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Mathematical Bio-Economics 2.0 for Sustainable Fisheries

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ABSTRACT

Reconciling food security, economic development, and biodiversity conservation in the face of global changes is a major challenge. The sustainable uses of marine biodiversity in the context of climate change, invasive species, water pollution, and demographic growth is an example of this bio-economic challenge. There is a need for quantitative methods, models, scenarios, and indicators to support policies addressing this issue. Although bio-economic models for marine resources date back to the 1950s and are still used in fisheries management and policy design, they need major improvements, extensions, and breakthroughs. This paper proposes to design a Mathematical Bio-Economics 2.0 (MBE2) for Sustainable Fisheries to advance the development of bio-economic models and scenarios for the management of fisheries and marine ecosystems confronted with unprecedented global change. These models and scenarios should make both ecological and socioeconomic sense while being well-posed mathematically and numerically. To achieve this, we propose to base the MBE2 framework for Sustainable Fisheries on four research axes regarding the mathematics and modeling of: (i) ecosystem-based fisheries management; (ii) criteria of sustainability; (iii) criteria of resilience; and (iv) governance and strategic interactions. The associated methodology of MBE2 draws mainly on dynamic systems theory, optimal and viable controls of systems, game theory, and stochastic approaches. Our analysis, which is based on these four axes, allows us to identify the main methodological gaps to fill compared to current models for fisheries management.

1 | Introduction

Balancing biodiversity conservation with food security and the preservation of a broader set of ecosystem services (ESs), in a context of ecological transition and climate change, is one of the greatest challenges of the century. The creation and development of the IPBES (International Platform for Biodiversity and Ecosystem Services) at the interface of decision-support and scientific knowledge is in direct line with these concerns. Implementing this bio-economic perspective is particularly

Summary

- Mathematical bio-economic models and scenarios are needed for fisheries sustainability and policies.
- Applied bio-economic models (e.g. MSY) dating back to the 1950s need major updates and extensions.
- New challenges relate to ecosystem dynamics, sustainability-resilience criteria, and governance issues.
- Complex systems, viable and stochastic controls, and dynamic games are key methodological frameworks to integrate.

important and challenging in the case of fisheries and marine ecosystems (Rice and Garcia 2011). Marine fisheries indeed employ 120 million people directly and indirectly around the world, and account for nearly 500 million people who depend on them for their livelihood (FAO and Duke University & WorldFish 2023; Basurto et al. 2025). Moreover, fisheries and marine ecosystems are experiencing accelerating changes affecting species, communities, and trophic webs, sometimes with alarming trends (Pauly et al. 2002; Österblom et al. 2016). An important part of these changes is due to past and current unsustainable fishing pressures and practices, raising key questions in terms of food security, in particular for developing countries in the tropics facing high human population growth and a growing middle-class demand for seafood (Srinivasan et al. 2010; Cojocaru et al. 2022). Climate change exacerbates the issues and inequities between countries by inducing new, or intensifying, risks and vulnerabilities (Cury et al. 2008; Sumaila et al. 2011; Fromentin et al. 2022; IPCC 2023) through, for example, changes in primary production and fish distribution, thus potentially affecting yields.

Ensuring the long-term sustainability of marine fisheries while preserving the marine biodiversity and ecosystems functioning that support them has become a major issue for national and international agencies (UNSDG; IPBES). Consequently, the agencies and other management institutions require quantitative methods, models, scenarios, and indicators to support policies addressing jointly food security, socioeconomic development, and conservation of biodiversity and ESs. Fortunately, with respect to marine fisheries, we are not starting from scratch. Mathematical models applied to fisheries and their sustainability have been used for many decades, building, in particular, on the seminal works of Gordon (1954) and Schaefer (1954), combining equilibrium and static optimality approaches. These key initial bio-economic contributions have been extended and generalized by (Smith 1969; Clark and Munro 1975; Clark 1990) and many others using the more dynamic frameworks of optimal control and capital theory. Some of the proposed quantitative and modeling concepts, such as Maximum Sustainable Yield (MSY) or Maximum Economic Yield (MEY), are still widely used worldwide to support management, public policy design, and development for fisheries (Sumaila et al. 2019, Thébaud et al. 2023). In that regard, important successes have been obtained applying MSY or MEY, including recovering stocks in Europe (Froese et al. 2018), Australia (Dichmont et al. 2009), Canada (Teh and Sumaila 2013), and at the global scale (World Bank 2017). Advocating the role of bioeconomic mathematical models in such successes should not overshadow the role and relevance of other tools for fisheries sustainability, such as community-based management (Kar 2021) or primary management (Cochrane et al. 2011).

Despite the successes of these key bio-economic models, major improvements, extensions, or breakthroughs are required in the face of the global marine biodiversity erosion, the stagnation of capture fishery landings, and the growing global demand for seafood (FAO 2020). New bio-economic models and mathematics are needed to assist in sustainably balancing food security, economic development of fisheries, and marine biodiversity conservation in the context of global changes. In particular, these new bio-economic models and mathematics need to explore broader conceptualizations of sustainability, more comprehensive ecosystem dynamics, and more participative and adaptive governance. We argue here that such scientific progress calls for new contributions and involvements of Mathematicians and Modelers (DeLara and Doyen 2008; Doyen 2018; Doyen et al. 2019). Thus, we advocate a new 'Mathematical Bio-economics for Sustainable Fisheries' to advance the development of models and scenarios for the management of fisheries and marine ecosystems. In particular, these models and scenarios should take into account the complexity of these systems, including their ecological and socioeconomic dimensions, while being well-posed mathematically and numerically. To achieve this, we propose to split the 'Mathematical Bio-economics 2.0 (MBE2) for Fisheries' into four main research challenges and axes, which are the mathematics and modeling of:

i. Ecosystem-based fisheries management and scenarios;

ii. Criteria of sustainability and conservation in fisheries;

iii. Criteria of resilience in fisheries;

iv. Governance, instruments, and strategic interactions for fisheries.

More specifically, challenge (i) refers mostly to the ecological complexity brought about by moving from single-species models exemplified by MSY or MEY toward multi-species and trophic web approaches. In that sense, bio-economics 2.0 now means 'biodiversity economics' rather than 'biological economics'. Challenge (ii) relates to both intergenerational equity and the multi-criteria perspectives underlying the definition of fisheries sustainability. Challenge (iii) essentially accounts for the numerous uncertainties underpinning the bio-economic dynamics for fisheries, including climate change. Challenge (iv) stresses the decisional complexity involved in fisheries management, in particular with regard to the governance of natural resources used in common.

