



HAL
open science

Mathematical Bio-Economics 2.0 for Sustainable Fisheries

L Doyen, M D Smith, U R Sumaila, G Zaccour, I Ekeland, P Cury, C Lett, O Thebaud, J.-C Poggiale, A Moussaoui, et al.

► **To cite this version:**

L Doyen, M D Smith, U R Sumaila, G Zaccour, I Ekeland, et al.. Mathematical Bio-Economics 2.0 for Sustainable Fisheries. 2024. hal-04446752v1

HAL Id: hal-04446752

<https://hal.inrae.fr/hal-04446752v1>

Preprint submitted on 8 Feb 2024 (v1), last revised 13 Feb 2024 (v3)

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

Mathematical Bio-Economics 2.0 for Sustainable Fisheries

L. Doyen, M. D. Smith, U. R. Sumaila,
G. Zaccour, I. Ekeland, P. Cury,
C. Lett, O. Thebaud, J.-C. Poggiale,
A. Moussaoui, J.-M. Fromentin, S. Gourguet,
P. Guillotreau, H. Gomes, , P. Courtois,,
R. Schaap, F. Blanchard, C. Rainer,
M. Cuilleret, T. Villain, F. Menard
& T. Sari



CEE-M Working Paper 2024-03

Mathematical Bio-Economics 2.0 for Sustainable Fisheries

L. Doyen^{*,1}, M. D. Smith², U. R. Sumaila³, G. Zaccour⁴, I. Ekeland⁵, P. Cury⁶, C. Lett⁶, O. Thebaud⁷, J.-C. Poggiale⁸, A. Moussaoui⁹, J.-M. Fromentin⁶, S. Gourguet⁷, P. Guillotreau⁶, H. Gomes¹⁰, P. Courtois¹, R. Schaap¹, F. Blanchard¹¹, C. Rainer¹², M. Cuilleret¹, T. Villain¹³, F. Menard⁸, and T. Sari¹⁴

¹CEEM, CNRS, INRAE, Univ. Montpellier, Supagro, Montpellier, France

²Nicholas School of the Environment and Department of Economics, Duke University, USA

³Oceans & Fisheries Economics, University of British Columbia, Canada

⁴GERAD, Groupe d'études et de recherche en analyse des décisions, HEC Montreal, Canada

⁵CEREMADE, Centre de Recherche de Mathématiques de la Décision, University of Paris-Dauphine, France

⁶MARBEC, Univ. Montpellier, CNRS, Ifremer, IRD, Sète, France

⁷Ifremer, Univ Brest, CNRS, UMR 6308, AMURE, Unité d'Economie Maritime, IUEM, Plouzané, France

⁸Aix Marseille Univ, Université de Toulon, CNRS, IRD, MIO, Marseille, France

⁹Abou Bakr Belkaid University of Tlemcen, Algeria

¹⁰AZTI, Marine Research, Basque Research and Technology Alliance (BRTA), Sukarrieta, Spain

¹¹Ifremer, USR LEEISA, Cayenne, French Guiana

¹²LMBA, Laboratoire de Mathématiques de Bretagne Atlantique, Brest University, France

¹³IEES, Sorbonne Université, Paris, France

¹⁴ITAP, Univ Montpellier, INRAE, Institut Agro, Montpellier, France

February 6, 2024

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.

*Corresponding author: luc.doyen@cnrs.fr

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 inequities 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.

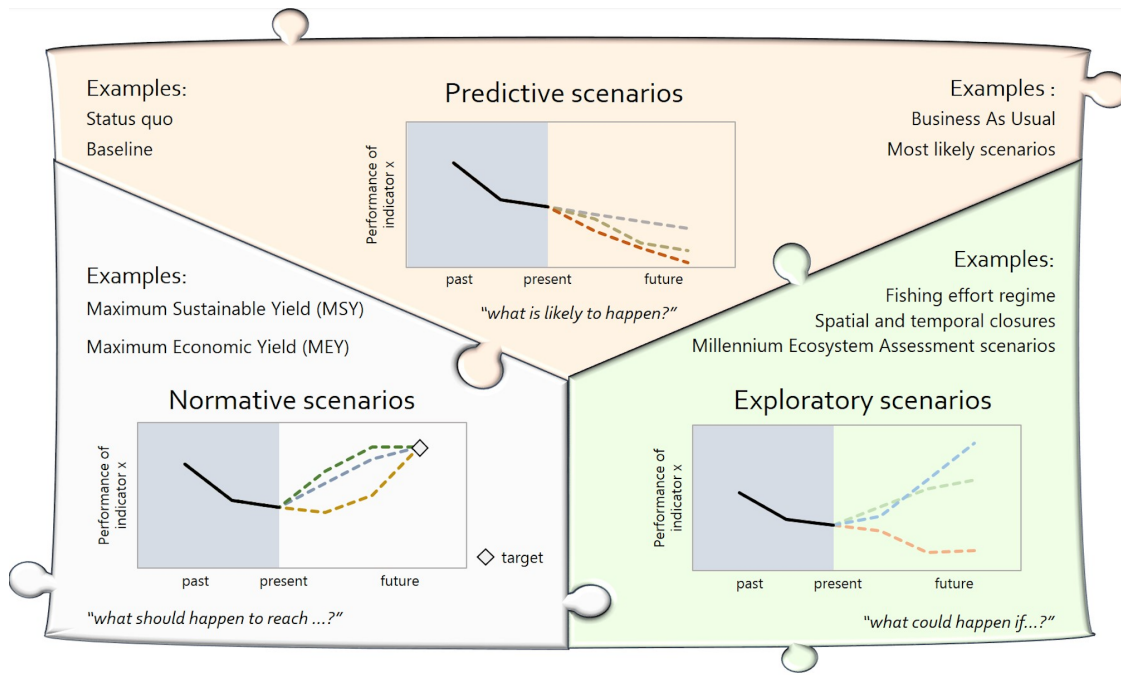


Figure 1: Description and use of predictive, exploratory and normative scenarios. Solid black lines correspond to past observed trajectories, and dashed color lines represent projected pathways. The figure is inspired by IPBES (2016).

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 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 synthesize, 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

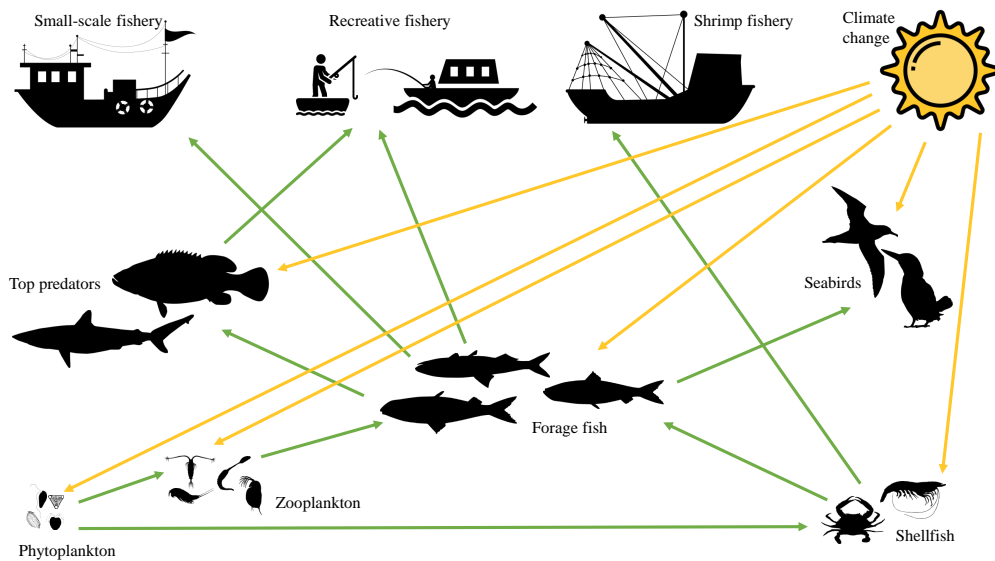


Figure 2: An illustration of marine ecosystem interactions and dynamics.

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 piscivores. 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); Beckenstein 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 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 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

<i>Challenges</i>	<i>Class models/features</i>	<i>Stylized bioeco models</i>	<i>MICE</i>	<i>Whole of Ecosystem models</i>	<i>Ideal Bioeco 2.0 Models</i>
	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	+			++
	Negotiation	+			++

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-Douglas, CES, ...)

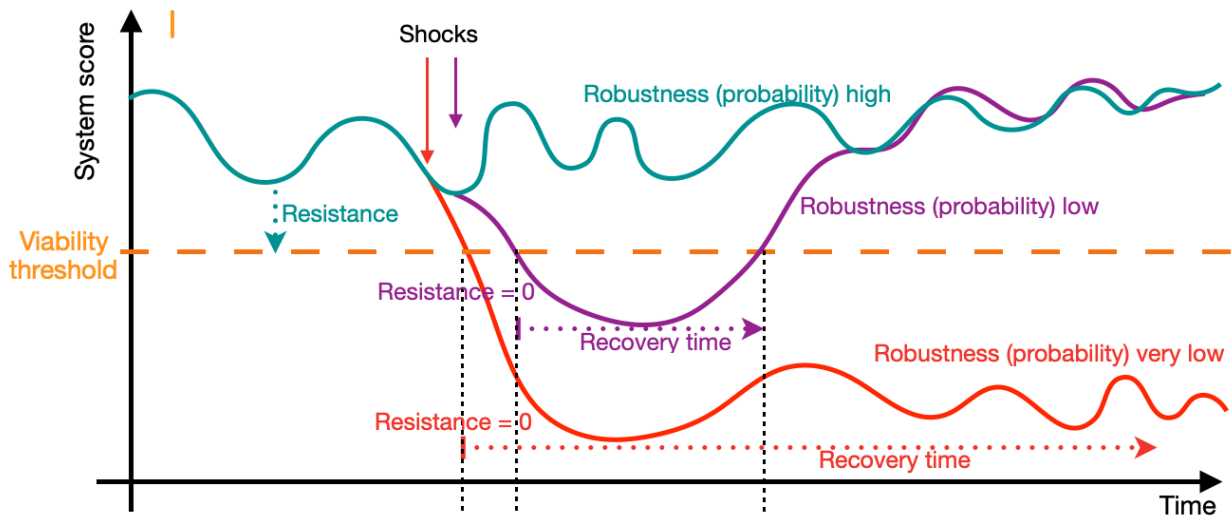


Figure 4: Illustration of the 3Rs of resilience: recovery, resistance and robustness with three contrasted trajectories in blue, purple and red.

