Rambo, H., A. Ospina-Alvarez, I. A. Catalán, F. Maynou, and V. Stelzenmüller 2022. Unraveling the combined effects of sociopolitical and climate change scenarios for an artisanal small-scale fishery in the Western Mediterranean. Ecology and Society 27 (1):43. https://doi.org/10.5751/ES-12977-270143

Research

Unraveling the combined effects of sociopolitical and climate change scenarios for an artisanal small-scale fishery in the Western Mediterranean

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ABSTRACT. Worldwide climate change will influence the spatial distribution and status of exploited fish stocks, often in uncertain ways with cascading effects on the social-ecological systems depending on them. Likewise, changes in sociopolitical conditions influencing consumer demand, fuel, and fish prices may jeopardize the viability of fisheries. Predicting whether existing management systems can adapt to these changes is key and especially challenging in data-poor fisheries. In the Mediterranean Sea, the tropical and subtropical dolphinfish (*Coryphaena hippurus*) is at its northernmost reproductive distribution area and has sustained a seasonal age-0 based artisanal small-scale fishery since ancient times. We built a quantitative Bayesian Belief Network (BBN) model integrating a diverse set of ecological, social, and economic input data to assess the impact of plausible midterm futures (2040-2059) on the seasonal economic profit for dolphinfish fishers in Mallorca (Balearic Islands, Western Mediterranean). These future scenarios accounted for increasing sea surface temperature based on global IPCC projections, population dynamics and growth of dolphinfish, economic forecasts of future fish and fuel prices, and stakeholders' views on feasible adaptations of the local management system. Seven out of twelve scenarios point towards increased profitability for fishers. To date, the fishery is managed locally although within a wider EU regulatory framework, and options such as advancing the opening date of the fishing season in response to climate-induced changes in growth and body size of dolphinfish might be economically beneficial. This will, however, depend critically on the evolution of unknown factors such as changes in other target species, consumption habits of people, and market dynamics. We show here that, even in fisheries without information on stock status, an integrated and holistic assessment of adaptive capacities of management systems is possible.

Key Words: *Bayesian Belief Networks; dolphinfish; midterm future; management; social-ecological system; scenarios; stakeholder participation*

INTRODUCTION

Worldwide climate change will have far-reaching effects on fish species as well as fisheries and fishing communities who exploit and depend on them (Brander 2007, Friedman et al. 2020, Godfray et al. 2010, Perry et al. 2005). These fisheries social-ecological systems (SES) are directly affected by the relative stability of ecosystem state and their abilities to adapt to state changes (Salgueiro-Otero and Ojea 2020). Especially, the effects of climate change on small-scale fisheries have gained attention in recent years (Jara et al. 2020, Krumhansl et al. 2017, Nurse 2011, Pranovi et al. 2013). Small-scale fisheries are undeniably important for the cultural identity and livelihoods of millions and for the supply of food and employment; worldwide, 90% of fishers supply half of the marine fish caught for human consumption (Kolding et al. 2014). These fisheries will not only be affected by a changing climate but also by shifts in demography, policy, demand, and global market dynamics, all of which increase the uncertainty about the future to come. Developments in these socio-political drivers may play an equally important role in the profits and prospects of these fisheries (Pinnegar et al. 2021). Despite the recent research attention, it remains challenging to predict or even quantify how these changes may affect their adaptive capacities, i.e., the ability to adjust to potential damage, to take advantage of opportunities, or to respond to consequences (IPCC 2014, WGII, Glossary) and whether existing management systems are flexible enough to cope with these changes.

The Mediterranean Sea is a global climate change hotspot with predicted water temperature increases of more than 4°C depending on the region by the end of the century (Hertig and Jacobeit 2008). For the Mediterranean small-scale fisheries, which make up to 81% of the entire fleet and provide almost 55% of the total employment onboard (FAO 2020a), climate change is thus a worrying threat. Emerging evidence shows the consequences of these changing conditions such as the redistribution of fish species, changes in abundance, fertility, survival, phenology and food web structure, loss of spawning habitats of pelagic fish, or a drastic increase of alien and invasive species (Albouy et al. 2013, Durrieu de Madron et al. 2011, Lasram et al. 2010, Marbà et al. 2015). Without a doubt, there will be many “losers” (e.g., species that contract or shift their distribution) but also some “winners” (e.g., species that expand their distribution) (Moullec et al. 2019). Fisheries based on warm-water species could thus benefit from global warming if only the development and growth of fish species linked to rising seawater temperatures were considered. Therefore, identifying these species is key to understanding the adaptive capacities of local small-scale fisheries. Adaptive capacities can be strengthened through management interventions, leading to socioeconomic benefits and a lower overall vulnerability of related SES (Lauerburg et al. 2020).

The common dolphinfish (*Coryphaena hippurus*) has supported small-scale fisheries in the Mediterranean Sea since ancient times and has a profound cultural value (Massutí and Morales-Nin 1997, Moltó et al. 2020a). Dolphinfish is a thermophilic species inhabiting the tropical and subtropical surface waters of the world, preferentially between 21°C and 30°C, with its reproductive northernmost distribution in the Mediterranean Sea

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(FAO 2019, Maguire et al. 2006, Quigley and Flannery 1996); therefore, it could be a climate change "winner". A study combining a climate, biogeochemistry, and a food web model projected that dolphinfish biomass in the Mediterranean Sea could increase up to 34% toward the end of the century under a high greenhouse gas emission scenario and current fishing mortality (Moullec et al. 2019). Another recent study also projected increases in the average length at catch under warming scenarios (Moltó et al. 2021).

Here, we illustrate the complex and multiple trade-offs that can be expected for the dolphinfish fishery on the island of Mallorca, Balearic Islands, known locally as *llampuga* fishery, as part of a plausible future change shared by many similar systems. In the Western Mediterranean, dolphinfish spawn from late spring to early summer and the juveniles are thought to leave these waters for the Atlantic Ocean at the beginning of winter (Besbes Benseddik et al. 2015, Gatt et al. 2015, Massutí and Morales-Nin 1995). In the Balearic Islands, these extremely rapidly growing age-0 juveniles, up to approx. 20 cm furcal length in their first month (Morales-Nin et al. 1999), are fished seasonally between August and November when they are most abundant by an artisanal small-scale fishery operating Fish Aggregating Devices (FADs). This fishery also takes place in Italy (Sicily), Malta and Tunisia. In Mallorca, dolphinfish is consumed mostly by locals as a whole, unprocessed fish.

