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Future Scenarios of Global Fisheries and Ocean Alkalinity Enhancement Under Socio-Economic and Climate Pathways

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Key Points:

- Our scenarios extend the Shared Socioeconomic Pathway/ Representative Concentration Pathway framework, focusing on fisheries and ocean alkalinity enhancement sectors
- We integrate ecological, economic, societal, and technological aspects to develop narratives and quantify key bio-economic parameters
- Our scenarios align with Intergovernmental Panel on Climate Change and IPBES model-based studies, providing a shared foundation for future research

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Abstract Achieving global climate goals while ensuring food security in a changing climate presents significant challenges, particularly when relying solely on land-based solutions. Covering over 70% of the Earth's surface, the ocean remains an underutilized resource for climate mitigation. Ocean alkalinity enhancement (OAE) is one such strategy, designed to strengthen the ocean's natural carbon sink, reduce atmospheric CO_2, and mitigate ocean acidification. However, its implications for fisheries, critical for food security and livelihoods, remain uncertain. This study examines the interplay between global fisheries, OAE, and different future socioeconomic and climatic conditions, using the Shared Socioeconomic Pathways (SSPs) and Representative Concentration Pathways framework. We explore how global fisheries and OAE could evolve under three combined scenarios: SSP1-2.6 (sustainability-focused), SSP3-7.0 (regional rivalry), and SSP5-8.5 (high fossil fuel dependency). By integrating ecological, economic, societal, and technological perspectives, we develop scenario narratives and quantify key bio-economic parameters, including technological progress, fishing costs, fisheries management, marine aquaculture, and ecosystem carrying capacity. High-emission (SSP5-8.5) and fragmented development (SSP3-7.0) scenarios present significant barriers to the coexistence of OAE and fisheries, whereas sustainability-focused pathways (SSP1-2.6) offer the most favorable conditions for their alignment. Successfully integrating OAE with fisheries management will likely depend on technological advancements, international cooperation, and socio-economic developments. These scenarios are aligned with those used in model-based scenario studies conducted under the frameworks of the Intergovernmental Panel on Climate Change and the Intergovernmental Platform on Biodiversity and Ecosystem Services (IPBES), providing a shared foundation for future work.

Plain Language Summary The world faces two major challenges: reducing climate change and ensuring food security. While many climate solutions focus on land, the ocean, covering over 70% of the Earth's surface, offers untapped potential. One proposed strategy is ocean alkalinity enhancement (OAE), which could help the ocean absorb more carbon dioxide from the atmosphere and reduce ocean acidification. However, little is known about how OAE might affect global fisheries, which are essential for food and livelihoods. Our study explores how fisheries and OAE could co-evolve under different future scenarios, considering climate change and socio-economic developments. We examine three possible futures: one focused on sustainability (SSP1-2.6), another marked by regional conflict (SSP3-7.0), and one with continued high fossil fuel use (SSP5-8.5). Using these scenarios, we analyze factors such as fishing costs, technology, aquaculture, and ecosystem health. We find that sustainability-focused pathways (SSP1-2.6) create the best conditions for OAE and fisheries, while high-emission and fragmented development scenarios present major challenges. The successful implementation of OAE alongside fisheries management will likely depend on technological progress, international cooperation, and economic policies. We expect that these scenarios will be a common starting point for future model-based scenario studies related to the work of the Intergovernmental Panel on Climate Change and Intergovernmental Platform on Biodiversity and Ecosystem Services.

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1. Introduction

Achieving both climate change mitigation and global food security will be very challenging if relying solely on land-based measures (Dooley et al., 2022; Fujimori et al., 2022; Oschlies et al., 2023). Therefore, exploring ocean-based solutions is worthwhile, given that the ocean covers about 70% of the Earth's surface and has the capacity to absorb a considerable amount of CO_2 (Friedlingstein et al., 2022). Implementing marine carbon dioxide removal (CDR) options would increase the ocean's uptake of CO_2 and could contribute to achieving net zero emissions, but it is important to be aware of potential side effects. First, it is important to note that OAE currently remains at a low technological readiness level (Eisaman et al., 2023), and substantial uncertainties persist regarding its potential impacts on marine ecosystems, including possible disruptions to food webs, shifts in species composition, and other untested biogeochemical and ecological responses (Lezaun & Valenzuela, 2024; Nawaz et al., 2023). While a management strategy focused on maximizing marine CDR may enhance carbon sequestration and contribute to climate change mitigation, balancing such efforts with food security and the health of marine ecosystems and fish stocks will depend on specific enabling conditions.

Global fisheries are integral to the sustenance of millions of individuals worldwide, significantly contributing to food security and economic stability. They provide a primary source of protein for over a billion people, particularly in developing regions where alternative protein sources are limited (FAO, 2024). Economic activities in fisheries support the livelihoods of millions, including small-scale artisanal fishers and large commercial operations, while making significant contributions to the global economy through trade and employment (Béné et al., 2015; FAO, 2024). However, global fisheries face significant pressures and challenges that threaten their sustainability and the ecosystems supporting them. Overfishing, driven by increasing global demand and insufficient regulatory frameworks, partly due to high costs (Riekhof & Noack, 2024), depletes fish stocks at rates faster than they can replenish (FAO, 2024). Bycatch, the unintended capture of non-target species, further exacerbates the decline in marine biodiversity (Davies et al., 2009). Destructive fishing methods, such as bottom trawling and blast fishing, cause severe habitat destruction, damaging vital marine ecosystems like coral reefs and seagrass beds, and further threatening the biodiversity and productivity of the oceans (Chuenpagdee et al., 2003). Additionally, illegal, unreported, and unregulated fishing undermines conservation efforts and economic stability (Agnew et al., 2009).

Compounding these issues, climate change is expected to have significant negative impacts on all types of fisheries, with marine fisheries particularly affected by rising ocean temperatures, ocean deoxygenation, and increased acidification. Rising ocean temperatures disrupt fish migration patterns and breeding cycles, leading to shifts in species distribution and declines in fish populations (Cheung et al., 2009; Salvatteci et al., 2022). Oxygen depletion controls the distribution of fish communities in the water column and the seafloor and with increased oxygen deficiency habitat compression for some species is expected (Pitcher et al., 2021). Ocean acidification, a result of increased CO_2 absorption and the consequent decrease in pH, further exacerbates the problem by harming calcifying organisms like shellfish and coral reefs, which are vital to marine food webs (Doney et al., 2009). Additionally, climate change leads to more frequent and severe weather events, impacting fishing operations, coastal infrastructure (Allison et al., 2009), and even influencing fishers' investment decisions (Kleemann & Riekhof, 2023).

Tackling the intertwined challenges of climate change and fisheries sustainability requires comprehensive and diverse strategies, such as reducing greenhouse gas emissions, expanding marine protected areas, and implementing adaptive management practices to enhance the resilience of fish stocks and marine ecosystems (Roberts et al., 2024; Worm et al., 2009). In addition to these established strategies, innovative techniques of marine CDR are discussed to support climate change mitigation measures. One promising approach is ocean alkalinity enhancement (OAE) (Eisaman et al., 2023; Oschlies et al., 2023). This geoengineering method is aimed at sequestering atmospheric CO_2, thereby accelerating the ocean's natural carbon sink (Renforth & Henderson, 2017), and offering the potential co-benefit of mitigating ocean acidification. OAE involves two primary methods: (a) Mineral weathering: this method accelerates natural processes where minerals like olivine or limestone react with CO_2 and water, generating bicarbonate ions that increase seawater alkalinity (Hartmann et al., 2013; Oschlies et al., 2023); (b) Direct addition of alkaline substances: substances such as calcium oxide or sodium hydroxide can be directly added to seawater, releasing ions that react with CO_2 to produce bicarbonate ions. Both methods aim to enhance natural processes that absorb CO_2 and raise oceanic pH levels. By artificially increasing the ocean's acid-neutralizing capacity, OAE can stabilize pH levels, creating a more hospitable environment for marine life and mitigating climate change impacts on fish habitats and populations (Hartmann et al., 2013). Although some studies have already investigated the effects of increased alkalinity on the marine ecosystem (Bach et al., 2019; Ferderer et al., 2022), few studies researched the implications of OAE on fish (Goldenberg et al., 2024b).

