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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 challenge. 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 for Sustainable Fisheries in order 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 economic senses while being well-posed mathematically and numerically. To achieve this, we propose to base the Mathematical Bio-Economics 2.0 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; (iv) governance and strategic interactions. The associated methodology of Mathematical Bio-Economics 2.0 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.

Keywords: Bio-economics, Fisheries, Marine Biodiversity, Marine Ecosystems, Ecosystem services, Modeling, Scenarios, Management, Public policy, Dynamic systems, Control theory, Game theory, Sustainability, Resilience, Governance.

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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 (Godfray et al., 2010; Rice and Garcia, 2011; Crist et al., 2017). 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 (Díaz et al., 2015). Implementing this bio-economic perspective is particularly important and challenging in the case of fisheries and marine ecosystems. Marine fisheries indeed employ 120 million people directly and indirectly around the world, and account for nearly 500 million people who depend on it for their livelihood (FAO, Duke University and Worldfish, 2023). Moreover, fisheries and marine ecosystems are experiencing accelerating changes affecting species, communities and trophic webs, sometimes with alarming trends (Butchart et al., 2010; Österblom et al., 2016; Smith et al., 2010; IPBES, 2019). 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 (Asche et al., 2022; Cojocaru et al., 2022). Climate change exacerbates the issues and iniquities between high-income and low-income countries by inducing new, or intensifying, risks and vulnerabilities (Cury et al., 2008; Sumaila et al., 2011; Fromentin et al., 2022; Barange et al., 2018) through e.g., changes in primary production and fish distribution, thus potentially affecting yields (Kroetz et al., 2022).

Ensuring the long-term sustainability of marine fisheries while preserving the marine biodiversity and ecosystems functioning that support them, have become a major issue for national and international agencies (UNSDG; IPBES). However, the agencies and other management institutions require more quantitative methods, models, scenarios and indicators to support policies addressing jointly food security, economic development, and conservation of biodiversity and ESs. Fortunately, with respect to marine fisheries, we are not starting from scratch. Mathematical models applied to fisheries have been used for many decades building, in particular, on the seminal works of Gordon (1954) and Schaefer (1954) combining equilibrium and optimality approaches. These key initial bio-economic contributions have been extended and generalized by Smith (1969); Clark (1973) 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 (Nielsen et al., 2018; Thébaud et al., 2023a). 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 (Sumaila et al., 2012; Bank, 2017).

Despite 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 (Food and Agriculture Organization, 2020). New bio-economic models and mathematics are needed to sustainably balance 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 require new contributions and involvements of Mathematicians and Modelers (De Lara and Doyen, 2008; Thébaud et al., 2014; Doyen et al., 2013; Doyen, 2018; Maury, 2010). Thus, we advocate a new 'Mathematical Bio-economics for Sustainable Fisheries' to advance the development of models and scenarios for the sustainable management of fisheries and marine ecosystems. In particular, these models and scenarios should take into account the full complexity of these systems, including their ecological and socio-economic dimensions, while being well-posed mathematically and numerically. To achieve this, we propose to split the 'Mathematical Bio-economics 2.0 for Fisheries' into four main research challenges and axes, that 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.

These four axes and challenges aim at bridging the gap between theory and management practice for fisheries.

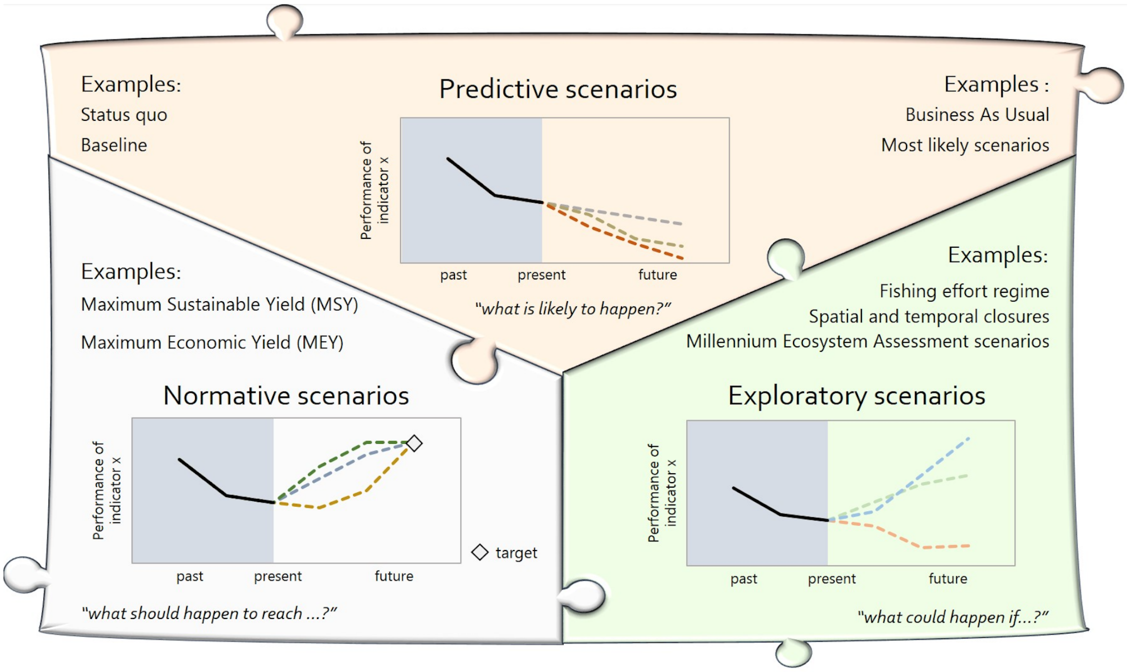


Figure 1: Description and use of predictive, exploratory and normative scenarios. Solid black lines correspond to past observed trajectories, and dashed color lines represent projected pathways. The figure is inspired by IPBES (2016).