Due to its thermal requirements for spawning and growing (above 21°C, Moltó et al. 2020a), increased warming will likely affect: 1) the duration and spatial extent of spawning due to changes in phenology (Asch et al. 2019); 2) the amount of time each year that the species is present in the Mediterranean Sea (Moltó et al. 2020a); and 3) the growth and average size attained at the current opening of the fishery at the end of August (Moltó et al. 2021). Conceivable consequences for the fishery include an increase in the average size of fish at the onset of the fishery opening date, change in the number of days when fishing this species is feasible due to an increase in days when marketable sizes are available (Moltó et al. 2021, Peck et al. 2020), and potentially a change in market behavior depending on the latter two points (Peck et al. 2020). This could lead to the adoption of adaptive management measures to strengthen these fisheries' viability in the face of change, including changing the timing of the fishing season and plans to incentivize the consumption of dolphinfish beyond local demand that may yield increased income.

According to the above, the evaluation of adaptive management options needs to be based on a profound knowledge of the interlinkages and dynamics of fisheries' SES (Friedman et al. 2020, Salgueiro-Otero and Ojea 2020). Transferring key SES components and uncertainties of the interlinkages and dynamics into quantitative models allows investigating the risk of management measures. Also, it enables further exploration of logical consequences of management actions on the provisioning of ecosystem services such as food provision (Baeta et al. 2018, Fronzek et al. 2012, Polasky et al. 2011, Stelzenmüller et al. 2011) by exploring the social-ecological trade-offs under different scenarios of multiple stressors (Katsanevakis et al. 2011, Stelzenmüller et al. 2013). Here we follow this approach and provide quantitative projections of the effects of future change to economic and environmental conditions for the traditionally and culturally important dolphinfish fishery around Mallorca Island. Specifically, we used Bayesian Belief Networks (BBN) to integrate data on sea surface temperature (SST) based on global Intergovernmental Panel on Climate Change (IPCC) projections under different scenarios, information on population dynamics and growth of dolphinfish, economic projections of future fish and fuel prices, and stakeholders' perceptions on feasible adaptations of the local management systems. BBNs are powerful graph-based probabilistic models that explain the causal relationships between variables (nodes) using conditional probability distributions. These models have been applied to several management systems governing small-scale fisheries (Coccoli et al. 2018, Mulazzani et al. 2016, Naranjo-Madrigal et al. 2015, van Putten et al. 2013). Furthermore, the BBN approach can help build a social-ecological model of fisheries in an environment that is partly data-rich (landings and economics statistics) and partly data-poor (abundance and distribution of resource).

Our study is among the first that fully quantify a model representing a SES that incorporates the potential effects of climate change and changes in fish and fuel prices in the context of small-scale fisheries despite the lack of formal stock assessments.

METHODS

Dolphinfish fishery in Mallorca

This ancient artisanal small-scale fishery is conducted by fishers operating small boats (~10m) and special surrounding nets (boat seines) to harvest juvenile dolphinfish that accumulate below FADs (Morales-Nin et al. 2000). Fishers own one boat and usually employ one person on board, so the number of licenses is equivalent to fishing effort in terms of boats per day (Morales-Nin et al. 2005). With less than 10% of effort (boat-days) devoted to this fishery annually, the seasonal dolphinfish fishery generates 26% in weight of all landed fish and 13% of the revenues in the Balearic Islands (Palmer et al. 2017).

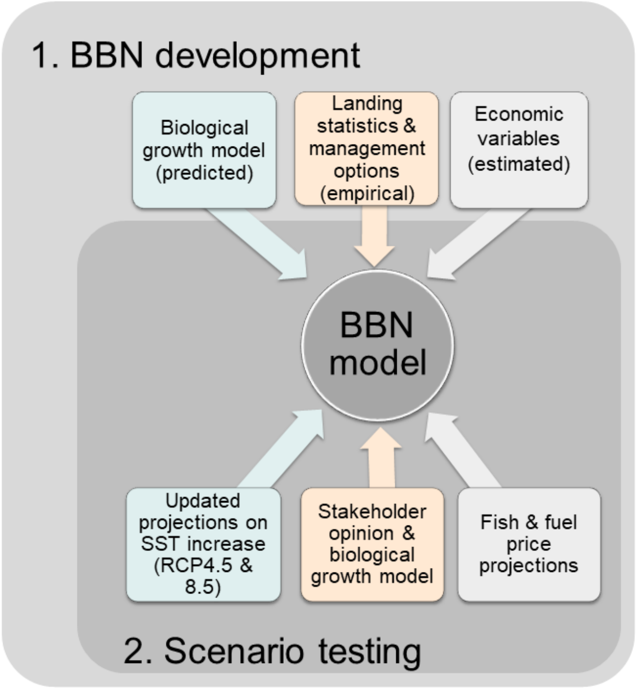
The management system of the dolphinfish fishery in Mallorca is quite comprehensive. This fishery is managed by the Agriculture, Food and Environment Ministry & Fisheries Directorate of Spain (which follows EU directives), advised by the fisheries directorate of the Balearic Islands regional government (Orden OAA/1688/2013). Current regulations in place include: 1) determining the date of opening of the fishery currently set at the 25th of August; 2) establishing weekends and bank holidays as no fishing days; 3) limiting the number of licenses and allocating a system for the distribution of FAD zones around Mallorca; and 4) restricting, to those boats, the use of gears during the established fishing season. Further, fishers have a self-imposed daily catch quota since 2012 that fluctuates around 150 kg per boat to control prices (Moltó et al. 2020a).

BBN development

We chose BBNs as a modeling environment due to several properties. BBNs are very flexible; multiple stressors and endpoints can be considered in the same framework and they are capable of combining qualitative and quantitative data stemming from different sources. Therefore, BBNs can integrate information across disciplines, they can deal with small and incomplete data sets, while their probabilistic nature accounts for uncertainty and the opportunity to perform scenario analysis (Benson and Stephenson 2018, Farmani et al. 2009, Grêt-Regamey et al. 2013, Marcot 2012, Sperotto et al. 2017, Stelzenmüller et al. 2010). Furthermore, the capacity of BBNs to integrate expert opinion directly includes stakeholders in the modeling process (Laurila-Pant et al. 2019). Easy-to-understand graphical outputs also facilitate communicating the results to stakeholders. BBNs consist of two structural model components: 1) a conceptual model (a directed acyclic graph, DAG) representing the best available knowledge about system functioning that represents dependencies between the model's variables (referred to as nodes); and 2) conditional probability tables (CPTs) denoting the strengths of the links in the graph (McCann et al. 2006). Directed arrows representing cause-effect relationships between the system's variables indicate the statistical dependency between different nodes. Each arrow starts in a parent node and ends in a child node. The graph is acyclic and, therefore, no feedback arrows from child nodes to parent nodes are allowed. The DAG can be developed either by experts and based on system understanding and/or via empirical observations. The resulting DAG structure forms the basis for developing an operational BBN. The probabilistic relationships between model nodes are then specified in CPTs. CPTs can be parameterized based on expert opinion, derived from mathematical or logical equations, or learned from the correlative structure in empirical data. Each node is constrained to a finite number of states that describe the probability distribution of the system variables (as an example this could be "increase" and "decrease" for discrete or 1-10; 10-30; 30-100 for continuous variables). Each given state of one variable (node) is associated with a probability between zero and one, so that the sum of state probabilities adds up to one (100%).

