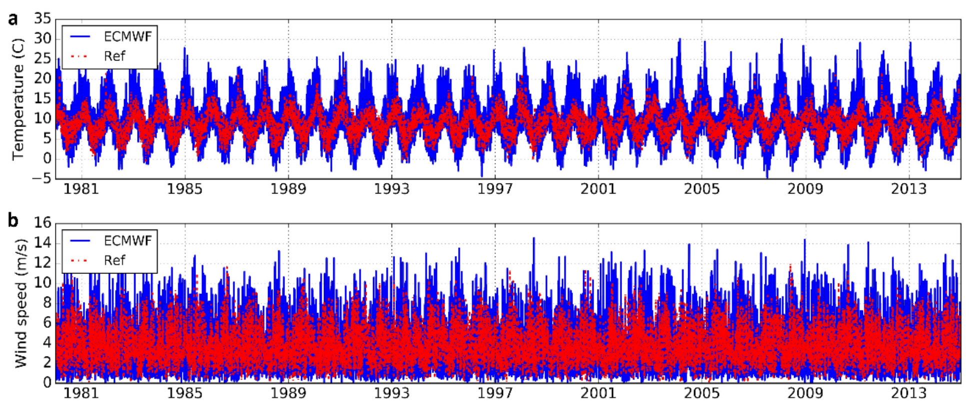

Figure S3: a) Temperatures and b) Wind speeds used to force the validation run (1980-2014), obtained from ECMWF ERA-Interim and the Reference run, obtained from the historical South American-CORDEX results.

Supplement 3. Linking the natural and social science models

Figure S4 provides an overview of the various models and tools used in the Ocean Certain project generally and with respect to the case study of the Gulf of Ancud and the community of Cochamó, Chile, and how these are linked.

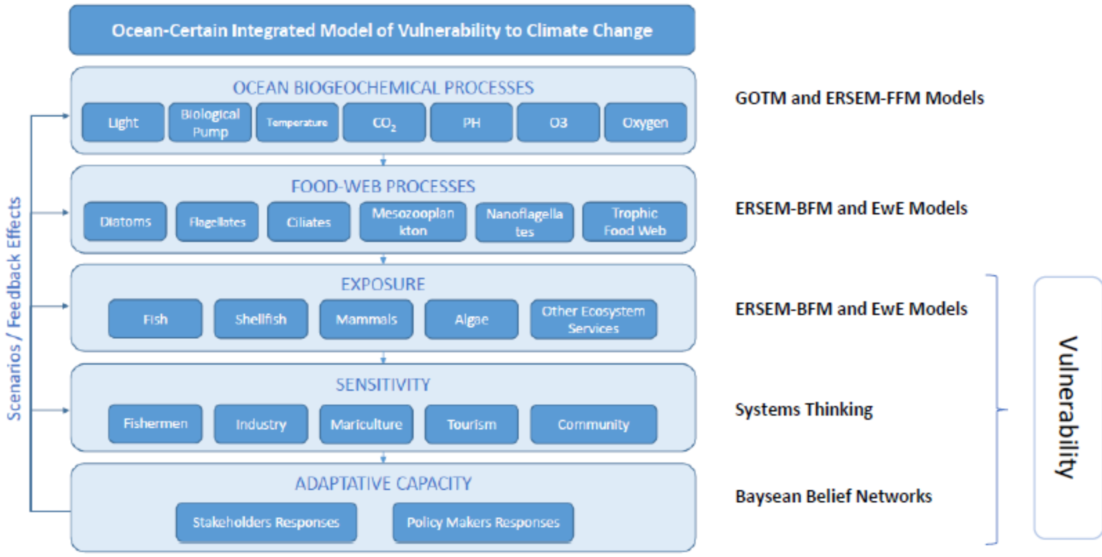

Figure S4: Connections between the different tools used to gauge impact of large-scale physical, chemical and biological changes on the community.