To evaluate its feasibility, effectiveness, and potential environmental impacts of OAE, scenario analysis is a useful and complementary tool, providing a robust framework for assessing the multifaceted impacts and strategies associated with uncertainty, especially within complex and dynamic systems (Mahmoud et al., 2009). Specifically, scenario analysis complements both modeling approaches and experimental work by exploring plausible futures and guiding research priorities in the face of incomplete knowledge. Scenario analysis already plays a crucial role in climate change research and policy-making by providing a framework to explore and understand potential future pathways under different socioeconomic and climate conditions. Within this context, Shared Socioeconomic Pathways (SSPs) and Representative Concentration Pathways (RCPs) have become a standard and widely used scenario (SSP-RCP) framework (O'Neill et al., 2017; Riahi et al., 2017; Van Vuuren et al., 2011). SSPs outline plausible future societal developments, such as population growth, economic trends, and technological advancements, while RCPs describe different greenhouse gas concentration trajectories resulting from various emission scenarios, thus different levels of climate change. These scenarios span the period from the present until the year 2100, allowing the exploration of long-term developments and impacts. The SSP-RCP framework serve as a foundation and archetype for scenario development, offering a global narrative, emissions trajectory, and projected level of warming as a basis for further exploration. Expanding on these SSP and RCP narratives is necessary to explore diverse solutions and to support more detailed analyses of climate response options and impacts, especially in specific sectors and locations (Van Ruijven et al., 2014). Such extensions, which may take a regional or sectoral perspective, provide the conceptual basis for more targeted assessments of climate risks, responses, and interactions across specific contexts, a need that our study begins to address through a sectoral lens focused on fisheries. This is crucial for conducting risk and vulnerability assessments at various scales (O'Neill et al., 2020), which emphasize the need for tailored approaches in evaluating climate impacts and adaptation strategies. Examples of such extensions are already emerging (Maury et al., 2017; Mitter et al., 2020), but only a few studies have crafted fisheries scenarios based on potential socioeconomic futures (Cheung et al., 2019; Hamon et al., 2021; Maury et al., 2017; Pinnegar et al., 2021; Teh et al., 2017; Zandersen et al., 2019). To our knowledge, no global scenarios of OAE deployment have been developed that integrate with SSP and RCP pathways. Such plausible scenarios are currently lacking and in this paper we introduce a novel extension of the SSP-RCP by developing sector-specific scenarios focusing on the evolution of fisheries and OAE under different SSP-RCP pathways. Moreover, the SSP-RCP framework, while useful, has limitations in addressing marine biodiversity and SDG 14. Our approach extends it by incorporating fisheries and OAE to better capture sectoral and ecological dynamics. This helps align scenarios with Intergovernmental Panel on Climate Change (IPCC) and Intergovernmental Platform on Biodiversity and Ecosystem Services (IPBES) frameworks for improved biodiversity and climate policy analysis. These scenarios offer a unique opportunity to examine key interplays, shedding light on potential synergies, trade-offs, and developments. Integrating fisheries and OAE within this shared framework enables a novel perspective on their interactions under widely used socioeconomic and climate scenarios, an angle that has not yet been explored in the existing literature.

Our aim is to explore the potential futures of global fisheries with or without future application of OAE through integrated narratives. Leveraging the SSPs and RCPs, we specifically focus on SSP1-2.6, SSP3-7.0, and SSP5-8.5 scenarios. Furthermore, we assess changes (trends) in essential bio-economic fishery parameters for each scenario by combining qualitative narratives with a numerical rating system to capture directional shifts. With this approach, we contribute to the development of sectoral and long-term interdisciplinary models that are both relevant for future policy and management strategies for climate change mitigation, as well as for sustainable use of marine ecosystems. These scenarios are aligned with those used in model-based scenario studies conducted under the frameworks of the IPCC and the IPBES, providing a shared foundation for future work.

2. Developing Scenarios

In this paper, we first construct narratives around potential futures of global fisheries, examining both qualitative and quantitative aspects. These narratives are based on the SSPs (O'Neill et al., 2017) and integrated with selected climate pathways, the RCPs (Van Vuuren et al., 2011), following a consistent timeframe until 2100. Specifically, we focus on the interactions between three scenarios: SSP1-2.6, SSP3-7.0, and SSP5-8.5 (O'Neill et al., 2020).

These scenarios were selected to cover a broad spectrum of plausible socio-economic development pathways and associated climate outcomes, ranging from sustainability-oriented low emissions (SSP1-2.6), through fragmented development with moderate to high emissions (SSP3-7.0), to fossil-fueled growth with very high emissions (SSP5-8.5). This selection allows us to explore a wide variety of potential futures for global fisheries under contrasting socio-economic and climate conditions. Additionally, we explore how OAE fits into these scenarios, incorporating supplementary narratives that consider variables such as geographic location, scale of operation, integration with marine policies, and potential effects on global fisheries. These narratives are designed to capture important social, economic, and governance dimensions relevant to fisheries and OAE deployment, embedded in a structured framework for examining plausible future developments. Rather than making predictions, this approach outlines plausible scenarios and identifies key factors that could shape future outcomes. To bridge the qualitative and quantitative components, we define a set of common bio-economic parameters frequently used in bio-economic modeling (Dao et al., 2023; Failler et al., 2022; Prellezo et al., 2012; Voss et al., 2014, 2022) (see Section 2.2).

2.1. Workshop Approach to Scenario Development

A workshop conducted in Kiel, Germany, on 6 September 2022, focused on formulating new scenarios to explore potential futures for global fisheries, both with and without OAE. The participants brought diverse expertise to enrich the discussion and scenario-building process. Fourteen professionals, serving as co-authors, were selected from various fields, including fisheries science and management, marine ecology, biogeochemistry, earth system modeling, fisheries modeling, economics, development cooperation, CDR, and marine geospatial science. The workshop program encompassed a diverse set of activities: (a) a blend of informative presentations covering the SSP-RCP scenario framework, OAE, and a global fishery model; (b) interactive breakout group discussions where participants were organized into three groups. Each group examined one of the three chosen SSP-RCP combinations, considering scenarios with and without OAE. The groups collaboratively formulated narratives and projections for the bio-economic parameters across different economies; and (c) comprehensive plenary discussions where participants shared presentations outlining the key characteristics and narratives developed by each group under each SSP-RCP pathway. This approach fostered consistency between scenarios and facilitated a diverse exploration of potential futures for global fisheries and OAE. In the aftermath of the workshop, the information provided by each group (notes, transcripts and audio recording) was used to further develop narrative drafts with aligned quantitative elements. These were afterward distributed to participants and additional experts for feedback before being finalized into the scenarios presented in this paper. They featured a descriptive title and engaging narratives that elucidate the potential progression of events. In crafting the scenarios, five factors were taken into account: plausibility (the likelihood of occurrence), differentiation (distinguishing them from mere variations of similar cases), consistency (lack of internal inconsistencies that would diminish the credibility of the scenarios), utility (offering insights into the future implications of present decisions), and challenge (broadening the scope beyond conventional wisdom regarding the future). These scenarios are not intended to provide predictions of the future, but offer alternative narratives against which certain outcomes can be evaluated and assessed by modeling or discussed for policy choices.

2.2. Selected Bio-Economic Parameters

In the workshop, we identified and discussed a distinct set of parameters specifically designed for projecting potential changes in global fisheries under OAE. A narrative was developed for each parameter, considering three selected combinations of SSPs and RCPs (SSP1-2.6, SSP3-7.0, SSP5-8.5), as well as the presence or absence of OAE (on and off) implementation. Table 1 presents the selected parameters that have been chosen for this purpose.

2.3. Semi-Quantitative Assessment of Selected Parameters

A two-stage "rating system" was employed to quantify directional changes in the values of the bio-economic parameters for all distinct scenarios. As each scenario represents a unique qualitative narrative that illustrates the potential development of the bio-economic parameters, they offer the foundational logic, assumptions, and rationales that are important for the assessment and quantification of these bio-economic parameters. During the workshop (stage 1), domain experts with relevant expertise assessed whether the parameters in each scenario were expected to increase, decrease, or remain unchanged. Within each scenario, the rating system ranges continuously

Table 1
Definitions and Explanations of Bio-Economic Parameters

Parameter	Definition
Technological progress	Technological progress refers to advancements and innovations in the methods, tools, and equipment used in fishing operations and related activities. It encompasses the development, adoption, and utilization of technologies, techniques, and practices to enhance the efficiency, effectiveness, and sustainability of fisheries
Fishing costs	Fishing costs refer to the various expenses incurred in the operation of commercial fishing activities. These costs encompass the financial outlays associated with equipment, labor, maintenance, fuel and energy, processing, and regulatory compliance. Costs under different scenarios are also compared given a certain state of the ecosystem and biomass
Fisheries management	Fisheries management encompasses a comprehensive approach and a range of strategies employed to govern the exploitation of fishery resources and their associated ecosystems. It entails the coordination of policies, regulations, and practices that aim to effectively regulate and oversee fisheries operations
Marine aquaculture	Marine aquaculture (mariculture) refers to the farming or cultivation of marine finfish species in controlled environments. These environments can include oceanic cages, ponds, or recirculating aquaculture systems (RAS). Here, the main objective of marine aquaculture is to rear and produce marine fish species for commercial purposes, primarily focused on food production as a direct substitute of wild marine captured fish
Other substitutes	The parameter "other substitutes" refers to alternative forms of aquaculture production that encompass a variety of options beyond marine finfish farming. These alternatives include the cultivation of crustaceans, mollusks, and freshwater fish, as well as the utilization of alternative protein sources for human consumption
Carrying capacity	Marine ecosystem carrying capacity refers to the maximum population size or biomass of a given species or group of species that can be sustained by a specific marine ecosystem over a certain period of time without causing significant ecological degradation or depletion of essential resources. It represents the balance between the available ecological resources and the demand placed on those resources by living organisms within the ecosystem