Here, expert scientists, including the authors of this publication, with ample experience in the particularities of the species and fisheries of the study area, were chosen as the most reliable and complete source of knowledge to reconstruct the links between the specific biological, environmental, and socioeconomic components to be included in a first draft of the DAG structure. With the first draft of the DAG structure in hand, a first interactive workshop was held in January 2018 with key responsible people in the Directorate General of Fisheries of the Balearic Islands, a key fisheries authority, to brainstorm on the locally relevant interlinkages of the social-ecological system mapped in the DAG. In total, five scientists and three representatives of fisheries management were consulted on the development of the BBN. The group of scientists, authors of this publication, developed a new DAG structure based on the gathered stakeholder advice to quantify the relationships between variables. Data scoping and data analysis furthered the development of the model to select the final set of parsimonious nodes to populate the CPTs. The BBN was shared with the same stakeholders to discuss ground-truth scenarios, debrief results, and refine useful outcomes in May 2019. We limited our interaction to highly informed stakeholders from the Directorate General of Fisheries, directly involved in local fisheries management, some of them being fishers in the past. These stakeholders had a strong background in fisheries policy and regulations from local to international governance levels, local market behavior, and fishery dynamics and technology. Providing that they were very familiar with all aspects of the dolphinfish fishery, we are confident that these key stakeholders provided appropriate information to develop key components of the BBN. In the following paragraphs, we detail the data sources and treatment for the different components of the BBN development and scenario analysis (see Fig. 1). All BBN nodes are further described in Table 1.

Fig. 1. Diagram of data input into 1) the Bayesian Belief Network(BBN) development and 2) subsequently for belief updating under the scenario testing (SST: Sea Surface Temperature, RCP: Regional Concentration Pathways).



Ecological component of the BBN

There is a notable lack of mechanistic and empirical knowledge about the ecology and spatial dynamics of this species and the stock status is unknown (Moltó et al. 2020a). Therefore, we defined the ecological component by the link between climate and the fishery as conducted through the estimation of how temperature affects spawning phenology and growth. For a given thermal scenario (see below), we calculated the probability at which day the average size of dolphinfish becomes vulnerable to the fishery. This exercise was conducted in part by the authors in Moltó et al. (2021) and is briefly explained below.

First, a model of the hatching date probability of individuals as a function of temperature was built using (1) a database of juveniles' daily otolith readings, (2) a database of gonadosomatic index (GSI) estimations (indicative of average population spawning state) around the world, and (3) Sea Surface Temperature (SST) estimations extracted from satellite imagery for each location and date. This hatching date probability model was in return built on two Bayesian sub-models: one predicted the probability that an individual belonging to a cohort was born on a specific date (from otolith readings and accounting for

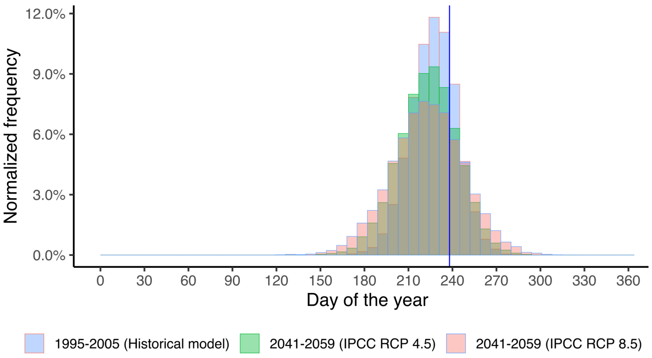
Table 1. Overview of all Bayesian Belief Network(BBN) model nodes, their node states, description, and data sources.

BBN nodes	States (S)	Description & data source
Opening of fishing season	25.08.; 18.08.; 11.08.; 04.08.; 28.07.	The fishing season is currently opened on Aug 25 in the Balearic Islands. This node provides the management option to prepone the opening up to four weeks maximum at weekly intervals. One week equals five fishing days given that fishing is not permitted on weekends.
Calendar day where d.=20cm	01.01. - 06.05.; 06.05. - 17.06.; weekly intervals from 17.06. - 23.09.; 23.09. - 07.10.; 07.10. - 28.10.; and 28.10. - 30.12.	This node indicates the probability for each day of the year (more specifically the week or larger interval it falls into) at which the mean length of dolphinfish (d.) has reached a marketable size of 20 cm. Probabilities are cumulative with 0% at the beginning of the year and a 100% at the end of the year. Days with (near) zero probability were grouped into larger states spanning weeks or months while all other days with higher probabilities were grouped into weekly intervals.
Actual fishing days	64 to 60; 69 to 74; 74 to 78; 78 to 83; 83 to 88; 88 to 93; 93 to 98	Range of days that the fishing activity takes place (days where at least one boat was fishing) per fishing season. Data from 2004 to 2016 indicate that fishing took place during 64 to 78 days from potentially 88 days (25 of August till 31 of December) minus weekends and bank holidays where fishing is prohibited. If the choice is made to open the fishing season two weeks earlier, 10 fishing days are added to the range of "Actual fishing days".
Fishing effort [boats/day]	10 to 16; 16 to 21; 21 to 25	The average number of boats (license holders) per 3rd and 4th quarter that operate per day (local fisheries statistics)
Fish price [EUR/kg]	3.3 to 5.4; 5.4 to 7.5; 7.5 to 9.6; 9.6 to 12; 12 to 14.4; 14.4 to 16.3	Historical (2004 until 2016) seasonally aggregated (3rd & 4th quarter) data on price per kilogram of dolphinfish (Palmer et al., 2017)
Quota [kg/boat/day]	<= 150; >150	A self-imposed quota system exists since 2012 and is currently set at 150 kg per boat per day. This node denotes how often catches exceeded this limit based on seasonally aggregated catch data (local fisheries statistics).
Landings [kg/boat/day]	40 to 88; 88 to 107; 107 to 177	The amount of dolphinfish caught per boat per day. Daily landings data were seasonally aggregated per 3rd & 4th quarter from 2004 till 2016 (local fisheries statistics).
Revenue [EUR/boat/day]	140 to 350; 350 to 650; 650 to 1,000; 1,000 to 1,450; 1,450 to 1,900; > 1,900	Product of the Landings and Fish price nodes
Bycatch [EUR/boat/day]	28 to 50; 50 to 100; 100 to 240	The revenue from sold bycatch caught per boat per day seasonally aggregated per 3rd & 4th quarter from 2004 till 2016 (local fisheries statistics).
Labor costs [EUR/boat/day]	75 to 116; 116 to 158; 158 to 210; 210 to 300	Historical (2004 until 2016) seasonally aggregated (3rd & 4th quarter) data on labor costs (adjusted from STECF data)
Fixed & variable costs [EUR/boat/day]	41 to 64; 64 to 87; 87 to 115; 115 to 166	Historical (2004 until 2016) seasonally aggregated (3rd & 4th quarter) data on fixed & variable costs adjusted from STECF data
Fuel price [EUR/L]	0.21 to 0.36; 0.36 to 0.58; 0.58 to 0.8; 0.8 to 1.02; 1.02 to 1.3; 1.3 to 1.42	Historical (2004 until 2016) seasonally aggregated (3rd & 4th quarter) data on price of fuel per liter (EUROSTAT)
Fuel costs [EUR/boat/day]	14 to 25; 25 to 37; 37 to 49; 49 to 63; 63 to 89; 89 to 97	Fuel price multiplied by the mean daily fuel consumption per boat (68.39 liters) adjusted from STECF data
Total costs [EUR/boat/day]	130 to 210; 210 to 280; 280 to 350; 350 to 420; 420 to 562	Sum of all cost nodes
Daily profit [EUR/boat]	Negative profit; 0 to 290; 290 to 590; 590 to 1,000; 1,000 to 1,600; More than 1,600	Sum of the Revenue and Bycatch nodes minus the Total costs node
Seasonal profit [EUR/boat]	Negative profit (S1); 0 to 18,000 (S2); 18,000 to 45,000 (S3); 45,000 to 45,000 (S4); 75,000 to 100,000 (S5); >100,000 (S6)	Product of the Daily profit and Actual fishing days nodes

