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Future Socio-Political Scenarios for Aquatic Resources in Europe: A Common Framework Based on Shared-Socioeconomic-Pathways (SSPs)

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It has proven extremely challenging for researchers to predict with confidence how human societies might develop in the future, yet managers and industries need to make projections in order to test adaptation and mitigation strategies designed to build resilience to long-term shocks. This paper introduces exploratory scenarios with a particular focus on European aquaculture and fisheries and describes how these scenarios were designed. Short-, medium- and long-term developments in socio-political drivers may be just as important in determining profits, revenues and prospects in the aquaculture and fisheries industries as physical drivers such as long-term climate change. Four socio-political-economic futures were developed, based partly on the IPCC SRES (Special Report on Emissions Scenarios) framework and partly on the newer system of Shared Socio-economic Pathways (SSPs). 'Off the shelf' narrative material as well as quantitative outputs were 'borrowed' from earlier frameworks but supplemented with material generated through in-depth stakeholder workshops involving industry and policy makers. Workshop participants were tasked to outline how they thought their sector might look under the four future worlds and, in particular, to make use of the PESTEL conceptual framework (Political, Economic, Social, Technological, Environmental, and Legal) as an *aide memoire* to help define the scope of each scenario. This work was carried out under the auspices of the EU Horizon 2020 project CERES (Climate change and European aquatic RESources), and for each 'CERES scenario' (World Markets, National Enterprise, Global Sustainability and Local Stewardship), additional quantitative outputs were generated, including projections of future fuel and fish prices, using the MAGNET (Modular Applied GeNeral Equilibrium Tool) modeling framework. In developing and applying the CERES scenarios, we have demonstrated that the basic architecture is sufficiently flexible to be used at a wide diversity of scales. We urge the climate science community to adopt a similar scenarios framework, based around SSPs, to facilitate global cross-comparison of fisheries and aquaculture model outputs more broadly and to harmonize communication regarding potential future bioeconomic impacts of climate change.

Keywords: scenario, marine, aquaculture, fisheries, climate change

INTRODUCTION

Climate change is anticipated to have long-term and widespread consequences for fisheries and aquaculture in Europe (Peck and Pinnegar, 2018; IPCC, 2019). However, it can be exceedingly difficult to distinguish between the long term consequences of climate change and those of other human drivers such as the intensity of fishing pressure, the prevalence and effectiveness of legislation, the spatial management of maritime activities and the price of fuel or energy, all of which can directly or indirectly affect trajectories of fisheries and aquaculture development. It can be extremely challenging to predict with confidence how human societies might evolve in the future given the compounding uncertainties in social, political and economic variables that exist (Msangi et al., 2013). Consequently, researchers have often chosen to articulate a set of contrasting scenarios that help to steer a course between the false certainty of a single forecast and the paralysis that might otherwise emerge when faced with a bewildering array of co-conspiring social, economic and environmental variables (O'Neill et al., 2014). Scenarios can be fully quantitative, such as those used by the United Nations Intergovernmental Panel on Climate Change (IPCC) or largely qualitative, i.e., they can exist only as a set of narrative storylines. Several typologies have been developed to describe different types of scenario (see Börjesson et al., 2006). They can be: (1) Predictive – i.e., describe what is expected to happen under certain pre-defined conditions; (2) Explorative – i.e., used to say what the logical outcome might be if the World develops in a particular coherent direction, or (3) Normative – i.e., outline the many possible ways that a desired outcome or destination could be reached. For scenarios to be useful they must always be possible and credible (Wodak and Neale, 2015). In the present study we have focused our attention on defining a set of four explorative scenarios; distinct visions of what the fisheries and aquaculture sector in Europe might look like, were the socio-political outlook of the continent to develop in each of four directions. As recognized by the United Nations Environment Programme (UNEP, 2002), 'scenarios do not have to be developed from scratch,' they can be borrowed or adopted from the literature. In the present case it was decided to make use of both quantitative outputs and the underlying qualitative narrative from the SRES (Special Report on Emissions Scenarios) storylines developed by the IPCC in 2000 (Nakićenović et al., 2000) as well as the newer Shared Socio-economic Pathways (SSPs) framework developed from 2010 onward (see O'Neill et al., 2014; van Vuuren et al., 2014), that will be a major feature of the IPCC 6th Assessment Report (AR6) in 2021.

The European Union CERES project (Climate change and European aquatic RESources) set out to provide better understanding of how climate change will impact fisheries and aquaculture over the next 20–30 years. This wide-ranging project involved participants from 15 European countries and 26 organizations (including universities, government research agencies, and industry stakeholders), spanning the whole continent (with case studies termed 'Storylines' from the Arctic to the Black Sea and from the open ocean to inland waters). During the first 6 months of the project, socio-political-economic narratives (henceforth known as the 'CERES scenarios') were developed, that were in-turn translated into quantitative combinations of drivers that could be used for regional modeling (see Kreiss et al., 2020; Hamon et al., under review, on fisheries and aquaculture, respectively). The four CERES Scenarios were deployed in all subsequent work packages of the project, and in a wide variety of CERES project deliverables (see Peck et al., 2020 for a summary).

Within the CERES project, socio-political-economic scenarios proved useful because:

(1) The future is uncertain. Examining the literally thousands of possible future states (using models) – depending on different assumptions and the time available – is complex and confusing. The number of permutations of climate vs. economic vs. political possibilities needed to be constrained by defining a smaller number of scenarios or pre-defined 'pathways' to cut-through this complexity.
(2) Humans matter. Governments manage people and their activities not the ecosystems themselves, therefore it is necessary to map-out how human societies might develop as well as changing physical/climatic variables.
(3) Speaking a common language is needed. Having a similar concept of how the future might unravel is very helpful. Scenarios can be used to connect seemingly disparate disciplines and make use of outputs from different modeling groups if a common architecture is used.

In the present paper, we describe the ethos and assumptions behind each of the CERES scenarios and how the four scenarios were derived. This paper is the first of a series of three in this IMBeR special issue of Frontiers in Marine Science and should be read alongside that of Hamon et al. (under review) on fisheries and Kreiss et al. (2020) on aquaculture. Elements of the scenarios are presented using the PESTEL approach, a concept that stems from the business world and is frequently used as an *aide memoire* to examine external factors that have an influence on a particular business or company (Johnson et al., 2017). PESTEL is a mnemonic, which in its expanded form denotes Political, Economic, Social, Technological, Environmental and Legal. Key questions from PESTEL analyses include:

- What is the political situation of the country or region (e.g., trade, fiscal, and taxation policies) and how might these affect the fisheries and aquaculture industry in each scenario?
- What are the prevalent economic factors in each scenario (e.g., employment or unemployment rates, raw material costs etc.)?
- How much importance do culture and societal issues have in each scenario (e.g., changing family demographics, education levels, cultural trends, attitude changes and changes in lifestyles) and how might it affect the fisheries and aquaculture industry?
- What technological innovations are likely to occur and affect the development pathway of the particular industry?
- What are the environmental concerns for the fisheries and aquaculture industry, including the impact of climate change?
- Are there legal instruments (treaties, directives, bylaws) that regulate the industry? Are changes anticipated that could determine how the fisheries and aquaculture industry might develop in the future?

MATERIALS AND METHODS

The Five-Step Process for Developing the CERES Scenarios

In developing the CERES scenarios, a five-step process was followed (**Figure 1**), whereby we: (1) reviewed the existing literature on maritime scenarios, including the IPCC SRES scenarios, (2) asked stakeholders to use the basic SRES architecture to map out their thoughts for what European aquaculture and fisheries might look like in 2050, (3) adapted the scenarios architecture so that it was consistent with the latest RCP-SSP matrix approach; (4) carried out additional economic modeling using the MAGNET general equilibrium modeling framework in order to generate outputs that could be used in bioeconomic models of downscaled fisheries and aquaculture; and (5) attempted to 'regionalize' the overarching CERES scenarios using quantitative model outputs as well as inputs from regional stakeholder meetings.

A key starting point for developing the CERES socio-political-economic scenarios was to examine previous efforts to build scenarios in similar marine studies, most notably scenarios stemming from the UK AFMEC project (Alternative Futures for Marine Ecosystems, Pinnegar et al., 2006b), the EU ELME project (European Lifestyles and Marine Ecosystems, Langmead et al., 2007) and the EU VECTORS project (Vectors of Change in Oceans and Seas Marine Life, Groeneveld et al., 2018), all of which were based on the IPCC SRES scenarios architecture. SRES scenarios, were first used in the IPCC Third Assessment Report (TAR), published in 2001, and in the IPCC Fourth Assessment Report (AR4), published in 2007 as well as forming the basis of the UN – Millennium Ecosystem Assessment published in 2005. Four different SRES narrative storylines (A1, A2, B1, and B2) were developed by the IPCC, each describing possible future worlds and taking into account factors such as global population trends, land-use changes, economic growth and per capita income. These contrasting SRES 'storylines' have subsequently proven to be of great utility. Over time, the SRES scenarios were given names to help illustrate their main characteristics, for example the United Kingdom Climate Impacts Programme (UKCP, 2001) provided socio-economic scenarios for climate change impact assessment and named them World Markets (A1F1), National Enterprise (A2), Global Sustainability (B1) and Local Stewardship (B2). In developing the CERES Scenarios, we retained these names and basic characteristics of the scenarios.

Building on the SRES Architecture Through Stakeholder Workshops

At the onset of the CERES project in April 2016, a basic outline of the four prototype CERES scenarios was provided to all project participants (World Markets WM, National Enterprise NE, Global Sustainability GS and Local Stewardship LS). Each participant was solicited to provide their personal vision (in hand-written notes) on how, in their opinion, the future might unfold under each of the four futures, specifically focusing on fisheries or aquaculture. These opinions were supplemented with further suggestions from participants at the ICES/PICES Workshop on Economic Modeling of the Effects of Climate Change on Fish and Fisheries (WKSICCME_Econ) on 3rd June 2016, in Brest, France. In writing their personal visions for the future, all participants were encouraged to make use of the PESTEL framework, i.e., they were asked to explain how the scenarios would differ in terms of (1) Political, (2) Economic, (3) Social/Cultural, (4) Technological, (5) Environmental, and (6) Legal considerations by the year 2050. The information was used to produce a 'Glossy Report Card' (CERES, 2016) that was subsequently made available as a reference material throughout the project.