from +1 to −1, with 0 serving as the baseline (i.e., reference point relative to today's values). Every participant provided their own estimated value for each parameter within this scale and in a second step (stage 2), these ratings were compared and aligned across all scenarios to ensure consistency. Final ratings for each scenario were established through consensus (stage 3), resulting in a unified score for each parameter. This approach is referred to as "semi-quantification" because it combines expert judgment and directional trends with a flexible, unit-free scale. The scale is designed to be adaptable to various bio-economic model structures while still allowing for the assessment of relative changes. The rationale for using this method lies in the nature of the information available: while the scenarios are rich in qualitative insights, they often lack the empirical data required for full numerical quantification. The semi-quantitative scoring method offers a pragmatic middle ground, enabling a structured translation of qualitative scenario content into parameter values that can be used as inputs for numerical modeling. This is particularly appropriate in contexts characterized by high uncertainty, limited data availability, and strong dependence on expert knowledge, as is the case when projecting long-term socio-economic and ecological developments in global fisheries under emerging climate intervention technologies such as OAE. However, the approach also has limitations. Because it relies on expert elicitation, it is subject to potential biases, such as groupthink, anchoring effects, or overconfidence. Moreover, the scores are inherently relative rather than absolute, which means they should not be interpreted as precise forecasts but rather as indicative estimates of the expected direction and magnitude of change. These parameter ratings provide initial quantitative inputs intended for integration into bio-economic models that can accommodate the social, economic, and ecological dimensions of fisheries (e.g., Dao et al., 2023; Failler et al., 2022; Prellezo et al., 2012; Voss et al., 2014, 2022).

Moreover, ratings were specified for three categories: developed economies, economies in transition, and developing economies, with specified quantifications for OAE being either implemented or not. For the classification of countries, we follow the United Nations World Economic Situation and Prospects 2024 (UN, 2024), which distinguishes three major groups based on economic structure and development status. (a) Developed Economies are characterized by advanced technological infrastructure, high per capita income, and established industrial bases. This group includes countries in Northern America (e.g., the United States, Canada), Europe

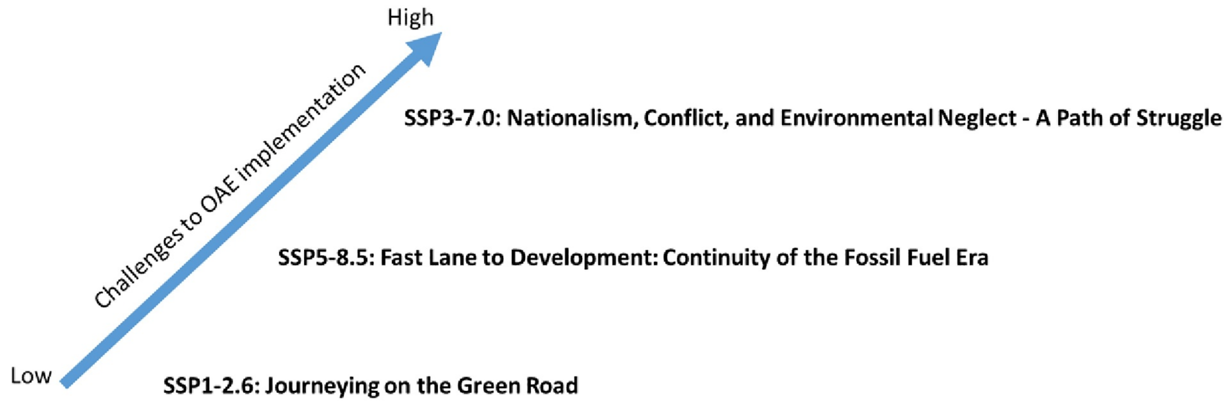

Figure 1. Assumed challenges to implement ocean alkalinity enhancement in the respective Shared Socioeconomic Pathway-Representative Concentration Pathway framework.

(e.g., Germany, France, Sweden, the United Kingdom, Norway, Spain), as well as Israel, Japan, the Republic of Korea, Australia, and New Zealand. (b) Economies in Transition refers to countries shifting from centrally planned to market-oriented economic systems. These are primarily located in Eastern Europe and Central Asia and include members of the Commonwealth of Independent States (CIS). Examples include the Russian Federation, Ukraine, Kazakhstan, and Turkmenistan. (c) Developing Economies comprise countries with lower levels of industrialization and income, and often face structural challenges such as higher poverty rates and limited access to essential services. These are primarily located in Africa (e.g., Nigeria, Kenya, South Africa, Egypt), Asia (India, Indonesia, Vietnam, Philippines), Latin America and the Caribbean (e.g., Brazil, Mexico, Argentina, Peru), and Oceania (e.g., Fiji, Papua New Guinea). This categorization allows us to account for heterogeneity in technological and institutional capacity, especially relevant in the context of fisheries management and OAE.

2.4. Scenario Illustrations

To visually represent the narratives of global fisheries and OAE deployment under different futures, scenario illustrations were employed (Figures 2a–2c). These illustrations depict the three distinct pathways: SSP1-2.6, SSP3-7.0, and SSP5-8.5. Each illustration highlights key differences among the scenarios, emphasizing their respective degrees of socioeconomic development, policy implementation, and climate change, as well as the impact of OAE.

3. Results

3.1. SSP1-2.6: Journeying the Green Road

3.1.1. International and Global Context (Adapted From O'Neill et al. (2017))

The world is shifting toward sustainable development that respects environmental boundaries, driven by increasing evidence and recognition of social, cultural, and economic costs of environmental degradation and inequality. Effective and persistent cooperation and collaboration of various organizations and institutions, the private sector, and civil society are improving management of the global commons. Investments in environmental-friendly technologies and changes in tax structures improve resource efficiency and reduce overall energy and resource use. Renewable energy becomes more attractive and available due to increased investment, financial incentives, improved regulatory efficiency, and changing perceptions. Consumption is oriented toward low material growth and lower resource and energy intensity, but overall demand is higher, due to a higher population and GDP. The international community recognizes the urgency of mitigating climate change and the need to limit global warming to well below 2°C above pre-industrial levels, as outlined in the Paris Agreement. The potential for adopting negative emissions technologies (NETs) like OAE is supported by several key factors: the intentional development of environmentally sustainable technologies, modest energy requirements, and the existence of strong and effective institutions. These robust institutions are characterized by their stability,