mortality effects); the other predicted the fraction of the population being at a specific spawning state at a specific month. Both sub-models are related to the temporal location of the spawning peak and the spread of the distribution of the actual dates of birth. The two sub-models were coupled in a Bayesian approach that functions as a predictive model for the hatching date of individuals from a fishery-dependent sampling with temporal biases (Moltó et al. 2020b). Second, a temperature and photoperiod-dependent growth model was used, based on otoliths collected from age-0 individuals born (and growing) under diverging thermal constraints, either early or late in the season within a determinate region or on similar dates but in different regions (Moltó et al. 2021). Third, the predicted hatching date of individuals (first model) was integrated within the individual growth model (second model), together with other key concurrent effects on size distributions, such as mortality sources, in an individual-based model that enables the calculation of the average body length of the dolphinfish simulated population at any date under thermal constraints (Moltó et al. 2021).

Finally, for each thermal scenario, the individual growth trajectories were independently estimated for each of 1 million simulated fish, according to the coupled models above. We extracted predictions of daily probabilities for average furcal length reaching 20 cm, which was approx. the minimum average length of marketed fish, hence taken here as a size of vulnerability to the fishery (Fig. 2). The origin and processing of daily temperature data needed to run the biological components is explained in Appendix 1. To include the output from the growth model as a BBN node, the daily probabilities (which add up to one) were grouped into intervals (see Fig. 2) and then used as state boundaries in the BBN node ("Calendar day where d.=20 cm").

Fig. 2. Predicted probabilities of the day of the year (binned into intervals) at which half the population of dolphinfish reach a size of 20 cm furcal length under the baseline scenario (blue), the IPCC RCP4.5 scenario (green) and the IPCC RCP8.5 scenario (red), the latter two both modeled over the time period of 2040 to 2059, while the blue line indicates the current opening day of the fishing season (IPCC: Intergovernmental Panel on Climate Change; RCP: Representative Concentration Pathways).



Socio-economic components of the BBN

We used daily fisheries statistics on landings and prices, and external information on fuel costs and production costs to expand the socioeconomic components. The statistics of the daily fish sales were supplied by the responsible agents in the centralized wharf to CSIC and were available from 2004 until 2016. In Mallorca, the commercialization of all the landings is made through a single central fishing wharf (OPMallorcaMar), which is a cooperative composed of all the boat owners in the island. In addition, fishers are associated in guilds by port (Confraries), which in turn are associated in the Balearic Fishers Federation (Federació Balear de Confraries de Pescadors). The landings are arranged in standard boxes by the fishers and auctioned daily in decreasing prices (Dutch auction). An automatic selling procedure, implemented since 2004, registers for each box, among other data, the commercial category, the weight in kilos, the price, and the name of the boat. We collected data on the number of boats per day (a measure of effort), dolphinfish landings and bycatch, as well as the number of annual licenses. To decrease the variability and spread, daily data were seasonally aggregated for the 3rd and 4th quarters to display more representative seasonal daily averages. We derived fish price, fuel price, labor costs as well as fixed and variable costs from four sources: 1) landings value, fish price, and daily effort (number of vessels for the two quarters 3Q and 4Q) were obtained directly from the database on sale bills (2004-2016; partially published in Palmer et al. 2017); 2) current fuel prices were obtained from the weekly database on national fuel prices maintained by Eurostat (https://ec.europa.eu/energy/en/data-analysis/weekly-oil-bulletin); 3) production costs (labor costs, fixed and variable costs) for the Spanish Mediterranean artisanal fleet were derived from the STECF economic database for the corresponding year, adjusted by effort (2 quarters instead of one full year) and fleet typology (https://stecf.jrc.ec.europa.eu/dd/fleet); 4) these costs were further calibrated for the small-scale *llampuga* fleet segment from interviews with fishers collected previously, published in Maynou et al. (2013). For the last two sources, the methodology for parameter estimation is given in Annex 6 of the Annual Economic Report (AER 2018, pp. 524-554).

Finally, data on the management system were gathered from stakeholder consultation. The final baseline model included the main components relevant to the dolphinfish fishery and the BBN was trained with the above explained data. The model endpoint is "Seasonal Profit per boat" which relates to the profit per license holder. The ecological component is represented by an output from a biological growth model calculating the day of the year at which the mean length of dolphinfish reaches a marketable size of 20 cm; the management system includes the current quota and licensing system, as well as the opening of the fishing season and the number of fishing days within a year. The amount of dolphinfish landings represents the fisheries yields, while the economic components include income from bycatch, fish and fuel prices, costs, revenue, and profits.

A sensitivity analysis was performed to identify to which degree the variability in its posterior probability distribution was explained by other variables (i.e., rank order) (Marcot et al. 2006). Therefore, we calculated the entropy reduction for the model node "Seasonal profit". All computations were done using the commercial software Netica (Norsys, version 5.24).