Challenge (i) refers mostly to the ecological complexity brought about by moving from single-species models exemplified by MSY or MEY towards multi-species and trophic web approaches. 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. Our paper detail the motivations, goals as well as the methodological content of these four axes. 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 Mathematical Bio-economics 2.0 for sustainable uses of of marine biodiversity.

The rest of the paper is organized as follows: a preliminary section 2 reminds the numerous intersecting interests of bio-economic models, mathematics and theory. Then, in Section 3, we elaborate on the mathematics of ecosystem-based fisheries management and scenarios. The mathematics for criteria of sustainability and of resilience in fisheries are then discussed in Section 4 and 5 respectively. Section 6 gives insights into the modeling and mathematical challenges emerging from the governance, instruments and strategic interactions in fisheries. We conclude, in particular, through Table 1, by identifying the major methodological gaps for the design of a successful Mathematical Bio-economics 2.0 for Sustainable Fisheries.

2 Why are bio-economic mathematical models and theory needed ?

A mathematical model is an abstract description of a concrete system using mathematical concepts and language. Mathematical models are used in many disciplines ranging from life sciences, physics to social sciences as well as engineering disciplines. Bio-economic models are models coupling biological and/or ecological systems with models of human and social systems including economic activities (Gordon, 1954; Schaefer, 1954; Clark, 1973; Wilen, 1985; Seijo et al., 1998; Béné et al., 2001; De Lara and Doyen, 2008; Smith, 2008). Bio-economic models can thus be applied to many environmental issues arising in forestry, agriculture, water use, fisheries management and, more broadly, to ecosystems and biodiversity management. Bio-economic models are thus used to study social-ecological systems (Ostrom, 2009), and are considered as early examples of modeling coupled human-natural systems (Abbott et al., 2018; Ferraro et al., 2019). In this preliminary section, we first question the interest of such mathematical models for fisheries. It turns out that the role and purpose of bio-economic models are multiple in nature, in particular, when dealing with fisheries and marine ecosystems. We hereafter distinguish between five key roles of models useful for Mathematical Bio-Economics 2.0 for Fisheries: (i) models **to understand the underlying systems; (ii)** models **for interdisciplinarity; (iii)** models **to fit the data; (iv)** models **to evaluate systems; (v)** models **for decision making.**

Firstly, **mathematical models are needed to understand the social-ecological systems** involved in fisheries and marine biodiversity. This is because mathematics, in particular, mechanistic models, simplify the processes at play and describe 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. In that regard, dealing with marine biodiversity is a challenge because of its intrinsic complexity (Doyen, 2018). In particular, processes involved in fisheries are numerous and nonlinear. Sections 3 and 6 pay particular attention to such complexity, both ecological and economic.

Secondly, **mathematical models are needed for interdisciplinarity.** Mathematics constitute an interdisciplinary or even transdisciplinary language. This is crucial for bio-economics and, in particular, for fisheries where there is a need to articulate the dynamics of ecological and economic systems and to manage their interactions, especially in a context of global change (Abbott et al., 2018; Sumaila et al., 2011; Thébaud et al., 2023a). The various ways that sustainability sciences refer to systems – coupled human and natural, social-ecological, or nature-society – all highlight their inherent interdisciplinary content. Bio-economics have been interdisciplinary since day 1, with models that depict the fish stock (the natural system) together with the fishing activity (the human system). The transdisciplinary virtue of models and in particular bio-economic models is beneficial to participatory approaches that aim to bring together different actors, despite their heterogeneity. Such a feature is elaborated in Section 4 where we discuss sustainability and the underlying multi-criteria requirements. This feature is also discussed in Section 6 where strategic interactions between stakeholders are considered.

Thirdly, **mathematical models are needed to calibrate and validate 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). For bio-economic models in fisheries, this can mean relying on spatio-temporal data about abundance (or biomass) of species, diet (stomach) information, data on sea surface temperature, ocean acidification as well as data on fishing catches, efforts, prices or seafood consumptions. Such data are clearly non-homogeneous. Moreover, these data can also be of poor quality, as many countries lack the institutional capacity to collect high-quality data and track large fleets in small-scale fisheries (Cojocaru et al., 2022).

Fourthly, **mathematical models can be used to evaluate marine social-ecological systems.** Models can also synthetize, summarize or highlight key information on the system performance and how it relates to reference values. Bio-economic indicators and metrics include biodiversity metrics, fishing fleet profits, demand of consumers, to mention a few (Seijo and Caddy, 2000); and increasingly there is interest in triple bottom line indicators (people, planet, profit) for fisheries (Péreau et al., 2012; Anderson et al., 2015). Such bio-economic indicators and criteria are necessary for relevant empirical analysis of fisheries data. Still, such indicators are clearly non-homogeneous and difficult to aggregate and integrate, and some simple indicators based on catches alone can be misleading about the status of the fishery (Li and Smith, 2021b). In that regard, of interest for bio-economic models are assessments relating to the good health, the safety, the sustainability and viability of systems based on tolerable or desirable thresholds (Bruckner et al., 1999; Béné et al., 2001; Cury et al., 2005; Rockström et al., 2009; Baumgärtner and Quaas, 2009; Oubraham and Zaccour, 2018).