These four axes and challenges aim at bridging the gap between theory and management practice for fisheries in line with Kvamsdal et al. (2016). In particular, these four axes will take advantage of key strengths of mathematical models. A first role of mathematical models regards the understanding of systems, since mathematics, in particular, mechanistic models, simplify the processes at play by describing them using equations. In other words, a model helps to explain a system, to disentangle its different components and to study the effects of these different components. This is crucial for challenge (i). A second role of mathematics is to contribute to calibrating and validating models with data. Said differently, mathematical models are useful to help confront our (conceptual) understanding of fisheries systems with observations of these systems' properties. What is meant here is that the mathematics and methods underlying statistics, machine learning, or econometrics play a pivotal role in rigorously fitting the data to models to understand system properties (Smith 2008; Cojocaru et al. 2022). This is also important for challenge (i). A third important role of mathematical models regards the evaluation of marine social-ecological systems, as mathematics is also well suited to synthesizing, summarizing, or highlighting key information on the system's performance. Such bio-economic indicators and criteria are necessary for relevant empirical analysis of fisheries data and challenges (ii)–(iii). Moreover, mathematical models are useful for interdisciplinarity. This is crucial for bio-economics and, in particular, for fisheries where there is a need to articulate the dynamics of ecological and socioeconomic systems and to manage their interactions, especially in a context of global change (Thébaud et al. 2023). This interdisciplinarity is pivotal for challenge (ii) and (iv). Bio-economics has been interdisciplinary since day 1, with models that depict the fish stock (the natural system) together with the fishing activity (the human system) (Gordon 1954; Schaefer 1954). Mathematical models and research challenges (ii), (iii), and (iv) are also useful for producing insights and results in support of decision-making and management. Once calibrated or estimated, bio-economic models can indeed be used to conduct ex post policy evaluation, i.e. to evaluate the causal effects of a policy that was put in place (Ferraro et al. 2019) or the gaps between observed outcomes of such a policy and those theoretically expected. Calibrated bio-economic models can also be used to conduct ex ante policy evaluation by projecting the effects of a policy intervention and incentives through scenarios (Ferrier et al. 2016). At this stage, it is worthwhile to distinguish between predictive, exploratory, and normative scenarios[1] as in Figure 1 (Ferrier et al. 2016; Maury et al. 2017; Doyen 2018). Implicit in developing predictive, normative, and exploratory scenarios is a parameterization of causal mechanisms (Smith et al. 2017; Ferraro et al. 2019; Li and Smith 2021).

Relying on these numerous strengths and the ubiquity of mathematics, the rest of our paper details the motivations, goals, as well as the methodological content of our four research axes (i)–(iv). We also synthesize the merits and shortcomings of the different classes of current models for fisheries, along with the key gaps to fill for achieving a successful MBE2 for sustainable fisheries. Our analysis paves the road for a general mathematical model integrating all the bioeconomic challenges in one. Although this perspective paper does not explicitly provide such a general mathematical bioeconomic model for sustainable fisheries, many generic and transverse mathematical contents underlying the MBE2 Program are portrayed in DeLara and Doyen (2008), Doyen et al. (2013), Doyen et al. (2019) and, Doyen (2018). A glossary is also displayed in the appendix to clarify, concisely, some technical terms.

2 | Mathematics of the Ecosystem-Based Management Approach

This section outlines the ecological complexity to consider in an MBE2 Program for Sustainable Fisheries. Many scientists and stakeholders indeed argue that the current shortcomings of public policies for the management of biodiversity and

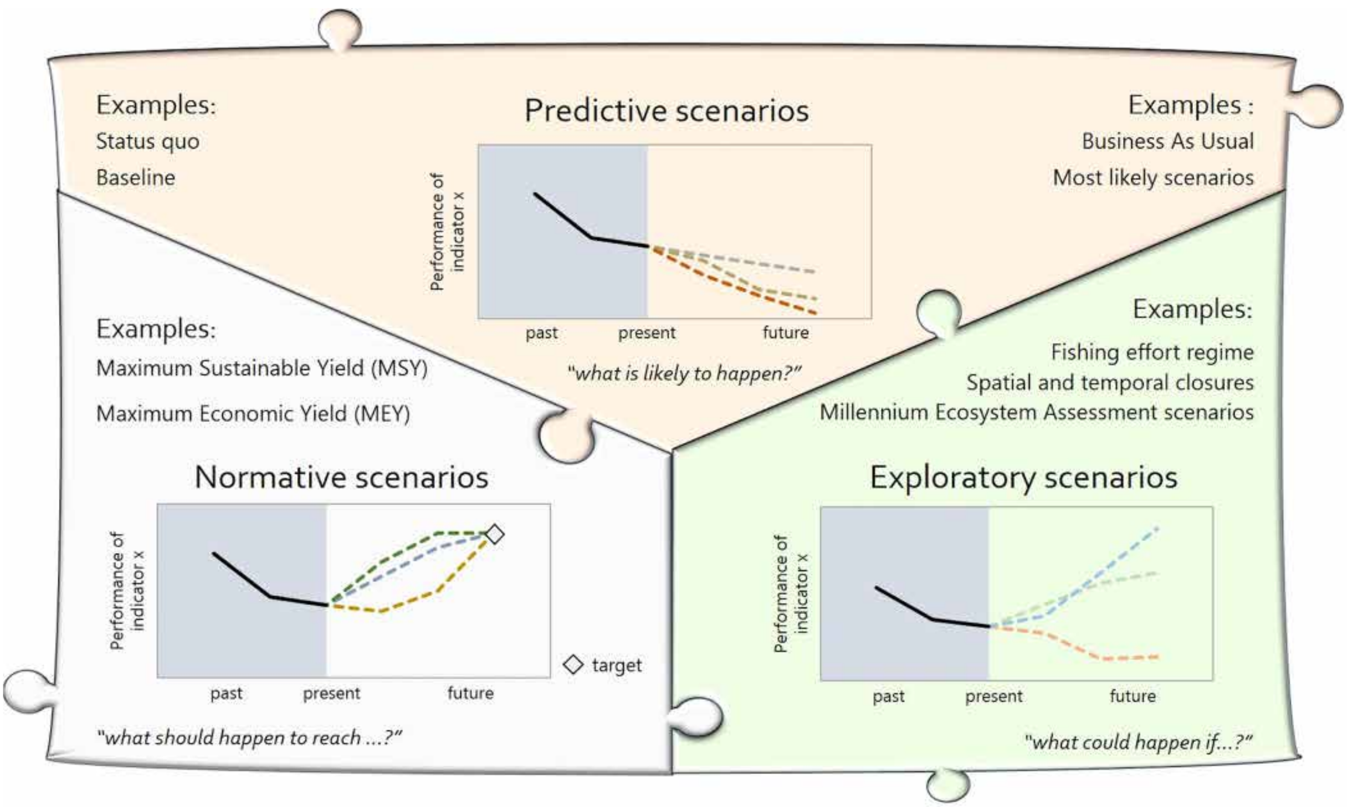

FIGURE 1 | Description and use of predictive, exploratory, and normative scenarios. Solid black lines correspond to past observed trajectories, and dashed color lines represent projected pathways. The figure is inspired by Ferrier et al. (2016).