Scenarios

We built our scenarios on four socio-political scenarios for aquatic resources in Europe that were developed under the Horizon 2020 project CERES (Peck et al. 2020). These scenarios, published by Pinnegar et al. (2021), were inspired by the IPCC Special Report on Emissions Scenarios framework (SRES, IPCC 2001) and combine the new system of Shared Socio-economic Pathways (SSPs, O'Neill et al. 2014) with Representative Concentration Pathways (RCPs). The SSPs themselves are scenarios that provide narratives for projected socioeconomic global changes up to 2100. SSP 1, SSP 2, SSP 3, and SSP 5 were used which deal with different challenges for mitigation and adaptation to climate change based on different assumptions on social and political futures. These were coupled with RCP 4.5, RCP 6.0, and RCP 8.5 which represent moderate, relatively high, and high greenhouse gas concentrations that increase radiative forcing on Earth by 4.5 W m^{-2}, 6.0 W m^{-2}, and 8.5 W m^{-2} at the end of the 21st century, respectively (Moss et al. 2010). This yielded four generic scenarios, namely Local Stewardship (RCP 6.0 and SSP2), World Market (RCP 8.5 and SSP5), National Enterprise (RCP 8.5 and SSP3),and Global Sustainability (RCP 4.5 and SSP1) (see further in the text), which differ in their focus on consumerism versus environmental goals, their local versus global outlook, technological development as well as on the severity of global warming. In addition, nominal price projections of future fuel and fish prices taken from Hamon et al. (2021), based on the macroeconomic general equilibrium model MAGNET (Woltjer and Kuiper 2014) were assigned to each of these four scenarios. To account for the uncertainty around these estimates historical price variability was analyzed to provide trends corresponding to the lower and higher bounds of the 95% confidence interval around MAGNET price projections (Hamon et al. 2021, Pinnegar et al. 2021). These scenarios have been applied to a suite of different European fisheries (Hamon et al. 2021) and aquacultures (Kreiss et al. 2020).

We regionalized these scenarios in order to make them applicable and relevant to the specific case of the dolphinfish fishery with both fisheries scientists and managers from the Regional Fisheries Directorate of the Balearic Islands as previously detailed. These stakeholders suggested different local management options in combination with the output from the biological growth model such as potential changes in landings and the opening date of the fishing season. Each scenario is envisaged for 2040 till 2059, as economic and other projections are highly uncertain after that period. Besides the social and economic implications of the scenarios described below, each scenario has a biological component that directly depends on each of the three RCPs. Essentially (see previous sections), warming at the three RCPs will impact spawning and growth, and thus the day in the year at which the average length of the cohort becomes vulnerable to the FAD fishery. The regionalized scenarios combining all imagined futures for this fishery were defined as follows.

The Local Stewardship (LS) scenario focuses on conservation efforts to preserve coastal habitats used by juvenile dolphinfish (the fished fraction) for feeding. Better control over coastal fishing practices would improve resource status but dolphinfish out of reach of coastal artisanal fisheries would not be effectively managed (including bycatch by long-liners, Macías et al. 2016). Self-regulation of artisanal fishery and policy incentives for local consumption would benefit the fishery. However, in the absence of reliable data on demand, we speculate with a potential 10% increase in catches under the assumption of enough population size and incentivization of market consumption.

In the World Markets (WM) scenario, a decline in apex predators of high value due to fishing (e.g., tunas, valued demersal fish) could increase prey available to adult dolphinfish. Alternatively, bycatch mortality from uncontrolled long-liners could increase the competitiveness of large fishery enterprises that may inundate local markets and blur local cuisine traditions, thus affecting the demand for dolphinfish. Most of the value of dolphinfish would be transferred to the recreational fishery. We speculate with a 10% decrease in catches, driven by the artisanal fishers, to keep profits.

Under the National Enterprise (NE), environmental degradation and fishing effort would be contained at levels similar to current ones. Artisanal fishing activities may benefit because they provide a relatively considerable number of jobs and because exports and imports are economically discouraged. Conflicts over the resource property could arise because of the high mobility of this species which represents a shared resource (Moltó et al. 2020a). Recreational fisheries would be reduced and national labeling schemes focusing on sustainability would exist. A potential legal extension of the fishery period of two weeks (10 fishing days) was envisaged.

Global Sustainability (GS) would lead to a reduction in fishing effort on many species, with uncertain consequences for dolphinfish. Assessment of dolphinfish would be compulsory and catch quotas would be implemented by the EU and inter-country management plans in the Western Mediterranean would be enforced. Reduced fishing pressure on spawners might increase the size of the stock. Artisanal fishers will be well paid because the fishery would be sustainable (catches of juveniles) and extremely selective, with almost no discards. Ecolabeling will add to these advantages.

In Table 2 we summarize the changes made to the respective model nodes under each of the four regionalized scenarios. We considered low, medium, and high projections on annual global fuel and fish price from Hamon et al. (2021) leading to a total of 12 scenarios. We used 2015 as a base year and projected prices until 2050 (the midpoint of the time slice) using nominal values. There is little difference between projected prices among scenarios; only between low, medium, and high projections. Therefore, all fish and fuel prices from 2015 (€6.905/kg and €0.295/l) were raised to their respective 2050 prices applying the annual change rates (Table 2) and were attributed to the state in which they fall with 100% probability. Two exceptions being fish price under GS which was much lower compared to all the other scenarios while the price of fuel was higher under NE, respectively. Here, medium and high fish price projections under GS were attributed to one state lower, and medium and high fuel price projections under NE to one state higher than under all other scenarios. While WM and GS scenarios have identical fuel price projections (+2.59% annually), NE and LS scenarios have similar projections on fish price (see Table 2). Taken together, fish and fuel prices are highest under the NE scenario and lowest under GS. Hence, WM and LS projections are overall most similar. Marginal differences between both could not be displayed by the BBN (both scenario projections were attributed to the same states for fish and fuel price). However, landings are simulated to decrease and increase by 10%, respectively. Therefore, all changes in seasonal profit between these two scenarios can be attributed to the differences in daily landings. Price projections were given in nominal prices. Hence, mean labor costs as well as fixed and variable costs and revenue from bycatch were corrected for inflation by an annual increase of 2% in all scenarios and were attributed to the highest state.

For the node “Calendar day at which d. = 20 cm”, probabilities were updated according to the biological growth model runs assuming different temperature increases under the respective RCPs. Essentially, by the end of 2059, increases in SST associated with RCP 8.5 would advance the date when juvenile dolphinfish would reach a vulnerable mean length by 10–20 days. Under RCP 4.5, an advance of five to 15 days earlier was predicted.

For each scenario, we calculated the relative change in profitability, defined as net profit divided by income, compared to 2015.

RESULTS

The derived BBN representing the key dynamics of the dolphinfish fishery is presented in Fig. 3, including the posterior probability distributions of the compiled model. These distributions reflect the average past conditions of the states of each node, also referred to as the baseline scenario. Under these historical conditions, the mean seasonal profit per boat or license holder was €32,800 with a standard deviation of almost similar magnitude. In the frame of a BBN, however, the probability distributions and changes therein are much more meaningful. The highest probable state for this node indicates that seasonal profit was between €18,000 and €45,000 with a probability of 44%, while the probability of earning more than €100,000 was extremely low, less than 2%, which indicates the potential range and uncertainty of these numbers.