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; Grønabæk 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; Grønbaek 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 equilibrium¹. 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.

¹The 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.

Acknowledgments. This work has been carried out with the financial support of the CNRS and IMPT (Institut des Mathématiques de la Planète Terre) through the network MESSH (Mathematics for bio-Economics and Sustainability of fiSHeries). In particular, this paper is a consequence of the international and interdisciplinary Symposium named ‘3Days MESSH’ held in Sète, France on January 2023. The support of the research centers MARBEC, CEREMADE, CEEM and AMURE was decisive. The role of the research projects COVPATH (Belmont Forum) and ENTROPIC (CNRS PRIME80) has also to be mentioned.

References

- J. K. Abbott, J. N. Sanchirico, and M. D. Smith. Common property resources and the dynamics of overexploitation: The case of the north pacific fur seal—a 42-year legacy. *Marine Resource Economics*, 33 (3):209–212, 2018. doi: 10.1086/698020. URL <https://doi.org/10.1086/698020>.
- C. Aldebert, D. Nerini, M. Gauduchon, and J. Poggiale. Structural sensitivity and resilience in a predator–prey model with density-dependent mortality. *Ecological Complexity*, 28:163–173, 2016. ISSN 1476-945X. doi: <https://doi.org/10.1016/j.ecocom.2016.05.004>. URL <https://www.sciencedirect.com/science/article/pii/S1476945X16300460>.
- J. L. Anderson, C. M. Anderson, J. Chu, J. Meredith, F. Asche, G. Sylvia, M. D. Smith, D. Anggraeni, R. Arthur, A. Guttormsen, J. K. McCluney, T. Ward, W. Akpalu, H. Eggert, J. Flores, M. A. Freeman, D. S. Holland, G. Knapp, M. Kobayashi, S. Larkin, K. MacLauchlin, K. Schnier, M. Soboil, S. Tveteras, H. Uchida, and D. Valderrama. The fishery performance indicators: A management tool for triple bottom line outcomes. *PLOS ONE*, 10(5):1–20, 05 2015. doi: 10.1371/journal.pone.0122809. URL <https://doi.org/10.1371/journal.pone.0122809>.

- F. Asche, H. Eggert, A. Oglend, C. A. Roheim, and M. D. Smith. Aquaculture: Externalities and policy options. *Review of Environmental Economics and Policy*, 16(2):282–305, 2022. doi: 10.1086/721055. URL <https://doi.org/10.1086/721055>.
- G. B. Asheim and I. Ekeland. Resource conservation across generations in a ramsey–chichilnisky model. *Economic Theory*, 61(4):611–639, Apr 2016. ISSN 1432-0479. doi: 10.1007/s00199-016-0965-4. URL <https://doi.org/10.1007/s00199-016-0965-4>.
- J.-P. Aubin and H. Frankowska. Viability kernel of control systems. In *Nonlinear synthesis*, pages 12–33. Springer, 1991.
- P. Auger and J.-C. Poggiale. Aggregation and emergence in systems of ordinary differential equations. *Mathematical and Computer Modelling*, 27(4):1–21, 1998. ISSN 0895-7177. doi: [https://doi.org/10.1016/S0895-7177\(98\)00002-8](https://doi.org/10.1016/S0895-7177(98)00002-8). URL <https://www.sciencedirect.com/science/article/pii/S0895717798000028>.
- M. Bailey, U. Rashid Sumaila, and M. Lindroos. Application of game theory to fisheries over three decades. *Fisheries Research*, 102(1):1–8, 2010. ISSN 0165-7836. doi: <https://doi.org/10.1016/j.fishres.2009.11.003>. URL <https://www.sciencedirect.com/science/article/pii/S0165783609003051>.
- W. Bank. *The Sunken Billions Revisited: Progress and Challenges in Global Marine Fisheries*. Environment and Development. World Bank, 2017. URL <http://hdl.handle.net/10986/24056>.
- M. Barange, T. Bahri, M. Beveridge, K. Cochrane, S. Funge-Smith, and F. Poulain. *Impacts of climate change on fisheries and aquaculture: synthesis of current knowledge, adaptation and mitigation options*. Food & Agriculture Organization of the United Nations (FAO), 2018. URL <https://www.fao.org/3/i9705en/i9705en.pdf>.
- E. B. Barbier. Habitat–fishery linkages and mangrove loss in thailand. *Contemporary Economic Policy*, 21(1):59–77, 2003. doi: <https://doi.org/10.1093/cep/21.1.59>. URL <https://onlinelibrary.wiley.com/doi/abs/10.1093/cep/21.1.59>.
- S. Baumgärtner and M. Quaas. Ecological-economic viability as a criterion of strong sustainability under uncertainty. *Ecological Economics*, 68(7):2008–2020, 2009. ISSN 0921-8009. URL https://econpapers.repec.org/article/eeecolec/v_3a68_3ay_3a2009_3ai_3a7_3ap_3a2008-2020.htm. Publisher: Elsevier.
- S. Baumgärtner and S. Strunz. The economic insurance value of ecosystem resilience. *Ecological Economics*, 101:21–32, 2014. ISSN 0921-8009. doi: <https://doi.org/10.1016/j.ecolecon.2014.02.012>. URL <https://www.sciencedirect.com/science/article/pii/S0921800914000597>.
- J. Beckensteiner, F. Boschetti, and O. Thébaud. Adaptive fisheries responses may lead to climate maladaptation in the absence of access regulations. *npj Ocean Sustainability*, 2(1):1–5, Mar. 2023. ISSN 2731-426X. doi: 10.1038/s44183-023-00010-0. URL <https://www.nature.com/articles/s44183-023-00010-0>. Number: 1. Publisher: Nature Publishing Group.
- M. Bellanger, R. Fonner, D. S. Holland, G. D. Libecap, D. W. Lipton, P. Scemama, C. Speir, and O. Thébaud. Cross-sectoral externalities related to natural resources and ecosystem services. Working Paper 28480, National Bureau of Economic Research, February 2021. URL <http://www.nber.org/papers/w28480>.
- C. Béné and L. Doyen. From Resistance to Transformation: A Generic Metric of Resilience Through Viability. *Earth’s Future*, 6(7):979–996, July 2018. ISSN 23284277. doi: 10.1002/2017EF000660. URL <http://doi.wiley.com/10.1002/2017EF000660>.
- C. Béné, L. Doyen, and D. Gabay. A viability analysis for a bio-economic model. *Ecological Economics*, 36(3):385 – 396, 2001.
- A. M. Birkenbach, D. J. Kaczan, and M. D. Smith. Catch shares slow the race to fish. *Nature*, 544(7649): 223–226, Apr. 2017.
- J. Boncoeur, F. Alban, O. Guyader, and O. Thébaud. Fish, fishers, seals and tourists: Economic consequences of creating a marine reserve in a multi-species, multi-activity context. *Natural Resource Modeling*, 15(4): 387–411, 2002. doi: <https://doi.org/10.1111/j.1939-7445.2002.tb00095.x>. URL <https://onlinelibrary.wiley.com/doi/abs/10.1111/j.1939-7445.2002.tb00095.x>.
- L. Börjeson, M. Höjer, K.-H. Dreborg, T. Ekvall, and G. Finnveden. Scenario types and techniques: towards a user’s guide. *Futures*, 38(7):723–739, 2006. Publisher: Elsevier.