ecosystems can be explained by an insufficient account for complexity in existing models. Typically, in fisheries, they advocate an ecosystem-based fishery management (EBFM) (ICES; NOAA). Operationalizing such a framework is, however, a difficult challenge that entails moving from single-species models such as those underlying MSY or MEY toward multi-species, trophic interactions, and spatially explicit models (Fulton et al. 2019; Pauly 2000; Ortega-Cisneros et al. 2024).

As a preliminary step before multi-species and ecosystem complexities, the account of life cycles in species dynamics can be considered as a first stage of complexity (Quinn and Deriso 1999). Recruitment of new individuals into a single population is indeed already a complex process in the sense that it is determined by many factors operating and interacting on multiple time and spatial scales in various environments (Pineda et al. 2009). Indeed, most marine organisms change across life stages while they disperse into the ocean from spawning to settlement areas into which they recruit, being successively eggs, then larvae carrying their own food reserve, then larvae able to feed externally, and finally juveniles with swimming capacities. Interspecific interactions constitute key elements of ecological complexity and EBFM (Cury et al. 2008, Plagányi et al. 2014; Doyen et al. 2017; Fulton et al. 2019) as illustrated by Figure 2. They include trophic (predator-prey), competition, and mutualism processes between species, species groups, or families. Understanding the interactions and feedback mechanisms among species in marine communities, food webs, and food chains is essential to the conservation of marine biodiversity and the management of fisheries. Such interactions can indeed mediate the distribution, abundance, and diversity of species within communities and across habitats, food webs, and ecosystems. Including dispersal and spatial connectivity among sites is also a crucial issue of EBFM, as emphasized by the major role played by marine protected areas in fostering marine biodiversity and ecosystems. Spatially explicit management of invasive species constitutes another challenging issue (Courtois et al. 2023). Dispersal in marine environments of suspended spores and larvae is mainly governed by ocean circulation, although vertical motility and differential mortality matter (Cowen and Sponaugle 2009). Analysis of dispersal network topologies, e.g. using graph theory, and metapopulation dynamics are very informative mathematical tools in that regard. The influence of environmental drivers such as climate and habitat changes is also pivotal for marine ecosystems and thus for fisheries management. In particular, climate change impacts primary production and fish distribution and thus potentially affects fishing yields (Cury et al. 2008; Sumaila et al. 2011; Fromentin et al. 2022; IPCC 2023). The key role of habitat for EBFM is exemplified by mangroves as nurseries for fishes or by coral reefs as a refuge for prey facing piscivores (Barbier 2003; Smith et al. 2007, Long et al. 2020). Mangroves and coral reefs are under pressure worldwide.

Going further into the integration of complexities for EBFM, thus adopting a very holistic viewpoint, (Brodziak and Link 2002; Link et al. 2017) also argue that EBFM should integrate social, economic, and human well-being dimensions of complexity. Such holistic viewpoint is also aligned with the Ecosystem Approach for Fisheries (Garcia et al. 2003; CDB: https://www.cbd.int/ecosystem). However, while the general idea of EBFM is widely accepted (Spence et al. 2018) and substantial progress has been made in EBFM implementation around the world, it remains rather unused in bio-economic models. The curse of dimensionality (DeLara and Doyen 2008) entailed by EBFM is a major methodological limitation for the use of operations research, mathematics of decision-

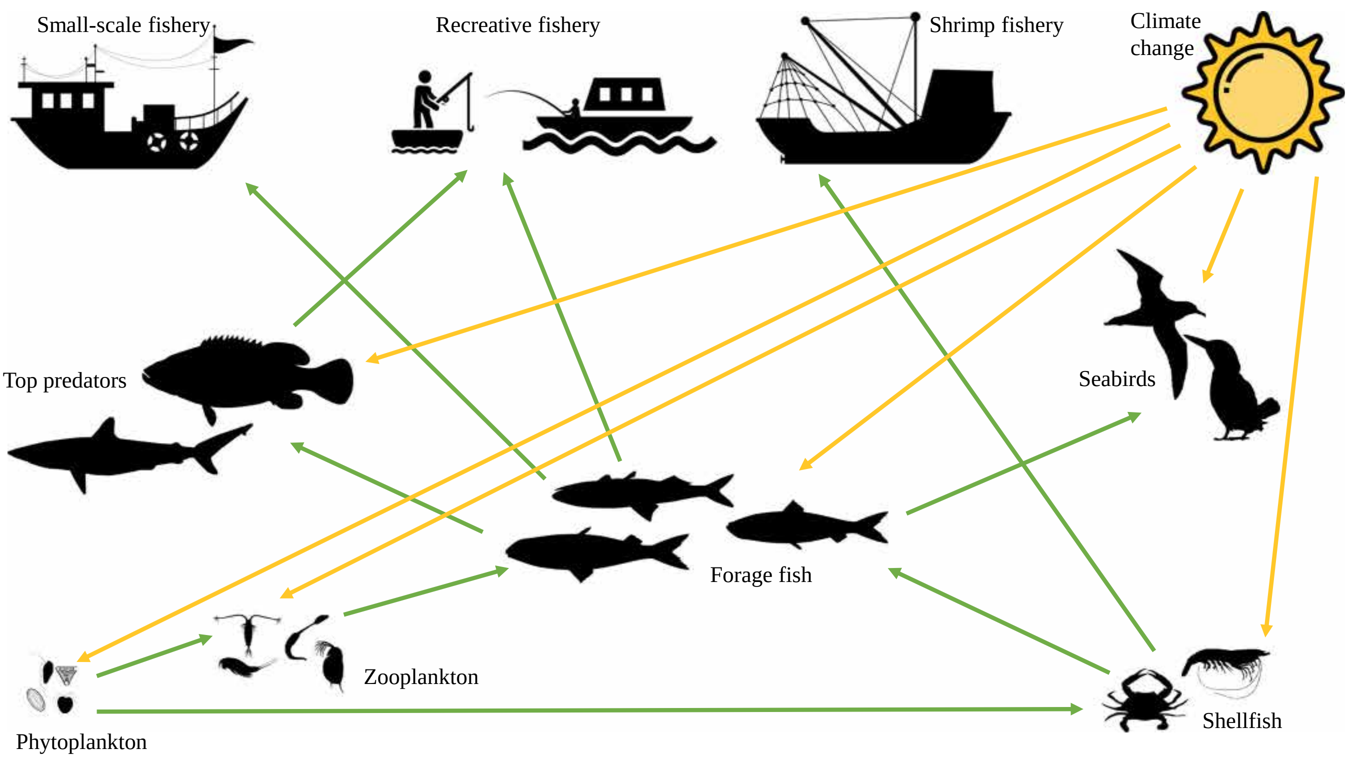

FIGURE 2 | An illustration of marine ecosystem interactions and dynamics.