Incorporation of the SSP and RCP Framework

Since 2010, an international team of climate scientists, economists and energy systems modelers has worked together to build a new generation of socio-political "pathways," intended to supersede the previous generation of SRES scenarios. These Shared Socioeconomic Pathways (SSPs) outline how global society, demographics and economics might change over the next century, but were largely unknown to the CERES project team in 2016. Each SSP consists of a narrative outlining broad characteristics of the global future and a set of quantitative model projections concerning country level human population

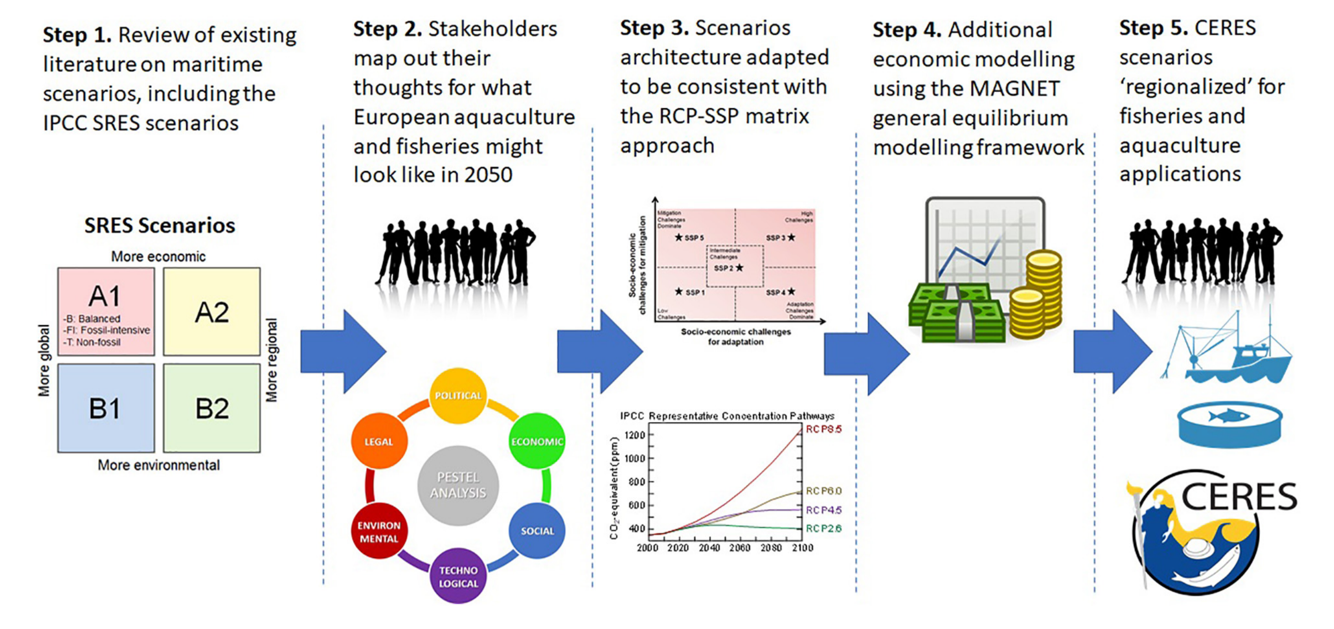

FIGURE 1 | Five-step process through which the CERES scenarios for fisheries and aquaculture were developed.

numbers, GDP, urbanization rate, energy and land-use. Information about the basic SSP architecture and ethos were described by O'Neill et al. (2014) and van Vuuren et al. (2014). More than 4,000 publications (Google Scholar 01/06/2020) have now made reference to the 'shared socioeconomic pathways' (SSP) framework, not only within the context of the climate change literature but also with regard to many other issues, e.g., urban development (Chen et al., 2020) or water usage (Graham et al., 2020). Given that the IPCC intends to use the SSP framework in their 6th Assessment Report (AR6) in 2021 and that a broadly comparable approach is being taken by other high-profile initiatives such as the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services – IPBES (Rosa et al., 2017), it was felt desirable to try to map the prototype CERES scenarios against this new SSP framework in order to enhance uptake and future utility of the results.

The five SSPs are differentiated along two axes (**Figure 2**): one on the basis of socioeconomic challenges to climate change mitigation (reducing greenhouse gas concentrations) and the other reflecting socioeconomic challenges to climate change adaptation (increasing societal and economic resilience to cope with the impacts from climate change). In other words, the SSPs describe worlds in which societal trends conspire to make mitigation of or adaptation to climate change harder or easier, without explicitly considering climate change itself (see O'Neill et al., 2014, 2017). The five scenarios and their descriptive names are:

- SSP1: Sustainability (Taking the Green Road)
- SSP2: Middle of the Road
- SSP3: Regional Rivalry (A Rocky Road)
- SSP4: Inequality (A Road divided)
- SSP5: Fossil-fueled Development (Taking the Highway)

The five SSPs have been designed to be used alongside and in combination with four Representative Concentration Pathways (RCPs) to analyze feedbacks between climate change and socioeconomic factors (O'Neill et al., 2014). The IPCC 5th Assessment (AR5) report, published in 2014 was the first to make use of RCPs. The four RCPs (RCP2.6, RCP4.5, RCP6.0, and RCP8.5), are named after the level of radiative forcing in the year 2100 relative to pre-industrial values (+2.6, +4.5, +6.0, and +8.5 W/m2, respectively). Radiative forcing is a measure of the energy absorbed and retained in the lower atmosphere – effectively the amount that the Earth's energy budget is out of balance. If all combinations of SSP and RCP were tested, this would yield 20 different permutations, although it is now becoming apparent that certain combinations are not really coherent. A high fossil fuel usage SSP5 scenario, for example, seems highly unlikely to go together with a low emissions RCP2.6 scenario and indeed models struggle to reconcile this combination (Rogelj et al., 2018). Conversely, only SSP5 is expected to lead to increases in greenhouse gas concentrations that reach RCP8.5 according to Rogelj et al. (2018).

van Vuuren and Carter (2014) provided a suggestion for how to align the previous generation of SRES scenarios and the new matrix of RCPs and SSPs. van Vuuren and Carter (2014) suggested that this was useful: (i) to assist researchers in using elements of existing scenarios in studies based on the new framework and (ii) to aid interpretation in assessments that compare findings using the new scenarios framework with results based on existing scenarios. The authors scanned the 4 RCP versus 5 SSP matrix to select coherent combinations that best approximated the four widely used SRES storylines. An A2 SRES 'National Enterprise' scenario best mapped onto RCP 8.5 and SSP3; a B2 SRES 'Local Stewardship' (or A1B) scenario best mapped onto RCP 6.0 and SSP2; a B1 SRES 'Global

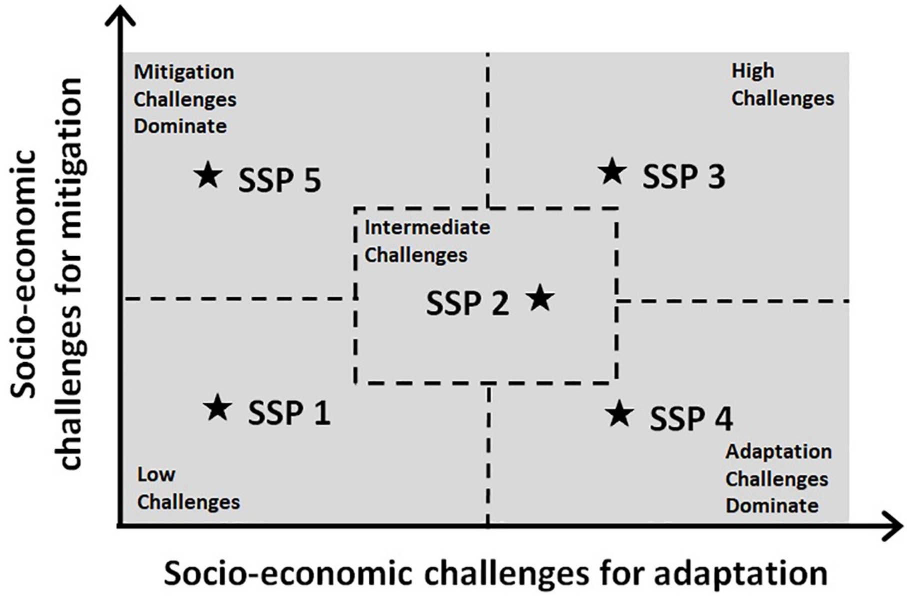

FIGURE 2 | Five shared socioeconomic pathways (SSPs) representing different combinations of challenges to mitigation and to adaptation (based on O'Neill et al., 2014).

Sustainability' scenario mapped onto RCP 4.5 and SSP1 and an A1FI SRES 'World Markets' scenario onto RCP 8.5 and SSP5. These recommended combinations were used as the basis for the CERES scenarios for European fisheries and aquaculture (**Figure 3**). However, limited time and resources for physical and biogeochemical modeling constrained CERES to only two RCP projections (RCP4.5 and RCP8.5). Hence, the 'local stewardship' scenario was assumed to comprise RCP4.5 and SSP2 rather than encompassing RCP6.0.

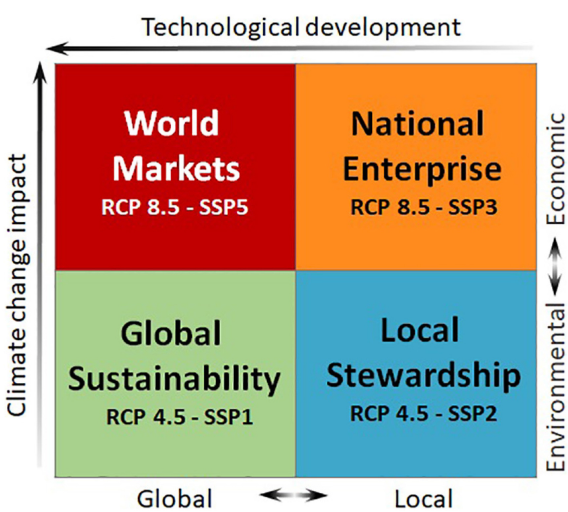

FIGURE 3 | Conceptualization of the four CERES scenarios in terms of impact and adaptation. Direction of the arrows indicates an increasing development/impact. Double arrows indicate diverging socio-political focus.

Detailed descriptions of each SSP and the prevailing socio-economic conditions were provided in the form of five published papers (one for each SSP) in the journal *Global Environmental Change*. The four papers (by Fricko et al., 2017; Fujimori et al., 2017; Kriegler et al., 2017; van Vuuren et al., 2017) that correspond with the four CERES scenarios were 'mined' for useful narrative material. This search yielded important insights with regard to societal goals, assumed land use changes, levels of innovation and technology uptake etc.

