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Integrating scientific knowledge, data and stakeholder perceptions for decision support

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Integrating scientific knowledge, data and stakeholder perceptions for decision support

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Abstract: the marine food web is considered to be a factor of key importance for the global carbon balance. The concept of the ‘Biological Pump’ refers to the mechanism by which CO_2 fixed by photosynthesis is transferred to the deep ocean through biologically-driven processes, resulting in sequestration of carbon for a period of decades or longer. Stressors affecting the efficiency of the biological pump include water column stability, sea temperature, acidity, excessive nutrients inputs, overfishing, pollution and other anthropogenic changes. The aim of the EU-FP7 project OCEAN-CERTAIN is to reduce the uncertainties in our understanding of the impacts of these stressors on the mechanisms underlying the biological pump, and the resilience of coastal and marine stakeholders for the social-economic impacts of changes in the marine food web. Modelling, field sampling and stakeholder workshops are combined for three case studies in the Arctic, the Eastern Mediterranean and Patagonia. The central paradigm of the project is ‘Consilience’ referring to the integration of data, information and scientific knowledge from different domains and sources to achieve an added value surpassing that of the individual elements. A close collaboration between natural and social scientists, and software engineers is inherent to the concept of consilience. The project results are used to design a Decision-Support System (DSS) integrating scientific knowledge with data and stakeholder expertise, serving as platform for policy analysis. Consilience, and more in particular systems analysis, are the basis for the DSS architecture but by themselves these cannot solve all the practical and methodological issues encountered. A challenge for the project is the integration of the findings and knowledge of the behavioral and natural sciences in the DSS. A combination of three techniques is used to address the issue: a component-based architecture, meta-modelling to represent the biophysical processes described by the components, and fuzzy cognitive mapping to represent narrative scenarios derived from local knowledge.

***Keywords**: Climate Change; Systems Analysis; Decision Support System; Model Integration; Fuzzy Cognitive Mapping; Resilience; Adaptive Capacity*

1 INTRODUCTION

The marine food web is considered to be of key importance for the fixation of atmospheric carbon and the mechanism which has come to be known as the so-called 'Biological Pump' (Longhurst and Harrison, 1989). The quantification of the impacts of the different climatic and non-climatic stressors on the functioning of the marine food web is subject to uncertainty although the mechanisms underlying this biological pump are qualitatively understood (Hensen et al., 2011) . The main objectives of the EU-FP7 research project 'Ocean-Certain' (www.oceancertain.eu) are to identify and reduce the uncertainties in our understanding of the feedback mechanisms governing the marine food web, and examine the social-economic impacts of potential changes, and adaptive capacity of regional stakeholders. The sources of information used in the Ocean-Certain project include field experiments, text mining, dynamic end-to-end modelling, and narrative storylines derived from stakeholder workshops. The central paradigm of the project is 'consilience', a concept introduced by Whewell in the 19th century (Whewell, 1840). Consilience refers to the combination of data, knowledge and perceptions to create a theory with an overall value surpassing that of the individual elements. A close collaboration of natural and social scientists in different work packages (Figure 1) is to result in a Decision-Support System (DSS) to support the analysis of long-term management strategies and facilitate the communication between model experts, stakeholders and marine managers.