Fifthly, **mathematical models are useful for producing insights and results in support of decision making and management.** In particular model-based scenarios to derive projections about the future from a model are very informative tools for management and public policies (IPBES, 2016) in fisheries as illustrated in Figure 1. As stressed by IPBES (2016) or Doyen (2018), model-based scenarios are paths-trajectories relying on a mathematical or numerical model that is consistent with historical or observed evolutions, dynamics and data. This consistency is usually obtained through the calibration of models. In other words, the estimation of the value of parameters underpinning the model is achieved by fitting the observations and data to the outputs induced by the model. Once calibrated or estimated, bio-economic models can be used

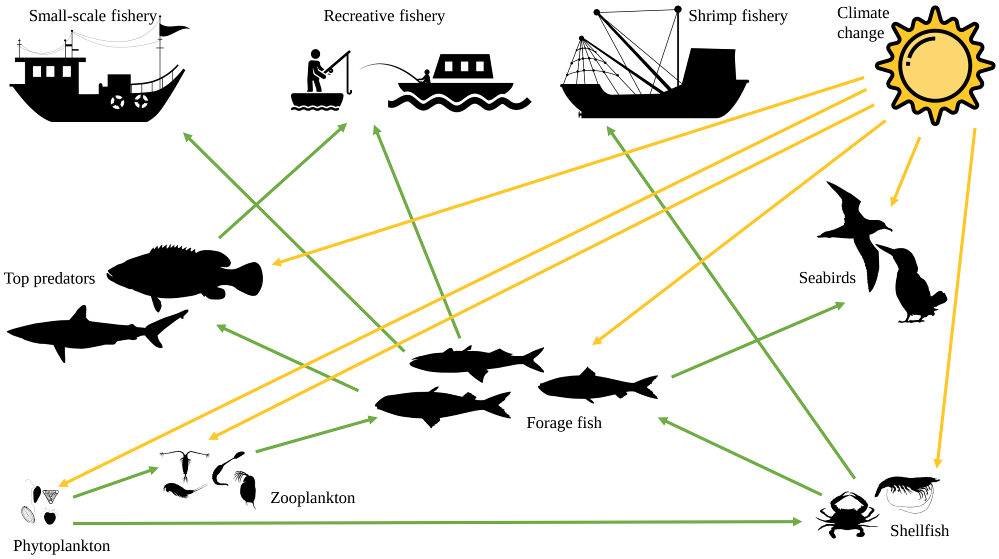


Figure 2: An illustration of marine ecosystem interactions and dynamics.

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. At this stage, it is useful to distinguish between predictive, exploratory and normative scenarios (Börjeson et al., 2006), as described in Figure 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... ?'* (Maury et al., 2017). They 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. The four scenarios of MEA (2005) including 'Global Orchestration', 'Adapting Mosaic', 'TechnoGarden' and 'Order from Strength' exemplify such explorative scenarios. By contrast, target-seeking scenarios or normative scenarios, deal with the question '*What should happen to reach...?*' and represent an agreed-upon future goals and scenarios that provide alternative pathways for reaching such an objective. In that normative context, determining sustainability scenarios for marine biodiversity and ecosystem services constitutes an important challenge. In the perspective of model-based scenarios, there is a debate between mechanistic and statistical causal inference models. Mechanistic models are based on laws, functional responses, dynamics and processes; as such, mechanistic models are valid far beyond the calibration space if they are well parameterized empirically. Such flexibility and ubiquity is limited with causal inference statistical models, which typically rely on fewer assumptions but are fundamentally about evaluating past interventions (e.g, the effects of catch shares on the race to fish as in Birkenbach et al. (2017)). In practice, one can easily change process setup and parameters in mechanistic models to generate process understanding, but they are only as good as their underlying assumptions and empirical grounding. Increasingly, there are efforts to combine bio-economic mechanistic models with policy evaluation to prevent us from drawing spurious inferences and thereby guarding against bad policy decisions (Smith et al., 2017; Ferraro et al., 2019; Li and Smith, 2021a). Implicit in developing predictive, normative, and exploratory scenarios is a parameterization of causal mechanisms, which creates a dialog between bio-economic model development and empirical causal inference studies in applied economics and other disciplines (Ferraro et al., 2019; Schlüter et al., 2023).

3 Mathematics of the ecosystem-based management approach

This section outlines the ecological complexity to consider in a Mathematical Bio-economics 2.0 Program for Sustainable Fisheries. Many scientists and stakeholders indeed argue that the current shortcomings of public policies for the management of biodiversity and ecosystems can be explained by an insufficient account for complexity in existing models. Typically in fisheries, they advocate an ecosystem-based fishery management (EBFM) (Pikitch et al. 2004; 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 towards multi-species, trophic interactions and spatially explicit models (Fulton et al., 2019).

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 as captured by Figure 2. Interspecific interactions 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 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 to foster 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 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 fisheries management. In particular, climate change impact primary production and fish distribution and thus potentially affect fishing yields (Cury et al., 2008; Sumaila et al., 2011; Fromentin et al., 2022; Barange et al., 2018; Kroetz et al., 2022). The key role of habitat for EBFM is exemplified by mangroves as nurseries for fishes or by coral reef as refuge for prey facing piscivors. Mangroves and coral reefs are under pressure worldwide.

