MASTER THESIS

# How to formalise complex population dynamics for a stylised ecological model of small-scale fisheries?

**Course of Studies:** M.Sc. Umweltmodellierung (Environmental Modelling)

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# I. Declaration of own work

I hereby declare that this thesis:

*How to formalise complex population dynamics for a stylised ecological model of small-scale fisheries?*

is entirely my work and that I have not used any sources or aids other than those indicated. Furthermore, I affirm that I have followed the general principles of scientific work and publication as set in the guidelines of good scientific practice of the Carl von Ossietzky University.

16.06.2020

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# II. Acknowledgement

The master thesis at hand was developed during the 6 months stay at the Stockholm Resilience Centre (SRC), with the collaboration of my home university (Carl-von-Ossietzky University Oldenburg).

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I am also grateful for the funding from the Swedish Research Council (Dnr 2018-05862) to the OctoPINTS project - Navigating the complexity of small-scale fishery interventions: An intersection of agent-based modelling and participatory empirical research and Sida (Swedish International Development Cooperation Agency) to the project GRAID - Guidance for resilience in the Anthropocene: Investments for development. In these projects that both target modelling SSF triggered this need for guidance in modelling the ecological aspects of small-scale fisheries and allowed for the guidance of this master project.

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# III. Abstract

In fisheries research and management, models are important tools to study, explore, test or predict certain outcomes of policy decision-making. The few existing models for small-scale fisheries (SSF) typically focus more on the social side, leaving the ecological side too simplistic for the diverse ecological realities of SSF. Especially when adopting a social-ecological systems (SES) perspective, the models of SSF are unbalanced as this perspective stresses the inclusion of both sides with equal focus. Important ecological aspects for SSF, such as other species, habitat, physical parameters, environmental variability etc. are often neglected. This thesis aims to determine how these models can be made ecologically more realistic, whilst maintaining a medium level of complexity. Simultaneously, a foundation shall be established for an interdisciplinary dialogue between modellers of different research fields. Therefore, starting from a literature review, the thesis addresses the following questions:

A. *Which fishery and/or ecosystem models exist? How compatible are these for modelling the ecosystem for small-scale fisheries; what can we learn from them for an approach for SSF?*
B. *How can relevant ecosystem dynamics be represented in models of small-scale fisheries, while retaining medium complexity?*

To answer these questions, I am first (A) finding, detailing, grouping and selecting a list of relevant models and then (B) producing a questionnaire supporting ecological implementations for SSF models of medium complexity. Subsequently, to test my findings the developed questionnaire was applied to a case study (OctoPINTS) and corresponding recommendations were given.

Analysis of the identified models demonstrated that the concept of a model of intermediate complexity ecosystem assessment (MICE) best captures the need for modelling fish dynamics for a stylised ecosystem model for SSF. Furthermore, best practice advice on how to design each aspect of an ecosystem model for fisheries, given by the Food and Agriculture Organization of the United Nations (FAO) (2008), were important to consider. The results indicate that depending on the objective of the conducted study, key entities and processes of the environment should be included rather than modelling the entirety of the ecosystem. Hence, every single model must be individually tailored with respect to the research aim, data availability, natural and human ecosystem dimensions, and medium complex aspects. In particular, guidance is developed for modellers focussing on the implementation of multispecies and spatial environmental considerations. But also general model resolution and structural recommendations as well as the link to the human component are discussed. Thereby, a detailed overview on ecological modelling is given, serving as a basis for collaboration of modellers from other fields (e.g. social science) to improve the interdisciplinary exchange.

**Keywords**: *small-scale fishery, social-ecological system, fishery models, ecosystem approach, ecosystem models, ecosystem-based modelling, medium complexity, intermediate complexity, minimum realistic, model resolution, model structure, population dynamics, multispecies, species interactions, spatiality, environmental drivers, anthropogenic drivers*

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| | |
|---|---|
| ABM | Agent-Based Model (also used for individual-based models) |
| CCAMLR | Commission for the Conservation of Antarctic Marine Living Resources |
| COFI | Committee of Fishery Industry |
| EAF | Ecosystem Approach to Fishery |
| EBFM | Ecosystem-Based Fishery Management |
| FAO | Food and Agriculture Organization of the United Nations |
| IBM | Individual-Based Model |
| IM | Integrated Management |
| LSF | Large-Scale Fisheries (or industrial/commercial) |
| LV | Lokta-Volterra |
| MICE | Models of Intermediate Complexity for Ecosystem assessments |
| MRM | Minimum Realistic Models |
| NOAA | National Oceanic and Atmospheric Administration |
| SES | Social-Ecological System |
| SM | Subset Models |
| SSF | Small-Scale Fisheries |
| WEM | Whole Ecosystem Models |

# 1. Introduction

As understood by social-ecological systems (SES), humans are an integral part of the biophysical world. The environment is not just the context in which social interactions take place, and equally, the environment cannot be viewed separately from anthropogenic influences. The challenge of connecting social and ecological science is that scientists of either field use different forms of communication. These can be compared to speaking different languages. Within this thesis the issue at hand is addressed by building a bridge between ecological modelling for marine ecosystems and social scientists developing fisheries models for small-scale fisheries (SSF) as an example of a strong SES.

SSF are very complex systems highlighted by their diverse, heterogenic, and flexible nature. They have long been neglected globally in fisheries science, policy and on national and global fisheries agendas in contrast to the commercial sector (Kittinger et al. 2013; FAO 2019; Jentoft et al. 2017; Guyader et al. 2013; FAO 2020f; Lindkvist et al. 2020; Smith and Basurto 2019; Herrón et al. 2019) Singleton et al. 2017; Prescott and Steenbergen 2017). Fisheries science is a multidisciplinary research field focussed on managing and understanding fisheries. A broad array of academic disciplines is used incorporating amongst others disciplines of oceanography, marine biology, meteorology, conservation, ecology, population dynamics, economics, statistics, social science, decision analysis and management (Leal and Maharaj 2008). The need for incorporating various fields highlights the problem of collaboration, and the previously stated undervaluation of SSF by fisheries science led to the unbalanced and partly underdeveloped research into SSF.

To study and manage these activities, the whole spectrum of fishing activities (captured fisheries) is often simplified and divided into "small-scale fisheries” (SSF; also referred to as "artisanal" or "traditional" fisheries) and "large-scale fisheries" (LSF; also called industrial or commercial) fisheries (Mathew 2003; Smith and Basurto 2019). It contains a multitude of tools and techniques involved in catching fish, ranging from spears and traps to sonar detection, as well as:

- families or collectives gathering by foot in the tidal zone,
- hiring small crews of fishers working from boats with outboard engines, and
- industrial trawlers the size of football fields with processing facilities onboard.

Where exactly to draw the line between LSF and SSF is debated, and at time of writing no consistent definition can be found for SSF. Actually, many SSF articles leave SSF descriptions indefinite or they exhibit attributes that are often unique to a particular fishery or locality (Smith and Basurto 2019; Salas et al. 2007; FAO 2015). Due to its complexity SSF face a diversity of interacting stakeholders, fishing methods, fish species and their exposure to a variety of different human and ecosystem related factors and changes. As a result many definition attempts are simplifying the true complexity of SSF, through the usage of reductionist definitions that focus on aspects that are most easily identified as small-scale, such as boats and fishing gear (Smith and Basurto 2019). In addition, the mobility of the fleet, the production methods, the organisational levels and the distribution of the products are used for defining SSF (Salas et al. 2007).

Instead of presenting SSF and LSF as coextensive categories, LSF was long seen as the more efficient and economically more important sector (Smith and Basurto 2019). This is also reflected in the marginalization that SSF systems experience. But on the contrary, SSF are critical for food and successful livelihoods globally, particularly in coastal areas, and frequently cited as necessary for poverty alleviation (Smith and Basurto 2019; Singleton et al. 2017; Prescott and Steenbergen 2017).

Hand in hand with abundant literature on SSF are existing models thereof. However, while the gap between literature focussing on SSF and LSF is decreasing, the modelling for SSF is lagging and often builds on simplified assumptions taken from traditional single-species stock assessments (Jentoft et al. 2017; Smith and Basurto 2019; FAO 2015).

Due to its highly complex, data-poor and often resource limited nature, modelling is very challenging (Kittinger et al. 2013; FAO 2019; Jentoft et al. 2017; Guyader et al. 2013; FAO 2020f; Lindkvist et al. 2020; Smith and Basurto 2019; Herrón et al. 2019). Above all, the ecological side (namely biological and physical considerations) of modelling suffers from enormous simplifications in favour of socio-economic development (Jentoft et al. 2017; Lindkvist et al. 2020).

The goal of fishery models is to understand the consequences of fishing practises, and then to inform decision-makers who are also aiming to sustain high yields (Hollowed 2000; NOAA 2018b). SSF should be looked at by the point of view of SES and ecological impacts need to be considered thereby. It is the basis to understand shifting fishery patterns and issues such as predation, habitat destruction, and optimal harvesting rates. For some time now, coupling human and natural systems has been recognised as being of high importance for understanding the joint dynamics of both fish stock and fishers including fleet dynamics (e.g. Béné and Tewfik 2001). A commonly used tool is fish stock assessments that provide managers of fisheries with the information they need to support sustainable fishing practices. A mathematical fish stock assessment model depicts the demography of a captured fish stock and produces estimates of relevant factors in fisheries, such as growth, mortality or abundance. The available models for assessing fish stocks range from simple to complex based on the available data for a given stock. This emphasises the problem of SSF, where often insufficient data is available. Scientists choose the model that best suits the life history and data availability of a stock and could trial several models to find the best fit (NOAA 2018a).

A holistic implementation of both sides is necessary when determining the health and abundance of fish as the environment surrounding the stock has an influential role on these parameters. By including ecosystem factors, the results of analysing fishing effects can be better interpreted (NOAA 2019a; Trochta et al. 2018).

Highly attributed for improving the modelling of both, LSF (since 1995) and SSF (since 2015), is the *Ecosystem Approach to Fishery* (EAF) (Mathew 2003; FAO 2003; 2015; Jentoft et al. 2017). EAF is defined by FAO as an approach to fisheries that:

> *“strives to balance diverse societal objectives, by taking into account the knowledge and uncertainties about biotic, abiotic and human components of ecosystems and their interactions and applying an integrated approach to fisheries within ecologically meaningful boundaries.” (FAO 2003, 6)*

However, this approach has not been sufficiently implemented, even for LSF, but especially when looking at SSF models (FAO 2015; Smith and Basurto 2019; Singleton et al. 2017; Lindkvist et al. 2020). For example, even though SSF systems are primarily multispecies fisheries, no “real” multi-species approach has been implemented for SSF thus far. If more than one species is recorded, associated feedback is missing (Prescott and Steenbergen 2017; Plank et al. 2017).

The issues that models for SSF face by having limited access to data while being tremendously diverse and flexible should be emphasized in comparison to LSF, which exhibit these problems to a lesser extent, and yet the integration of realistic stock assessment models including ecosystem considerations is still challenging (NOAA 2018b).

Models for SSF either consider only one stock (aka single-species) (e.g. SMILI (Lindkvist), FIBE (Wijersmans et al. 2020), FMMHLF (Sheppard 2012), Salmon-abm (Salmon-abm 2016) or the models of Horta e Costa, Gonçalves, and Gonçalves (2013)) or they include multiple stocks of species and neglect ecological considerations as species interactions (e.g. POSEIDON (Burgess et al. 2018; Bailey et al. 2019) or the models of Ruttan et al. (2000); Rueda and Defeo (2003); Cissé et al. (2013), this was also highlighted by Jentoft et al. (2017). Further, spatial implementation is mostly applied for modelling the migratory aspects of fishers (e.g. fleet dynamics) in contrast to the ecological dynamics of spatiality in stock dynamics. Yet, the most elaborated SSF models can be found for Australia (Jentoft et al. 2017; Pavlowich, Kapuscinski, and Webster 2019; Plank et al. 2017).

Hence, this thesis aims to expand on this underdeveloped issue of ecological formulation options for SSF within complex coupled systems, specifically to tackle the subject of modelling stock dynamics more realistically. Furthermore, given the difficulty for social scientists to scour the jungle of ecological modelling this thesis is dedicated to this topic by answering the research questions:

A. *Which fishery and/or ecosystem models exist? How compatible are these for modelling the ecosystem for small-scale fisheries; what can we learn from them for an approach for SSF?*
B. *How can relevant ecosystem dynamics be represented in models of small-scale fisheries, while retaining medium complexity?*

To answer these questions, existing ecosystem and fishery models were reviewed and subsequently a guide to formalize the ecological side of stock dynamics suitable to support model developers for SSF was developed.

The remainder of the thesis will address these research questions and is summarized in Figure 1. Within this figure, methods and main findings are highlighted.

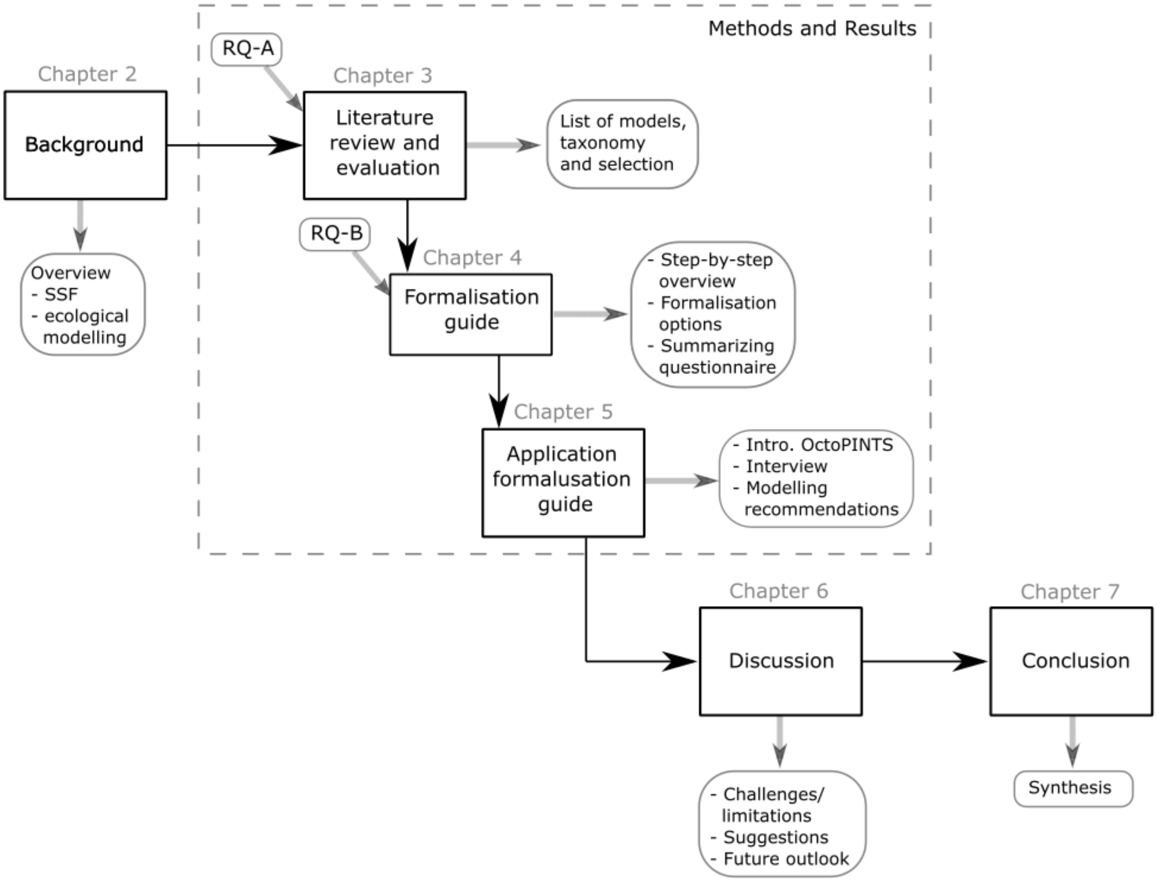


***Figure 1**: Layout of the remaining chapters, as well as contribution to the total thesis.*

Firstly, background information on small-scale fisheries will be provided, focussing on their importance, their history of sustainable assessment and the challenges arising in modelling SSF. Furthermore, how to design ecosystem models is presented as well as categorization approaches found in literature, the relationship of model performance and complexity, as well as the dimensions of getting from a traditional single-species assessment to a more holistic ecosystem approach.

In chapter 3 the core of this thesis is presented by researching literature for existing fishery and/or ecosystem approaches and models and classifying these models into a suitable taxonomy. On this basis, the benefits of these models for ecological-based modelling for SSF are evaluated. From the attempt at defining SSF, the heterogeneity, data-poor and flexible nature of SSF is already presented. Therefore, selection criteria included the complexity of the model, data demand and adaptability to various environments and scenarios.

Subsequently, on the basis of the previous chapters and being guided by the concept of Models of Intermediate Complexity Ecosystem Assessment (MICE) and the FAO best practice guidelines for ecosystem models (FAO 2007), an attempt to model the ecological side of SSF is presented within chapter 4. Insights into modelling stock dynamics more “realistically” but staying moderately complex are given in a step by step manner and within a condensed questionnaire. This is done by introducing the development of stock assessment for multispecies and species in different environments. Further, the link to the human component is provided. This attempt at modelling advice for the ecological side is then audited within the model development for octopus fishery in the Western Indian Ocean (OctoPINTS[1]) as seen in chapter 5.

Within chapter 0 the results gathered in chapter 3, 4 and 5 are reflected and discussed. Challenges that occurred during the process, as well as aspects limiting the results and ways to overcome these challenges and limitations are presented. Additionally, an outlook for possible future work is given.

At the end of the thesis a synthesis is drawn in chapter 7, highlighting the significance and implications of my findings and pointing out the contribution this thesis made.

Attached to this work is supplementary information, including a glossary, information on regional differences of SSF, a list of references used of the models found in section 3.1. and exclusion criteria for individual models as further information on section 3.3.

[1] OctoPINTS project - Navigating the complexity of small-scale fishery interventions: An intersection of agent-based modelling; see https://octopints.wordpress.com/

# 2. Background

Within this chapter, the knowledge required to understand the following chapters is provided. Primarily SSF and ecological modelling will be covered.

## 2.1. Background: Small-Scale Fisheries (SSF)

Within this section, carved out is the global importance and strength of SSF for policy and decision-making, historic development of guidelines and regulations, and codes for SSF and threats, challenges and limitations SSF assessment face nowadays.

### 2.1.1. The global importance of SSF

Small-scale fisheries (SSF) have a long history of marginalisation in political processes and are disregarded in policy. Why this does injustice to the sector of SSF will be made clearer in this section. For clarification, related terms such as capture fishery, large-scale fishery (LSF), small-scale fishery, (SSF) SSF Guidelines can be viewed in IX.i Glossary (Appendix).

SSF[2] purportedly have a low impact on the ecosystems on which they depend due to the low intensity of fishing gears and practices compared to LSF (Naranjo-Madrigal, van Putten, and Norman-López 2015). However, if one does not look at every single small-scale fisher, but on the entire sector all over the word, something else becomes clear. In fact, the vast majority of the world's capture fisheries are characterized as small-scale/artisanal (Nayak, Oliveira, and Berkes 2014; Finkbeiner and Basurto 2015; WorldFish, FAO, and Duke University 2018), although they're total catch is generally low. In summary, SSF play a major role globally (Guyader et al. 2013).

SSF have an important role for human well-being and sustainable development, as they contribute to food security, health, livelihoods and poverty alleviation and contribute substantially to household, local and national economies (thereby influencing the structure of seafood markets) as well as economic growth (FAO 2019; 2020f; Eriksson et al. 2016; Kittinger et al. 2013; WorldFish, FAO, and Duke University 2018), Smith and Basurto 2019).

The contribution SSF is making is highlighted in Figure 2. It shows that SSF are a reliable and important source for food with more than 50% of global fish landings, or about half of global fish catches (FAO 2019; Herrón et al. 2019; Kittinger et al. 2013; Salas et al.

[2] The terms artisanal or traditional fishery can be seen as synonyms, although these are often specific types of SSF

2007). Especially in the developing world, where SSFs provide the largest share of the fish consumed (FAO 2020f).

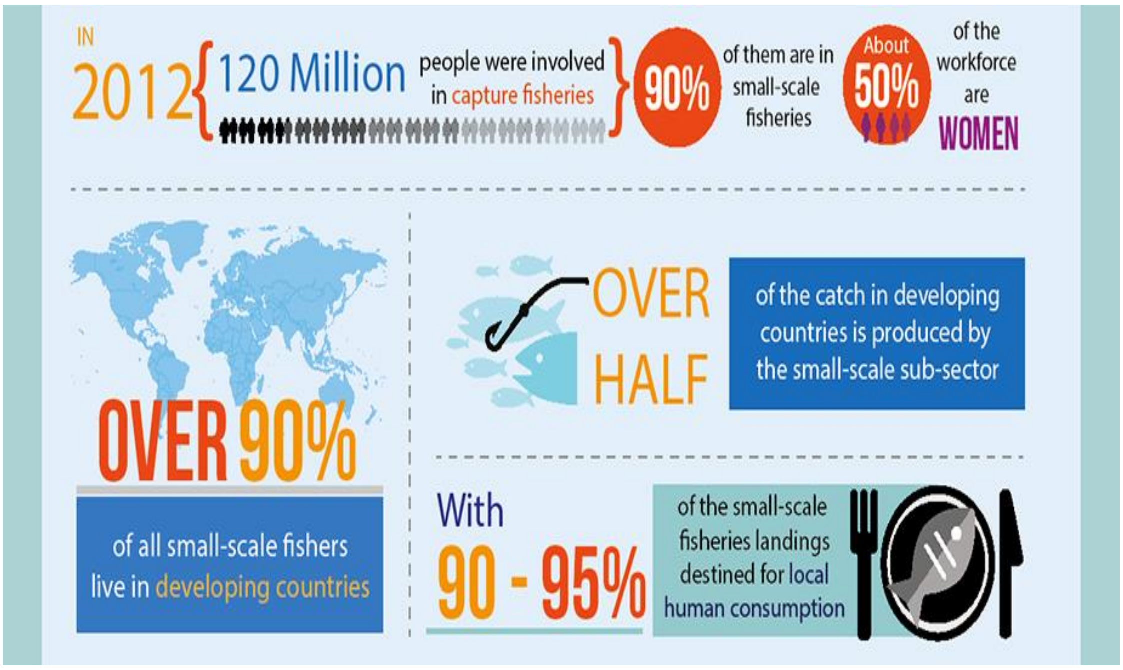


*__Figure 2:__ The importance of SSF (FAO 2015).*

Furthermore, SSF are by far the oceans' largest employer, more than in all other maritime sectors combined (World Bank 2012; WorldFish, FAO, and Duke University 2018). The entire global fisheries sector employs directly and indirectly around 120 million people (status 2012), whereby 51 million of them are directly involved in fishery activities (FAO 2020f; Jentoft et al. 2017). 90% of the 120 million people are involved in the SSF sector, whereby around 37 million people are directly employed in fishing activities of small-scale fisheries, most of whom live in developing countries (FAO 2020g). Indirect fishing activities are related activities such as fish processing and marketing, boat building and net making. Also, many more people are involved in part-time or seasonal fisheries activities, and the benefits of fish consumption are widely significant around the world. (FAO 2020g; Jentoft et al. 2017).

The SSF sector is employing not only men but also women throughout its value chain as well as service functions (FAO 2019). Women represent nearly half of SSF workers globally (World Bank, 2012). They are found along the entire SSF value chain, but primarily dominate post-harvest and processing activities (FAO 2015).

SSF is also deeply rooted in local communities, traditions and values. Many small-scale fishers are self-employed and usually provide fish for direct consumption in their households or communities (FAO 2015; 2019; Nayak, Oliveira, and Berkes 2014). SSF are often culturally important to the identity of those involved, and can be central to trade, social structures and interactions within and among communities (Guyader et al. 2013).

The great diversity of SSF makes their assessment and management complex, especially when considering the multiple links between social and ecological components of the fishery system (Naranjo-Madrigal, van Putten, and Norman-López 2015). Policy needs to keep in mind the environmental impacts and/or changes and thus not only focus on the complexities of the people and communities involved in SSF. But to also address the fundamental topics of nutrition and food security, vulnerability and poverty, gender, migration, health and education, microfinance, as well as livelihoods (FAO 2020f). This includes adequately assessing the ecological side, namely the resource fish, its habitat and its physical and biological characteristics.

### 2.1.2. History of sustainable fishery assessment

At the beginning of the twentieth century the modern institutions of fisheries science and management were established to meet the challenges of industrial fishing and increased exploitation of resources. These institutions disregarded SSF with a substandard status and a lower priority in national and global fisheries agendas. This led to persisting inequalities between SSF and industrial fisheries (Smith and Basurto 2019).

Early on, it became clear that a new approach, which brings greater focus onto the debate and environmental concerns, was urgently needed. Fishers, fish worker organizations and related civil society organizations (CSOs) began calling for the development of a specific set of guidelines (FAO 2012; Smith and Basurto 2019). Especially after unsuccessful attempts to adapt the global approach to fisheries, which provides effective management and sustainable development, to the threats towards sustainable fisheries by introducing Exclusive Economic Zones (EEZs) and adopting the United Nations Convention on the Law of the Sea in 1982 (FAO 2012). As early as 1995, fishery organisations joined forces in the adoption of the Code of Conduct for Responsible Fisheries (FAO 2012; Smith and Basurto 2019). These guidelines provide the necessary framework for national and international efforts to ensure the sustainable use of living marine resources. The Code has established principles and standards that apply to the conservation, management and development of all fisheries. In addition, it has already served to highlight the benefits of an ecosystem approach to fisheries (EAF) (FAO 2012). But the guidelines, which supposedly set standards for global best practices in relation to all capture fisheries, contained only four mentions of the specific needs of SSF (Smith and Basurto 2019).

Since the new millennium, SSF are increasingly pushed on national and global agendas and concerns related to food security, employment and poverty in SSF, scientific attention, regulations and guidelines. But are still widely and globally discussed within a minimal status and a lower priority on national and global fisheries agendas. Included below are examples of increased focus on SSF in national and global agendas:

- In 2002 at the World Summit for Sustainable Development in Johannesburg: discussions on concerns related to food security, employment and poverty in SSF (Salas et al. 2007)
- In 2004 at the first Coast Fish Conference in Mérida, Mexico: to contribute to a better understanding of SSF in Latin America and the Caribbean (LAC), to bring together scientists, managers and fishers to share information and experiences in managing marine SSF, and to identify challenges in data collection, assessment and management of these fisheries within the region (Salas et al. 2007)
- In 2005, FAO published technical guidelines for responsible fisheries aiming specifically to address poverty in small-scale fisheries, as part of the Code of Conduct (Salas et al. 2007; FAO 2005).
- In 2008 the First Global Conference on Small-Scale Fisheries “Securing Sustainable Small-Scale Fisheries: Bringing together responsible fisheries and social development” in Bangkok was held. Reaffirming that human rights are critical to achieving sustainable development and calling for an international instrument on small scale fisheries (FAO 2020i)
- In 2010 the FAO convened three regional workshops in Africa, Asia and the Pacific, and Latin America and the Caribbean to consult with national and regional stakeholders, to identify good practices in the governance of small-scale fisheries, and to provide their views on how to fulfil their potential (FAO 2020i)
- In 2012, the FAO collaborated with the World Bank and WorldFish researchers to generate better global estimates of SSF independent of self-reported national fisheries statistics, compiled within the Hidden Harvest Report (Smith and Basurto 2019; The World Bank 2012). Forthcoming, the Illuminating Hidden Harvests Report will be released to revalue the contribution of small-scale fisheries to sustainable development (WorldFish, FAO, and Duke University 2018).
- The adoption in 2014 of the FAO Voluntary Guidelines to Securing Sustainable Small-scale Fisheries in the Context of Food Security and Poverty Eradication (SSF Guidelines) signalled a historic turnaround for SSF. Having been the first

globally negotiated policy specifically for the small-scale fisheries sector, the SSF Guidelines differ from other fisheries instruments because they were developed in an inclusive, participatory process and took a human rights-based approach to fisheries policy (FAO 2015; Smith and Basurto 2019).

- Since 2009 SSF is a noticeable part of the Sessions of COFI which has driven the development of the SSF Guidelines forward by expressing the need for an international recognized instrument on small-scale fisheries. This would guide national and international efforts to secure sustainable small-scale fisheries and create a monitoring framework approving the development of guidelines on small-scale fisheries. The framework would draw on existing instruments and complement the Code of Conduct for Responsible Fisheries based on the conclusions and recommendations of the regional workshops, and the beginning of the development of the SSF Guidelines (FAO 2020i). The latter gave SSFs their own permanent agenda item at the biennial meeting of the COFI, an improvement on their low representation within global politics for many years. 2022 was even declared the Year of Artisanal Fisheries and Aquaculture, and a growing cohort of Member States publicly committed themselves to implement the SSF Guidelines in their national fisheries (Smith and Basurto 2019; FAO 2020i).

Scientific attention to SSF is also expanding, as evidenced by a significant increase in peer-reviewed publications on SSF over the past two decades, and the development of global partnerships for collaborative SSF research such as the Too Big to Ignore network (Smith and Basurto 2019; Jentoft et al. 2017)

Small-scale fisheries and communities make up the majority of the livelihoods associated with fishing worldwide and support food security for millions of people globally. Yet they are often not recognized and overlooked in national, regional, and global decision- and policy-making processes that influence their lives and future (Kittinger et al. 2013; FAO 2019; Jentoft et al. 2017). However, numerous environmental, socio-economic, and governance challenges, such as climate change, global market pressures, poverty and marginalization from policy processes, threaten the sustainability of these fisheries. Achieving sustainable small-scale fisheries requires balancing ecological and social objectives through interdisciplinary solutions that link science and policy(Salas et al. 2007; Kittinger et al. 2013; Lindkvist et al. 2020), such as modelling. The next section gives an overview on challenges of modelling the SSF sector has to face.

### 2.1.3. Challenges of modelling SSF

It is already known that SSF have long been neglected and overlooked in government, law and fishery science or hidden within national fisheries statistics (see Chapter 1), although they are economically and socially very important (see 2.1.1). Recently, this is changing (see 2.1.2) and SSF are appearing more commonly on the agenda of these institutions. However, it is crucial to first overcome these challenges because approaching global threats (e.g. climate change, population growth, diminishing fish resources, etc.) combined with poor management limits the ability of these fisheries to support their social and economic benefits (Eriksson et al. 2016). As well as the reasons of negligence in the first place; the economic underestimation of SSF next to LSF, still remains (Singleton et al. 2017; Smith and Basurto 2019). Furthermore, while the smaller commercial sector received more attention, the more dispersed artisanal and traditional coastal fisheries have not been recognized enough (FAO 2014). These challenges, with a focus on the problems that arise in modelling, will now be presented.