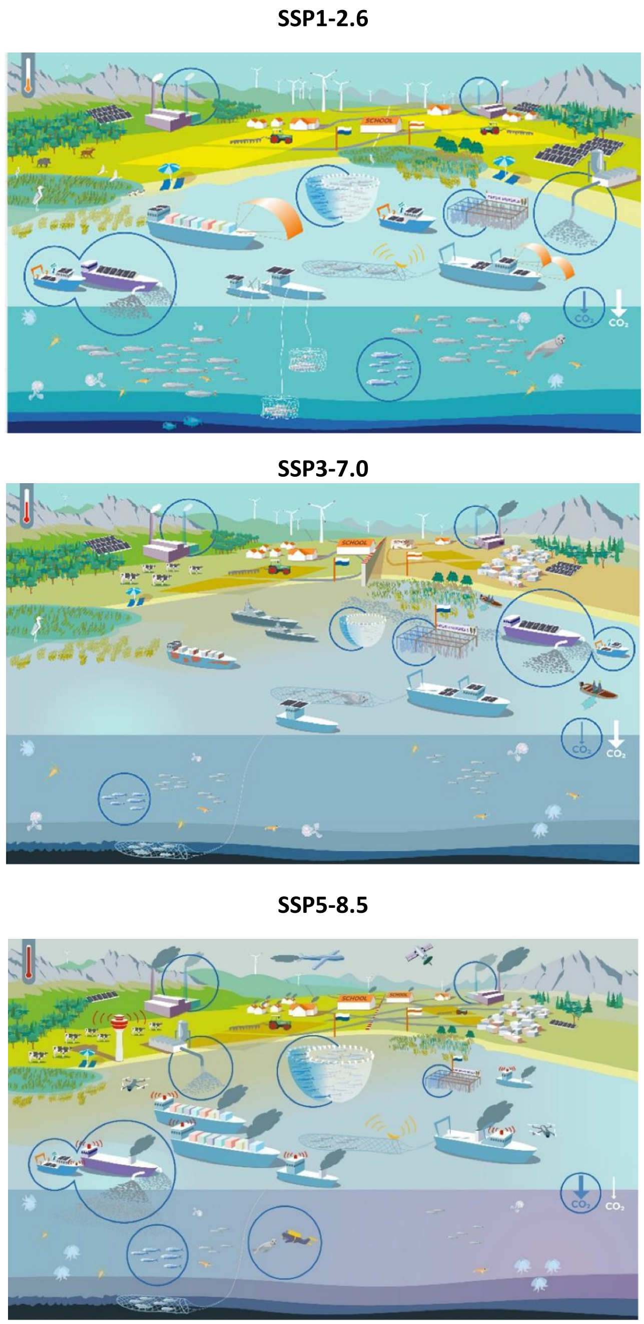

Figure 2. Comparative illustrations of the scenarios: SSP1-2.6, SSP3-7.0, and SSP5-8.5. These graphics visually represent the narratives of each scenario across different futures, emphasizing key differences in socio-economic development, policy implementation, climate change, fisheries, and the impact of OAE. Each illustration depicts two neighboring countries and the adjacent ocean, providing a spatial frame for comparison. The circles within each illustration highlight the differences in outcomes when OAE is implemented. Note: The graphics are designed to encourage active engagement by the reader, with limited textual detail to allow for independent exploration of the scenarios and reflection on how these dynamics unfold under varying socio-economic and climate pathways. Consider the following guiding questions: Do you notice changes in color related to water, atmosphere, or land? How might these relate to temperature or pollution? How do the types and numbers of human activities (e.g., energy use, infrastructure) differ across scenarios and between neighboring countries? Are there observable changes in ecosystem use?.

effectiveness in policy implementation, and ability to adapt and respond to environmental challenges, playing a crucial role in facilitating the adoption of OAE, implying low challenges for its implementation (Figure 1).

3.1.2. Development of Key Bio-Economic Parameters

Technological progress plays a crucial role in shaping the fisheries industry, leading to a more efficient and environmentally friendly approach to fisheries. Nations worldwide embrace the principles of sustainable development, fostering international cooperation and knowledge-sharing. Technological breakthroughs lead to the development of precision fishing methods (advanced sensors, underwater cameras, smart nets), reducing bycatch and minimizing impacts on the environment and non-target species.

Fishing costs encompass substantial upfront investments necessary for the modernization of fishing fleets, the establishment of advanced monitoring systems, and the transition to more selective and sustainable fishing gear. Costs are also influenced by fishers' wages, and thus increase especially for those actively engaged in sustainable fishing practices, as well as better access to training programs that improve their knowledge and skills in sustainable fishing techniques, resource management, and entrepreneurship. However, governments, international organizations, and financial institutions provide support through grants, subsidies, and low-interest loans to facilitate this transition, ensuring that the financial burden is manageable for the fishing industry.

Fisheries management fully integrates an ecosystem-based approach (e.g., ecosystem approach to fisheries) and relies heavily on scientific research and data to inform decision-making. Management bodies significantly enhance the efficiency of their measures by incorporating input and perspectives from a diverse range of stakeholders, including fishers, coastal communities, indigenous peoples, scientists, and conservation organizations. This inclusive approach to decision-making greatly improves compliance with management recommendations and action plans, leading to more effective and sustainable fisheries management.

Marine aquaculture undergoes a notable transformation, embracing sustainable practices driven by technological innovation. Emphasis is placed on cultivating low trophic level fish species and local species, or at least those that do not pose a risk as invasive species if they were to escape from aquaculture facilities. While land-based state-of-the-art recirculating marine aquaculture systems (RAS) that control water quality, minimize waste, and reduce disease outbreaks are commonly used, the industry's growth still slows down. Aquaculture production remains modest and limited due to strict environmental regulations and the development of alternative (other) substitutes.

Other substitutes like algae and other low trophic level species (e.g., mussels, oysters, and scallops) gain recognition and their culture expands, due to their high protein content, nutritional value, and sustainable cultivation methods. Cell-cultured fish offers a sustainable and ethical alternative for fish lovers, and plant-based seafood substitutes are made with ingredients that mimic the texture, taste, and nutritional profile of various fish species.

Carrying capacity is a key consideration in the strong focus on sustainability, which leads to overall reduced pollution and habitat degradation. Continuous conservation and restoration efforts are improving numerous marine ecosystems. However, the carrying capacity of ecosystems along the equator will slightly decrease, even if the progression of climate change is limited.

3.1.3. Potential Ways of OAE Application

Rapid and targeted technological advancements have paved the way for a carefully planned approach to OAE that balances scientific, environmental, socio-economic, and regulatory considerations, with a focus on precision and control. Marine spatial planning ensures the sustainable coexistence of fisheries and OAE through careful zoning and adaptive management. Areas for OAE deployment are strategically selected to avoid critical marine habitats and minimize disruptions to fish migration and larval stages. Real-time monitoring systems allow for flexible adjustments, balancing OAE's role in climate mitigation with the preservation of marine ecosystems and fisheries. This approach helps to avoid undesirable secondary precipitation thresholds, while minimizing any potential negative impacts on marine ecosystems. The deployment strategy focuses mainly on alkaline solutions that are introduced into the water column via chemical reactors. The shifts in the carbon chemistry take place in a chamber and not directly in the seawater, which is gentler on biological organisms. However, a number of other complementary application options (e.g., application of alkaline powder and fine grains via ships or on beaches) are

Table 2
Model Parameters Adjusted Under the SSP1-2.6 Scenario to Semi-Quantitatively Reflect the Broad Socioeconomic Considerations Captured in the Scenario Narrative by 2100 Related to the Business-As-Usual (BAU), as Resulting From the Experts' Group Semi-Quantification

	OAE off			OAE on		
SSP1-2.6	I	E	D	I	E	D
Technological progress	0.6	0.6	0.6	0.8 (↑)	0.8 (↑)	0.8 (↑)
Fishing cost	0.3	0.3	0.3	0.5 (↑)	0.4 (↑)	0.4 (↑)
Fisheries management	0.9	0.9	0.9	1.0 (↑)	1.0 (↑)	1.0 (↑)
Marine aquaculture	0.27	0.3	0.33	0.33 (↑)	0.35 (↑)	0.38 (↑)
Other substitutes	0.3	0.3	0.3	0.32 (↑)	0.32 (↑)	0.32 (↑)
Carrying capacity	0.1	−0.1	−0.1	0.2 (↑)	0.0 (↑)	0.0 (↑)

Note. I: developed economies, E: economies in transition, D: developing economies. No change related to the BAU is reflected by a 0. Upward (↑), downward (↓), and equals (=) symbols are used as redundant visual cues to indicate increases, decreases, or no change in parameter values due to the inclusion of ocean alkalinity enhancement (OAE), relative to their corresponding values without OAE.

used to achieve net zero emission targets. The implementation of OAE starts within the next few years, and efforts are gradually intensified alongside advancements in technology. OAE is being deployed globally, with major hotspots along (a) ship tracks where cargo and container ships are carrying the deployment, (b) regions that are particularly suitable for mineral dissolution, and (c) areas where mining facilities are present, and land-based infrastructure facilitates the deployment. This deployment pattern is increasingly being integrated into national and regional marine spatial planning frameworks, which aim to mediate competing claims to ocean space. Through participatory planning and stakeholder engagement, marine spatial planning helps to align OAE initiatives with existing ocean uses, such as fisheries, shipping, and conservation. This approach is incentivized and made feasible by a combination of factors, including a high carbon price and inclusion in carbon markets, a strong GDP, extensive political cooperation, and effective international governance, all contributing in the same time to the affordability and viability of OAE.

3.1.4. Semi-Quantification of Parameter Values Under OAE

Changes in technological progress are slightly increasing when using OAE (OAE on) as compared to not using OAE (OAE off; see Table 2) as more ocean activity results in more data and a higher degree of technological transfer between nations. Costs typically experience a more pronounced increase under OAE on compared to OAE off, mainly attributable to factors such as deployment and monitoring of OAE infrastructure. This is most pronounced in industrialized countries, as wages increase due to generally higher economic activities (part of the CO_2 emissions are taken up by OAE measures, leading to higher economic activity while assuming the same RCP). Additionally, it might be mandatory, and costly, to participate in OAE activities. Management effectiveness, aquaculture supply, and substitute availability are slightly higher under OAE on, as OAE activities will lead to better and more monitoring as well as benefit fish aquaculture and other substitute production, for example, production of shellfish. The catch-up dynamics result in slightly varied numbers across regions, as developing and emerging countries progressively narrow the gap with developed nations. The active deployment of OAE buffers against ocean acidification, so that the carrying capacity increases in all areas compared to no OAE. The relative increase is assumed to be identical for all regions.