making, and management sciences for EBFM. The phenomenon of ecological structural instability is another limitation (Yodzis 1988; Fung et al. 2015). Ecological structural instability indeed stresses the sensitivity of equilibria of ecological communities and consequently the difficulty of parameterizing complex food web models. Thus, operationalizing the EBFM approach will benefit from new models or, at a minimum, the expansion and adaptation of existing ones to make them fit for purpose.

In that regard, after early developments in bio-economics based on single stocks typically through MSY-MEY approaches, a number of generalizations have extended models to include key features of ecosystems and more realistic depictions of fish population dynamics, such as age-structure (Tahvonen 2009; Smith et al. 2008), multiple species interactions (Hannesson 1983), habitat dependence (Smith et al. 2007), and spatial-dynamics of a metapopulation (Sanchirico and Wilen 1999). Some attempts to deal with the dimensionality and EBFM also used stylized approaches, such as financial portfolio theory, but are limited by losing the mechanistic content of the underlying bio-economic system. Other areas in which bioeconomic modeling is expected to continue developing include the effects of environmental changes on tradeoffs associated with managing a fishery, such as the expected gradual impacts of warming on fish population dynamics (Beckensteiner et al. 2023), and interactions between fisheries and other uses of marine areas and resources. More globally, there is a methodological debate when operationalizing the EBFM between 'Whole of Ecosystem' (e.g. end-to-end models), such as Atlantis, Osmose, or Apecosm (Shin and Cury 2004; Fulton et al. 2019), and 'Models of Intermediate Complexity for Ecosystem' (MICE) (Plagányi et al. 2014; Cuilleret et al. 2022). 'Whole of Ecosystem' or end-to-end models adopt a very holistic approach, articulating many system components (see FISHMIP community). In contrast, the use of MICE aims to maintain the simplicity of stylized mathematical models and the ability to use statistical methods for their calibration, while also accounting for ecosystem dynamics, in relation to a limited number of management goals. We here argue that 'Whole of Ecosystem' models and MICE or stylized models are not contradictory but complementary and belong to a hierarchy of models that make sense in both ecological and socioeconomic terms while being well-posed mathematically and numerically. The differences and complementarity between whole ecosystem models and MICE refer to 'bias-variance trade-off': Increasing complexity by including more parameters (the whole system approach) should increase accuracy (decrease bias), but at the cost of greater uncertainty and therefore higher variance. From that viewpoint, the theory and tools of nonlinear and complex dynamic systems, both in discrete and continuous time, will play a major role. In particular, the description of marine ecosystems, and more broadly social-ecological systems, in terms of states, controls, parameters, disturbances, and observations allows for relevant integrated modeling taking into account the complex dynamics, the multiplicity of drivers (external, direct, indirect), decisions, and uncertainties underlying scenarios of biodiversity and ecosystem services (Ferrier et al. 2016). Such a mathematical approach can thus represent in a synthetic way multi-species, multi-drivers, and multi-scale dynamics while also capturing various sources of uncertainty as required by EBFM (Doyen et al. 2017).

At this stage, a methodological and mathematical question that arises is how to deal with complexity and ideally simplify it. Dynamical systems theory provides us with several methods for dealing with the complexity of models and model reduction (Poggiale et al. 2020; Moussaoui et al. 2023). For example, one such method is the separation of system dynamics into fast and slow components. This approach is particularly useful when modeling systems with multiple time scales of behavior, where the fast dynamics can be approximated using steady-state assumptions, while the slow dynamics require more detailed modeling. Of interest is also the strategy to reduce the complexity in MICE, consisting of a focus on questions related to management and public policies. In the words of Plagányi et al. (2014), MICE 'limit complexity by restricting the focus to those components of the ecosystem needed to address the main effects of the management question under consideration'.

The first rows of Table 1 list the merits and shortcomings of the different classes of models regarding EBFM and thus highlight gaps that need to be addressed in MBE2 for Fisheries. The different classes of models include 'classical stylized bioeconomic models' in line with seminal works of Gordon - Schaefer - Clark, MICE models, and 'whole of ecosystem' models such as EwE or Atlantis models. The comparison in the first rows relies on different key items derived from EBFM challenges and the complexity of the ecosystem. We first focus on the content of models in terms of dynamics, multi-species, multi-fleet, spatiality, habitat quality, and climate. Notation '+' means a moderate account of the item in the model class, while the symbol '++' stands for a strong focus of the model class. Such a qualitative evaluation of model classes is not based on any statistical analysis but on the multidisciplinary knowledge and scientific expertise of the numerous authors of this paper.

3 | Mathematics for Sustainable Fisheries

Operationalizing sustainability for fisheries is a major challenge in terms of criteria, standards, and management strategies. In this section, special attention is paid to both intergenerational equity and multi-criteria issues underpinning sustainability. The assessment of sustainability is crucial for an 'MBE2 for Fisheries' program. It is achieved through the evaluation of bioeconomic management, policies, and model-based scenarios, whether they are predictive, exploratory, or normative (goal seeking) (Ferrier et al. 2016; Doyen 2018). Again, we are not starting from scratch here since the word 'sustainable' is central in the very definition of MSY (maximum sustainable yield), but focused on the 'ecological' dimension of sustainability. In other terms, MSY does not take into account key social and economic aspects of sustainability, such as the equitable distribution of access and costs and benefits from the use of marine biodiversity (Intergovernmental Science 2022). More broadly, the different mathematical approaches to characterize and design sustainable fisheries draw on the theory of controlled dynamic systems, in particular, steady-state, optimal, and viable controls. Below, we discuss the merits of these different approaches in that framework.