Table 2. Summary of the Bayesian Belief Network(BBN) nodes that were adapted under the various scenarios (d.: dolphinfish; RCP: Representative Concentration Pathway; SSP: Shared Socio-economic Pathway; WM: World Market; NE: National Enterprise; LS: Local stewardship; GS: Global sustainability). The labor costs, fixed and variable costs as well as the bycatch revenue node (not shown in this table) were projected by an annual increase of 2% under all 12 scenarios.

		BBN nodes				
Socio-political scenarios (2041-2060)	Scenario name	Calendar day where d. = 20cm	Opening of fishing season	Landings	Fish price [†,1]	Fuel price[†,1]
World Markets [RCP 8.5, SSP5]	WM_med	model output	no change	10% decrease	+1.57%	+2.59%
	WM_low				+0.84%	+1.04%
	WM_high				+2.31%	+4.16%
National Enterprise [RCP 8.5, SSP3]	NE_med	model output	2 weeks earlier	no change	+1.67%	+2.89%
	NE_low				+0.94%	+1.33%
	NE_high				+2.41%	+4.47%
Local Stewardship [RCP 6.0, SSP2]	LS_med	model output	no change	10% increase	+1.64%	+2.61%
	LS_low				+0.91%	+1.06%
	LS_high				+2.37%	+4.18%
Global Sustainability [RCP 4.5, SSP1]	GS_med	model output	no change	no change	+1.33%	+2.59%
	GS_low				+0.60%	+1.04%
	GS_high				+2.06%	+4.16%

[†] Annual change rate in nominal value for the period between 2016 and 2050.
[1] Hamon et al. (2021), Pinnegar et al. (2021)

Changes in the probability distribution of seasonal profit (the probability of seasonal profit falling into one of the six states S1-S6 defined in Fig. 4 and Table 1) as well as the relative change in profitability under each of the four scenarios (WM, NE, GS, LS) and three price projections (low, medium, high) compared to the probability distribution and mean value of the baseline scenario (BL) are summarized in Fig. 4a and 4b, respectively.

The probability of seasonal profit being larger than €100,000 (falling into the highest state; S6, Fig. 4a) was between 2.6% (WM) to 8% (NE) for low price projections and 23% (GS) to 43.2% (NE) for high price projections (Fig. 4a). Under all scenarios with low price projections, probabilities were similar to the baseline scenario and remained highest between €18,000 and €45,000 (S3). Under the assumption of medium and high projected prices, differences between scenarios with a global (GS and WM) versus a local/national (LS and NE) outlook became apparent. For the former, the most likely state for seasonal profit to fall in was between 45,000 and 75,000 (S4). For the latter, both medium and high price scenarios under LS and the high price scenario under NE were most likely to yield profits larger than €100,000 (S6). Under the baseline scenario, total daily costs per boat ranged between €210 and €280 with a probability of 48.5%, while in the future, they will likely double to €420 to €562 with probabilities between 61% and 100%.

The absolute seasonal profit increased in all scenarios ranging from 18% (WM_low) to 263% (LS_high and NE_high). However, given that we calculated in nominal values that include inflation and does not account for value loss, we also looked at relative changes in daily revenues versus daily costs and the relative change in profitability. While total costs doubled across all scenarios, revenues increased asymmetrically from 1.2 to 3 times. In all scenarios with low price projections, revenues increased less than the costs leading to a net loss in profit. This was also confirmed in a decrease in relative profitability ranging from -3.8% under LS to -12.7% under the WM scenario (Fig. 4b). The GS scenario with medium price projection showed no change, neither in the revenue to cost ratio nor in profitability (-0.6% can be interpreted as no change). For all other scenarios, revenues increased relative to costs, and profitability improved by 3% (WM_med) to 11.8% (LS_high). The best profitability performance was achieved under the LS scenarios followed by NE confirming that scenarios with a local or national future outlook (LS and NE) outperformed scenarios with a global focus (WM and GS). Here, the WM scenarios performed slightly better than GS, except for the low price projection scenarios.

Our projections revealed that the uncertainty in the derived economic nodes daily revenue, daily profit, and seasonal profit was high; standard deviations ranged from 35% to 99%. Also, in all nodes the most probable states were predicted to occur between 30% and 43% only, indicating an overall likelihood of 70% to 53% to fall into the five remaining states. Contrarily, uncertainty in the costs nodes was low.

The sensitivity analysis of the BBN showed that landings and fish price accounted for 23% and 14% variance reduction in the “Seasonal profit” node while fuel price only contributed marginally (0.03%). All management nodes combined account for 4%. Not surprisingly, the highest reduction in variance was achieved by the daily profit and revenue node with 74% and 56%, respectively.

The projected ecological changes, when linked to advancing the fishing season by two weeks, produced slight changes in seasonal profits of 12%. Roughly, starting fishing season earlier by two weeks had the same economic benefit as increasing landings by 10%.

DISCUSSION

Our study provides one of the few examples of a fully quantified model of a SES related to an artisanal small-scale fishery under climate and socio-political change. With the help of a profound scenario analysis, we demonstrated potential stakeholder-elicited adaptations to the current management system to mitigate future economic and environmental changes (changes in dolphinfish

Fig. 3. Bayesian Belief Network(BBN) model describing the key components and interactions of the dolphinfish fishery around Mallorca Island. Posterior probability distributions of the compiled net are shown for all nodes while colors indicate the different components of the model (ecological: blue; management: red; yield: orange; economic: grey). Each node is described in Table 1.