Supplement 4. Lower and higher trophic levels: model details and coupling

Lower trophic level model

The ERSEM-BFM model operates on a functional group basis, tracking nitrogen, phosphorous, silicate, oxygen and carbon throughout the system. It is derived from the original ERSEM model (European Regional Seas Ecosystem Model, see Baretta et al. 1995) and its successor BFM (Biological Flux Model, see Vichi et al. 2003, 2007a,b, http://bfm-community.eu) and has been adapted at the CEFAS (UK) and NIOZ (NL) institutes to specifically include shallow shelf seas processes. This includes in particular an extensive benthic compartment, but also benthic diatoms with a resuspension phase, *Phaeocystis* colonies (a coastal nuisance algae) and enhanced filter feeder dynamics (pelagic larvae, young filter feeders and adult filter feeders, i.e. inclusion of life history). TEP production by nutrient-stressed diatoms is also included, causing a fast sink out after a diatom bloom as TEP is quite sticky (forming macro-aggregates). This process forms one of the main food sources of filter feeders, as the fast-sinking rate prevents remineralization by bacteria within the water column. Pelagic phytoplankton is represented by six functional groups: diatoms, flagellates, picophytoplankton, dinoflagellates, resuspended benthic diatoms and *Phaeocystis* colonies. Benthic diatoms form an additional group which resides on the bed but which can resuspend into the water column. Zooplankton consists of 5 functional groups: filter feeder larvae, heterotrophic nanoflagellates, microzooplankton, omnivorous mesozooplankton and carnivorous mesozooplankton. Benthic functional groups include young filter feeders, adult filter feeders, meiobenthos, deposit feeders, infaunal predators and megabenthos. However, the application in the Gulf of Ancud, with its rocky bed, limited the benthos groups to mainly filter feeders and precluded use of the extensive sediment dynamics incorporated in the model. Pelagic and benthic bacteria are also included, including anaerobic bacteria in the bed and nitrifying bacteria/archaea in the pelagic and benthic. The ERSEM model was designed specifically to include varying nutrient ratios within the organisms (i.e. not purely Redfield ratio's), and thus allows for luxury uptake of nutrients by organisms for later use. For use in the Gulf of Ancud the light requirements of the phytoplankton were adapted within the model: at 40° S: the phytoplankton are less light sensitive and more protected against UV radiation than the normal settings aimed at Northern Europe (49 – 60° N) applications. The carbonate system includes CO_2, HCO_3^-, CO_3^{2-}, $p$$CO_2$, pH, DIC and total alkalinity (TA). The latter is influenced by the biological uptake of nitrate and ammonia and the nitrification and denitrification processes, but not by any calcification processes as these are not included except through parameterization. Biological production and consumption of CO_2 is fully accounted for.

Validation of the lower trophic level model was performed on a separate simulation applying the more realistic ERA40 meteorological forcing data (1958–2008). Results showed an overestimation of winter surface salinity and a dominance of flagellates over diatoms for longer than observed (given the sparse species-specific observations), with generally lower biomass values than those reported for the area. In general, the model reproduced the observed seasonal characteristics of the system (diatoms dominance in austral summer, flagellate dominance in austral winter) but observed peak values for diatoms were not reproduced. We think this is mainly due to the forcings applied, i.e. the relaxation of the model to the observed temperature and salinity profiles, and the estimation of the river influence. These approximations will underestimate the natural variance of the system and lead to lower than observed peak values. Benthic processes were hindered by the water-column approach and permanent stratification of the system, leading to very limited refreshing of the oceanic bottom layer (nutrients are purposely supplied to the bottom layer to ensure constant availability). Hence, we only present percentage change results for the benthic system, as benthic biomass results were compromised by the lack of fresh oceanic oxygen. Being mostly dependent on the vertical exchange, the simulated depth of 273 m (combined with the rocky sea floor so no sediment dynamics) was not sufficient to sustain a healthy benthic community without horizontal processes adding nutrients, food and oxygen.