Going further into the integration of complexities for EBFM thus adopting a very holistic viewpoint, FAO (2003); Pitcher et al. (2009); Plaganyi (2007); Link et al. (2017) also argue that EBFM should integrate social, economic and human well-being dimensions of complexity. However, while the general idea of EBFM is widely accepted (Spence et al., 2018), it remains largely unused in bio-economic models, and therefore in supporting decision making. The curse of dimensionality (De Lara and Doyen, 2008) entailed by EBFM is a major methodological limitation for the use of operations research, mathematics of decision making and management sciences for EBFM. Thus operationalizing the EBFM approach requires new models or, at the 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; Ragozin and Brown, 1985), habitat dependence (Barbier, 2003; Smith, 2007; Jean-Marie and Tidball, 2023), and spatial-dynamics of a metapopulation (Sanchirico and Wilen, 1999; Smith et al., 2009). Many of these models share a common mathematical structure. For example, a spatial-dynamic bio-economic model with continuous time and discrete (patchy) space (Sanchirico and Wilen, 1999) resembles a predator-prey or multispecies bio-economic model in continuous time (e.g, Hannesson (1983)) if one attaches different interpretations to the species or spatial interaction terms (Smith et al., 2012). Some attempts to deal with the dimensionality and EBFM also used stylized approaches, such as financial portfolio theory (Sanchirico et al., 2008), 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 (e.g. Hamon et al. (2014); Lagarde et al. (2018); Diop et al. (2018); Beckensteiner et al. (2023)), and interactions between fisheries and other uses of marine areas and resources (e.g. Boncoeur et al. (2002); Scheld et al. (2022); see also section 5 below).

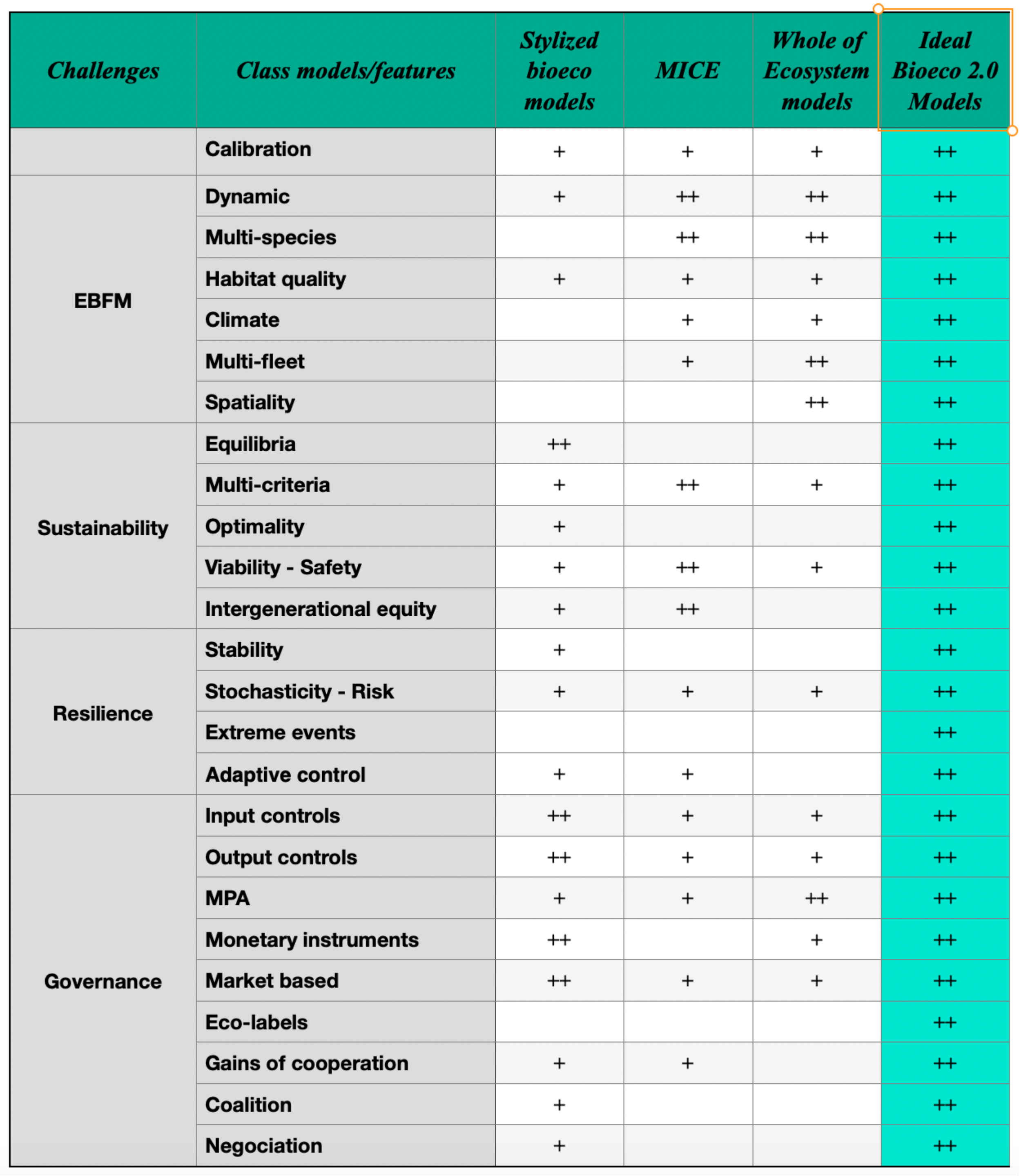
Anyway, more globally, there is a methodological debate when operationalizing the EBFM between ‘Whole of Ecosystem’ (e.g. end-to-end models), such as Atlantis, Osmose or Apecosm (Shin and Cury, 2004; Fulton et al., 2011; Maury and Poggiale, 2013) and ‘Models of Intermediate Complexity for Ecosystem’ (MICE) (Hannah et al., 2010; Plagányi et al., 2014; Gomes et al., 2021; Cuilleret et al., 2022). ‘Whole of Ecosystem’ or end-to-end models adopt a very holistic approach articulating many system components. Sometimes such models integrate a fleet dynamics and other economic components (see FISHMIP community). In contrast, the use of MICE aims to maintain the simplicity of stylized mathemaical 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 economic terms while being well-posed mathematically and numerically. 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 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 (Doyen, 2018). 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 (Sanchirico et al., 2008).