- H. Boudjellaba and T. Sari. Stability loss delay in harvesting competing populations. *J. Differ. Equ.*, 152(2): 394–408, Mar. 1999.
- H. Boudjellaba and T. Sari. Dynamic transcritical bifurcations in a class of slow–fast predator–prey models. *J. Differ. Equ.*, 246(6):2205–2225, Mar. 2009.
- R. Bravo de la Parra, J.-C. Poggiale, and P. Auger. The effect of connecting sites in the environment of a harvested population. *Math. Model. Nat. Phenom.*, 18:4, 2023. doi: 10.1051/mmnp/2023004. URL <https://doi.org/10.1051/mmnp/2023004>.
- M. Breton and M. Y. Keoula. A great fish war model with asymmetric players. *Ecological Economics*, 97:209–223, 2014. ISSN 0921-8009. doi: <https://doi.org/10.1016/j.ecolecon.2013.11.002>. URL <https://www.sciencedirect.com/science/article/pii/S0921800913003315>.
- M. Breton, I. Dahmouni, and G. Zaccour. Equilibria in a two-species fishery. *Mathematical Biosciences*, 309:78–91, 2019. ISSN 0025-5564. doi: <https://doi.org/10.1016/j.mbs.2019.01.004>. URL <https://www.sciencedirect.com/science/article/pii/S0025556418305212>.
- F. Briton, C. Macher, M. Merzeréaud, C. Le Grand, S. Fifas, and O. Thébaud. Providing Integrated Total Catch Advice for the Management of Mixed Fisheries with an Eco-viability Approach. *Environmental Modeling & Assessment*, 25(3):307–325, June 2020. ISSN 1420-2026, 1573-2967. doi: 10.1007/s10666-019-09685-7. URL <http://link.springer.com/10.1007/s10666-019-09685-7>.
- J. Bronnmann, M. T. Stoeven, M. Quaas, and F. Asche. Measuring motivations for choosing ecolabeled seafood: Environmental concerns and warm glow. *Land Econ.*, 97(3):641–654, Aug. 2021.
- T. Bruckner, G. Petschel-Held, F. Tóth, H.-M. Füssel, C. Helm, M. Leimbach, and H.-J. Schellnhuber. Climate change decision-support and the tolerable windows approach. *Environmental Modeling and Assessment*, 4(4):217–234, 1999.
- S. H. M. Butchart, M. Walpole, B. Collen, A. van Strien, J. P. W. Scharlemann, R. E. A. Almond, J. E. M. Baillie, B. Bomhard, C. Brown, J. Bruno, K. E. Carpenter, G. M. Carr, J. Chanson, A. M. Chenery, J. Csirke, N. C. Davidson, F. Dentener, M. Foster, A. Galli, J. N. Galloway, P. Genovesi, R. D. Gregory, M. Hockings, V. Kapos, J.-F. Lamarque, F. Leverington, J. Loh, M. A. McGeoch, L. McRae, A. Minasyan, M. H. Morcillo, T. E. E. Oldfield, D. Pauly, S. Quader, C. Revenga, J. R. Sauer, B. Skolnik, D. Spear, D. Stanwell-Smith, S. N. Stuart, A. Symes, M. Tierney, T. D. Tyrrell, J.-C. Vié, and R. Watson. Global biodiversity: Indicators of recent declines. *Science*, 328(5982):1164–1168, 2010. doi: 10.1126/science.1187512. URL <https://www.science.org/doi/abs/10.1126/science.1187512>.
- D. S. Butterworth. Why a management procedure approach? Some positives and negatives. *ICES Journal of Marine Science*, 64(4):613–617, 03 2007. ISSN 1054-3139. doi: 10.1093/icesjms/fsm003. URL <https://doi.org/10.1093/icesjms/fsm003>.
- R. D. Cairns and N. V. Long. Maximin: a direct approach to sustainability. *Environment and Development Economics*, 11(3):275–300, 2006.
- R. D. Cairns and H. Tian. Sustained development of a society with a renewable resource. *J. Econom. Dynam. Control*, 34(6):1048–1061, 2010.
- P. Cannarsa and C. Sinestrari. Convexity properties of the minimum time function. *Calculus of Variations and Partial Differential Equations*, 3(3):273–298, Jun 1995. ISSN 1432-0835. doi: 10.1007/BF01189393. URL <https://doi.org/10.1007/BF01189393>.
- P. Cardaliaguet, M. Quincampoix, and P. Saint-Pierre. Optimal times for constrained nonlinear control problems without local controllability. *Applied Mathematics and Optimization*, 36(1):21–42, Jul 1997. ISSN 1432-0606. doi: 10.1007/BF02683336. URL <https://doi.org/10.1007/BF02683336>.
- R. Chen and A. Hastings. Advantages and disadvantages of rotating spatial closures for managing fisheries. *Ocean-Land-Atmosphere Research*, 2:0002, 2023. doi: 10.34133/olar.0002. URL <https://spj.science.org/doi/abs/10.34133/olar.0002>.
- W. W. L. Cheung, T. L. Frölicher, V. W. Y. Lam, M. A. Oyinlola, G. Reygondeau, U. R. Sumaila, T. C. Tai, L. C. L. Teh, and C. C. C. Wabnitz. Marine high temperature extremes amplify the impacts of

- climate change on fish and fisheries. *Science Advances*, 7(40):eabh0895, Oct. 2021. ISSN 2375-2548. doi: 10.1126/sciadv.abh0895. URL <https://www.science.org/doi/10.1126/sciadv.abh0895>.
- A. Cissé, L. Doyen, F. Blanchard, C. Béné, and J.-C. Péreau. Ecoviability for small-scale fisheries in the context of food security constraints. *Ecological Economics*, 119:39–52, Nov. 2015. ISSN 09218009. doi: 10.1016/j.ecolecon.2015.02.005. URL <https://linkinghub.elsevier.com/retrieve/pii/S0921800915000440>.
- C. W. Clark. The economics of overexploitation. *Science*, 181(4100):630–634, 1973.
- C. W. Clark. *Mathematical bioeconomics*. Pure and Applied Mathematics (New York). John Wiley & Sons, Inc., New York, second edition, 1990.
- C. W. Clark and G. P. Kirkwood. On uncertain renewable resource stocks: Optimal harvest policies and the value of stock surveys. *Journal of Environmental Economics and Management*, 13(3):235–244, 1986. ISSN 0095-0696. doi: [https://doi.org/10.1016/0095-0696\(86\)90024-0](https://doi.org/10.1016/0095-0696(86)90024-0). URL <https://www.sciencedirect.com/science/article/pii/0095069686900240>.
- C. W. Clark and G. R. Munro. The economics of fishing and modern capital theory: a simplified approach. *Journal of environmental economics and management*, 2(2):92–106, 1975. Publisher: Elsevier.
- A. L. Cojocar, Y. Liu, M. D. Smith, W. Akpalu, C. Chávez, M. M. Dey, J. Dresdner, V. Kahui, R. B. M. Pincinato, and N. Tran. The “seafood” system: Aquatic foods, food security, and the global south. *Review of Environmental Economics and Policy*, 16(2):306–326, 2022. doi: 10.1086/721032. URL <https://doi.org/10.1086/721032>.
- F. Cordoleani, D. Nerini, M. Gauduchon, A. Morozov, and J.-C. Poggiale. Structural sensitivity of biological models revisited. *Journal of Theoretical Biology*, 283(1):82–91, 2011. ISSN 0022-5193. doi: <https://doi.org/10.1016/j.jtbi.2011.05.021>. URL <https://www.sciencedirect.com/science/article/pii/S0022519311002633>.
- C. Costello, S. D. Gaines, and J. Lynham. Can catch shares prevent fisheries collapse? *Science*, 321(5896):1678–1681, 2008. doi: 10.1126/science.1159478. URL <https://www.science.org/doi/abs/10.1126/science.1159478>.
- C. Costello, B. Nkuiya, and N. Quérou. Spatial renewable resource extraction under possible regime shift. *Am. J. Agric. Econ.*, 101(2):507–527, Mar. 2019.
- P. Courtois, C. Martinez, and A. Thomas. Spatial priorities for invasive alien species control in protected areas. *Science of The Total Environment*, 878:162675, 2023. ISSN 0048-9697. doi: <https://doi.org/10.1016/j.scitotenv.2023.162675>. URL <https://www.sciencedirect.com/science/article/pii/S0048969723012913>.
- R. K. Cowen and S. Sponaugle. Larval dispersal and marine population connectivity. *Annual Review of Marine Science*, 1(1):443–466, 2009. doi: 10.1146/annurev.marine.010908.163757. URL <https://doi.org/10.1146/annurev.marine.010908.163757>. PMID: 21141044.
- E. Crist, C. Mora, and R. Engelman. The interaction of human population, food production, and biodiversity protection. *Science*, 356(6335):260–264, 2017. doi: 10.1126/science.aal2011. URL <https://www.science.org/doi/abs/10.1126/science.aal2011>.
- M. Cuilleret, L. Doyen, H. Gomes, and F. Blanchard. Resilience management for coastal fisheries facing with global changes and uncertainties. *Economic Analysis and Policy*, 74:634–656, June 2022. ISSN 0313-5926. doi: 10.1016/j.eap.2022.03.016. URL <https://www.sciencedirect.com/science/article/pii/S0313592622000455>.
- P. Cury, C. Mullon, S. Garcia, and L. Shannon. Viability theory for an ecosystem approach to fisheries. *Ices Journal of Marine Science*, 62:577–584, 2005. ISSN 1054-3139. URL <http://www.documentation.ird.fr/hor/fdi:010042308>.
- P. M. Cury, Y.-J. Shin, B. Planque, J. M. Durant, J.-M. Fromentin, S. Kramer-Schadt, N. C. Stenseth, M. Travers, and V. Grimm. Ecosystem oceanography for global change in fisheries. *Trends in Ecology & Evolution*, 23(6):338–346, 2008. ISSN 0169-5347. doi: <https://doi.org/10.1016/j.tree.2008.02.005>. URL <https://www.sciencedirect.com/science/article/pii/S0169534708001262>.
- I. Dahmouni, B. Vardar, and G. Zaccour. A fair and time-consistent sharing of the joint exploitation payoff of a fishery. *Natural Resource Modeling*, 32(3):e12216, 2019. doi: <https://doi.org/10.1111/nrm.12216>. URL <https://onlinelibrary.wiley.com/doi/abs/10.1111/nrm.12216>.