The GOTM-ERSEM-BFM model was coupled one-way (bottom-up) to the higher trophic level model. As such, top-down pressures like fishing do not impact upon lower trophic level dynamics and fishing-regulated changes in grazing on zooplankton are not included, limiting the variability of the zooplankton functional groups. Note that the LTL model does include biomass-based grazing pressure, ensuring more grazing when biomass increases. However, two-way coupling should be applied, with proper zooplankton dynamics, for a more realistic coupling.

Higher trophic level model

The Ecopath with Ecosim model was originally developed at NOAA with the main subsequent development occurring at the University of British Columbia (Christensen & Pauly 1992, Walters et al. 1997, Steenbeek et al. 2016). Here, the Ecopath model describes the static food web, while Ecosim provides the temporal development of the static system in response to external, time-varying, drivers. The model is widely used in management (Heymans et al. 2014, Heymans et al. 2016, Hyder et al. 2016) due to its easy use and representation of the main food web (as opposed to single species stock models). Here, the application for the Inner Sea of Chiloé was used (which includes the Gulf of Ancud), see Pavés et al. (2013, 2014, 2015). The species included are given in Table S2.

Table S2: Species included in the application of the food web model Ecopath with Ecosim to the Inner Sea of Chiloé. Note that the EwE set-up operates mostly on family level, whereby one family consists of multiple species.

	Taxon	Common name(s)		Family name	Common name(s)
1	Otariidae	Eared seals	19	Appendicularia	Pelagic tunicates
2	Aves	Birds	20	Siphonophore	
3	Orcinus orca	Orca	21	Salpida	Pelagic tunicates
4	Mysticeti	Baleen whales	22	Decapoda (L)	Larval crustaceans
5	Delphinidae	Dolphins	23	Euphausiacea	Krill
6	Gempylidae	Snake mackerel family, includes snook	24	Chaetognatha	Arrow worms
7	Sciaenidae	Drums/croakers	25	Cladocera	Water fleas
8	Atherinopsidae	Neotropical silversides	26	Copepoda calanoida	Copepods
9	Ophidiiformes	Includes cusk-eels and pearlfishes	27	Copepoda cyclopoida	Copepods
10	Gadiformes (A)	Adult Cod	28	Copepoda nauplii (L)	Larval copepod
11	Gadiformes (J-L)	Juvenile and larval Cod	29	Ciliophora	Ciliates
12	Carangidae	Jack Mackerel	30	Microphytoplankton	
13	Clupeiformes (J-A)	Adult and juvenile herring	31	Microflagellates	
14	Clupeiformes (L)	Larval herring	32	HNF	Heterotrophic nanoflagellates
15	Ichthyoplankton (L)	Plankton consisting of fish eggs and larvae	33	ANF	Autotrophic nanoflagellates
16	Scyphomedusae	Jellyfish	34	Bacteria	
17	Hydromedusae	Jellyfish	35	DOM	Dissolved organic matter
18	Ctenophora	Comb jellies	36	Detritus	

The parameter settings for this model can be found in Pavés et al. (2013): Annex 1 and 2. Fishing pressure values are provided in Pavés et al. (2013): Table 3 and annex 3. The EwE model application of the Inner Sea of Chiloé includes artisanal fisheries impact on Clupeiformes (purse-seine fisheries), Sciaenidae and Atherinopsidae (gillnet fisheries), Carangidae (purse-seine), Gempylidae (line-hand fishery), and gadoids and Ophidiiformes (long-line fishery), as stated in Pavés et al. (2013). As such, it does not represent the commercial fishing pressure in that area.

Coupling of the lower and higher trophic level model

Linking of the two models was achieved via Couplerlib (Beecham et al. 2016) as managed coupling: a management layer between the two models handles the data exchange and where necessary converts, validates, reorganizes, splits or merges the data. Plankton biomass time series generated by GOTM-ERSEM-BFM (diatoms, autotrophic nanoflagellates, heterotrophic nanoflagellates, ciliates, omnivorous and carnivorous mesozooplankton), were coupled to EwE to microphytoplankton, autotrophic nanoflagellates, heterotrophic nanoflagellates, ciliates and microflagellates respectively. Daily temperature times series as calculated by GOTM were also used in the EwE forcings, with the top mixed layer temperature linearly applied to pelagic species and the bottom mixed layer temperature linearly applied to benthic-oriented species. Within EwE temperature affects mortality rates and the food-consumption estimates of species. Note that bacteria, dissolved organic matter

(DOM) and detritus were not used in the linking: this way each model retains its own bacterial loop for regeneration. For more details on an actual ERSEM-EwE coupling see Beecham et al. (2016).