Quantitative outputs for European countries were available through 'off the shelf' SSP data products downloaded from the International Institute for Applied Systems Analysis (IIASA). For example, country-specific projections for economic growth (Dellink et al., 2017), human population growth (Samir and Lutz, 2017); urbanization (Jiang and O'Neill, 2017); land use (Popp et al., 2017) and energy use (Bauer et al., 2017) were all available under each SSP and therefore the corresponding CERES scenario. However, these high-level statistics proved insufficient on their own for the more complex bioeconomic modeling activities envisaged within the CERES project (see Kreiss et al., 2020; Hamon et al., under review). Consequently, it was necessary to obtain more comprehensive projections of fuel and fish prices from another source. These more detailed economic outputs were obtained from a global general equilibrium model, developed at Wageningen Economic Research (Woltjer and Kuiper, 2014) but assuming exactly the same SSP framework (with simulations performed for SSP1, SSP2, SSP3, and SSP5).

Economic Quantification

MAGNET (Modular Applied GeNeral Equilibrium Tool) is a global general equilibrium modeling framework based on the earlier GTAP (Global Trade Analysis Project) tool

(Woltjer and Kuiper, 2014). A distinguishing feature of MAGNET is its modular structure. In recent years, MAGNET has been used to simulate the impact of agricultural, trade, land and bioenergy policies on the global economy with a particular focus on nutrition and household food security. The MAGNET framework has been successfully used to investigate the potential impact of a hard Brexit on European fisheries (Bartelings and Smeets Kristkova, 2018), as part of the EU Horizon 2020 project SUCCESS.

The MAGNET model, similar to other macroeconomic frameworks, tracks changes in both the demand and supply of commodities. Income earned from land, labor and capital, as well as that raised from taxes defines total demand. Each commodity is produced by one sector, and each sector produces one commodity (e.g., one agriculture sector, one producer of fish, and one producer of fuel oil) in each country or region. Trade between countries and regions is followed and the model also attempts to simulate trade barriers (tariffs) between regions (Woltjer and Kuiper, 2014). Policy simulations compute consumption and trade (both imports and exports) by sector, as well as the price levels that ensure equilibrium in national and international markets (Woltjer and Kuiper, 2014).

In the present analysis the MAGNET modeling framework was used to assess future changes from a pre-defined baseline for different policy options (socio-political scenarios). Projections of GDP, human demographics and other key indicators were needed to construct the necessary baselines and as drivers of future changes. These projections were available from various sources and, in the present case (to generate the CERES scenarios) the MAGNET simulations were differentiated according to the various SSPs using GDP and population development assumptions from Dellink et al. (2017); Samir and Lutz (2017), and Doelman et al. (2018). All fish and shellfish were aggregated as one commodity. Future trends in fish and fuel prices were extracted from the MAGNET model for the period 2010–2050. The prices were provided in real terms and were corrected for inflation using a GDP deflator projection for Europe given that the CERES bioeconomic models use nominal prices (Woltjer and Kuiper, 2014).

Regionalization the 4 CERES Scenarios

A wide diversity of bioeconomic models was applied in the CERES project, each model with different data needs. Hence, it was necessary to tailor the scenario outputs to match the requirements of particular modeling teams as well as the geographic focus of their work.

CERES developed 24 Storylines (case studies) to help capture the high diversity of activities within the European fisheries and aquaculture sectors, spanning from marine to freshwaters and from high to low latitudes (see Peck et al., 2020). With regard to fisheries, eight single species and wider ecosystem modeling frameworks were applied and used to carry out economic simulations (e.g., FISHRENT, SIMFISH, Atlantis, Random Utility Models, and MEFISTO) (see CERES, 2019). Some of these modeling frameworks work on a spatial basis, whereas others only work at the whole system or macro-economic level. For practical reasons, not all elements of the four scenarios (Political, Economic, Social, Technological, Environmental, and Legal) could be investigated across all CERES Storylines (see Peck et al., 2020). In some cases, such as in the North Sea many different elements were investigated (see Hamon et al., under review), whereas simpler scenarios were examined elsewhere, for example to model fisheries in the Bay of Biscay (see CERES, 2019). In almost every case, information was needed on future fish and fuel prices, hence the MAGNET results were widely utilized throughout the project (see CERES, 2019; Hamon et al., under review).

For several geographic regions, scenario-construction exercises had already been attempted, often employing the same basic SRES or SSP architecture. In these instances, a considerable amount of thought had already been directed toward elaborating how each scenario might play out at the local level. Examples of this were the Baltic Sea where Zandersen et al. (2019) made use of SSPs to develop explorative scenarios focused on agriculture, wastewater treatment, fisheries, shipping and atmospheric deposition, and in the Dutch part of the North Sea where Matthijsen et al. (2018) outlined future scenarios of space utilization based on the original SRES four scenarios. In developing and 'regionalizing' the CERES scenarios, we endeavored to make use of these other works, and to make the resulting downscaled scenarios as complimentary as possible.

To facilitate the regional downscaling or specification of the CERES scenarios a specially convened fisheries and aquaculture engagement workshop was held in The Hague (Netherlands) on 21st–22nd November 2016. Stakeholders were asked how the future might look, under each CERES scenario for their particular farm or fishing fleet. They were requested to consider possible barriers to successful adaptation, any exogenous factors that might influence development trajectories and any issues that could or should be elaborated further through quantitative modeling. In addition, a series of face-to-face stakeholder meetings were held in Ireland, Netherlands, Turkey, and Romania and these helped the modeling teams to decide what a sensible approach might be in each particular context.

Several of the authors participated in two stakeholder workshops organized in 2017 by the Netherlands Environmental Assessment Agency. The workshops were attended by representatives of different sectors including fisheries, energy, sand extraction and recreation, as well as government officials, environmental NGOs and scientists who worked on four spatial scenarios translated into maps by landscape architects (see Matthijsen et al., 2018). Their four scenarios align well with the chosen CERES scenarios and were therefore used directly in the modeling described by Hamon et al. (under review).

The EU ELME project (European Lifestyles and Marine Ecosystems) made use of the SRES architecture to outline how various human drivers, notably pollutant discharge, fishing effort, shipping activity, tourism activity, oil and gas production, agricultural runoff etc., might evolve over the 21st Century for several European coastal seas (Baltic Sea, Black Sea, Mediterranean Sea, and Northeast Atlantic). The ELME project team outlined whether they would expect each driver to increase, remain stable, or decrease under each SRES scenario (see Langmead et al., 2007). These directional indications proved helpful when deciding upon the magnitude and direction of change in the CERES scenarios, especially where other information was lacking.

Kreiss et al. (2020) describe how the CERES scenarios have been applied to the European aquaculture sector. In contrast to the multiple model applications in the fisheries example, a single model type was used across all aquaculture storylines (case studies). That work was based on a well-established benchmarking approach to contrast present day and future economic performance of "typical farms." Applications within the CERES project ranged from rainbow trout farms in Germany, Denmark, Turkey, and the United Kingdom, common carp farms in Poland and Germany, Atlantic salmon farms in Ireland and Norway, Gilthead seabream/European seabass farms in Turkey and Spain, blue mussel farms in Denmark and the Netherlands. To make bioeconomic projections of the impacts of climate change on the European aquaculture sector, the high-level CERES scenarios required additional refinement so that their narratives addressed additional PESTEL elements such as future fishmeal and fish oil prices, the price and availability of alternative (substitute) feed products, consumer acceptance and associated buying trends, trade and subsidy policy, etc. (see Kreiss et al., 2020).

RESULTS

In the following sections, we explore how each element of the 'PESTEL' analysis (Political, Economic, Social, Technological, Environmental, and Legal) could look under the four CERES storylines, and the relevance for European Fisheries and Aquaculture. We then go on to summarize outputs of the stakeholder engagement workshops, whereby experts provided their more specific vision of how they thought fisheries and aquaculture might look in each of the four future worlds.

PESTEL Analysis

P – Political

Many previous scenario exercises (e.g., SRES: Nakićenović et al., 2000) have chosen similar criteria to define their 'possibility-space,' with an axis that broadly represents a 'local to global' political outlook and an axis that tries to capture the prevailing value system, ranging from 'environmentalism to consumerism.' The CERES scenarios can be viewed as being similarly structured, comprising two outward-looking internationalist scenarios (WM and GS) and two more entrenched, inward-facing scenarios (NE and LS). They can also be viewed in terms of the implied level of state/government intervention, which is low under the WM scenario, but high under NE and somewhat intermediate in the LS and GS scenarios.

Under the WM scenario, sometimes characterized as being more 'capitalist' or consumer-focused, government takes a more arms-length approach to managing economic affairs and minimizes the provision of healthcare, education and other social services. Subsidies are strongly discouraged and the general ethos is to reduce taxes with public services privatized or privately managed. In stark contrast, the GS scenario assumes policy is increasingly coordinated at the inter-governmental level, either through the auspices of the United Nations or other bodies such as the European Union. In the GS scenario, society attaches greater value to balancing economic, social and environmental welfare (as opposed to economic growth) in a spirit of cooperation. Fair access to environmental resources (including *trans*-boundary fish stocks) and the conservation of global biodiversity are important aspirations.

Under the NE scenario, relationships with the EU or other international bodies remain more distant, with the balance of opinion favoring entrenchment in economic, foreign and defense policy. Nationalist and separatist movements (as exemplified by the recent exit of the United Kingdom from the European Union) gain ground, causing major disagreements about fisheries quota allocation, access rights and *trans*-boundary issues. This is generally a higher tax scenario with subsidies to protect national industries (e.g., fisheries), employment or food security. Long-term economic growth is heavily constrained by government policies that restrict international competition. Under the LS scenario there is also less focus on international cooperation although less overtly so from a nationalistic perspective. There is a strong emphasis on equity, social inclusion and democratic values at the local level. The co-operative movement is encouraged to expand whereby aquaculture and fisheries businesses, are owned and jointly run by their members, who share the profits or benefits (and also the risks). The LS scenario assumes high levels of public provision for health, education and social services, funded through moderately high taxes.

E – Economic

Dellink et al. (2017) provided long-term economic growth projections (GDP and per capita) for each country of the world, according to the various Shared Socioeconomic Pathways (SSPs). Average GDP-per-capita (expressed as 1,000 US$) for European countries in 2050 is projected to reach 57.8 under a WM (SSP5) scenario; 39.3 under a NE scenario (SSP3), 50.0 under a GS (SSP1) scenario and 45.9 under a under a LS (SSP2) scenario (CERES, 2016). Within the CERES project we supplemented this information by calculating fuel prices and commodity (fish) prices under each SSP from the MAGNET model.