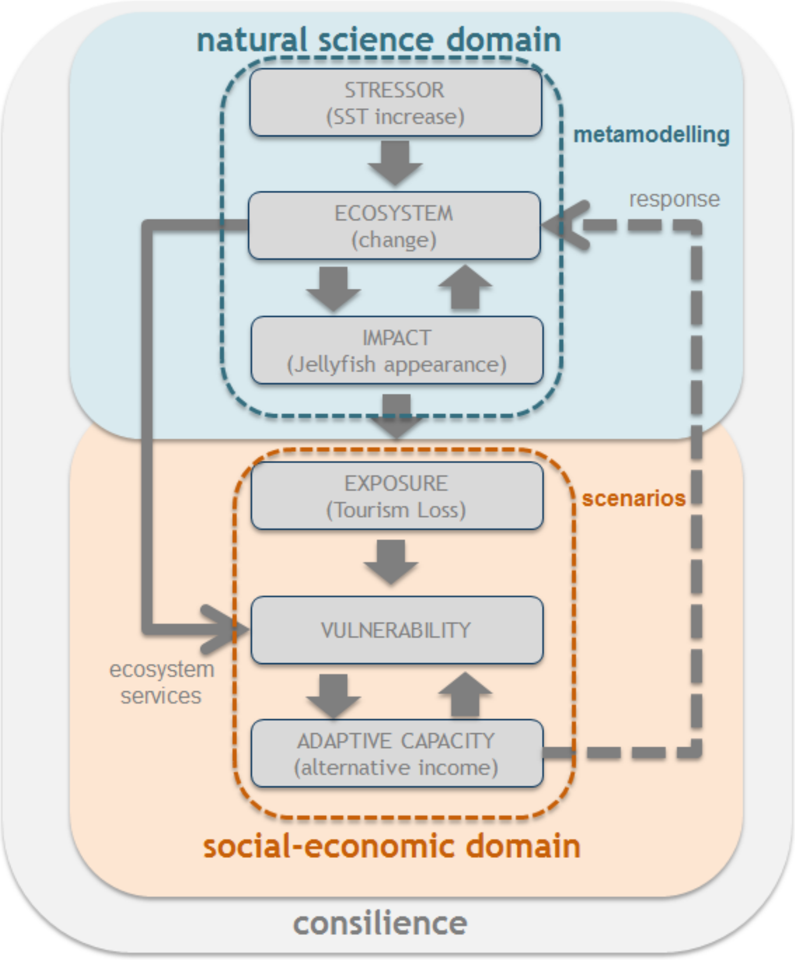


Figure 1. Examples of knowledge integration in OCEAN-CERTAIN (De Kok et al., 2015a).

Systems thinking (Senge and Sterman, 1992) is used as the common framework of analysis for Ocean-Certain and for the DSS architecture (Figure 1). The systems approach started early on in the project with the researchers designing a causal loop diagram describing the interdependencies between the main stressors, key state variables and selected policy indicators. Potential stressors in this conceptual model included changes in sea level, air temperature increase, ocean acidification, eutrophication, overfishing and marine pollution. Three sectors were identified by the research team as being of key relevance to the project objectives: (1) coastal and offshore fisheries, (2) aquaculture, and (3) coastal and marine tourism. Before we present the analytical framework for integration we discuss the models for the natural and social subsystems.

2 MODEL ARCHITECTURE

The overall purpose of the system model is to develop the natural science understanding necessary to model the impact of multiple stressors (e.g. climate change, overfishing, and pollution) on the overall functioning of the ecosystem food web and biological pump (Figure 2).

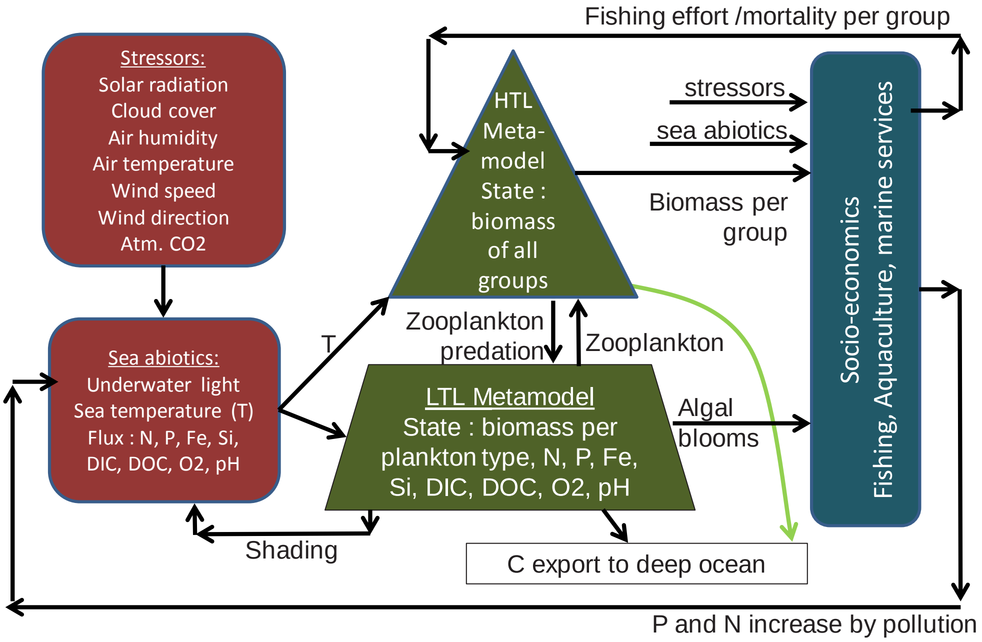


Figure 2. Conceptual model of the system model used as general framework for the DSS (DIC stands for Dissolved Inorganic Carbon while DOC stands for Dissolved Organic Carbon).