SSF are SES (see 2.1.4) and the management of such systems creates challenges with respect to complex and sometimes even contradictory objectives such as economic efficiency, livelihood, food security, and environmental sustainability. As a result, certain policies can lead to simultaneous successes and failures, and policies that neglect local institutional and environmental contexts and their interaction can have unintended consequences. In addition, fisheries authorities in developing countries often lack the financial, human and political resources for adequate implementation and enforcement, which points to the limitations of centralised approaches to SSF governance and the need for greater involvement of local stakeholders (Finkbeiner and Basurto 2015).

Most of the problems that arise for the modelling of SSF can be traced back to the same origin: The complexity, variety and flexibility of SSF. These characteristics make it seemingly impossible to define SSF or even to predict the results of interventions in SSF. Moreover, the plurality of SSF prevents efforts to capture them systematically and reliably with higher standards, to understand the dominant processes and to define a unified and effective voice for advocacy. Their challenges thus consist of a chronic lack of institutional capacity and political will to set SSF priorities, their specific data needs and their unique methodology. (Smith and Basurto 2019; Lindkvist et al. 2020; WorldFish, FAO, and Duke Univerity 2018).

SSF are confronted with a wide variety of social, institutional and environmental entities, the interactions within and between these entities, the large-scale driving forces and the diverse social, economic and environmental context, and the range of outcomes that result from these interactions (Smith and Basurto 2019). SSF are increasingly affected by both local threats and external pressures worldwide, and vulnerability to these pressures threatens coastal communities and ecosystems (Kittinger et al. 2013). Internal pressures may include increasing fishing effort and limited investment in management, which make the costs of marginalization increasingly obvious (WorldFish, FAO, and Duke University 2018). In addition, there may be a broader context in which SSF are embedded - external pressures. These include: international trade relations, technological change, increased tourism and competition for space and resources through: inter alia, fisheries migration, LSF and recreational fishing (Kittinger et al. 2013; Eriksson et al. 2016; WorldFish, FAO, and Duke University 2018; Guyader et al. 2013). Also, external threats such as invasive species, infrastructure development, pollution, overfishing, climate change and the exploitation of the oceans (Duke Nicholas Institute 2018). Hence, not only the long-term effects of fishing, but the effects from further activities affect the sustainability of the practice via damaging coral reef health, overfishing and environmental degradation (Salas et al. 2007).

Lack of access to management, government, law and research of SSF leads to sometimes inappropriate incentives, less sustainability and eventually possibly even higher poverty (Singleton et al. 2017; Herrón et al. 2019; Gianelli et al. 2018; Lindkvist et al. 2020; World Bank 2012; Salas et al. 2007). The example of poverty in SSF shows how complicated it can be to address problems in this sector. Poverty is a multidimensional issue and is caused not only by diminishing fisheries resources and low incomes, but also by factors that impede the full exercise of human rights, including civil, political, economic, social and cultural rights. The often complex livelihood strategies of fishing communities are not always understood, and SSF issues are often inadequately addressed, both in terms of resource management and from a broader perspective of social and economic development (FAO 2019). Poverty is a major issue in SSF, since despite the fact that SSF are a crucial source of livelihood, 20% of the world's fishers earn less than one dollar a day (Finkbeiner and Basurto 2015).

SSF can be described as systems that harvest on a diversity of different species in many different locations. They are distributed around the globe and use a variety of fishing gear, vessels and fishing methods. They are therefore often referred to as multi-gear and multi-species fisheries. SSF fleets are highly dynamic and migratory and often several fleets share the same area, for example a reef (Kittinger et al. 2013; Prescott and Steenbergen 2017; Herrón et al. 2019). Tropical multi-species SSF fisheries in particular are characterized by large spatial and temporal variation in landings, high species diversity, different fishing gear and fishing methods, the dispersion of landing sites along the coast and high uncertainty in access to resources (Naranjo-Madrigal, van Putten, and Norman-López 2015). Cases where a single species is dominant in small-scale tropical fisheries are extremely rare. A tropical example from the Gulf of Thailand, where many different fishing methods are used, illustrates the problem of multitude of species with its different vulnerabilities (Satumanatpan and Pollnac 2020).

It further cannot be assumed that similar SSF (e.g. in terms of boat size and type of fishing gear) lead to similar social, economic and environmental relationships, as these are very context-specific and also depend on the catch, access to resources and dependency, the market for which they are caught (local or global), etc. Also within the same country, even within the same fishery, resource access and dependency on fishery-livelihoods amongst stakeholders vary greatly in SSF (Smith and Basurto 2019). This makes interdisciplinary implementation, using bioecological, socio-cultural as well as bio-economic instruments depending on the study objective necessary. Each discipline is itself very complex and increases the difficulty of the modelling approach (Salas et al. 2007). Combined with complexity, these challenges limit understanding of how a policy is received and are often at the heart of unintended policy outcomes. There are also communication problems, such as transferring complex outcomes to local decision-makers who are experienced in dealing with these issues (Lindkvist et al. 2020).

Furthermore, model development of these systems is limited due to the issue of data availability on environmental and social dimensions caused by the undervaluation of these systems (Kittinger et al. 2013; Prescott and Steenbergen 2017; Herrón et al. 2019; Lindkvist et al. 2020). In Brazil, for example, the Federal Government stopped conducting fishery statistics around 2010. Since then, too much important information has not been collected, posing a major threat to stock assessment and management regulations for target species (TBTI 2018). Limitations of systematic data collection, including the lack of continuous and missing standardisation methods, and integrated information on SSF were much less addressed than for LSF. More information is available on LSF because they produce large yields and make a high contribution to national GDP (Salas et al. 2007). For example, while international organisations such as the FAO regularly provide information on landings from fisheries, a distinction is rarely made between landings from SSF and LSF. Hence, there is a lack of necessary information and knowledge on fleet structure, length-to-frequency catch data, fish abundance, growth, reproductive characteristics and fishing mortality of target species. But it is not only the data that are limited in these systems, the inconsistency and quality of the available data is also a problem, which entails high uncertainties (Guyader et al. 2013; Herrón et al. 2019). The collection of this data is generally costly and, at least for some countries, difficult to implement in the long term as there is often a lack of financial resources and the ability to collect independent information on fisheries. Often the catch and effort statistics are then used as a basis, which are not always reliable. Additionally, there are limitations in obtaining economic information due to a lack of confidence between the SSF sector and managing instances (Salas et al. 2007). Not only in developing countries, but also in Europe, data availability is an issue as it is generally difficult to obtain data in heterogeneous fisheries. Also these systems are diverse, where fishers may likely change fishing strategy (i.e., métier) conditioned by multiple drivers (Palmer et al. 2017). As a result, there is a lack of fine resolution of cultural, socio-economic and ecological data, which makes it difficult to develop, implement and evaluate policies and management strategies that are adapted to the local context (Jentoft et al. 2017; Lindkvist et al. 2020). Self-monitoring initiatives are beginning to spread among local communities, especially with the help of NGOs and academic researchers. If it is not possible to rely on governments for such fundamental components to ensure the sustainability of small-scale fisheries (and fisheries in general), it is important to invest in local approaches to assessing and maintaining fishing activities (TBTI 2018).

As a result of the underestimation experienced in SSF (Singleton et al. 2017; Herrón et al. 2019; Gianelli et al. 2018), namely the lack of systematic studies on SSF and the lack of skills, leads to the problem that gaps in knowledge still exist today. This in turn leads to the formulation of assumptions rather than the intangible elements defining the sector. Furthermore, skills to conduct interdisciplinary research that goes beyond traditional approaches, including for example the entire ecosystem, are missing. SSF issues cannot be tackled with these traditional simple single-species management approaches (Salas et al. 2007). This makes it almost impossible for management structures in SSF to take into account complex interrelationships that exist across several socio-ecological dimensions (Eriksson et al. 2016). This limits the development of realistic, robust and informative models (Guyader et al. 2013). Here, it is not helpful that there is more information available for LSF as a counterpart to SSF in capture fisheries. In making this classification it should be kept in mind that not all assessment and management tools are equally suitable for all types of fisheries (Salas et al. 2007). They differ widely in terms of focus, linkages, driving forces and the higher degree of flexibility of SSF, which quickly adapt to the abundance of animals present. For example, in the case of SSF, not only economic profit, but also lifestyle and tradition, i.e. social and cultural factors, can influence the fisher's choice of location. In order to capture these characteristics of SSF, i.e. to determine the individual choices of individual fleets, simulations in individual-based models are necessary. However, fisher's behavioural models are primarily quantitative data, and it is precisely such data that is often missing in SSF. Socio-cultural information is mostly qualitative and therefore difficult to include (Naranjo-Madrigal, van Putten, and Norman-López 2015).

SSF management nowadays is not sufficiently structured to address the complex linkages that exist across several socio-ecological dimensions. The mismatch between governance institutions, ecosystem dynamics and patterns of human activity possibly result in poor representation of the system. This situation is exacerbated by a lack of research and management capacity. Fisheries management and its shortcomings are context-specific, and it is not possible to formulate 'best suited' solutions that are universally applicable. Understanding the existing conditions and managing change is therefore an important part of any improvement process (Eriksson et al. 2016).

### 2.1.4. Social-ecological system (SES) perspective

As already mentioned at the beginning, the aim of this thesis is to provide a modelling option for the ecological side of Social-Ecological Systems (SES), which describe the close coupling of human and natural systems. Ecosystems are influenced by humans and in turn provide ecosystem services to society and are thus the basis of human well-being. These interactions are constantly changing due to feedback and internal or external factors and take place on different temporal and spatial scales, making SES highly dynamic (see 2.1.3). Incorporating a SES perspective includes considering the complex nature and dynamics of the resource, resource users and the governance subsystems, together with the relevant external drivers affecting them (Ostrom 2009; M. Schlüter et al. 2012; Schulze et al. 2017; FAO 2019).

Global sustainability is challenged by the effects of globalisation and climate and environmental change on ecosystems and the human societies embedded within them. To develop a better understanding of what these changes can mean for society and the natural resources on which it depends, SES research proposes a complex perspective for adaptive systems. Today this has become a crucial part of the global sustainability challenge. While important factors such as strong governance, social cohesion and incentives have been associated with sustainable cooperative management of natural resources, questions remain as to how these factors interact over the long term to contribute to social and environmental sustainability. This is particularly challenging in low-income countries, which often suffer from a lack of data, drastically limiting the applicable methodologies for analysing change compared to those in data-rich contexts. (OctoPINTS, 2020). What effects these linkages of different system drivers could have is illustrated in Figure 3.

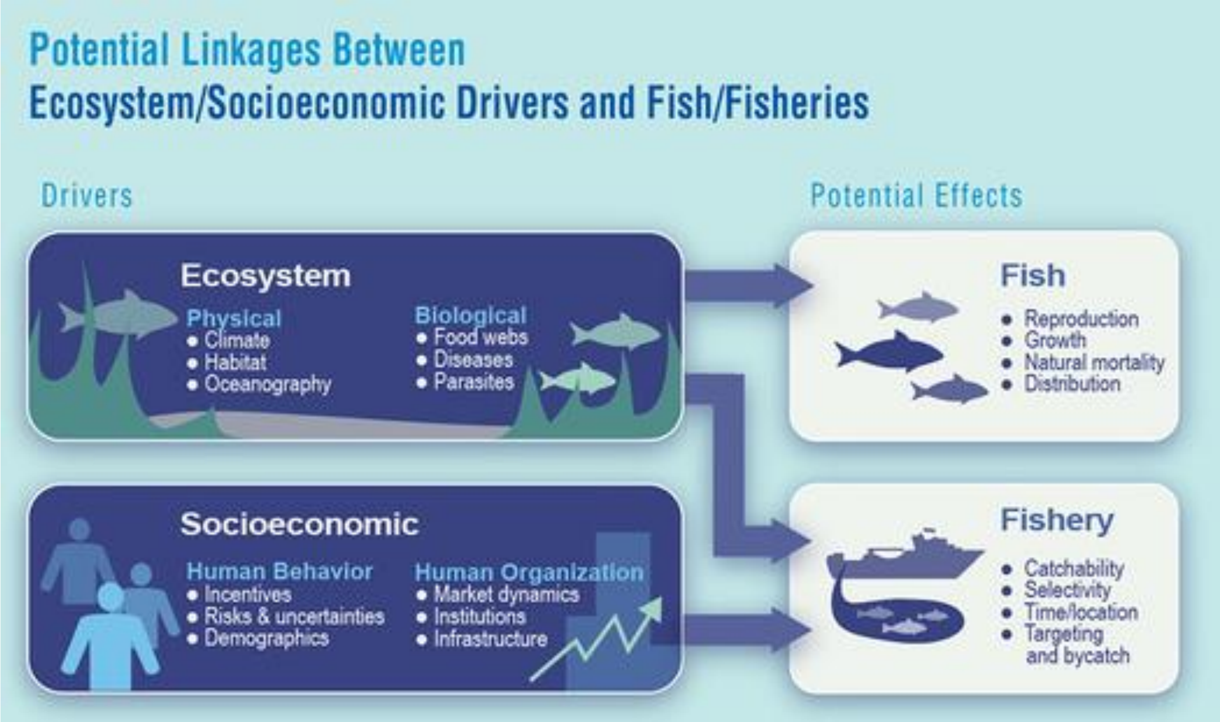


***Figure 3:*** *Illustration of potential linkages between ecosystem and socioeconomic drivers as well as fish and fisheries (NOAA 2019b).*

Conventional approaches to natural resource management are too limited to meet the challenges those systems face. Understanding the dynamics of SES is therefore crucial to support sustainable management of resources to ensure ecosystem integrity (Schulze et al. 2017).

Looking through an SES perspective is particularly important when SSF are considered, giving the specifications of SSF being an ecologically and social driven system (Prescott and Steenbergen 2017). Modelling of fisher's interactions with SES is one approach to better understand ecological responses. For instance, undesirable changes may be anticipated and potentially avoided if the behaviors of fishers, the institutions, and the ecological feedback is included in management planning (Naranjo-Madrigal, van Putten, and Norman-López 2015). Thus, in managing these fisheries as SES, it is necessary to consider not only the dynamics of the resource users and the governance sub-systems, together with the relevant external factors influencing them, but also the complex nature of the resource itself (FAO 2019). Especially since SSF are often at risk of poverty, as poverty is a process rooted in social and institutional factors and influenced by environmental dynamics. Understanding poverty requires a focus on SES as a whole, and likewise, fighting poverty requires not only the reconstruction of collapsed stocks, but of the entire social-ecological system, including the restoration of the relationships between resources and humans. (Nayak, Oliveira, and Berkes 2014).

## 2.2. Background: Ecological modelling

The second part of this chapter is dealing with modelling aspects. At first the “simple” fish stock assessment is described and thereby the importance of ecosystem considerations is highlighted. Afterwards ecosystem modelling and the ecosystem approach to fishery (EAF) is introduced. Due to the variety of ecosystem modelling approaches, categorization designs found in the literature are then reviewed. As complexity plays a significant role in ecosystem modelling, the relationship between model performance and complexity is provided. Finally, importantly, the dimensions of implementing ecosystem considerations are presented and explained.

### 2.2.1. Fish Stock Assessment

A biological fish stock is a group of fish of the same species living in the same geographical region and which mix together for reproduction. A management stock may refer to a biological stock or to a multi-species complex managed as a unit (NOAA 2020).

Fish stock assessment:

> *“is the process of collecting, analyzing, and reporting demographic information to determine changes in the abundance of fishery stocks in response to fishing and, to the extent possible, predict future trends of stock abundance (NOAA 2018a)”*

With Stock Assessment, effects of fishing can be examined, as well as questions on current status of fish stock and its size. Plus being able to predict how the stock will respond to human behavioral or environmental changes provides the scientific basis for successful and sustainable fisheries management by giving information on current health and future trends of a fish stock and its fishery (Thorson et al. 2017; NOAA 2018a; Hoggarth 2006)

Therefore, mathematical models to evaluate and specify the present and probable future conditions of a fishery are used. These fish stock assessment models represent the processes of birth, natural death, growth, and fishery catch that affect the fish stock over time. Required data comprises of abundance (measure, or relative index, of the number or weight of fish in the stock), biological (provides information on fish growth rates and natural mortality) and catch (the amount of fish removed from a stock by fishing) data. Fish stock assessments combine and incorporate many different complex observations into a holistic picture of the situation. The more complex the simulations are (multiple stocks and stock areas, several fishing fleets etc.), the more data and parameters are needed (Storch et al. 2017; NOAA 2018b)

Stock assessments are, by necessity, simplified approximations of what is happening in the real world. It cannot account for the entirety of processes taking place. The key is knowing when a simpler set of data and models is good enough and when it must be expanded to include more factors. Historically, this approach solely involved abundance, biological, and catch data. Now a need to add environmental and ecosystem data to track changing conditions is considered, which comes with huge challenges through complexification (NOAA 2018b).

Given that factors other than fishing can play an influential role in determining the health status and abundance of fish stocks, environmental and ecosystem data are not only important for fish populations; but by including them in the analysis of the impact of fisheries, the results of stock assessments can be better interpreted. Ecosystem factors such as the food web, interactions between species, habitat, physical environment, and large-scale climate patterns may be important. This ecosystem-based fisheries management (EBFM) is supported by stock assessments using integrated ecosystem assessments (NOAA 2019a). For more detailed information see 2.2.2.

### 2.2.2. Ecosystem Modelling

As introduced in chapter 1. and in 2.1.2, applying an Ecosystem Approach to Fishery (EAF) is recommended for SSF as well as LSF fisheries. Therefore, in this section a closer look into EAF, as well as ecosystem modelling in general, is given. For clarification, related terms such as ecosystem, fishery management, ecosystem(-based) management, ecosystem approach to fishery, ecosystem-based fishery management, integrated management, can be viewed in IX.i Glossary (Appendix).

When it comes to the ecological assessment of fishery stocks, ecological modelling is about providing a scientific basis for the sustainable use of renewable resources that depend on more than what can be reproduced in traditional single-species stock assessment, which used to be, to a large extent, the exclusive source of scientific advice (Plagányi and Butterworth 2012). The focus within this assessment is on isolated single-species affected by fishing. However, fishing is only one variable affecting a species' population. Additional elements come into play, such as interactions with other species, the effects of environmental changes, or pollution and other stresses on habitat and water quality (NOAA 2017)

This awareness of the limitations of a single-species approach to fisheries management has led to a global recognition of the need for a more comprehensive approach. The ecosystem approach to fisheries (EAF) for assessment and management, as a strategy, was developed, and also guidelines for the EAF of SSF (FAO 2008; 2015).

EAF is not the only approach which pursues this goal. Other approaches that have the same or similar aim are the following (FAO 2003):

- Ecosystem-Based Fishery Management (EBFM)
- Integrated Management (IM)

Although they have different definitions and conceptual approaches to integrating ecosystem considerations into fisheries management decisions, due to different perspectives or approaches, they are generally all holistic approaches. They take into account not only the impact on target stocks, but also the impact on the wider ecosystem resulting from fishing activity, its social and economic results and the conditions supporting the achievement of the objectives set. For reasons of simplicity, I will solely refer to EAF (FAO 2003).

The resulting ecosystem modelling tries to express theories of ecology in the form of mathematical models. As knowledge about ecological systems progresses, more and more details are integrated into the models. However, the attempt to represent the full complexity of natural processes leads to mathematical models that may be unsolvable and usually lead to difficulties in parameter estimation. Therefore, the art lies in finding the right compromise between biological complexity and mathematical comprehensibility (Plagányi and Butterworth 2012). Fishermen's interaction within the ecosystem requires the identification of four main ecosystem compartments (FAO 2003):

- a biotic compartment, including target fish resources, associated and dependent species and living habitat (seaweed, algae beds, corals)
- an abiotic compartment characterised by its topography, soil types, water quality and local weather/climate
- a fishing compartment where harvesting and processing activities of a highly technological nature take place, and
- an institutional compartment consisting of laws, regulations and organisations required for fisheries management

As part of the biotic component of the ecosystem, humans obtain resources, food, services and livelihoods. Furthermore, they are the driving force behind the fishery component. Fisheries are also influenced by non-fishing activities, the global climate, neighbouring interchanging ecosystems, and the socio-economic environment as reflected in the market, relevant policies and societal values (FAO 2003). Ecosystem models representing a broader range of technological and ecological processes affecting species in the ecosystem (including multi-species and whole ecosystem models), are potentially important tools for providing this broader scientific information (FAO 2008). When deciding on management solutions, it is therefore important to consider this broader spectrum of societal goals. On the one hand, the interactions in the ecosystem, on the other, a holistic way of managing fisheries and marine resources. The Aim is to maintain ecosystems in a healthy, productive, and resilient condition so they can provide the necessary services for humans (NOAA 2017). A simplified diagram of interactions in an exploited ecosystem is given in Figure 4 below.

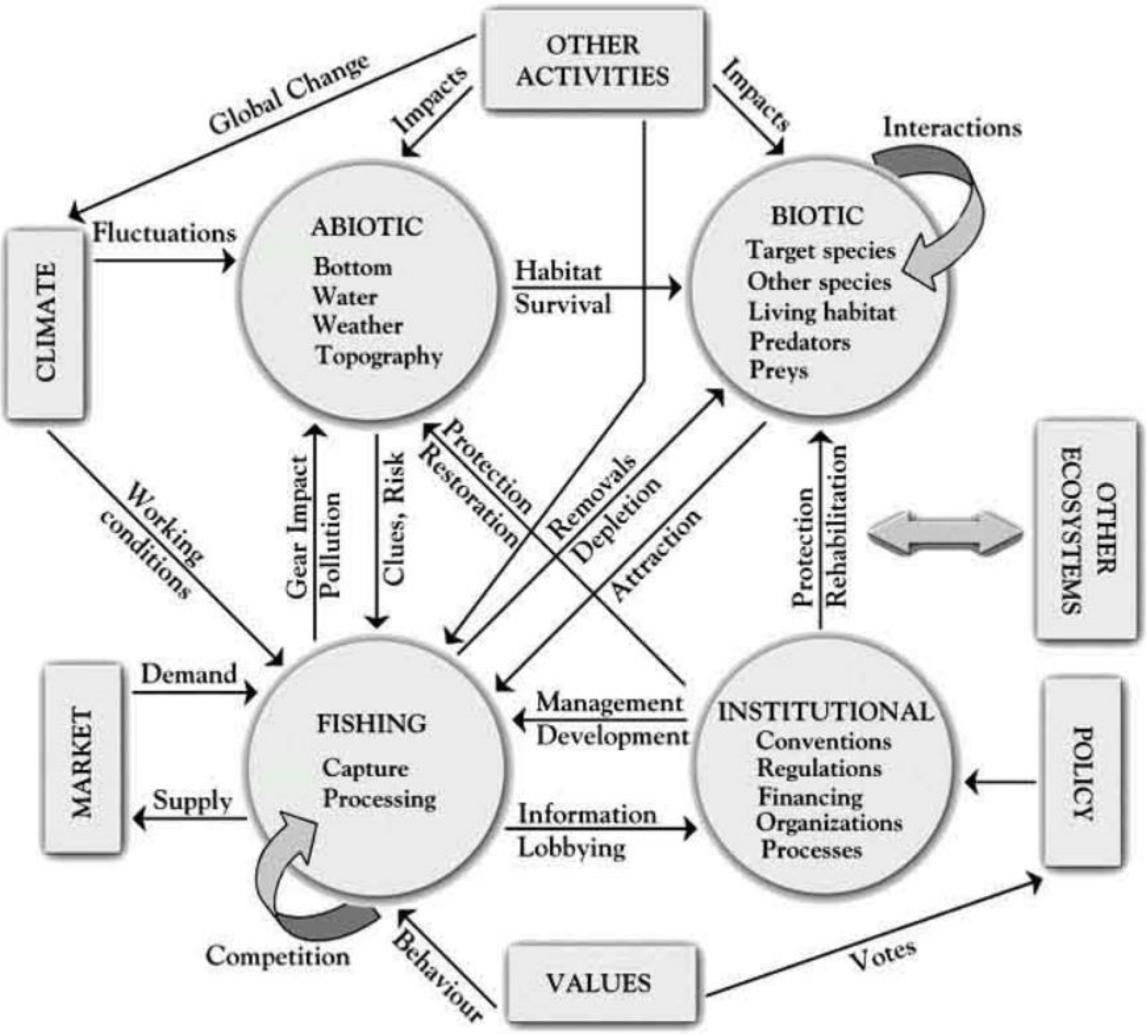


***Figure 4:*** *Diagram of a fishery ecosystem and its components (FAO 2003).*

Many different types of ecosystem models exist, which can vary greatly in their complexity. For example, there are ecosystem models that seek to include only species considered likely to have important interactions with the species of primary interest, hence; only a small selected component of the ecosystem is modelled. In contrast, there are ecosystem models that are generic and capable of explicitly including most ecosystem components as well as incorporating lower trophic levels and primary production. Basically, more and more complex models are used to increase the ecological realism of the model. This is often at the expense of greater scientific uncertainty due to imperfect knowledge of both the functional relationships and the parameters used in the model (FAO 2008; Plagányi 2007). The next section covers the classification of ecosystem models and examines some of the categorization methods found in literature.

### 2.2.3. Categorization approaches for ecosystem models found in literature

Many different approaches exist to categorize different types of ecosystem models. The variety of models differ in structure and parametrisation since they have been developed to address different questions by researchers with different philosophies and approaches (Hyder et al. 2015). There are several needs and uses for these models and some models better serve certain purposes than others (Collie et al. 2016). In section 3.2 I decided to present my own structure. However, the approaches that inspired me will be presented in this section ordered by year of publication.

The first categorization I am presenting is that from Hollow (2000). She identifies four different *types of multispecies models*, as shown in Table 1. Starting with the simplest form implementing multispecies considerations and ending with the most complex. Further, example models are listed (published until 2000).

***Table 1:*** *Categorization of models according to their multispecies consideration provided by Hollow (2000)*

| *Types* | Description | Example |
|---|---|---|
| *Descriptive multispecies models* | ➢ Mainly empirically based with simple dynamics<br>Handles predator prey feedback, not handling environment and lower trophic levels as well as no age-structure | multispecies production models |
| *Dynamic multispecies models* | ➢ Consider functional relationships among individual species in a fished system.<br>➢ Build upon single-species theory to understand the dynamics of multispecies fisheries (predator-prey interactions)<br>➢ Addresses subsets of the ecosystem (and interaction)<br>➢ Do not model competitive interactions explicitly, but often include constraints | MSVPA |

| | | |
|---|---|---|
| | Handles predator prey feedback as well as age-structure, not handling environment and lower trophic levels | |
| *Aggregated system modes* | ➢ Are primarily used to examine the energy flow and the mass balance of whole ecosystems as well as trophic interactions within a community<br>➢ Data aggregation, and mostly equilibrium (steady-state) assumptions to allow the user to solve for unknown biomasses.<br>➢ Some spatial resolution and migration can be incorporated into the simulation<br><br>Handles predator prey feedback as well as environment (but rarely) and lower trophic levels, not handling age-structure | EwE[3] |
| *Dynamic system models* | ➢ Trophodynamic structure, high level of detail at the species level and include detailed coupling of physical forcing (bottom up) and its effect on biological (top down) interactions at temporal as well as spatial scale<br>➢ High level of mechanistic coupling invokes a large computational cost.<br><br>Handles predator prey feedback, environment and lower trophic levels, as well as age-structure | Spatial explicit models (ERSEM, MULTSPEC and BORMICON)<br><br>and individual-based models (IBM) |

Since the focus was on multispecies models, spatial considerations are solely mentioned sparsely. Plagányi (2007) takes up this classification fanning out the spatial considerations (adding the differentiation “spatial aggregated system” and “spatial dynamic system models”). Thereof, Plagányi (2007) focuses on the *types of models* shown in Table 2. Again, example models are listed (published until 2007).

[3] More recent implementations of EwE include structuring the population, as well as a spatial representation through coupling with ECOSPACE

***Table 2:** Categorization of ecosystem models types provided by Plagányi (2007)*

| *Types* | Description | Example |
|---|---|---|
| *Whole ecosystem Models* | - Attempt to consider all trophic levels in the ecosystem | ➢ EwE |
| *Dynamic system models*<br>*(incl. biogeochemical models)* | - Attempt to represent both bottom-up (physical) and top-down (biological) forces interacting in an ecosystem | ➢ Individual-Based Models (IBM), OSMOSE, INVITRO,<br>➢ biogeochemical models e.g. ERSEM, SSEM, IGBEM, BM2, ATLANTIS, and SEPODYM/SEAPODYM |
| *Minimum realistic models (MRM)* | - Comparable to Hollow et al. (2000) category Dynamic multispecies models but not equal<br>- Restricted to represent a limited number of species most likely to have important interactions with a target species of interest | ➢ MRM models<br>➢ MSVPA & MSFOR,<br>➢ Scenario Barents Sea,<br>➢ Systmod (System Model),<br>➢ BORMICON/GADGET<br>➢ SEASTAR;<br>➢ CCAMLR predator-prey models,<br>➢ Individual-Based Models (IBM)<br>➢ MSM |
| *Extensions of single-species assessment models* | - Models that expand on current single-species assessment models taking only a few additional interactions into account | ➢ ESAM |

Another classification Plagányi (2007) used to classify ecosystem models, besides *ecosystem model types*, is the classification by *modelling approaches* and therefore extends to include a comparison in terms of their parameters, assumptions and data requirements. The list of modelling approaches is included in Table 3 and resembles but does not equal Table 2.