Following the Brundtland Report, many quantitative methods, metrics, and criteria have been proposed to operationalize sustainability (Cairns and Long 2006; Asheim and Ekeland 2016), particularly in the bio-economics context. The challenge for an

TABLE 1 | Comparative analysis of the merits of the different classes of models for fisheries, along with the gaps for Mathematical Bioeconomics 2.0 for Fisheries.

Challenges	Class models/features	Stylized bioeconomic models	MICE	Whole of ecosystem models	Ideal BIOECO 2.0
	Calibration	+	+	+	++
EBFM	Dynamic	+	++	++	++
	Multi-species		++	++	++
	Habitat quality	+	+	+	++
	Climate		+	+	++
	Multi-fleet		+	++	++
	Spatiality		+	++	++
Sustainability	Equilibria	++			++
	Multi-criteria	+	++	+	++
	Optimality	+			++
	Viability - Safety	+	++	+	++
	Intergenerational equity	+	++		++
Resilience	Stability	+			++
	Stochasticity - Risk	+	+	+	++
	Extreme events				++
	Adaptive control	+	+		++
Governance	Input controls	++	+	+	++
	Output controls	++	+	+	++
	MPA	+	+	++	++
	Monetary instruments	++		+	++
	Market based	++	+	+	++
	Eco-labels				++
	Gains of cooperation	+	+		++
	Coalition	+			++
	Negociation	+			++

Notation '+' means a moderate account of the item in the model class, while symbol '++' stands for a strong focus of the model class.

'MBE2' program is to go beyond the seminal approach of MSY (Gordon 1954; Schaefer 1954) based on equilibrium and steady-state controls. A first weakness of these MSY-MEY approaches indeed emerges from their extension to the multispecies and ecosystem-based contexts investigated in Legović and Geček (2010), Farcas and Rossberg (2016), and Tromeur and Doyen (2019) as it can be proved that overexploitation and even extinction occurs for some species. Such a finding clearly questions the sustainability of these multispecies MSY-MEY targets. Another weakness of the MSY-MEY approaches obviously arises from their static nature. Adopting a more dynamic viewpoint with the optimal control approach, Clark (1990) proposes generalizations of MSY-MEY with discounted (or dynamic) MEY versions and informs on the transients towards these long-run equilibria. However, the discounted approach underlying the usual optimal control approach in economics, qualified as a 'dictatorship of the present' is criticized because this criterion over discounts long-run payoffs, entailing unsustainable trajectories (Sumaila 2004; Quaas et al. 2012) and 'optimal' extinctions (Clark 1990).[2] As an alternative criterion, the maximin (Cairns and Long 2006), defined as the highest payoff level that can be sustained over time, promotes intergenerational equity. In addition, Sumaila (2004) or Sumaila and Walters (2007) included future generations, alongside the present one, in the current welfare function, with suitable Pareto weights. This overlapping generations approach leads to more practical recommendations for the sustainable management of fish stocks (Ekeland et al. 2015; Sumaila 2021).

Nevertheless, the use of optimization methods to quantify sustainability, including the maximin criterion or overlapping generations, is globally criticized because sustainability conditions need to be imposed before the maximization of any social welfare. In that regard, the account for safety, conservation, and biophysical constraints to fulfill over time emerges as a crucial issue (Rockström et al. 2009). If the constraints induced by reference points, thresholds, standards, and tipping points have to be satisfied over time, such sustainability problems can be formulated into the mathematical framework of viable control (Aubin and Frankowska 1991; Béné et al. 2001; Cury et al. 2005; Martinet et al. 2007; Schuhbauer and Sumaila 2016; Oubraham and Zaccour 2018). Basically, the viable control approach investigates the consistency between controlled dynamic systems and thresholds, constraints, and/or targets. In this framework, reference and tipping points not to exceed for ecological, economic, or social indicators stand for sustainable management objectives in line with the triple bottom line of sustainability. In fisheries, typical examples of such thresholds are given by ICES (International Council for the Exploration of the Sea), which defined, in the frame of the precautionary approach, spawning stock biomass limits named B_{lim}, or B_{pa} (Kell et al. 2005). But thresholds may also pertain to economic and social sustainability criteria (Maynou 2014; Doyen et al. 2017). The viability approach has been applied by numerous authors to the sustainable management of renewable resources and fisheries (Schuhbauer and Sumaila 2016; Oubraham and Zaccour 2018). The strong sustainability content of the viable control approach is pointed out (Baumgärtner and Quaas 2009; Doyen and Gajardo 2020) as opposed to the weak sustainability content underlying the optimal control framework. Weak sustainability indeed allows for substitutability between the economic, social, and ecological metrics and scores, for instance, through monetary values, social welfare, or aggregated scores. In contrast, by clearly distinguishing between ecological, economic, and social metrics, thresholds, and constraints, viable control brings important insights into strong sustainability. Such nonsubstitutability occurs, for instance, in fisheries management since biodiversity and some ecosystem services (e.g. carbon sequestration, generation of oxygen and protection from sea level rise, and recreational values) may not have clear and agreed-upon monetary values.

Interestingly, it turns out that the maximin and viability approaches are strongly connected since maximin emerges as a 'maximal viability'. More specifically, it can be proved that the value function of the maximin problem is the solution of a static optimization (Pareto) problem involving the viability kernel as state constraint (Doyen and Gajardo 2020). Consequently, maximin trajectories or controls are specific and extreme viable trajectories or controls. Moreover, Doyen and Gajardo (2020) proved that MSY-MEY play key roles for the identification of multi-criteria maximin solutions. In other words, optimal and viable control frameworks are not contradictory and should be articulated through maximin criteria or optimization under constraints. Therefore, for the 'MBE2 for Fisheries' program, we suggest that the scientific works inspired by maximin and viability criteria be intensified, for instance, by integrating social indicators.

Again, Table 1 captures the pros and cons of the different classes of models for fisheries regarding the operationalization of sustainability. In this table, the comparison of sustainability focuses on the content of models in terms of intergenerational equity and multi-criteria, equilibrium, optimality, and viability.