A distinction is made between the Lower Trophic Level or LTL (phytoplankton, bacteria, zooplankton, and most invertebrates …) and the Higher Trophic Level or HTL (fish, invertebrate macrofauna, birds and mammals). Modelling of the abiotic environment and LTLs is carried out using a one-dimensional (water column) process-based model GOTM-ERSEM-BFM, a hydro-biogeochemical model jointly developed by the NIOZ (Netherlands) and Cefas (UK) institutes using the GOTM hydrodynamic model (www.gotm.net). The biogeochemical part is based on the European Regional Seas Ecosystem Model or ERSEM Model (Baretta et al., 1995) and the subsequent Biological Flux Model or BFM (Vichi et al., 2004), with additional developments (mainly related to water column and seabed coupling) that make it distinct from both. For details please see van der Molen et al. (2013) and van Leeuwen et al. (2013, 2016). The model is forced by appropriate boundary conditions to represent the effects of advection and other important processes (such as Atlantic water inflow in the Barents Sea). ERSEM-BFM is an ecosystem model designed to simulate carbon and nutrient cycling and ecosystem response, originally focused on European shelf seas. It is related to NPZD (nutrient-phytoplankton-zooplankton-detritus) type models but includes many additional refinements necessary to correctly represent the key processes of temperate shelf ecosystems; the main ones being increased plankton community complexity, inclusion of the microbial loop, variable nutrient stoichiometry, carbon-oxygen dynamics and inclusion of processes and lifeforms in and on the seabed. For the higher trophic levels the coupled EwE model (Ecopath with Ecosim), the Ecopath with Ecosim (EwE) modelling software suite (www.ecopath.org) is the tool of choice to examine the impacts of environmental stressors on the fish stocks. The approach, its methods, capabilities and pitfalls are described in detail by Pauly et al. (2000). The model suite is essentially a food web model (i.e. based on known interactions between species) with a temporal dimension.

Another component of the Natural Sciences model is the minimum 'killing the winner' food web model by Thingstad et al. (2007). This model simulates interactions in the lower trophic food web and has been built to identify the set of main controlling mechanisms, rather than adding numerous elements to obtain a perfect numerical fit between observations and model. This model will be used in conjunction with the results of the mesocosm field experiments to ascertain whether the different dominant trophic pathways during experimental manipulations can be explained using this set of basic food web components. Since this model has been shown to be quite robust in such types of experiments (Thingstad et al., 2007) the minimum model results will then be compared to one-dimensional runs of the lower trophic level ecosystem model (GOTM-ERSEM-BFM) to assess the performance of both models using the same controlled setup. The LTL and HTL models will be validated independently from the social-economic sub model. Existing and new data from mesocosm experiments and field cruises will be used for this purpose.

A direct reimplementation of the biophysical and food web models with all detail in the DSS would not fit the functional requirements of end users, and slow down simulations considerably. Several design decisions were therefore taken for the implementation of the LTL and HTL sub models in the DSS. Temporally varying model results of depth-averaged, depth-integrated and depth-difference variables were considered sufficient to represent the impacts of the food-web mechanisms on the biological pump which are dominated by the vertical processes. Furthermore, the researchers concluded that a time step of one month was reasonable for typical end users in view of the typical time horizon for climate change impacts (10-100 years).

The overall objective of the behavioral sciences (economics and sociology) in Ocean-Certain is to improve the understanding of the impacts that climate-induced changes in marine systems may have on the human communities that depend on them. Analysis of the impact on the three relevant economic sectors (fisheries, aquaculture and tourism) is addressed conceptually with the Vulnerability Analysis for Sustainability (VAS) framework developed by Turner II et al. (2003). In this approach, an impact is understood to be a function of the exposure of the place (or analogously, the sector) to a given change, the sensitivity of the human and natural systems to the change, and the resilience of both systems under stress. The adaptive capacity of the local community is a key factor with respect to their resilience (Lorenzoni et al., 2000; Adger, 2003). Local knowledge is viewed as a key source of information for eliciting the adaptive capacity (and the determinants of adaptive community) of a community (Richards et al., 2013). Participatory workshops organized with stakeholder representatives of the three economic sectors were used to elicit stakeholder perceptions of exposure, social resilience and adaptive capacity. Fuzzy Cognitive Mapping (Kosko, 1986; Gray et al., 2015) was used for integrating the behavioral aspects in the DSS because of the natural support for analysing system feedback in a straightforward manner. Fuzzy Cognitive Maps (FCMs) are directed graphs linking state variables, with 'fuzzy' weights assigned to the causal linkages. Scenarios can be compared by iterative computation of the state changes of variables, starting from the initial state and changes in the driving factors. Figure 3 shows the FCM which is currently implemented in the DSS to represent the social-economic subsystem. The design is generic and integrates the climate-induced changes with three economic sectors. FCMs are semi-quantitative, with variables usually expressed in a range between 0 (minimum) and 1 (maximum), whereas the weights are given a value in the range [-1,+1]. The weights and initial values of the variables were set by the social scientists organizing the workshops. After implementation of the FCM model by the DSS development team the results were examined to fine tune the weights and initial states.