***Table 3:** Categorization of modelling approaches provided by Plagányi (2007)*

| ***Types*** | **Description** | **Example** |
|---|---|---|
| *Whole ecosystem Models and Dynamic System Models* | ➢ Attempt to take all trophic levels in the ecosystem into account, from primary producers to top predators | ➢ EwE,<br>➢ biogeochemical models (ERSEM, SSEM, IGBEM, BM2, Atlantis, SEAPODYM) |
| *Minimum realistic models (MRM)* | - To describe the concept of restricting a model to those species most likely to have important interactions with the species of interest.<br>- Reducing the number of species considered, or aggregating similar species into groups, reduces the number of inter-species links which need to be modelled, but consequently also reduces the number of weak links included in the model | ➢ MRM models<br>➢ ESAM<br>➢ MSVPA approach<br>➢ MULTISPEC<br>➢ Scenario Barents Sea,<br>➢ BORMICON/GADGET<br>➢ SEASTAR;<br>➢ FLEXIBEST<br>➢ MSM |
| *Individual-based models* | - Follow the fate of individuals through their life cycle, under the assumption that individual behaviour has an appreciable effect on a population's dynamics.<br>- Sometimes referred to as "agent-based" models with the "individual/agent" being represented by either individual animals and plants, or composite units such as fish schools or fishing fleets.<br>- Typically, been applied to investigate the dynamics of a single population within the marine environment, but a number of applications extend these analyses to consider multi-species dynamics as well | ➢ OSMOSE<br>➢ InVitro |
| *Bioenergetic models* | - A separate suite of models includes those based on bioenergetic and allometric reasoning, which involves parameterising a model using power functions of individual body mass | ➢ - |
| *CCAMLR model development* | - Models developed according to the adoption of the Convention for the Conservation of Antarctic Marine Living Resources (CCAMLR) | ➢ Predator-prey models,<br>➢ FOOSA/KPFM,<br>➢ EPOC<br>➢ SMOM |

The third publication I am introducing is that from Fulton (2010). It firstly differentiates *ecosystem models* and *end-to-end ecosystem models* where ecosystem models are more ecologically focused and composed of physical–chemical–biological-anthropogenic processes active within a space–time unit. Contrasting to ecosystem models, end-to-end models are more expanded models, drawn in more system component, representing the entire trophic structure and physical components of the ecosystem at a fine spatial scale (see also Rose et al. 2010). Fulton further distinguishes four main approaches when developing end-to-end models:

- Minimum realistic: including key processes such as transport processes, production, predation and harvesting but do not fully specify the trophic web
- Intermediate complexity: sacrificing complicated process details, for a modest complexity representation of all modelled system components
- Rhomboid (middle out) approach: linking detailed models of key or best understood parts of systems to simpler representations of the rest of the system
- Coupling: linking of detailed models by also defining relationships between the models creating hybrid models

Whereby the latter three are for developing a more inclusively dynamic end-to-end model than the first. Furthermore, the paper distinguishes four different types of models, including example models published until 2010, shown in Table 4.

***Table 4:*** *Categorization of end-to-end ecosystem model types provided by Fulton (2010)*

| ***Types*** | **Description** | **Example** |
|---|---|---|
| *Qualitative/conceptual models* | - Providing substantial insights into system functioning<br>- Can be rapidly developed<br>- Allow incorporation of stakeholder advice and input<br>- Ensuring stakeholder requirements are addressed<br>- Useful for identifying key system components and processes<br>- Isolating relevant subsystems and essential processes for inclusion in any quantitative system model | ➢ - |

| | | |
|---|---|---|
| *Aggregated (network-based) Models* | - Based on trophodynamic networks of the entire system, including bioenergetic or mass-balance network models<br>- Addressing questions regarding environmental influences on ecosystems, ecological dynamics and ecosystem effects of fishing strategies and management policy options. | ➢ Most prominent example: EwE and the spatial explicit form ECOSPACE |
| *Biogeochemical based:* | - Track nutrient flows throughout the compartments of the ecosystem<br>- They grew from nutrients only to include lower trophic levels and then vertebrates and human activities | ➢ Atlantis,<br>➢ ERSEM |
| *Coupled-hybrid model platforms:* | - Specifically designed to couple different types of models together, not the capacity of models to couple to other models.<br>- Often include size spectra models e.g. coupling to environmental drivers<br>- Promising forms are agent-based models, allowing for fluid representation of processes like movement, growth, phenotypic expression and genetic heritability and evolution | ➢ OSMOSE<br>➢ InVitro<br>➢ APECOSM<br>➢ SEAPODYM, |

Previously pointed out by Fulton (2010) is the differentiation between minimal realistic and intermediate complex models. This distinction, which was not made by Plagányi (2007), is elaborated in the paper by Plagányi et al (2014) by presenting the concept "Models of Intermediate Complexity Assessment (MICE)". MICE are categorized here between traditional single-species stock assessment models and whole-of-ecosystem models, attempting *“to explain the underlying ecological processes for a limited group of populations (typically <10) subject to fishing and anthropogenic interactions and include at least one explicit representation of an ecological process (e.g. interspecific interactions or spatial habitat use).”* (Plagányi et al. 2014, p.3). Detailed comparison can be viewed in Plagányi et al. (2014).

Contrasting MICE and MRM ensues that MICE can be applied for strategic as well as tactical question, whereas MRM serves mostly strategic evaluations. MICE intent to include explicit representation of an ecological process, whereas with MRM some implementation is possible, but in reality, they imply mostly one-way species interactions or either have a spatial representation nor imply movement. Same is applied to linkages between MRM and economic models. Examples of MICE are (e.g. Morello et al. 2014; Angelini et al. 2016; Punt et al. 2016; Thorson, Adams, and Holsman 2019; Kaplan et al. 2019).

Apart from classification according to complexity or structure, ecosystem models can also be distinguished according to their use in policy, highlighted by FAO (2008), Fulton (2010), Plagányi et al. (2014), and Collie et al. (2016) in conceptual, strategic and tactical tools.

The conceptual use is aimed at developing an understanding of ecosystem processes and serves educational purposes on where quantitative models can fit the requirements. These models are easy to build and often serve as the basis for further models, that describe the ecosystem, its form, function, and interactions. Although they may not be used explicitly in decision-making or scientific advice, they form the underlying context for detailed management planning and decision-making (tactical models); of the structure, functioning and interactions of the ecosystem under consideration.

Strategic tools are chosen if the goal is to identify a trend. These models focus on broad scale assessment of directions and patterns of change in the ecosystem. Hence, they are generally long-range, broadly-based and inherently adaptable. Like conceptual models, their uses include improving understanding, but for more specific questions concerning for example the impact of different management alternatives of the structure and functioning of an ecosystem, as well as the social and the economic consequences.

Whereas tactical tools are used to follow operational objectives in the form of a rigid set of instructions. They are used short term and provide specific advice, hence, knowledge about the current situation is essential. Therefore, the modelling has to be very precise to be able to provide information on abundance and exploitation rates, reference points and relationships between species and between environmental variables. For example, recruitment success or habitat prediction, and spatial management, as these are important tactical advice management categories. Models of these category also referred to as operation models (see Plagányi 2016).

While it is generally recognized that most ecosystem models will be used in a conceptual and strategic context (e.g. FAO 2008), actual fishery management largely involves tactical decisions that impact day-to-day regulations in fisheries in contrast to conceptual explorations. But tactical applications of ecosystem models are extremely rare because in most cases it is not necessary or ideal to base tactical management consulting on the results of ecosystem models. In some cases, however, tactical tools can be helpful for specific issues, for example the estimation of current abundance and exploitation rate (Plagányi et al. 2014).

### 2.2.4. Relationship between model performance and complexity (balance between Model Bias and Parameter Uncertainty)

When models are considered and evaluated, it is particularly important not to lose sight of their complexity. Especially since this work deals with medium complex models, it is essential to consider complexity and the associated uncertainties.

Research on model complexity shows that there is a relationship between model performance and complexity. Very simplified models cannot capture critical interactions and system components and are therefore of little use. However, even extremely complicated models are not necessarily useful because they are particularly subject to uncertainty and there is a risk that large models are descriptive rather than predictive. In addition, there are considerable computational problems when using very large models. For reasons of computational cost, uncertainty and performance, it is therefore not advisable to include details beyond those required for the objective of the study. Models are appropriately complex when all critical processes, drivers and components under investigation are included (Fulton 2010). The more complex the dimensions are represented; the more parameters are needed. But the more parameters that are needed for fully augmented models, an increased understanding of species and environmental interactions to specify the dynamics in greater detail is required. This leads to a high parameter uncertainty most notably if no data is available. A solution to this issue is to simplify the description of each component of the model by reducing the number of parameters. But then models may not be able to identify important aspects of ecosystem dynamics and the uncertainty in these models shift from parameter uncertainty to model bias. It is, therefore, crucial to find the optimal balance between model uncertainty and model bias, see Figure 5 (Collie et al. 2016; Plagányi et al. 2014).

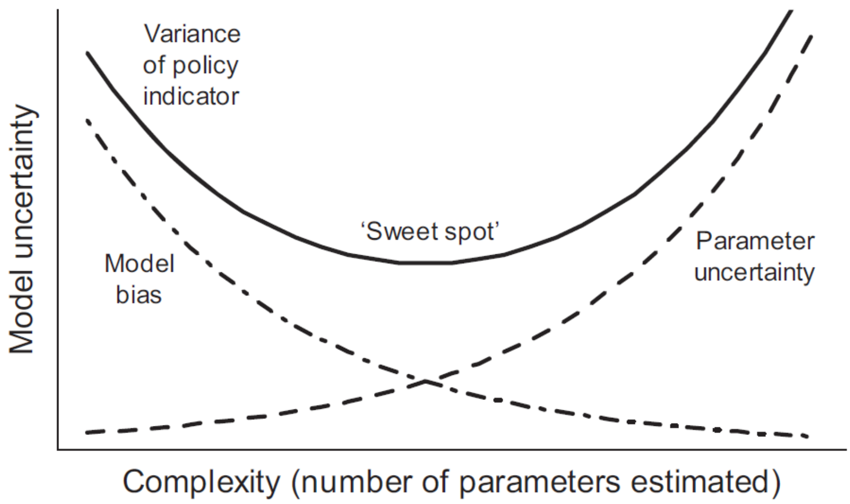


***Figure 5:*** *Schematic representation of the behavior of model bias and parameter uncertainty in response to increasing model complexity (Collie et al. 2016).*

Considering these aspects is especially important when SSF models are designed, as they are data-poor systems, therefore affecting parameter uncertainty and are additionally very complex, (diverse, flexible plus their exceptional social dynamics) possibly resulting in a wide range of parameters (Kittinger et al. 2013; Prescott and Steenbergen 2017; FAO 2019; Smith and Basurto 2019; Herrón et al. 2019; Lindkvist et al. 2020).

To keep the overall complexity of the model in mind, it is important to know the individual components of the models and how they can be developed. The next chapter introduces and explains these dimensions in general – not yet making any assumptions for SSF.

### 2.2.5. Dimensions of implementing ecosystem modelling

As shown in section 2.2.3 many approaches exist typifying models into different categories, but this does not tell us how the models implement ecosystem considerations. Furthermore, we know from section 2.2.4 that ecosystem considerations have to be made very carefully to balance between model bias and parameter uncertainty, which again does not tell us anything about how these considerations could look like. Therefore, for being able to adequately design an ecosystem model a deeper understanding of how the models are constructed is required.

Collie et al. (2016) summarizes the increase in complexity added by ecosystem considerations in at least four different dimensions, starting from an unstructured single-species model without environmental or human influences, by adding:

1. population structure in time, space, age, size, length, sex or life-stage,
2. number of species, with nonlinear trophic interactions among food-web components,
3. environmental influences affecting larval dispersal, lower trophic levels, and the growth, fecundity and survival of upper trophic levels and
4. human interactions beyond harvest (e.g. fleet dynamics, economics and policy influences).

Any ecosystem model, depending on its use, will have increased complexity in one or more of these dimensions, whereby a full ecosystem model adds complexity in all four dimensions (Collie et al. 2016; Plagányi et al. 2014).

These dimensions go along with suggestions from Fulton et al (2010) noting the:

> "*degree of spatial, temporal and taxonomic resolution the kind of components included (e.g. only biophysical or the inclusion of extra components such as human industries); the physical, chemical, ecological and anthropogenic detail included."* (Fulton 2010, p. 175).

Additionally, they resemble the "best practice" to include ecological-related attributes given by FAO (2008).

A closer look into each of the four dimensions highlighted by Collie et al. (2016) are given in the following subsections.

#### 2.2.5.1. Population structure and implementation

Modelling the population more realistically involves structuring, as well as the resolution of the structuring. Structuring can be implemented via time, space, taxonomic and/or age/size/stage-based (Collie et al. 2016, Fulton 2010).

*Temporal resolution and structure*

Structuring according to time turns a static model into a dynamic model. Especially when there are large seasonal or generally temporal differences in the movements or production of species. It is also particularly important for answering questions related to predatory fishing and the negative effects of the temporal (and spatial) location of fisheries, as these effects are often seasonal (FAO 2008, Fulton 2010). Furthermore, there are seasonally changing space-species characteristics (space-dependent population growth) or time-dependent dynamics of different species (slow- or fast growing). For example, short-lived target species, such as shrimp, may need to be modelled with weekly time steps, while other groups, such as sharks, whose population variables do not change as quickly, an annual time step may be sufficient (Plagányi et al. 2014). Even when dealing with temporally differentiated environmental and anthropogenic impacts, and fishing for spawning fish, the temporal structure must be taken into account. In principle, the finer the temporal resolution, the more accurately the dynamics can be represented. However, this is at the expense of increased computing effort and the need for more detailed data. Appropriate temporal resolution varies and is for example tidal, daily, weekly, any timeframe up to annually for the system components depending on the temporal variability of the physical environment, the species concerned and the issues to be addressed. Temporal resolution can be applied differently for the individual groups (FAO 2008, Fulton 2010, Collie et al. 2016).

Besides the representation of the resolution the depiction of the progression varies. Each of which has its own computational and numerical implications. The most common progressions for time are:

- Synchronous time steps: when all components share a common time step size
- Adaptive time steps: where the rate of instantaneous change of biological groups dictates the size of sub-steps, which are cumulatively iterated until a full-time step is completed (typically used for lower trophic levels in biogeochemically- based models (e.g. Atlantis).

An innovative way of dealing with time is that different groups can use different time steps, just as they use different spatial scales (see below). One of the most innovative forms of this is InVitro, which uses an asynchronous approach to time management, where the time step for each component shifts depending on the actions it performs. Therefore, attention can be focussed onto critical events and there is no need for all components to use the same time step at the same time (Fulton 2010).

*Spatial resolution and structure*

Many of the same considerations of temporal resolution are required for the handling of space. For spatiality, decisions are needed on the internal vertical and horizontal spatial resolution and should be dictated by the ecological, environmental and anthropogenic length scales (Fulton 2010).

How the spatial structure is to be modelled depends on the management issues and ecological aspects that give rise to concern. Below are some examples of when the spatial structure needs to be included to be able to estimate variation in species density and/or productivity at spatial scales (FAO 2008, Collie et al 2016):

- Existing major ontogenetic shifts in location through the course of a species life history (e.g. if individuals at each age have different vital rates at different locations or animals move between different areas or strata)
- Spatial dependencies on stock structure of a species (e.g. sedentary species) or on critical habitat;
- Existing spatially localized biological interactions or anthropogenic impacts (e.g. if they are exposed to different fishing mortality rates)

Hence, it is important for the spatial resolution of a model to capture the major characteristics of the system. Spatial resolution can vary in its finest implication from micrometre bacterial scale to ocean basin, and even global, and should be carefully chosen due to the associated cost of computing time. However, this does not mean that processes on finer scales can or should be ignored. It is crucial to determine the importance of processes on finer scales. It should also be considered whether analytical or statistical formulations should be used to represent these fine-scale processes. Many models will need to include some degree of spatial resolution, depending on the complexity of the physical environment, the species involved and the issues to be addressed (FAO 2008, Fulton 2010).

Spatial structure can be described as explicit or implicit (Collie et al. 2016):

- Explicit structuring: definition of the spatial characteristics through spatial, physical or anthropogenic parameters and included into population dynamics (hereafter referred to as quantitative implementation) or
- Implicit structuring: the population dynamics can be set or estimated for the different locations (hereafter referred to as qualitative implementation).

Either way, spatial structuring should be considered when defining biological and other components, as otherwise erroneous dynamics could arise. Implementing quantitative spatial handling for a model can be for example through homogeneous grids and heterogeneous networks of nodes, patches or polygons. It is also possible to have different model components using alternative spatial representations. For instance, modelling bathymetry via a regular grid, while other features (e.g. habitat) may be more effectively represented as polygons (as this focuses on “hot spots” of activity and available data - e.g. as implemented in InVitro (Fulton 2010)). Models that do implement a quantitative spatial structure are Atlantis, SEAPODYM, EwE, StrathSPACE, StrathE2E, SMOM and the MICE from Thorson, Adams, and Holsman (2019).

When a fishery catches more than one stock of a particular species, the models must be able to distinguish between these different stocks. Especially if these stocks are influenced to different degrees by the fishery. It is then necessary to determine the presence, number and distribution of the different stocks which can be difficult. Management should aim to conserve all stocks in order to maintain genetic diversity and make the species as a whole more resilient to environmental changes (FAO 2008).

To note the complexities in modelling the difficulties of determining spatial population characteristics, the example of animal movement is used in this thesis. As of writing, including fish movement is still the exception rather than the rule, mainly due to the lack of data to estimate for example the rates of movement. Tag capture data are most meaningful in terms of movement, but estimations of movement parameters from tagging data is not guaranteed. Even when tagging data is integrated with catch, effort and even survey information, the estimation of motion parameters from the data is not guaranteed. Therefore, even in data-rich scenarios, there are still great challenges to overcome. However, models of animal movement behaviour can be somewhat simplistically classified into two main categories (Fulton 2010):

- Time-invariant (or random) movements, driven predominantly by diffusive processes in which a fixed fraction of the animals migrate from one area to the next within a given time.
- Dynamic movement includes time-dependent factors such as reproduction or prey/competitor density and environmental conditions affecting the movement rates.

*Taxonomic resolution and species-based structure*

Taxonomic resolution defines the representation of the resource and non-target species and is fundamental to all forms of multispecies and ecosystem models. It defines whether all components of an ecological system (entire food web) are represented or solely the key species. Further, it determines if the considered species are aggregated (functional group) or represented individually. Again, these decisions depend on the availability of data on different species. The number of groups also depend strongly on the research question and the subsystems involved. For a small subsystem, an explicit representation of all members is possible, otherwise aggregation within functional groups is advisable, or else the choice of key species. Functional groups can be defined based on predator and prey associations, size and rates, ontogeny, role, habitat use, behaviour, other non-tropical interactions and spatial structure (movement patterns and distribution) (Fulton 2010, Collie et al. 2016). However, models such as SEAPODYM, APECOSM and OSMOSE use a more innovative mix of functional group types, using size structured representations (i.e. biomass size spectra representations) for parts of the trophic web, for example forage layers in SEAPODYM (Fulton 2010). Clear methods for this definition of group membership, such as cluster formation or network theory, are essential. Both excessive aggregation and excessive detailing lead to a declining performance and should be avoided. (FAO 2008). It has been shown that more detail is not guaranteed to be better, and even models integrating a subsystem instead of all of a system´s ecological components showed a strong performance. Too highly aggregated systems in turn could overlook behavioural state (Fulton 2010).

The taxonomic resolution is a major source of model uncertainties and should therefore always be considered in conjunction with the uncertainty itself. It is therefore advisable to try different levels of taxonomic complexity. It depends on personal preference whether one starts more aggregated and detailed or vice versa. Both approaches are promising, but the former is used more commonly (FAO 2008)

Another important form of ecological structuring, to enhance population realism, is the species-based structure. This meaning whether the population is presented as a whole or broken down by sex or life history (age-, size-, length-, and/or stage-based), usually in terms of biomass or number, for biogeochemical models there are also nutrient-pool-based formulations (Plagányi 2007, Plagányi et al. 2014, Collie et al. 2016). This is especially true in situations where there are major ontogenetic shifts in the behaviour of the species of interest through the course of its life. Since effects of predatory fishing and human based fishing are usually size-dependent, these are particularly important to consider at this point. It is also important in spatial models where different parts of the population inhabit different areas or different parts of the water column. The number of age/length classes should be carefully considered, as experience has shown that using a smaller number of age or size classes greatly reduces computational time with minimal loss of information. Providing management advices, including age, size, or stage structure of the target species is oftentimes necessary (FAO 2008). For example, an age-based structure is necessary, if predation only affects the juvenile, a length-based could be necessary if the gear used is size-selective, and a space or area-based approach is necessary if different areas are presented (Collie et al. 2016).

There are models that do not implement species-based structure at all (e.g. PDMM, StrathE2E); other models implement a size-structure (e.g. size-based is implemented by

CCSSM, FCSRM, MIZER, SSSM). Also, some models combine species-based with a spatial structure, for example MICE used by Angelini et al. (2016) and MULTISPEC implements an age-space structure. OSMOSE and StrathSPACE implement a size-space-based structure and ATLANTIS an age-space)[4].

The temporal, spatial and taxonomic resolutions will direct appropriate levels of process detail (and to some extent vice versa).

#### 2.2.5.2. Species interactions

Species interactions can be categorized into trophic, non-trophic and technical interactions. In this section, trophic interactions are presented, whereas non-trophic interactions are described in 2.2.5.3 and technical in 2.2.5.4.

The mathematical representation of species interaction has long been studied, but still many challenges remain, which will be discussed further (FAO 2008, Collie et al. 2016). Four different types of models are identified by Hollowed (2000): descriptive multispecies, dynamic multispecies, aggregated systems and dynamic system models (see 2.2.3). The threads of aggregated systems and dynamic system models resulted in a food web approach (incorporate all species/functional groups within an ecosystem) implemented either with mass-balance energy budgets or, and more recently used, by converting it to dynamic systems of coupled differential equations. Whereby aggregated system models often lack structure for individual species. Dynamic multi-species models (models including a subset of key species) started by including Lokta-Volterra (LV) predator-prey dynamics and were extended to include more species (up to 10) with more realistic interaction terms. The predator-prey thread has led to age and size-structured multispecies models, but often lack a holistic ecosystem view (Collie et al. 2016). Some recently developed models such as MICE are trying to bridge these gaps through a developed understanding of important ecosystem processes, which were then additionally included (Plagányi et al. 2014).

Even the change from a single-species to a two species approach makes the analytical calculation of system dynamics, stability characteristics and the effects of harvesting and the choice of target reference points very complex. Hence, choosing to include key species (species that are essential to solve a particular management issue) instead of all species can avoid over-complex models (Collie et al. 2016). Plagányi et al (2014) proposed a rule of thumb to include interacting species to account for at least 90% of the mortality of the target species.

[4] For more information on these models see 3.1.1 and Appendix 1.

The differences of these two approaches (Food web or LV) and corresponding models can be identified in Figure 6 via a trophic pyramid. The food web approach includes all trophic layers of the pyramid: primary producers (e.g. phytoplankton and detritus), primary consumers (e.g. zooplankton and filter feeders), secondary consumers (carnivore e.g. forage fish as tuna) and tertiary consumers (carnivore, e.g. sharks, mammals and seabirds), or at least the layers relevant to an individual environment, whereas the LV approach includes only a selected subset of the whole system.

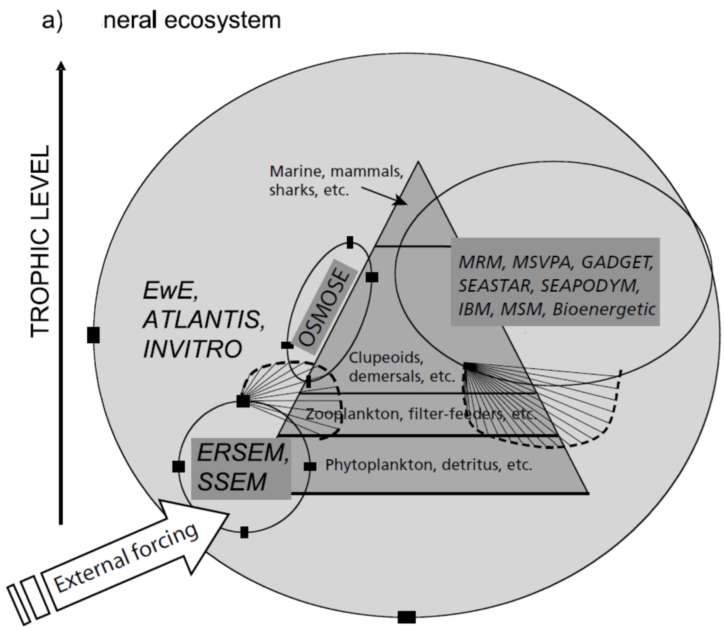


**Figure 6:** *Schematic summary showing the trophic level focus of different Ecosystem Models for a general ecosystem (Plagányi 2007)*

Within the food web as well as LV-predator-prey approaches, the connection of species is made via the term of natural mortality[5] (part of a population growth equation), which is a dynamic function of predator abundance and prey availability (Collie et al. 2016). There are two ways of connecting the prey and the predator:

- One-way feedback: either the prey abundance affects predator reproduction success or predator abundance affects the prey's survival
- Two-way feedback: prey and predator abundance simultaneously affect each other. Models based on the principles of conservation of matter include two-way feedback by assuming that prey eaten is converted into predator biomass or numbers.

[5] Mortality in a fishery system consists of fishing and natural mortality. For the Predation effect only the natural mortality is considered.

The more realistic representation of predator-prey interactions is bidirectional. Nevertheless, sometimes it is appropriate to include only a one-way interaction e.g. due to simplifications or if the opposite process shows no relevance (FAO 2008).

Great importance is attributed to the choice of the appropriate form of functional responses (which includes prey-predator interaction conditions) and feeding selectivity/suitability. However, the lack of suitable data and experimental studies hampers research in this area (FAO 2008). Ideally, the parameters and form of the predator-prey functional response should be estimated by fully integrating predation and diet data in the parameter estimation process, making these kinds of feedbacks highly data-driven (see MSVPA). If no suitable data is available, an alternative would be to assess the robustness of model outputs to a range of alternative functional response formulations (see Hunsicker et al. (2011) for an overview of functional response types, the current state of the art and the challenges in their use). A third approach would be to bound the uncertainty in the predator-prey relationship, i.e., by the use of a generalized functional response curve that is parameterized to bound the uncertainty of the likely level of sensitivity of a predator to its prey (Plagányi et al. 2014).

Besides predation being the basic interaction that needs to be described when moving past single species models, there are also effects of cannibalism (e.g. feeding on the young, but this term can usually be neglected and is therefore rarely included) and competition from species of the same trophic level that compete for the same food source or habitat (Plagányi et al. 2014).

#### 2.2.5.3. (Spatial) Environmental

This subsection deals with the description of the "natural" environment within models. The processes are hereby also discussed in terms of spatiality.

Initially there were debates about whether unusual variability in fish populations were due to natural or anthropogenic drivers. Therefore, incorporating environmental measurements have been used to achieve a better understanding of the drivers of population dynamics to adjust migration, productivity, survival and growth estimates, and to better predict based on available or inexpensive observations of the state of the environment. Implementation of environmental drivers can be realized by coupling population dynamic models with for example hydrodynamic models (FAO 2008, Collie et al. 2016). For the coupling, it is essential to match input and output of the respective models. This represents an explicit, or quantitative description of the environment, or the spatial structure in comparison to qualitative descriptions using indicators of the ecosystem instead (Collie et al. 2016).

Environmental measurements can be on the one hand abiotic (physical) characterisations such as temperature, salinity, oxygen, nutrients and upwelling values. On the other hand, biotic characterisations (habitat type) such as mangroves, coral reefs, inshore/offshore, sediment types, ocean depth to name a few were chosen (Thorson, Adams, and Holsman 2019; Plagányi et al. 2014).

It has been shown that the results of models actually fit better with historical trends or time series, such as recruitment, growth and spatial distribution of catches, when environmental forcing is integrated. Historical patterns can be captured and then used as a basis for for projections into the future. Careful consideration should therefore be given to whether environmental forcing is needed to capture system dynamics (FAO 2008). However, there is some scepticism about the reliability of forecasts in a changing environment. Collie et al. (2016) explains that the mechanisms linking environmental variables to biological responses need to be better specified and quantified before they can be used to predict population trends. Mechanistic connections between upper trophic level fish and their environment can be very complex. They depend simultaneously on the trophic level of fish; the flexibility of its diet and the habitat needs. Similarly, models developed for fish at the lower trophic level can be further complexed by bottom-up and top-down influences.

This can be very important for the assessment of habitat dependencies or spatial refuges as part of non-trophic interactions. Furthermore, non-trophic interactions may be important because of their perceived role in amplifying or mediating the effects of climate change. Much attention is paid to the potential impacts on target and endangered species through the displacement or loss of biogenic habitats because of climate change (FAO 2008).

Ecosystem considerations are further intertwined with (FAO 2008):

- The required spatial resolution of a model (or at least to the way spatial processes are represented within a model), (see 2.2.5.1)
- The anthropogenic (as a possible driver of habitat degradation) and technical interactions (could modify the habitat) (see 2.2.5.4)
- Fleet dynamics (varying fishing pressure) (see 2.2.5.4), and
- The decision to represent age, stage or size structure in the modelled populations (as possibly only certain phases of life history are dependent on the habitat or, conversely, the habitat itself must be represented in a size- or age-based manner to capture recovery residues) (see 2.2.5.1).

It is very important to carefully determine how future forcing time series are generated. For example, by (FAO 2008):

- The extraction of future trends from climate models,
- The complete repetition of historical time series and the derivation of time periods from them,
- The derivation from a statistical distribution based on historical data, or
- The use of scenarios to represent a much higher/lower frequency or magnitude of environmental factors.

An advantage for the consideration of environmental drivers is that more and more of the necessary data becomes available. Due to the increasing breadth of observations on the ocean state becoming available from land, sea and satellite monitoring, as well as further development of improved circulation models, will support the implementation of environmental drivers in the future. Observation- and model-derived data makes it possible to develop mechanistic models representing the relationships between the environment and the biological responses at the appropriate spatial and temporal scales. As well as projecting future environmental conditions in the context of global climate change (Collie et al. 2016).

If environmental drivers have been captured solely by statistical adjustments, it is important to consider alternative models (with and without the driver or with different forms of the driver) in the evaluation (FAO 2008).

Using a path analysis, in combination with quantitative multivariate statistics, as a method for constructing reasonable connections and deriving a mechanistic understanding of how an environmental factor directly or indirectly affects the fish population of interest, could be an implementation approach (Collie et al. 2016).

In conclusion, there is a rising level of knowledge about how oceanographic processes influence the life history stages of marine species, and the potential for quantifying oceanographic variables at the proper spatial scales is increasing. Modelling that takes these environmental contexts into account will have a higher explanation power and will demand greater computing power. This kind of modelling effort must take into account that environmental effects tend not to be additive, and that new approaches may be required to address this state dependency (Collie et al. 2016).

#### 2.2.5.4. Human dimension

Lastly, the incorporation of the "anthropogenic" environment within models, hence, the human dimension is presented. Although this compartment is commonly a part of social modelling, it is mentioned in this thesis since all compartments and dimensions in an ecosystem are interconnected and humans play a central role.

Just as the model complexity for the dynamics of natural resources is very high, there is also a wide range of ways to model human interactions with marine ecosystems, ranging from simple indicators to complex coupled models (Plagányi et al. 2007). Fundamental differences, and thus a big challenge, between human and ecological systems, is to reconcile their different driving forces acting on different scales (Collie et al. 2016). Within the human dimension, one can distinguish between economic and socio-cultural considerations. Socio-cultural considerations are also very important and can help to avoid unintended consequences from regulations and thus improve future potential policy outcomes (Collie et al. 2016).