4 | Mathematics of Resilience for Fisheries

Operationalizing resilience, i.e. the ability to cope with shocks and uncertainties, is also a key challenge for fisheries in terms of criteria, standards, strategies, and harvest control rules (Fromentin et al. 2014; Grafton et al. 2019; Voss and Quaas 2022). Resilience influences many decisions and policies, including management objectives of influential multilateral and United Nations agencies (e.g. FAO; World Bank). As a result, resilience is now emphasized in several Sustainable Development Goals (SDGs), including SDG 1 (No Poverty), SDG 2 (Zero Hunger), SDG 9 (Industry, Innovation, and Infrastructure), and SDG 14 (Life Below Water). This rising popularity of resilience contrasts, however, with a lack of clarity over the concept and how to implement it in practice. In particular, practical guidance and modeling about how to operationalize resilience-based management are still required for fisheries and marine ecosystems. To address uncertainties of bioeconomic models, it is very common to complete the study with parameter sensitivity analysis. Such analysis informs the manager about the uncertainty of the model outcomes with respect to the variability of the parameters. Less common but very important is the structural sensitivity (Cordoleani et al. 2011). This approach completes the sensitivity analysis by considering the importance of functional choices made in the model formulation. Think of the population dynamics (logistic, Ricker, Beverton-Holt, Gomperz, ...) or production functions (Schaefer, Cobb-Douglass, CES, ...) underlying stylized bio-economic models.

Beyond parameter and structural sensitivity analysis, there is an abundant literature about uncertainties and stochasticities in fisheries modeling (Reed 1979; Clark and Kirkwood 1986). Being focused on harvest control rules, Kvamsdal et al. (2016) provide a broad discussion of uncertainty and complexity in fisheries models. The accounting of uncertainties in fisheries management has also been put forward for decades with the concept of Adaptive Management and Feedback Control (Rasch 1989). Adaptive management is a strategy for considering unpredictable changes in the ecosystem, such as recruitment failure, as major causes of stocks and fisheries collapse. Recent works identifying adaptive fishing strategies based on risk aversion and diversification include Gourguet et al. (2014). Moreover, all fishers learn from their successes and failures. Thus, adaptive management is an iterative process that consists of an integrated progression of learning by doing. Such an iterative process also relates to 'Management Strategy Evaluation' (Grafton et al. 2007; Butterworth et al. 2010; Thébaud et al. 2014). Kalman filters, in particular their extensions to nonlinear and complex systems (Julier and Uhlmann 1997), can be relevant mathematical tools to deal with adaptive management and management strategy evaluation.

We argue that resilience-based management should constitute an extension of adaptive management in the face of uncertainties. Recently, significant progress in the definitions and objectives of resilience-based management for environmental issues has been made (Grafton et al. 2019; Cuilleret et al. 2022). These authors postulate that resilience-based management needs to be first defined with respect to desired and normative situations for the system at play and to answer the question 'resilience with respect to what?'. For fisheries, marine biodiversity and bio-economic issues, we postulate that such desired states correspond to safe or sustainable states of fisheries as investigated in the previous section about sustainability. Such a sustainability target for resilience expands the usual approaches associating resilience mainly with the stability of equilibria (Levin and Lubchenco 2008; Derissen et al. 2011). At this stage, it is of interest to consider and evaluate the bio-economic resilience of natural living resources through the so-called 3 Rs of resilience— recovery, resistance, and robustness, which are complementary quantitative ingredients of resilience. Recovery relates to the time necessary for a system to bounce back to safe, sustainable, or viable situations after shocks, perturbations, or adverse events (Holling 1973; Pimm 1984; Martinet et al. 2007). Resistance refers to the magnitude of shocks, perturbations, and uncertainties that can be withstood by a system to remain in safe, sustainable, or viable systems (Holling 1973). Robustness, or reliability, refers to the probability of coping with shocks and uncertainties with respect to a sustainable system (Doyen et al. 2017). Said differently, recovery highlights the temporal dimension of resilience in line with the well-known minimal time problem (Cannarsa and Sinestrari 1995) in control theory. Resistance gives insights into the 'room for manoeuvre for resilience in line with the basin of attraction for stability issues or the capture basin for target issues. And robustness (or reliability) sheds light on the probability of resilience, in line with risk management (Rockafellar 2014), the so-called chance constraints, and the value at risk. In that regard, accounting for extreme events such as heatwaves (Cheung et al. 2021) within the probability distributions is a key challenge because shocks relate to uncertain events with low probability and high impact. More globally, by integrating recovery, resistance, and robustness issues, the 3R-based management is a way to reconcile risk and crisis management.

More generally, we argue that the mathematics related to stable control, decision under uncertainty, risk management, and stochastic control will play major roles in the resilience-based management of fisheries and the MBE2 program for Fisheries. Table 1 also synthesizes the pros and cons of different classes of models for fisheries with respect to the operationalization of resilience. In this table, the comparison focuses on the content of models in terms of stochasticity, risk, and stability.

5 | Mathematics of the Governance for Bio-Economic Public Policies

Bioeconomic models should facilitate dialog across stakeholders to promote sustainable fisheries. This governance issue is challenging because the heterogeneity of actors involved in fisheries contributes to the difficulty of management and public decisions. These actors, which include stakeholders, fishermen, scientists, NGOs, consumers, tourists, conservation agencies, and regulating agencies, can indeed differ in their preferences, strategies, levels of information, and inputs into the marine ecosystems. Furthermore, agents do not consider all the external consequences (externalities) of their actions. A catastrophic outcome of such a process is the resource collapse as stressed by the tragedy of the commons and fish war, a typical example of deficient governance of natural resources used by different individuals, groups, or countries (Munro 1979; Levhari and Mirman 1980; Sumaila 1999; Vallee and Guillotreau 2017; Breton and Keoula 2014, Grønbeak et al. 2018; Doyen et al. 2018; Dahmouni et al. 2019; Dahmouni et al. 2023). Moreover, the goals of the different agents or groups are often contradictory, and public policies may result in trade-offs. Bioeconomics is thus required to design instruments entailing consensus, coordination, and participation among agents toward ecosystem-based, sustainable, and resilient fisheries. Existing cooperative structures for fisheries vary in scale, ranging from RFMO (Regional Fishery Management Organization) at the international scale to local fishing committees at national scales. At these different scales, there are many instruments for fisheries management, including:

- Total allowable catch (TAC) or output controls (often based on MSY reference points);
- Fishing effort limits, access controls (i.e., licenses, limited number of boats or gear; restrictions on the number of trips), or input controls;
- Marine protected area (MPA), spatial and time closures, Territorial Use Rights for Fishing (TURFs), and other effective area-based conservation measures (OECMs);
- Selectivity or technology constraints: restrictions on the size of fish that can be caught or retained;
- Monetary instruments: taxes, subsidies on fishing catches, and efforts;
- Individual (or community) Transferable quotas (ITQs), and a more global allocation of shares in a fishery that can be traded on a market with a price;
- Information instruments for consumers, such as the Marine Stewardship Council (MSC) eco-label.