- I. Dahmouni, E. M. Parilina, and G. Zaccour. Great fish war with moratorium. *Mathematical Biosciences*, 355:108939, 2023. ISSN 0025-5564. doi: <https://doi.org/10.1016/j.mbs.2022.108939>. URL <https://www.sciencedirect.com/science/article/pii/S0025556422001286>.
- M. De Lara and L. Doyen. *Sustainable management of natural resources: mathematical models and methods*. Springer Science & Business Media, 2008. URL <https://link.springer.com/book/10.1007/978-3-540-79074-7>.
- S. Derissen, M. F. Quaas, and S. Baumgärtner. The relationship between resilience and sustainability of ecological-economic systems. *Ecological Economics*, 70(6):1121–1128, Apr. 2011. ISSN 09218009. doi: 10.1016/j.ecolecon.2011.01.003. URL <https://linkinghub.elsevier.com/retrieve/pii/S0921800911000103>.
- C. Dichmont, S. Pascoe, T. Kompas, A. E. Punt, and R. Deng. On implementing maximum economic yield in commercial fisheries. *Proceedings of the National Academy of Sciences*, 107(1):16–21, 2009. URL <https://doi.org/10.1073/pnas.09120911>. Publisher: National Acad Sciences.
- B. Diop, N. Sanz, Y. J. J. Duplan, E. H. M. Guene, F. Blanchard, J.-C. Pereau, and L. Doyen. Maximum economic yield fishery management in the face of global warming. *Ecological Economics*, 154:52–61, 2018. ISSN 0921-8009. doi: <https://doi.org/10.1016/j.ecolecon.2018.07.027>. URL <https://www.sciencedirect.com/science/article/pii/S0921800918301113>.
- J. do Val, O. Guillotreau, and T. Vallée. Fishery management under poorly known dynamics. *European Journal of Operational Research*, 279(1):242–257, 2019. ISSN 0377-2217. doi: <https://doi.org/10.1016/j.ejor.2019.05.016>. URL <https://www.sciencedirect.com/science/article/pii/S0377221719304205>.
- B. J. Downes, F. Miller, J. Barnett, A. Glaister, and H. Ellemor. How do we know about resilience? An analysis of empirical research on resilience, and implications for interdisciplinary praxis. *Environmental Research Letters*, 8(1):014041, Mar. 2013. ISSN 1748-9326. doi: 10.1088/1748-9326/8/1/014041. URL <https://iopscience.iop.org/article/10.1088/1748-9326/8/1/014041>.
- L. Doyen. Mathematics for Scenarios of Biodiversity and Ecosystem Services. *Environmental Modeling & Assessment*, 23(6):729–742, 2018. URL <https://link.springer.com/article/10.1007/s10666-018-9632-4>. Publisher: Springer.
- L. Doyen and P. Gajardo. Sustainability standards, multicriteria maximin, and viability. *Natural Resource Modeling*, n/a(n/a):e12250, 2020. doi: 10.1111/nrm.12250. URL <https://onlinelibrary.wiley.com/doi/abs/10.1111/nrm.12250>.
- L. Doyen and V. Martinet. Maximin, viability and sustainability. *J. Econom. Dynam. Control*, 36(9):1414–1430, 2012a.
- L. Doyen and V. Martinet. Maximin, viability and sustainability. *Journal of Economic Dynamics and Control*, 36(9):1414–1430, Sept. 2012b. ISSN 01651889. doi: 10.1016/j.jedc.2012.03.004. URL <https://linkinghub.elsevier.com/retrieve/pii/S0165188912000668>.
- L. Doyen and J.-C. Péréau. Sustainable coalitions in the commons. *Math. Social Sci.*, 63(1):57–64, 2012.
- L. Doyen, M. De Lara, J. Ferraris, and D. Pelletier. Sustainability of exploited marine ecosystems through protected areas: A viability model and a coral reef case study. *Ecological Modelling*, 208(2):353–366, 2007. ISSN 0304-3800. doi: <https://doi.org/10.1016/j.ecolmodel.2007.06.018>. URL <https://www.sciencedirect.com/science/article/pii/S0304380007003146>.
- L. Doyen, A. Cissé, S. Gourguet, L. Mouysset, P.-Y. Hardy, C. Béné, F. Blanchard, F. Jiguet, J.-C. Péréau, and O. Thébaud. Ecological-economic modelling for the sustainable management of biodiversity. *Computational Management Science*, 10(4):353–364, 2013.
- L. Doyen, C. Béné, M. Bertignac, F. Blanchard, A. A. Cissé, C. Dichmont, S. Gourguet, O. Guyader, P.-Y. Hardy, S. Jennings, L. R. Little, C. Macher, D. J. Mills, A. Noussair, S. Pascoe, J.-C. Péréau, N. Sanz, A.-M. Schwarz, T. Smith, and O. Thébaud. Ecoviability for ecosystem-based fisheries management. *Fish and Fisheries*, 18(6):1056–1072, Nov. 2017. ISSN 14672960. doi: 10.1111/faf.12224. URL <http://doi.wiley.com/10.1111/faf.12224>.
- L. Doyen, A. Cissé, N. Sanz, F. Blanchard, and J.-C. Péréau. The tragedy of open ecosystems. *Dynamic Games and Applications*, 8(1):117–140, 2018. Publisher: Springer.

- S. Díaz, S. Demissew, J. Carabias, C. Joly, M. Lonsdale, N. Ash, A. Larigauderie, J. R. Adhikari, S. Arico, A. Báldi, A. Bartuska, I. A. Baste, A. Bilgin, E. Brondizio, K. M. Chan, V. E. Figueroa, A. Duraiappah, M. Fischer, R. Hill, T. Koetz, P. Leadley, P. Lyver, G. M. Mace, B. Martin-Lopez, M. Okumura, D. Pacheco, U. Pascual, E. S. Pérez, B. Reyers, E. Roth, O. Saito, R. J. Scholes, N. Sharma, H. Tallis, R. Thaman, R. Watson, T. Yahara, Z. A. Hamid, C. Akosim, Y. Al-Hafedh, R. Allahverdiyev, E. Amankwah, S. T. Asah, Z. Asfaw, G. Bartus, L. A. Brooks, J. Caillaux, G. Dalle, D. Darnaedi, A. Driver, G. Erpul, P. Escobar-Eyzaguirre, P. Failler, A. M. M. Fouda, B. Fu, H. Gundimeda, S. Hashimoto, F. Homer, S. Lavorel, G. Lichtenstein, W. A. Mala, W. Mandivenyi, P. Matczak, C. Mbizvo, M. Mehrdadi, J. P. Metzger, J. B. Mikissa, H. Moller, H. A. Mooney, P. Mumby, H. Nagendra, C. Nesshover, A. A. Oteng-Yeboah, G. Pataki, M. Roué, J. Rubis, M. Schultz, P. Smith, R. Sumaila, K. Takeuchi, S. Thomas, M. Verma, Y. Yeo-Chang, and D. Zlatanova. The ipbes conceptual framework — connecting nature and people. *Current Opinion in Environmental Sustainability*, 14:1–16, 2015. ISSN 1877-3435. doi: <https://doi.org/10.1016/j.cosust.2014.11.002>. URL <https://www.sciencedirect.com/science/article/pii/S187734351400116X>. Open Issue.
- K. Eisenack, J. Scheffran, and J. P. Kropp. Viability analysis of management frameworks for fisheries. *Environ. Model. Assess.*, 11(1):69–79, Feb. 2006.
- I. Ekeland, L. Karp, and R. Sumaila. Equilibrium resource management with altruistic overlapping generations. *Journal of Environmental Economics and Management*, 70:1–16, 2015. ISSN 0095-0696. doi: <https://doi.org/10.1016/j.jeem.2014.12.001>. URL <https://www.sciencedirect.com/science/article/pii/S0095069614001028>.
- P. J. Ferraro, J. N. Sanchirico, and M. D. Smith. Causal inference in coupled human and natural systems. *Proceedings of the National Academy of Sciences*, 116(12):5311–5318, 2019. doi: 10.1073/pnas.1805563115. URL <https://www.pnas.org/doi/abs/10.1073/pnas.1805563115>.
- S. Ferrier, K. Ninan, P. Leadley, R. Alkemade, L. Acosta, H. R. Akcakaya, L. Brotons, W. Cheung, V. Christensen, K. A. Harhash, J. Kabubo-Mariara, C. Lundquist, M. Obersteiner, H. Pereira, G. Peterson, R. Pichs-Madruga, N. Ravindranath, C. Rondinini, and B. Wintle. *IPBES (2016): Summary for policymakers of the methodological assessment of scenarios and models of biodiversity and ecosystem services of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services*. Secretariat of the Intergovernmental Platform for Biodiversity and Ecosystem Services: Bonn, Germany. IPBES, Jan. 2016.
- M. Finus and A. Caparrós. *Game theory and international environmental cooperation*. The International Library of Critical Writings in Economics Series. Edward Elgar Publishing, Cheltenham, England, Jan. 2015.
- R. D. Fischer and L. J. Mirman. The compleat fish wars: Biological and dynamic interactions. *Journal of Environmental Economics and Management*, 30(1):34–42, 1996. ISSN 0095-0696. doi: <https://doi.org/10.1006/jjeem.1996.0003>. URL <https://www.sciencedirect.com/science/article/pii/S009506969600030>.
- O. Flaaten. On the bioeconomics of predator and prey fishing. *Fisheries Research*, 37(1):179–191, 1998. ISSN 0165-7836. doi: [https://doi.org/10.1016/S0165-7836\(98\)00135-0](https://doi.org/10.1016/S0165-7836(98)00135-0). URL <https://www.sciencedirect.com/science/article/pii/S0165783698001350>.
- M. Fleurbaey. On sustainability and social welfare. *Journal of Environmental Economics and Management*, 71:34 – 53, 2015.
- Food and Agriculture Organization. *The state of world fisheries and aquaculture 2020 (SOFIA)*. The State of World Fisheries and Aquaculture (SOFIA). Food & Agriculture Organization of the United Nations (FAO), Rome, Italy, July 2020.
- R. Froese, H. Winker, G. Coro, N. Demirel, A. C. Tsikliras, D. Dimarchopoulou, G. Scarcella, M. Quaas, and N. Matz-Lück. Status and rebuilding of European fisheries. *Marine Policy*, 93:159–170, July 2018. ISSN 0308-597X. doi: 10.1016/j.marpol.2018.04.018. URL <https://www.sciencedirect.com/science/article/pii/S0308597X17307364>.
- J. Fromentin, D. Emery, M.R., M. J., Danner, A. Hallosserie, D. Kieling, G. Balachander, E. Barron, R. Chaudhary, M. Gasalla, M. Halmy, C. Hicks, M. Park, B. Parlee, J. Rice, T. Ticktin, and D. e. Tittensor. Summary for policymakers of the thematic assessment of the sustainable use of wild species of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES), Dec. 2022. URL <https://doi.org/10.5281/zenodo.7411847>.