Two different methods were utilized to generate price data: (1) to obtain an annual price range for simulated time series and (2) a fixed price variation range for endpoint scenario calculations, based on the available time-series (1997–2016 for fish prices and 1980–2016 for crude-oil prices). To define the width of the ranges, we used historical price variability. With regard to fish, we used European prices (only frozen, fresh, chilled and portioned fish and seafood products) from the FAO FishStat database (FAO, 2018) and for fuel we used European prices of crude oil import from the OECD (OECD, 2018).

Fuel and fish price difference among the four scenarios was somewhat limited (**Figure 4**). Annual change in prices ranged from +1.3 to +1.7% per year for fish and +2.6 to +2.9% per year for fuel. Other sources of future fuel and fish prices were examined and compared to the MAGNET outputs, given the importance of these variables to the CERES fisheries and aquaculture simulations (see Kreiss et al., 2020; Hamon

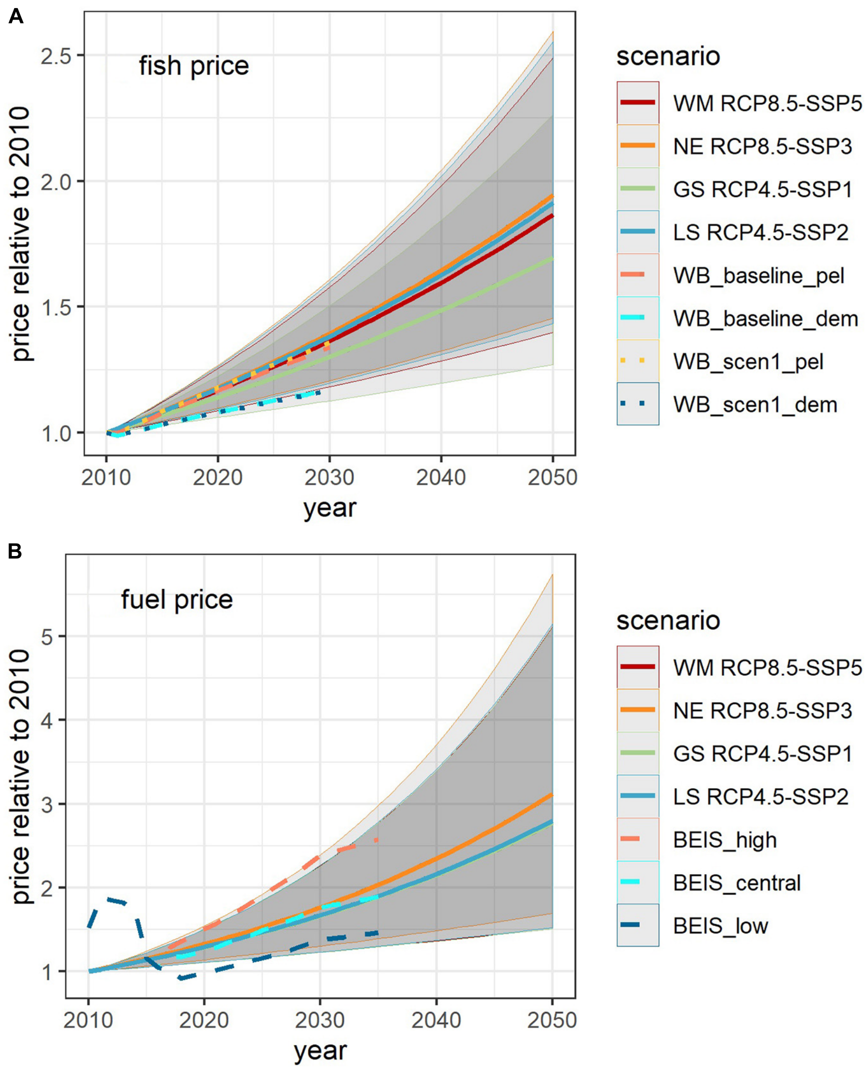

FIGURE 4 | Fish **(A)** and fuel **(B)** price trends relative to 2010 for the four CERES scenarios and for the other data sources (WB: World Bank and UK BEIS: Department for Business, Energy and Industrial Strategy). The shaded areas correspond to the 95% confidence intervals around the CERES price trend projections. In the lower panel the WM scenario is obscured by the LS and GS lines.

et al., under review). Several datasets were available, but each alternative had its own shortcomings and, thus, we believe that the MAGNET outputs represent the best currently available. For example, the projection period used in other studies was often too short to be useful in bioeconomic models of fishery and aquaculture development, or there was usually a poor match with the SSP scenarios. On the other hand, we felt it desirable to test our assumptions regarding the choices of the trends and the range in values used. Consequently, we compared the MAGNET projections with the World Bank future fish prices (Msangi et al., 2013) and future fuel prices provided by the UK Department for Business, Energy and Industrial Strategy (BEIS, 2017). Comparison with alternative sources of data suggested that the ranges used in the CERES model outputs did match the broad trends estimated in other projection studies (see **Figure 4**) and that in every case simulated prices rose in the future (even though corrected for monetary inflation), with fish prices projected to rise slightly slower in the GS scenario compared to the others, and fuel prices rising faster in the more fossil-fuel intensive WM and NE scenarios compared to the 'greener' GS and LS scenarios (see **Figure 4**). Kreiss et al. (2020) and Hamon et al. (under review) demonstrate the consequences of this assumption for fisheries and aquaculture, when compared alongside the potential impact of future climate change. In an application to the North Sea flatfish fishery for example, fuel and fish prices proved much more influential than climate change with regard to determining the future viability of fisheries (Hamon et al., under review).

S – Social

Samir and Lutz (2017) provided human population trajectories for each SSP (and thereby each CERES scenario) by age, gender and level of education for all countries of the world up to

2100. They describe these as "the human core of the shared socioeconomic pathways." Trajectories of human population growth resulting from the five SSPs differ very little up until 2030. This is due to the momentum of population growth and the fact that differences in the assumed trajectories of the components only phase in gradually. As might be expected, during the second half of the 21st century the differences increase with SSP3 (NE) reaching 12.6 billion in 2100 and SSP1 (GS) falling to 6.9 billion which is lower than today's world population. For Europe specifically (36 countries), the human population projections are: 748 million by 2050 under a WM (SSP5) scenario; 606 million under an NE scenario (SSP3); 679 million under a GS (SSP1) scenario; and 672 million under a LS (SSP2) scenario (CERES, 2016).

These human population data can be used as the basis for calculating the demand for seafood products, both within Europe and internationally (Delgado et al., 2003). Within the European Union, the average consumption of fish is 24.3 kg/person/year, however, consumption varies from only 5.2 kg/person/year in Hungary to 57.0 kg/person/year in Portugal (EUMOFA, 2018). Failler et al. (2007) published fish consumption, production and trade (exports and imports) projections for 28 EU countries plus Norway, spanning 1989 to 2030. The projections suggest an increase in the demand for seafood products to 2030, driven partly by increases in the human population size of European countries, but also changes in per capita fish consumption related to changing societal affluence (especially in eastern European countries). Within the CERES project, in order to provide initial estimates of total demand for seafood products out to 2050, national population estimates from Samir and Lutz (2017) were combined with per-capita seafood consumption estimates reported from Failler et al. (2007), assuming that per-capita consumption profiles in 2050 are broadly similar to those reported by Failler et al. (2007) for 2030. In **Figure 5**, we provide estimates of total seafood consumption by the EUR-28 countries and Norway under each CERES Scenario. Under a WM (SSP5) scenario, total demand for seafood by 2050 is 16.1 million tons, compared to 11.8 million tons under an NE scenario (SSP3), 14.3 million tons under a GS (SSP1) scenario and 13.9 million tons under a LS (SSP2) scenario. It is important to note that these calculations do not take account of potential changes to societal attitudes and in particular with regard to eating animal (meat or fish) protein. Other authors have chosen to differentiate the SSPs in this regard, with both the WM (SSP5) and NE (SSP3) scenarios characterized by diets high in animal protein; GS (SSP1) with low animal-calorie shares and LS (SSP2) somewhat intermediate (Popp et al., 2017). The MAGNET model takes into account societal attitudes when determining demand for meat products, however, it does not consider societal attitudes with regard to fish consumption. In this case, demand for fish products was directly related to income (GDP/capita), price of fish and price of cereals (see explanation in Kreiss et al., 2020).

T – Technological

Devising scenarios for future advances in technology is challenging and verges toward 'science fiction.' Despite this, the uptake of and/or reliance on new technologies has been considered important when developing future scenarios, most notably in the Millennium Ecosystem Assessment (MEA, 2005). The MEA derived four scenarios including a 'TechnoGarden scenario' that depicts a globally-connected world strongly relying on technology and on highly-managed and often engineered ecosystems to deliver goods and services. Similarly, Constanza (2000) opted for four scenarios distinguishing between 'technological optimism' and 'technological skepticism.' Some of this technological narrative from the MEA and Constanza (2000) was included in the CERES scenarios (see **Figure 3**). From the more recent SSP literature (e.g., O'Neill et al., 2017), the WM (SSP5) scenario is characterized by rapid technological progress whereas this is less of a feature under the other scenarios. Under the WM (SSP5) scenario, local environmental impacts and challenges are, at least partially, addressed by technological solutions, but there is little effort or applied innovation to avoid global environmental impacts. Under the NE scenario (SSP2), investments decline in education, and thereby, technological innovation is heavily stifled. Difficulty in achieving international cooperation and slow technological uptake result in major challenges to climate change mitigation or adaptation (O'Neill et al., 2017). For the GS (SSP1) scenario, investment in green technology and changes in tax incentives lead to more sustainable resource utilization. Increased climate change mitigation and decreased impacts on marine and freshwater systems result from a combination of directed development of environmentally friendly technologies, a favorable outlook for renewable energy, international cooperation (i.e., learning from international 'best practice'). Under the LS (SSP2) scenario, incremental advances in technology continue, but there are no fundamental breakthroughs as innovations are typically small-scale and regional. Further detail on scenarios of technological development in the fisheries and aquaculture sectors in Europe can be found in the companion papers by Kreiss et al. (2020) and Hamon et al. (under review), respectively.