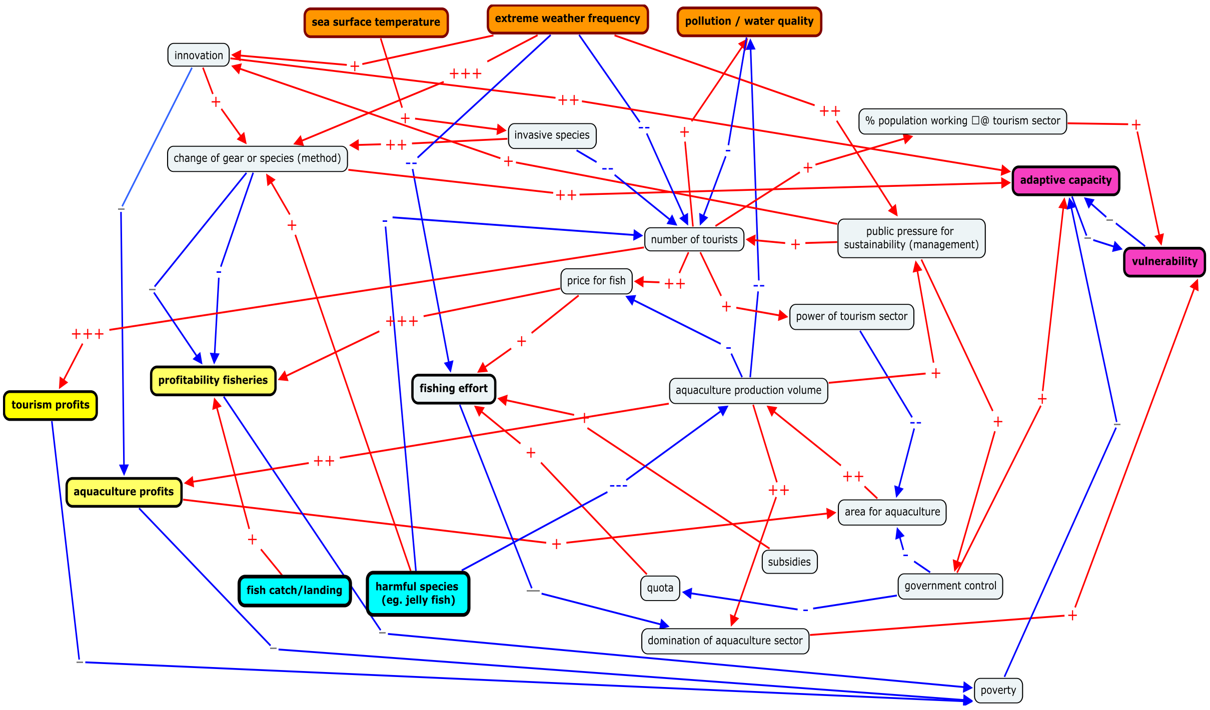


Figure 3. Generic fuzzy cognitive map used in the DSS to describe the direct and indirect impacts of climate change on the economic sectors for the three case studies. Developed with MentalModeler (www.mentalmodeler.org).