With respect to the community interests of Cochamó, the model is able to represent mussels, mollusks and limpets (filter feeders: ERSEM-BFM), Trophon top shell (megabenthos: ERSEM-BFM), snook (Gempylidae: EwE), silversides (Atherinopsidae: EwE) and Jack Mackerel (Carangidae: EwE). All these representations are at functional group or family level, so that a one-to-one relationship with the fished resource is not possible.

The short-lived herring required strong smoothing to see scenario impacts. Figure S5 presents the unsmoothed results, showing fast adjustment in the spin up period (1958-1978) and stable biomass during the reference period (1979-2008).

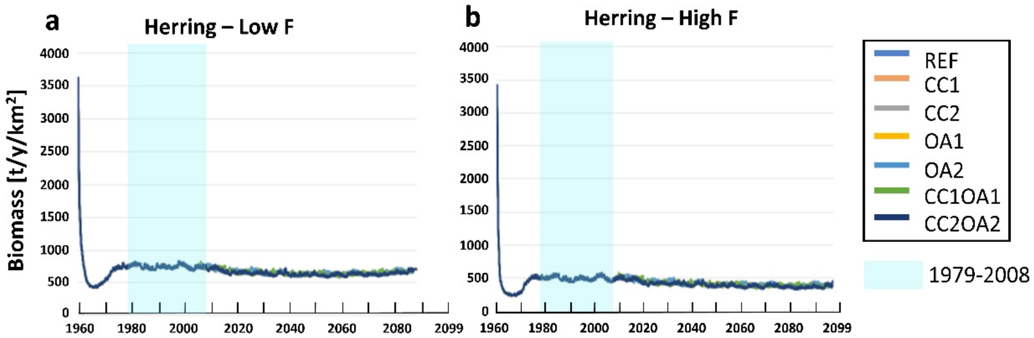

Figure S5: unsmoothed herring stock biomass over the simulated period. For an explanation of the scenario acronyms, see Table 1 in the main text.

Supplement 5. Systems Thinking models and BBN Trees

For reasons of space and visual clarity, the graphics produced in the Systems Thinking (ST) and Bayesian Belief Network (BBN) sessions for each workshop are described or simplified in the main text (see sections 2.3 and 3.4). Three workshops were held, one with artisanal and mussel-seed collectors (Cochamó, morning 22-Jul-2015), one with a diverse local group (Cochamó, afternoon 22-Jul-2015) and one with representatives from various government agencies and associated consultants (Valparaíso, 28-Aug-2015), as described in section 2.3. We present here one example of the mental models produced in the ST sessions and one example of the BBN trees produced by each workshop. More information on these methodologies can be found in Haapasaari, et al. (2012), Richards et al. (2013), Salgado et al. (2015) and Tiller et al. (2013). Note that feedback pathways are not allowed in Bayesian networks and therefore the entire network must be acyclical (i.e. one direction of causality). The implications for this constraint include the inability to model the influence of reinforcing (positive feedback) or balancing (negative feedback) pathways on the system being modeled. Such feedback pathways are important for understanding the temporal evolution of a system (i.e. how it changes overtime) and how it might respond to 'perturbations' (Sterman 2000). Whilst there are techniques that can enable feedback pathways in BBNs these can quickly lead to cumbersome models with a large number of nodes, even for very simple feedbacks (Kjærulff & Madsen 2008). If the purpose of a model is to explore the role of feedback pathways in governing temporal dynamics, then other modeling methodologies such as systems dynamics (Sterman 2000) would be more appropriate to use than Bayesian statistical modeling. However, here we are interested in using a methodology that allows straightforward integration of multi-disciplinary (environmental, social and economic) variables, accommodates ‘expert opinion’ as a data source and where models can be developed even when data is relatively scarce. Furthermore, in this work we are focused on scenario analysis (i.e. what if?) where changes in conditions may be used to update our prior understanding of an event (e.g. the priority issue in our model) to posterior understandings. These ideals are well-matched by the attributes of BBNs.