The merits of these different instruments are discussed (Clark 1990, Thébaud et al. 2023). TACs, licenses, and MPAs are among the most applied or studied instruments. We argue that the role of MPAs (Reithe et al. 2014; Herrera et al. 2016; Smith and Wilen 2003), of market-based solutions including ITQs (Costello et al. 2019), as well as eco-labels (Sainsbury 2023) need to be explored more intensively for incorporation in a Mathematical Bio-economics Program 2.0 for Sustainable Fisheries.

To assess the ability of these different instruments in supporting the sustainability of uses of marine biodiversity and the resilience of marine ecosystems, we here claim that the mathematical tools of game theory, from both cooperative and non-cooperative branches (Munro 1979; Sumaila 1999; Breton and Keoula 2014, Grønbaek et al. 2018; Dahmouni et al. 2019) are extremely useful. Cooperation is indeed crucial for the sustainable use of renewable resources, exploited ecosystems, and biodiversity, as stressed by the well-known tragedy of the commons. Game theory is a particularly relevant modeling tool to study such bioeconomic issues because it provides important quantitative and qualitative insights into the strategic interactions between users exploiting a common renewable resource. It can also be used to study policy interventions that incompletely control the behaviors of fishery participants (Huang and Smith 2014). In the extensive game theory literature applied to fisheries, the dynamic model of Levhari and Mirman (1980) provides a solid framework for analyzing the consequences of users' strategies on the resource in open-access fisheries. Using a dynamic Cournot-Nash solution, these authors show that the non-cooperative equilibrium yields a higher harvest fraction and a smaller steady-state stock than the cooperative equilibrium. Between these two extreme cases, full cooperation and no cooperation, the sustainability of partial cooperation has also been studied (Breton and Keoula 2014). Mean-field games (Cardaliaguet et al. 2019) can also be informative in the case of numerous agents.

However, the majority of game-theoretic models have been applied to single stocks. Notable exceptions exist, such as the study of predator-prey models (Mesterton-Gibbons 1996), metapopulations distributed over connected areas (Costello et al. 2019), or multi-species dynamics (Doyen et al. 2018). Nevertheless, the use of game theory in the broader EBFM context remains an open research field. Said differently, the generalization of the dynamic game approach to multi-species and spatial frameworks is an important challenge in the area of ecosystem-based and biodiversity management.

More generally, we argue that the mathematics related to dynamic game theory and strategic interactions will play major roles in relevant governance toward resilience and sustainability-based management of fisheries and 'MBE2'. They should help reduce the gap between the theoretical insights of MBE2 and practical fisheries management that incorporates the behavior and interests of stakeholders. The last rows of Table 1 summarize the merits of different classes of models for fisheries with respect to such governance issues, in particular, in terms of instruments and strategic interactions.

6 | Conclusions

Balancing marine biodiversity conservation with food security, the conservation of marine ecosystem functioning and services, and the economic viability of fisheries in a complex and dynamic context of global change, is among the greatest challenges of the century. Dealing with such a challenge implies the development of models and model-based scenarios of biodiversity and ecosystems that make sense economically, socially, ecologically, and biologically, and that are well-posed mathematically and numerically. In that vein, our perspective paper proposes to design a 'Mathematical Bio-Economics 2.0 Program for Sustainable Fisheries'. The paper addresses the 'MBE2' Program for Fisheries with four general challenges: (i) the mathematics and modeling of ecosystem-based fisheries management, (ii) the mathematics and modeling of sustainability criteria and strategies, (iii) the mathematics and modeling of resilience criteria and strategies, and (iv) the mathematics and modeling of governance and strategic interactions. As detailed in the previous sections, our research agenda based on those four axes makes it possible to elicit guidelines and more specific key mathematical and modeling gaps to fill up for a relevant 'Mathematical and Modeling Bio-Economics 2.0 Program for Sustainable Fisheries' when compared to models currently used, ranging from stylized bio-economic models (e.g. MSY-MEY) to 'Whole of Ecosystem' models. At this stage, let us point out that, through challenge (ii) about EBFM, the key term 'bio-economics' of our title now means 'biodiversity economics' instead of the historical sense 'biological economics', which may appear too restrictive. Although overlaps exist in practice between the four axes, these challenges should allow modelers and mathematicians to focus on specific methodological domains and issues, typically complex dynamic systems for challenge (i), control theory criteria for challenge (ii), stochastic control for (iii), and dynamic games for challenge (iv).

Moreover, our research agenda based on those four axes also provides modeling and mathematical insights in line with the IPBES Chapter (Ferrier et al. 2016) devoted to 'Methodological assessment of scenarios and models of biodiversity and ecosystem services'. In particular, we argue that complex dynamic systems combined with control theory, including optimal, viable, and stochastic control together with dynamic game theory, constitute a relevant methodological framework to design models and predictive, exploratory, and normative model-based scenarios of marine biodiversity, ecosystems, and the services they provide. Such relevance to design bio-economic models and scenarios arises first because these domains of applied mathematics constitute a transdisciplinary language, potentially articulating the ecological, social, and economic dimensions of these systems and handling their interactions. Thus, the ubiquity of these mathematical frameworks makes it possible to operationalize and quantify both the ecosystem approach, sustainability, resilience, and governance of fisheries.

Although our paper does not explicitly provide a mathematical model of MBE2 for sustainable fisheries, it paves the road and advocates the search for a generic model incorporating all the challenges in one. For this very ambitious task of designing and publishing an integrated MBE2 for sustainable fisheries, many generic and transverse mathematical ingredients can already be found in DeLara and Doyen (2008), Doyen et al. (2013), Doyen et al. (2019), and Doyen (2018). As intermediary steps and more focused tasks, we would like to stress some more specific cutting-edge research and challenges aligned with Table 1:

- Highlight bioeconomic resilience gains of ecosystem-based MEY (EBMEY) when compared to ecosystem-based MSY (EBMSY). Such an intermediary challenge relates to axis (i) as a multi-species issue and clearly to axis (iii) about resilience. The underlying intuition is that single single-species MEY state is known to be more stable than the MSY state. We wonder to what extent such stability gain can be generalized to the multi-species and ecosystem context.
- Application of multi-criteria, maximin, and viable control approach for sustainable and resilient fisheries. Such an intermediary challenge relates to axis (ii) because maximin and viability criteria constitute cutting-edge approaches clearly addressing sustainability evaluation.
- Account of extreme events in resilience-based management for fisheries through flat-tailed random distribution. Such an intermediary challenge clearly refers to axis (iii), stochastic control and risk management.
- Application and analyses of bioeconomic sustainability (and resilience) gains versus loss of market-based instruments for the decentralization of public policies for fisheries. Such an intermediary challenge is aligned with axis (iv) about governance issues.
- Propose and analyze MICE models of sustainable seafood systems (From Fish to Fork). Such an intermediary challenge is in line with axis (iv) about instrument and public policy issues, along with the ecological complexity underlying axis (i).