3.2. SSP3-7.0: Nationalism, Conflict, and Environmental Neglect—A Path of Struggle

3.2.1. International and Global Context (Adapted From O'Neill et al. (2017))

In a world dominated by nationalism, regional conflicts, and concerns about competitiveness and security, countries are increasingly turning inward, prioritizing domestic and regional affairs. This trend has led to authoritarian governance in several regions, along with highly regulated economies and reduced investments in education and technology. Countries prioritize energy and food security in their regions, often neglecting broader (global) development goals. As a result, this world is seeing important imposition of trade barriers, particularly in energy, agriculture, and fisheries markets. Slow economic growth exacerbates inequalities, especially in developing countries where resource-intensive consumption patterns persist due to their growing populations, intense industrialization, and increasing urbanization. Global institutions are limited in their effectiveness, causing both fragmented global coordination and cooperation on environmental issues. Environmental concerns are marginalized, resulting in significant degradation of ecosystems in areas with accelerated industrialization, political instability leading to weak governance, high population density straining available resources, and a focus on immediate economic gains rather than long-term sustainability. Despite some isolated progress in the adoption of clean energy sources and sustainable practices (limited to the richest countries), global economic, political, and technological challenges impede more significant emissions reductions. Consequently, global greenhouse gas emissions continue to rise unabated in the absence of comprehensive international agreements and regulatory measures. Fossil fuel consumption remains high. The combination of hampered development, limited environmental focus, and slow technological progress toward environmental mitigation solutions poses considerable challenges for the implementation of NETs like OAE, implying high challenges for its implementation (Figure 1).

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3.2.2. Development of Key Bio-Economic Parameters

Technological progress in the fisheries sector is restrained by limited sustainability efforts. Given the high population growth, intense resource competition, inefficiency of global institutions, and limited environmental regulations, there is a lack of funding and prioritization for technological innovations and solutions that could combat overfishing, improve fishing efficiency, and reduce its environmental impact. In the absence of significant technological advancements and monitoring, less sustainable fishing techniques (e.g., bottom trawling, dynamite fishing, gill-netting) continue to predominate, leading to habitat destruction and bycatch. Technological advances, albeit limited, in the fishing industry are most evident in the wealthiest and industrialized nations. However, these advances are not being transferred to other regions and have yet to bring about transformative changes.

Fishing costs are indirectly affected by intense rivalries between regions, accompanied by regional food security issues and a decline in global cooperation. Fish remains a sought-after source of protein, particularly in populous developing countries. However, the costs associated with fishing vary widely from region to region, reflecting differences in access to cheaper energy in oil-producing nations and industry subsidies. Few countries can afford to subsidize capital-intensive fishing vessels and long-distance fleets, while the majority rely on smaller, less expensive, and poorly regulated vessels for their fisheries. Wages in the fishing industry are generally low due to sluggish economic growth. Trade is largely confined to local and occasionally regional levels, hampered by significant trade barriers that impede global integration. This disruption causes delays in transportation and storage, compromising product freshness and overall quality. The collapse of global value chains leads to the unavailability of once-widespread commercial species outside their extraction regions. Limited resources drive the use of less desirable fishing grounds or methods, impacting catch quality. These challenges exacerbate problems related to food security, as the decrease in product quality and the higher prices contribute to increased difficulties and costs in the disrupted global fishing landscape.

Fisheries management is almost entirely focused on meeting food security needs arising from population growth and conflicts between regional blocs, as well as supporting impoverished fishing communities. Thus, the main emphasis is on short-term goals of maximizing local food supplies and minimizing unemployment. A lack of cooperation within and across organizations is caused by opaque decision-making processes and high levels of corruption. Weak international institutions contribute to inadequate enforcement of policies and managing measures due to their limited capacity. They have also failed to address the lack of cooperation among countries on shared migratory fisheries resources. Compliance is severely hindered by weak economic development, rendering effective monitoring and management of fish stocks and the implementation of conservation measures (protecting endangered species and sensitive marine habitats) difficult.

Marine aquaculture is under increased pressure as an alternative to marine capture fisheries for providing a source of protein. However, due to insufficient investments (limited technological advancements), marine aquaculture practices are facing significant challenges and limitations that have reduced the sector's potential for growth and productivity. The aquaculture markets for fishmeal and fish oil have collapsed due to a shift in demand towards human consumption of small pelagic fish. As a result, the production of non-feed aquaculture has increased. In light of trade barriers, some affluent nations' leading aquaculture producers have taken to "colonizing" the shores of low-income countries, overcoming import challenges, in order to fulfill their demand for large quantities of fish. However, adopting this approach incurs a substantial cost, impacting both economic and ecological aspects that are borne collectively at local level.

Other substitutes have emerged due to the uneven distribution of financial, fisheries, and marine resources, restricted access to markets, and inadequate infrastructure in certain regions, particularly in developing nations and areas with less established economic structures. These factors have led to food security challenges, with limited access to animal proteins contributing to reduced dietary diversity and increased reliance on alternative protein sources. As a result, traditional dietary habits are changing, and substitutes such as insect proteins (crickets, grasshoppers, worms), plant-based proteins (lentils, chickpeas, and beans), and algal proteins are now primarily consumed by the most vulnerable populations in the most affected regions.

Carrying capacity of marine ecosystems is limited by a multitude of interacting factors. The lack of international cooperation and ineffective governance systems have contributed to the rampant issue of overfishing. Additionally, the insufficient measures to address climate change have resulted in ocean acidification and intensified storm events. The severity of climate change impacts varies with latitude, disproportionately affecting lower

Table 3
Model Parameters Adjusted Under the SSP3-7.0 Scenario to Semi-Quantitatively Reflect the Broad Socioeconomic Considerations Captured in the Scenario Narrative by 2100 Related to the Business-As-Usual (BAU), as Resulting From the Experts' Group Semi-Quantification

	OAE off			OAE on		
SSP3-7.0	I	E	D	I	E	D
Technological progress	0.2	0.3	0.1	0.3 (↑)	0.4 (↑)	0.1 (=)
Fishing cost	0.1	0.3	−0.1	0.1 (=)	0.3 (=)	−0.3 (↓)
Fisheries management	−0.1	−0.2	−0.3	−0.1 (=)	−0.2 (=)	−0.3 (=)
Marine aquaculture	0.3	0	−0.1	0.4 (↑)	0.1 (↑)	−0.1 (=)
Other substitutes	0.2	0.2	0	0.3 (↑)	0.3 (↑)	0 (=)
Carrying capacity	0.2	−0.5	−0.5	0.25 (↑)	−0.5 (=)	−0.5 (=)

Note. I: developed economies, E: economies in transition, D: developing economies. No change related to the BAU is reflected by a 0. Upward (↑), downward (↓), and equals (=) symbols are used as redundant visual cues to indicate increases, decreases, or no change in parameter values due to the inclusion of ocean alkalinity enhancement (OAE), relative to their corresponding values without OAE.

latitudes. As a result, ecosystems in developing and emerging countries are unequally impacted. Moreover, the absence of adequate environmental regulations and monitoring systems as well as lax enforcement has led to unregulated coastal development and unchecked industrial and extractive activities. Coastal waters are heavily polluted by industrial waste, untreated sewage, and agricultural runoff, causing severe eutrophication issues.

3.2.3. Potential Ways of OAE Application

The deployment of OAE as a climate mitigation strategy faces numerous challenges and obstacles. Conflicting national interests and political tensions hinder collaboration on climate change mitigation strategies, including OAE. Given limited resources, insufficient research funding, and a lack of global scientific collaboration, significant progress in understanding and developing OAE technologies is being slowed. In most regions, the attention required to implement OAE is overshadowed by urgent socio-economic issues. Moreover, carbon prices are low and reduce the economic incentive to invest in OAE projects. CDR initiatives are not fully incorporated due to the nascent nature of these markets. At low carbon prices, the expenses associated with implementing and maintaining OAE exceed the financial gains obtained by carbon credits or offsets. As a result, OAE is applied on a small and local scale for specific purposes rather than as a global carbon removal strategy. The addition of alkaline powder and fine mineral grains to coastal waters and beaches is the common approach to the cost-effective introduction of OAE. Governments (that are able to afford it) and the private sector have an intrinsic motivation to pay for the local application of OAE to conserve and manage specific economically and culturally valuable ecosystems (e.g., the great barrier reef). In regions where oyster and mussel production are important industries, local companies are interested in paying for OAE to optimize conditions for shellfish growth and therefore profits. Marine spatial planning for fisheries and OAE faces significant challenges in this context, particularly for developing countries and economies with weaker governance structures. With limited global cooperation, weak governance, and a lack of comprehensive regulation, OAE deployments are often uncoordinated and overlap with key fishing zones. This increases competition for marine space, exacerbates tensions, and risks further disruptions to essential ecosystems, such as fish spawning areas, due to unregulated changes in ocean chemistry. Low-income nations or small island developing states (SIDS), where both economic development and environmental conservation are at odds, are especially vulnerable to these conflicts. The absence of inclusive planning mechanisms and lack of recognition for small-scale fishers' spatial claims worsens inequities in access to and control over marine areas.