Human impacts can be differentiated into fishing and other anthropogenic forces. Where fishing is implemented explicitly, the latter is mostly included as external drivers and includes all forms of impacts human activity can have on the marine ecosystem, such as pollution, coastal development, tourism, oil and gas extraction, local and regional economies and infrastructure. An exception is the ABM InVitro, which also implements these further anthropogenic impacts explicitly (Fulton 2010).

The parameter describing the connection of human impact on biological population dynamics is determined by the spatial and temporal distribution of fishing mortality. Fishing mortality is effected by the use of fishing gear, the duration and location of fishing trips, the seasonal decisions on fishing activities, entering or leaving of a fishery, and investment in fishing vessels (Plagányi et al. 2014).

Some of the most widely used forms of analysis to support decision making are the use of socio-economic information through cost-benefit analysis, social impact analysis and indicators. Besides, there are also dynamic models that incorporate human behaviour at different levels. These may include spatio-temporal studies of fleet behaviour and be based on individual vessels, so-called fishing choice location models or fleet dynamic models. Taking fleet dynamics into account is important when significant changes in the spatial distribution of fisheries may occur. It could then be necessary to develop a model in which fishing effort patterns can change in response to the different locations. These can then be linked to a biological model of fish distribution or site-specific production models (FAO 2008, Collie et al. 2016). If several fleets are of interest, models should distinguish between different fleets if they have different impacts on target, and by-catch species or habitat for the same catch and/or when such distinctions have important social and economic impacts (FAO 2008).

Fishing activity also causes technical interactions that relate to the impact of fishing that additionally catch species other than the main target. These include multi-species fisheries, and fisheries nominally targeting a single species but catching by-catches of other fish stocks caught by other fisheries. Technical interactions must be included in a model if the issue the model is to address relates to the direct impact of a fishery on another species or habitat. When technical interactions are included in a model, other characteristics are likely to be required, including: age/size/stage structure (because by-catch often consists of juvenile fish), spatial structure (because different areas may contain different age groups of fish), fleet dynamics and multiple fleets (because the species or impacts of interest are taken or caused by more than one particular fleet at the same time), and social and economic aspects (FAO 2008).

As mentioned, in addition to influences from fisheries, there are other anthropogenic pressures on marine ecosystems resulting in nutrient loads and contaminant, large-scale changes in freshwater flow or water properties and habitat degradation. Inclusion of such external aspects is usually done by forcing (e.g. with time series of pollution) rather than by a detailed model of the process. Especially in shallow or coastal waters, the inclusion of anthropogenic drift has in many cases improved adaptation to historical trends or time series as it can improve the outcome of system dynamics. The nature of the impacts, and the often high site association of these other anthropogenic pressures, means that their inclusion is closely linked to the spatial structure of the model. They are often also linked to the social and economic components of the model (FAO 2008)

Notable ecosystem models implementing the human component are EwE, including explicit economic and social parameterisations, product chain tracking and fleet behaviours, as well as Atlantis and InVitro allowing the use of detailed (socially and economically driven) behavioural models (Fulton 2010).

# 3. Literature review and evaluation of models

In this chapter I present the preparations that had been made to be able to formalize an implementation guide for the ecological part of SES models for SSF by answering the first research question “*Which fishery ecosystem models exist and how do they implement the ecological side?”*. To answer these questions: (i) lists of relevant models and case studies will be found by researching the literature, (ii) a taxonomy of these models and case studies as well as (iii) test of adequacy thereof for the integration in SSF models and integration possibilities are presented. Besides the presentation of the results, the methods used are also described.

## 3.1. Overview/list of ecological/fishery models

For answering part one of the first research question, a literature review was conducted regarding identifying available and relevant options for modelling the ecological part by collating a list of existing models. Therefore, an intense search of existing fishery as well as marine ecosystem models has been done.

Besides a goal-oriented search through keywords (e.g. fishery models, small-scale fishery, socio-ecological, multispecies, spatial), literature was found by means of the snowball principle within a broader manner. This included literature recommended from authors found during the first step of the search as well as additional findings through adapted keywords via increased knowledge of this topic, (e.g. ecosystem models, ecosystem-based, ecosystem approach to fishery) and specific searches for certain concepts (MICE, MRM, ABM, bio-economic models) and models.

This extension was necessary as there were insufficient small-scale fishery models focusing on the formalisation of the ecological part. Up until now, small-scale fishery models mostly neglect the ecological side (see chapter 1, 2.1.2 and 2.1.3). Therefore, this section aims to find models that include the EAF not specifically for the SSF sector but for captured fisheries in general in order to examine the different implementation approaches for ecological dynamics suitable to implement into SSF models.

For the models found, focus was cast on whether they implement at least one of the mentioned ecological extensions, multispecies and spatial, or whether there are other extensions that are particularly important. Models where this was not the case were not included in the list.

The results from researching the literature show that many different models exist for the marine ecosystem or marine fishery and the concepts used vary greatly from one another (see 2.2.3). I found 57 different models which at the minimum included multispecies, spatial or generally ecosystem considerations (see 2.2.5), which are listed in Table 5. Further detailed for each model is whether they represent economic aspects and what type of biological characterisation is used (e.g. age, size, stage or sex). The addition of economic aspects gives an indication as to whether the elaboration of the economic side is associated with a neglection of the social/economic side, and thus for the potential of a SES perspective of the model. Considerations of the biological characterisation indicates the implemented population realism of the model.

All ecosystem models are multispecies but not necessarily spatial. Most models are multispecies (50 out of 57), but solely 21 can count as ecosystem. 35 models include both, multispecies and spatial considerations. The scope of the models ranges from very simple models, considering only very few components, to very detailed models. A table including references can be seen in Appendix 1 (IX.ii)).

Furthermore, I identified 14 case studies using relevant modelling approaches[6] relevant (see Table 6). They are relevant, as the approaches of Agent-Based or Individual-Based Models (ABM), Models of Intermediate Complexity Ecosystem Assessment (MICE), Minimum Realistic Models (MRM) and Bioeconomic Models are capable to adapt to many different circumstances while able to stay rather simple (see 2.2.3 and 3.3) as well as already merging biological and economic questions (e.g. bioeconomic models).

***Table 5:*** *Overview of Models that reflect marine ecosystems and fishery models including ecological aspects. Alphabetically ordered by their acronyms. Data for each heading is a binary (yes/no) option whereas biological structure uses age, size, sex or non (x).*

| No | Acronym | Name | Multispecies | Spatial | Ecosystem | Economic | Biology. Character. |
|---|---|---|---|---|---|---|---|
| 1 | APECOSM | The Apex Predators ECOSystem Model | yes | yes | yes | no | size |
| 2 | ATLANTIS | ATLANTIS | yes | yes | yes | yes | age |
| 3 | B SEA ECON-ECOL | Baltic Sea Ecological-Economic Optimization Model | yes | yes | no | yes | age |
| 4 | BEMEF | Bio-Economic Model of European Fleets (extended EIAA) | yes | yes | no | yes | x |

[6] In this thesis, an approach is a concept of how a model can be designed whereas a model uses a certain approach for its formalization process.

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| 5 | BORMICON | BOReal Migration and CONsumption model | yes | yes | yes | no | x |
| 6 | Bioenergetic/ Allometric Model | Multi-species trophodynamic model using bioenergetic and allometric approach | yes | no | no | no | x |
| 7 | CCSSM | Coupled Community Size-Spectrum Model | yes | no | no | no | size |
| 8 | DISPLACE* | Individual Vessel-Based Spatial Planning and Effort Displacement | yes | yes | no | yes | size, age |
| 9 | ECO | Bio-Economic Module Connecting Ecology and Economy | yes | yes | no | yes | x |
| 10 | EIAA | Economic Interpretation of ICES Advisory Committee for Fisheries Management | no | yes | no | yes | x |
| 11 | ELFSIM* | Effects of Line Fishing Simulator | yes | yes | no | yes | size, age, sex |
| 12 | EPOC | Ecosystem Productivity Ocean Climate model | yes | yes | yes | yes | size, age |
| 13 | ERSEM I+II | European Regional Seas Ecosystem Model | yes | yes | yes | no | x |
| 14 | ESAM | Extended Single-species Assessment Models | yes | no | no | - | - |
| 15 | EwE | Ecopath with Ecosim and Ecospace | yes | yes | yes | yes | age |
| 16 | FCSRM | Fish community size-resolved model | yes | no | yes | no | size |
| 17 | FCUBE | Fleets and Fisheries Forecast Model | yes | yes | no | yes | age |
| 18 | FIBE | Fisher Behavior Model | no | yes | no | yes | x |
| 19 | FishMob | Fishers Mobility Models | no | yes | no | yes | x |
| 20 | FishRent | FishRent | yes | yes | no | yes | x |
| 21 | FishSUMS | Strathclyde length-structured partial ecosystem model | yes | no | no | no | size |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| 22 | FLBEIA | Bio-economic Impact Assessment using Fisheries Library in R | yes | yes | no | yes | age |
| 23 | GADGET | Globally applicable Area Disaggregated General Ecosystem Toolbox | yes | yes | no (but can be linked) | yes | size, age |
| 24 | GBFWCGE | Coupled Georges bank Food Web and Computable General Equilibrium Model | yes | yes | yes | yes | x |
| 25 | GEM | Generic Ecosystem Model | yes | no | yes | yes | size, age |
| 26 | IAM* | Impact Assessment Model for Fisheries Management | yes | yes | no | yes | age |
| 27 | IGBEM | Integrated Generic Bay Ecosystem Model | yes | yes | yes | yes | age |
| 28 | IMATSTRL | Integrated model for Australian Torres Strait Tropical Rock Lobster | no | yes | no | yes | age |
| 29 | InVitro* | InVitro | yes | yes | yes | yes | size, age |
| 30 | ISIS-FISH | Integration of Spatial Information for Simulation of Fisheries | yes | yes | no | yes | size, age |
| 31 | LeMANS | Length-based Multispecies Analysis by Numerical Simulation for the North Sea | yes | no | no | no | size |
| 32 | LIEM | Linear Inverse Ecosystem | yes | - | yes | no | - |
| 33 | MAQ | Ecological Modelling of Multiannual Quota | no | yes | no | yes | x |
| 34 | MEFISTO | Mediterranean Fisheries Simulation Tool | yes | yes | no | yes | age |
| 35 | MIZER | Multispecies size spectrum ecological modelling in R | yes | size distribut ion | yes | no | size |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| 36 | MOOVES* | Marine Object-Oriented Virtual Ecosystem Simulator | yes | ? | yes | ? | size, age |
| 37 | MSM | Multi-species Statistical Model | yes | yes | no | yes | age |
| 38 | MSPM | Multispecies Stock Production Model | yes | yes | no | no | x |
| 39 | MSVPA and MSFoR | Multi-species Virtual Population Analysis and Multi-species Forecasting Model | yes | no | no | no | age |
| 40 | MULTSPEC | Multi-species model for the Barents Sea | yes | yes | no | no | size, age |
| 41 | NECLH | New England Coupled Lobster Model | yes | no | no | yes | size, age |
| 42 | NPF BIOECON | Simplified Bio-Economic Model for the Australian Northern Prawn Fishery | yes | yes | no | yes | size |
| 43 | NPFTPBEM | Australia Northern Prawn Fishery Tiger Prawns Bio-economic Model | yes | yes | no | yes | size, age |
| 44 | OSMOSE* | Object-oriented Simulator of Marine ecosystem Exploitation | yes | yes | yes | no | x |
| 45 | PDMM | Population-Dynamical Matching Model | yes | no | yes | no | x |
| 46 | POSEIDON | POSEIDON | yes | yes | no | yes | x |
| 47 | SEAPODYM | Spatial Ecosystem and Population Dynamics Model | yes | yes | yes | no | age |
| 48 | SEASTAR | Stock Estimation with Adjustable Survey observation model and TAg-Return data | yes | no | no | no | detailed |
| 49 | SIMFISH | Spatial Integrated bio-economic Model for Fisheries (Wageningen University, NL) | yes | yes | no | yes | age |
| 50 | SMOM | Spatial Multi-species Operating Model | yes | yes | no (but coupled) | - | breeding (yes/no) |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| 51 | SRRMCF | Swedish Resource Rent Model for the Commercial Fisheries | yes | yes | no | yes | x |
| 52 | SS-DBEM-IOT | Size-spectrum bio-climate envelope model & input/output tables | yes | yes | yes | yes | size |
| 53 | SSEM | Shallow Seas Ecological Model | yes | no | yes | no | x |
| 54 | SSSM | Species Size-Spectrum Model | yes | no | yes | no | size |
| 55 | STOCH HCR | Stochastic Age-Structure Optimization Model + ITQ Wealth Model | yes | yes | no | yes | age |
| 56 | StrathE2E | Strathclyde end-to-end ecosystem model | yes | yes | yes | no | x |
| 57 | StrathSPACE | Strathclyde spatial population dynamics model | no | yes | no | no | size |

***Table 6**: Overview of puplications found implementing medium complex fishery models using specific modeling approaches. Data for each heading is a binary (yes/no) option whereas stock unit used biomass or number and biological structure uses age, size, sex or non (x).*

| Approach | No. | Year | Author | Multi species | Spatial | Ecosystem | Economic | Stock unit | Biol. struct. |
|---|---|---|---|---|---|---|---|---|---|
| ABM | 1 | 2006 | Soulié and Thébaud | no | yes | no | yes | biomass | x |
| | 2 | 2017 | Cenek and Franklin | yes | no | no | yes | daily bin | x |
| Bio-economic | 3 | 2000 | Ruttan et al. | yes | no | no | yes | number | length |
| | 4 | 2003 | Rueda and Defeo | yes | yes | no | yes | biomass | x |
| | 5 | 2006 | Wilson | yes | yes | no | yes | number | age |
| | 6 | 2012 | Cissé et al. | yes | no | yes | yes | biomass | x |
| | 7 | 2019 | Carvalho et al. | no | yes | no | yes | biomass | x |
| MICE | 8 | 2004 | Morello | yes | no | no | no | number | age |
| | 9 | 2016 | Punt | yes | yes | yes | no | number | age |
| | 10 | 2016 | Angelini | yes | no | yes | no | prey: biomass; pred.: number | length |
| | 11 | 2017 | Doyen et al. | yes | no | yes | yes | biomass | age, size, sex |
| | 12 | 2019 | Kaplan et al. | yes | yes | yes | no | number | age |
| | 13 | 2019 | Thorson | yes | yes | yes | yes | number | weight |
| MRM | 14 | 2015 | Thorson et al. | no | yes | no | yes | biomass | weight, stages |
| | 15 | 2017 | Thorson et al. | yes | yes | no | yes | number | x |

## 3.2. A taxonomy of ecological/fishery models according to complexity and multispecies and spatial considerations

To be able to distinguish models based on their simplicity versus complexity on the dimension of what they represent (all compassing) and how they represent (level of detail) I developed a categorisation for models (Table 5) and modelling approaches (Table 6) found in the literature in Table 7.

In literature various approaches exist to typify ecosystem models for fishery (Hollowed 2000; Plagányi 2007; Fulton 2010; Plagányi et al. 2014; Hyder et al. 2015; Collie et al. 2016; Plagányi 2016; Melbourne-Thomas et al. 2017; Nielsen et al. 2018). Explanations for the individual classifications as well as examples for which models are placed in which the categories can be found in 2.2.3. The mentioned approaches partly complement, overlap, or contradict each other. Therefore, in order to find a suitable form of grouping for the purpose of this thesis, I have applied my own grouping, derived from the above-mentioned literature combined with information from the background section 2.2.5. Within the description I will also mention the model's complexity[7] and complication[8], which I will further refer to as complexity only.

The first group relates to the categories "whole-of-system", "whole ecosystem", "dynamic system", "biogeochemical/biogeochemical-based", "aggregated system/network-based" and "end-to-end ecosystem" models (Hollowed 2000; Plagányi 2007; Fulton 2010; Plagányi et al. 2014) and is summarized under the term "Whole Ecosystem Models (WEM)". As indicated, these models covering the entire ecosystem, hence, for multispecies that means all parts of the food web (top-down processes). This group is subcategorized into "advanced" and "simplified" WEM. Advanced WEM include a multispecies and a spatial representation and also frequently bottom-up processes (physical), wheareas simplified WEM solely include multispecies.

The second group relates to the categories "Dynamic Multispecies", "Minimum Realistic", "Intermediate Complex" "Models of Intermediate Complexity Ecosystem Assessment" and "Extensions of Single-Species Assessment" models (Hollowed 2000; Plagányi 2007; Fulton 2010; Plagányi et al. 2014) and is summarized as "Subset Models (SM)". These models aim to represent subsets rather than the entire ecosystem. For multispecies, this means that not the entire food web is presented, but key species derived from the models' purpose. Included are models that still fall into the category of ecosystem models as well as simpler models that do not meet the requirements by this very same (see

[7] Adding non-linearity and detailed feedbacks
[8] Increasing size of the model and number of parameters

2.2.2). This group is subcategorized into "advanced" and "simplified" SM. Advanced SM include a multispecies and a spatial representation, whereas simplified subset models either include a multispecies or a spatial representation.

***Table 7:*** *Taxonomy/Categorization of models and approaches into "Whole Ecosystem Models (WEM)" and "Subset Models (SM)" with respective subcategories "Advanced" and "Simplified". For each category corresponding models and approaches are listed (if known)*

| **Whole Ecosystem Models (WEM)** Multispecies = all species in system | | **Subset Models (SM)** Multispecies = only key species | |
|---|---|---|---|
| **Advanced** (multispecies AND spatial) | **Simplified** (multispecies, NO spatial) | **Advanced** (multispecies AND spatial) | **Simplified** (multispecies OR spatial) |
| ➢ EPOC, EwE, GBFWCGE, StrathE2E, LIEM, SysMod, SS-DBEM-IOT<br>➢ ABM: InVitro, MOOVES, OSMOSE<br>➢ Biogeochemical: ERSEM, SSEM, IGBEM, BM2, ATLANTIS, SEAPODYM | ➢ CCSSM, earlier EwE, FCSRM, FOOSA, GEM, GEEM, MIZER, PDMM SSEM; SSSM | ➢ FCUBE, ISIS-FISH, MEFISTO, MSPM, SRRMCF, STOCH HCR,<br>➢ Bioeconomic: B SEA ECON-ECOL, BEMEF, ECO, FishRent, FLBEIA, NPF BIOECON, NPFTPBEM, SIMFISH, Rueda and Defeo (2003), Wilson et al. (2006)<br>➢ ABM: ELFSim, DISPLACE, IAM<br>➢ MICE: Punt et al. (2016); Kaplan et al. (2019); Thorson, Adams, and Holsman (2019) MRM: GADGET, MULTISPEC, MSM, SMOM, Thorson et al. (2017) | **Spatial**<br>➢ EIAA, IMATSTRL, StrathSPACE, MAQ<br>➢ ABM: FIBE, FishMob, Soulié and Thébaud (2006), Carvalho et al. (2019)<br>➢ MRM: Thorson et al. (2015)<br>**Multispecies**<br>➢ FishSums, LeMANS, NECLH<br>➢ ABM: Cenek and Franklin (2017)<br>➢ Bioeconomic: (Ruttan et al. 2000; Cissé et al. 2013)<br>➢ MICE: Morello et al. (2014), Angelini et al. (2016), Doyen et al. (2017)<br>➢ MRM: Esam, Seastar, Bioenergetic/allometric models MSVPA&MSFOR, |

## 3.3. Towards relevant ecosystem formalisations for SSF models: the selection process

In this section, the taxonomy provided in 3.2 is used to get one step closer to an implementation process for SSF, by firstly reviewing these existing models groupwise and subsequently model and approach wise. Recapitulating thereby the goal of this study, implementing an approach for SSF, hence requesting for medium complexity and the particularities of SSF. Criteria to which the models are compared are:

- Degree of complexity, involving size of the model, number of parameters, computational power, non-linearity of outputs and resolution of feedbacks
- Adaptability to diverse conditions (location, …)
- Data demand

These criteria lead to the exclusion of advanced WEM, as these models represent the most complex way of modelling the ecosystem. Generally said, they are huge models, requiring a vast number of parameters and high computational power. Consequently, a high data input. Despite, this can be adaptable to various conditions, especially Atlantis and EwE that have been used in many case studies already. EwE is the most broadly used ecosystem model so far.

In addition, simplified WEM are characterized by a high number of parameters as well, since they likewise represent the entire food web and follow the concept of ecosystem models. Within this group, however, there are also models that have reduced the number of parameters to a minimum due to high aggregation. These include PPDM and SSSM.

Table 8 shows the results for the individual models of the two remaining model groups of SM. These models are by nature medium complex; hence this criterion is not further applied. Models are only recommended if they comply with both criteria. Instead of looking into each case study, as they are either way very specific, here, the focus was on the approaches instead.

***Table 8:*** *Selection criteria for model groups, whether they fit the SSF implementation. The comment column indicates the basis of the decision. Do not have or did not look for information on that: (-).*

| | Model Acronym | Data demand | Adaptability | Species interactions |
|---|---|---|---|---|
| Advances SM | FCUBE | - | Focus on fleets | - |
| | FishRent | | Good, focus more on economics than ecological stock dynamics | Non |
| | ISIS-FISH | Many parameters included (e.g. structured, maturation, migration, reproduction, gear selectivity, life history traits, etc.) | Good, as it is as generic as possible.<br>species interaction can be neglected as it covers the complex system of fisheries | Non |
| | MEFISTO | - | For the Mediterranean | - |
| | MSPM | High | - | One-way |
| | SRRMCF | - | Swedish fleet model for commercial fishery | Non |
| | STOCH-HCR | Rather high (e.g. time series of recruits), but also stochastic assumptions | Economic oriented | |
| | B SEA ECON-ECOL | - | Model for the Baltic sea | - |
| | BEMEF | - | Modified EIAA model for European fleets | - |
| | ECO | - | - | - |
| | FLBEIA | Good | Good for models of this purpose (fleets) | non |
| | NPF BIOECON | - | Australian model for prawns | - |
| | NPFTPBEM | - | Australian model for prawns | - |
| | SIMFISH | Low data requirements | Focus on fisher's behaviour, includes spatial explicit stock dynamics | No access |
| | ELFSim | High as many parameters | For coral reefs | - |
| | DISPLACE | ? | two species includable | - |

| | | | | |
|---|---|---|---|---|
| | IAM | - | - | - |
| | GADGET | Adaptable | Good | Two-way |
| | MULTISPEC | Extremely high | - | One-way |
| | MSM | Ok, as data for the species included is already available | Just for included species | Two-way |
| | SMOM | adaptable | Antarctica | One-way |
| **Simplified SM** | EIAA | - | - | Non |
| | IMATSTRL | - | MSE in Lobster fishery | Non |
| | StrathSPACE | adaptable | Good | Non |
| | MAQ | - | - | Non |
| | FIBE | - | Swedish Baltic Sea, focus on fisher behaviour | Non |
| | FishMob | Good | Fisher migration, adaptable for other regions | Non |
| | FishSUM | Adaptable, as possible to aggregate | Good | Two-way |
| | LeMANS | High | Only for the Northern Sea | Two-way |
| | NECLH | - | Low - For new England and lobster | |
| | ESAM | High | Low - as simple only few included considerations | One-way |
| | Seastar | High | Low - as simple only few included considerations | One-way |
| | Bioenergetic/allometric | High | - | - |
| | MSVPA&MSFOR | High | outdated | One-way |

Now a closer look at the approaches of the case studies are provided.

<u>Bio-economic models</u> by name include the biological side of fisheries, by focusing on the interactions of fishing fleets with biological stock. They consider the dynamics of individual fisheries. Especially important for SSF, bioeconomic models are used within mixed fisheries when multispecies are caught by multiple fleets by finding a suitable balance between replicating the details of the complex fishery system and simplifying a model to the level that makes it manageable but still useful (Scott et al. 2016; Larkin et al. 2011). These simplifications often lead to the avoidance of species interaction as seen in e.g. ISI-FIS, FLBEIA, FishRent. These models are multispecies, without applying a

predation or competition term. Also models of this approach focus more broadly on the economic side. These models provide good knowledge when it comes to merging the ecological side to the human side. However, they only give limited information on how to model the ecological side more realistically as they model the ecological side mostly from a very simplistic economic perspective. Despite, this, considerations of multispecies species interactions have been taken as well as environmental influences (Knowler 2002; Seijo, Defeo, and Salas 1998).

As MICE rely on quantitative data, the data demand for these models is generally very high. Depending on the goal of the study or the respective data availability there are models available that adapt to data poor conditions. Hence, it is possible to formulate an MRM for data poor systems by using more qualitative methods for stock assessment or spatial implementation. The same applies to MRM. These approaches are not solely concepted for fisheries but for issues such as pollution, climate change and biodiversity and are hence focused on ecologic implementations. Deep insights into ecological modelling in a medium complex way is therefore given in these approaches, as well as a broad variety of different realisations. They can be applied very simply up to a more holistic representation including multispecies, spatiality, environmental drivers and the human dimension by building up on single-species stock assessment and making use of aspects of whole-of-ecosystem models. The choice of the level of complexity for an ecosystem model is critical, and it is acknowledged that adopting an MRM approach may have possible losses on the realism of the results due to excluding second order effects. Reducing the number of species considered, or aggregating similar species into groups as in this case, reduces the number of inter species links that need to be modelled. But also consequently reduces the number of weak links included in the model that may lead to incorrect inferences regarding possible behaviour of the system.(Plagányi 2007; Plagányi et al. 2014; Plagányi 2016; Collie et al. 2016).

Agent-based modelling (ABM) has become particularly popular for SES research because ABM is rooted in complexity thinking, enables the investigation of emergent processes and has proven to be a valuable tool for inter- and transdisciplinary collaboration (Cenek and Franklin 2017; Schlüter et al. 2019). It is a computer-based modelling approach that can take into account the complexity and dynamics of fisheries by modelling and simulating entities as individual players with different characteristics and behaviours (Lindkvist et al. 2020). Thus, these models explicitly describe the behaviour of individuals, firms or vessels in order to understand and predict their aggregated behaviour. Therefore are well suited to understand the emerging consequences of fishermen interactions, heterogeneity and bounded rationality, especially in complex ecological, social and institutional contexts (Burgess et al. 2018). These including among other things, SSF interactions, can cause newly emerging phenomena such as overfishing and social inequalities. The realistic structural design of agent-based models enables stakeholders, experts and scientists from different disciplines and sectors to reconcile different knowledge bases, assumptions, and goals. ABMs can also be designed using any combination of theory, quantitative data or qualitative data  (Lindkvist et al. 2020). To summarise, this form of model development is generally very adaptable, and the data requirements depend very much on the design of the model (Fulton 2010).

The literature research, taxonomy and selection process have served to identify relevant aspects of the ecologic side of fishery systems to form an accurate counterpart to the social side from a socio-ecological system. It also highlighted the need for an approach that covers the wide application possibilities and hence no model or case study can serve as a basis. But there are modelling approaches like bioeconomic, agent-based and intermediate complex and minimum realistic models that are especially useful for getting to a medium complex SSF model. Also, the case studies and models can be very useful for specific applications (see 4.2). But rather than adopting a model already available, it is practical to develop a model from scratch as it is totally dependent on the models aim rather than using an existing model as a baseline. Hence, these approaches, simplified and advanced SM and the case studies are used in developing a guide to formalising the ecology in SSF (see chapter 3).

# 4. Guide to formalising the ecology in SSF

Chapter 3 is the core of this work, as it provides the answer to the second research question – the guidance to formulate a medium complex model for stock dynamics in SSF leaned on an ecosystem-based approach. Within this chapter, developers are introduced into considerations, questions and steps to identify building block that form the basis for modelling the ecological side for fishery systems and should be answered beforehand (section 4.1). Afterwards, they are led through each step separately, to systematically define parameters and methods (functions/equation) on the basis of models and case studies presented in chapter 3., focusing on the aspects of multispecies and spatiality (section 4.2).Finally all steps and questions are summarized in a comprehensive questionnaire (section 4.3).

The following guidance is mainly based on the concept of MICE to meet the requirements for medium complexity (see Box 1 and Plagányi et al. 2014). As are the FAO Best Practice Guidelines for Ecosystem Implementation, which contain recommendations for each aspect of model design and content, including the scope and specification of the model, implementation, evaluation and advice on the presentation and use of results. The overall objective of the guidelines is to help ensure that the best possible information and advice is generated from ecosystem models and used wisely in management. (for best practice keywords see Table 9 and FAO 2008). It also builds on the previous chapters, in particular the background section on Fisheries and Ecosystem Models (2.2) and Chapter 3.

***Box 1:** A synthesis of the concept of Models of Intermediate Complexity Ecosystem Assessment (MICE) (based on (Plagányi et al. 2014; Collie et al. 2016; Punt et al. 2016; Plagányi and Fulton 2017; Kaplan et al. 2019)*

A synthesis of Models of Intermediate Complexity Ecosystem Assessment (MICE)

The major components of MICE comprise a model of the ecological system, how it is impacted by anthropogenic factors, and how the ecological and human processes represented in the model impact on, and are impacted by, management.

Facts:

- Relatively simple multispecies models, restricted to focus on the interaction of a small number of key processes (environmental, biological, economic, and social)
- Flexible, structured to target a small, specific set of questions
- Parameters determined to fit to available data, literature values, assumption, speculations or outputs from other models by maximising the likelihood functions
- Possible to use standard data fitting methods
- Include properties that advance their use as tools for ecosystem assessment
    - Able to apply all kinds of population dynamics (e.g. structured-, production-, delay-difference models)
    - two-way predator-prey feedback
    - environmentally and anthropogenic-driven recruitment
    - spatially structured
    - different time steps for different groups
    - effects of fishery (harvest)
- The approach focuses on finding the sweet spot where uncertainty is reduced (by including key drivers considered as externalities in past single species models) and the utility of these models to management is maximized
- In between whole-of-ecosystem models and traditional single-species assessment models
    - In common with whole-of-ecosystem models: possibility to link physical models (to quantify environmental forcing and two-way relationships between habitat and resources) as well as models of human behaviour (social and economic processes that will impact model forecasts and would represent key feedbacks between resources, resource users and stakeholders involved in management)
    - In common with stock assessment models: fitted to all available data using the same methods as applied in stock assessment models, and hence provide rigorous multispecies assessments together with quantification of the associated uncertainty
- MICE have considerable potential to bridge the divide between fisheries and conservation managers because they are capable of simultaneously accounting for the sustainability of a fishery, the major ecosystem impacts of fishing, and the need to meet conservation goals in a timely way (both in terms of computation and the length of development/implementation
- Extended to include economic and social aspects by
    - Focusing on specific decision processes that are shown to determine the outcomes of interest
    - Using already existing approaches (bioeconomic models)
    - Including a Sense of Place Index (SoPI) to dynamically link the two-way feedbacks between ecological systems and socioeconomic systems. Used as a model variable, SoPI allows for the quantitative integration of environmental psychology into socioecological models.
    - Going in line with the principles outlined by Ostrom's social–ecological systems (SES) framework, but focusing on key linkages only and representing these in the simplest manner as possible while still capturing the important dynamics

***Table 9:*** *FAO best practice: what should be considered in an ecosystem model (FAO 2008, Christensen, 2012)*

| FAO best practice key words | |
|---|---|
| Initially | System boundaries<br>Modularization<br>#modules |
| Structure | Stock structure<br>Age, size, stages structure<br>Spatial structure<br>Seasonal, temperature structure |
| Parameters | Recruitment<br>Mortality<br>Distribution<br>Abundance<br>Movement<br>Functional response |
| Linkages | Predator-prey relationship<br>Technical interactions<br>Non-trophic interactions<br>Fishing fleets and dynamics<br>Environmental forcing<br>Anthropogenic forcing<br>Primary production and nutrient cycling<br>Social economic |
| Finally | Alternative stable states<br>Fitting to data<br>Parameter, Model structure and implementation uncertainty<br>Process and observation error<br>Open source code |

## 4.1. Step by step, from the idea to implementation

This section shows how to approach the problem of developing a model from the start.

