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Governance Relevant Insights on Harvesting in the Mesopelagic Zone

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SUMMARY

With the population growing and countries becoming more affluent, diets shift. These global dietary shifts contribute greatly to increasing greenhouse gas emissions because of their higher carbon and water intensities. This development is problematic considering both the growth in our global economy as well as our population. It is therefore crucial to find ways to reduce the impact of food systems.

The mesopelagic zone in the ocean has recently been found to host a vaster source of biomass than expected, however, designing harvesting policies poses a deep uncertain issue. The mesopelagic zone promises a new source for the human food supply chain, especially serving as fish meal for aquaculture. Aquaculture is currently the worlds' fastest growing food sector. However, unlocking the potential of the mesopelagic zone has challenges. The working of the mesopelagic zone and its ecosystem are still vastly unknown, as is the magnitude and variety of impacts harvesting might have on this. Moreover, the zone is located at a location beyond national legislation and still lacks overarching regulation.

To acknowledge this research gap, this study focuses on how robust decision making methods can support decision making on harvesting in the mesopelagic system. This is done by analysing the current governance arena, the working of the mespelagic zone, and finally applying these findings to a System Dynamics model and performing Many-Objective Robust Decision Making (MORDM). Ultimately, to understand possible mesopelagic futures and thus gain governance relevant insights on harvesting in the mesopelagic zone.

Exploring the model behaviour over a variability of plausible futures demonstrated that several uncertainties have a crucial impact on the mesopelagic system's best and worst case behaviour. It seems that profitability of mesopelagic harvesting relative to regular fishing is the most prominent indicator for collapses of the mesopelagic biomass. Additionally, factors concerning low food availability seem to be strongly linked to biomass collapse and vice versa. Moreover, reproductive parameters (e.g., a high female fraction of the biomass) as well as a high ratio of myctophidea to Maurolicus muerelli positively influenced the magnitude of food provision.

Furthermore, other noteworthy findings are that an optimal harvesting quota seemed to act as a balancing tool for profitability. Additionally, exploration of the uncertainty space clarified which uncertainties have the strongest influence when no harvesting limits are in place. The two most influential uncertainties are the profitability of mesopelagic fish versus regular fish and the type of risk reward mechanism. This finding reduces the uncertainty space for decision makers by clarifying which indicators to focus on and which uncertainties might not even be relevant to consider for decision making.

Moreover, it can be concluded that by harvesting according to the selected policies, the atmospheric carbon levels in 2100 would rise significantly enough to cause added pressure on the climate. This strengthens the call for considering climate change as well as biomass conservation when thinking about mesopelagic governance

In conclusion, this research found several governance relevant insights for harvesting in the mesopelagic zone. The set of policies and the insights they provided serve as a promising starting point for stakeholders to learn about harvesting in the mesopelagic zone. Considering the mesopelagic decision arena, this study shows that current marine governance is unprepared to manage the magnitude and variety of the impacts harvesting can have on the mesopelagic biomass and its carbon sequestration function. Also, this research strengthens the call for including the mesopelagic zone and its role in the climate in future governance. These findings facilitate a discussion between stakeholders, which was previously impossible due to the deep uncertain character of the mesopelagic zone. This study is a first demonstration of the added value of MORDM for decision making on an intricate system like the mesopelagic zone.

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Above all, I want to thank my friends and family. Many thanks to my parents, brother, and cousin on whose support and advice I can always count - especially thank you Felix, your help has been indispensable. Finally, special thanks to my friends who have provided me with motivation, but more importantly with much needed distraction.

Julie van Deelen,
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ABBREVIATIONS

CBD	Convention on Biological Diversity
COP	Conference of the Parties
DPS	Direct Policy Search
DVM	Diel Vertical Migration
EMA	Exploratory Modelling and Analysis
ESD	Exploratory System Dynamics
ESDMA	Exploratory System Dynamics Modelling and Analysis
GtC	Gigaton Carbon
IPCC	Intergovernmental Panel on Climate Change
KDE	Kernel Density Estimation
MF	Mesopelagic fish
MOEA	Many-objective evolutionary algorithm
MORDM	Many-Objective Robust Decision Making
MPA	Marine Protected Areas
MSY	Maximum Sustainable Yield
NBSAP	National Biodiversity Strategy and Action Plans
NDC	national implementation plans
PRIM	Patient Rule Induction
RDM	Robust Decision Making
RFMO	Regional fisheries management organisations
SD	System Dynamics
TAC	Total Allowable Catch
UNFCCC	United Nations Framework Convention on Climate Change
UNFSA	United Nations Fish Stocks Agreement

1 INTRODUCTION

As countries become more affluent, diets are shifting towards containing more meat and dairy (Popp et al., 2010). These global dietary shifts contribute greatly to greenhouse gas emissions (Tilman & Clark, 2014) because of their higher carbon and water intensities (Davies et al., 2016). This trend is problematic considering the global economic growth and population growth. It is therefore crucial to find ways to reduce the impact of food systems. Global dietary shifts towards lower meat consumption can reduce the negative environmental impact of the current global food system (Davies et al., 2016; Popp et al., 2010; Springmann et al., 2018; Tilman & Clark, 2014). The mesopelagic biomass has potential to contribute by providing fish meal for aquaculture, also since fish is found to be a low carbon food source (Sandison, 2021). Aquaculture is the worlds' fastest growing food sector (FAO,2018). At the same time however, the ocean itself is one of the largest carbon sinks on earth which function should not be compromised.