The first workshop with stakeholders was held on the morning of 22 July 2015. The workshop began with 17 members of the fishermen’s cooperative but only 12 remained for the second round (BBN). These participants were self-employed in several activities, including small-scale fishing, small-scale aquaculture, diving or as service providers for aquaculture companies, some tourist fishing but were most reliant upon mussel seed collection. A second workshop was held the afternoon of the same day, but with a different group of stakeholders. An attempt was made to reach out to those engaged in other economic sectors, including tourism, and researchers had some success in doing so. The group included former fishermen, fishermen’s spouses, members of the local radio station, fishermen engaged in fishing tourism and a member of the Navy in charge of enforcing local fishing operations and permits. Ten of these stakeholders remained through the BBN exercise.

In the Systems Thinking sessions, project researchers led workshop participants in a wide-ranging discussion about their socio-ecological system. The group was presented with a scenario composed of preselected factors that could change the resources base (drivers). Participants were then invited to use their own knowledge and experience to speculate on how changes in the preselected drivers would affect their resources and how such changes would in turn affect them. This exercise revealed the degree to which and how community members understood the exposure and sensitivity of their community to changes in key ecosystem services.

The resulting ST sessions were lively, generating much discussion as participants negotiated among themselves what variables were to be included in the mental model and how they connected these to other variables. In those sessions, the facilitator recorded the comments of the participants using sticky notes and drawing connective arrows. This allows participants to have an immediate visual representation of the discussion, ensuring that facilitators capture the intent of the participants and also stimulating further discussion. This material is simultaneously entered into the Vensim software (Ventana Inc.). The software produces graphics such as Figure S6 and S7, below. While the software is very useful in storing the needed information (relevant factors/nodes and causal pathways generated by the discussion) and is subsequently useful in tracking pathways, the graphic is not always easy to read. Figure S6 presents the mental model produced in the artisanal fishers’ and mussel-seed collector’s workshop.