These questions and tasks do not essentially differ from a model development of other models than SSF.

It has been shown that the implementation process of the ecological side cannot be totally cut off from the development of the whole model, e.g. the social side. Therefore, I collected six questions the developers have to keep in mind at all times while implementing ecological aspects. These questions are:

1. What is the goal of the study? Why is the development of the model important? What should it contribute? For whom is it?
2. Which resources are available (e.g. data, sources[9], financial, knowledge, cooperation, computing power)?
3. Do the available resources satisfy the models objective? If not: how can simplifications, assumptions, estimations and tools tackle these issues?
4. What is the simplest model addressing the issue?[10]
5. What are the systems boundaries?
6. How to keep the model as easy as possible?

The last question is quite important as model complexity (as in number of parameters) correlates inversely with predictability. Hence, FAO (2007) emphasis on model components necessary to fulfil the studies goal by implying modularisation of the ecosystem.

All following tasks are dependent on the questions above and are aiming on defining the model:

A. Selection of system component/entities: Spatial and species
B. Number of modules/entities (#modules spatial and #modules species)
C. Choice of resolution (e.g. temporal, spatial and species-based)
D. Characterisation of the component(s) by attributes: quantifying state variables and rates/flows
E. Integration of species interactions (if #modules_species > 1)
F. Integration of spatiality (if #modules_spaces > 1)

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[9] including sources detailing relationships between environmental data and biological processes.
[10] Conceptual/qualitative models can be rapidly developed providing quite substantial insights into system functioning, can be rapidly developed, allow incorporation of stakeholder advice and input, ensuring stakeholder requirements are addressed, and can ultimately improve…

G. Linking ecosystem characteristics (spatial and physical) and human behaviour (social and economic, institutional) to population parameters

The concept of MICE introduces the components resource, target species (in the following summarized as species or multispecies), spatial, physical, social, and economic. Another aspect that could be considered is institutional.

## 4.2. Implementation examples and formalisation options for each step

This section presents the actual guidance of on the process of model realisation, adapted to the underlying goal of this thesis of having ecological formalisation options for the stock dynamics of SSF models (see Box 2 for a resume of what sets SSF). Especially for the development of multispecies and spatial models (A. Selection of system components). The entire method of the model development process can be seen in Figure 7. Each separate step will be zoomed in within sections 4.2.1 – 4.2.6.

***Box 2:*** *Resume of SSF specifications that need to be considered when developing a SSF model*

Resume of SSF specifications:

1. Medium complex: avoid model approaches of high complexity (linearization, feedbacks and linkages) and complication (size of model and # of parameters)
2. Active, diverse and heterogenic: mandatory to provide options adaptable to various scenarios (e.g. single-species, multispecies, locations (e.g. region, territory, climate, habitat)), multiple objectives of SSF and changing conditions
3. Adapted to limited resource availability. Especially data availability due to the data poor nature of SSF (though the possibility of estimations, assumptions, statistical methods, etc.) but also limited financial resources or computational power.
4. Understudied: not many examples available. Approaches from other captured fisheries (LSF) need to be adjusted as their applications vary from those of SSF

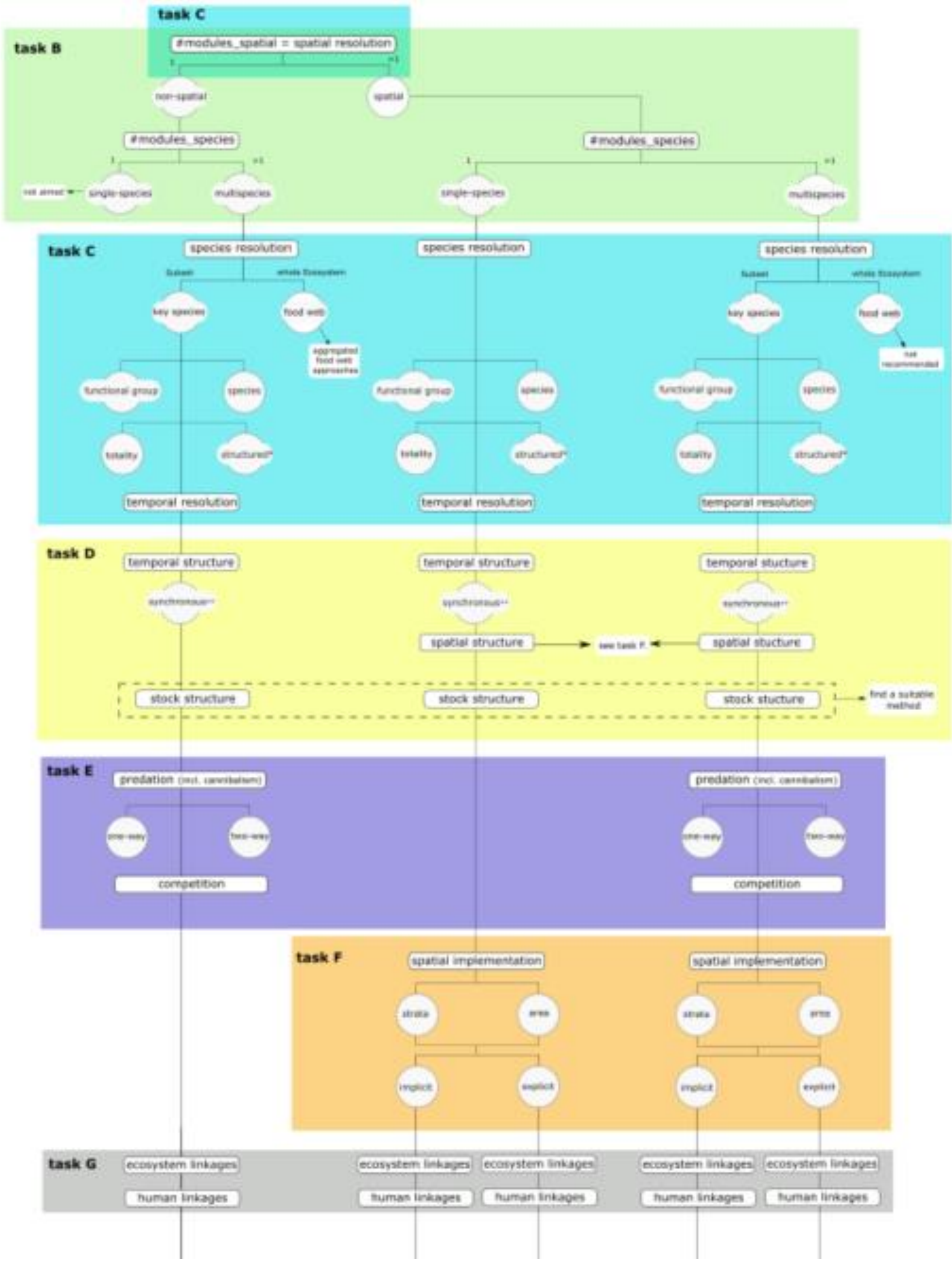


***Figure 7:*** *Flow chart of the process of developing an ecosystem oriented SSF model of medium complexity.*

### 4.2.1. B. Number of modules (#modules)

Setting #modules > 1 (as choosing #modules = 1 is a non-spatial or respectively single-species model), depending on number of spaces or species important for answering the goal of the study and covering all necessary processes (e.g. predation and competition of key species). Figure 8 illustrates this situation further as “#modules_spatial = spatial resolution” shown in task C.

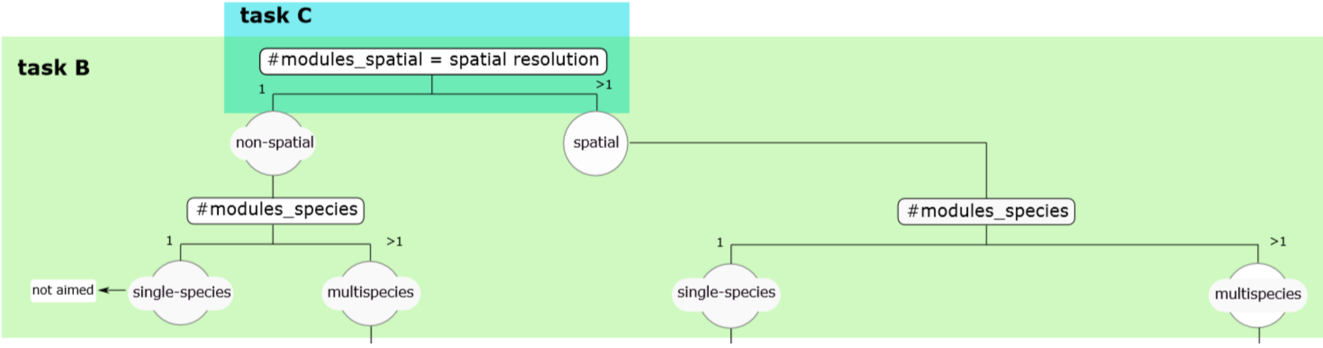


*__Figure 8:__ Overview for editing task B, including spatial resolution for task C.*

I strongly recommend paying attention to the complexity at this point. The more modules that are chosen, the more complex the model becomes. Remember to select only those modules (spaces or species) that are of great importance for the study goal. Especially, if both spatial and multispecies aspects are taken into account. Selecting the species that are relevant can be quite challenging since all species in a food web are most likely to affect the system biologically.

Questions developers can ask themselves are:

- What is/are the type(s) of fish represented?
- What is its/their ecology and biology
- Where do the species reside and/or move)?
- How can the space(s) be represented?

For further information see Table 11 in section 4.3.

### 4.2.2. C. Choice of resolution: temporal and species-based

The resolution considered here is temporal, spatial and species-specific (taxonomic). For the resolution, the possibility for #modules to be handled on differing scales should exist (Fulton 2010). Furthermore, considering the overall complexity, data availability and study goal is very important. Keep in mind: the finer the resolution, the more complex the model, the more data is demanded, or the more assumptions have to be made. Figure 9 pictures the implementation of the resolution.

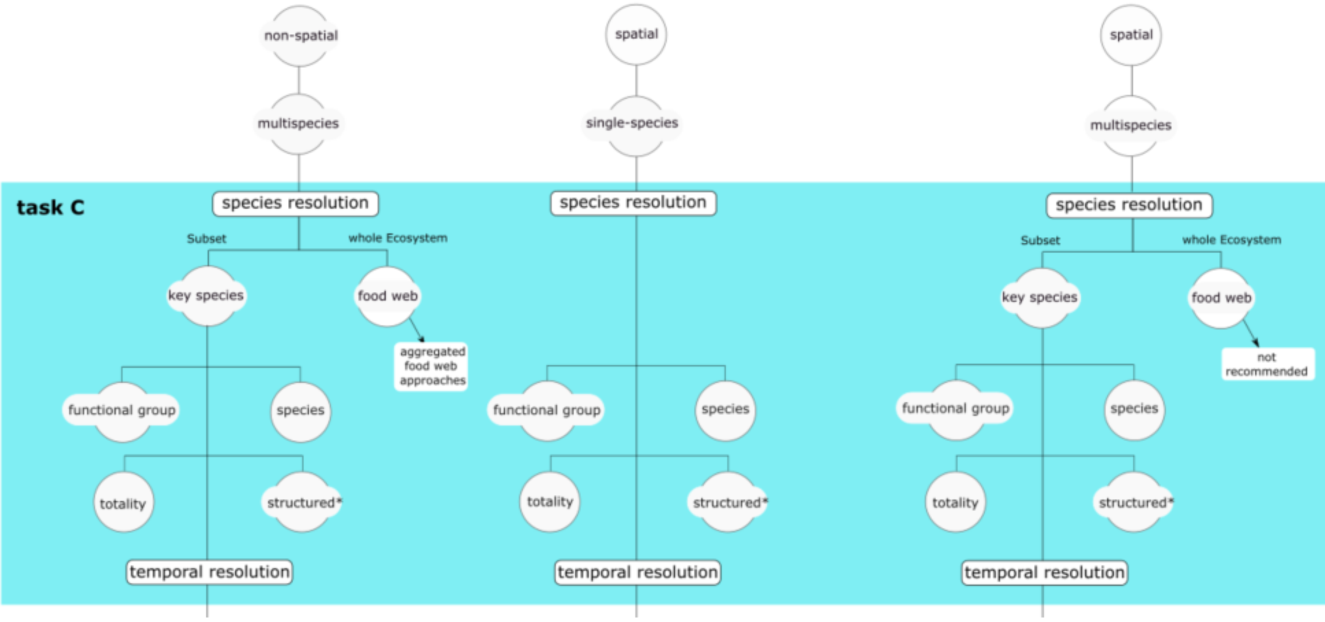


*__Figure 9__: Overview for editing task C. *structured: life history (age, size, weight, length, stage), sex and space*

<u>Temporal resolution</u> varies from seconds to decades in different ecosystem models. For appropriate temporal resolutions I recommend a range from tidal, daily, weekly, monthly, seasonal to annual time steps. In general, the finer the temporal resolution, the more accurately the dynamics can be represented at the expense of complexity. The choice of temporal resolution depends on the types of species implemented (see task B.), e.g. if it is a fast-growing species a finer resolution is recommended than for a slow-growing species.

<u>Spatial resolution</u> see #modules_spatial for the structure according to space

<u>Species-based resolution</u> also known as taxonomic structure, including ecological/population structure. This refers to whether the whole food web is represented or a part of it, whether the species are presented species-specific or aggregated into functional groups[11]. Also often called "lumped" or whether the species are represented as a total or fanned out into categories of life history or sex (ecologically structured).

Rarely is it necessary to include the entire food web, thus, I recommend focusing on key species, as mentioned in section 3.3 and following the MICE concept. But if a non-spatial model is expressed and is unavoidable to meet the objective of the study, a food web approach could be possible with highly aggregated functional groups (see e.g. PDMM or SSSM). Generally, if many species are included, I suggest summarizing the individual

[11] Species can be grouped if they have the same trophic level also having similar ecosystem function or population dynamics

species in functional groups, especially if the species are associated or dependent species and not a focus for fisheries (targeted resource species). For combining species into groups, the questions from Task B should be considered – to not group species of totally different types. Most likely it is necessary to include the species of special interest individually. Resolution representing the ecological structure of the species is again dependent on the studies goal, type of fish, data availability and the compartments and modules already implemented (see again questions task B). Giving some examples:

- Life-stage structuring for example juveniles and adults if habitat changes throughout the species lifespan or if cannibalism is included, including a parameter indicating maturation
- Size- or length structuring if size-selective gear is used by fishers
- Age-structuring if the predation pressure changes dependent on the age of the prey
- Sex-structuring if the recruitment is a function of number of (matured) females

### 4.2.3. D. Characterisation of the component(s): population dynamics

The starting point for population dynamics are single-species stock assessments, where later additional components are linked (e.g. other species (see task E.), spatiality (see task F.) or other ecosystem or human linkages (see task G.). Figure 10 illustrates the steps that have to be made for task D.

For the application of dynamics, I suggest synchronous time steps (see section 2.2.5.1).

The stock is normally displayed according to their abundance as biomass $B$ or number of individuals $N$ at time $t$ and is calculated for the next time step $t+1$ by growth and immigration increasing and mortality and emigration  decreasing (see Figure 11).

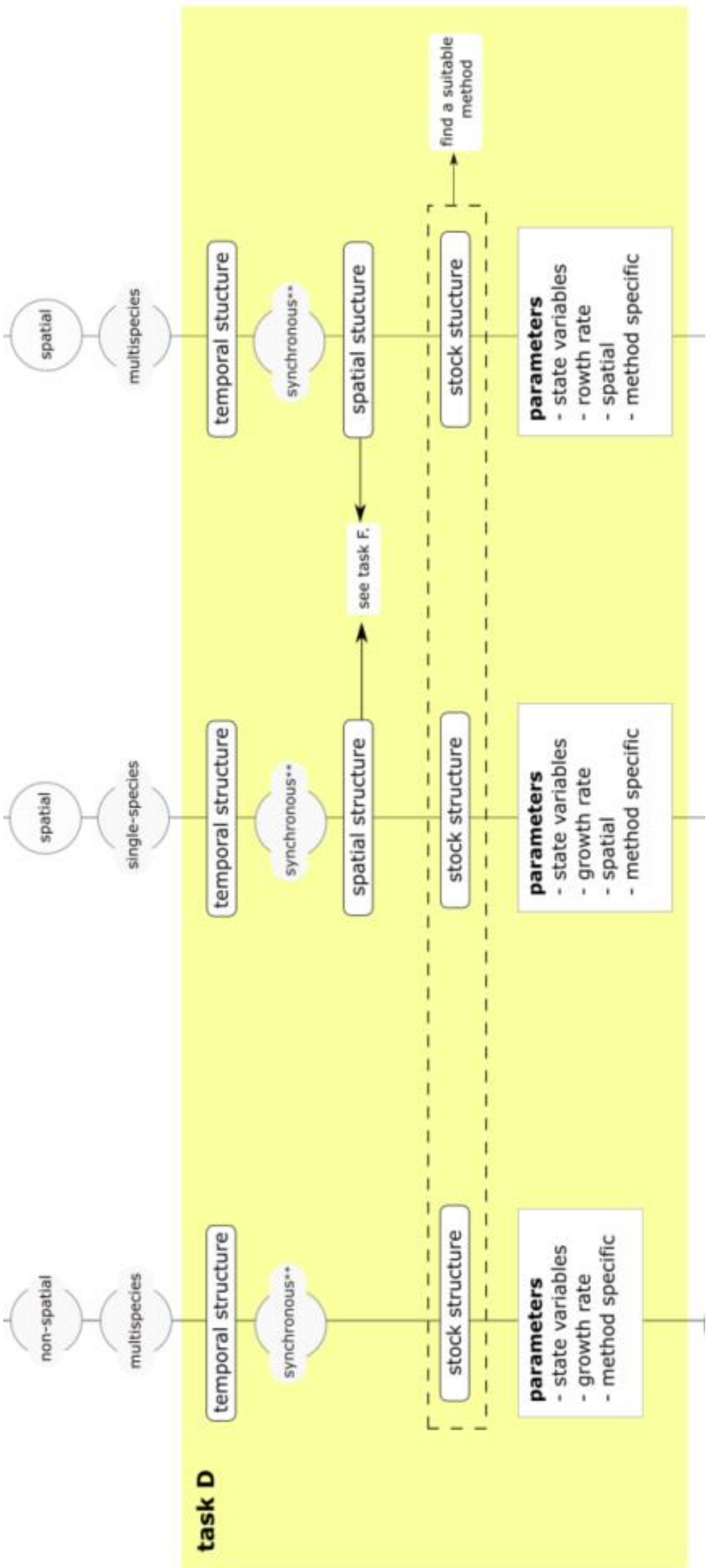


***Figure 10:*** *Overview for editing task D. The insights for the stock structure can be seen in* ***Figure 11****.*

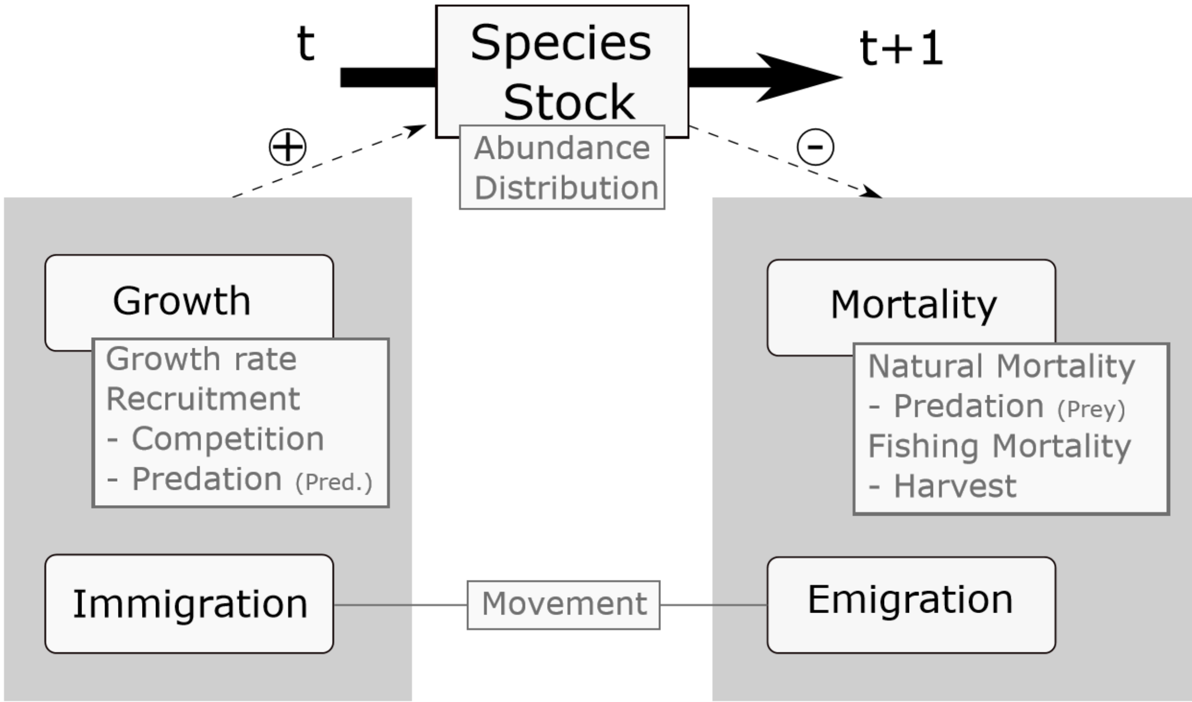


***Figure 11:*** *Illustration of population dynamics occurring from time t to t+1. Species stock is increasing due to growth and immigration and decreasing through mortality and emigration. Related parameters are indicated.*

When modelling a multi-species system or a system with several spatial areas or layers, the single-species stock assessments are no longer sufficient. Additional complexity has to be added, as the population parameter for one species may be negatively impacted by increased abundance of another species that shares an ecologically similar niche (competition), influenced by the interaction indicating parameters of predation (see 4.2.4 multispecies task E) or population parameter dependent on the spatial distribution of the species (see paragraph below or task F.). Affected population parameters are the carrying capacity[12], parameter of production model, growth/mortality, and recruitment.

Questions developers can ask themselves are summarized in Table 10.

[12] Parameter of production model, maximum capacity a location can hold.

***Table 10:*** *Summary of questions a developer can ask during task D.*

| | Questions | Parameters |
|---|---|---|
| General | How many are there? | - Abundance |
| | How fast do the species grow? | - Growth rate<br>- Mortality/survival rate |
| | How quickly do they reproduce? | - Recruitment<br>- Reproduction rate/fecundity<br>- maturation |
| Spatial | Where are they? | - Distribution |
| | How do they move? | - Movement |

For further information see Table 11 in section 4.3.

In the following the highlighted parameters are shortly introduced.

Growth rate $r$ indicates the biomass growth of a population or an individual in size/length or weight.

Mortality/survival rate $Z$ is split into natural and fishing mortality/survival if exploitation occurs. Natural mortality $M$ includes deaths of natural causes dependent on age/length, food supply, pollution, and predation etc. (for the latter see 4.2.2.3 multispecies task E). Whereas fishing mortality $F$ is caused by harvesting $H$ (see task G).

Recruitment $R$ refers to the number/mass of offspring at any point after egg stage that enter population in a given year. If an age structured assessment is chosen, recruitment is a function of age = 0. Recruitment can be a function of reproduction success, fecundity, maturation and/or sex-ratio and can be can either be implemented constant, proportional or density dependent by e.g. using stock recruitment relationships (e.g. Beverton-Holt or Ricker)

Distribution is a state variable for specifying the abundance of species in different locations. It is influenced by location preferences and seasonally and evolutionary migration (movement)

Movement describes immigration and emigrations; if spatiality is neglected, it is often assumed that immigration equals emigration. Estimation of movement is challenging, even for data-rich scenarios (see 2.2.5.1). Two types of movement can be differentiated:

- Time-invariant (or random) movements, driven predominantly by diffusive processes in which a fixed fraction of the animals migrates from one area to the next within a given time.
- Dynamic movement includes time-dependent factors such as reproduction or prey/competitor density and environmental conditions affecting the movement rates (see task F).

As the choice of an adequate methodology is often more a matter of personal judgment than strict logic (FAO 2006), giving recommendations thereon is rather complicated and won't be presented here. Furthermore, there are a lot of different methods, with various modifications available for each method. However, FAO provides an overview on bioeconomic models (Seijo, Defeo, and Salas 1998), as well as a manual for fish stock assessment (FAO 2003). Overviews of stock assessment methods can be found here:

- FAO (2006), including the "Fisheries Management Science Programme" (FMSP) stock assessment tools
- NOAA fisheries integrated toolbox (NOAA FIT) provides toolboxes for fishery stock assessment (Fish-Tools) and protected species (NPST). The latter tools may be particularly relevant for SSF, as often little data is available for protected species as well. Also tools for the ecosystem and general modelling tools can be found there (NOAA Fisheries 2020).

To name only two different approaches:

Broadly used in the models studied in chapter 3. for non-ecologically structured biomass models is the production model (e.g. Schaefer Production Model; Burns 2014):

$$B_{t+1} = B_t + rB_t(1 - \frac{B_t}{K})$$

Where $B_t$ or respectively $N_t$ is the total abundance of the species (in biomass or numbers) at time t, the intrinsic growth rate $r$ and $K$ the carrying capacity. Additionally, the term $-P_t$ and/or $-H_t$ can be implemented, simulating extraction (natural or fishing mortality) through predation (see task E.) and/or harvest (see task G.).

However, most real populations exhibit life history structure (see 2.2.5.1 and 4.2.2). If detailed structuring is required structuring of one aspect or even a combination of several structuring aspects (e.g. age and sex or length-at-age) can be implemented within a structured or analytical model (see e.g. Hilborn et al. 2017; or Beverton-Holt Model)) or stock recruitment model (e.g. Ricker model). Here, the abundance of the species at $t=0$ is equated with recruitment ($B_0 = R$ or respectively $N_o = R$), followed by the population dynamic in the following time step. The use of these models for SSF can be limited as they require a lot of data.

An intermediate option between total mass, number models and structured models are delay difference models. These are based on some key simplifying assumptions that allow (age-)structuring to be simplified to a single equation involving total biomass and numbers only (see e.g Thorson et al. 2015). As this method does not require much information to design “realistic” models it could be perfect for SSF models.

Delay difference models for the total number of animals in a population are represented by:

$$N_{t+1} = N_t s_t + f(N_{t-L+1}) \qquad \text{or} \qquad N_{t+1} = N_t e^{(-Z)} + r_t$$

Or for the total biomass in a population by:

$$B_{t+1} = B_t g s_t + R(B_{t-L+1}) \qquad \text{or} \qquad B_{t+1} = B_t g e^{(-Z)} + r_t$$

Where $B_t$ or respectively $N_t$ is the total abundance of matured species (in biomass or numbers), $s_t$ is survival from all causes, $L$ is lag from birth to maturity and $f$ /$r_t$ is a recruitment function including recruitment and survival from birth to age $L$, $g$ is proportional change in mass from one year to another (growth) and $Z$ is total mortality ($M$-$F_t$) (see Thorson et al. 2015)

### 4.2.4. E. Integration of species interactions

The functional form used to represent inter- and intra-specific trophic and non-trophic interactions (biological interactions differentiated from technical interactions see task F) in MICE are predation (including cannibalism) and competition applied to the stock assessment via Lokta-Volterra equations (see 2.2.5.2 and Plagányi et al. 2014). Figure 12 illustrates the pathway of considering multispecies.

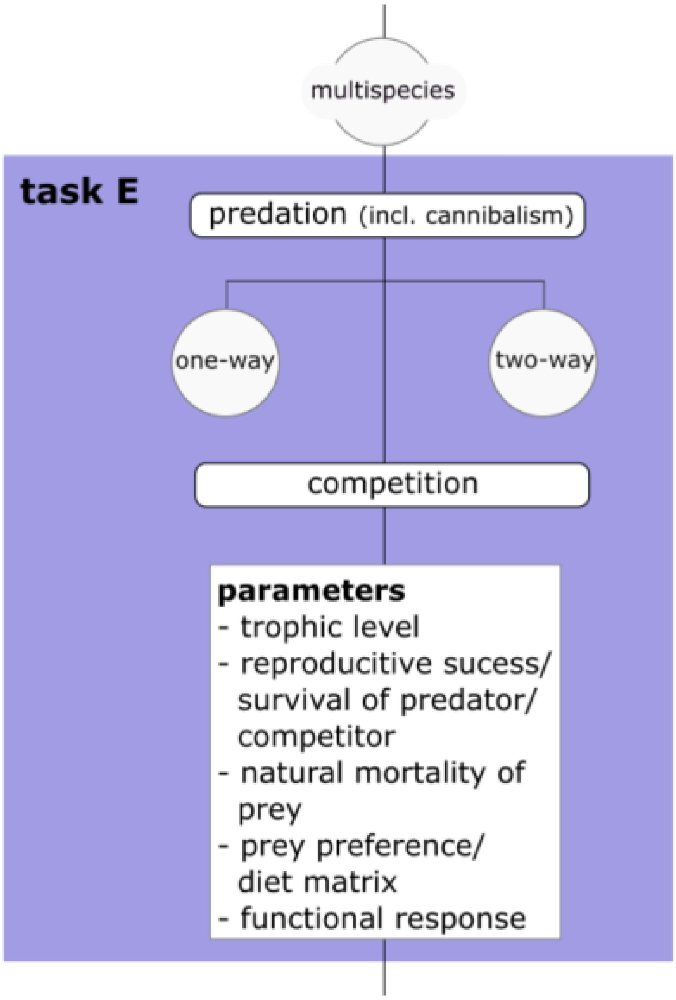


***Figure 12:*** *Overview for editing task E. For more detailed information see* ***Figure 13****.*

Predation (incl. cannibalism) is the fundamental feedback of species interaction and can be implemented either one-way or two-way (based on the principle of conservation matter, prey eaten converted into predator biomass or number). It is dependent on the trophic level that the species have and the diet preference of the predator.