The mesopelagic zone, also referred to as the twilight zone, is the layer lying directly under the surface of the ocean, usually at about 200 to 1000 metres deep. About 1 to 0% of the sunlight reaches this layer. Recent studies found that the mesopelagic zone contains an unexpectedly vast biomass, as much as 2 to 19,5 gigatons (Hildago & Browman, 2019; Proud et al., 2019; StJohn et al., 2016). This is roughly 10 times as much as previously thought. This means the mesopelagic biomass makes up for about 90% of the global fish biomass (SUMMER, 2019). This new finding on the magnitude of the mesopelagic biomass has implications for global food supplies, and at the same time on climate change and marine ecology.

The newly discovered biomass has the potential to provide part of the solution for food security (StJohn et al., 2016) - the biomass equals 100 times the current annual global fish catch (Hildago & Browman, 2019). This means that if in one year just 1% of the mesopelagic biomass is harvested, the global annual fish catch would be doubled (StJohn et al., 2016). Besides posing a potential solution to the global food crisis by providing fishmeal the biomass could be used as pharmaceuticals and food supplements, for example due to its richness in Omega-3 oils (Hildago & Browman, 2019; StJohn et al., 2016). All these factors together underscore that this is a source that should not be overlooked. However, as learned from previous ocean exploitation (Hilborn et al., 2003), management of this source requires a sustainable approach to prevent this resource from exhaustion.

Fishing has an influence on not only the ecology of the ocean, but also on the oceans' storage capacity of CO2 (Cavan & Hill, 2020). The ocean functions as an immense carbon storage. Due to uptake of atmospheric carbon dioxide by the upper ocean layer the ocean controls the atmospheric carbon dioxide levels (Passow & Carlson, 2012). As much as 98.5% of pre-industrial carbon dioxide is stored in the ocean (Marinov & Sarmiento, 2004). In addition, it is found that the oceanic response to increasing carbon levels includes self-enforcing feedbacks, climate tipping points, and eventually irreversible changes (IPCC, 2019). All this underscores how the ocean acts as a cornerstone in the atmospheric carbon levels and consequentially climate change. At the same time, it shows that this immense carbon sink is in a vulnerable and uncertain state, which can have enormous and potentially disastrous effects on climate change (IPCC, 2019; Passow & Carlson, 2012). Understanding and then incorporating these dynamics in harvesting policies is crucial for managing this resource robustly, which can be defined as policies that perform well over different scenarios (McPhail et al., 2018).

Yet another challenge is to be found within the governance aspect of this case. Governing the twilight zone is challenging due to the fact that this resource is relatively newly discovered and is positioned at a location beyond national legislation (Hildago & Browman, 2019; ICES.dk, 2019), and therefore lacks overarching regulation (Gjerde et al., 2019). The potential of the mesopelagic biomass has sparked increased interest from several stakeholders in the use of the biomass (ICES.dk, 2019). Out of the interest in the commercial possibilities the European Commission has set up the Blue Growth Strategy. At the same time, countries like the United States are hesitant to exploit these commercial opportunities since there are no adapt management strategies in place yet. The same goes for organisations like the Pacific Council (Hildago & Browman, 2019).

The response of an ecosystem on the initiation of fishing in an unfished environment has shown earlier to be dramatic for the structure of fish communities (Jennings & Kaiser, 1998). It has been found that the biomass in lower trophic levels is more vulnerable to harvesting (Eide et al., 2019). This, in combination with the research gap regarding the functioning of mesopelagic biodiversity as an ecosystem service, and the lack of knowledge on the interconnectivity of mesopelagic organisms makes that previous harvesting policies on other marine ecosystems will not be sufficient for guidance (Hildago & Browman, 2019). This weak background for managing the resource is problematic, recalling the influence of mesopelagic fish on CO_2 concentrations (Anderson et al., 2019; Koslow et al., 2011; Passow & Carlson, 2012; Proud et al., 2019).

The complications of the current food system in combination with the critical role the ocean plays in climate change pose a dilemma in which trade-offs in carbon sequestration and food provision play part. The ambiguity of the mesopelagic ecosystem, climate change, and weak regulation present a problem linked to deep uncertainty (IPCC, 2019), meaning there is uncertainty about the working of the system and/or the external context of it (Marchau et al., 2019). All these factors cause the decision making arena in which possible governance options are positioned to be highly complex. Considering the described knowledge gap, the main outcome of this research will therefore be to inform decision making on harvesting in the mesopelagic zone. This research therefore aims to answer the following question:

What governance relevant insights does MORDM produce on decision making for harvesting in the mesopelagic zone?

It is critical that appropriate modelling is used to support decision making, considering the high potential of the mesopelagic fish as a food source and the deep uncertainty linked to marine ecosystems, harvesting, and climate change. As pointed out by earlier studies most existing models assessing impacts of fishing in marine ecosystems look purely at the effects within the ecosystem itself (Audzijonyte et al., 2013; Jacobsen et al., 2014), and not outside of one specific focus-area (Saba et al., 2021). Unification of perspectives from different areas like fisheries, food webs, and carbon sequestration pathways is necessary for novel and more complete insights (Saba et al., 2021).

Despite the high increase in research activity on the mesopelagic zone as a potential food source, much uncertainty remains about the working of the mesopelagic zone and its boundaries, making it a deeply uncertain system (Marchau et al., 2019).