E – Environmental

The CERES scenarios assume two different carbon emission and therefore warming trajectories, RCP8.5 (WM and NE) and RCP4.5 (GS and LS). Within the CERES project the well-established POLCOMS-ERSEM coupled biogeochemical model framework was used to generate climate change projections for the northeast Atlantic and Mediterranean Sea, whereas in the Baltic Sea a regional coupled atmosphere-ice-ocean-land surface model RCA4-NEMO was used (see CERES, 2018). In the Baltic Sea, temperatures were projected to rise by about 1°C in the first half of the century, with a further 2°C rise by the end of the century under RCP8.5, but only 0.5°C under RCP4.5. The North Sea was projected to warm by about 2°C during the 21st century under RCP8.5 and about 1°C under RCP4.5, with comparable increases at the sea surface and bottom. Surface temperatures in the Mediterranean Sea were projected to rise by 3°C during the 21st century under RCP8.5, with an increase of about 1.5°C under RCP4.5. Temperatures under the two RCPs were similar for the first few decades, but clear differences were anticipated by mid-century (Peck et al., 2020).

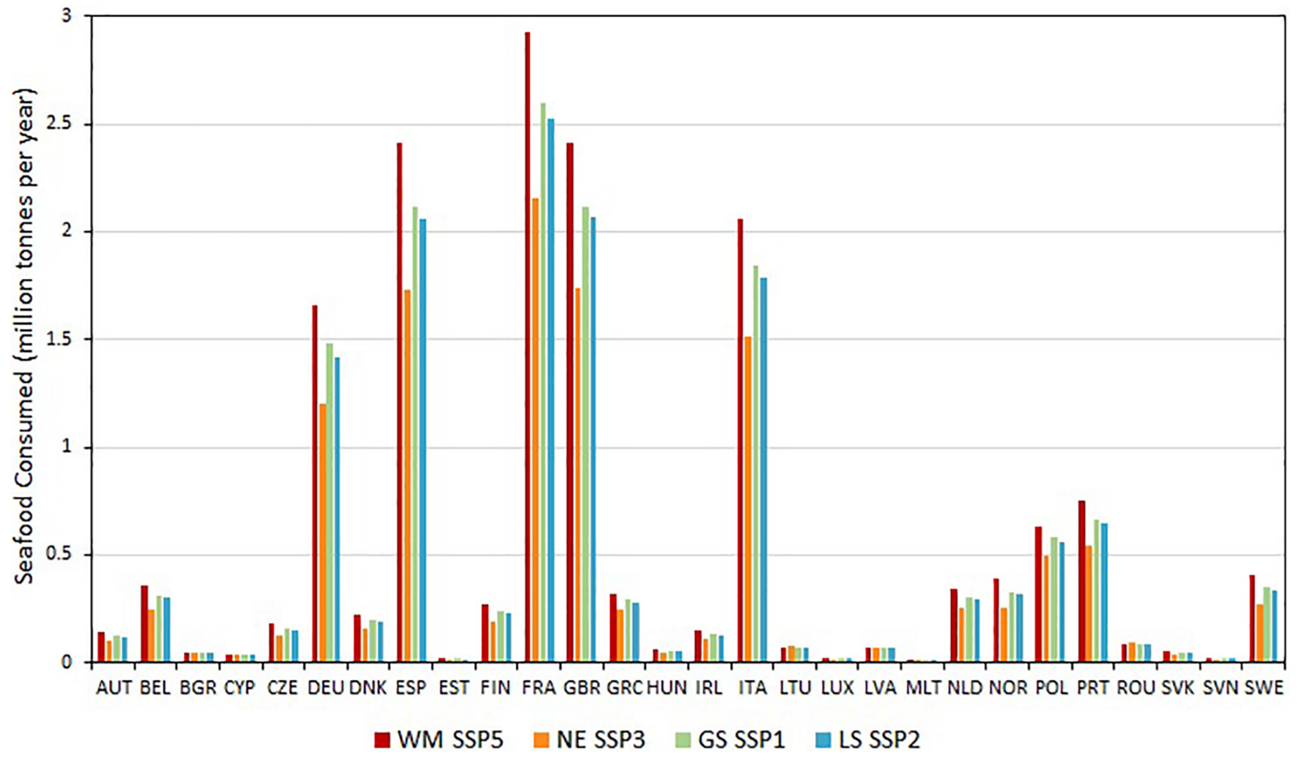

FIGURE 5 | Total seafood consumption derived from both fisheries and aquaculture of EU28 countries (plus Norway) by 2050, under each of the CERES scenarios. Three-letter country codes as defined in ISO 3166-1.

For the Norwegian and Barents Seas projections were available up to 2070, but only under RCP4.5, using the NORWECOM modeling framework (NORWegian ECOlogical Model) (Skogen et al., 2018). CERES fisheries modelers used information from global climate models to give equivalent extended projections to end of the century for RCP8.5. Sea surface temperatures were projected to rise by 0.5°C in the Norwegian Sea and 2.5°C in the Barents Sea by 2060 relative to present conditions, under the RCP4.5 climate scenario and by 0.6 and 3°C, respectively, by the end of the century. The corresponding increases for RCP8.5 were 1°C in the Norwegian Sea and 5.3°C in the Barents Sea.

Projections of river discharge and nutrient loading (used for modeling of freshwater aquaculture, see CERES, 2018) were obtained from the E-HYPE hydrological model at the Swedish Meteorological Institute (SMI). River discharges were projected to decrease in southern Europe by up to 25% under RCP4.5, and up to 50% under RCP8.5 by the 2080s. The biggest increases were projected for Norway and Sweden, with discharges 10–25% higher by the 2080s. The magnitude of change intensifies throughout the century and is greater under RCP8.5 than under RCP4.5 scenario (Donnelly et al., 2016).

Popp et al. (2017) examined land-use futures under each SSP. This is relevant to fisheries and aquaculture in Europe as changes in land-use can determine runoff patterns and hence water quality with downstream consequences for aquaculture sites but also pollutant run-off and therefore nutrients reaching the adjacent ocean. Nutrient emission scenarios were a major feature of the modeling work conducted by CERES scientists in the Baltic Sea. For the Baltic, an 'Atlantis' ecosystem model was developed, assuming the two climate change scenarios (RCP4.5 and RCP8.5) but also 3 nutrient load (eutrophication) scenarios that were broadly consistent with SSP1, SSP2 and SSP5, i.e., with water quality improvements under the Baltic Sea Action Plan (BSAP), a scenario of today's level (reference) and a scenario of deteriorating water quality (worst) (CERES, 2019). A recent paper by Zandersen et al. (2019) also made use of SSPs to develop explorative scenarios for the Baltic Sea., with a focus on agriculture, wastewater treatment, fisheries, shipping and atmospheric deposition.

As might be expected, the release of nutrients heavily depends on the types of agricultural practices that predominate under each SSP. Within the WM (SSP5) scenario, it is assumed that agricultural subsidies, if present at all, are low (particularly those based on production) and prospects for nutrient emissions are mixed. On the one hand, precision farming techniques with carefully timed and targeted fertilizer application achieve higher yields. On the other hand, global supply chains reduce the price of fertilizer which encourages excessive use with little punitive action or intervention from governments, resulting in greater run-off of nutrients to the sea. Under the NE (SSP2) scenario by contrast, the goal of agricultural policy is to help ensure national food and income security. Agricultural production relies on high levels of fertilizer and pesticide input with weak control over application rates and timing. Therefore, high levels of nutrient run-off to river systems and eventually to the marine environment are expected under the NE scenario. For the LS (SSP2) and GS (SSP1) scenarios, the overall requirement for food is lower (due to slower population growth rates) and environmental regulation is stricter, hence nutrient inputs to riverine and marine environments are substantially reduced (relative to other scenarios). Traditional, low-intensity farming practices are particularly favored under the GS scenario (SSP1) in which large areas of land are removed from agricultural production (Popp et al., 2017).

L – Legal

There is already a vast number of byelaws, acts of parliament, EU Directives and international treaties that regulate fisheries and aquaculture in Europe (Boyes and Elliott, 2014). In constructing the CERES scenarios we considered whether or not there would be any substantive change in the legal landscape, given the socio-political conditions that are presumed to be prevalent in each future world. Under the WM scenario, social and environmental governance is increasingly achieved through international free trade agreements, establishing minimum legal standards and implemented primarily through market-based approaches [e.g., the General Agreement on Tariffs and Trade (GATT) via the World Trade Organization (WTO)]. Under the NE scenario, the EU remains at arms-length, with the balance of opinion favoring national entrenchment and thus a weakening of the EU Common Fisheries Policy as well as other EU Directives that govern fisheries and aquaculture development, including water quality issues such as the Marine Strategy Framework Directive (MSFD) and Water Framework Directive (WFD). Under the GS scenario, management of the global commons improves through binding international treaties that primarily work toward nature conservation or poverty alleviation [e.g., the United Nations Convention on Biological Diversity (CBD) or the United Nations Framework Convention on Climate Change (UNFCC)], facilitated by increasingly effective cooperation and collaboration among local, national and international organizations and institutions, the private sector and civil society. *Trans*-boundary environmental issues, including fisheries management are effectively resolved. Under the LS scenario, fisheries and aquaculture are regulated via a complex 'mosaic' of small-scale local byelaws and national legislation. Communities and cooperatives are involved in the management of the marine environment and in making decisions about development.

CERES Marine Fisheries Scenarios

In the following section we provide a commentary on the CERES marine fisheries scenarios based on an interpretation of the issues, differences and characteristics that became apparent from the PESTEL analysis (see above) as well as insights gained from previously published marine socio-economic scenarios. In addition, we drew extensively on the marine fisheries scenarios narratives elaborated by experts and stakeholders at the initial workshop (summarized in **Figure 6**).

Under the CERES World Markets (WM) Scenario the primary objective is generation of wealth and the production of large quantities of low-cost seafood. This scenario assumes completely open markets and global trading of seafood commodities. The price and flows of seafood are largely governed by supply and demand. Growing demand in Asia and developing countries means that it is harder for European countries to compete and therefore to secure sufficient supplies from elsewhere in the world. National quota allocation keys (e.g., within the EU Common Fisheries Policy) are abandoned as a protectionist measure that distorts the market. This is a low tax, low government intervention scenario with few legal or technical restrictions on fishing practices. A major focus is on achieving 'Maximum Economic Yield,' i.e., the most revenue that can be achieved from a fishery (see Hamon et al., under review). This could involve the elimination of competing predators (e.g., marine mammals, elasmobranchs), so that overall yields are maximized. The fishing industry is dominated by large multinational companies, with only a few high-tech boats. Fish quotas are owned and traded among large companies. Discarding regulations are not strict and there are few spatial restrictions on fishing practices (e.g., Marine Protected Areas – MPAs or offshore windfarms). Because of their economic value, fisheries are viewed as being more important than conservation. Destructive fishing gears continue to be tolerated. Labor in the European fishing industry is supplemented by low-cost immigrant workers.