Functional form representing predation feedbacks is critical to the system dynamics and difficult to estimate. MICE avoid these challenges by considering consumption effects (i.e. survival, reproduction, and growth rate) rather than consumption itself by expressing the dependence of predators on prey through a survival and reproductive success factor. This factor depends on the available abundance of the prey and works as a multiplier for the recruitment parameters of the juveniles, namely the reproductive and/or survival rate of the juveniles (see Figure 13). In this way, the notion of predator-prey interaction directly links predator breeding success to prey abundance, thus avoiding the need for an explicit consumption-related notion. A single parameter controls the level of prey frequency (relative to the carrying capacity for one or more species) below a noticeable negative impact on predator breeding success. Examples of implementing predation can be seen in Plagányi et al. (2014).

Consequences of competition (species of same trophic level competing on same food resource and/or habitat) also affects growth and survival rates (see also Figure 13). Since, for example, the absence of competitors (or one species being the benefitting competitor) can lead to increased growth, due to sufficient food supply. This may lead to reduced mortality or increased survival due to predation since faster growth of the prey away from a vulnerable size. Here also decreased survival of predator due to prey scarcity is important. However, the reduced presence of other competitors may also result in exploitation of one species (increased predator mortality) (Plagányi et al. 2014).

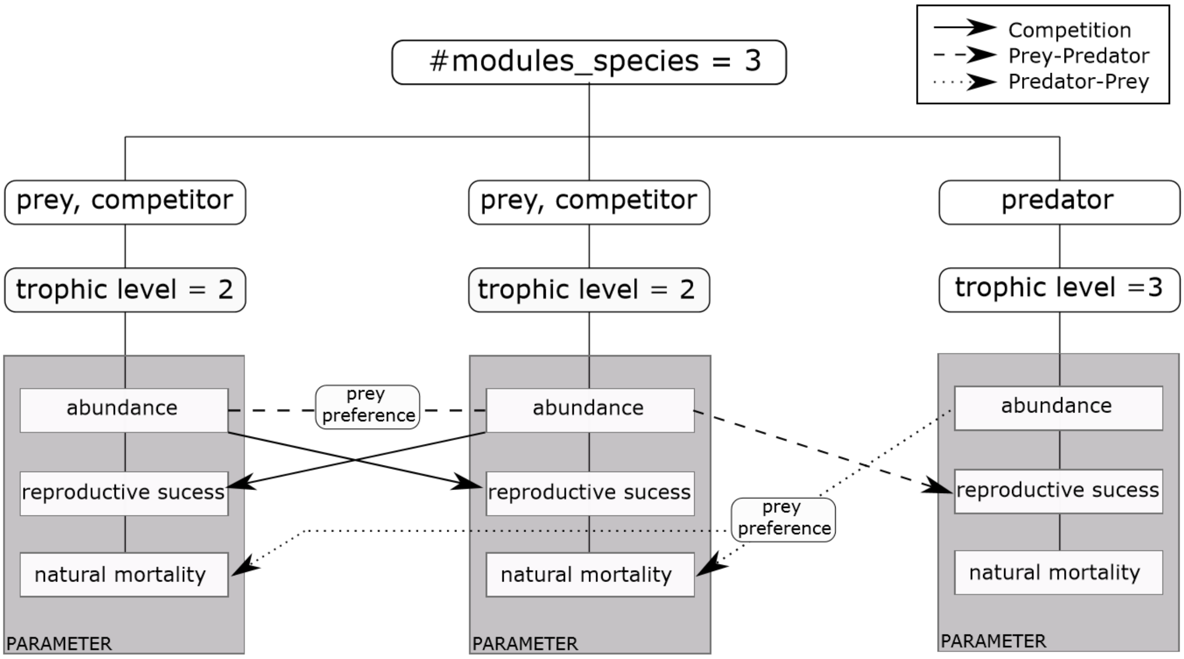


***Figure 13:*** *Illustration of how to implement species interactions into a multispecies SSF model. Example showing two-way feedback of two prey species, competing for the same resources, both being hunted by the same predator.*

For MICE it is recommended to account for uncertainty. Ideally the parameters and form of the predator-prey functional response should be estimated by fully integrating predation and diet data into the parameter estimation process. However, this is not suitable for SSF models, therefore I recommend using statistical methods instead. I found two ways of determining functional responses statistically. First by assessing the robustness of model outputs to a range of alternative functional response types (for an overview see Hunsicker et al. (2011)). Or a generalized functional response curve which is parameterized to bound uncertainties of the likely level of sensitivity of a predator to its prey (Plagányi et al. 2014).

### 4.2.5. F. Integration of spatiality or ecosystem considerations

Implementation of the spatial environment (or ecosystem considerations if spatially does not play a significant role) serves to determine location-specific species traits. Inherent distribution and movement dependent amongst others on the habitat preferences of the individual species and evolutionary or seasonal migration. In medium complex models, like MICE, spatial differences are often described quantitative by following relatively simple relationships or rules for e.g. modifying spatial recruitment patterns. This can be achieved for example by varying recruitment success over space or transport of recruits to other regions rather than quantitative modelling of physical transport processes. Especially for models that represent a combination of spatial and multispecies assessments, the quantitative representation should be chosen. For single-species models, which focus on individual locations, an qualitative representation is possible, also if the model is not spatial explicit but the represented area has some specific environmental characteristics, these can be implemented as either constants or even with certain variability – seasonally or as a result of the climate crisis.

Spatial variations can be illustrated either in form of an ordinate-based implementation (by uploading a map) or by implementing a grid. Within a grid either one cell or a sum of cells (a patch) can serve as one location (often habitats), in contrast within an ordinate-based approach, spatial environments can be displayed as e.g. polygons or lines.

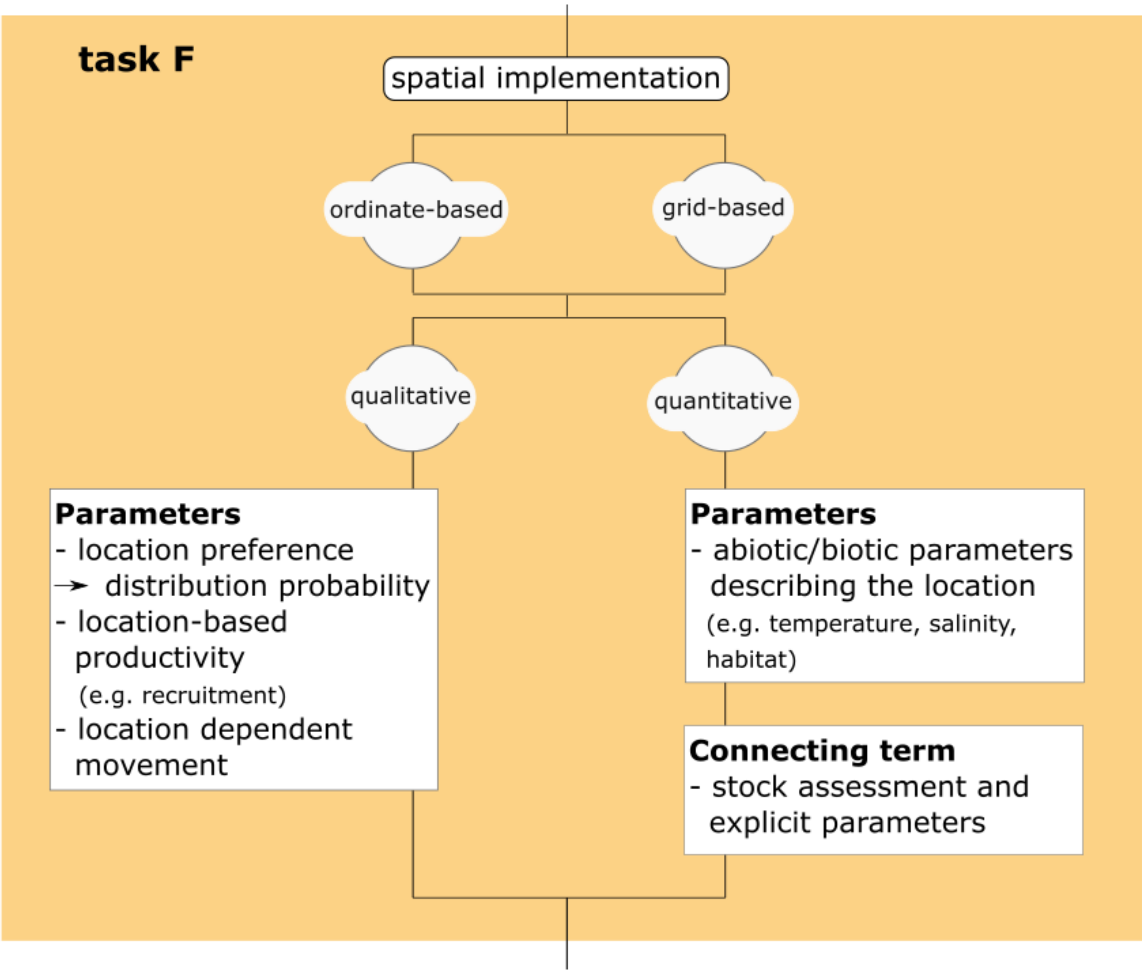


***Figure 14:*** *Overview for editing task F.*

An approach for implicit spatial implementation is, for instance, linking recruitment to the different locations $r_t(s)$ by representing spatial variations in productivity within a matrix $P(s)$ and defining for example time-dependent variation in spatial distribution $D_t(s)$ (Thorson et al. 2015). Also possible is the linkage between space and mortality and growth. Knowledge of where the population prefers to be or which areas, they avoid is vital (location, habitat abiotic condition preferences). See questions regarding the types of fish implemented in 4.2.1.

Compared with explicit implementation, where the productivity is indirectly affected through a matrix of conditions and a term that defines the relation/dependence of the animal to the given conditions based on relationships to physical (flow volume) and biological (availability of meiofauna) components.

Modelling dynamic movement by using preference or habitat suitability functions (see 2.2.5.3), whereby each spatial region is assigned a level of preference (conditional on the key movement-influencing factors) for a particular animal and a probabilistic movement model constructed based on the relative preference of each area by that animal.

Spatial methods are for example:

- Joint dynamic species distribution models (JDSDM) (Thorson et al 2019)
- VAST (MICE-in-space; Thorson et al 2019, open source)
- Spatial population dynamics in patches using Schaefer production model (Carvalho et al. 2019)
- spatial delay-difference model (Thorson et al 2015, open source)
- Spatial dynamic factor analysis (SDFA) (Thorson et al. 2016, open source)

Spatial models:

- ISIS-Fish (especially for models including human entities)
- StrathSPACE

### 4.2.6. G. Linking ecosystem characteristics (physical) and human behaviour (social and economic) to population parameters

This section creates the link between the species and spatial modules and the potential other modules of the model. Namely human and ecosystem components and is intended to give ideas about how the connection can look like, without being given full implementation guidelines (see Figure 15).

The ecosystem component is very similar to the quantitative/explicit spatial implementation and can be used if spatiality is not realized. Ideas for the implementation can therefore be found in the section above. Variability is also added, which would include changing the abiotic and biotic conditions over time.

Human linkages are for instance already considered in task D. when it comes to fishing mortality. Fishing mortality can be added by a term indicating selectivity. Fishing also causes technical interactions between fishing gear and species. These can either be direct, gears compete on the same fish at the same time. Or sequential, one gear catches fish before they become available to the other, either due to the different selectivity's of the gears or to the location or times that they are fished. Technical interactions are often the cause of problems with "bycatches" or "discards", where such discards reduce the catches available in other fisheries. Technical interactions of course add complexity but can be handled relatively easy. These interactions can be caught for example by multi-fleet dynamic models (see Doyen et al. 2017). Furthermore, aspects like culture, gender or communities play a role in SSF models. An example for the role of gender is given in Chapter 4 within the case study for OctoPIN.

Additionally, species and spatial implementation can be affected by laws or regulations (for example by introducing harvest and non-harvest-zones and maximum sustainable yield ending in maximum fishing quotas).

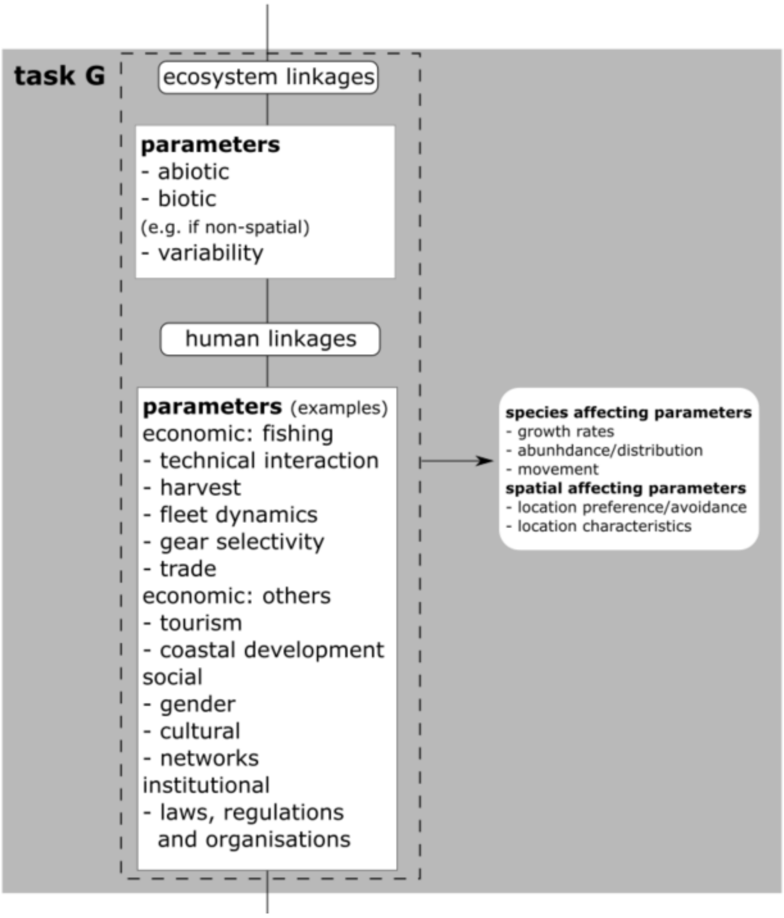


***Figure 15:*** *Overview for editing task G.*

Questions developers can ask themselves are for instance:

For ecosystem linkages:

- How could ecosystem characteristics be defined? (habitat, water quality (e.g. nutrients, oxygen, pollution), salinity, topography, sediment types, currents, upwelling, weather/climate zone (e.g. temperature, precipitation),
- How does the ecosystem characteristics change over time? (climate change, seasonal characteristics)

For human linkages:

- How does harvesting affect other species? (see technical interactions)

- What species are being caught?
- Who is catching them and how? (gear-types)
- What do the exploitation patterns look like? What is the size/length/age that is caught? (selective gear, catchability, location)
- How much can be caught sustainably?

For further information see Table 11 in section 4.3.

## 4.3. Developed questionnaire for ecological modelling in SSF

Section 4.3 gives an overview/summary of the above mentioned sections in form of a questionnaire (Figure 16) and a table (Table 11).

| Implementation | Selection | #modules | Comments |
|---|---|---|---|
| Spatial | ☐ | | add block 3, include Block 4 **#modules**-times |
| Multispecies | ☐ | | add block 2, include Block 1 and 4 **#modules**-times, |
| Ecosystem characteristics | ☐ | | include block 5 |
| Human behaviour | ☐ | | include block 6 |

| Block | | Questions | | Selection | | | | Comment |
|---|---|---|---|---|---|---|---|---|
| 1 Type of Fish | | | | species 1 | species 2 | species 3 | ... | see #modules_multispecies |
| | .1 | species name/aggregation | | | | | | |
| | .2 | trophic level | | | | | | |
| | .3 | growth velocity | | | | | | |
| | .4 | evolution | | | | | | |
| | .5 | migration | | | | | | |
| | .6 | habitat | | | | | | |
| | .7 | species specification | Prey | ☐ | ☐ | ☐ | ☐ | if multispecies |
| | .8 | | Predator | ☐ | ☐ | ☐ | ☐ | if multispecies |
| | .9 | | Competitor | ☐ | ☐ | ☐ | ☐ | |
| | .10 | | Cannibalist | ☐ | ☐ | ☐ | ☐ | |
| | .11 | commercial value | target species | ☐ | ☐ | ☐ | ☐ | |
| | | | associated species | ☐ | ☐ | ☐ | ☐ | |
| | .12 | data availability | | | | | | |
| 2 Multispecies | | | | general | species 1 | species 2 | species 3 | |
| | .1 | predation: one-way | prey-predator | ☐ | | | | |
| | | | predator-prey | ☐ | | | | |
| | .2 | predation two-way | | ☐ | | | | |
| | .3 | cannibalism | | ☐ | | | | implement life-stages |
| | .4 | competition | | ☐ | | | | |
| | | | Species competing: | ☐ | ☑ | ☑ | ☑ | |
| | .5 | prey preference | | | | | | if 2.7 = prey and #prey > 1; for each prey species |
| | .6 | functional response | | | | | | to account for uncertainty |
| 3 Spatial | | | | general | space 1 | space 2 | .... | see #modules_spatial |
| | .1 | grid-based | | | | | | |
| | .2 | ordinate-based | | | | | | |
| | 3 | qualitatively | | ☐ | | | | |
| | .4 | quantitatively | | ☐ | | | | |
| | .5 | Parameters | | | | | | |
| | .6 | Variability | | | | | | |

| | | | space 1 | | space 2 | | |
|---|---|---|---|---|---|---|---|
| **4** | **Stock Assessment** | | species 1 | species 2 | species 1 | species 2 | see #modules_spatial<br>see #modules_species |
| .11 | temporal resolution | | | | | | see block 1 |
| .12 | stock resolution | species-based | ☐ | ☐ | ☐ | ☐ | see 1.11 |
| | | functional group | ☐ | ☐ | ☐ | ☐ | |
| | | structure | | | | | necessary? |
| .13 | type of abundance | biomass | ☐ | ☐ | ☐ | ☐ | |
| | | number | ☐ | ☐ | ☐ | ☐ | |
| .14 | species state variable | abundance | | | | | |
| | | carrying capacity | | | | | if production model |
| .15 | species flow | recruitment | | | | | see block 1 and 2 |
| | | fishing mortality | | | | | if stock is exploited |
| | | natural mortality | | | | | see block 1 and 2 |
| | | growth | | | | | see block 1 |
| .16 | spatial state variable | distribution | | | | | see block 3 |
| .17 | spatial flow | movement | | | | | see block 3 |
| .18 | method to account for uncertainty | | | | | | e.g. MCMC, maximum likelihood |
| **5** | **Human behaviour** | | | | | | non-spatial but ecological conditions |
| .1 | technical interactions | | | | | | |
| .2 | how the species are caught? | selectivity | | | | | |
| | | catchability | | | | | |
| | | commercial interest | | | | | |
| | | other | | | | | |
| .3 | who is catching? | | | | | | fleets, community, village, men, woman |
| .4 | fishing method | | | | | | |
| .5 | equipment | | | | | | |
| .6 | institutional | regulations | | | | | sustainable yield, non-harvest zones |
| | | laws | | | | | |
| | | organisations | | | | | |

***Figure 16:*** *Questionnaire of how to formalise the ecology in SSF*

***Table 11:*** *Summary of possible ecological parameters to add to an SSF model, their explanation and examples, derived from answering the questionnaire Figure 16.*

| **Parameter** | **Explanation** | **Examples** |
|---|---|---|
| **Species Types** | | |
| Trophic level | Position in the food web | 1 (primary producer),<br>2 (primary consumer)<br>3 (secondary consumer)<br>4 (tertiary consumer) |
| Trophic interaction | Interactions between trophic levels | Predation |
| Non-trophic interaction | Other interactions than between trophic levels | Competition, cannibalism, habitat |
| Evolution/ecology | Changes of the species behaviour or characteristics over its life span | Maturation, growth, life stage behaviour, |
| Growth velocity | how fast the species is growing | Fast, medium or slow-growing |
| Migration | If the species are changing the location | Highly migratory or resident (seasonally and evolutionary) |

| | | |
|---|---|---|
| Location preference | Where the species are probably staying | Benthic (Groundfish) pelagic, inshore or offshore, deep sea, shallow water, habitat, abiotic conditions) |
| Commercial value | Economic interest of fishers in the species | Target, exploited species/resource<br>Associated, dependent species (unexploited) |
| **Model Structure** | | |
| Time | Temporal resolution | Tidal, daily, monthly, quarterly or yearly<br>(depending on growth velocity and availability) |
| | Time steps | Synchronous |
| Space | Spatial resolution | #modules_spatial |
| | Spatial implementation | Ordinate or grid based<br>Horizontal or vertical |
| | | **Implicite (qualitative)** or explicit (quantitative) |
| Species | Ecosystem resolution | Food web, **key species, single-species** |
| | Ecosystem implementation | Food web approach, Loktra-Volterra Predator-Prey, single-species stock assessment |
| | Taxonomic resolution | Individual species, functional groups |
| | Taxonomic Implementation | Lumped, Biomass or Number of individuum |
| | Species-structure resolution | Non, age, size, length, stage, sex |
| | Species-structure implementation | Single-species stock assessment e.g. production, difference-delay, structured, stock recruitment |
| **General population parameters** | | |
| Abundance | Species state variable<br>Quantity of species | Biomass or number |
| Growth | Species flow<br>Increasing biomass though growth<br>If abundance based on biomass<br>Possibly dependent on food availability, location, | Intrinsic growth rate |
| Mortality or Survival | Species flow<br>Decreasing stock through deaths of natural causes | Natural mortality |

| | | |
|---|---|---|
| | Possibly dependent on predation, competition, location, pollution, life history (e.g. age) | |
| | If exploited species<br>Species flow<br>Decreasing stock through deaths of anthropogenic causes (fishing)<br>Possibly dependent on harvesting, gear used (e.g. size selectivity), catchability, location, type of species | Fishing mortality |
| Recruitment | Species flow<br>Increasing stock through offspring<br>Possibly dependent on fecundity of female, sex-ratio, reproduction success, maturation, abundance, location (habitat, physical conditions), predation success, competition, | Constant, proportional or density dependent |
| **Spatial population parameters** | | |
| Distribution | Spatial state variable<br>Location-based abundance<br>Dependent on habitat preferences/ movement | Prespecified distribution<br>Time-dependent variation in distribution<br>Joint dynamic species distribution models (JDSDM) |
| Movement | Spatial flow: emigration and immigration<br>Changing distribution due to migration or dispersion<br>Can be assumed equal for non - spatial models | time-invariant (dependent e.g. on currents)<br>dynamic movement (dependent on e.g. on seasonally or evolutionary migration) |
| Habitat (quantitative) | If implicit spatial implementation | Preferred habitat (distribution probability), location-based productivity (matrix of spatial variability in productivity) |
| Habitat (qualitative) | If quantitative/explicit spatial implementation | Biotic: Mangroves, Sea grass, coral reef,<br>Abiotic: Temperature, salinity, currents, sediment types, topography,<br>Connecting term in population function |
| **Multispecies population parameters** (see also species types) | | |
| Predation | One-way: either predator effecting preys' survival OR prey effecting | Abundance of prey effect reproduction success/survival of predator OR abundance of predator effects natural mortality/survival |

| | | |
|---|---|---|
| | predators' growth (latter less common) | of prey (see e.g. (Punt et al. 2016; Angelini et al. 2016) |
| | Two-way: principles of conservation of matter<br>predator effecting prey's survival AND prey effecting predators' growth | Abundance of prey effect reproduction success/survival of predator and abundance of predator effects natural mortality/survival of prey (see e.g. (Cissé et al. 2013; Thorson, Adams, and Holsman 2019) |
| Prey preference | Dietary preference of predator for one prey over another | Predation pressure<br>Diet matrix |
| Competition | Interactions between species of the same trophic level competing on same resources | Abundance of competitor A effects reproduction success/survival of B and vice versa (Thorson, Adams, and Holsman 2019)<br>Declare the benefitting species |
| Uncertainty:<br>Functional response | functional form used to represent predation-based feedbacks (Plagányi et al. 2014) | Diet data (not recommended as data-driven)<br>Statistical:<br>- Functional response types (Hunsicker et al. 2011)<br>- Generalized functional response curve |
| **Parameters though ecosystem and human linkages** | | |
| Ecosystem conditions | If non spatial, ecosystem conditions affecting the stock | Abiotic and biotic factors, climate zone, |
| Ecosystem variability | Changing ecosystem conditions | Climate change, seasonal (e.g. through changing temperature) |
| Human behaviour | Impacting fishing mortality | Harvest:<br>Fishing mortality, term for harvest (often In relation to size of fish)<br>Harvest and non-harvest zones<br>Gender-specific<br>Cultural |
| | arising from shared impacts of fishing activities | Technical interactions |
| | | Fleet dynamic (FCUBE, Doyen et al. 2017) |
| Institutional | Regulations, laws and organisations | Non-harvest-zone, maximum sustainable yield, |

# 5. Application example: OctoPINTS

This chapter uses the OctoPINTS[13] project to show how the guidance developed in Chapter 3 can be applied to a specific example. The project is introduced briefly and an interview with Dr Emilie Lindkvist[14] is evaluated. To conclude, a resumé is drawn.

## 5.1. Introduction to the Project OctoPINTS

The OctoPINTS is a project for octopus' fisheries in the Western Indian Ocean. Octopus are of high value in these areas due to their rapid growth and high market value which result in quick payoffs. To meet SSF challenges, communities and NGOs in East Africa are adopting periodic octopus closures[15] as an innovative way to balance livelihoods and sustainability (OctoPINTS 2020). The closures started spreading in 2004 in Madagascar in the Western Indian Ocean with successful outcomes in raised incomes at the community level due to advantages Octopus provides (Westerman and Benbow 2013). The closures are further of interest due to their novelty, their catalytic quality for co-management, the gender dynamics they entail (with women as the traditional octopus hunters), and the obscurity surrounding their long-term impacts for ecological sustainability and human wellbeing. The diversity of actors including fishermen, fisherwomen, traders, exporters and women processors, all stand to be affected differentially from these interventions (Rocliffe and Harris 2015).

By developing an agent-based model of a general octopus closure, OctoPINTS attempts to build a generic understanding of how octopus closures affect different social groups that depend on fishing as well as the ecological improvement and community cohesion. To meet this aim, a stylized empirical model needs to be developed that contains the relevant ecological complexity in relation to how the social system uses the resource but also the key underwater dynamics. Within the project, the approach will be exemplified by case studies of fishing communities selected at different stages of the adoption of the closure model in Zanzibar. Hereby, the main mechanisms and processes taking place at different points in time shall be identified.

For more information visit the projects website: https://octopints.wordpress.com/

[13] OctoPINTS project - Navigating the complexity of small-scale fishery interventions: An intersection of agent-based modelling; see https://octopints.wordpress.com/

[14] Contact person of the PctoPINTS project; has a PhD in sustainability sciences, and has been working with stylized models in interdisciplinary contexts.

[15] Periods when fishing is not allowed at certain locations

## 5.2. Questionnaire, Interview with Dr Emilie Lindkvist

As marked in section 4.1 the first step in model development is to reflect on some project-related questions. During the interview with Dr Lindkvist on 25 May 2020, the “first step” questions from section 4.1 and the questionnaire from section 4.3 were answered for developing the ecological side of the model for the OctoPINTS project. Below, first are the results of the questions and then the filled-in questionnaire (Figure 17) is presented.

1. *What is the goal of the study? Why is the development of the model important? What should it contribute?*

Some of the aims are already summarized in section 5.1. Specific questions asked in the project are:

- What factors and processes such as gender, perceptions of closures and closure locations, will allow the fishing community to evolve towards equitable and sustainable outcomes?
- What are common trade-offs between human-wellbeing, ecological health, and gender equity for short- and long-term outcomes?
- How can actors in the fishing community adapt their behaviour (e.g., trade- and fishing arrangements) to become more resilient towards shocks and pressures?
- What is the nature of decision-making and benefit sharing from octopus closures for different actors involved (e.g. small-scale male traders, women processors, large male exporters)?

The project set out to contribute to understanding the interactions between biophysical and human processes, as well as those related to human behaviour, towards building a general understanding of why, and why not certain drivers of change (e.g., closures) lead to more equitable and sustainable outcomes.

2. *Which resources are available (e.g. data, sources[16], financial, knowledge, cooperation, computing power)?*

SSF in low-income countries are in general rather data-poor systems, and financial resources as well as computational power are usually limited. Since this project is in cooperation with different universities and local organizations, these limitations can be compensated in some areas and access is gained to the following existing data:

- Social science:

[16] including sources detailing relationships between environmental data and biological processes.

    - In-depth interview data from three different fishing communities around closures from different social groups (male divers, women foot fishers etc.), collected within OctoPINTS.
    - Expert knowledge from local organizations.
- Ecological:
    - Landings data on Octopus weight, length and gender before and after closures across several sites.
    - GIS data on fishing areas
    - Previous models: Octopus growth models e.g. (André et al. 2009)

3. *Do the available resources satisfy the models objective? If not: how can simplifications, assumptions, estimations, and tools tackle these issues?*

Since many experts are available for parameter estimations, it is assumed that the question can be adequately addressed with the available resources.

4. *What is the simplest model addressing the issue?*

See 5.3

5. *What are the systems boundaries?*

The model will represent one fisheries community/village but account for external drivers such as incoming neighbouring fishers and change in global price structures (weight and size based).

6. *How to keep the model as simple as possible?*

Link tightly to the aims and RQs of the project. To measure certain outcomes, one needs to include enough detail to do this, with respect to habitat/spatiality, octopus growth, spatial “access”, effects of closure on the species etc.