- J.-M. Fromentin, S. Bonhommeau, H. Arrizabalaga, and L. T. Kell. The spectre of uncertainty in management of exploited fish stocks: The illustrative case of atlantic bluefin tuna. *Marine Policy*, 47:8–14, 2014. ISSN 0308-597X. doi: <https://doi.org/10.1016/j.marpol.2014.01.018>. URL <https://www.sciencedirect.com/science/article/pii/S0308597X1400030X>.
- E. A. Fulton, A. D. Smith, D. C. Smith, and I. E. van Putten. Human behaviour: the key source of uncertainty in fisheries management. *Fish and fisheries*, 12(1):2–17, 2011. Publisher: Wiley Online Library.
- E. A. Fulton, A. E. Punt, C. M. Dichmont, C. J. Harvey, and R. Gorton. Ecosystems say good management pays off. *Fish and Fisheries*, 20(1):66–96, 2019. doi: <https://doi.org/10.1111/faf.12324>. URL <https://onlinelibrary.wiley.com/doi/abs/10.1111/faf.12324>.
- P. Gajardo, M. Olivares, and H. Ramírez C. Methods for the sustainable rebuilding of overexploited natural resources. *Environmental Modeling & Assessment*, 23(6):713–727, Dec 2018.
- M. Giacomarra, M. Crescimanno, D. Vrontis, L. Miret Pastor, and A. Galati. The ability of fish ecolabels to promote a change in the sustainability awareness. *Marine Policy*, 123:104292, 2021. ISSN 0308-597X. doi: <https://doi.org/10.1016/j.marpol.2020.104292>. URL <https://www.sciencedirect.com/science/article/pii/S0308597X20309386>.
- H. C. J. Godfray, J. R. Beddington, I. R. Crute, L. Haddad, D. Lawrence, J. F. Muir, J. Pretty, S. Robinson, S. M. Thomas, and C. Toulmin. Food security: The challenge of feeding 9 billion people. *Science*, 327(5967):812–818, 2010. doi: 10.1126/science.1185383. URL <https://www.science.org/doi/abs/10.1126/science.1185383>.
- H. Gomes, C. Kersulec, L. Doyen, F. Blanchard, A. A. Cisse, and N. Sanz. The Major Roles of Climate Warming and Ecological Competition in the Small-scale Coastal Fishery in French Guiana. *Environmental Modeling & Assessment*, May 2021. ISSN 1420-2026, 1573-2967. doi: 10.1007/s10666-021-09772-8. URL <https://link.springer.com/10.1007/s10666-021-09772-8>.
- H. S. Gordon. The Economic Theory of a Common-Property Resource: The Fishery. *The Journal of Political Economy*, 62(2):124–142, 1954. URL <http://www.jstor.org/stable/1825571>.
- S. Gourguet, O. Thebaud, C. Dichmont, S. Jennings, L. Little, S. Pascoe, R. Deng, and L. Doyen. Risk versus economic performance in a mixed fishery. *Ecological Economics*, 99:110–120, 2014. Publisher: Elsevier.
- R. Grafton, D. Squires, and K. Fox. Private property and economic efficiency: A study of a common-pool resource. *The Journal of Law and Economics*, 43(2):679–714, 2000. doi: 10.1086/467469. URL <https://doi.org/10.1086/467469>.
- R. Q. Grafton and L. R. Little. Risks, resilience, and natural resource management: Lessons from selected findings. *Natural Resource Modeling*, 30(1):91–111, Feb. 2017. ISSN 08908575. doi: 10.1111/nrm.12104. URL <http://doi.wiley.com/10.1111/nrm.12104>.
- R. Q. Grafton, T. Kompas, and V. Schneider. The bioeconomics of marine reserves: A selected review with policy implications. *Journal of Bioeconomics*, 7(2):161–178, Jan. 2005.
- R. Q. Grafton, L. Doyen, C. Béné, E. Borgomeo, K. Brooks, L. Chu, G. S. Cumming, J. Dixon, S. Dovers, D. Garrick, A. Helfgott, Q. Jiang, P. Katic, T. Kompas, L. R. Little, N. Matthews, C. Ringler, D. Squires, S. I. Steinshamn, S. Villasante, S. Wheeler, J. Williams, and P. R. Wyrwoll. Realizing resilience for decision-making. *Nature Sustainability*, 2(10):907–913, Oct. 2019. ISSN 2398-9629. doi: 10.1038/s41893-019-0376-1. URL <http://www.nature.com/articles/s41893-019-0376-1>.
- R. Q. Grafton, D. Squires, and S. I. Steinshamn. Towards resilience-based management of marine capture fisheries. *Economic Analysis and Policy*, 77:231–238, 2023. ISSN 0313-5926. doi: <https://doi.org/10.1016/j.eap.2022.11.012>. URL <https://www.sciencedirect.com/science/article/pii/S0313592622001965>.
- L. Grønbaek, M. Lindroos, G. Munro, and P. Pintassilgo. Game theory and fisheries. *Fisheries Research*, 203:1–5, 2018. ISSN 0165-7836. doi: <https://doi.org/10.1016/j.fishres.2017.11.027>. URL <https://www.sciencedirect.com/science/article/pii/S0165783617303351>. Game Theory and Fisheries.
- K. G. Hamon, S. D. Frusher, L. R. Little, O. Thébaud, and A. E. Punt. Adaptive behaviour of fishers to external perturbations: simulation of the tasmanian rock lobster fishery. *Reviews in Fish Biology and Fisheries*, 24(2):577–592, June 2014.

- C. Hannah, A. Vezina, and M. S. John. The case for marine ecosystem models of intermediate complexity. *Progress in Oceanography*, 84(1-2):121–128, Jan. 2010. ISSN 00796611. doi: 10.1016/j.pocean.2009.09.015. URL <https://linkinghub.elsevier.com/retrieve/pii/S0079661109001487>.
- R. Hannesson. Optimal harvesting of ecologically interdependent fish species. *Journal of Environmental Economics and Management*, 10(4):329–345, 1983. ISSN 0095-0696. doi: [https://doi.org/10.1016/0095-0696\(83\)90003-7](https://doi.org/10.1016/0095-0696(83)90003-7). URL <https://www.sciencedirect.com/science/article/pii/0095069683900037>.
- R. Hannesson. Fishing as a supergame. *Journal of Environmental Economics and Management*, 32(3): 309–322, 1997. ISSN 0095-0696. doi: <https://doi.org/10.1006/jeem.1997.0971>. URL <https://www.sciencedirect.com/science/article/pii/S009506969709712>.
- G. E. Herrera, H. V. Moeller, and M. G. Neubert. High-seas fish wars generate marine reserves. *Proc. Natl. Acad. Sci. U. S. A.*, 113(14):3767–3772, Apr. 2016.
- R. Hilborn, R. O. Amoroso, C. M. Anderson, J. K. Baum, T. A. Branch, C. Costello, C. L. de Moor, A. Faraj, D. Hively, O. P. Jensen, H. Kurota, L. R. Little, P. Mace, T. McClanahan, M. C. Melnychuk, C. Minto, G. C. Osio, A. M. Parma, M. Pons, S. Segurado, C. S. Szuwalski, J. R. Wilson, and Y. Ye. Effective fisheries management instrumental in improving fish stock status. *Proceedings of the National Academy of Sciences*, 117(4):2218–2224, 2020. doi: 10.1073/pnas.1909726116. URL <https://www.pnas.org/doi/abs/10.1073/pnas.1909726116>.
- C. S. Holling. Resilience and stability of ecological systems. *Annual review of ecology and systematics*, 4(1): 1–23, 1973. Publisher: Annual Reviews 4139 El Camino Way, PO Box 10139, Palo Alto, CA 94303-0139, USA.
- R. Howarth. Sustainability under uncertainty: A deontological approach. *Land Economics*, 71(4):417–427, 1995.
- L. Huang and M. D. Smith. The dynamic efficiency costs of common-pool resource exploitation. *American Economic Review*, 104(12):4071–4103, December 2014. doi: 10.1257/aer.104.12.4071. URL <https://www.aeaweb.org/articles?id=10.1257/aer.104.12.4071>.
- IPBES. Summary for policymakers of the global assessment report on biodiversity and ecosystem services, Nov. 2019. URL <https://doi.org/10.5281/zenodo.3553579>.
- A. Jean-Marie and M. Tidball. Dynamic fishing with endogenous habitat damage. *Dyn. Games Appl.*, July 2023.
- M. Jonell, B. Crona, K. Brown, P. Rönnbäck, and M. Troell. Eco-labeled seafood: Determinants for (blue) green consumption. *Sustainability*, 8(9), 2016. ISSN 2071-1050. doi: 10.3390/su8090884. URL <https://www.mdpi.com/2071-1050/8/9/884>.
- V. Kaitala and M. Lindroos. *Game Theoretic Applications to Fisheries*, pages 201–215. Springer US, Boston, MA, 2007. ISBN 978-0-387-71815-6. doi: 10.1007/978-0-387-71815-6_11. URL https://doi.org/10.1007/978-0-387-71815-6_11.
- V. Kaitala and G. Munro. The economic management of high seas fishery resources: Some game theoretic aspects. In *Control and Game-Theoretic Models of the Environment*, pages 299–318. Birkhäuser Boston, Boston, MA, 1995.
- L. Kell, M. Pastoors, R. Scott, M. Smith, F. Van Beek, C. O’Brien, and G. Pilling. Evaluation of multiple management objectives for Northeast Atlantic flatfish stocks: sustainability vs. stability of yield. *ICES Journal of Marine Science*, 62(6):1104–1117, 01 2005. ISSN 1054-3139. doi: 10.1016/j.icesjms.2005.05.005. URL <https://doi.org/10.1016/j.icesjms.2005.05.005>.
- J. Krawczyk and K. Kim. Satisficing solutions to a monetary policy problem: A viability theory approach. *Macroeconomic Dynamics*, 13(1):46?80, 2009.
- K. Kroetz, L. Nøstbakken, and M. Quaas. The future of wild-caught fisheries: Expanding the scope of management. *Review of Environmental Economics and Policy*, 16(2):241–261, 2022. doi: 10.1086/721097. URL <https://doi.org/10.1086/721097>.
- A. Lagarde, L. Doyen, A. Ahad-Cissé, N. Caill-Milly, S. Gourguet, O. L. Pape, C. Macher, G. Morandeau, and O. Thébaud. How Does MMEY Mitigate the Bioeconomic Effects of Climate Change for Mixed Fisheries.