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. For example, when a system has components exhibiting characteristic time scales of different orders of magnitude, there are methods allowing to analyze the system by splitting the system in several parts (Auger and Poggiale, 1998; Boudjellaba and Sari, 1999, 2009; Poggiale et al., 2020). In a first step, it allows us to simplify the analysis because we can deal with subsystems which are simpler than the whole system. Furthermore, the theory allows to make the link between the dynamics of the subcomponents and that of the whole system. For example, one such method is the separation of system's 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. There are several references in the literature that discuss the use of fast-slow dynamics and model reduction techniques. For instance, Moussaoui and Auger (2021); Moussaoui et al. (2023); Bravo de la Parra et al. (2023) discuss the use of aggregation methods in model reduction in ecological and fishery systems. Some promising extensions of the method would be very useful to deal with more complex systems (Poggiale et al., 2020) exhibiting complex dynamics, like rapid population collapses after a smooth and small perturbation for instance. Of interest is also the strategy to reduce the complexity in MICE consisting in 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 lists the merits and shortcomings of the different classes of models regarding EBFM and thus highlights the gaps that need to be addressed in Mathematical Bio-economics 2.0 for Fisheries. The different classes of models include ‘classical stylized bio-economic 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 on the first rows relies on different key items derived from EBFM challenges and the complexity of the ecosystem. We here first focus on the content of models in terms of dynamics, multi-species, multi-fleet, spatiality, habitat quality, climate. Notation ‘+' means a moderate account of the item in the model class while 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.

4 Mathematics for sustainable fisheries

Operationalizing sustainability for fisheries is a major challenge in terms of criteria, standards and 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 a ‘Mathematical Bio-economics 2.0 for Fisheries’ program. It is achieved through the evaluation of bio-economic management, policies and model-based scenarios whether they are predictive, exploratory or normative (goal seeking) (IPBES, 2016). Again, we are not starting from scratch here since the word ‘sustainable’ is central in the very definition of MSY (maximum sustainable yield) but restricted to the sole ‘ecological’ dimension of sustainability. In other terms, MSY does



Challenges	*Class models/features*	*Stylized bioeco models*	*MICE*	*Whole of Ecosystem models*	*Ideal Bioeco 2.0 Models*
	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	+			++

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

Figure 3: The triple bottom line of sustainability stressing the need of multi-criteria approaches.

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 (IPBES 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 Tian, 2010; Asheim and Ekeland, 2016; Doyen and Martinet, 2012a; Fleurbaey, 2015) in particular in the bio-economics context. The challenge for a 'Mathematical Bio-economics 2.0' program is to go beyond the seminal approach of MSY (Gordon, 1954; Schaefer, 1954) based on equilibrium and steady state controls by adopting a more dynamic viewpoint. In that perspective, the results obtained by Clark (1973) from the optimal control approach in terms of transient and generalization of MSY-MEY (with the discounted or dynamic MEY versions) are pivotal and very fruitful. 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) and 'optimal' extinctions as stressed by Clark (1973); Swanson (1994). As an alternative criterion, the maximin (Cairns and Long, 2006), defined as the highest utility level that can be sustained over time, promotes intergenerational equity. In addition, Sumaila (2004); 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 in Howarth (1995) who argues that sustainability conditions need to be imposed prior to the maximization of any social welfare. In that regard, the account for safety or conservation constraints to fulfill over time emerges as a crucial issue (Rockström et al., 2009). In addition, it may prove difficult in practice to identify a unique measure of system performance that is considered adequate to support management decision-making. Multiple, non aggregable evaluation criteria may often coexist and serve as the basis for assessing whether a fishery is meeting sustainability objectives. 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; Eisenack et al., 2006; Martinet et al., 2007; Krawczyk and Kim, 2009; Doyen and Martinet, 2012a; Schuhbauer and Sumaila, 2016; Oubraham and Zaccour, 2018; Gajardo et al., 2018). 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 illustrated by Figure 3. 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 (Krawczyk and Kim, 2009; Maynou, 2014; Cissé et al., 2015; Doyen et al., 2017;

Briton et al., 2020). Among other approaches close to the viability approach and based on safety thresholds, one can mention the concept of Safe Minimum Standards (SMS) (Margolis and Naevdal, 2008) where tipping thresholds and risky areas are introduced (do Val et al., 2019), or the Tolerable Windows Approach (TWA) (Bruckner et al., 1999), based on safe boundaries and feasibility regions. Similarly, Rockström et al. (2009) developed a framework based on boundaries that delineate the safe operating space (SOS) for humanity, associated with the planet's biophysical subsystems or processes. The viability approach has been applied by numerous authors to the sustainable management of renewable resources and fisheries, as recently reviewed in Schuhbauer and Sumaila (2016); Oubraham and Zaccour (2018). The approach has also been proposed in support of identifying operational management objectives in the context of Management Strategy Evaluations involving stakeholder participation (Thébaud et al., 2014). Furthermore, Baumgärtner and Quaas (2009); Doyen and Martinet (2012b) point out the strong sustainability content of the viable control approach as opposed to the weak sustainability content underlying the optimal control framework (Neumayer, 2010). 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 non-substitutability 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, recreational values) may not have clear and agreed upon monetary values.

Interestingly, it turns out that maximin and viability approaches are strongly connected since the maximin emerges as a 'maximal viability' (Martinet et al., 2007; Doyen and Martinet, 2012b). More specifically, Doyen and Martinet (2012b) proved that the value function of the maximin problem is the solution of a static optimization problem involving the viability kernel as state constraint. Such a result has been generalized in the context of strong sustainability using Pareto optimality in Doyen and Gajardo (2020). Consequently, maximin trajectories or controls are specific and extreme viable trajectories or controls and thus inherit viability properties. 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 'Mathematical Bio-economics 2.0 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 about sustainability focuses on the content of models in terms of intergenerational equity and multi-criteria, equilibrium, optimality and viability.