3 KNOWLEDGE INTEGRATION

The challenge lies in balancing the complexity and robustness of the scientific models used with the accessibility and utility of the DSS required by decision makers. An operational definition of Consilience was given in the introductory Section. The main goal of the DSS development team is to bring together the knowledge and expertise of natural and social scientists in a transdisciplinary collaboration, providing an added value transcending the potential of the individual disciplines. Hence, the concept of consilience is closely linked to interdisciplinarity. Beichler et al. (2014) used socio-ecological resilience as a bridging concept for interdisciplinarity. They pointed out that the reason to use a bridging concept is that the social and ecological systems cannot be analyzed separately, due to the presence of feedback and interactions. System Dynamics models or SD models (Forrester, 1961; Sterman, 2000) provide a natural mathematical platform for interdisciplinary integration, obliging researchers to contribute to a common framework of analysis. The semi-qualitative nature of the FCM model does not allow a *direct* integration with the natural science models in an SD framework, even if these have been simplified. Figure 4 shows how SD modelling was used to address the problem in the DSS.

The natural-social subsystem integration is based on common exchange variables (for example fishing pressure or income) which are scaled from the qualitative range [0,1] to the physical domain or vice versa. An 'integrator' component determines the physical range of these exchange variables and uses this information to (re)scale the variables resulting from or read by the FCM model. This central feedback mechanism through exchange variables can be switched off for testing purposes. Look-up tables and metamodelling (Barton, 1992; Chan et al., 2000; Janssen et al., 2005) based on detailed numerical model output are used to obtain the output for the biophysical model for a given selection of the stressors and policy options. The number and type of variables are automatically adapted with the contents of the look-up tables to make the design as flexible as possible, allowing for delays or updates in the delivery of model results feeding the DSS database.

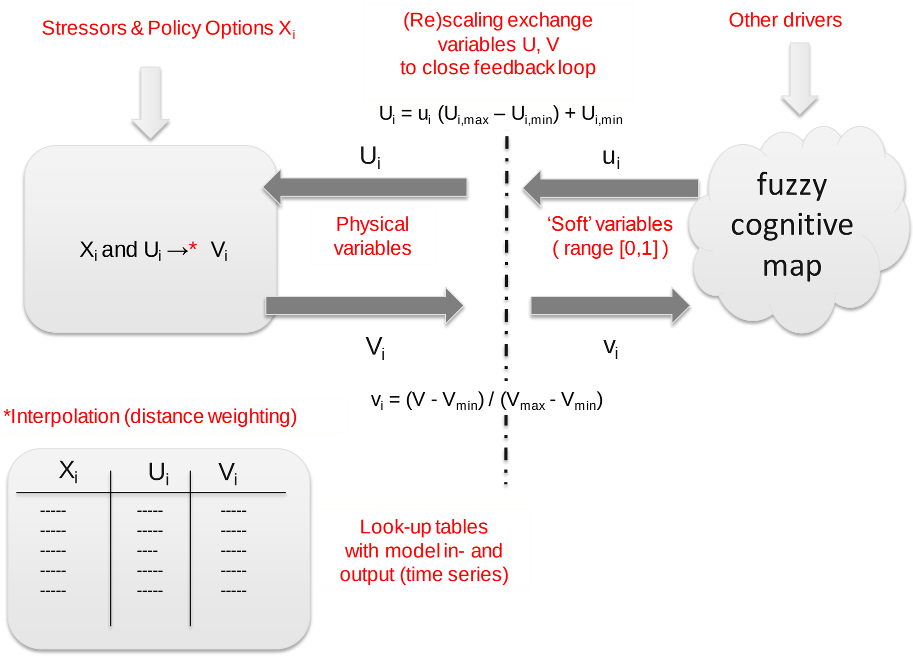
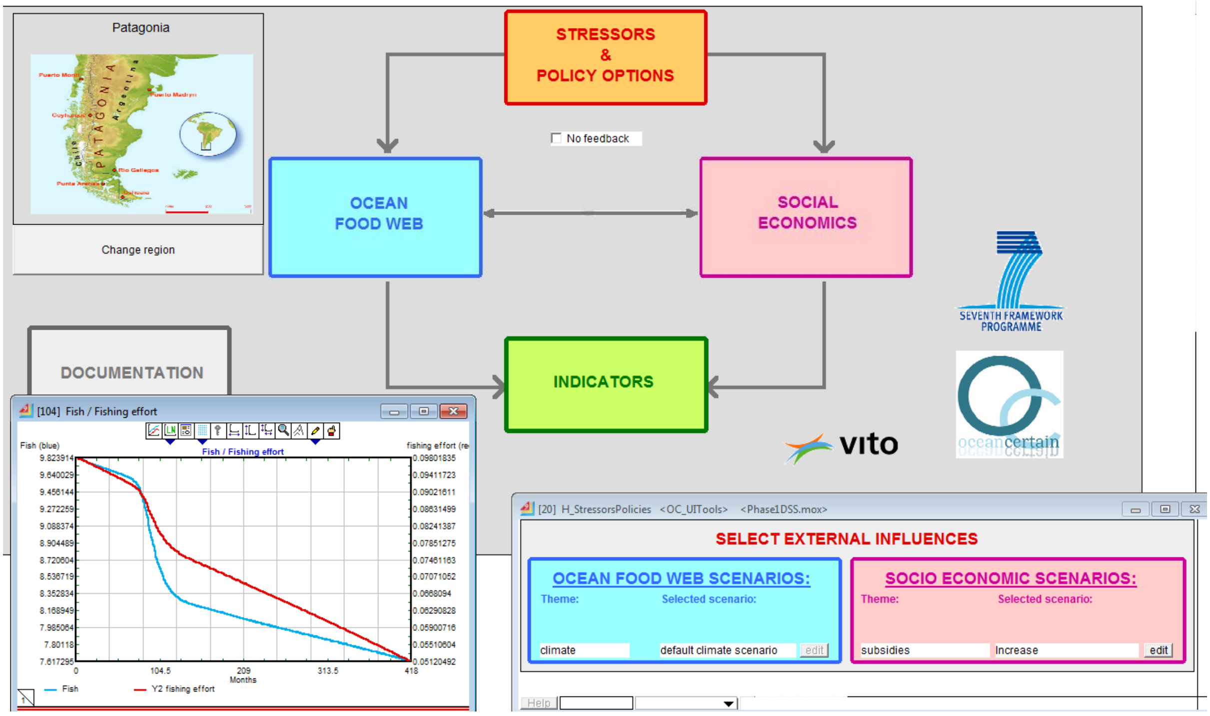