Especially in terms of mesopelagic harvesting; there are some case studies and long-term monitoring studies on the effect of harvesting on marine ecosystems. However, there is not enough empirical data to successfully understand impacts on such a complex ecosystem (Jacobsen et al., 2014). In addition, there still is a lack of understanding on the role of marine ecosystems in carbon sequestration, especially for the mesopelagic zone (Brito-Morales et al., 2020; Cocco et al., 2013; Passow & Carlson, 2012; Robinson et al., 2010; Santora et al., 2017). Several ecosystem models like STRATHSPACE, SEAPODYM and NORWECOM.E2E have been developed to analyse the mesopelagic system. However, none of these model the complete mesopelagic biomass on a global scale, while including effects of harvesting pressures (bio.uib.no, n.d.; masts.ac.uk, n.d.; seapodym.eu, n.d.), while literature indicates a more thorough understanding of the interaction between mesopelagic fish and carbon sequestration is needed (Anderson et al., 2019) as well as understanding the consequences of harvesting mesopelagic fish (Hildago & Browman, 2019).

Considering the mentioned research gaps on the working of the mesopelagic system, its governance, and current modelling approaches, the main research question stated earlier is addressed by answering the following sub questions:

- *What is the decision arena for harvesting in the mesopelagic zone?*
- *How does the mesopelagic system work?*
- *How might this system evolve over possible futures given policy interventions and uncertainties?*

In order to answer the first sub question, literature research is done to better understand the governance situation and select a scope for the decision arena. The second question will include literature research as well, and expert consultation with ecologists. This literature research will help to comprehend the current knowledge and uncertainties of the mesopelagic system, using this to conceptualise and specify the mesopelagic system into a model fit for answering the main research question. Finally, for the last sub question a robust decision making method is selected, to study how this method could support decision making. This will act as a proof of concept showcasing the potential added value of a robust decision making method on this specific research case.

Structure of the document

The report is structured in the following manner. Chapter two presents the methods used in this study. In chapter three the decision making arena of the mesopelagic zone is analysed. Chapter four describes the working of the mesopelagic system, the resulting conceptualisation and validation of the model, and the set up for the SD model and MORDM. In chapter five the results are presented. Finally, the discussion and conclusion are presented in chapter six and seven, respectively.

2 METHODS

This chapter presents the methods that are used in this research. This research will use both System Dynamics (SD) as well as Exploratory Modelling Analysis (EMA). Combining these methods is referred to as Exploratory System Dynamics Modelling and Analysis (ESDMA) (Kwakkel & Pruyt, 2015). This approach combines the function of an Exploratory SD model to produce complex and plausible behaviour over time with the function of the EMA workbench to explore deep uncertainty (i.e. uncharacterised uncertainty) and robustness of policies. ESMDA allows for using the EMA workbench to systematically explore the possible dynamics of the ESD model over time (Auping, 2018).

Several ecosystem models like STRATHSPACE, SEAPODYM and NORWECOM.E2E have already been developed to analyse the mesopelagic system. As this study aims to model the mesopelagic system globally, over a longer time period, and including harvesting dynamics, a vast magnitude of uncertainty and complexity will need to be taken into account. Therefore, ESMDA is deemed to be most appropriate.

Similar approaches have been used to explore other complex and uncertain systems. For example, the FeliX model developed by IIASA is a system dynamics model that includes social, economic and environmental sub models and their interconnectivities (iiasa.ac.at, 2020). Also, the En-ROADS model represents the energy system in a simplified way. The model is build using SD and allows for scenario exploration. Another relevant example is the use of System Dynamics to model dietary shifts within a population. The SD model was used to identify the main mechanisms behind global diet change (Eker et al., 2019).

2.1 SYSTEM DYNAMICS

System Dynamics (SD) is a modelling method that builds models out of differential equations. In SD, these differential equations are visualised using stocks and flows. Stocks are defined by integral equations. Stocks change over time due to input and output, referred to as flows. An SD model typically also includes other parameters (i.e. constants or auxiliary variables). Between all these elements, positive and negative feedbacks can occur. The stocks also allow for modelling accumulation and delays.

The mesopelagic system is dynamically complex. The system for example contains feedbacks between mesopelagic fish, phytoplankton, and carbon sequestration, in addition to many delays, for example information delays between fisheries capacity and harvesting quotas, or risk perception of a decreasing biomass. Therefore, it is crucial to adopt a modelling method that allows to incorporate these characteristics of the system. Since the SD method entails constructing models out of differential equations, (complex) behaviours over time are inherently taken into account. SD is a method that is suitable for deep uncertainty as well, in the sense that it allows for incorporating for example parametric and structural uncertainties. A structural uncertainty within the mesopelagic system would be the vertical migration patterns of mesopelagic fish.

In addition, the suitability of SD for modelling a complex system like the mesopelagic system lies in relatively quick runtimes, flexibility in incorporating structural uncertainties and the holistic insights on system behaviour it can reveal. Exploring the impact of uncertainties can be done with Exploratory System Dynamics (ESD) models, which are often manageable and thus highly abstracted models (Pruyt, 2010).

The SD model is build up out of several sub models. The ecologic sub model is an expansion of the predator-prey model as proposed by Lotka-Volterra (Lotka, 1920). Additionally, this sub model is build by interviewing experts in the field of the mesopelagic ecology. The global carbon cycle is build using the description as stated in Chapter 3 of TAR-03 by the IPCC (2001). The harvesting, decision-making and oceanic sub models are build using multiple sources from literature.