Under the CERES National Enterprise (NE) Scenario the primary objective is national food security and maintaining employment opportunities. The fishing industry is managed at the national scale and this leads to many disagreements regarding quota allocation for stocks that cross international boundaries as well as fishery access rights. Each country restricts fishery access within its own territorial waters (Exclusive Economic Zone – EEZ), costs of enforcement are high and state subsidies are provided to maintain capacity or employment in the industry as well as national food security. A major focus is on achieving 'Maximum Social Yield,' i.e., the most employment that can be achieved from a fishery (see Hamon et al., under review). This leads to slower uptake of technology within the industry and many small (relatively inefficient) fishing vessels. Fisheries are regulated via a complex array of national laws and restrictions, resulting in a 'mosaic' of different management practices across Europe. In some places, innovative quota allocation schemes are tried, such as Individual Transferable Quotas (ITQs) but quota can only be traded within the nation state. Some discarding regulations are introduced and there is pressure to make use of unwanted catches to generate fishmeal for use in the indigenous aquaculture sector. Campaigns are launched to encourage citizens to eat seafood products that are derived from national waters, rather than relying on imported products from elsewhere in the world. High import tariffs are imposed and exports are discouraged. National labeling schemes take precedence (highlighting that the product derives from indigenous waters) rather than international schemes focused on sustainability or quality.

Under the CERES Global Sustainability (GS) Scenario the primary objective is global sustainability of fisheries and preventing the deterioration of marine environments. Fish are traded world-wide, but greater emphasis is placed on

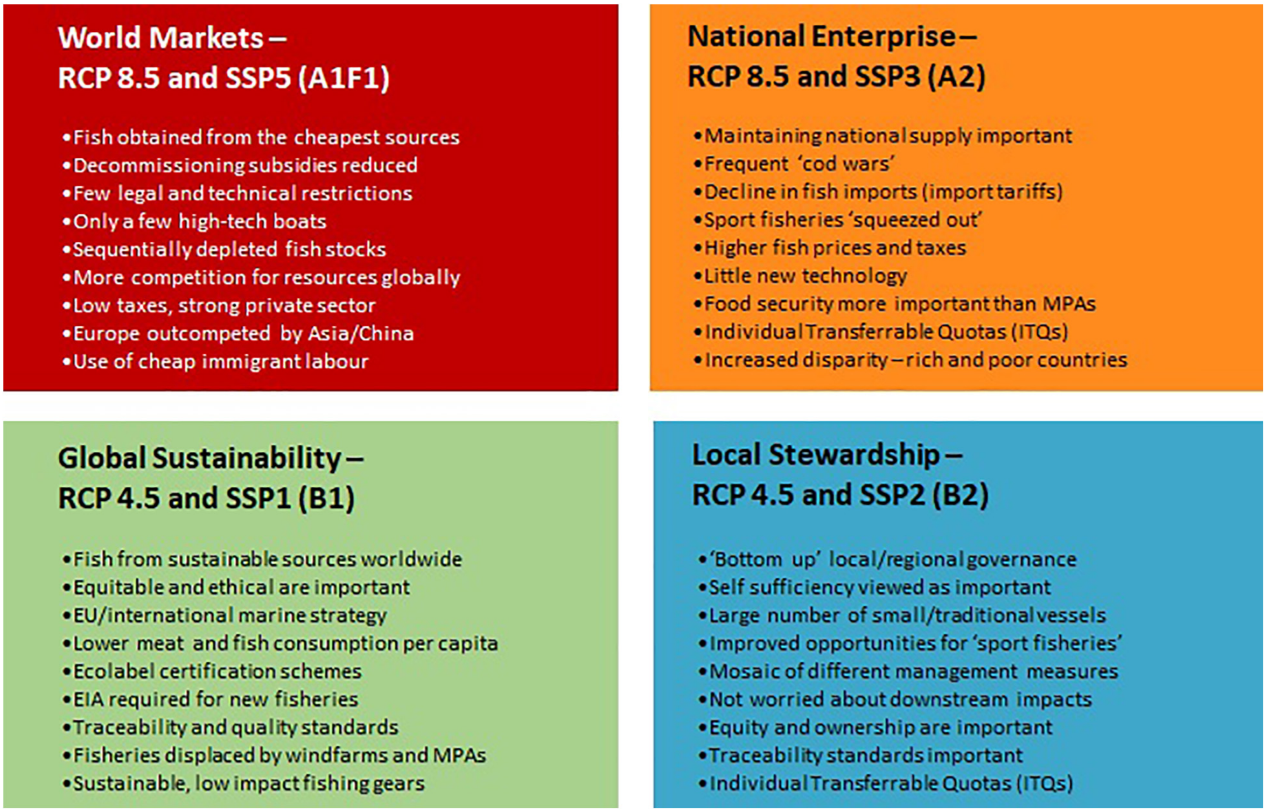

FIGURE 6 | Draft socio-political scenarios elaborated for European fisheries by CERES partners and stakeholders.

sustainability and on ethical production. Binding international agreements are reached and this results in strict regulation of fishing practices. A major focus is on achieving 'Maximum Ecological Yield,' i.e., minimizing the impact of commercial fisheries in natural populations and ecosystems (see Hamon et al., under review). Permissible levels of fishing mortality are set at a low level in order to protect the most vulnerable marine organisms (e.g., sharks and rays). Quotas are freely traded among companies and countries but with strong environmental obligations. Quota buy outs by conservation organizations and NGOs become commonplace. Many MPAs are introduced and fully closed to fishing to protect vulnerable species and habitats as well as to rebuild stocks and protect spawning/nursery grounds. Huge expansion of offshore renewable energy facilities leads to disruption in the fishing industry, with spatial access heavily regulated. Per capita consumption of fish products (and animal protein in general) is lowest in this scenario, as is human population growth. This has major consequences for the future demand for seafood products.

Under the CERES Local Stewardship (LS) Scenario, the primary objective is maintaining local sustainability of fisheries resources. It is possible that fisheries quota allocation or trading might occur at the sub-national level and that management would be achieved via regional panels, including extensive stakeholder or cooperative involvement. Fisheries are regulated via a complex 'mosaic' of regional byelaws and national legislation, resulting in an array of different management practices everywhere. This leads to positive outcomes in some places, but negative consequences elsewhere. A major focus is on achieving 'Maximum Sustainable Yield,' i.e., obtaining the most out of a population without damaging the resources or the underlying ecosystem (see Hamon et al., under review). It is anticipated that there would be improvement in the status of many inshore stocks for example shellfish or small-scale artisanal fisheries as a result of responsible exploitation practices, conversely effective management of stocks or species that traverse international boundaries would become much more difficult. Fishing fleets are characterized by large numbers of small/traditional vessels under local ownership. Minimizing 'food miles' is viewed as important, as is local self-sufficiency. Campaigns are launched to encourage citizens to eat seafood products that are derived from local waters, rather than relying on imported products from elsewhere (nationally or internationally).

Within the CERES project freshwater fisheries were addressed separately and are only discussed very briefly here. Under the WM and GS scenarios, the downward trend suggested by Failler et al. (2007), in demand for freshwater fish resources in much of eastern Europe, either from aquaculture or from wild-capture fisheries (and their replacement by imported marine products) would be expected to continue, whereas under the NE scenario such trends would be reversed as nationalities seek to make the most of their indigenous resources. Under the WM scenario freshwater fisheries would suffer as a result of degradation of freshwater habitats due to a lack of adequate controls on pollution and development. Buy-outs of traditional freshwater fishing rights by multinational companies or recreational groups might be expected, as would significant human pressures on water resources, e.g., extraction for irrigation, drinking water etc. Under the NE scenario the primary focus is on national food security, therefore freshwater recreational fisheries are not a priority. There is heavy extraction of water resources for irrigation and energy-intensive industries, impacting river flows and lake water levels. There are major disagreements regarding allocation and exploitation of stocks where these traverse national boundaries (e.g., on the Danube). Diadromous fish species are not effectively managed and decline in abundance. Under the GS international agreements are established to manage stocks where these traverse borders. Human pressures on water resources (e.g., extraction for irrigation, drinking water, etc.) are reduced compared to other scenarios, however, this scenario would witness the greatest expansion of hydropower and tidal energy schemes that could restrict the passage of diadromous species including salmon and eels. Conservation or recreational groups might engage in buy outs of freshwater fishing rights. Under the LS scenario, minimizing 'food miles' and protecting local habitats are viewed as important among citizens and government. A complex mosaic of different managements systems is established. This leads to positive outcomes in some places, but negative consequences elsewhere. Small-scale freshwater habitat restoration schemes are established, this is viewed as a more sustainable way of preventing local flood damage. Native freshwater fish species are reintroduced, to rivers and lakes from which they have previously been extirpated (e.g., sturgeon and burbot).

CERES Marine Aquaculture Scenarios

An overview of the CERES scenarios created for European aquaculture is shown in **Figure 7** (adapted from CERES, 2016). In comparison with fisheries, much less effort had previously been dedicated toward deriving scenarios for aquaculture (although see FEUFAR, 2008), hence, this narrative was based almost entirely on suggestions made by stakeholders and project participants. Some of the biggest differences between the four scenarios concern the availability, potential replacement and/or utilization of fishmeal and fish oil in aquaculture. This topic is discussed in detail in the companion paper by Kreiss et al. (2020) where outputs from the MAGNET model were used to drive a separate Fishmeal and Fish Oil (FMFO) model (Mullon et al., 2016). In the analyses of by Kreiss et al. (2020), the differences in society's acceptance of genetically modified (GM) organisms as sources of protein within fishmeal (e.g., soya or other land-based alternatives versus 'traditional' marine based ingredients) greatly impact prices of fish feed. In developing the CERES scenarios such factors were taken into account by using a demand flexibility parameter in the FMFO model (see Kreiss et al., 2020). Substitute materials for expensive fishmeal and fish oil were assumed to be more readily available in the WM and GS scenarios (high demand flexibility) and less available (low demand flexibility) in the more introvert NE and LS scenarios. Using the same underlying SRES scenario architecture (but only for the WM and GS scenarios), Merino et al. (2010) evaluated the combined role of market perturbations and climate variability (both short-term El Niño fluctuations and long-term global warming) on the global fishmeal production and consumption system. The authors concluded that the sustainability of small pelagic fish critical for traditional fishmeal and fish oil production, depended more on how society responds to climate impacts from an economic and political perspective than on the magnitude of climate alterations *per se*.