Figure 4. Framework for integration and exchange of variables in the DSS with modular design.

For the implementation of the SD model, ExtendSim® was selected as software platform because of its user-friendliness, the in-built support for generic libraries with generic, reusable model building blocks or MBBs (De Kok et al., 2015b), and its extensive set of graphical modelling tools. A generic prototype of the DSS has already been implemented, while the models for the natural and social subsystem are still under development and have only partially been validated. Figure 5 shows the front-end interface of the DSS with an example of results for the trend of the fish biomass and fishing effort (case with feedback included).



Theme: climate
Selected scenario: default climate scenario

Theme: subsidies
Selected scenario: Increase

Figure 5. Front-end interface of the DSS with natural-social subsystem feedback switched on.

The control options available in the user dialogues (stressors and policy interventions) are automatically updated with changes in the contents of the look-up tables in terms of sample size and the type of variables. This makes the DSS development less dependent on the timeline of the model development. New case studies are easily added as long as the internal architecture of the region databases is respected.

4 DISCUSSION

The objectives of the project of understanding the behaviour of the socio-ecological system framed around the dynamic interactions between the marine food web and three socio-economic sectors facilitates a systems approach. A systems methodology provides a framework for integrating multiple dimensions (social, economic, environmental) of the system and for linking system structure (interdependencies and feedbacks) to system behaviour (fish stock decline, limits to growth etc.). The main challenge in SD modelling is to identify and model the unexpected, long-term changes affecting the marine food web, human activities and interactions between the two. Examples of such changes are the introduction of the Common Fisheries Policy and introduction of salmon culture. It also facilitates participatory engagement with stakeholders, drawing upon their mental models (cognitive maps) of the socio-ecological system and increasing the probability of research-policy exchange. However, systems modelling can be challenging. Model integration focusing on the software aspects of the problem can quickly lead to ‘integronsters’ which are of limited use due to their complexity and maintenance problems. (Voinov and Shuhgart, 2013). A more promising approach is to use a modular design, where the data produced by the individual modules defines the variations around a baseline trajectory within a validated range. This approach was also adopted for the DSS design in Ocean-Certain, particularly for the natural-social science integration and incorporation of local knowledge in the model. A modular DSS architecture with proper attention for the interfacing between components ensures the DSS developers are less dependent on the different project timelines and contributions (modelling, data collection, knowledge extraction). Obviously, this approach can only be successful with considerable and regular communications between the domain experts and DSS developers, which is a crucial success factor of the consilience methodology. Currently, the DSS development focuses on the definition of interface variables linking the social-economic module with the other modules, the accuracy of the interpolation algorithm used for the metamodelling, and the control options for users of the DSS.

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