2.2 EXPLORATORY MODELLING AND ANALYSIS

Initiating harvesting is expected to impact the dynamics of the mesopelagic zone (Hidalgo & Browman, 2019; Passow & Carlson, 2012). In order to form robust policy options, these uncertain impacts need to be accounted for. A fitting approach for this research is therefore an exploratory modelling approach (Bankes, 1993; Kwakkel, 2017). This is a method that mitigates the complexity and uncertainty of systems by performing many computational experiments (Bankes, 1993). The open-source Exploratory Modelling and Analysis workbench (EMA workbench) supports this approach. The EMA workbench allows to use existing models, identify patterns within systems, and iterate policies to avoid undesirable dynamics (Kwakkel, 2017). There are different approaches to use within the EMA workbench. The Many-Objective Robust Decision Making (MORDM) is one of these approaches and will be used for this research. The method is explained in the following section. Prior to performing MORDM, an open exploration is done.

2.2.1 Open exploration

Prior to starting the MORDM cycle, some open exploration analyses are done to analyse and validate the behaviour of the model. These open explorations are done for the base case of the system, two static harvesting quotas, and a case with zero harvesting. The base case of the model represents the system without any policy intervention. In other words, there is no limitation on harvesting throughout the entire run time. This is not a realistic scenario, however this will help to understand the behaviour of the model and gain confidence in the working of the model.

2.2.2 Kernel Density Estimation & Feature Scoring over time

Two other analyses are applied prior to the MORDM approach in order to reduce the number of uncertainties in the mesopelagic system as well as the run time. These two analyses are Kernel Density Estimation and Feature Scoring over time. Applying Kernel Density Estimation clarifies the outcome distribution of the different experiments throughout the simulation.

Feature scoring illustrates by which uncertainties the outcomes are driven the most over time. The higher the score of an uncertainty, the bigger the correlation between that uncertainty and the outcome at that time point. These two analyses will support in selecting which uncertainties are most relevant to include in the problem formulation.

2.2.3 Many-Objective Robust Decision Making

MORDM is an approach that combines many objective evolutionary optimisation and robust decision making (Kasprzyk et al., 2013). The method is considered adequate for analysing the mesopelagic for several reasons.

First of all, MORDM is in particular apt for complex environmental systems undergoing change (Kasprzyk et al., 2013). In addition, MORDM allows for dealing with multiple objectives, which is useful considering this issue includes trade-offs between for example food provision and carbon sequestration; MORDM includes optimising over the multiple objectives in order to find robust policies with maximised desirable outcomes. Lastly, the use of robust decision making techniques to find robust policies makes the MORDM approach suitable to mitigate deep uncertainty (Kasprzyk et al., 2013).

In contrast to MORDM, other Robust Decision Making methods of this type (e.g. Many-Objective Robust Optimisation (MORO)) often require higher computational effort (Bartholomew & Kwakkel, 2020), making them less suitable for this research.

The MORDM approach contains the following four steps (Kasprzyk et al., 2013). This cycle is usually executed in an iterative manner.

- **Step 1: Problem formulation**

  In this step relevant uncertainties, decision levers and objectives are defined.

- **Step 2: Searching for candidate solutions**

  In this step candidate solutions that create the most optimal outcomes are searched. These candidates are selected by searching over the lever space to find Pareto optimal solutions, or near Pareto optimal solutions (Kasprzyk et al.,2013). This search is done using a many-objective evolutionary algorithm (MOEA) to optimise over the lever space. For this research the e-NSGA-II algorithm is used as MOEA, which is an algorithm that efficiently searches the lever space by adapting the size of the set of policies over time by adding new policies.

  Also, the solutions are checked for convergence using epsilon progress as a convergence metric. Epsilon progress represents the advancement of adding new policies to the set. If adding policies does not bring more optimal solutions, convergence is reached.

- **Step 3: Generating scenarios & selecting robust policies**

  In this step, an ensemble of scenarios is generated to understand the impact of uncertainties on the candidate solutions that were found in step 2. A scenario can be defined as different combinations of uncertainties. Using robustness metrics, the solutions are then re-evaluated for their robustness over these scenarios. Different metrics measure different types of robustness, using numerous metrics is thus desirable (McPhail et al., 2018). In this research two robustness metrics are computed: signal to noise and maximum regret.

  The signal to noise ratio is a measure for the variability of the system, since it is computed by dividing the mean by the standard deviation. This metric is chosen because an ideal quota policy would have little performance variability over different scenarios. Maximum regret is a metric which measures the discrepancy between the performance of a policy in scenarios compared to performance in the best case scenarios (McPhail et al., 2018). An ideally robust policy would have a small discrepancy in performance for all objectives.

- **Step 4: Scenario discovery**

  By considering plausible scenarios, vulnerabilities of the candidate solutions can be detected, and solutions can be improved. Vulnerabilities of policies refer to combinations of uncertain parameters that produce a low performance of the policies. This is useful for decision makers since it demonstrates in which scenarios the policies might not be adequate enough (Bryant et al., 2010). For scenario discovery, the Patient Rule Induction (PRIM) algorithm is used (Friedman et al.,1999). For PRIM a threshold for an outcome can be defined, performance above or under that threshold is considered unsatisfactory performance. The algorithm then searches for uncertainties that have the most influence on producing this undesirable outcome. For the PRIM algorithm a value for alpha needs to be defined. By setting the alpha low, the algorithm peels of a smaller amount of the uncertainty space per iteration and is therefore able to define the values of impactful uncertainties with a higher precision. PRIM also requires a coverage threshold to be defined. The coverage threshold defines the percentage of undesirable outcomes the scenarios cause.

3 GOVERNANCE ANALYSIS

This chapter analyses the decision making arena of the mesopelagic zone. It presents the groups of stakeholders of the mesopelagic zone, the key overarching conventions, and the underlying decision making processes. The conclusions drawn in this chapter will provide insight on how to conceptualise and demarcate the model, especially the decision making sub model. Also, it serves to define the decision space for the exploratory research design.