The CERES WM scenario assumes completely open markets and global trading of aquaculture products (see Kreiss et al., 2020). The primary objective is the generation of wealth and the production of large quantities of low-cost seafood. Growing demand (as well as production) in Asian countries means that it is harder for European countries to compete and conversely to secure sufficient supplies from elsewhere in the world. Some aquaculture facilities in Europe are established explicitly with the aim of producing products that can be sold to the burgeoning Asian markets. Large-scale marine aquaculture facilities are established, owned and operated by a small number of multinational companies. Technology and automation are important in this scenario, as a means of cutting labor costs. A divergence in the European aquaculture markets develops whereby some consumers choose low-cost anonymous 'white fish' products with little regard to where it comes from or how it is produced, whereas other consumers seek high-quality, higher-cost products that are produced to more stringent quality standards, with full traceability. Common 'minimum standards' are established, within the context of international trade negotiations. There is very little government intervention or regulation at the national level. Completely open markets for fishmeal and fish oil lead to over-exploited wild stocks. Extensive use of fish waste to produce inexpensive (but low quality) fishmeal, creates a market for this material – this leads to depletion of previously non-target wild fish stocks. Given the increasing demand in China, European aquaculture companies find it hard to compete on global fishmeal markets, and so have to seek alternatives.

Under the CERES NS scenario, the primary objective is national food security and maintaining employment opportunities within the aquaculture sector (see Kreiss et al., 2020). There is little incentive to produce aquaculture products for the export market and indeed, the primary focus is on culturing 'native' species to meet local needs and tastes. The sector is characterized by small-scale aquaculture facilities with high energy and labor costs and less technological innovation. Given that the focus is on maintaining future production, conservation objectives are less important. There is competition for space with other users of the marine environment, e.g., wild capture fisheries, windfarms, conservation, oil and gas extraction, etc. and for freshwater resources. The allocation of space is largely determined by the national public benefit. The recent decrease in consumer demand for freshwater aquaculture products in Eastern Europe (e.g., Romania, Bulgaria, and Poland) is reversed, as pressure increases to fully utilize indigenous resources. Governments are less worried about downstream, *trans*-boundary consequences of aquaculture

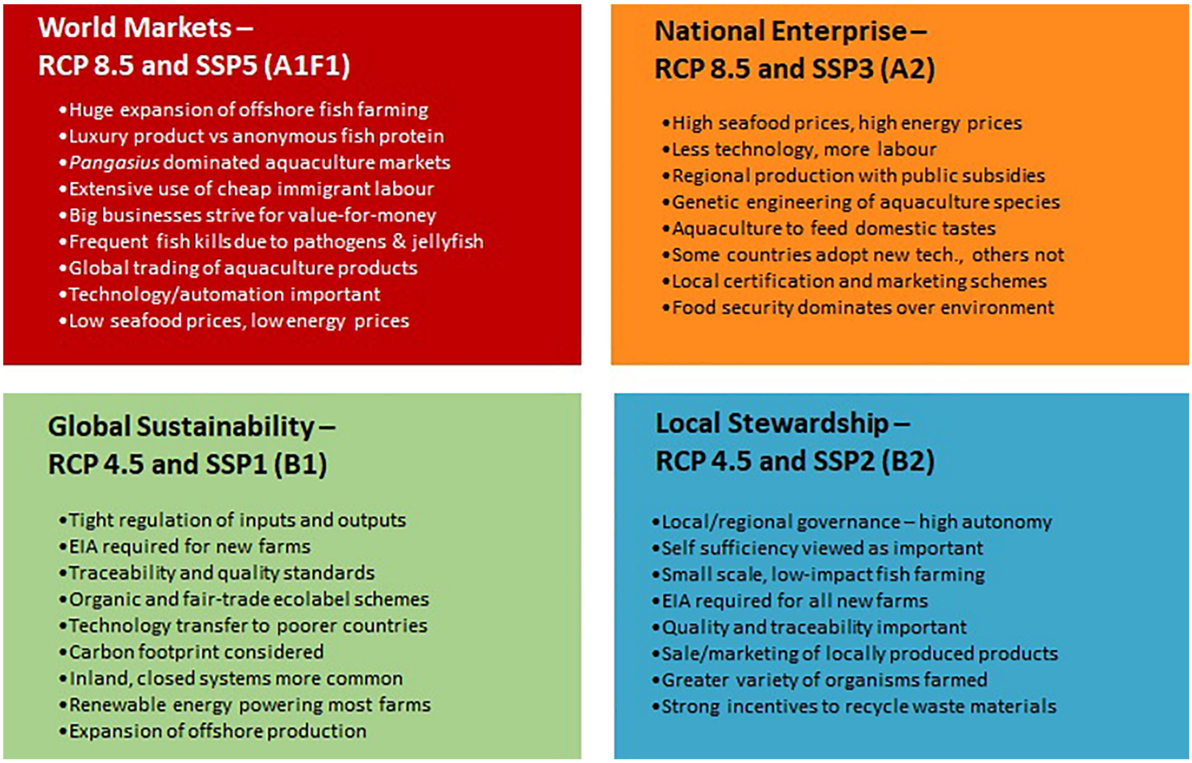

FIGURE 7 | Draft socio-political scenarios elaborated for European aquaculture by CERES partners and stakeholders.

facilities (e.g., pollutants). National labeling schemes take precedence (highlighting that the product derives from indigenous aquaculture facilities) rather than schemes focused on sustainability or quality. Imports of fishmeal from Latin America are greatly reduced – more emphasis is placed on making use of indigenous sources, for example sandeel in the North Sea, sardinella and anchovy in the Mediterranean – this leads to localized depletions of wild fish stocks. Fishmeal prices are high, due to import tariffs and limited supplies to market.

Under the CERES GS scenario, the primary objective is global sustainability of aquaculture, protecting the public and preventing the deterioration of marine and freshwater environments (see Kreiss et al., 2020). Fish are traded world-wide, but greater emphasis is placed on sustainable and ethical production. Binding international quality standards are introduced and this results in strict regulation of aquaculture practices (e.g., chemical pollution, feed supply, labor conditions) as well as 'traceability.' This scenario would witness wide-scale technology transfer between countries and establishment of guides to international 'best practice.' Per capita consumption of fish products (and animal protein in general) is lowest in this scenario, as is human population growth. This has major consequences for the future demand for aquaculture products. Ecolabel certification schemes assume greater prominence (e.g., organically produced, 'fair-trade,' welfare-friendly). A full Environmental Impact Assessment (EIA) is required before a new aquaculture facility can be constructed. Co-location of large-scale aquaculture facilities is envisaged together with offshore windfarms. Renewable energy sources are used to power aquaculture facilities. The 'carbon footprint' of production is considered important, indeed oyster aquaculture has less than 0.5% of the GHG-cost of beef, pork, and poultry in terms of CO_2-equivalents per kg protein, and so might be a particularly attractive option under this scenario (Ray et al., 2019). Fishmeal and fish oil are traded world-wide, but greater emphasis is placed on sustainable production and product substitution (with non-animal protein). As wild-capture fisheries worldwide are carefully managed, the potential supply of fish-meal is higher, however, the demand for aquaculture (and animal protein in general) is lower, and hence prices of fishmeal and fish oil on global markets are also lower. More aquaculture is based on herbivorous fish species (e.g., Cyprinidae species) rather than salmonids.

Under the CERES LS scenario, the primary objective is maintaining local self-sufficiency in aquaculture. This scenario anticipates an expansion of small-scale, low-impact fish farms or shellfish beds growing primarily 'native' species for the local market. Minimizing 'food miles' and protecting local habitats are viewed as vitally important. Smaller companies predominate. Aquaculture is regulated via a complex 'mosaic' of local bylaws, resulting in different management practices across Europe. Large-scale *trans*-boundary environmental problems are not tackled. Quality and traceability are very important – although a bewildering array of local standards as well as ecolabels make comparison very difficult. The allocation of space is determined by local development plans, that are developed in close cooperation with stakeholders. Moderate expansion of small-scale offshore windfarms in support of achieving local energy self-sufficiency creates some opportunities for 'co-location' with aquaculture facilities (e.g., fish cages or seaweed beds) between the turbines. Fishmeal prices are moderately high, due to limited availability of sustainable sources. Strong incentives exist to reduce waste, recycle materials and eliminate the need for wild-caught fish stocks for the production of fishmeal in aquaculture feeds, hence greater use of fishery discards is encouraged for this purpose.

DISCUSSION

The application of socioeconomic scenarios in the fisheries and aquaculture sector is in its infancy. Only a handful of previous studies have attempted to map out how these two sub-sectors might look in the future (e.g., Teh et al., 2016; Maury et al., 2017; Cheung et al., 2019) and, in the vast majority of cases only broad-brush descriptions of possible socioeconomic trajectories have been provided. By contrast, the CERES scenarios described here were explicitly developed to provide the forcing variables necessary for bio-economic models and hence to make it possible to conduct quantitative comparisons of alternative governance and management strategies taking account of future climate change.

In the two companion papers to this manuscript, Hamon et al. (under review) and Kreiss et al. (2020) the authors demonstrate how the CERES scenarios were taken up and used across the different model implementations, in order to identify possible threats and opportunities to the fisheries and aquaculture sectors in Europe over the next 20–30 years. CERES (2019) and Peck et al. (2020) describe how the four scenarios have been applied to wild-capture fisheries as diverse as Northeast Atlantic small pelagics (e.g., herring and mackerel), western Mediterranean small pelagics (sardine and anchovy), Aegean Sea mixed demersals (hake, red mullet, striped red mullet, and deep water rose shrimp), Norwegian/Barents Sea cod, capelin and herring, using many different bioeconomic modeling frameworks (e.g., SIMFISH, Atlantis, RUM, FISHRENT, and MEFISTO). A particular application to the North Sea flatfish fishery (plaice and sole) is provided by Hamon et al. (under review). In this latter paper, the authors show that the impacts of economic and political factors (most notably fish and fuel prices) are expected to outweigh the direct impact of climate change by mid-century. The change in temperature projected for the North Sea and its main ecological consequences for the distribution of sole and plaice are anticipated to remain small until mid-century. The fact that the profitability of fleets is so strongly driven by fish and fuel prices leads us to pay more attention to assumptions regarding the prices used in the scenarios. The prices were derived from the global MAGNET model, however, some price dynamics are not captured by these smooth upward trends (see discussion below).