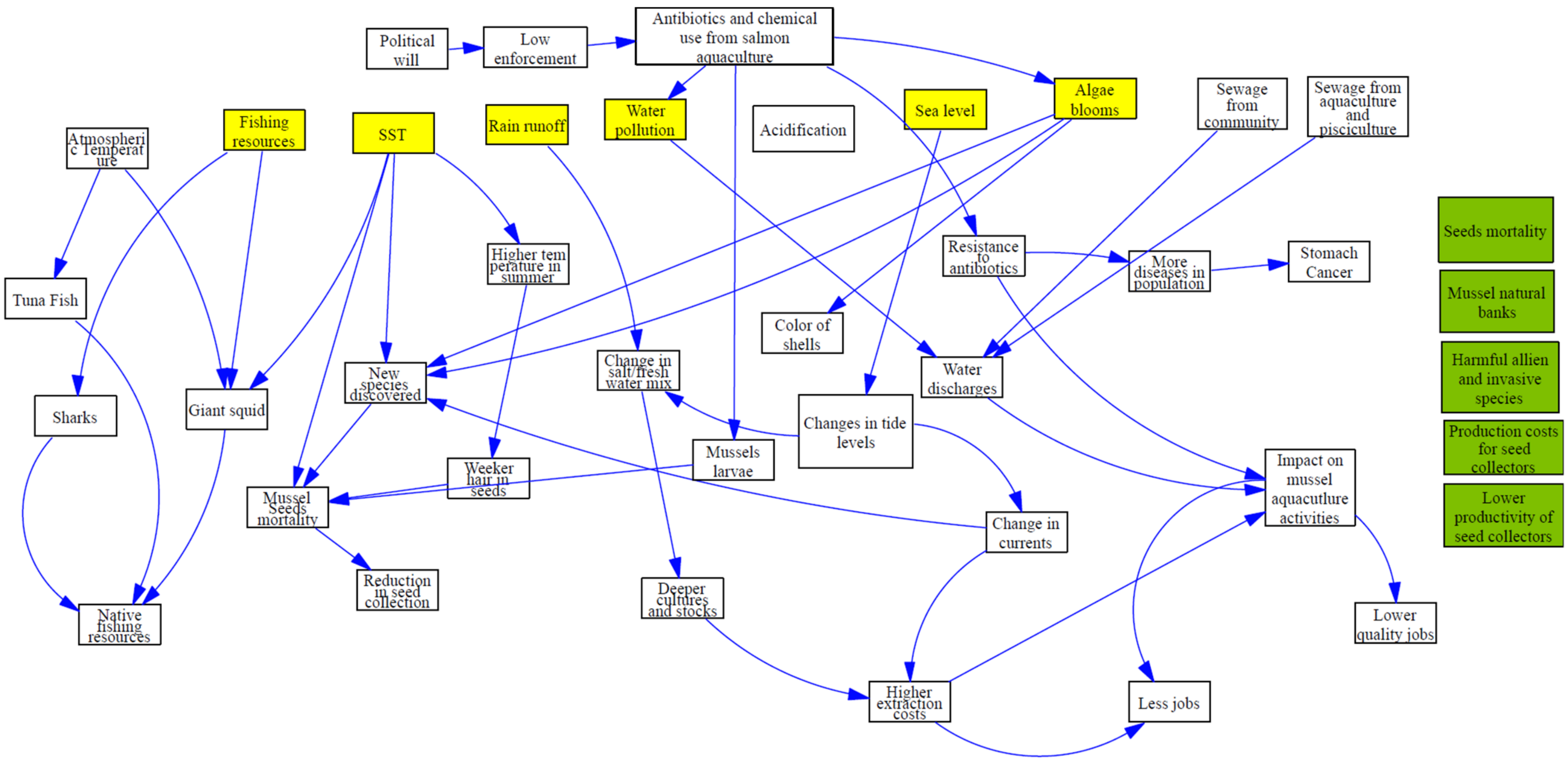

Figure S6: Output of participatory workshops. Systems-Thinking generated mental model as for the workshop of artisanal fishers and mussel-seed collectors, produced by Vensim software.