3.1 RELEVANCE OF GOVERNING THE MESOPELAGIC ZONE

Interest in exploiting the mesopelagic biomass has increased the last few years due to its newly discovered potential (ICES.dk, 2019). The potential of the mesopelagic biomass lies first of all in the vastness of the source for harvesting fish meal. In addition, the biomass can be used for pharmaceuticals and food supplements. Blue growth strategies are adopted globally, pushing the interest for exploitation (St. John et al., 2016). Considering the impact exploitation could have on ocean carbon sequestration, it is crucial that adequate regulations are in place before large-scale exploitation starts. However, despite the thriving interest in exploiting this vast resource, mesopelagic fish have yet been ignored in marine management negotiations (Blue Marine Foundation, 2020).

Although mesopelagic fish exploitation is currently not yet economically viable (Prellezo, 2019), future developments make that management of these species should not be omitted. The fish have a low catchability due to their widespread and patchy distribution, and their effective trawl avoidance. Also the fisheries have high operating costs due to large amounts of fuel needed, in addition to the need to processes the catch (Blue Marine Foundation, 2020). However, triggers in the form of current and upcoming effort limitations on regular fisheries, growing fish and aquaculture markets, as well as technological innovation will presumably cause mesopelagic fishing to become more profitable in the future (Prellezo, 2019). Additionally, some mesopelagic species already are economically viable, like the Maurolicus muelleri, since these fish school together and are closer to the shore (Armstrong & Prosch, 1991).

Governing the mesopelagic zone is challenging. The areas in which the mesopelagic zone is located, often referred to as the high seas, are positioned at a location beyond national legislation (Hildago & Browman, 2019; ICES.dk, 2019), and therefore owned by no-one and everyone. The vastness of the resource increases the difficulty to manage it. In addition, the link between marine populations and oceanic carbon sequestration is often omitted in both marine and climate governance (Elsler et al., n.d.). The zone therefore yet lacks adequate regulation (Gjerde et al., 2019).

To understand the decision arena of the mesopelagic zone, existing global regulations will be analysed to understand the decision making processes and available management tools. In addition, primary stakeholders are identified in order to take major stakeholder groups into account. These findings can then be incorporated in the SD model.

3.2 OVERARCHING CONVENTIONS

The following section present the conventions that are most relevant for strengthening high sea governance. It is relevant to analyse the decision making processes taking place within these conventions, so this can be incorporated in the model.

Since mesopelagic fish play a role in carbon sequestration, governance of the mesopelagic zone should focus on both conserving marine biomass as well as on climate change. There are several overarching conventions and agreements in place that regulate one of these two aspects (Elsler et al., n.d.). The three most relevant for governing mesopelagic harvesting on a global scope are the United Nations Framework Convention on Climate Change (UNFCCC) which focuses on climate change, the Convention on Biological Diversity (CBD) which focuses on protecting biodiversity, and the United Nations Fish Stocks Agreement (UNFSA) which aims to conserve and manage marine resource exploitation.

3.3 DECISION MAKING PROCESSES

Since there are no specific regulations in place for the mesopelagic zone yet, the decision making processes do not currently take place specifically for the mesopelagic zone. However, the conventions include regulations with direct relevance for fisheries in the mesopelagic zone such as new and exploratory fisheries regulations (Caddell, 2018), and are thus relevant. An overview of the conventions and their objectives, actors, management tools, and decision making processes are presented in Table 3.1.

Table 3.1: Overarching conventions relevant for governing the mesopelagic zone

Convention	Objective	Actors	Management tools	Binding/Non-binding	Decision making process
UNFCCC	Mitigate climate change	National governments	NDC's: MPA, domestic fisheries catch	Non-binding	Yearly COP
CBD	Protect biodiversity	National governments	NBSAs: MPA	Non-binding	Bi-annual COP
UNFSA	Conserve & manage marine resource exploitation	RFMO	RFMO policies: TACs, MPAs	Non-binding	Two UN review conference in 2006 & 2010

None of the overarching conventions are directly binding. The UNFCCC aims to regulate climate change through the national implementation plans (NDCs) from the Paris Agreement. The UNFSA provides RFMOs with directives for marine exploitation. Lastly, the CBD is hosted by the UNEP and is implemented through National Biodiversity Strategy and Action Plans (NBSAPs).

The decision making processes differ per convention in terms of frequency of meetings, but are similar in process. Implementations are reviewed and assessed by all parties, followed by voting for possible changes in policies (CBD.int, n.d.; Leroy & Morin, 2018; Mofa.go.jp, n.d.). Orach et al. (2020) mentions a similar decision making process for fishery regulations. The process Orach et al. present additionally implies that external parties like fishing industries or environmental groups can influence decision making through lobbying. The management tools per convention are as follows:

- **UNFCCC:** Marine Protected Areas (MPAs) and domestic fishery quotas are implemented via national implementation plans (Gallo et al., 2017).
- **CBD:** Marine Protected Areas are implemented, as well as efforts made on public information, education and awareness, harmonisation of national policies, monitoring of threats, transfer of technology, and subsidisation for conservation practices (Chandra & Idrisova, 2011).
- **UNFSA:** Total Allowable Catch (TACs), Marine Protected Areas, bycatch regulation, data collection, reviewing of TACs, regulation of illegal fishing, conservation plans are implemented via RFMO policies (Pentz et al., 2018).