5 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 and strategies (Fromentin et al., 2014; Grafton et al., 2023). Resilience influences many decisions and policies including how to tackle risk management in the private sector (Sheffi, 2015), development and finance investments (OECD), and management objectives of influential multilateral and United Nations agencies (e.g. FAO; World Bank). As a result, resilience is now included in several Sustainable Development Goals (SDGs): SDG 1 (No Poverty); SDG 2 (Zero Hunger); SDG 9 (Industry, Innovation and Infrastructure); SDG 11 (Sustainable Cities and Communities); SDG 13 (Climate Action); 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 (Downes et al., 2013; Quinlan et al., 2016; Grafton and Little, 2017; Béné and Doyen, 2018). For several decades now, leading scientists from different disciplines ranging from ecology, engineering sciences, psychology to economics have highlighted the significance of resilience and, importantly, the need for much better inclusion of resilience management into decision-making (Levin et al., 1998). In particular, practical guidance and modeling about how to operationalize resilience management are still required for fisheries and marine ecosystems.

To address uncertainties, it is very common to complete the study of the bioeconomic models 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; Aldebert et al., 2016). 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 (Shaefer, Cobb-Douglass, CES, ...)

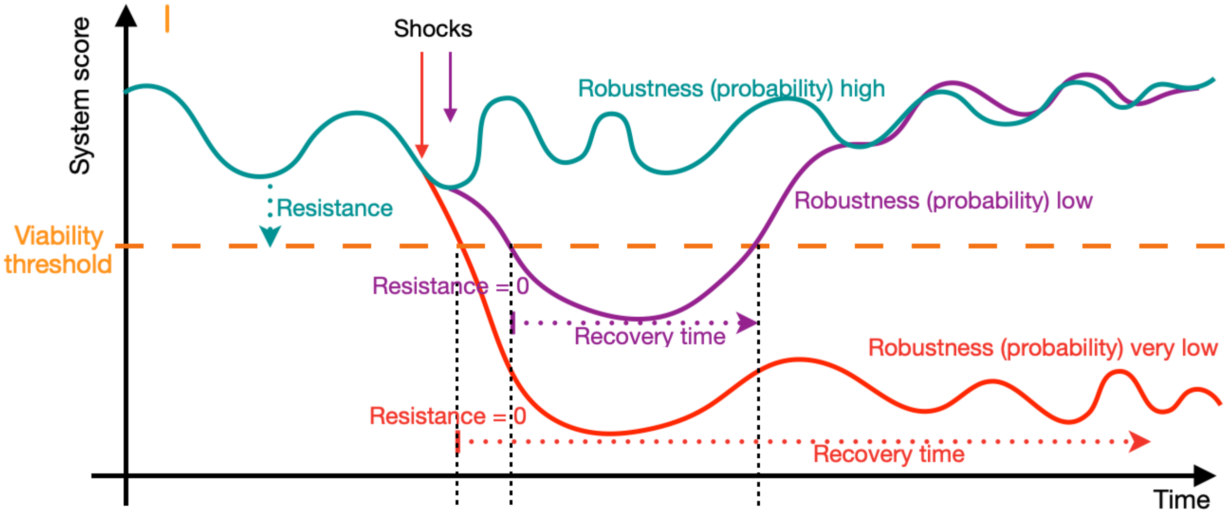


Figure 4: Illustration of the 3Rs of resilience: recovery, resistance and robustness with three contrasted trajectories in blue, purple and red.

underlying stylized bio-economic models. The model can indeed provide very different outputs even with qualitatively similar functional forms.

Beyond parameter and structural sensitivity analysis, there is an abundant literature about uncertainties and stochasticities in fisheries modeling, starting with, among others (Reed, 1979; Clark and Kirkwood, 1986) and later (Sethi et al., 2005). The accounting of uncertainties in fisheries management has been also put forward for decades with the concept of Adaptive Management and Feedback Control (Holling, 1978; Walters, 1986). Adaptive management is a strategy for considering unpredictable changes in the ecosystem, such as recruitment failure, as major causes of stock collapse. Recent works identifying adaptive fishing strategies based on risk aversion and diversification include Gourguet et al. (2014); Tromeur et al. (2021). Moreover, all fishers learn from their successes and failures. A fisher will try a new fishing method, for example, monitor the results and see how the results compare to what was predicted to happen. Thus, adaptive management is an iterative process that consists of an integrated progression of learning by doing. Such an iterative process also relate to 'Management Strategy Evaluation' (Butterworth, 2007; Thébaud et al., 2014). Kalman Filter can be a relevant mathematical tool 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, Béné and Doyen (2018); Grafton et al. (2019); Cuilleret et al. (2022); Grafton et al. (2023) have made significant progress in the definitions and objectives of resilience-based management for environmental issues. They postulate that resilience-based management needs to be first defined with respect to desired and normative situations for the system at play (*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 4 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 3R's of resilience— recovery, resistance and robustness. The 3Rs are complementary quantitative ingredients of resilience as exemplified by Figure 4. 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; Martin, 2004). 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; Béné and Doyen, 2018). Robustness, or reliability, refers to the probability of coping with the shocks and uncertainties with respect to a sustainable system (Baumgärtner and Strunz, 2014). Said differently, recovery highlights the temporal dimension of resilience in line with well-known minimal time problem (Cardaliaguet et al., 1997; Cannarsa and Sinestrari, 1995) in control theory. Resistance gives insights on the 'room for manoeuvre' for resilience in line with basin of attraction for stability issues or capture basin for target issues. And robustness (or reliability) sheds light on the probability of resilience, in line with risk management (Rockafellar, 2010), the so-called chance constraints and the value at risk. In that regard, accounting for extreme event 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. Such a 3R-based framework has recently been applied to fisheries management by Cuilleret et al. (2022) in the case of small-scale fisheries in French Guiana.