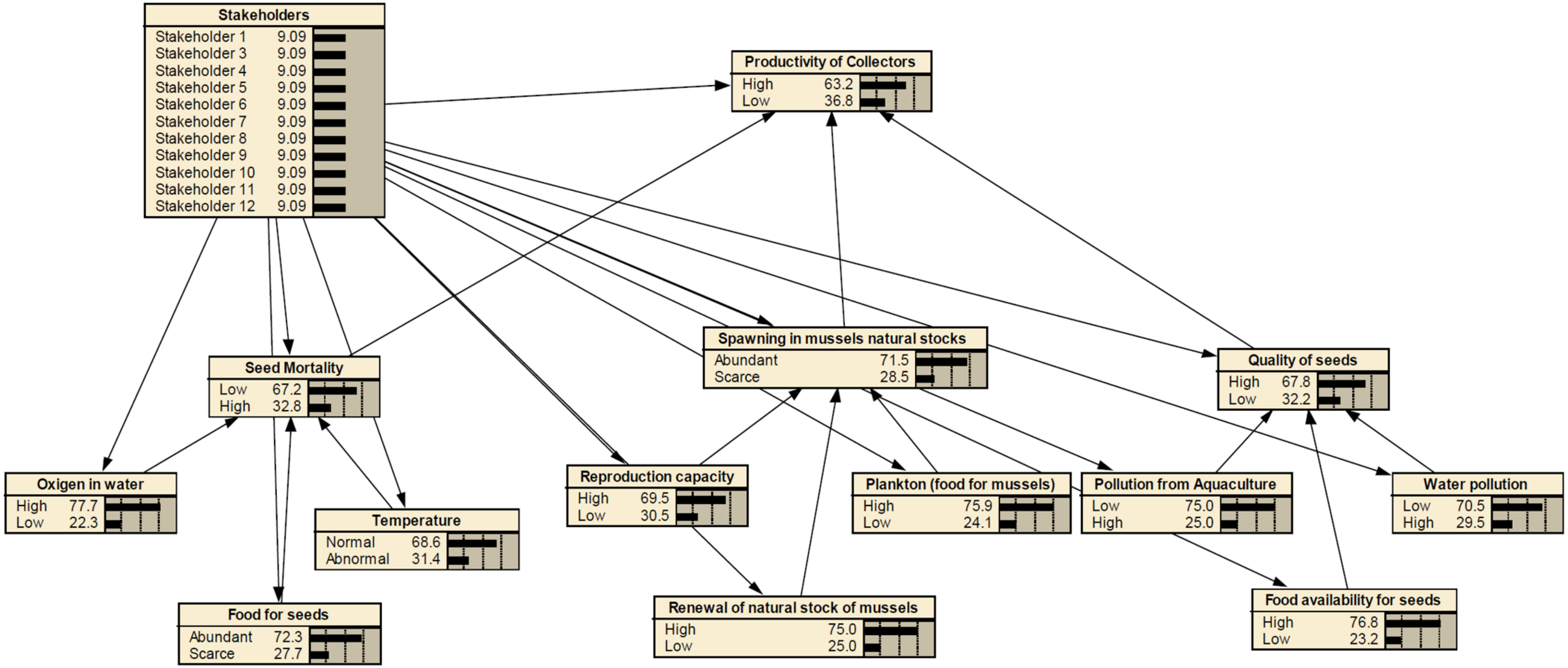

Figure S7: Output of participatory workshops. BBN tree from the artisanal fishers' and mussel-seed collectors' workshop.

In the second part of each workshop, project facilitators led workshop participants in the construction of the BBN tree. BBN modeling is extremely well-suited for coalescing knowledge from a variety of sources (e.g. several stakeholders) into a single modeling framework (Tiller et al. 2015). These methodologies take the place of in-depth socio-economic modeling which requires large amounts of highly detailed data: They treat stakeholders as local experts on their socio-ecological systems who draw upon their own assessment of their socioeconomic and natural resource bases. Participants collectively chose the single issue of most concern to them and identified the factors that most affect that issue. Participants were free to choose whatever priority issue and factors they liked, even if not related to climate change or the marine environment. The priority issue constitutes the first variable node (the parent node) in what becomes a three-tiered BBN network. The group was then asked to agree upon two values for the priority variable, a desirable and an undesirable state. They were then asked to select three variables (first-level child nodes) that were, in their opinion, most likely to determine the state of the first variable. Participants then established desirable and undesirable values for each of these three nodes. They next selected a final set of nodes: for each of the three first-tier nodes, they selected three variables most likely to determine its state (second-level child nodes). Working together, the group then assigned a desirable and undesirable value to each of those nine nodes. The result was a three-tier tree of causally linked variables that flows uni-directionally towards the primary node. The contents of the BBN trees are presented in a combined and simplified form in section 5.1 for reasons of visual clarity and space. An example of the BBN tree for the artisanal fishers and mussel-seed collectors is presented in Figure S7. The figure includes the probability the group collectively awarded to each positive and negative state of each node, allowing researchers to identify the factors/nodes the group held to be most important to outcomes. The Systems Thinking sessions are wide-ranging and allow for the capture of information from participants that is not later included in the BBN modeling. This creates the possibility of identifying feedback loops in the mental model produced in the discussion. In the main text, it was noted that in the BBN, causality flows only one way because the model becomes too complex if feedbacks are introduced (Kjæerulff & Madsen 2008). In the event, the ST discussions did not identify feedback loops. The limitations of the BBN methodology accordingly did not result in a loss of information generated by the ST session.

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