The two most used management tools for fisheries are harvesting quotas and marine protected areas, as can be seen in Table 3.1. Since the high seas are so enormous, they comprise 43% of the Earth's entire surface (Blue Marine Foundation, 2020), marine protected areas will not be adequate in protecting the fish. In this research, it is therefore assumed that the mesopelagic fish will be managed by a harvesting quota in the future.

3.4 STAKEHOLDER GROUPS

Since voting is influenced by lobbying of interest groups, the following section identifies the stakeholders that are linked to exploitation of the mesopelagic zone. Two main groups with opposing interests were identified: an industry focused group and a environmentally focused group. By looking at previous governance of high sea fisheries, Blasiak & Yagi (2016) determined five primary stakeholder groups that are likely to be most impacted by future decision making on high seas governance. These groups are: the conservation community (NGOs), the fishing & shipping industry, the scientific community, seabed mining concerns (Blasiak & Yagi, 2016). It can be assumed that the industry group has profit as their main interest. This stakeholder group can therefore be expected to lobby for a higher quota, and vice versa for the remaining stakeholders, which prioritise conservation of the ocean.

In this research, these two stakeholder groups are referred to as the environmental group and the industry group. This research assumes these are the two primary groups influencing the decision making process, and therefore the harvesting quota, due to lobbying. The industry and environmental groups are assumed to lobby for a lower and higher harvesting quota, respectively.

4 UNDERSTANDING AND MODELLING THE MESOPELAGIC SYSTEM

This chapter describes the working of the mesopelagic system. Using these findings the conceptualisation of the model is presented, as well as the key uncertainties and the validation of the SD model. The remaining two sections present the modelling settings of the SD model and the methodological set up of how MORDM will be performed, which includes the objectives, decision variables, and the reference scenario.

4.1 UNDERSTANDING THE MESOPELAGIC ZONE

In this section the core concepts describing the working of the mesopelagic system are explained. This is done by zooming in on the relationships between the mesopelagic zone, carbon sequestration, and fishing. In light of this research acting as a proof of concept for MORDM, not all mentioned dynamics are modelled as detailed as mentioned here. Nevertheless, comprehension of these aspects is thought essential in order to adequately model the mesopelagic system.

4.1.1 Carbon sequestration by the mesopelagic biomass

The ocean is one of the main pillars in the global carbon cycle and mesopelagic fish play an important part in this. The uptake of atmospheric carbon by the ocean determines the concentration of atmospheric carbon dioxide (Passow & Carlson, 2012). The ocean therefore has a key role in climate change. The mesopelagic fish form an essential link between phytoplankton and higher predators (Anderson et al., 2019, Proud et al., 2019), therefore having the potential to influence this food web (Koslow et al., 2011). Consequentially, mesopelagic fish influence the working of the carbon pumps in the ocean, as these heavily rely on phytoplankton (Passow & Carlson, 2012).

Fish mediated carbon export is one of the several carbon sequestration pathways within the biological pump, see Figure 4.1. The process that takes place between oceanic carbon uptake from the atmosphere towards fish mediated carbon export starts with oceanic uptake, followed by primary production by phytoplankton. The phytoplankton concentration therefore partly determines the amount of available carbon in the surface. The growth of phytoplankton is influenced by the amount of sunlight and the carbon concentration in the surface (Charalampous et al., 2018; Edwards et al., 2016 ; Schippers et al., 2004). Phytoplankton is then eaten by zooplankton, which in turn are eaten by mesopelagic fishes. These processes happen mainly in the surface waters.

The mesopelagic fish feed on zooplankton in the surface layer at night and migrate downwards to the mesopelagic zone during the day. This process is called Diel Vertical Migration (DVM). The consumed zooplankton contains carbon. Since the mesopelagic fish then respire, excrete, and defecate, the carbon ends up in the mesopelagic layer (Davison et al., 2013; Saba et al., 2021). Of these processes, respiration as a function of fishs' metabolism is thought to be the greatest contributor to carbon export (Davison et al., 2013). As this happens at a greater depth and most importantly in or below the thermocline, the carbon is stored for a longer time than when this happens in surface waters. This is the case because in the thermocline vertical mixing rates are much lower (IPCC, 2018). The vertical migration patterns of fish therefore greatly determine how long carbon is stored. Not all mesopelagic fish migrate towards the same depths and sometimes they do not even leave the mesopelagic layer at all. Figure 4.1 shows an overview of the described processes. In this research, the flux of carbon that is migrated by mesopelagic fish is referred to as vertical migration of carbon.