The filled-in questionnaire is shown in Figure 17.

| Implementation | Selection | #modules | Commen |
|---|---|---|---|
| Spatial environment | ☑ | 6? | add block 3, include Block 4 **#modules**-times |
| Multispecies | ☐ | ? | add block 2, include Block 1 and 4 **#modules**-times, |
| Ecosystem | ☐ | | include block 3 (spatial environment; qualitativ) |
| Human behaviour | ☑ | | include block 6 |

| Block | | Questions | | Selection | | | | Comment |
|---|---|---|---|---|---|---|---|---|
| **1** | | **Type(s) of Fish - overview** | | species 1 | species 2 | species 3 | ... | see #modules_multispecies |
| | .1 | species name/aggregation | | Octopus | | | | |
| | .2 | trophic level | | - | | | | not needed, as no species interactions |
| | .3 | growth velocity | | fast (exponential) | | | | |
| | .4 | life history traits | | maturation<br>weight/size gain<br>female/male ratio | | | | sex ratio --> reproduction ?, weight increase?<br>Maturation: harvest of adults, closed reefs during growth; reproduction size/weight-selectiv harvest (number and biomass) |
| | .5 | resident/migratory? | | assumed to be resident | not yet decided | not yet decided | not yet decided | maybe movement offspring-matured; but neclected as only harvest of adults and probably marginal |
| | .6 | habitat | | reefs with cleaves | | | | |
| | .7 | species specification | Prey | ☐ | | | | if multispecies |
| | .8 | | Predator | ☐ | | | | if multispecies |
| | .9 | | Competitor | ☐ | | | | |
| | .10 | | Cannibalist | ? ☐ | | | | |
| | .11 | commercial value | target species | ☑ | | | | consequentally fishing mortality |
| | | | associated species | ☐ | | | | |
| | .12 | data availability | | not yet answerable | | | | |
| **2** | | **Species Interaction** | NOT considered | general | species 1 | species 2 | species 3 | see #modules_species |
| | .1 | predation: one-way | prey-predator | ☐ | | | | |
| | | | predator-prey | ☐ | | | | |
| | .2 | predation two-way | | ☐ | | | | |
| | .3 | cannibalism | | ☐ | | | | implement life-stages |
| | .4 | competition | | ☐ | | | | |
| | | | Species competing: | ☐ | ☐ | ☐ | ☐ | |
| | .5 | prey preference | | | | | | if 2.7 = prey and #prey > 1; for each prey species |
| | .6 | functional response | | | | | | to account for uncertainty |
| **3** | | **Spatial environment** | | general | space 1 | space 2 | .... | see #modules_spatial |
| | .1 | grid-based | | not yet decided; seafloor in meters, distance from shore, ocean depth, and reef quality | | | | |
| | .2 | ordinate-based | | | | | | |
| | 3 | qualitatively | | ☑ | | | | descriptiv |
| | .4 | quantitatively | | ☐ | | | | biophysical parameters |
| | .5 | Parameters | | | - **ocean depth** (2stages: foot-huntable-diving)<br>- **reef quality**/providing homes (3stages: good, medium, bad)<br>- **open or closed areas** (harvesting yes/no)<br>**--> matrix for distribution (and productivity)** | | | matrix of productivity can also contain the same recruitment/growth rate for each location |
| | .6 | Variability | | | | | | |

| | | | space 1 | | space 2 | | |
|---|---|---|---|---|---|---|---|
| **4** | **Stock Assessment** | | species 1 | species 2 | species 1 | species 2 | see #modules_spatial<br>see #modules_species |
| .11 | temporal resolution | | daily - weekly | not yet decided | not yet decided | not yet decided | see block 1 |
| .12 | stock resolution | species-based | ☑ | | | | see 1.11 |
| | | functional group | ☐ | | | | |
| | | structure | weight/size, age, sex | | | | weight-age-relation, maturation at certain age |
| .13 | type of abundance | biomass | ☐ | | | | |
| | | number | ☑ | | | | |
| .14 | species state variable | abundance | yes, see 4.16 | | | | |
| | | carrying capacity | not yet decided | | | | if production model |
| .15 | species flow | recruitment | yes, possibility of habitat-dependent recruitment | | | | see block 1 and 2 |
| | | fishing mortality | yes, time-dependent (open/closed reefs, fishers compliance) fishing method/location-specific | | | | if stock is exploited |
| | | natural mortality | yes | | | | see block 1 and 2 |
| | | growth | yes (weight based) | | | | see block 1 |
| .16 | spatial state variable | distribution | yes, dependent on reef quality | | | | see block 3 |
| .17 | spatial flow | movement | no | | | | see block 3 |
| .19 | method to account for uncertainty | | not yet decided | | | | e.g. MCMC, maximum likelihood |
| **5** | **Human behaviour** | | | | | | |
| .1 | technical interactions | | not important | not yet decided | not yet decided | not yet decided | |
| .2 | further information on how the species are caught | selectivity | yes, but dependent on compliance | | | | |
| .3 | | catchability | yes, dependent on distribution of animal and equipemnt/fishing method | | | | |
| | | commercial interest | high | | | | |
| .4 | | other | poaching and allowed fishing | | | | see 1.11 |
| .5 | who is catching? | | diving: men<br>foot-hunted: women, children, old men<br>poaching and allowed fishing is also done by neighboring villages or migrant fishers | | | | fleets, community( here: **village**, genders,... |
| .6 | fishing method | | - diving<br>- foot-hunted | | | | |
| .7 | equipment | | not important (wooden sticks) | | | | |
| .8 | instituional | | - closed and open reefs<br>- women first<br>- size-specific catches<br>--> degree of compliance? E.g. cultural as small octopus are lucky charms | | | | regulations, laws, organisations |

***Figure 17.*** *Completed questionnaire for the ecological part of the project OctoPINTS*

## 5.3. Recommendation summary

The ecological side of the model is the spatial explicit single-species stock assessment of octopus. Hence answering “Selection of system component/entities” (task A) and “Number of modules/entities” (task B), result in the chosen entity species (octopus; #modules_species = 1) and the different spatial environments implemented (three different reef qualities and two different accessibilities; #modules_spatial 2*3 = 6). Then differentiated into reef quality (good, medium, bad) and distance from shore (accessible via foot, not accessible via foot).

The choice of temporal resolution (task C) is daily, as processes like octopus fishing, poaching, and patrolling, as well as open or closing reefs can change on a daily basis. In addition, octopus are very fast growing and require shorter temporality than many other species that can be implemented with yearly growth. For the spatial resolution I recommend implying different resolutions for the two different characterisations accessibility and reef quality. For accessibility I would suggest dividing the whole area into these two conditions, where a resolution in the kilometre range is likely sufficient. For reef quality, which could be implied as a couple of cells next to each other (grid-based) or a polygon drawn on a map, a finer resolution, likely in the meter range is more accurate. The resolution of the species itself is species-based structured into the aspects of age and weight, maturation as well as sex. Age and corresponding weight are important as there can be regulations stating ‘to only fish octopus at a certain age/weight’ that may interfere with traditions in fishing smaller Octopus. Sex structuring is also important, as growth of octopus is sex dependent.

“Characterisation of the component(s) by attributes and quantifying state variables and rates/flows” (task D) results in the need to incorporate the following parameters:

- Abundance / distribution displayed in number of octopus and spread out in the mentioned structure
- Recruitment (dependent on matured female animals)
- Growth rates (indicating the biomass increase individual animals will have over time)
- Natural Mortality
- Fishing mortality (dependent on age/weight, location and octopus closures, poaching)

As including a species structure is mandatory (see task C), methods such as the surplus production, or simple difference-delay models are not serving the models purpose. At minimum a structured age/weight- space model must be chosen. It is suggested to find published octopus growth models and build your models from those.

“Integration of species interactions” (task E; if #modules_species > 1) will not be implemented as it is a single-species assessment.

Instead the integration of spatiality (task F; if #modules_spaces > 1) is especially important as the stay of the octopus has an effect on how the animals are harvested (by foot or by diving). At time of writing, no decision is made on the method of depicting the area (ordinate-based or grid-based.). However, it can already be determined that defining the spatial environmental qualitatively by describing the sites, serves the best purpose. Hence, no real abiotic or biotic data is used to classify the locations.

In addition to site characterisations that are permanent, such as reef quality and accessibility, there is also a characterisation that changes overtime, namely the octopus closures, will affect the different spatial environments. The distribution of the octopus is dependent on the quality of the reef and will be set at the beginning. Furthermore, the accessibility will affect the fishing mortality as well as the time-dependent aspect of closures.

As the model focuses on the effect of closures on different social groups that depend on fishing, besides the ecological improvement and community cohesion, it is of major significance connecting the ecological environment with the social environment. This is part of the final task (G); linking ecosystem human behaviour and social and economic institutional to population and habitat parameters. Which individuals are caught (and how) is dependent on the selectivity and the catchability of the individuals as well as poaching vs. allowed fishing. Two different types of fishers can be identified. Fishermen who dive to deeper areas and fisherwoman, children and old men, who harvest close to shore, where the water is shallower. Poaching and allowed fishing is also carried out by fishers from neighbouring villages.

Regulations that are under investigation are octopus closure and size specific catches, as well as regulations on how to strengthen the role of women in this sector by allowing them to harvest before men. Here, the degree of compliance is important to consider, as it is not certain if all fishers will adhere to the regulations or even are aware of the regulations, as fishers from different villages might migrate to the studied areas. Hence, fishing mortality cannot be ignored during octopus closures.

The to be developed OctoPINTS model belongs into the taxonomy spatial “*simplified SM”* (see 3.2). It does not follow the MICE approach, as MICE models that I found all include multispecies aspects. Models that can serve as inspiration are StrathSPACE, the MRM from Thorson et al. 2015 or the ABM from Carvalho et al. 2019, which also study closures. A summary of relevant ecological parameters for modelling OctoPINTS are listed in Table 12.

***Table 12:*** *Overview of conclusions of how to best implement the ecological part of the model.*

| **Summary Parameters Stock Assessment** | | |
|---|---|---|
| Structure | | weight-at-age<br>sex-ratio<br>space |
| State variable | Distribution | Matrix of Number of octopus (dependent on reef quality) |
| Flow | Recruitment | Matrix of number of birth (function of number female, fecundity, reef quality) function of age = 0; |
| | Growth | Sex- weight-time dependent |
| | Natural mortality | constant |
| | Fishing mortality | matrix incorporating human behaviour |
| Human behaviour | Compliance | Affecting fishing mortality |
| | Selectivity | |
| | Fishing method | |
| | Gender | |
| | Regulations | Octopus closure; affecting fishing mortality |
| Model insights | Approach | Agent-Based Modelling |
| | Method | Age-weight-sex-space structured population analysis |

# 6. Discussion

Within this chapter, the accomplishments of the previous chapters are discussed and interpreted and here. Included are solution suggestions how these can be minimized. Also, the goals of this thesis and answers to the research questions are considered. Furthermore, a short outlook on future work is given.

## 6.1. Challenges and Limitations

This section builds on the difficulties and limitations I faced while producing the results in chapters 3,4, and 5. The order will be synchronised with the thesis structure. First gathering of existing models will be discussed, followed by the analysis of creating a taxonomy including selecting suitable models and approaches, SSF ecosystem and SES modelling challenges, using MICE as a basis, including species interactions and a spatial environment as well as minding uncertainties.

### 6.1.1. Literature review to find existing models

The conducted literature review should find existing suitable models that support the process of developing a guide to formulate the ecological side of the SSF model. The research started with a review of SSF models, but it soon became clear that there are only a very limited number of SSF models that adequately implement ecosystem considerations. Therefore, the search was extended to fisheries and ecosystems in general, i.e. also to LSF models and marine ecosystem models. This search no longer followed a structured search, and as a result, and due to the large number of models available, the completeness of the model list is far from guaranteed.

Furthermore, and highlighted by highly case-specific dependencies, when looking for specific species or ecosystem characterizations, I recommend searching for specialized models that implement these conditions. This has the advantage that case specific implementation methods can be found, which instead of a general implementation of this problem, address the problem in a very practical way.

Despite, having this broad overview on existing models, as well as insights into different model types, already provides a great insight into the availability and possibilities of ecosystem modelling to fisheries and hereby helped answer the first part of research question A. (*Which fishery and/or ecosystem models exist?)*

### 6.1.2. Building a taxonomy of the models found as a basis for the selection process

As presented in 2.2.3, there are various ways for grouping fishery or rather ecosystem models into categories (Hollowed 2000; Plagányi 2007; Fulton 2010; Plagányi et al. 2014; Hyder et al. 2015; Collie et al. 2016; Plagányi 2016). None of these did fulfil the form of division I wanted, which is why I decided to develop my own taxonomy. Nevertheless, the available structuring approaches did help figure out the differences and common features that these models have. For example: number of parameters, methods applied, overall complexity or use in policy. The resulting taxonomy aimed to make it easier to get a quick overview of the different models collected, allowing, in a further step, to quickly select models that might be of high importance for SSF.A disadvantage of sorting based on previously applied structuring is that models are no longer viewed individually and are thus sorted out on which, on closer examination, could have perfect solutions for certain problems. Just because the model as a whole is quite complex, it does not mean that it could not apply simpler solutions in parts. For example, implying a highly complex food web does not exclude a suitable implementation of spatial environment.

Furthermore, the categorisation of models can be fluid, resulting in having a "rather simple" dynamic system model almost suitable to fit into the group of advanced SM. OSMOSE is a good example. OSMOSE falls into the category of "Whole of system/dynamic model" (Plagányi 2007) and "End-to-end ecosystem models" (Fulton 2010), both indicating very complex system dynamics. However, OSMOSE is by definition not a real food web model, although it can implement more than 10 species, and the relationship between spatial characterisation and population dynamics consist of rather simple assumptions (OSMOSE n.d.).

A consideration of the structural design of the models of each dimension (model realism/structure, species interactions, environmental drivers, and human behaviour/impact) could therefore be more appropriate than a blunt categorisation of the models. However, this could not be provided in this work due to the immense effort that would have been necessary. In order to partly tackle this issue, in addition to the taxonomy developed in 3.2 and the selection criteria in 3.3, a table was provided in the appendix (Appendix 1), which shows advantages and disadvantages of some models.

Furthermore, the given categorization into the use of the model (conceptual, strategic or tactical) could be of interest, as this question has a great impact on the way of modelling. For example, if the use is mostly educational, a quantitative model can fit the requirements. Quantitative or conceptual models are easy to build and often serve as the basis for further model development (Fulton 2010). If the goal is to identify a trend, strategic models are to be chosen. They are generally long-range, broadly-based and inherently adaptable (Plagányi 2007). Whereas in tactical models' knowledge about the current situation is essential and therefore the modelling must be adapted to short-term processes. Tactical applications of ecosystem models are extremely rare, as it is often not necessary or ideal to base tactical management consulting on the results of ecosystem models (Plagányi et al. 2014).

Nevertheless, the developed taxonomy enormously simplifies the clarity and crystallizes models that deserve a closer look in any case. The taxonomy and the subsequent selection process therefore help to answer the second part of research question A (How compatible are these for modelling the ecosystem for small-scale fisheries; what can we learn from them for an approach for SSF?). An additional major contribution is provided in section 2.2.5, which provides a literature review on implementation of the dimensions of ecosystem models, which also provides a basis for answering the next research question (B. How can relevant ecosystem dynamics be represented in models of small-scale fisheries, while retaining medium complexity?). The Answer to question B will be discussed further in 6.1.3 to 6.1.6.

### 6.1.3. Modelling challenges: ecosystem- and SES-based

It has been shown that the implementation of an ecosystem approach is not straightforward and varies greatly from model to model and from approach to approach. Especially with regard to the number of parameters, the decision on the resolution, the choice of compartments to be added and the linkages between them. Rather than choosing a model, type of model and approach etc. I recommend looking at the development of the dimensions of an ecosystem model (see 2.2.5) step by step, and decide for each model to develop ecosystem considerations individually. By introducing six tasks for the guidance of formalizing ecosystem considerations in SSF models in chapter 4, I have tried to take that advice to heart.

The challenges of ecosystem are based on the complexity of these models and that certain requirements must be addressed. These are:

- Constructing a variety of different models to address the full range of issues as no single model is capable of addressing all aspects.
- Implementation of certain aspects:
    - species and technical interactions,

- the changes in the species composition, e.g. through the fishing of other species or the introduction of non-indigenous species, and lastly
- the impact of physical/environmental factors on the resources.

The consequences of changes in the state of the ecosystem should be considered e.g. the success of regulations and action plans, habitat changes, human impacts alongside fisheries (FAO 2008). On top of the general challenges which ecosystem modelling entails, difficulties of modelling SSF, thus SES modelling issues are to be added (see 2.1.34).

The complexity of SSF imply that they are challenging for designing a model and that a good deal of experience, training or guidance is necessary to develop those kinds of models well, from their initial implementation, through to interpreting their output. SSF are very adaptive fishery systems including fisheries of multispecies as well as single-species, multi-gear and multiple fishing methods. They furthermore often migrate frequently from one area to another, but also there are resident fishers. The flexibility of these fisheries can be observed very well in multispecies fisheries, where the fishers switch from one species to another regularly, depending on reasons such as seasonally or abundance. This as well as the fact that they are often very migratory implies that different habitat types, including different habitat references of different species must be considered (changing spatial environment). The social aspects must not be neglected in these systems. Among other things, cultural aspects play an important role in most SSF. For example, this does often affect women to a greater extent than men because, as in the case of OctoPINTS, they are not able to harvest squid far from the shore. This underlines that for SSF, which are incomparable in their complexity, are particularly difficult to find adapted and pre-sorted approaches without neglecting specific aspects.

Adhering to the perspective of SES is obviously complicated. On the one side, attempting a holistic approach that does not give either side a focus, and on the other side formulating both sides adequately. Ultimately, the decision lies with the model developers and how they place the focus. It is impossible to consider all dimensions of the ecosystem itself plus the social system equally, and it is also not recommended in the literature (FAO 2008; Fulton 2010; Collie et al. 2016). Rather, it is recommended to modularize the ecosystem and then to depict the modules of importance in the model. However, this promotes the problem of a somewhat one-sided view, because if a developer approaches the model with a social focus, the focus will continue to be on the human dimension and its linkages. likewise, if an ecological developer approaches a model, the focus will be more ecological, as can be seen in existing models (social side:

bioeconomic models and ecological side: ecosystem models). Nevertheless, it is also apparent that knowledge in the importance of a holistic approach is gradually becoming more accepted in science (see this master thesis, as well as the Ecosystem Approach to Fishery, which is also recommended for SSF (SSF Guidelines), as highlighted by FAO (2015)).

When linking the developed advices for implementing the ecological side into formerly more social focused models, assuming that human impact human is limited to fishing rather than other impacts such as tourism, coastal development etc., contacting factors can be:

- Varying fishing pressure:
    - to different **species**, age- and/or size levels due to preference harvest or selective gear types or the effect of harvesting from one species on another dependent species
    - to different **location**, due to non-closure zones, difficulties of accessibility due to existing equipment, habitat types or governmental, cultural as well as gender-based regulations and the resulting adaptive behaviour of the resource
    - at different **times** e.g. seasonally due to cultural festivals or religious abstinence,
- Destruction of habitats, disruption of sensitive reproductive behaviour or behaviour adjustment of animals to the modified environment through e.g. coastal development, tourism or fishing activities.

Access to such experience will grow with increasing use of these kinds of models, but the aspects mentioned in this section should still be kept as a cautionary note for practitioners new to the field.

### 6.1.4. MICE as basis of the formalization guidance

The decision for taking MICE as the basis for formalising guidance of ecosystem modelling originated from the following arguments:

- MICE is a concept following a medium complex approach; hence the methods different MICE are introducing are per se not too complex.
- MICE is a recently developed concept (presented by Plagányi et al in 2014) incorporating the recent accomplishments in fishery research
- MICE is being directed to integrate human aspects to create a balanced SES.

- Designing a MICE follows certain rules and standards, resulting amongst others in complying with uncertainty issues as positively elaborated in Collie et al. (2016), see also 2.2.4.
- MICE incorporate advantages from both, traditional single-species assessments and whole system models.
- Rebuilding fish stocks: complicated by confounding between natural and anthropogenic sources of mortality --> MICE that have been used to understand the underlying process mediating stock decreases, as well as the timescale and likelihood of future recovery.
- Setting up a MICE depends on data-availability, although it is developed as a rather quantitative approach. Lack of data can be tackled by including statistical methods or uncertainty calculations.
- Coupling of MICE and other models for example hydrodynamic models is possible.

However, limiting oneself to this approach alone could lead to limited action, so I continue to refer to the collection of medium complex models and the research of models suitable for the present case studies. Furthermore, as MICE intend to “only” model a limited number of species (up to 10) and by prioritizing this approach as a basis I do not imply that a food web approach is to refuse For certain case studies implementing an aggregated or simplified version of a food web approach is possible, but in general this approach used in MICE is usually preferable as it sufficiently limits uncertainty. It has been demonstrated that more is not guaranteed to be better and that including a subset, instead of the entire food web, showed a strong performance without integrating all of a system’s ecological components (Fulton 2010).

### 6.1.5. Population realism

Population realism is composed of the temporary, spatial and taxonomic including species-specific structure (see 2.2.5.1). A recommendation for a medium-complex model cannot be given here, as it depends on several factors: the overall objective of the study, the number of total components included, data availability, available resources (knowledge, finances, computing power), etc. Nevertheless, I recommend not to use too complex an approach, such as the temporary resolution of the in vitro model (asynchronous approach to time management, where the time step for each component shifts according to the actions it performs) or even an adaptive time step, but rather a synchronous time step that is adapted for the different compartments. The resolution of the time step for species is usually additionally dependent on whether the species is fast or slow growing, whereas the time step should be shorter for a fast-growing species (Plagányi et al. 2014).

For the spatial resolution I rather recommend an implicit, i.e. qualitative spatial implementation, i.e. that the effect of space influences the affected component. For species in different areas or layers, this means, for example, that the growth parameters of a cell in a grid or patch will change, or that the distribution preference will be defined depending on which characteristic is assigned to which cell/spot, rather than being calculated directly by linking the specific properties within the growth/distribution function. However, it is also possible that a specific question may require an explicit linking of these components at the expense of simplifying other aspects, for example, if that very relationship is the focus of the study. Nevertheless, care should be taken to simplify the linking method, e.g. based on homogeneous (stationary physical conditions) rather than heterogeneous flows. In any case, for medium-complex models, an extensive environmental representation and spatial resolution in fine scale should be avoided for the time being. Nevertheless, distribution, movement and migration are important spatial parameters that must be directly or indirectly related to species, habitat or socio-economic specific or physical properties.

Regarding taxonomic resolution, the first question that arises is whether it is necessary to include the entire food web or whether the presentation of key species serves the purpose. The disadvantage of a food web approach in a medium-complex model is the need for increased aggregation of individual species, which in turn might overlook behavioural states. In contrast, the approach of implementing only key species in the model shows a strong performance, although not all ecological components of a system are integrated (Fulton 2010). Since most real populations have an ecological structure in terms of life stage, age, length, size or sex, the inclusion of these in the population dynamics could favour the outcome of the model (Plagányi et al. 2014). For example, harvesting juvenile fish can have an enormous impact on the entire population and then the fishery cannot be sustainable (Yonvitner et al. 2020).

In summary, in general, a method should be chosen that is not the most complex type of modelling. Furthermore, there will be conflicts of complexity if several compartments have to be implemented to achieve the study objective. Therefore, the implementations must be simplified to ensure the performance of the model. In any case, it cannot be argued at this point which structure is more important than another. For example, an age-based structure may be necessary if the predation concerns only juvenile fish, a size-based structure may be necessary if the fishing gear used is size-selective, and a space or area-based approach is necessary if different areas are represented where only different types of fishing are possible or where fishing is prohibited at all (Collie et al. 2016).

In particular, the information collected in Section 2.2.5 is a good starting point for model developers who come from disciplines other than ecological modelling. I also recommend using the FAO Technical Guidelines for Responsible Fisheries (2008) and the publication by Collie et al (2016).

### 6.1.6. Species interaction and spatial environment

Implementation of species interactions and spatial environmental considerations were the aspects focused on in this thesis and are, hence, now further discussed.

The dynamics of marine species are regulated by biological interactions such as predation and competition and are also influenced by technical interactions resulting from the joint impact of fishing activities. As a result, harvesting may have a direct impact on target species and may also indirectly affect interdependent species through changes in natural mortality and resource availability. The indirect effects of harvesting on non-target species can be counter-intuitive, and fisheries management requires information on these effects both to mitigate the impact of fishing on non-productive species and to identify management strategies that are expected to work well for a wide range of stakeholders (Thorson, Adams, and Holsman 2019). It was shown that species interactions have not yet been implemented in existing models. Although there were models that included several species, the interactions between them whether trophic or non-trophic could not be found (e.g. FishRent, FLBEIA, ISIS-Fish). This simplification is not only common in SSF models, but also in for example bioeconomic models for LSF. If species interactions are included, mostly only a one-way predation is implied (e.g. Punt et al. 2016; Angelini et al. 2016; SMOM; ESAM). Therefore, in this thesis, implementation options are given for the most common species interactions, predation (prey-predator as well as predator-prey) and food competition (as non-trophic interactions). These implementation options were taken from the MICE approach, which guarantees the adherence to a medium-complex model. Species interactions are a very complex feedback and are designed for data-rich scenarios. MICE also specify implementation options when data availability is a problem, which affects the uncertainties of the model (see 6.1.7). These uncertainties can be addressed by including functional response formulations that are designed either for the presence of nutritional data or for available theoretical functional response functions (Hunsicker et al. 2011; Plagányi et al. 2014). The feasibility of species interactions in SSF models remains questionable and should only be implemented if absolutely necessary. Nevertheless, this thesis provides possibilities how the implementation can be done while maintaining the overall reliability of the model.

Besides the competition for food resources, it would certainly also be interesting to implement competition for habitats. This brings me to the second important aspect to be implemented when integrating ecological aspects into models: the environment or related to the inclusion of multiple environments as spatial environments. Environments can either be defined quantitatively in form of biotic (habitats) or abiotic (physical) aspects or qualitatively. Models that do not take account of ecosystem changes due to spatial shifts may be less accurate in predicting the performance of alternative management practices, and in some cases may result in reduced performance when informing fisheries management (Thorson, Adams and Holsman 2019). Despite, the case of variable environmental aspects was hardly considered in this thesis, although they are particularly important in a changing environment due to climate change or human impact, but also seasonal fluctuations. For reasons of simplification, it was recommended in this thesis to use more qualitative descriptions of the environment, making links between biological and physical aspects. In other words, a more biological approach to the environment but a holistic ecological approach. For some models this may be sufficient, but in others, in which environmental variations are of particular importance, a quantified approach is essential and thus the implementation of this approach is beneficial. Furthermore, the choice of the spatial resolution on which the necessary processes can be adequately mapped is important. This requires a deep knowledge of such processes. There are physical models available that can be coupled to models that perform these tasks. When coupling, it is important to make sure that the input and output of the respective models' match. Such a coupling is envisaged in MICE and this approach will simplify the coupling.

The presentation of a spatial environment implementation, was compiled and provided in a form that can be understood and carried out by developers from other disciplines, as shown in the application example OctoPINTS. However, this approach is lagging behind with regard to the current and future strongly changing environmental conditions. It is probably not enough to apply current conditions to predictive models.

### 6.1.7. Uncertainty

In this thesis It has been regularly highlighted the importance of considerations of uncertainty. Nevertheless, it is not sufficiently known how to deal with uncertainties for ecological implementation in SSF models. Especially as SSF probably face uncertainties to a significant degree due their specifications and data poor nature.

Many factors may be needed in complex situations with multispecies, multiple stock areas, several fishing fleets, different fishing methods, regulations and community behaviour, and adaptation. Designing models for these highly complex systems, and limited data availability, intensifies the problem of structural and parameter uncertainty, while too extreme simplifications on the other hand intensifies model bias.

To counteract the parameter uncertainty, data from distant locations or taxonomic groups is often used. Here, the danger of creating a 'house of cards' is given. Such an approach is not generally unsuitable for theoretical exercises, but it is dangerous if a model is to represent a very specific ecosystem. Furthermore, there are considerable calculation problems when using very large models. For reasons of computational cost, uncertainty and efficiency, it is therefore not advisable to include details that go beyond what is necessary to deal with the subject in question. Models are reasonably complex when all critical processes, drivers and components under investigation are included (Fulton 2010). The modulation emphasized in this thesis by including only entities and feedbacks of all ecosystem dimensions of particular importance in the model, is a step towards tackling these issues (FAO 2008; Fulton 2010; Collie et al. 2016).

On some occasions I pointed out the necessary attention to the uncertainties, but how these can be implemented remains unanswered. Considerations of uncertainties is discussed in every model I examined and should, hence, be part of all models designed for SSF. Many publications address this issue and especially MICE has this issue high on its agenda, likewise EAF and end-to-end ecosystem modelling (Fulton 2010; FAO 2008; Plagányi et al. 2014; Collie et al. 2016).

## 6.2. Outlook into the future

After discussing the challenges and limitations I want to continue the discussion chapter by providing inspiration on further work within this focus of research.

This thesis is going to support the collaboration of fishery scientists from different disciplines by providing insights into ecological modelling through a guide of the formalization of ecological aspects. Next steps could be to create a counter-draft questionnaire from a social perspective, helping amongst others, ecological modellers to better understand the perspective from a social scientist point of view. Encouraging the collaboration of different disciplines is becoming more prevalent due to the recognition of the interwoven processes that interdisciplinary research entails.

Next to developing a guide for the social side, I suggest creating a guide for uncertainty assessment of SSF models. The reliability of the model results is dependent on the uncertainty of the parameter values and processes. Therefore, by adding new parameters, processes and/or feedbacks, the results can easily become extremely difficult to analyse or to understand. Especially because SSF are highly complex and data-poor systems, and these issues result in various forms of uncertainty (e.g. parameter, structure or implementation uncertainty), SSF face difficulties in formulating robust models. Notable at this point is, that there are organisations which are counteracting the problem of data availability in SSF, for example  the Hidden Harvest and the Illuminating Hidden Harvest Report (WorldFish, FAO, and Duke University 2018).

Ecosystems are not equilibrium or static systems and they are characterised by change, whether due to changing genetic structures and evolution, shifts in biodiversity, environmental shifts (e.g. changing climates, but also other environmental cycles and variability) or changing pressures in the system due to shifting human behavioural responses. Especially in view of the approaching climate crisis as an external driver causing greater changes and shifts in the ecosystem that even historical data is no longer relevant to current situations (as one of the few data sources existing). Therefore, the variability of the ecosystem has to be increasingly considered and implementation possibilities for future modelling activities have to be devised (Kittinger et al. 2013, Collie et al. 2016). In the context of the research field of ecosystem SSF modelling, this primarily means to better understand the link between environment and population, as well as the sensitivity of habitats, which requires integrating spatial heterogeneity into fishery models at fine spatial scale (Thorson, Adams, and Holsman 2019). Yet the implementation thereof is still underrepresented in models of medium complexity, - even for LSF being a sector already investigated in great detail due to its complexity. However, complex ecosystem models allow for instance, investigating the combined effects of climate change and fishing on the ecosystem revealed that the different response of fishers to climate change is due to the flexibility of fisheries. Very flexible systems may even see increase in income , while less flexible systems may see a decrease. (Lehuta et al. 2016). As a very flexible system, SSF could have an advantage here, but their deep roots with traditions could be an obstacle. Therefore, it would be important and interesting to look at these changes of the system within models.