Advancing these more specific issues should allow for bridging the divide between theoretical MBE2, model-based scenarios, and the practical quantitative management of fisheries and seafood systems. This is not contradictory with and does not preclude the search for a generic and integrated model of mathematical bioeconomics 2.0 for sustainable fisheries.

Author Contributions

L Doyen: conceptualization, writing – original draft, writing – review and editing. **M D Smith:** writing – review and editing. **U R Sumaila:** writing – review and editing. **G Zaccour:** writing – review and editing. **I Ekeland:** writing – review and editing. **P Cury:** writing – review and editing. **C Lett:** writing – review and editing. **O Thébaud:** writing – review and editing. **J-C Poggiale:** writing – review and editing. **A Moussaoui:** writing – review and editing. **J-M Fromentin:** writing – review and editing. **S Gourguet:** writing – review and editing. **P Guillotreau:** writing – review and editing. **H Gomes:** writing – review and editing. **P Courtois:** writing – review and editing. **R Schaap:** writing – review and editing. **F Blanchard:** writing – review and editing. **C Rainer:** writing – review and editing. **M Tidball:** writing – review and editing. **M Cuilleret:** writing – review and editing. **T Villain:** writing – review and editing. **F Menard:** writing – review and editing. **T Sari:** Writing – review and editing.

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Data availability

This study does not use specific data.

Endnotes

[1] Predictive scenarios, such as forecasts, can respond to the question 'What is likely to happen?' Predictive scenarios include status quo or business as usual, baseline, or most likely scenarios. Exploratory scenarios describe other alternatives of the future and intend to respond to the question 'What could happen if?'. They not only aid in the decision support process to investigate the outcomes of specific management strategies or drivers, including economic, social, or technological factors, but also climate change. By contrast, target-seeking scenarios or normative scenarios deal with the question 'What should happen to reach?' and represent agreed-upon future goals and scenarios that provide alternative pathways for reaching such an objective.

[2] Grafton et al. (2012) and Nævdal and Skonhoft (2018) discuss the conditions for such an optimal extinction to occur. In particular, Nævdal and Skonhoft (2018) argue that the stock cannot rationally be fished to extinction based on the 'shadow' value of the stock and the opportunity cost of harvest. Kvamsdal et al. (2020) propose a similar discussion in a food-web context.

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Appendix A. Acronyms

- **EBFM**: Ecosystem-Based Fisheries Management.
- **ES**: Ecosystem Service.
- **IPBES**: International Platform for Biodiversity and Ecosystem Services.
- **ITQ**: Individual Transferable Quota
- **MBE2**: Mathematical Bio-Economics 2.0.
- **MEY**: Maximum Economic Yield: maximization of the profit at equilibrium.
- **MICE**: Model of Intermediate Complexity.
- **MPA**: Marine Protected Area.
- **MSE:** Management Strategy Evaluation.
- **MSY**: Maximum Sustainable Yield: maximization of the catches at equilibrium.
- **SES**: Social-Ecological System.
- **TAC**: Total Allowable Catch.
- **3 R** (of resilience): recovery, resistance, and reliability (or robustness).

Appendix B. Glossary

- **Adaptive control**: Control depending on the states of a system. Typical forms are feedback or Markovian controls as opposed to open-loop control, which only depends on time.
- **Bioeconomic system**: A model that depicts the coupled dynamics of a natural resource and anthropogenic activities on this resource.
- **Calibration (of a system)**: Empirical estimation of the parameters of a system.
- **Dynamic games**: Game theory in the context of dynamic systems.
- **Dynamic system**: A mathematical model describing the mechanism by which a state changes in time. Time can be continuous or discrete.
- **Eco-label**: A label for food and consumer products informing on ecological and sustainability issues.
- **Equilibrium (of a system)**: stationary state (and control)
- **Exploratory scenario**: Scenario based on new trajectories of drivers and actions.
- **Extreme (or rare) event**: An event that occurs with low frequency but with a widespread effect on systems.
- **Fish war**: The tragedy of the commons for fisheries and marine resources.
- **Game theory**: The study of how and why individuals and entities (called players or agents) make decisions in situations of (strategic) interactions.
- **Graph theory**: The study of graphs, which are mathematical structures used to model pairwise relations between objects.
- **Input controls (of a fishery)**: Restrictions on the access of fishers to fishing resources. Typically, fishing licenses or an MPA.
- **Intergenerational equity**: Fairness or justice between generations.
- **Kalman filter**: In control theory, Kalman filtering uses a series of measurements observed over time to produce estimates of variables by estimating a joint probability distribution over the variables for each time step.
- **Market-based instrument (for fisheries)**: A market-based instrument is a tool relying on markets and prices to manage fisheries. Typically ITQs.

- **Maximin criterion (for sustainability)**: Criterion maximizing the minimum possible payoff across time and generations.
- **Mean-field game**: A game with a large number of agents but having small interactions.
- **Metapopulation**: A group of spatially separated populations of the same species that interact at some level.
- **Normative scenario (or prescriptive or target-seeking)**: A scenario describing a prespecified future achievable (or avoidable) only through specific actions and drivers.
- **Output control (of a fishery)**: A direct limit on the amount of fish coming out of a fishery. Typically TAC.
- **Predictive scenario**: A scenario extrapolating from past trends.
- **Risk management**: The process of identifying, assessing, and managing threats to a system.
- **Scenarios**: Future trajectories consistent with past and current trajectories.
- **Stability (of an equilibrium)**: The ability of an equilibrium state to smoothly react to changes in parameters or states. You can distinguish between local, global, and asymptotic stability.
- **Stochastic control**: Control of systems in the face of a random probability distribution affecting the system dynamics.
- **Strong sustainability**: Sustainability when ecological, social, and economic metrics are not interchangeable, meaning that the different scores are measured with different units.
- **Sustainability**: Meeting the needs of the present without compromising the ability of future generations to meet their needs.
- **Tragedy of the commons**: Open access to a natural resource implies its overexploitation and may entail its collapse.
- **Trophic interaction**: When one organism feeds on another.
- **Viable control**: Control of dynamic systems in the face of state and control constraints.
- **Weak Sustainability**: Sustainability when ecological, social, and economic metrics are interchangeable in the sense that they are measured in the same way and can be aggregated.