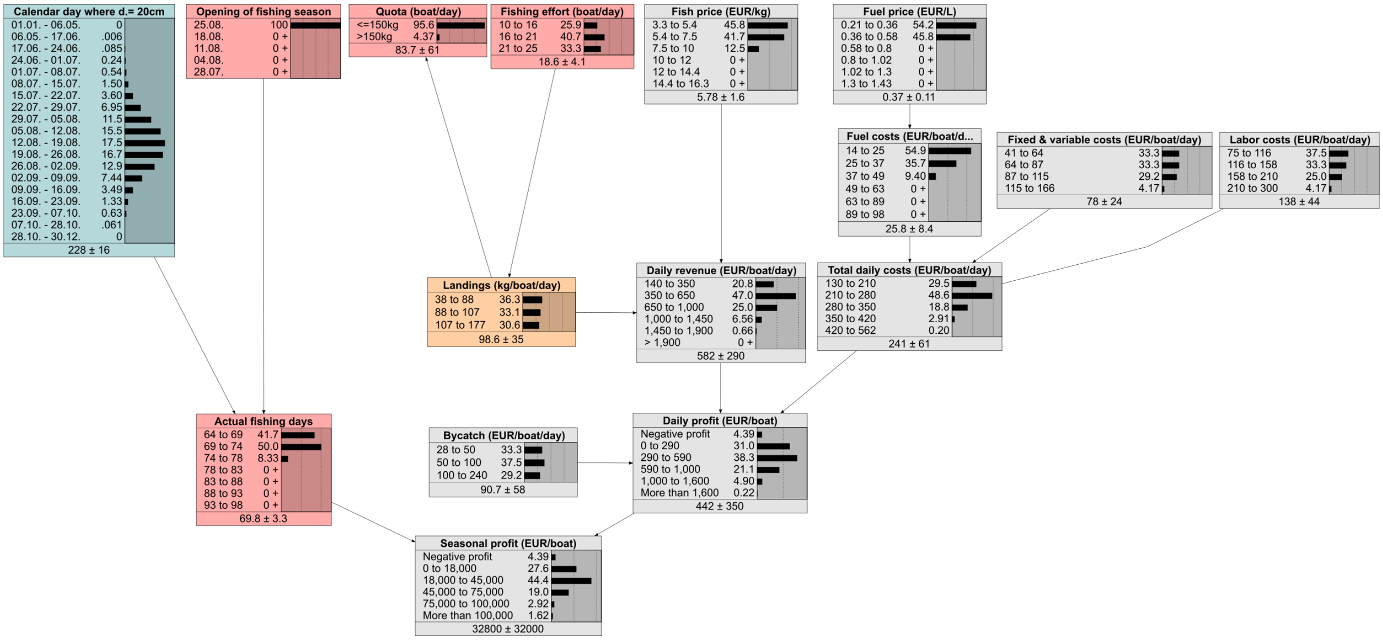
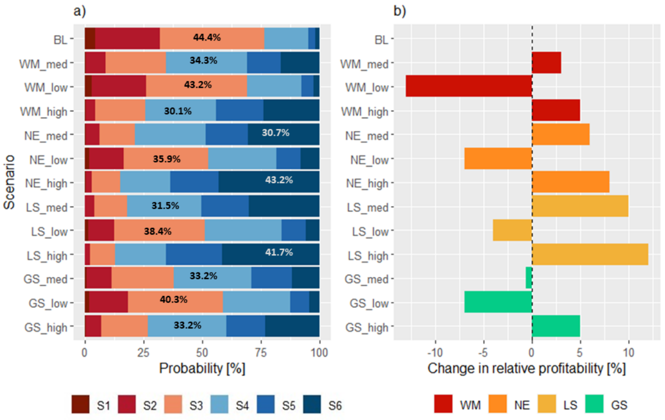


Fig. 4. The probability of seasonal profit falling into one of the six states (S1: <0€; S2: 0-18.000€; S3: 18.000-45.000€; S4: 45.000-75.000€; S5: 75.000-100.000; S6: >100.000€), and b) the relative change of profitability compared to the baseline scenario (BL) under each of the four scenarios (WM: World Market, NE: National Enterprise, LS: Local stewardship, GS: Global sustainability) and medium, low, and high price projections leading to 12 scenarios (e.g., WM_med refers to the World Market scenario with medium price projections etc.). The baseline scenario represents the average weighted past conditions. The percentage for the most probable state under each scenario is given in 4 a) and the dashed line in 4 b) indicates no change.



growth due to increases in water temperature). These adaptations leading to improved profitability included advancing the current opening of the fishery (e.g., LS scenarios) or increasing the landings by 10% (e.g., NE scenarios). While we focused our model runs on these adaptations, the model further enables the simulation of changes in all other main management strategies, such as the provision of licenses via the number of boats (fishing effort), adapting the daily landings per boat, or co-deciding a daily quota system larger than the current 150 kg per boat.

Overall, the NE and LS scenarios outperformed the scenarios with a "global" outlook. This is largely due to the stakeholder choices in specific management adaptations. Stakeholders felt that only in these nationally focused scenarios adequate support from governments would be granted to support this local fishery and allow for an increase in landings or an extension of the fishing season despite the fact that the growth model suggested the feasibility of advancing the fishing season under all scenarios. The higher increases in fuel costs as predicted under the NE scenarios did not change the positive outcome under these scenarios. This is because fuel consumption is moderate and fuel costs are only associated with visiting FADs close to their base ports instead of needing to take longer trips in search of fish to catch. Generally, in small-scale fisheries energy consumption is not the main cost, contrary to fisheries based on industrial fleets (Guyader et al. 2013). However, the fishing method is sensitive to severe weather (strong currents, extreme winds), resulting in FAD loss or impeding gear deployment, which incurs higher variable cost and loss in revenues. Climate model projections are highly uncertain for storms and indicate that for southern Europe these may in fact decrease (Kay et al. 2018). If additional data would become available this could easily be incorporated into the model by adapting cost nodes or the number of fishing days per season.

Contrary to this, fish price had a significant impact on future profits and plays a key role in local management regulating landings to keep prices stable. This was the main reason the GS scenarios performed less well even though the overall future under these scenarios would be sustainable. However, fish prices as predicted by the MAGNET model are projected to decrease the most under GS. Hence, seasonal profit and profitability under the GS_med scenario was lower than the WM_med scenario, even though under this globalized future with limited to no governmental control a 10% decrease in landings was assumed by the stakeholders. Given that in all low price projection scenarios the same state for fish price was assumed, WM_low performed worse than GS_low.

Even though fish price was predicted to increase only under high price scenarios (more than the annual average 2% inflation), all scenarios with medium price projections improved their profitability buffered by adaptations in management or remained the same. This suggests that fishers could actually tolerate a slight decrease in fish prices (in real terms) without threatening the feasibility of this fishery.

It has to be mentioned that the uncertainty in all scenario predictions measured by the standard deviation and probability distributions was high. This is quite common given that the model was calibrated with fisheries statistics that tend to have a large range of values and are prone to misreporting. Also, the model integrates a large range of different data and assumptions of how different futures may affect this fishery. All results should be interpreted as indications of possible trends instead of taking them at face value.

Lastly, due to the lack of estimates on stock abundance, the fishery is managed via prices instead of stock assessment, which is why the present model lacks an indicator of abundance. It is thus not possible to predict the impacts of the scenarios (e.g., changes in landings or the opening of the fishing season) on the dolphinfish stock. The General Fisheries Commission of the Mediterranean (GFCM) has recently started an effort toward the assessment of the stock via data-limited approaches (FAO 2020b). Until this is finalized, transitional measures following the precautionary approach are recommended. Although our model incorporates some effects of warming on the populations, much needs to be advanced on, for example, the interaction of this species with other species in future conditions. Current models suggest increased biomass of dolphinfish in the Mediterranean by the end of the century (Moullec et al. 2019).

The overall perception of stakeholders of the BBN was positive. Not only is there no quantitative stock assessment for this species but there is also no qualitative approach to examine potential responses of fish and fishers to climate change (or any other external stressor). Stakeholders were very proactive in offering alternative states of the system, particularly giving their opinion on how fishers would react to sudden increases or decreases in prices or abundance. They found the overall assumptions made on the effects of climate change on this fishery reasonable but were more reluctant to believe that projections (economic, social, and biological) could be taken too far. They shared that the worst problem for the fishery is the lack of attractiveness for fishers. Licenses have decreased by two thirds since 1974 (Barrientos et al. 2020). Generally, the fisheries in the Balearic Islands have been declining since the 1950s (Maynou et al. 2013).