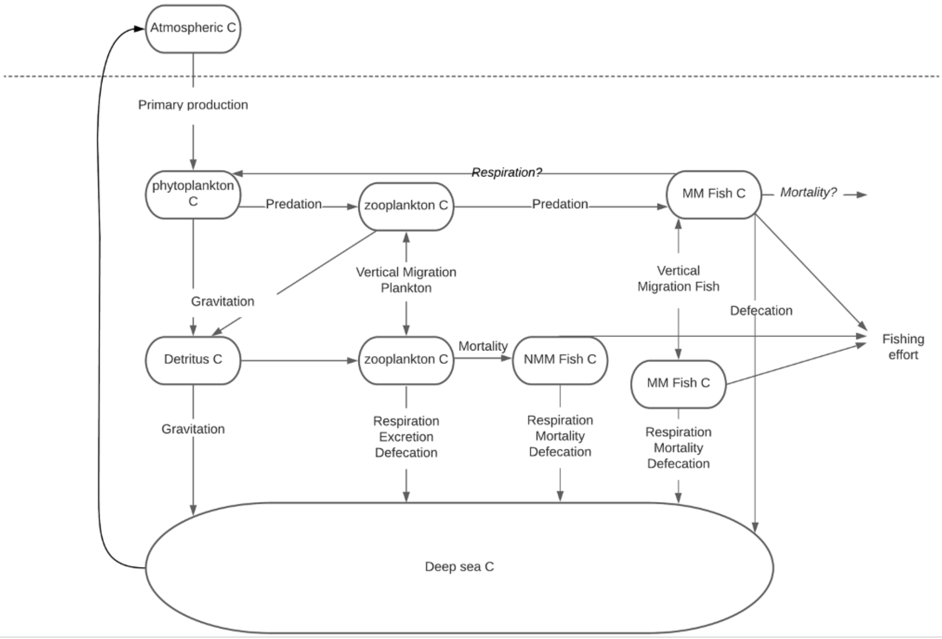

Figure 4.1: *Synthesis of carbon sequestration pathways via the biological pump mentioned in literature (Boyd et al., 2019; Davison et al., 2013; Saba et al., 2021).*

The vertical migration patterns of fish are driven by different factors. The fish migrate up towards clearer waters for food. However, clearer waters cause more risk of predation. The migration behaviour could therefore be explained by a risk reward mechanism. This mechanism would propose that dominant drivers of vertical migration patterns are thought to be light levels and food availability (Aksnes et al., 2017; Kaartvedt et al., 2017).

Carbon sequestration pathways can differ per region. A common distinction is made based on latitude (Boyd et al., 2019). Higher latitudes for example sequester carbon for a longer period of time, therefore contributing more to the carbon flux, while lower latitudes have a lower contribution to the carbon flux. Another distinction in carbon sequestering per region can be made by dividing the ocean up into oligotrophic, upwelling or seasonally stratified regions, like Saba et al. (2021) did.

4.1.2 Harvesting in the mesopelagic zone

There are direct and indirect effects of harvesting. The direct effect of harvesting in the mesopelagic biomass is a reduction in biomass. Effects of harvesting directly depend on parameters like biomass, harvesting effort, and catchability of the mesopelagic fish (FAO.org, n.d.). Literature indicates that several more indirect and complex effects are induced by (mesopelagic) harvesting as well, like changes in migration patterns of the mesopelagic fish (Peña, 2019) or changes in trophic relations. Harvesting effort could induce trophic cascades if high trophic species are harvested which in turn impact low trophic species that sequester carbon.

The effect of harvesting is variable. Impacts can differ greatly depending on which species are harvested, since not all mesopelagic fish migrate in the same manner (Lehody et al., 2010; Saba et al., 2021) and therefore contribute to carbon export differently. It might also depend on the region in which is harvested, since not all regions contribute the same amount of carbon export. Also the amount of bycatch has an influence, since it lowers the carbon sequestration (Cavan & Hill, 2020). The effect of harvesting also depends on the type of fishery. There are fisheries targeted at harvesting one specie and fisheries harvesting mixed species. For the mesopelagic, the latter is thought to be more difficult to manage but seems to have less strong ecological impacts (W. Melle, personal communication, April 20 2021). Finally, harvesting itself is influenced by fish demand, the regulations set in place, and the capacity of fisheries.

4.2 CONCEPTUALISATION OF THE MESOPELAGIC SYSTEM

There are multiple ways to conceptualise the mesopelagic system. The conceptualisation is set up in a way that is relevant and apt to study the systems' behaviour over plausible futures. The model takes into account the global mesopelagic biomass, harvesting effort and decision making, and the global carbon cycle, since these are deemed to be relevant aspects to analyse the system for governance insights. All modelling choices are made in light of the goal to communicate the added value of MORDM. Figure 4.2 shows an overview of all sub models and illustrates how these sub models interlink. The main structures of the sub models and their assumptions are explained in the rest of this section. Figures showing the entire model can be found in Appendix A.3 as Figures A.1 - A.5