- Ecological Economics*, 154:317–332, Dec. 2018. ISSN 09218009. doi: 10.1016/j.ecolecon.2018.07.001. URL <https://linkinghub.elsevier.com/retrieve/pii/S0921800917317688>.
- D. Levhari and L. J. Mirman. The great fish war: An example using a dynamic cournot-nash solution. *The Bell Journal of Economics*, 11(1):322–334, 1980. ISSN 0361915X, 23263032. URL <http://www.jstor.org/stable/3003416>.
- S. A. Levin and J. Lubchenco. Resilience, Robustness, and Marine Ecosystem-based Management. *BioScience*, 58(1):27–32, 01 2008. ISSN 0006-3568. doi: 10.1641/B580107. URL <https://doi.org/10.1641/B580107>.
- S. A. Levin, S. Barrett, S. Aniyar, W. Baumol, C. Bliss, B. Bolin, P. Dasgupta, P. Ehrlich, C. Folke, and I.-M. Gren. Resilience in natural and socioeconomic systems. *Environment and development economics*, 3(2):222–235, 1998. Publisher: JSTOR.
- Q. Li and M. D. Smith. Fishery collapse revisited. *Marine Resource Economics*, 36(1):1–22, 2021a. doi: 10.1086/711233. URL <https://doi.org/10.1086/711233>.
- Q. Li and M. D. Smith. Fishery Collapse Revisited. *Marine Resource Economics*, 36(1):1–22, Jan. 2021b. ISSN 0738-1360, 2334-5985. doi: 10.1086/711233. URL <https://www.journals.uchicago.edu/doi/10.1086/711233>.
- T. Lindahl, A.-S. Crépin, and C. Schill. Potential disasters can turn the tragedy into success. *Environ. Resour. Econ. (Dordr.)*, 65(3):657–676, Nov. 2016.
- J. S. Link, O. Thébaud, D. C. Smith, A. D. Smith, J. Schmidt, J. Rice, J. J. Poos, C. Pita, D. Lipton, M. Kraan, and others. *Keeping humans in the ecosystem*. Oxford University Press, 2017.
- M. Margolis and E. Naevdal. Climate change decision-support and the tolerable windows approach. *Environmental Resource Economics*, 4(40):401, 2008. doi: 10.1007/s10640-007-9162-z.
- S. Martin. The cost of restoration as a way of defining resilience: a viability approach applied to a model of lake eutrophication. *Ecology and Society*, 9(2), 2004. Publisher: JSTOR.
- V. Martinet, O. Thébaud, and L. Doyen. Defining viable recovery paths toward sustainable fisheries. *Ecological Economics*, 64(2):411–422, Dec. 2007. ISSN 09218009. doi: 10.1016/j.ecolecon.2007.02.036. URL <https://linkinghub.elsevier.com/retrieve/pii/S0921800907001656>.
- O. Maury. An overview of apecosm, a spatialized mass balanced “apex predators ecosystem model” to study physiologically structured tuna population dynamics in their ecosystem. *Progress in Oceanography*, 84(1):113–117, 2010. ISSN 0079-6611. doi: <https://doi.org/10.1016/j.pocean.2009.09.013>. URL <https://www.sciencedirect.com/science/article/pii/S0079661109001463>. Special Issue: Parameterisation of Trophic Interactions in Ecosystem Modelling.
- O. Maury and J.-C. Poggiale. From individuals to populations to communities: A dynamic energy budget model of marine ecosystem size-spectrum including life history diversity. *Journal of Theoretical Biology*, 324:52–71, 2013. ISSN 0022-5193. doi: <https://doi.org/10.1016/j.jtbi.2013.01.018>. URL <https://www.sciencedirect.com/science/article/pii/S002251931300043X>.
- O. Maury, L. Campling, H. Arrizabalaga, O. Aumont, L. Bopp, G. Merino, D. Squires, W. Cheung, M. Goujon, C. Guivarch, S. Lefort, F. Marsac, P. Monteagudo, R. Murtugudde, H. Österblom, J. Pulvenis, Y. Ye, and B. van Ruijven. From shared socio-economic pathways (ssps) to oceanic system pathways (osps): Building policy-relevant scenarios for global oceanic ecosystems and fisheries. *Global Environmental Change*, 45:203–216, 2017. ISSN 0959-3780. doi: <https://doi.org/10.1016/j.gloenvcha.2017.06.007>. URL <https://www.sciencedirect.com/science/article/pii/S0959378016306343>.
- F. Maynou. Coviability analysis of Western Mediterranean fisheries under MSY scenarios for 2020. *ICES Journal of Marine Science*, 71(7):1563–1571, Oct. 2014. ISSN 1054-3139. doi: 10.1093/icesjms/fsu061. URL <https://doi.org/10.1093/icesjms/fsu061>.
- M. Mesterton-Gibbons. A technique for finding optimal two-species harvesting policies. *Ecol. Modell.*, 92(2-3):235–244, Dec. 1996.
- A. Moussaoui and P. Auger. A bioeconomic model of a fishery with saturated catch and variable price: Stabilizing effect of marine reserves on fishery dynamics. *Ecological Complexity*, 45:100906, 2021. ISSN 1476-945X. doi: <https://doi.org/10.1016/j.ecocom.2020.100906>. URL <https://www.sciencedirect.com/science/article/pii/S1476945X20301860>.

- A. Moussaoui, A. Ducrot, A. Moulai-Khatir, and P. Auger. A model of a fishery with fish storage and variable price involving delay equations. *Mathematical Biosciences*, 362:109022, 2023. ISSN 0025-5564. doi: <https://doi.org/10.1016/j.mbs.2023.109022>. URL <https://www.sciencedirect.com/science/article/pii/S0025556423000639>.
- G. R. Munro. The optimal management of transboundary renewable resources. *The Canadian Journal of Economics / Revue canadienne d'Economique*, 12(3):355–376, 1979. ISSN 00084085, 15405982. URL <http://www.jstor.org/stable/134727>.
- E. Neumayer. *Weak versus Strong Sustainability: Exploring the Limits of Two Opposing Paradigms*. Edward Elgar Publishing, third edition, 2010.
- R. G. Newell, J. N. Sanchirico, and S. Kerr. Fishing quota markets. *Journal of Environmental Economics and Management*, 49(3):437–462, 2005. ISSN 0095-0696. doi: <https://doi.org/10.1016/j.jeem.2004.06.005>. URL <https://www.sciencedirect.com/science/article/pii/S0095069604001147>.
- J. R. Nielsen, E. Thunberg, D. S. Holland, J. O. Schmidt, E. A. Fulton, F. Bastardie, A. E. Punt, I. Allen, H. Bartelings, M. Bertignac, E. Bethke, S. Bossier, R. Buckworth, G. Carpenter, A. Christensen, V. Christensen, J. M. Da-Rocha, R. Deng, C. Dichmont, R. Doering, A. Esteban, J. A. Fernandes, H. Frost, D. Garcia, L. Gasche, D. Gascuel, S. Gourguet, R. A. Groeneveld, J. Guillén, O. Guyader, K. G. Hamon, A. Hoff, J. Horbowy, T. Hutton, S. Lehuta, L. R. Little, J. Leonart, C. Macher, S. Mackinson, S. Mahevas, P. Marchal, R. Mato-Amboage, B. Mapstone, F. Maynou, M. Merzéréaud, A. Palacz, S. Pascoe, A. Paulrud, E. Plaganyi, R. Prellezo, E. I. van Putten, M. Quaas, L. Ravn-Jonsen, S. Sanchez, S. Simons, O. Thébaud, M. T. Tomczak, C. Ulrich, D. van Dijk, Y. Vermard, R. Voss, and S. Waldo. Integrated ecological–economic fisheries models—evaluation, review and challenges for implementation. *Fish and Fisheries*, 19(1):1–29, 2018. doi: <https://doi.org/10.1111/faf.12232>. URL <https://onlinelibrary.wiley.com/doi/abs/10.1111/faf.12232>.
- OECD. Resilient Cities. URL <https://www.oecd.org/cfe/resilient-cities.htm>.
- E. Ostrom. A General Framework for Analyzing Sustainability of Social-Ecological Systems. *Science*, 325(5939):419–422, July 2009. doi: [10.1126/science.1172133](https://doi.org/10.1126/science.1172133). URL <https://www.science.org/doi/10.1126/science.1172133>. Publisher: American Association for the Advancement of Science.
- E. Ostrom, M. A. Janssen, and J. M. Anderies. Going beyond panaceas. *Proceedings of the National Academy of Sciences*, 104(39):15176–15178, 2007. doi: [10.1073/pnas.0701886104](https://doi.org/10.1073/pnas.0701886104). URL <https://www.pnas.org/doi/abs/10.1073/pnas.0701886104>.
- A. Oubraham and G. Zaccour. A survey of applications of viability theory to the sustainable exploitation of renewable resources. *Ecological economics*, 145:346–367, 2018. Publisher: Elsevier.
- J.-C. Péreau, L. Doyen, L. Little, and O. Thébaud. The triple bottom line: Meeting ecological, economic and social goals with individual transferable quotas. *Journal of Environmental Economics and Management*, 63(3):419 – 434, 2012.
- E. Pikitch, C. Santora, E. Babcock, A. Bakun, R. Bonfil, D. Conover, P. Dayton, P. Doukakis, D. Fluharty, B. Heneman, and others. Ecosystem-based fishery management. *Science*, 305(5682):346–347, 2004. Publisher: American Association for the Advancement of Science.
- S. L. Pimm. The complexity and stability of ecosystems. *Nature*, 307(5949):321–326, Jan. 1984. ISSN 0028-0836, 1476-4687. doi: [10.1038/307321a0](https://doi.org/10.1038/307321a0). URL <http://www.nature.com/articles/307321a0>.
- J. Pineda, N. B. Reyns, and V. R. Starczak. Complexity and simplification in understanding recruitment in benthic populations. *Population Ecology*, 51(1):17–32, 2009. doi: <https://doi.org/10.1007/s10144-008-0118-0>. URL <https://esj-journals.onlinelibrary.wiley.com/doi/abs/10.1007/s10144-008-0118-0>.
- T. J. Pitcher, D. Kalikoski, K. Short, D. Varkey, and G. Pramod. An evaluation of progress in implementing ecosystem-based management of fisheries in 33 countries. *Marine Policy*, 33(2):223–232, 2009. Publisher: Elsevier.
- É. E. Plaganyi. *Models for an ecosystem approach to fisheries*. Food & Agriculture Org., 2007.
- E. Plagányi, A. E. Punt, R. Hillary, E. B. Morello, O. Thébaud, T. Hutton, R. D. Pillans, J. T. Thorson, E. A. Fulton, A. D. M. Smith, F. Smith, P. Bayliss, M. Haywood, V. Lyne, and P. C. Rothlisberg. Multispecies fisheries management and conservation: tactical applications using models of intermediate complexity.