3.2.4. Semi-Quantification of Parameter Values Under OAE

In a world described by SSP3-7.0, the application of OAE would only have minor effects on fisheries and its driving forces (Table 3). Given the strong regionalization of countries and the application of OAE being limited to local and small scale, spillover effects on the entire marine ecosystem do not occur. Especially developing economies do not progress in terms of technology under OAE as they highly depend on knowledge transfer. In terms of fishing costs, the experts do not expect any changes of the parameter. Although OAE has the potential to indirectly benefit fish populations (e.g., by mitigating ocean acidification, which can enhance the health and biodiversity of habitats such as coral reefs, and by increasing CO_2 absorption, which may contribute to the stabilization of marine ecosystems), its limited geographical application restricts the extent to which these benefits can be fully realized. Overall, in this segmented world, OAE marginally influences the carrying capacity positively in developed economies. The overall capacity of the entire ecosystem, particularly in the open ocean, remains unaffected due to the absence of any nation taking responsibility for action. Likewise, the impact of OAE on fisheries management remains negligible, as the potential enhancements resulting from expanded monitoring initiatives are once more restricted by their limited-scale implementation. The advantage of global monitoring approaches, for example, via earth observation systems, with the help of which a global environmental system can be monitored without administrative borders, no longer applies. The parameters for marine aquaculture and other substitutes modestly increase under OAE in developed economies and economies in transition to maximize the production of food sources such as shellfish, whereas they remain constant in developing economies. Overall, in this segmented world, OAE marginally influences the carrying capacity positively in developed economies. The overall capacity of the entire ecosystem, particularly in the open ocean, remains unaffected due to the absence of any nation taking responsibility for action.

3.3. SSP5-8.5: Fast Lane to Development—Continuity of the Fossil Fuel Era

3.3.1. International and Global Context (Adapted From O'Neill et al. (2017))

The advancement of competitive markets and the encouragement of innovation drive rapid technological progress and foster the integration of global markets. Emphasis is placed on maintaining competition and removing institutional barriers to the participation of disadvantaged populations in global markets. Economic and social development predominantly relies on the utilization of fossil fuel resources and the adoption of resource- and energy-intensive lifestyles. Additional investments in areas such as health, education, and institutions reduce inequalities within and among nations. International mobility increases as income disparity decreases. Recognition of benefits of promoting comprehensive global development have made technology transfer prevalent. The world relies on geo-engineering and technological solutions to address local environmental impacts, but is less concerned about potential global environmental impacts because of a perceived trade-off with highly prioritized economic progress. Greenhouse gas emissions continue to increase rapidly throughout the 21st century, resulting in high atmospheric concentrations. On the one hand, the world's strong reliance on fossil fuels and the high technological standard present significant incentives for efforts in implementing NETs. On the other hand, the lack of global environmental concern is a non-negligible barrier to the implementation of NETs, implying medium challenges to the implementation of NETs like OAE (Figure 1).

3.3.2. Development of Key Bio-Economic Parameters

Technological progress in fisheries tends to prioritize boosting productivity and efficiency over sustainability and conservation. This focus stems from a world marked by rapid economic growth, reliance on fossil fuels, and environmental issues that are often viewed as localized rather than global. Robotic and automation technologies are being used in various aspects of fisheries, such as automated fishing vessels and on-board fish processing and packaging. Advanced remote sensing technologies, including satellite-based monitoring and aerial drones, now provide comprehensive real-time information on oceanographic conditions, fish distribution and migration patterns. Coupled with data analytics and machine learning algorithms, fishing effort is being optimized and leads to the identification of previously unexploited resources and new fishing grounds (e.g., mesopelagic zone).

Fishing costs with a continued reliance on fossil fuels, the costs of fuel for fishing vessels are rising in proportion to the global energy demand and associated fuel prices given bounded supply. As economic growth and industrialization progress, labor costs also increase, especially in transitioning and developing economies. Technological advances have made fishing more efficient and reduced their cost. However, additional costs such as the purchase and maintenance of new fishing gear and vessels and new demand for skilled labor (captains, engineers, and technicians) for technologically advanced fishing operations outweigh the financial benefits of technological development.

Fisheries management is primarily focused on meeting market demand and fulfilling immediate priorities, often at the expense of conserving non-traded resources and unpriced ecosystem services. Compliance with fisheries regulations is generally good due to low levels of corruption, strong rule of law, and technological advances that enable effective monitoring and management measures. Economic efficiency is a key objective for fisheries, and the concept of Maximum Economic Yield (MEY) is widely embraced as a management goal.

Marine aquaculture practices have seen notable advancements due to the rapid pace of technological progress. These advancements encompass various aspects such as feed formulations, water quality management, disease prevention, and selective breeding. In turn, this results in highly efficient production systems, increased profitability and economic growth in the marine aquaculture sector. To capitalize on these developments, large-scale marine aquaculture facilities are established, with technology and automation playing a vital role in their operation. The cultivation of high-demand species like tuna and salmon takes place on a large scale in open ocean areas, maximizing the utilization of available space. Moreover, deep-sea aquaculture ventures target the cultivation of unique species adapted to extreme depths, taking advantage of advances in pressure-resistant enclosures and feeding technologies. The remainder of production focuses on premium/high-end fish and specialty products to serve niche markets and luxury segments, further driving industry growth. The expansion of marine aquaculture is also driven by open markets and global trade of aquaculture products.

Other substitutes industrial agriculture and intensive livestock farming continue to play an important role in food production. The global food system is heavily relying on land-based animal-based protein sources such as meat, poultry, and dairy products. The production and consumption of these animal-based proteins is widespread, being prevalent in industrialized countries and is being adopted in emerging and developing countries too, thus continuing to dominate the dietary landscape. The development and adoption of alternative protein sources, including plant-based proteins, cultured meats, and insect-based proteins, are minimal and have not gained significant traction.

Carrying capacity strong climate change has disrupted marine ecosystems through ocean warming and acidification, leading to shifts in species distribution and abundance, coral bleaching, and overall biodiversity loss. In addition, coastal ecosystems are being damaged and ecological processes disrupted by the increasing frequency and intensity of extreme events. This results in an overall decline in the productivity of marine ecosystems. Many tropical and subtropical species have shifted their distribution range to higher latitudes, seeking more suitable conditions. In high latitudes, there is a slight increase in carrying capacity, while it decreases in low latitudes.

3.3.3. Potential Ways of OAE Application

The relentless burning of fossil fuels has continued unabated, resulting in skyrocketing greenhouse gas emissions and a rapid rise in global temperatures. Ocean acidification is of local and/or regional concern and a testimony of the adverse effect of the resource- and energy-intensive lifestyle around the world. The society relies heavily on the use of CDR methods to avoid having to compromise on the prevailing lifestyle. Case-specific OAE initiatives are implemented in an effort to mitigate ocean acidification effects. Technological progress has been a major driver of development and economic growth, and the world is taking advantage of it to support and accelerate the rate of development and deployment of OAE. Researchers and private companies are rapidly developing various OAE techniques. All conceivable strategies (CO_2 equilibrated and non-equilibrated approach) are used to implement OAE in order to store as many emissions as possible in the ocean. International collaboration and knowledge sharing are prioritized to develop and deploy OAE technologies. However, limited testing and valuation of the potential environmental impacts are conducted due to time constraints and a rush to employ the technologies. Yet, deployment is not occurring on a broad scale but strategically in areas where it is economically advantageous. Nevertheless, marine spatial planning is increasingly shaped by industrial and technological interests, with OAE zones expanding into areas traditionally used by fisheries, many of which lack the capacity to adapt to overlapping industrial ocean uses. This often leads to spatial displacements and growing competition for marine space, tipping the balance in favor of high-tech interventions at the expense of ecosystems and vulnerable fishing communities. The current planning framework tends to prioritize techno-optimistic scenarios over ecosystem resilience and precautionary management. The emphasis is on small-scale operations in specifically selected regions that allow for continuous monitoring and adaptive management. However, the absence of clearly defined spatial buffers or exclusion zones for critical habitats and fishery-dependent areas amplifies the risk of unintended consequences.