It turned out that during the work many challenges had to be faced, but that nevertheless many ecological questions for SSF modelling could be answered. Furthermore, a contribution was made to combine different disciplines of fishery science. It also became clear that other exciting tasks remain. Finally, I am drawing the implication and presenting the contributions this thesis has within the last chapter.

# 7. Conclusion

Despite the fact that the development of ecosystem models as well as fishery models imply the considerations of both human and natural aspects equally, anthropogenic components are typically not greatly focused on in ecosystem models, whereas in fishery models ecosystem aspects are. It is compelling, that either way, one side is refined at the expense of other. This uneven treatment is unfortunate and represents huge issues that are necessary to achieve high quality research results. This is partly a result of an insufficient interdisciplinary approach and the semantic and philosophical divides between biophysical and social sciences (Fulton 2010).

This thesis underlines the importance of balanced coupling of human and natural systems and presents a guide for modelling the ecological aspects of SSF, as an example of a strong SES by directing the reader through the complexity of ecological modelling.

Although needed in models of SSF, the implementation of ecosystem aspects can easily reach a high complexity, for example, by trying to implement a complete ecosystem model instead of focusing on key aspects. This thesis addresses this problem by disentangling the representation of ecological aspects within the range of models of medium complexity. Firstly, to identify possible ecosystem aspects, I conducted a literature review to find existing ecosystem models and fishery models. Secondly, I clustered these models according to a custom designed taxonomy, in order to classify them regarding their suitability for modelling the ecological component of SSF. This preliminary work then served as a basis for the development of a guide for the formalization of ecological aspects tailored to SSF specifications.

The results show that several approaches and models can be considered when implementing ecosystem aspects depending on the objective of the study, and the availability of data and resources. In particular, I used the concept of Models of Intermediate Complexity Ecosystem Assessment (MICE) to formalize a modelling guide, since these models are inherently medium complex and adaptable to many different scenarios and aspects. In addition, both the best practice advice from FAO (2007) on ecosystem modelling and the knowledge collected in the previous two chapters (2 and 3) were incorporated in the modelling guide.

The diverse nature of SSF make it unrealistic to set modelling standards for SSF. In these systems, different and seasonally changing species are targeted using varying fishing methods and multiple gears within various habitats. Moreover, SSF have a unique complexity in social dynamics, hence, they are more complex and diverse than LSF. Furthermore, the ecosystems SSF are embedded within can vary to great extend around the globe. Ranging from complex tropical environments to simpler environments, like in temperate climate zones such as the Baltic Sea. This guide is thus an important contribution to navigating the difficult space in how to model these diverse and complex SSF.

Further, balancing model complexity is central, however deciding on the most important social and ecological processes is a difficult task. This decision is often biased by the model developer's personal preferences and disciplinary background. Ecological modelers would probably emphasize different key aspects than physicists or social scientists. Thus, the choices do not only depend on the ecosystem itself but also on the individual choices, background and preferences of the developer and the team involved.

Essentially, there is no general “best way” of constructing a model including ecosystem considerations, as the best practice is directly connected to the purpose of the model. In line with Collie et al. (2016), Fulton (2010); FAO (2008); Plagányi (2007) I recommend designing a model as simple as possible and as complex as necessary including:

- Not implementing extreme resolution in all dimensions
- Implementing only key compartments (e.g. species) and key interactions
- Applying constants rather than dynamics
- Using a qualitative description of the environment rather than a quantitative description

To meet these challenges, it is essential that scientists from different disciplines can meet on the same level and benefit from each other’s experience, accumulated knowledge and resources. Interdisciplinary studies, such as fishery science should form the basis for such collaborations.

The **main contributions** of this thesis are:

- To improve the understanding and accessibility of ecosystem modelling for modelers from other disciplines
- Designing a taxonomy of existing models and approaches of fishery and marine ecosystem models
- Developing guidance on how to model species interactions and a spatial environment in social-ecological models of medium complexity

Additional contributions are (i) a broad overview on how ecosystem extensions can be implemented into simple models including arising challenges and limitations, (ii) a selection of approaches suitable to support modelers to develop balanced social-ecological models of medium complexity (iii) to point out vulnerabilities and hardships in SSF modelling and (iv) an outlook on possible future work.

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# IX. Appendix

## i. Glossary

The glossary serves to clarify the meaning of complicated, new or possibly unknown terms. It is structured alphabetically, and the definitions provided are mostly not from my writing - I am, hence, not claiming to be the author.

*Capture fisheries*

Fishing for naturally occurring fish using a variety of fishing gears and methods (e.g. trawls, gillnets, purse seines, traps and barriers). The term “fishery” refers to harvesting fish that are farmed (aquaculture) or caught in the wild (capture fishery) (Staples et al. 2014)

*Coastal small-scale fishery*

Salas et al. (2017) set some common characteristics, which apply to most marine SSF in Latin America and the Caribbean (LAC):

- targeting of a mix of species using multiple types of boats and fishing gears, making it difficult to evaluate the state of the resources and the fishing intensity exerted
- low levels of capital investment by fishers, and the use of labour-intensive harvesting, processing and distribution methods to exploit the fishery resources
- a wide range of landing sites used by fishers along the coast (often in small communities), making it difficult to effectively record catches and fishing effort
- seasonal use of fishing resources, and fishing income that is often complemented by other economic activities (with the frequent presence of part-time fishers in the fishery)
- significant provision through fishing as protein and jobs for people in coastal areas
- attraction of migrant people to the coast in the search for income, with typically less investment needed to enter the fishery, in terms of capital and skills, or the option of becoming “workers” in private companies
- limited power of fishers to influence the fish market, given their small-scale capital commitment; and consequently, a greater dependence on middlemen for marketing and loans
- lack of social mechanisms for health and employment provision to the fishers.

*Ecosystem*

An ecosystem is a very complex structure with many interactive components. It can be defined as a relatively self-contained system that contains plants, animals (including humans), micro-organisms and non-living components of the environment, as well as the interactions between them (FAO 2003; Staples et al. 2014)

*Ecosystem Approach to Fishery (EAF)*

EAF aims to achieve a balance between different societal objectives by considering biotic, abiotic and human components of ecosystems and their interactions. It will apply an integrated approach to fisheries within ecologically sound boundaries, it is hence, a practical way to implement sustainable development principles. EAF is a risk-based management planning process that incorporates the principles of sustainable development, including the human and social elements of sustainability, not just the environmental and ecological components. While the term EAF can be misinterpreted because this name doesn't include the non-ecological components of sustainability, EAF not only deals with all the ecological consequences of fishing, but it also explicitly deals with the social and economic implications generated by the management and institutional arrangements related to fisheries. EAF includes conventional fisheries management and doesn't need complete knowledge about the ecosystem (FAO 2003; 2008; Staples et al. 2014; NOAA 2019).

*Ecosystem(-based) fishery management*

"The fisheries component of ecosystem-based management but focused on a single sector. EBFM considers both the impacts of the environment on fisheries health and productivity and the impacts that fishing has on all aspects of the marine ecosystem. Often used interchangeably with an ecosystem approach to fisheries management (EAFM)" (Staples et al. 2014).

*Ecosystem(-based) management*

A management framework that integrates biological, social and economic factors into a comprehensive strategy aimed at protecting and enhancing sustainability, diversity, and productivity of natural resources. EBM emphasizes the protection of ecosystem structure, functioning and key processes; is place-based in focusing on a specific ecosystem and the range of activities affecting it; explicitly accounts for the interconnectedness among systems, such as between air, land and sea; and integrates ecological, social, economic and institutional perspectives, recognizing their strong interdependences. Often used interchangeably with the Ecosystem approach to fisheries (FAO 2003; Staples et al. 2014)

*Fishery management*

An integrated process to improve the benefits that society receives from harvesting fish. It includes the activities of information gathering, analysis, planning, consultation, decision-making, allocation of resources and formulation and implementation, with enforcement, as necessary, of regulations or rules which govern fisheries activities. The main aim is to ensure the continued productivity of the resources and accomplishment of other fisheries objectives (FAO 2003; Staples et al. 2014).

*Integrated ecosystem assessment*

IEAs are a way to better manage resources, and they provide a sound scientific basis for ecosystem fishery management. These assessments provide a structure to assess ecosystem status relative to objectives of different groups (e.g., fishing, recreation, energy production, shipping, agriculture, forestry, food, clean water), account for the holistic impact of management decisions, and guide management evaluations. IEAs consist of analyses that help resource managers make more informed and effective management decisions. For example, IEAs contain (NOAA 2017):

- Assessments of status and trends of the ecosystem condition, including ecosystem services.
- Assessments of activities or elements in an ecosystem that can stress it.
- Prediction of the future condition of the ecosystem under stress if no management action is taken.
- Prediction of the future condition of the stressed ecosystem under different management scenarios, and evaluation of the success of management actions in achieving the desired target conditions.

(NOAA 2019a)

*Integrated Management (IM)*

“The process of simultaneously and synergistically working towards multiple objectives and goals, rather than undertaking separate activities in parallel or sequentially. Integration is carried out at the scale of priority geographical or management areas. For governance, integration means working across sectors.” (Staples et al. 2014). IM “involves comprehensive planning and regulation of human activities towards a complex set of interacting objectives and aims at minimizing user conflicts while ensuring long-term sustainability” (FAO 2003)

*Large-scale fishery (LSF)*

“The sub-sector of a fishery typically operated by larger vessels equipped with large fishing gear and sophisticated technology and powered by large engines. Vessels can be owner-operated or owned by large companies.” (Staples et al. 2014)

*Small-scale/Artisanal fishery*

Defining SSF is not easy (Smith and Basurto 2019). They differ ecologically, organizationally, economically, culturally, and technologically, not just from one region to the next but often also from one type of fishery to another. They exhibit attributes that are often unique to a particular fishery or locality (FAO 2015). Hence, many definition attempts are simplifying the diversity of SSF, through the usage of reductionist definitions that focus on aspects that are most easily identified as small-scale, such as boats and fishing gear, the mobility of the fleet, the production method, the organisational levels and the distribution of the products (Salas et al. 2007; Smith and Basurto 2019). Some further characteristics worth mentioning:

- SSF are very adaptable, therefore they have been around since time immemorial (Smith and Basurto 2019)
- The boundaries of an SSF system are permeable. What happens inside small-scale fisheries is often due to what happens outside small-scale fisheries, which means that the problems facing small-scale fisheries are not necessarily caused by them (Jentoft et al. 2017)
- Many SSF are either self-managed through informal agreements or are co-managed through cooperation between fishermen, managers and scientists (Lindkvist, Basurto, and Schlüter 2017).

(see also → *Coastal small-scale fishery*)

*SSF Guidelines*

In its entirety: Voluntary Guidelines for Securing Sustainable Small-Scale Fisheries in the Context of Food Security and Poverty Eradication

The SSF Guidelines have the ambitious goal of supporting the development of small-scale fisheries and fishing communities through a human rights-based approach to fisheries that is socially and environmentally sustainable. Achieving this goal will require substantial support from governments, private enterprise, international donors and NGOs. A key element in building the case for this support is better illuminating the diverse contributions of these fisheries, and providing new evidence in a way that can be used by communities and advocates to make a strong case for investment in the sector (FAO 2015).

*Stock Assessment*

“A stock assessment is the process of collecting, analyzing, and reporting demographic information to determine changes in the abundance of fishery stocks in response to fishing and, to the extent possible, predict future trends of stock abundance.

Managers use stock assessments as a basis to evaluate and specify the present and probable future condition of a fishery” (NOAA 2018a).

### ii. SSF around the world – similarities and distinctions

SSF communities are distributed around the globe (FAO 2020f; Smith and Basurto 2019) and while the fish species involved, vessels and fishing methods, as well as management approaches are varying widely, they are sharing many similar issues, such as its underestimation in government, law, economics and science. Concerning e.g. resource use, community impact and policy. Likewise, strong similarities exist within constraints and challenges (see 2.1.3). To tackle these difficulties, experiences and development approaches of local characteristics should be shared and compared, resulting in a more general best practice.

First, reference is made to the regionally independent characteristics of SSF. The most striking similarity is that SSFs have generally been largely undervalued despite significant fishery resources, high local consumption and market importance, and a long history of use and impacts (Kittinger et al. 2013; FAO 2019; Jentoft et al. 2017; FAO 2020a; Guyader et al. 2013; FAO 2020e; 2020h). Possible reasons for this are the high heterogeneity of fisheries in the smallholder sector and its mobility and adaptability, which have posed considerable governance challenges everywhere In many cases, fishing activities, catches, values and impacts are relatively unrecorded by national or local administrations, and therefore trends in ecosystem and resource quality, small-scale fisheries production and their social and economic impacts, although known to be important, are not yet well defined. Another major problem related to the management of SSFs is the complexity of the sector and the lack of systematic studies. As a result, there is a lack of quantitative data and knowledge that can serve as a key requirement for the sustainable development of fisheries for the present and future well-being of the bio-ecological system, the human system and the management process (FAO 2020h; Guyader et al. 2013). Nevertheless, there is a steady global shift in policy focus, commitment, management and regulation towards more sustainable resource use and service provision. It is confirmed that SSFs contribute very strongly to most economies, rural and urban food supply, employment, trade and export (FAO 2020b; 2020a; 2020h).

Other similarities between regions are for instance the important role of Regional Fishery Bodies (RFB) within fisheries management, especially where shared stocks and fishing activities are involved. While RFB have often focused on the industrial sector and international access to fisheries, the importance of small-scale fisheries for resource use and social and economic impacts is increasingly recognised and incorporated more explicitly into policy and management approaches. Also at the international, intergovernmental level, conventions, agreements and strategic policy development in various thematic areas increasingly involve or even target small-scale fisheries and the communities dependent on them (see 2.1.2) (FAO 2020g).

After first dealing with the similarities between SSFs worldwide, the distinctions between different regions are addressed below. It should be borne in mind that there can be major differences not only between different regions, but also within regions.

Remarkable differences occur between developing and developed countries: in many developed countries of Africa and Asia, fish accounts for more than 50% of the total animal protein intake (FAO 2020f). Whereas globally fish and fish products account for only around 20% of animal-based protein consumption (Duke Nicholas Institute 2018). Additionally, a fundamental problem for most small-scale fishing families in developing countries is their comparatively low standard of living and frequent poverty despite decades of remarkable overall development of fisheries and national economic growth (FAO 2020f). It is expected that SSF in developing countries will play a significant role in the coming decades in reducing poverty, creating sustainable livelihoods and improving ecosystem management. Whether this potential will be realized depends heavily on how they are governed. Many SSFs around the world are either self-governed through informal arrangements or are co-managed through the collaboration of fishers, managers and scientists (Lindkvist, Basurto, and Schlüter 2017).

The United Nation’s Food and Agriculture Organization (FAO), characterizes these different SSF areas and divides them into the regions of Africa, Asia, Europe, North and Central America, Oceania and South America.

Starting with Asia: the Asian region is by far the most populous in the world, with the largest fisheries and aquaculture production and the largest markets for fisheries products. It is also the most important region in terms of employment, production and economic value of small-scale fisheries (FAO 2020b) - it is estimated that 90% of the people directly employed in small-scale fisheries work in Asia (FAO 2020h). A wide variety of methods and species are involved, with much of the production coming from productive tropical or subtropical mixed waters in inland and coastal areas, which are relatively resilient in terms of biomass, although the higher value species are often under great pressure (FAO 2020b).

In Africa, small-scale fisheries play a particularly critical role because they are highly dependent on the community and vulnerable to resource competition and conflict, lack of market power, health issues - including HIV/AIDS in particular - and problems of access to more comprehensive livelihood services. There are considerable challenges, not only in establishing and maintaining rights of access to resources and ensuring that they can be maintained, but also in securing the broader means of reducing vulnerability and access to public services, often in conditions where national economies and political processes are under severe pressure from resource scarcity and competing development needs (FAO 2020a).

In Europe, SSFs are represented in all European Union member states (Guyader et al. 2013), but the SSF sector is relatively small in most national economies. Still, it continues to be important in many coastal areas, particularly in more remote and less serviced locations, and continues to be the focus of wider political attention. These range of small-scale fisheries catch several highly valued species related to particular fleets and fishing methods (FAO 2020c). They are made up of relatively small fishing groups with a low degree of division of labour, and fish products are usually intended for local sale. Fishing is conducted relatively near to shore (Guyader et al. 2013). The sector displays a mix of traditional rights and cooperative fishing in coastal areas, often seasonal or part-time, and in some areas considerable capitalization and capacity development in the small commercial sectors. Recreational fisheries are also very important, particularly in inland waters, with major programmes of restocking and considerable economic weight. In the marketed sector the EU Common Fisheries Policy has had a particular role in ensuring cross-community access to fishing resources, while attempting to rationalize effort and manage stocks. This has resulted in a considerable reduction of effort, buyout of capacity, and increasing support of devolved and co-management approaches, derived in part from traditional models of fishing guilds, evolving to producer associations with increasing focus on market development and optimizing catch value (FAO 2020c).

The North and Central American SSF is characterised by a strong traditional/indigenous focus in the northern parts of North America, with significant resource and management rights associated with fishing, a dynamic small commercial sector in most of the region and a rather mixed indigenous/imported small-scale fishery in Central America. An important feature of the North American region is the role of recreational fishing, which is usually highly regulated and licensed, but employs a significant number of vessels and has a significant impact on many fish stocks. In these generally prosperous areas, the value of fish as a recreational resource is many times greater than its corresponding commercial value, and policy objectives increasingly reflect this. This region is characterised by relatively good access to the major urban markets, with good transport links favouring the landing and sale of high-quality fresh produce. This area is also characterised by strong national policies and a strong political influence on resource and environmental management, and while this broadly favours small-scale selective fishing schemes, significant investment in stocking and enhancement, conservation pressures may result in more and more areas of the resource being subject to access restrictions (FAO 2020d).

In Oceania, the impact of foreign fishing is often very important, with policy challenges in securing adequate licence revenues, local value creation and avoiding potential conflicts with local fishing activities. In larger nation states, the context for small-scale fisheries varies widely, from traditional and relatively undefined and unregulated coastal fisheries in less developed economies to highly regulated fisheries that are increasingly based on quota management and the allocation of transferable rights and effectively privatize access. Throughout the region, transport and distribution issues are crucial in linking catches to high value markets. The region is also distinguished by its ecological importance, with a number of highly sensitive and globally valued ecosystems and habitats for whose protection and conservation there is increasing international support (FAO 2020e).

South America is characterized by its highly productive coastal fisheries which, together with the large river/estuarine system of the Amazon basin and a number of smaller river systems, lakes and wetlands, represent a vast resource that is largely exploited by a variety of small-scale fisheries It is a mixture of artisanal and small commercial fisheries with a wide variety of ecosystem conditions, fish and shellfish species, fishing methods, markets and management characteristics (FAO 2020h). SSF catches, here, are a particularly important source of food, employment and livelihood (Salas et al. 2007).

## iii. Associated sources of the models found

In the table (Appendix 1), the sources that were used for processing in chapter 3 are listed.

***Appendix 1:*** *Extension of Table 5 by associated references of the named models.*

| No | Acronym | Name | Sources |
|---|---|---|---|
| 1 | APECOSM | The Apex Predators ECOSystem Model | Fulton 2010; Maury 2010 |
| 2 | ATLANTIS | ATLANTIS<br>Version: 6425 (2019) | (Plagányi 2007; Fulton 2010; Hyder et al. 2015; Nielsen et al. 2018)<br>https://www.masts.ac.uk/research/marine-ecosystem-modelling/model-summaries/,<br>https://research.csiro.au/atlantis/ |
| 3 | B SEA ECON-ECOL | Baltic Sea Ecological-Economic Optimization Model | Nielsen et al. 2018 ; Voss et al. 2019 |
| 4 | BEMEF | Bio-Economic Model of European Fleets (extended EIAA) | Nielsen et al. 2018; Carpenter, 2015 |
| 5 | BORMICON | BOReal Migration and CONsumption model | Plagányi 2007 |
| 6 | Bioenergetic/ Allometric Model | Multi-species trophodynamic model using bioenergetic and allometric approach | Plagányi 2007 |
| 7 | CCSSM | Coupled Community Size-Spectrum Model | Hyder et al. 2015,<br>https://www.masts.ac.uk/research/marine-ecosystem-modelling/model-summaries/ |
| 8 | DISPLACE* | Individual Vessel-Based Spatial Planning and Effort Displacement<br>V.1.0.3 (2020) | Nielsen et al. 2018;<br>https://displace-project.org/blog/<br><br>Francois Bastardie |
| 9 | ECO | Bio-Economic Module Connecting Ecology and Economy | Nielsen et al. 2018 |
| 10 | EIAA | Economic Interpretation of ICES Advisory Committee for Fisheries Management | Nielsen et al. 2018 |
| 11 | ELFSIM* | Effects of Line Fishing Simulator | Nielsen et al. 2018;(Little et al. 2009 |

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|---|---|---|---|
| 12 | EPOC | Ecosystem Productivity Ocean Climate model | Plagányi 2007 |
| 13 | ERSEM I+II | European Regional Seas Ecosystem Model<br>Version (2016) | Plagányi 2007, Hyder et al. 2015, https://www.masts.ac.uk/research/marine-ecosystem-modelling/model-summaries/; https://cordis.europa.eu/project/id/MAS20032<br>Contact: Prof. Icarus Allen |
| 14 | ESAM | Extended Single-species Assessment Models | Plagányi 2007 |
| 15 | EwE | Ecopath with Ecosim and Ecospace<br>Version: 6.6 (2019) | (Plagányi 2007; Fulton 2010; Hyder et al. 2015; Nielsen et al. 2018), https://www.masts.ac.uk/research/marine-ecosystem-modelling/model-summaries/<br>http://ecopath.org/ |
| 16 | FCSRM | Fish community size-resolved model | Hyder et al. 2015, https://www.masts.ac.uk/research/marine-ecosystem-modelling/model-summaries/ |
| 17 | FCUBE | Fleets and Fisheries Forecast Model | Nielsen et al. 2018 (Iriondo et al. 2008) |
| 18 | FIBE | Fisher Behavior Model<br>Version 1.0.0 (2020) | Contact: Dr Nanda Wijermans |
| 19 | FishMob | Fishers Mobility Models<br>Version 1.0.0 (2019) | https://www.comses.net/codebase-release/9e025075-af23-4acd-9fe2-18b4faba9c7c/ |
| 20 | FishRent | FishRent | Nielsen et al. 2018; https://fishrent.thuenen.de/ |
| 21 | FishSUMS | Strathclyde length-structured partial ecosystem model | Hyder et al. 2015, https://www.masts.ac.uk/research/marine-ecosystem-modelling/model-summaries/<br>https://www.strath.ac.uk/science/mathematicsstatistics/smart/marineresourcemodelling/researchtools/fishsums/<br>Contact: Dr Douglas C. Speirs |
| 22 | FLBEIA | Bio-economic Impact Assessment using Fisheries Library in R<br>Version 3.1.0 | Nielsen et al. 2018; Garcia et al. 2017; 2012 |
| 23 | GADGET | Globally applicable Area Disaggregated General Ecosystem Toolbox<br>Version 2.3.5 | Plagányi 2007, https://hafro.github.io/gadget2/docs/userguide/ |

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|---|---|---|---|
| 24 | GBFWCGE | Coupled Georges bank Food Web and Computable General Equilibrium Model | Nielsen et al. 2018 |
| 25 | GEM | Generic Ecosystem Model | Nielsen et al. 2018 |
| 26 | IAM* | Impact Assessment Model for Fisheries Management | Nielsen et al. 2018 |
| 27 | IGBEM | Integrated Generic Bay Ecosystem Model | Nielsen et al. 2018 |
| 28 | IMATSTRL | Integrated model for Australian Torres Strait Tropical Rock Lobster | Nielsen et al. 2018 |
| 29 | InVitro* | InVitro | Plagányi 2007, Fulton 2010 |
| 30 | ISIS-FISH | Integration of Spatial Information for Simulation of Fisheries Version 4.4.4.3 | Nielsen et al. 2018 ; http://isis-fish.org/v4/user/usermanual/introduction.html |
| 31 | LeMANS | Length-based Multispecies Analysis by Numerical Simulation Version (2019) | Hyder et al. 2015, https://www.masts.ac.uk/research/marine-ecosystem-modelling/model-summaries/ Contact: Dr Robert Thorpe |
| 32 | LIEM | Linear Inverse Ecosystem | Kones et al. 2009; Stukel et al. 2012; van Oevelen et al. 2010 |
| 33 | MAQ | Ecological Modelling of Multiannual Quota | Nielsen et al. 2018 |
| 34 | MEFISTO | Mediterranean Fisheries Simulation Tool | Nielsen et al. 2018 http://webco.faocopemed.org/old_copemed/en/activ/infodif/mefisto.htm |
| 35 | MIZER | Multispecies size spectrum ecological modelling in R Version 2.0 (2020) | Hyder et al. 2015 ; https://www.masts.ac.uk/research/marine-ecosystem-modelling/model-summaries/ |
| 36 | MOOVES* | Marine Object-Oriented Virtual Ecosystem Simulator | Plagányi 2007 |
| 37 | MSM | Multi-species Statistical Model | Plagányi 2007 |
| 38 | MSPM | Multispecies Stock Production Model | Nielsen et al. 2018; Horbowy 2005 |
| 39 | MSVPA and MSFoR | Multi-species Virtual Population Analysis and Multi-species Forecasting Model | Plagányi 2007 |

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|---|---|---|---|
| 40 | MULTSPEC | Multi-species model for the Barents Sea | Plagányi 2007 |
| 41 | NECLH | New England Coupled Lobster Model | Nielsen et al. 2018 |
| 42 | NPF BIOECON | Simplified Bio-Economic Model for the Australian Northern Prawn Fishery | Nielsen et al. 2018 |
| 43 | NPFTPBEM | Australia Northern Prawn Fishery Tiger Prawns Bio-economic Model | Nielsen et al. 2018 |
| 44 | OSMOSE* | Object-oriented Simulator of Marine ecosystem Exploitation Version 3.3.3 (2018) | Plagányi 2007 ; Fulton 2010 ; Duboz et al. 2010 http://www.osmose-model.org/object-oriented-simulator-marine-ecosystems |
| 45 | PDMM | Population-Dynamical Matching Model | Hyder et al. 2015; https://www.masts.ac.uk/research/marine-ecosystem-modelling/model-summaries/ Contact: Dr Axel G. Rossberg |
| 46 | POSEIDON | POSEIDON Version 6.2.2 (2020) | Burgess et al. 2018; Bailey et al. 2019; http://carrknight.github.io/poseidon/appendix.html https://oceanconservancy.org/sustainable-fisheries/poseidon/ |
| 47 | SEAPODYM | Spatial Ecosystem and Population Dynamics Model | Plagányi 2007; Fulton 2010; http://www.seapodym.eu/ |
| 48 | SEASTAR | Stock Estimation with Adjustable Survey observation model and TAg-Return data | Plagányi 2007 |
| 49 | SIMFISH | Spatial Integrated bio-economic Model for Fisheries (Wageningen University, NL) | Nielsen et al. 2018; Bartelings et al. 2015 |
| 50 | SMOM | Spatial Multi-species Operating Model | Plagányi 2007 |
| 51 | SRRMCF | Swedish Resource Rent Model for the Commercial Fisheries | Nielsen et al. 2018; https://www.agrifood.se/Files/AgriFood_WP20131.pdf |
| 52 | SS-DBEM-IOT | Size-spectrum bio-climate envelope model & input/output tables | Nielsen et al. 2018; Euro-Basin 2012 |

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|---|---|---|---|
| 53 | SSEM | Shallow Seas Ecological Model | Sekine et al. 1991 |
| 54 | SSSM | Species Size-Spectrum Model | Hyder et al. 2015; https://www.masts.ac.uk/research/marine-ecosystem-modelling/model-summaries/ Contact: Dr. Axel G. Rossberg |
| 55 | STOCH HCR | Stochastic Age-Structure Optimization Model + ITQ Wealth Model | Nielsen et al. 2018; Simons et al. 2014 |
| 56 | StrathE2E | Strathclyde end-to-end ecosystem model Version (2016) | Hyder et al. 2015; https://www.marine-ecosystems.org.uk/Resources/News/Development_of_the_StrathE2E_model, https://www.masts.ac.uk/research/marine-ecosystem-modelling/model-summaries/ |
| 57 | StrathSPACE | Strathclyde spatial population dynamics model | Hyder et al. 2015; https://www.masts.ac.uk/research/marine-ecosystem-modelling/model-summaries/ |

## iv. Advantages and disadvantages for models not suitable for medium complex SSF models

The list in Appendix 2 shows models that were excluded from the selection process of section 3.3. On the one hand, the disadvantages are presented (-), but in addition, advantages are also highlighted (+). The order is not is random.

***Appendix 2:*** *List of advantages and disadvantages of some of excluded models mentioned in Table 4 and in section 3.3*

| Acronym | Further Comments |
|---|---|
| *ATLANTIS* | - highly complex<br>- data intense<br>+ spatial explicit<br>+ environmental effects<br>+ age-structured<br>+ migration |
| *Bioenergetic* | - highly data driven<br>+ medium complex |
| *BM2* | Precursor of **ATLANTIS** |
| *IGBEM* | Superseded by **ATLANTIS** |

| | |
|---|---|
| *ERSEM /+//* | - mainly plankton model,<br>- no ecological structure<br>- limited fish dynamics<br>- highly complex<br>- data intense<br>+ link physical parameters, environmental processes and habitat |
| *EwE* | - highly complex<br>- data intense<br>+ spatial explicit<br>+ widely used<br>+ age-structure<br>+ consideration of environmental and physical effects |
| *SSEM* | - highly complex<br>- data intense<br>- Not suitable for broader questions related to the ecosystem impacts of fisheries.<br>- focus on lower trophic levels<br>+ model for coastal development |
| *SEAPODYM* | - highly complex<br>- data intense<br>+ for multispecies and multi-gear fisheries<br>+ spatial focus: implementing movement and habitat |
| *INVITRO* | - highly complex<br>- data intense<br>+ explicit inclusion of human impact further than fishery<br>+ data-intensity depends on agent-type selected |
| *OSMOSE* | - No physical or habitat processes, migration<br>- fixed functional response<br>- focus on secondary consumers<br>- highly complex<br>+ easy use<br>+ environmental effects<br>+ age-structure<br>+ spatial species interactions<br>+ simple individual predation rules<br>+ adaptable data demand |
| *MSVPA* | - highly data-driven |

| | |
|---|---|
| | - One-way feedback<br>- No spatial representation<br>+ age-structure<br>+ environmental considerations |
| *ESAM/Seastar* | - highly data-driven<br>- No consideration of further part of the ecosystem |
| *MULTSPEC* | Outdated |
| *BORMICON* | Incorporated as a special implementation of **GADGET**, only for Arcto-Boreal ecosystems |
| *MSM* | - for additional species_ data intense<br>+ Focus on a few species which often have data |