Another issue is the lack of demand. For example, catches cannot be too high because there is no market yet to absorb them beyond local consumption. Currently, the fishing season does not last until the official end of December 31st because even local consumption patterns shift toward Christmas for other species (pers. comm., I. Catalan), and autumn storms and declines in juvenile dolphinfish abundance toward winter make this fishery less favorable. The stakeholders' general view was that assuming dolphinfish would be favored climatically in the coming decades as predicted by the growth model, only substantial increases in demand will allow fishers to benefit from a longer fishing season. If demand cannot be improved, incentives for fishers will be lower to increase overall landings. Improvements in demand may be achieved for example, through active marketing campaigns toward tourists, who may not yet appreciate this local species to a full extent. This could be achieved through government-sponsored incentives to consumption, or incentives to process the fresh product. Further, exporting dolphinfish (which is currently only consumed locally as a whole, unprocessed fish) to other areas where the fish is highly appreciated might be considered.

The dolphinfish fishery is comprehensively managed at the local level, including measures such as a licensing system and restrictions on how, when, and where to fish that are well implemented. In a future climate, where not only our biological models but other projections on phenology (e.g., Asch et al. 2019) suggest advancements of around two weeks in spawning phenology, it is likely that the length of the fishing season can be slightly increased. In this specific case, the advancement of two weeks could be made at the local/national level by the Agriculture, Food and Environment Ministry & Fisheries Directorate of Spain, advised by the fisheries directorate of the regional government of the Balearic Islands (Orden OAA/1688/2013). However, the European Union has set a minimum date of mandatory opening to August 15th. Quotas are not in place, but fishers exert a self-imposed daily quota per boat to control prices. However, these quotas are no guarantee of price maintenance: dolphinfish price fluctuated greatly after their establishment suggesting that the quota did not stabilize the prices (Grau and Camiñas 2011; Camiñas et al. 2016). In any case, these changes in quotas should be effectively communicated to managers. It is likely that multinational (quota) agreements will be required in the future to manage this shared stock, given the fact that several nations exploit juvenile dolphinfish using FADs in the Mediterranean (Moltó et al. 2020a). More knowledge on its population dynamics and stock status is needed to reduce the uncertainty in the models and assess whether potential future increases in overall landings are within safe ecological limits.

To summarize, the management system in place has so far assured the commercial viability of the fishery even in the absence of a formal stock assessment, likely due to the artisanal small-scale nature of the fishery targeted only to satisfy local demand. However, whether fishers are likely to realize climate change-induced benefits will depend critically on other factors such as the evolution of other target species, people's consumption habits and market dynamics. Market uptake of dolphinfish could be enhanced by facilitating a certification scheme, improving branding and marketing of dolphinfish beyond local consumption while maintaining cultural heritage of the product, and incentivizing young people to take part in this fishery. This will require the assistance of the local government. The strongest expected changes are therefore more dependent on social, political, and marketing issues than on projected biological changes alone.

CONCLUSION

Climate change will no doubt influence fisheries in the decades to come, often with negative consequences, but as shown here and in other works, there is room for "winners" (Moullec et al. 2019). However, the usual definition of winners and losers tends to rely on purely biological components. From a fisheries perspective, many other factors must be accounted for such as changes in prices, costs, and demand. Further, future socioeconomic benefits that may arise for these fisheries can only be harnessed through adaptive management action stressing the importance of investing in adaptive capacities of fisheries SES.

Here we provide an example approach that allowed integrating various data sources to fully quantify an SES associated with the dolphinfish fishery and its response to plausible scenarios. Our results show the interconnectedness of many factors that affect the fisheries' adaptive capacity, hence here presented as seasonal profits. Further, we exemplify the relevance to develop a perception of SES together with selected and knowledgeable stakeholders.

It is often argued that formal fisheries management objectives (e.g., MSY) based on traditional stock assessments are indispensable to managing a fishery. We show here that relatively data-poor fisheries such as the artisanal small-scale dolphinfish fishery can be analyzed by integrating different data sources to circumvent the absence of formal knowledge of stock status to provide concrete management advice. Further knowledge on stock abundance, species interactions, and better physical projections would nevertheless help to improve this probabilistic approach.

Responses to this article can be read online at:
https://www.ecologyandsociety.org/issues/responses.php/12977

Acknowledgments:

This study received funding from the European Union's Horizon 2020 research and innovation program under grant agreement No 678193 (CERES - Climate change and European Aquatic Resources). HR was supported in part by the CERES project and in part by the BMBF-funded project SeaUseTip (funding code: 01LC1825A-C). AOA was supported by H2020 Marie Skłodowska-Curie Actions (746361). Parts of the work conducted by IC benefited from the collaboration of the Fundación Biodiversidad, from the Ministry for Ecological Transition, through the PLEAMAR program, co-funded by FEMP. We thank OPMallorcaMar and Federació Balear de Confraries de Pescadors for their support and collaboration. We also thank A. Grau and F. Riera, from the DG Fisheries of the Balearic Islands, for their useful inputs. Further, we thank C. Kreiss for useful discussions on the price projections. Part of the data used in this study was obtained from the FAO-Copemed and FAO-Copemed II projects (http://www.faocopemed.org/) as well as the E.U. Copernicus Marine Service Information.

Data Availability:

The aggregated data and BBN model that support the findings of this study are openly available at www.openagrar.de/receive/openagrar_mods_00074060.

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Appendix 1

Background material on temperature projections

The physical model used to calculate present and future surface water temperature is the Proudman Oceanographic Laboratory Coastal Ocean Modelling System (POLCOMS, (Holt and James 2001), which is a baroclinic three dimensional model with the ability to run in regions which include both the deep ocean and the continental shelf using 40 sigma layers. The model was provided by PML, UK (Kay et al. 2018) and has been validated for surface values in the Mediterranean (Ramírez-Romero et al. 2020). Within the frame and efforts of an EU project (CERES, https://ceresproject.eu/), projections for the RCPs were made using data from the global climate model MPI-ESM-LR (http://www.mpimet.mpg.de/en/science/models/mpi-esm.html) and downscaled to regional climate model. Model data from surface temperatures for present runs (average 2006-2016) was corrected for bias for each week (typically 0.3-1°C) using satellite data for the same period (CMEMS, scaled to model resolution), by differentiation of average temperatures (modelled – observed). This was conducted averaging a grid of approx. 200km (bounded by 40.5N - 2E, 38.75N, 4.25E) km around the Balearic Islands, which was taken as representative of the thermal conditions for the spawning area. The projection of warming in the different RCPs was averaged for the decade 2041-2060 (referred to as 2050).

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