3.3.4. Semi-Quantification of Parameter Values Under OAE

In the scenario SSP5-8.5 (Table 4), few changes are expected for the bio-economic parameters if OAE is applied. The parameters - technological progress, fishing costs and fisheries management stay constant under the implementation of OAE. Higher growth is expected in developing economies and economies in transition. The strong reliance on fossil fuels leads to thriving technological progress. While developed economies already have a high degree of technology in the fisheries sector, countries with weaker economies are catching up. The projected progress in fisheries management can be attributed to the presence of improved institutions, although their primary focus is on food security rather than environmental concerns. Rising population and a preference for an animal-based diet leads to an increase of marine aquaculture supplies (OAE off). This effect is even higher under OAE as it favors aquaculture productivity. At the same time, no change is expected for other substitutes between the scenarios with and without OAE. Generally, we observe more severe impacts in developing and transitioning economies, highlighting the unequal and disproportionate effects of climate change on them. Even though climate

Table 4
Model Parameters Adjusted Under the SSP5-8.5 Scenario to Semi-Quantitatively Reflect the Broad Socioeconomic Considerations Captured in the Scenario Narrative by 2100 Related to the Business-As-Usual (BAU), as Resulting From the Experts' Group Semi-Quantification

	OAE off			OAE on		
SSP5-8.5	I	E	D	I	E	D
Technological progress	0.4	0.6	1	0.4 (=)	0.6 (=)	1 (=)
Fishing cost	0	0.5	0.5	0 (=)	0.5 (=)	0.5 (=)
Fisheries management	0	0.6	0.6	0 (=)	0.6 (=)	0.6 (=)
Marine aquaculture	0.5	0.5	0.5	0.7 (↑)	0.7 (↑)	0.7 (↑)
Other substitutes	−0.1	−0.6	−0.6	−0.1 (=)	−0.6 (=)	−0.36 (↑)
Carrying capacity	0.3	−0.5	−0.5	0.4 (↑)	−0.3 (↑)	−0.3 (↑)

Note. I: developed economies, E: economies in transition, D: developing economies. No change related to the BAU is reflected by a 0. Upward (↑), downward (↓), and equals (=) symbols are used as redundant visual cues to indicate increases, decreases, or no change in parameter values due to the inclusion of ocean alkalinity enhancement (OAE), relative to their corresponding values without OAE.

change is dominating (e.g., fish migrate toward the poles), OAE has the power to positively influence the carrying capacity by reducing ocean acidification and thus increasing larval survival (i.e., positively affecting fisheries recruitment processes).

4. Discussion

This work presents an approach that aligns explorative futures of global fisheries and OAE with the SSP-RCP framework, a key tool in climate change research and policy analysis (O'Neill et al., 2020). By developing contrasting scenario narratives at both global and sectoral levels, we explore how the interplay of different socio-economic conditions (SSPs) and varying levels of climate change (RCPs) might shape fisheries and OAE worldwide. Integrating these interactions into an established scenario framework ensures methodological rigor, internal consistency, and cross-study comparability, thus supporting the systematic exploration of plausible futures and advancing ongoing research efforts in climate impact assessments. By decoupling socioeconomic and climate forcing dimensions, our approach captures the complexity of OAE and fisheries interactions with different governance structures, economic conditions, and policy priorities.

However, while the SSP-RCP framework has proven valuable in scenario-based climate research, it also has notable limitations, particularly concerning marine biodiversity. The sixth Assessment Report of the IPCC (WGII Ch18) highlights that none of the SSP scenarios fully align with the Sustainable Development Goals (SDGs), particularly SDG 14, which aims to conserve and sustainably use the oceans, seas, and marine resources. This misalignment suggests that the framework, originally designed to address climate change mitigation and adaptation, does not sufficiently account for the scale of transformation needed to meet biodiversity targets. Recent studies (Roberts et al., 2024; IPBES reports) emphasize the need for more comprehensive and integrated approaches that explicitly incorporate biodiversity preservation alongside climate objectives.

In light of these limitations, our scenario approach aims to contribute to addressing this gap by expanding the SSP-RCP framework with tailored and sectoral narratives focused on fisheries and OAE. Fisheries exert significant pressures on marine ecosystems, while OAE has the potential to mitigate climate change impacts on the marine environment. Both are and will be shaped by complex socio-economic, policy-driven, and climatic dynamics, yet they have remained underrepresented in SSP-RCP scenario development. By integrating and extending the framework to include these specific sectoral dynamics, we highlight key societal factors that influence and are influenced by these activities, ensuring that biodiversity-related transformations are more explicitly accounted for within the framework. While our study does not fully resolve the SSP-RCP framework's limitations regarding marine biodiversity, it takes a significant step toward addressing this gap. By integrating fisheries and OAE into already established (SSP-RCP) scenario-based analyses, we contribute to a broader understanding of how these sectors interact with socio-economic and climate dynamics, while also ensuring that these interactions are framed within a systematic and internationally recognized framework that facilitates cross-study comparability and global policy discussions. Our scenarios are thus aligned with those employed in model-based scenario studies by the IPCC and the IPBES, offering a common foundation for advancing future research and policy analysis.

Moreover, the interplay between OAE and fisheries is particularly significant because fisheries are not only a vital source of food and livelihoods, but they are also deeply intertwined with ocean chemistry and ecosystem health. Large-scale OAE deployment could influence fish stocks through various pathways, including changes in ocean carbonate chemistry, primary production, and habitat conditions, all of which could have cascading effects on fisheries yields and economic stability. Additionally, the governance, monitoring, and technological advancements needed for responsible OAE implementation align closely with those required for sustainable fisheries management. For instance, improvements in ocean monitoring technologies and data-sharing frameworks for OAE could directly benefit fisheries by enhancing stock assessments, early warning systems, and adaptive management strategies. Ignoring this interplay would mean missing crucial opportunities to leverage synergies between climate mitigation, ocean resource sustainability, and biodiversity conservation.

Our scenarios are developed based on the best current knowledge and assumptions regarding the feasibility and efficacy of OAE. While our approach takes an optimistic view of the potential benefits and feasibility of OAE, it is crucial to acknowledge that uncertainties remain regarding its effectiveness and practicality (Keller et al., 2014; Nawaz et al., 2023; Renforth & Henderson, 2017). Key uncertainties include the ability of increased ocean alkalinity to effectively enhance CO_2 absorption for global warming mitigation while ensuring minimal long-term environmental impacts and stable chemical processes. Significant challenges such as technological readiness for large-scale dispersal of alkaline substances, logistical hurdles, and potential negative environmental consequences require further investigation and resolution. The implications of these uncertainties are particularly relevant for fisheries, as shifts in carbonate chemistry and the introduction of nutrients from OAE could affect fish and their supporting food webs (Goldenberg et al., 2024a). Fish physiology is highly sensitive to changes in bicarbonate, CO_2, and H^+ concentrations, all of which are influenced by OAE (Perry & Gilmour, 2006). Altered seawater chemistry may impose additional energetic demands for maintaining homeostasis, potentially diverting resources from growth and reproduction or exceeding critical thresholds that could impact population viability. Negative environmental impacts of OAE are likely to affect ecosystem functioning, biodiversity and ecosystem services, which would be at odds with the Convention on Biological Diversity (CBD). Further, one of the targets of the CBD addresses the need to effectively conserve and manage, by 2030, at least 30% of terrestrial, inland water, coastal and marine areas, in particular areas of high importance for biodiversity and ecosystem functions and services. Currently, only about 8% of national waters are protected. As more areas are protected, fewer economic activities will be allowed, potentially limiting the scope for fisheries and OAE. This scope may be further reduced by the new United Nations Convention on the Protection of Biodiversity on the High Seas. Moreover, uncertainties surround public acceptance, regulatory frameworks, and cost-effectiveness relative to other climate mitigation strategies. Our scenarios are not designed to definitively answer these questions but rather to be embedded within a structured, coherent framework that incorporates varying assumptions about technological, environmental, socio-economic, and political conditions, thereby offering complementary insights. In light of these issues, our scenarios are not intended to predict definitive outcomes, but to explore plausible trajectories within a structured framework that integrates a range of assumptions about technological, ecological, socio-economic, and political conditions. In line with Tank et al. (2025), we emphasize the importance of distinguishing between the desirability and feasibility of the futures we explore and encourage future research to integrate feasibility analyses to complement and refine the insights presented here.

Building on this foundation, the scenarios we presented highlight distinct pathways, ranging from sustainable transitions (SSP1-2.6) to fragmented development (SSP3-7.0) and high fossil fuel dependency (SSP5-8.5), each posing unique challenges and opportunities for fisheries and OAE. Since the RCPs are held constant within each scenario, independent of whether OAE is applied, the application of OAE is associated with higher emissions and, therefore, presumably higher growth. Alternatively, one could keep output constant and reduce greenhouse gas concentrations via OAE. While this may be the more likely case, we chose to keep the concentration constant for simplicity and better comparability.