More generally, we argue that the mathematics related to stable control, decision under uncertainty, risk management and stochastic control will play major roles for the resilience-based management of fisheries and the Mathematical Bio-economics 2.0 program for Fisheries. Table 1 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.

6 Mathematics of the governance for bio-economic public policies

The heterogeneity of actors involved in fisheries also 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; Hannesson, 1997; Sumaila, 1999; Vallee and Guillotreau, 2017; Bailey et al., 2010; Breton and Keoula, 2014; Grønbæk et al., 2018; Doyen et al., 2018; Breton et al., 2019; Dahmouni et al., 2019, 2023). Moreover, the goals of the different agents or groups are often contradictory and public policies may result in trade-offs (Bellanger et al., 2021). Bio-economics is thus required to design instruments entailing consensus, coordination and participation among agents towards ecosystem-based, sustainable and resilient fisheries. Existing cooperative structures for fisheries vary with scales, 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, efforts;
- Individual (or community) Transferable quotas (ITQs); and more globally allocation of shares in a fishery that can be trade 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 in Clark (1990); Thébaud et al. (2023b) to mention a few. TAC, licenses and MPAs are among the most applied or studied instruments. We argue that the role of MPAs, of market-based solutions including ITQs (Costello et al., 2008; Péreau et al., 2012) as well as eco-labels need to be especially explored for incorporation in a Mathematical Bio-economics Program 2.0 for fisheries. We discuss below in more details the strengths and drawbacks of these instruments.

Restricting access to fisheries and allocating shares of a Total Allowable Catch (TAC) is a key and often successful tool for regulating fisheries (Hilborn et al., 2020). With costs and fishing abilities varying among fishers, the addition of transferability of individual quotas (ITQs) allows fishers to choose between continuing to fish or transferring (by sale or lease) their quota holdings to other fishers. ITQs thus offer a decentralized method of allocating catch possibilities within fisheries that should promote efficient resource use (Grafton et al., 2000). Recent reviews of the experience with ITQs in fisheries show that they are increasingly being adopted, and that this has been associated with improved status of fish stocks and levels of catches (Newell et al., 2005; Thébaud et al., 2012). In contexts where excess capacity in the fishery exists, introducing ITQs should lead to a decrease in fishing capacity as catch privileges are transferred to the more efficient fishers. Although this is an impact that could be expected, and to some extent desired, it has turned out to be one of the key points of debate on the opportunity and effectiveness of introducing ITQs as a management instrument in fisheries. The social consequences of these reductions have in some cases been considered important enough that they may outweigh the expected ecological and economic benefits of the regulations, leading to questions about their acceptability and feasibility (Péreau et al., 2012). These criticisms demonstrate once again that no single management instrument is a panacea (Ostrom et al., 2007). Some authors (e.g., Sumaila (2018)) have tried to identify design considerations for ITQs that can mitigate some of their shortcomings.

MPAs - areas where fishing is prohibited or restricted - are a multipurpose fishery management and conservation tool in line with sustainability (Sumaila, 2002). They are particularly useful to protect habitat, biodiversity, and species of particular concern, and they may be a useful hedge against uncertainty and thus promote resilience, provided that effective and efficient control of access to the MPA be in place (Grafton et al., 2005; Doyen et al., 2007; Reithe et al., 2014). Their bio-economic relevance however strongly depends on the fish spillovers between the conservation areas and the surrounding fished areas whenever these MPA have fixed locations. Rotational MPAs constitute another option (Chen and Hastings, 2023).

Regarding eco-labels, they relate to consumer choices which are based on a wide variety of motivations, ranging from social responsibility to specific individual needs. Interesting in this perspective is that consumers, worldwide, are more and more aware of the necessity of ensuring that the environment is protected and that their individual choices and actions can contribute towards achieving this goal (Vermeir and Verbeke, 2006). In that context, eco-labels (Salladarré et al., 2010; Jonell et al., 2016; Giacomarra et al., 2021; Bronnmann et al., 2021) can play a major role in increasing the awareness of consumers regarding sustainability issues. Since their introduction in the late 1990s, fishery sustainability certification has become a major ingredient of marine conservation strategies. Many of these programs emerged largely from increased concerns within civil society that current stock management and policies have failed in ensuring the sustainability of fisheries (Sainsbury, 2023). The key function of these programs is to differentiate fisheries through a set of standards relating to stock status, management practices, and ecosystem impacts.

To assess the ability of these different instruments in supporting sustainability of uses of marine biodiversity and resilience of marine ecosystems, the conceptual tools of game theory, from both cooperative and non cooperative branches, are extremely useful (Munro, 1979; Sumaila, 1999; Kaitala and Lindroos, 2007; Bailey et al., 2010; Breton and Keoula, 2014; Grønbæk et al., 2018; Dahmouni et al., 2019). 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 issues because it provides important quantitative and qualitative insights into the strategic interactions between users exploiting a common renewable resource (see e.g. Kaitala and Munro (1995); Hannesson (1997); Finus and Caparrós (2015)). 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[1]. The result of Levhari and Mirman (1980) illustrates the famous tragedy of over-exploitation of resources in open access. Between these two extreme cases, full cooperation and no cooperation, the sustainability of partial cooperation has been recently studied by Breton and Keoula (2014); Doyen and Péreau (2012). It also turns out such sustainability of partial cooperation can be enhanced by the closeness to bioeconomic tipping points and critical limits (Lindahl et al., 2016; Flaaten, 1998).