- Fish and Fisheries*, 15(1):1–22, 2014. doi: <https://doi.org/10.1111/j.1467-2979.2012.00488.x>. URL <https://onlinelibrary.wiley.com/doi/abs/10.1111/j.1467-2979.2012.00488.x>.
- J.-C. Poggiale, C. Aldebert, B. Girardot, and B. W. Kooi. Analysis of a predator–prey model with specific time scales: a geometrical approach proving the occurrence of canard solutions. *Journal of Mathematical Biology*, 80(1):39–60, Jan. 2020.
- A. E. Quinlan, M. Berbés-Blázquez, L. J. Haider, and G. D. Peterson. Measuring and assessing resilience: broadening understanding through multiple disciplinary perspectives. *Journal of Applied Ecology*, 53(3):677–687, June 2016. ISSN 00218901. doi: 10.1111/1365-2664.12550. URL <http://doi.wiley.com/10.1111/1365-2664.12550>.
- T. J. Quinn and R. B. Deriso. *Quantitative fish dynamics*. Oxford University Press, 1999.
- D. L. Ragozin and G. Brown. Harvest policies and nonmarket valuation in a predator — prey system. *Journal of Environmental Economics and Management*, 12(2):155–168, 1985. ISSN 0095-0696. doi: [https://doi.org/10.1016/0095-0696\(85\)90025-7](https://doi.org/10.1016/0095-0696(85)90025-7). URL <https://www.sciencedirect.com/science/article/pii/0095069685900257>.
- W. J. Reed. Optimal escapement levels in stochastic and deterministic harvesting models. *Journal of Environmental Economics and Management*, 6(4):350–363, 1979. ISSN 0095-0696. doi: [https://doi.org/10.1016/0095-0696\(79\)90014-7](https://doi.org/10.1016/0095-0696(79)90014-7). URL <https://www.sciencedirect.com/science/article/pii/0095069679900147>.
- S. Reithe, C. W. Armstrong, and O. Flaaten. Marine protected areas in a welfare-based perspective. *Marine Policy*, 49:29–36, 2014. ISSN 0308-597X. doi: <https://doi.org/10.1016/j.marpol.2014.04.002>. URL <https://www.sciencedirect.com/science/article/pii/S0308597X14001134>.
- J. C. Rice and S. M. Garcia. Fisheries, food security, climate change, and biodiversity: characteristics of the sector and perspectives on emerging issues. *ICES Journal of Marine Science*, 68(6):1343–1353, 04 2011. ISSN 1054-3139. doi: 10.1093/icesjms/fsr041. URL <https://doi.org/10.1093/icesjms/fsr041>.
- J. Rockström, W. Steffen, K. Noone, A. Persson, F. S. Chapin III, E. F. Lambin, T. M. Lenton, M. Scheffer, C. Folke, H. J. Schellnhuber, B. Nykvist, C. A. de Wit, T. Hughes, S. van der Leeuw, H. Rodhe, S. Sörlin, P. K. Snyder, R. Costanza, U. Svedin, M. Falkenmark, L. Karlberg, R. W. Corell, V. J. Fabry, J. Hansen, B. Walker, D. Liverman, K. Richardson, P. Crutzen, and J. A. Foley. A safe operating space for humanity. *Nature*, 461:472 – 475, 09 2009.
- K. Sainsbury. Review of ecolabelling schemes for fish and fishery products from capture fisheries. 5 2023. URL https://figshare.utas.edu.au/articles/report/Review_of_ecolabelling_schemes_for_fish_and_fishery_products_from_capture_fisheries/23173058.
- F. Salladarré, P. Guillotreau, Y. Perraudeau, and M.-C. Monfort. The demand for seafood eco-labels in france. *Journal of Agricultural Food Industrial Organization*, 8(1), 2010. doi: doi:10.2202/1542-0485.1308. URL <https://doi.org/10.2202/1542-0485.1308>.
- J. N. Sanchirico and J. E. Wilen. Bioeconomics of spatial exploitation in a patchy environment. *Journal of Environmental Economics and Management*, 37(2):129–150, 1999. ISSN 0095-0696. doi: <https://doi.org/10.1006/jeem.1998.1060>. URL <https://www.sciencedirect.com/science/article/pii/S009506969810609>.
- J. N. Sanchirico, M. D. Smith, and D. W. Lipton. An empirical approach to ecosystem-based fishery management. *Ecological Economics*, 64(3):586–596, 2008. Publisher: Elsevier.
- M. B. Schaefer. Some aspects of the dynamics of populations important to the management of the commercial marine fisheries. *Inter-American Tropical Tuna Commission Bulletin*, 1(2):23–56, 1954.
- A. M. Scheld, J. Beckensteiner, D. M. Munroe, E. N. Powell, S. Borsetti, E. E. Hofmann, and J. M. Klinck. The Atlantic surfclam fishery and offshore wind energy development: 2. Assessing economic impacts. *ICES Journal of Marine Science*, 79(6):1801–1814, 06 2022. ISSN 1054-3139. doi: 10.1093/icesjms/fsac109. URL <https://doi.org/10.1093/icesjms/fsac109>.
- M. Schlüter, C. Brelsford, P. J. Ferraro, K. Orach, M. Qiu, and M. D. Smith. Unraveling complex causal processes that affect sustainability requires more integration between empirical and modeling approaches. *Proceedings of the National Academy of Sciences*, 120(41):e2215676120, 2023.
- A. Schuhbauer and U. R. Sumaila. Economic viability and small-scale fisheries-A review. *Ecological Economics*, 124:69–75, 2016. URL http://ac.els-cdn.com/S092180091630132X/1-s2.0-S092180091630132X-main.pdf?_

tid=b3a751dc-b18c-11e6-9133-00000aab0f02&acdnat=1479913035_05838483be6bc12fe950da520adb8f40.
Publisher: Elsevier.

- J. Seijo, O. Defeo, S. Salas, Food, and A. O. of the United Nations. *Fisheries Bioeconomics: Theory, Modelling and Management*. FAO fisheries technical paper. Food and Agriculture Organization of the United Nations, 1998. ISBN 9789251040454. URL https://books.google.fr/books?id=plszARs_y04C.
- J. C. Seijo and J. F. Caddy. Uncertainty in bio-economic reference points and indicators of marine fisheries. *Mar. Freshwater Res.*, 51(5):477–483, 2000.
- G. Sethi, C. Costello, A. Fisher, M. Hanemann, and L. Karp. Fishery management under multiple uncertainty. *Journal of Environmental Economics and Management*, 50(2):300–318, Sept. 2005. ISSN 00950696. doi: 10.1016/j.jeem.2004.11.005. URL <https://linkinghub.elsevier.com/retrieve/pii/S0095069605000057>.
- Y. Sheffi. *The power of resilience: How the best companies manage the unexpected*. mit Press, 2015.
- Y.-J. Shin and P. Cury. Using an individual-based model of fish assemblages to study the response of size spectra to changes in fishing. *Canadian Journal of Fisheries and Aquatic Sciences*, 61(3):414–431, 2004. doi: 10.1139/f03-154. URL <https://doi.org/10.1139/f03-154>.
- C. R. Smith, L. J. Grange, D. L. Honig, L. Naudts, B. Huber, L. Guidi, and E. Domack. A large population of king crabs in Palmer Deep on the west Antarctic Peninsula shelf and potential invasive impacts. *Proceedings of the Royal Society B: Biological Sciences*, 279(1730):1017–1026, Mar. 2012. ISSN 0962-8452, 1471-2954. doi: 10.1098/rspb.2011.1496. URL <https://royalsocietypublishing.org/doi/10.1098/rspb.2011.1496>.
- M. Smith. Generating Value in Habitat-Dependent Fisheries: The Importance of Fishery Management Institutions. *Land Economics*, 83:59–73, Feb. 2007. doi: 10.3368/le.83.1.59.
- M. D. Smith. Bioeconometrics: Empirical modeling of bioeconomic systems. *Marine Resource Economics*, 23(1):1–23, 2008. doi: 10.1086/mre.23.1.42629599. URL <https://doi.org/10.1086/mre.23.1.42629599>.
- M. D. Smith, J. Zhang, and F. C. Coleman. Econometric modeling of fisheries with complex life histories: Avoiding biological management failures. *Journal of Environmental Economics and Management*, 55(3):265–280, 2008. ISSN 0095-0696. doi: <https://doi.org/10.1016/j.jeem.2007.11.003>. URL <https://www.sciencedirect.com/science/article/pii/S0095069608000181>.
- M. D. Smith, J. N. Sanchirico, and J. E. Wilen. The economics of spatial-dynamic processes: Applications to renewable resources. *Journal of Environmental Economics and Management*, 57(1):104–121, 2009. ISSN 0095-0696. doi: <https://doi.org/10.1016/j.jeem.2008.08.001>. URL <https://www.sciencedirect.com/science/article/pii/S009506960800082X>. *Frontiers of Environmental and Resource Economics*.
- M. D. Smith, C. A. Roheim, L. B. Crowder, B. S. Halpern, M. Turnipseed, J. L. Anderson, F. Asche, L. Bourillón, A. G. Guttormsen, A. Khan, L. A. Liguori, A. McNevin, M. I. O’Connor, D. Squires, P. Tyedmers, C. Brownstein, K. Carden, D. H. Klinger, R. Sagarin, and K. A. Selkoe. Sustainability and global seafood. *Science*, 327(5967):784–786, 2010. doi: 10.1126/science.1185345. URL <https://www.science.org/doi/abs/10.1126/science.1185345>.
- M. D. Smith, A. Oglend, A. J. Kirkpatrick, F. Asche, L. S. Benneer, J. K. Craig, and J. M. Nance. Seafood prices reveal impacts of a major ecological disturbance. *Proceedings of the National Academy of Sciences*, 114(7):1512–1517, 2017. doi: 10.1073/pnas.1617948114. URL <https://www.pnas.org/doi/abs/10.1073/pnas.1617948114>.
- V. L. Smith. On models of commercial fishing. *Journal of Political Economy*, 77(2):181–198, 1969. URL https://digitalcommons.chapman.edu/economics_articles/22/.
- M. A. Spence, J. L. Blanchard, A. G. Rossberg, M. R. Heath, J. J. Heymans, S. Mackinson, N. Serpetti, D. C. Speirs, R. B. Thorpe, and P. G. Blackwell. A general framework for combining ecosystem models. *Fish and Fisheries*, 19(6):1031–1042, 2018. doi: <https://doi.org/10.1111/faf.12310>. URL <https://onlinelibrary.wiley.com/doi/abs/10.1111/faf.12310>.
- R. Sumaila. *How to make individual transferable quotas work economically, socially, and environmentally*. Oxford University Press, Nov. 2018.
- U. R. Sumaila. Strategic dynamic interaction: The case of barents sea fisheries. *Marine Resource Economics*, 12(2):77–93, 1997. ISSN 07381360, 23345985. URL <http://www.jstor.org/stable/42629187>.