4.1. Key Findings From Scenario Narratives

Our scenario narratives underscore that the SSP1-2.6 pathway, characterized by a transition toward renewable energy and sustainable practices, presents the most conducive conditions for responsible fishing practices and the deployment of OAE. This pathway's emphasis on sustainability, international cooperation, and technological innovation facilitates the widespread adoption of OAE, thereby maximizing its potential benefits. The synergistic effects of OAE in reducing atmospheric CO_2 levels and mitigating ocean acidification could enhance fish stocks and marine biodiversity, aligning with broader sustainability objectives. Improved fish stocks and marine health would not only benefit global fisheries but also contribute to long-term sustainability and economic stability for fishing-dependent communities. However, challenges associated with this scenario include substantial financial investments required for OAE technology development and deployment, as well as the necessity for robust international regulatory frameworks to govern its implementation. Additionally, achieving the required level of international cooperation and technological innovation necessitates overcoming political and economic barriers, ensuring equitable access to resources, and addressing potential environmental risks linked to large-scale OAE projects. A prominent example for the effectiveness of technological innovation is global Earth Observation technology. Since the 1970s, the changing global political climate has made satellite-based Earth observation a cornerstone of serious collaboration and international cooperation. However, nationalistic trends and nations have always been, and will remain, a central challenge to any international monitoring system that may limit national sovereignty for the purposes of global governance and the pursuit of mutual gains among states (Copelovitch & Pevehouse, 2019).

In contrast, the SSP3-7.0 scenario, reflecting a fragmented world with significant challenges in mitigation and adaptation, poses obstacles for fisheries and large-scale OAE deployment. Limited international cooperation and uneven economic development could hinder widespread implementation of OAE, limiting its potential benefits. Regions with strong governance and supportive policies might successfully execute localized OAE initiatives, providing crucial refuges for marine ecosystems. However, the global effectiveness of OAE under this scenario would be considerably diminished, underscoring the critical need for international collaboration and equitable economic development to support large-scale geoengineering projects. For fisheries, this fragmented approach may exacerbate existing inequalities, with varying impacts on fish stocks and marine biodiversity across different regions. Moreover, regional self-sufficiency and limited resource sharing could lead to competition and conflicts over marine resources, complicating efforts to achieve sustainable fisheries and OAE deployment. Uneven adoption of OAE technologies might also result in inconsistent regulatory standards and environmental oversight, increasing the risk of unintended ecological consequences. Furthermore, disparities in technology, technological access and economic capacity among regions could widen the gap between developed and developing nations, undermining global sustainability and exacerbating socio-economic inequalities.

The SSP5-8.5 scenario, characterized by rapid economic growth and high dependency on fossil fuels, presents both significant challenges and opportunities for OAE. While technological advancements could facilitate large-scale deployment of OAE, continued high CO_2 emissions may outweigh the benefits of acidification mitigation. This scenario underscores the urgent need for substantial technological breakthroughs and aggressive implementation strategies to offset high emissions. For fisheries, this situation implies that despite potential advancements in OAE technologies to enhance marine environments and fish stocks, persistent high emissions could undermine these benefits, perpetuating stress on marine ecosystems and fisheries. Moreover, the scenario highlights a dilemma where technological capabilities for OAE may exist but are potentially hindered by policies and economic frameworks favoring continued high emissions, thereby reducing economic incentives for sustainable practices. The reliance on fossil fuels in the SSP5-8.5 scenario complicates the development of sustainable economic models, making it challenging to effectively fund and prioritize OAE projects. Rapid economic growth might lead to environmental trade-offs, prioritizing short-term economic gains over long-term ecological health. Additionally, disparities in technological advancements could create inequities in the ability to deploy and benefit from OAE, potentially widening the gap between affluent and less affluent regions. This dualistic nature emphasizes the critical need to integrate technological innovation with comprehensive policy shifts toward sustainability, ensuring that the benefits of OAE are fully realized and equitably distributed.

4.2. Future Research Directions

The next step for the scenarios developed in this study is their integration into computational models and simulations. Such modeling is essential for deepening our understanding of the dynamic interactions among socio-economic drivers, climate change, fisheries, and OAE. Embedding these scenarios into quantitative frameworks advances the exploration of plausible futures under varying socio-economic and climatic conditions, offering quantitative insights into the sustainability and resilience of global fisheries and ocean health. Simulations also provide a valuable means to evaluate the effectiveness of policy interventions, technological innovations, and regulatory strategies within a structured, data-driven environment. Our semi-quantitative scenario design serves as an initial step toward transitioning from qualitative narratives to practical tools for evidence-based decision-making. The quantitative elements were intentionally kept general to allow compatibility with a range of bio-economic models (Failler et al., 2022; Maury et al., 2025; Voss et al., 2014, 2022), thereby supporting flexible application across diverse modeling contexts. Looking ahead, the bio-economic projections generated through our framework should be incorporated into broader Integrated Assessment Models (IAMs). Such integration would enable the assessment of systemic trade-offs among climate mitigation strategies and their socio-economic consequences. Positioning fisheries and OAE within IAMs enhances their relevance in global sustainability discourse, contributing to a more comprehensive understanding of their roles within coupled human-Earth systems. As these models become increasingly sophisticated, they can offer more precise and policy-relevant insights to guide governance and management strategies for marine ecosystems and the fisheries sector at both global and regional levels. To support this integration, critical data gaps must be addressed, including empirical evidence on the ecological effects of large-scale OAE deployments, spatially explicit data on fish stock dynamics under altered ocean chemistry, and socio-economic indicators capturing the vulnerability and adaptive capacity of fishing communities. Filling these gaps will improve the realism and robustness of IAMs that include fisheries and OAE.

However, while our global scenarios provide valuable insights, there is also a growing need to adapt them to more localized contexts. A regionalized approach is necessary to capture the diverse conditions under which OAE and fisheries interact at a finer scale. Although our global scenarios offer a broad framework for understanding potential impacts, the distinct socio-economic, political, and environmental conditions in different regions or countries can significantly influence the outcomes of OAE implementation. For instance, small-scale fisheries in regions such as West Africa and Southeast Asia may face greater economic instability and weaker governance, which could exacerbate the challenges associated with OAE. Conversely, industrialized regions like the North Atlantic and Japan, with more robust regulatory frameworks, may experience a more controlled and balanced implementation of OAE. Incorporating such regional dynamics into the scenario development process will ensure that OAE strategies are tailored to local conditions, improving the relevance and applicability of the findings. This approach will also provide more actionable insights for policymakers and stakeholders working at regional or country-specific levels, ultimately enhancing decision-making and the design of context-sensitive, effective OAE strategies.

Lastly, our scenario narratives and graphical illustrations can serve as communication tools to facilitate stakeholder engagement by providing visual and qualitative representations of potential future outcomes. This enhances communication and collaboration among scientists, policymakers, industry leaders, and local communities, fostering a shared understanding of the challenges and opportunities associated with different socio-economic and environmental pathways. While stakeholder groups usually have different understandings of "sustainability," scenarios can help in facilitating understanding and consideration of other groups' needs despite differing views on sustainability (Schaber et al., 2022). The narratives create relatable and compelling stories and illustrations that capture the complexity of future scenarios in a way that purely quantitative data cannot. By weaving together scientific insights with human experiences, these narratives help stakeholders envision the real-world implications of different societal and climate trends with policy and management choices. Engaging stakeholders through both qualitative narratives, illustrations and quantitative simulations not only aids in illustrating the possible trajectories of marine ecosystems under various socio-economic conditions, but also in emphasizing the interconnectedness of human and environmental well-being. Future research should focus on developing regional scenarios based on global trends, ensuring they are grounded in the realities and priorities of local stakeholders. This will provide a platform for evaluating the potential implications of various socio-economic and environmental pathways in specific regions. It will also be crucial for assessing the feasibility of strategies such as OAE within regional contexts. Ongoing consultations will be necessary to refine and adapt these scenarios, addressing the unique challenges and opportunities of each region.

5. Conclusion

In this study, we developed scenario narratives for global fisheries and OAE based on the SSP-RCP framework (SSP1-2.6, SSP3-7.0, and SSP5-8.5). These scenarios provide key assumptions and rationale for quantifying bio-economic parameters that describe plausible future evolution of OAE and global fisheries. While this study focuses on developing these narratives and quantifying the parameters, the next step will involve integrating them into bio-economic models to generate projections of fisheries outcomes under each scenario. These projections should subsequently be incorporated into Integrated Assessment Models (IAMs), such as those employed by the IPCC and IPBES, to assess the broader socio-economic and environmental implications of OAE in the context of global climate mitigation and sustainability efforts. By integrating bio-economic projections into IAMs, we aim to explore the complex trade-offs between environmental, economic, and social factors, which will help inform policies aimed at balancing ocean health, fisheries, and food security.

Data Availability Statement

This study did not use or generate new data or code. The scenarios were derived from the Shared Socioeconomic Pathways (SSPs), a widely adopted framework in climate research designed to support integrated analysis of future climate impacts, vulnerabilities, adaptation, and mitigation. Detailed information on the SSP framework and scenario development process can be found in Moss et al. (2010), Van Vuuren et al. (2014), O'Neill et al. (2014), and Kriegler et al. (2014). The SSP framework organizes scenarios along a matrix of climate forcing levels, represented by RCPs (Van Vuuren et al., 2011), and socioeconomic conditions. The SSP database is maintained by the IIASA Energy Program and is accessible at https://tntcat.iiasa.ac.at/SspDb.

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