However, as pointed out by Bailey et al. (2010), 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; Flaaten, 1998), meta-populations distributed over connected areas (Costello et al., 2019), or the works of Fischer and Mirman (1996); Breton et al. (2019); Doyen et al. (2018) which account for the interaction between different species of fish, including prey-predator relations, symbiotic interactions and mutual competition.

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[1] The non-cooperative situation refers to a framework in which each user maximizes its own intertemporal payoff without taking into account other users' scores (Sumaila, 1999). In contrast, in the cooperative case, users jointly define a harvesting strategy.

A computational application of a predator-prey model can be found in Sumaila (1997) in which a game theoretic cod-capelin predator-prey model was developed. Herrera et al. (2016) also showed that MPAs may also play a role in ensuring sustainable fisheries on the high seas, where a limited number of countries compete in a noncooperative fishing game. Nevertheless, the use of game theory in broader ecosystem-based 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 game theory and strategic interactions will play major roles for a relevant governance towards resilience and sustainability-based management of fisheries and 'Mathematical Bio-economics 2.0'. They should help reduce the gap between the theoretical insights of Mathematical Bio-economics 2.0 and practical fisheries management that incorporates the behavior and interests of stakeholders. Last rows of Table 1 summarizes the merits of different classes of models for fisheries with respect to such governance issues, in particular, in terms of instruments and strategic interactions.

7 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 model-based scenarios of biodiversity and ecosystems that make sense economically, ecologically, 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 'Mathematical Bio-Economics 2.0' 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; (iv) the mathematics and modeling of governance and strategic interactions. Our analysis 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.

To this end, the present paper provides modeling and mathematical insights in line with IPBES Chapter (Ferrier et al., 2016) devoted to 'Methodological assessment of scenarios and models of biodiversity and ecosystem services'. We argue that complex dynamic systems combined with control theory, including stochastic control together with game theory, is relevant to design predictive, exploratory and normative model-based scenarios (Börjeson et al., 2006; Doyen, 2018) of marine biodiversity, ecosystem and the services they provide. Such relevance to design bio-economic model-based 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. These mathematical frameworks for the design of bio-economic model-based scenarios make it possible to operationalize and quantify both the ecosystem approach, sustainability, resilience and governance of fisheries. Indeed, challenge (i) addresses the capability of this general modeling framework to account within model-based scenarios for the various degrees of complexity occurring in ecological processes and at their interfaces with social and economic processes as in bio-economics. In particular, the description of natural and social marine systems in terms of states, controls, parameters, disturbances and observations allows for relevant integrated modeling to consider the complex dynamics, the multiplicity of drivers, decisions and uncertainties underlying scenarios of biodiversity and ecosystem services. Such a mathematical approach can thus represent in a synthetic way multi-species, multi-fishing fleets, multi-drivers, spatially explicit and multi-scale dynamics while also capturing various sources of uncertainty. Furthermore, challenge (ii) about sustainability modeling and metrics addresses multi-criteria and multi-target issues underpinning the evaluation of scenarios of marine biodiversity and ecosystem services. The multiplicity of metrics needed to address sustainability issues for fisheries management is exemplified by the numerous indicators of biodiversity as well as the numerous marine ecosystem services. The ability of the optimal and viable control approach to balance such various ecological and economic scores and to promote sustainability through scenarios (Clark and Munro, 1975; Doyen, 2018; Oubraham and Zaccour, 2018) shows the relevance of the general framework based on (dynamic) control theory advocated in this paper. The sustainability approach of challenge (ii) addresses through normative scenarios the ability of such modeling framework to reconcile short and long terms and promoting intergenerational equity (Doyen and Martinet, 2012a; Ekeland et al., 2015). Challenge (iii) focusing on resilience stresses that the control theory of dynamics systems under uncertainty combined with bio-economic viability objectives is well-suited for the mitigation of bio-economic risks and vulnerabilities by considering uncertainties, shocks within management strategies and scenarios, including endogenous uncertainty. The governance issues constitute another major challenge as pointed out in Bailey et al. (2010). Facing the heterogeneity of stakeholders involved in biodiversity dynamics and including consumers, farmers, fishers, ONGs, or regulating agencies, there is an obvious need for decision makers to coordinate them or to limit the failures of cooperation and the tragedy of open-access. In that regard, the dynamic framework put forward in our paper can also be easily expanded by using tools and concepts from dynamic game theory to address the challenges relating to strategic interactions and the relevance of regulatory instruments in terms of sustainability and resilience. On all five axes, bioeconomic models have the potential to help mediate discussions relating to collective choices, as part of the decision-making processes which structure policy design and implementation regarding sustainable ocean uses. In particular, MathBioEco 2.0 should support stakeholder engagement in model-based approaches in line with the purpose of science-policy interfaces (see e.g. Gail et al., 2022).

More specifically, among the main gaps emerging from Table 1 for a Mathematical and Modeling Bio-Economics 2.0 for Sustainable Fisheries, we would like to stress the following cutting-edge research and challenges:

- Definition and quantification of an ecosystem-based MSY (EBMSY) and MEY (EBMEY);
- Highlight bioeconomic resilience gains of 'EBMEY' when compared to 'EBMSY';
- Application of multi-criteria, maximin and viable control approach for sustainable and resilient fisheries;
- Account of extreme events in resilience-based management for fisheries through flat tail random distribution;
- Application and analyze bioeconomic sustainability (and resilience) gains vs. loss of market-based instruments for the decentralization of public policies for fisheries;
- Propose and analyse MICE models of sustainable seafood systems (From Fish to Fork).

Advancing these more specific issues should allow for bridging the divide between theoretical mathematical bioeconomics 2.0, model-based scenarios and the practical quantitative management of fisheries and seafood systems.

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