- U. R. Sumaila. A review of game-theoretic models of fishing. *Mar. Policy*, 23(1):1–10, Jan. 1999.
- U. R. Sumaila. Marine protected area performance in a model of the fishery. *Natural Resource Modeling*, 15(4):439–451, 2002. doi: <https://doi.org/10.1111/j.1939-7445.2002.tb00097.x>. URL <https://onlinelibrary.wiley.com/doi/abs/10.1111/j.1939-7445.2002.tb00097.x>.
- U. R. Sumaila. Intergenerational cost–benefit analysis and marine ecosystem restoration. *Fish and Fisheries*, 5(4):329–343, 2004. doi: <https://doi.org/10.1111/j.1467-2679.2004.00166.x>. URL <https://onlinelibrary.wiley.com/doi/abs/10.1111/j.1467-2679.2004.00166.x>.
- U. R. Sumaila. *Infinity Fish; Economics and the Future of Fish and Fisheries*. Elsevier, 2021.
- U. R. Sumaila and C. Walters. Making future generations count: Comment on “remembering the future”. *Ecological Economics*, 60(3):487–488, 2007. ISSN 0921-8009. doi: <https://doi.org/10.1016/j.ecolecon.2006.02.007>. URL <https://www.sciencedirect.com/science/article/pii/S0921800906000772>.
- U. R. Sumaila, W. W. L. Cheung, V. W. Y. Lam, D. Pauly, and S. Herrick. Climate change impacts on the biophysics and economics of world fisheries. *Nature Climate Change*, 1(9):449–456, Dec 2011. ISSN 1758-6798. doi: 10.1038/nclimate1301. URL <https://doi.org/10.1038/nclimate1301>.
- U. R. Sumaila, W. Cheung, A. Dyck, K. Gueye, L. Huang, V. Lam, D. Pauly, T. Srinivasan, W. Swartz, R. Watson, and D. Zeller. Benefits of rebuilding global marine fisheries outweigh costs. *PLOS ONE*, 7(7):1–12, 07 2012. doi: 10.1371/journal.pone.0040542. URL <https://doi.org/10.1371/journal.pone.0040542>.
- T. M. Swanson. The economics of extinction revisited and revised: a generalised framework for the analysis of the problems of endangered species and biodiversity losses. *Oxford Economic Papers*, pages 800–821, 1994. Publisher: JSTOR.
- O. Tahvonen. Economics of harvesting age-structured fish populations. *Journal of Environmental Economics and Management*, 58(3):281–299, 2009. ISSN 0095-0696. doi: <https://doi.org/10.1016/j.jeem.2009.02.001>. URL <https://www.sciencedirect.com/science/article/pii/S0095069609000515>.
- L. C. L. Teh and U. R. Sumaila. Contribution of marine fisheries to worldwide employment. *Fish and Fisheries*, 14(1):77–88, 2013. doi: <https://doi.org/10.1111/j.1467-2979.2011.00450.x>. URL <https://onlinelibrary.wiley.com/doi/abs/10.1111/j.1467-2979.2011.00450.x>.
- O. Thébaud, J. Innes, and N. Ellis. From anecdotes to scientific evidence? A review of recent literature on catch share systems in marine fisheries. *Frontiers in Ecology and the Environment*, 10(8):433–437, 2012. Publisher: Wiley Online Library.
- O. Thébaud, L. Doyen, J. Innes, M. Lample, C. Macher, S. Mahevas, C. Mullon, B. Planque, M. Quaas, T. Smith, and others. Building ecological-economic models and scenarios of marine resource systems: Workshop report. *Marine Policy*, 43:382–386, 2014. Publisher: Pergamon.
- O. Thébaud, J. R. Nielsen, A. Motova, H. Curtis, F. Bastardie, G. E. Blomqvist, F. Daurès, L. Goti, J. Holzer, J. Innes, A. Muench, A. Murillas, R. Nielsen, R. Rosa, E. Thunberg, S. Villasante, J. Virtanen, S. Waldo, S. Agnarsson, D. Castilla Espino, R. Curtin, G. DePiper, R. Doering, H. Ellefsen, J. J. García del Hoyo1, S. Gourguet, P. Greene, K. G. Hamon, A. Haynie, J. B. Kellner, S. Kuikka, B. Le Gallic, C. Macher, R. Prelezo, J. Santiago Castro-Rial, K. Sys, H. van Oostenbrugge, and B. M. J. Vastenhoud. Integrating economics into fisheries science and advice: progress, needs, and future opportunities. *ICES Journal of Marine Science*, 80(4):647–663, 02 2023a. ISSN 1054-3139. doi: 10.1093/icesjms/fsad005. URL <https://doi.org/10.1093/icesjms/fsad005>.
- O. Thébaud, J. R. Nielsen, A. Motova, H. Curtis, F. Bastardie, G. E. Blomqvist, F. Daurès, L. Goti, J. Holzer, J. Innes, A. Muench, A. Murillas, R. Nielsen, R. Rosa, E. Thunberg, S. Villasante, J. Virtanen, S. Waldo, S. Agnarsson, D. Castilla Espino, R. Curtin, G. DePiper, R. Doering, H. Ellefsen, J. J. García del Hoyo1, S. Gourguet, P. Greene, K. G. Hamon, A. Haynie, J. B. Kellner, S. Kuikka, B. Le Gallic, C. Macher, R. Prelezo, J. Santiago Castro-Rial, K. Sys, H. van Oostenbrugge, and B. M. J. Vastenhoud. Integrating economics into fisheries science and advice: progress, needs, and future opportunities. *ICES Journal of Marine Science*, 80(4):647–663, 02 2023b. ISSN 1054-3139. doi: 10.1093/icesjms/fsad005. URL <https://doi.org/10.1093/icesjms/fsad005>.

- E. Tromeur, L. Doyen, V. Tarizzo, L. R. Little, S. Jennings, and O. Thébaud. Risk averse policies foster bio-economic sustainability in mixed fisheries. *Ecological Economics*, 190:107178, Dec. 2021. ISSN 09218009. doi: 10.1016/j.ecolecon.2021.107178. URL <https://linkinghub.elsevier.com/retrieve/pii/S0921800921002366>.
- T. Vallee and P. Guillotreau. Nash versus stackelberg equilibria in a revisited fish war. *Environmental Economics*, 1(2), Mar. 2017.
- I. Vermeir and W. Verbeke. Sustainable food consumption: Exploring the consumer “attitude – behavioral intention” gap. *J. Agric. Environ. Ethics*, 19(2):169–194, Apr. 2006.
- J. E. Wilen. Chapter 2 bioeconomics of renewable resource use. volume 1 of *Handbook of Natural Resource and Energy Economics*, pages 61–124. Elsevier, 1985. doi: [https://doi.org/10.1016/S1573-4439\(85\)80005-1](https://doi.org/10.1016/S1573-4439(85)80005-1). URL <https://www.sciencedirect.com/science/article/pii/S1573443985800051>.
- H. Österblom, J.-B. Jouffray, and J. Spijkers. Where and how to prioritize fishery reform? *Proceedings of the National Academy of Sciences*, 113(25):E3473–E3474, 2016. doi: 10.1073/pnas.1605723113. URL <https://www.pnas.org/doi/abs/10.1073/pnas.1605723113>.

CEE-M Working Papers¹ - 2024

- WP 2024-01 Ivric Valaire Yatat-Djeumen, **Luc Doyen**, Jean Jules Tewa & Bapan Ghosh
« Bioeconomic Sustainability and Resilience of Savanna »
- WP 2024-02 **Mathieu Cuilleret, Luc Doyen & Fabian Blanchard**
« Reducing IUU for Bioeconomic Resilience of Fisheries: Necessary but Not Sufficient »
- WP 2024-03 **Luc. Doyen, M. D. Smith, U. R. Sumaila, G. Zaccour, I. Ekeland, P. Cury, C. Lett, O.Thebaud, J.-C. Poggiale, A. Moussaoui, J.-M. Fromentin, S. Gourguet, P. Guillotreau, H. Gomes, Pierre. Courtois, Robert Schaap, F. Blanchard, C. Rainer, Mathieu Cuilleret, T. Villain, F. Menard, & T. Sari.**
« Mathematical Bio-Economics 2.0 for Sustainable Fisheries »

¹ CEE-M Working Papers / Contact : laurent.garnier@inrae.fr

- RePEc <https://ideas.repec.org/s/hal/wpceem.html>
- HAL <https://halshs.archives-ouvertes.fr/CEE-M-WP/>