Similarly, Kreiss et al. (2020) describe how the CERES scenarios have been applied to the European aquaculture industry. Applications within the CERES project ranged from rainbow trout farms in Germany, Denmark, Turkey, and the United Kingdom, common carp farms in Poland and Germany, Atlantic salmon farms in Ireland and Norway, gilthead seabream/European seabass farms in Turkey and Spain, blue mussel farms in Denmark and the Netherlands. Analyses by Kreiss et al. (2020) suggested that profitability of 'typical farms' at mid century (2050) was most sensitive to changes in feed costs, price trends and marketing options, rather than the direct, biological effect of climate change on culture environments and target species.

These diverse applications of the CERES scenarios clearly demonstrate that the concept is 'scalable' and sufficiently flexible for use at the level of a single aquaculture farm or equally a massive industrial fishery operating throughout the northeast Atlantic. Similarly, we have shown that the same scenario architecture can be applied to both freshwater and marine systems and in vastly different socio-political contexts (e.g., from the Black Sea to the Arctic). We argue that considerable benefit could be gained from rolling out this scenario framework more broadly and deriving comparable scenarios for global analyses, perhaps within the context of the Fisheries and Marine Ecosystem Model Intercomparison Project (Fish-MIP) (see Tittensor et al., 2018) which has a 'Scenarios working group.' A similar approach has been advocated by Maury et al. (2017) who constructed a series of socio-political scenarios for global oceanic fisheries also based on the SSPs, although the authors called them "Oceanic System Pathways" (OSPs). Within the approach taken by Maury et al. (2017) two major driving forces were chosen to structure the OSPs: (1) the demand for seafood resources, (2) the costs of harvesting, processing and transporting these resources and associated products. The two drivers of global marine fisheries governance chosen to structure the OSPs were: (1) inter-state relations and (2) the global reach of firms (Maury et al., 2017).

There are many different ways to construct scenarios for fisheries and aquaculture. A common approach has been to base them on existing architectures such as the SRES or SSP framework, with or without extensive stakeholder engagement. The CERES scenarios, those of Maury et al. (2017) and the scenarios developed by Cheung et al. (2019) are all deeply rooted in the architecture of the Shared Socioeconomic Pathways (SSPs). Similarly, Teh et al. (2016) used the SSPs to construct fisheries scenarios for Canada. An alternative approach, however, can be to build up scenarios from first principles, starting with key drivers. Planque et al. (2019) used this bottom-up approach to build new scenarios for various Marine Social-Ecological Systems (MSES) based on experiences of stakeholders working in the Barents Sea. Workshop participants were tasked to describe the current state and trends in the MSES from each individual perspective (i.e., ecosystem, fisheries management, ocean and climate, or global governance). During the second step, participants produced multiple narratives about the possible futures of the MSES, separately for each individual perspective. These were elaborated according to a few contrasted storylines, typically "baseline," "positive," and "negative." The third step was dedicated toward integration, when actors were asked to explore more complex and multi-faceted futures. In the EU FEUFAR (The Future of EUropean Fisheries and Aquaculture Research) project a very similar participatory approach was taken and this yielded five distinct future scenarios for the European seafood industry (FEUFAR, 2008). The FEUFAR project started with 42 drivers that broadly encompassed regulation, markets and economy, social dynamics, ecosystems, climate change, production and research. For each driver a set of contrasting 'hypotheses' (trajectories) was elaborated. These were aggregated into 'micro-scenarios' that were themselves built up, into the five contrasting 'macro-scenarios.'

It is important to note that no single scenario will ever come to pass in its entirety. Certain elements from each of the four CERES scenarios are likely to feature in the future and the main purpose is to bracket the uncertainty-space, even though this means that the resulting scenarios look like somewhat cartoonish end-points of reality. The IPCC always maintained that it was neither possible nor desirable to attach probability estimates to their four basic (SRES) scenarios (see Grübler and Nakicenovic, 2001) and the same would be true of the newer SSPs. However, in a recent paper, Hausfather and Peters (2020) made reference to the SSPs and highlighted the more nuanced possibilities that the combined SSP/RCP matrix approach can allow. In particular, these authors argued that the combined RCP8.5 and SSP5 (i.e., World Markets) scenario, is now "Highly unlikely" given current development trajectories. By contrast the authors argued that the combined RCP4.5 and SSP2 (i.e., Local Stewardship) scenario is "Likely – given current policies."

It should be noted that none of the CERES socio-political scenarios assume RCP2.6 or SSP4. The main reason for this decision was that van Vuuren and Carter (2014) did not include this combination in their mapping of RCPs and SSPs against the SRES scenarios. RCP2.6 represents the IPCC 'best case' scenario and relies not only on reducing CO_2 emissions, but also that CO_2 is actively removed from the air after 2050 via aggressive 'carbon capture and storage' measures (CCS), which some authors view was being overly optimistic. Conversely, other commentators had begun to treat RCP8.5 as the 'business as usual' scenario (i.e., what would happen if we do not rapidly change our ways), however, Hausfather and Peters (2020) have questioned this premise. RCP8.5 paints a dystopian future that is fossil-fuel intensive and excludes any meaningful climate mitigation policies, leading to nearly 5°C of warming by the end of the century. The authors argue that for emission pathways to get to RCP8.5 it would require an unprecedented fivefold increase in coal use by the end of the century, whereas in reality it is thought that global coal use may have peaked in 2013.

In preparation for the 6th IPCC Assessment Report (AR6) due to be published in 2021, a Scenario Model Intercomparison Project (ScenarioMIP) was established, with the stated aim to "Facilitate integrated research leading to a better understanding not only of the physical climate system consequences of these scenarios, but also of the climate impact on societies, including considerations of mitigation and adaptation" (see O'Neill et al., 2016). Part of the work of this group has involved agreeing which particular combinations of SSP and RCPs climate modelers should investigate over the next few years. The ScenarioMIP group decided upon four 'Tier 1' combinations that should be prioritized going forward and some, but not all, of these coincide with those combinations recommended by van Vuuren and Carter (2014) that were subsequently used as the basis for the CERES scenarios. Combinations chosen by the ScenarioMIP team that were not considered in the CERES project include SSP1-RCP2.6, SSP2-RCP4.5, and SSP3-RCP7 although the overarching narrative developed by ScenarioMIP was broadly comparable in character to that outlined for the four CERES scenarios. These particular combinations were chosen primarily to span a wide range of uncertainty in future forcing pathways rather than to encapsulate plausible futures from a social-economic-political perspective (see O'Neill et al., 2016).

As recent events with the global COVID-19 pandemic effectively illustrate, socio-economic or political change does not occur slowly or steadily over time but, more often, occurs suddenly as a result of surprise events such as economic recession, political upheavals or rapid changes in the natural environment. The approach taken in developing the CERES scenarios (and in most other scenario exercises) suggests that change occurs gradually along a single trajectory. In the CERES scenarios, for example, fuel and fish prices were assumed to increase at a steady rate into the future (see **Figure 4**), as projected by the MAGNET general equilibrium model. In reality, prices can be incredibly volatile and are buffeted by shocks on both the supply and demand side. Poos et al. (2013) demonstrated that North Sea beam trawl fisheries are incredibly responsive to fuel price. In recent years, increased fuel prices have resulted in the widespread adoption of energy saving technologies including switching to less energy-demanding fishing gears and vessels. By contrast, in 2020 fuel prices plummeted as a result of a disagreements between Russia and OPEC oil producing countries, who argued about the need to cut oil production at a time of limited demand. In the short term at least, this may increase revenues and profits in some parts of the fishing and aquaculture industries.

Similarly, fish prices can also exhibit considerable volatility and are unlikely to follow the smooth trajectory illustrated in **Figure 4**. Fish prices can increase as a result of scarcity on the market, linked to limited supply (e.g., as a result of poor weather episodes, reduced stock size etc.) but also as a result of increasing demand, linked to changes in consumer tastes or preferences (see Pinnegar et al., 2006a). Conversely, fish prices may decrease if demand subsides, for example during the recent COVID19 outbreak when almost all seafood restaurants in Europe were closed (FAO, 2020). Aquaculture has the effect of increasing the availability of certain fish on the market and thus through the laws of supply and demand, can result in lower seafood prices. Increased cage culture for Atlantic salmon for example, has resulted in a marked decline in salmon prices globally. In Europe, increased farming of seabass and seabream has also resulted in relative price reductions in these species (see Pinnegar et al., 2006a).

Groeneveld et al. (2018) bemoaned the fact that, despite the growing prevalence of scenarios in the fisheries and aquaculture literature over recent years, scientists still need to overcome skepticism and misunderstanding so as to persuade their colleagues that this approach is useful. Scenario development requires a degree of speculation that can prove uncomfortable to many workshop participants and that academics are generally trained to avoid. It takes bravery to propose a scenario that will most certainly not come true. At the beginning of the CERES project, workshop participants found it highly implausible for example, that a more nationalist future could emerge, especially given the high level of political and legislative integration that exists with regard to fisheries in Europe under the auspices of the EU Common Fisheries Policy. Everything changed, however, following a referendum in the United Kingdom on 23 June 2016 and the subsequent departure of the United Kingdom from the European Union and hence the EU Common Fisheries Policy. This decision will have widespread consequences for fisheries management, fishery access rights in relation to territorial boundaries and quota allocation (see Bartelings and Smeets Kristkova, 2018; Phillipson and Symes, 2018; Shepherd and Horwood, 2019). Therefore, the NE scenario suddenly become a major focus for work within CERES and fisheries researchers across Europe. The CERES scenario framework and in particular the narrative of the NE Scenario (RCP 8.5 and SSP3) had to be adapted accordingly (see Hamon et al., under review). These events illustrate that circumstances can change very quickly and underline the fact that where possible, in scenario development we should not be bound by current mind sets/preconceptions. The trajectory that society is taking at present, could change very quickly to reflect new realities and this might be especially true in the post-COVID19 world.

DATA AVAILABILITY STATEMENT

Publicly available datasets were analyzed in this study. This data can be found here: https://tntcat.iiasa.ac.at/SspDb/dsd?Action=htmlpage&page=about.

ETHICS STATEMENT

Ethical review and approval was not required for the study on human participants in accordance with the local legislation and institutional requirements. The patients/participants provided their written informed consent to participate in this study.

AUTHOR CONTRIBUTIONS

JP, CK, KH, and MP contributed to conception and design of the study. JP led the work and (together with GE) drafted the initial manuscript. AT conducted the future price projections (MAGNET). KH, CK, and SR conducted the price variation analysis. All authors contributed to manuscript revision and approved the submitted version.

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