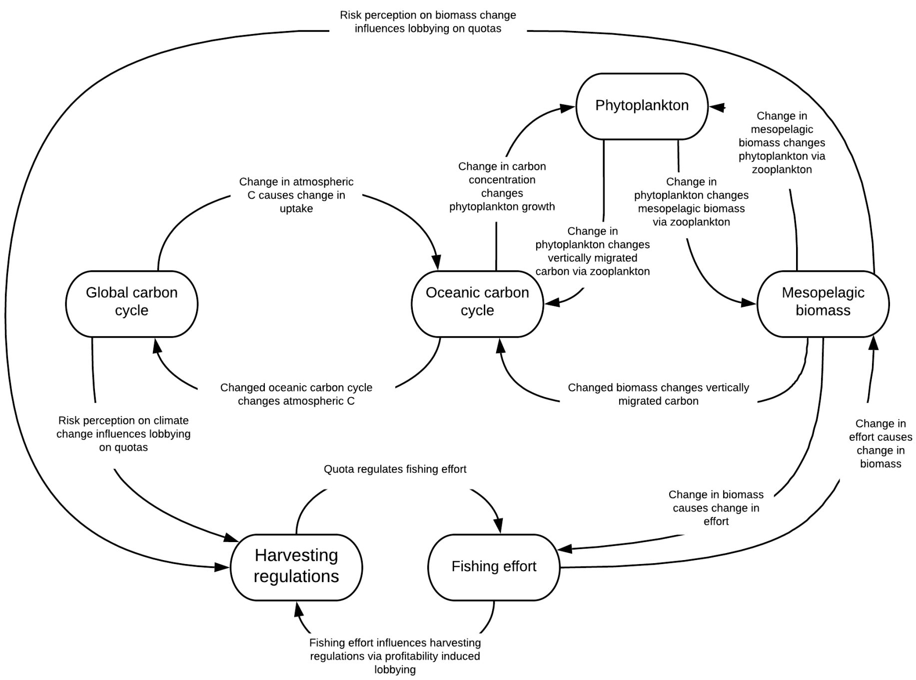

Figure 4.2: *Subsystem diagram of the SD model*

4.2.1 Mesopelagic biomass

The global biomass of mesopelagic fish in modelled via a predator prey model, as presented in Figure 4.3. In reality marine trophic systems are much more complex. The trophic interactions are for example variable over time and predators are opportunistic rather than specifically bound to one specie. This complexity is a challenge when modelling marine ecosystems. Still, often basic assumptions for predator prey models are made to represent marine systems (Hunsicker et al., 2011). Since the goal of this model is to provide a proof of concept of deep uncertainty methods applied to the mesopelagic zone, this abstraction is made here as well.

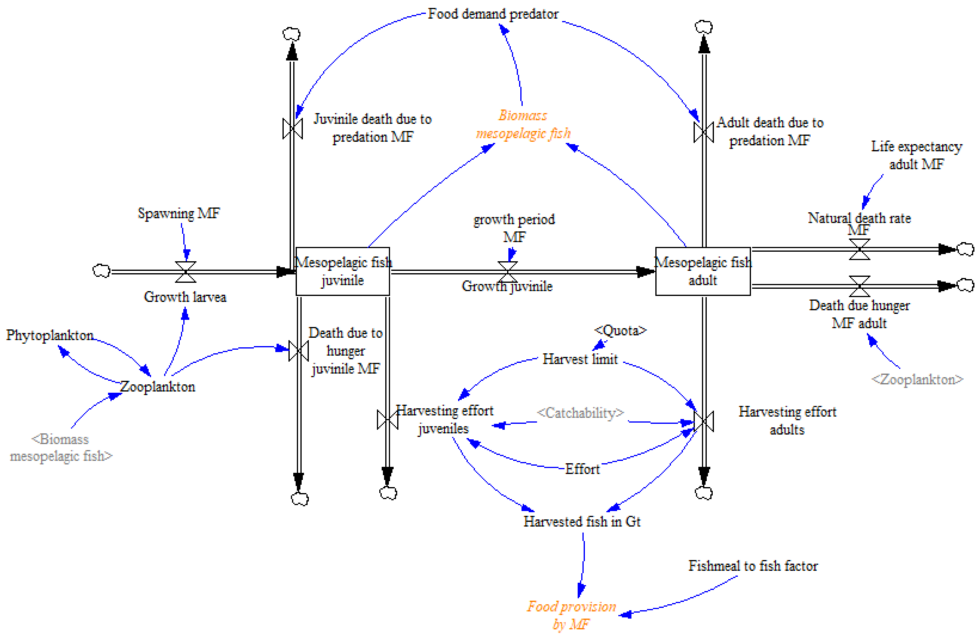

Figure 4.3: *Main structure of the mesopelagic biomass sub model, outcomes are in orange italics*

The flows of the model consist of individual fish. The mesopelagic fish are divided into the different life history stages juvenile fish and adult fish, since these groups differ in weight. The death rates of both groups of mesopelagic fish are influenced by the food demand of their predator. Mesopelagic fish are predated by many different species like sea mammals, sea birds, fish, and squid (Cherel et al., 2010; Koz, 1995). The predator in the model is based on data from large squids since these are found to be large consumers of mesopelagic fish (Choy et al., 2017; Koz, 1995) and therefore a representative predator.

The diet of mesopelagic fish mainly exists of zooplankton, more specifically mostly copepods (Koz, 1995). The biomass of zooplankton acts as a carrying capacity of the mesopelagic fish by influencing their birth and death rate. The carrying capacity of the zooplankton is related to the amount of phytoplankton (Brett et al., 2009). The growth of phytoplankton in turn is positively influenced by the carbon concentration in the ocean surface and negatively influenced by the amount of sunlight (i.e., the concentration of phytoplankton). This results in a balancing loop.

The model parameters can be switched between two fish types: myctophidae and the Maurolicus muelleri. The myctophidae family is the most abundant mesopelagic family globally (Catul et al., 2011; Proud et al. 2018). One of the most abundant myctophidae is the Benthosema pterotum (Catul et al. 2011), which is therefore used as reference specie for myctophidae. On the other hand, the Maurolicus muelleri seems the most likely of the mesopelagic fish to be harvested, because of its habitation closer to the shore and its higher catchability because of its schooling behaviour (Armstrong & Prosch, 1991). Thus, the economic viability of this specie is thought to be higher and will therefore be more prone to harvesting than other mesopelagic species. At the same time, this specie presumably has a less relevant role in carbon sequestration because of its smaller migration patterns. The model therefore includes data on both these two types of fish and incorporates this using fuzzy logic.

Fuzzy logic allows to switch between two possibilities in a non-binary way (Novák et al., 2012). Instead of switching between representing either Maurolicus muelleri or myctophidae, fuzzy logic allows to model both species at once by sampling over a spectrum between the two options. By setting the switch to 0.7 for example, the model will represent 70% of the biomass as myctophidae and 30% as Maurolicus muelleri. The group of parameters that can be switched are found in Appendix A.1.

For all biomass types the assumption is made that if the total biomass is relatively lower than it was initially, predation decreases since the catchability decreases consequentially. The mesopelagic biomass is additionally influenced by harvesting.

4.2.2 Oceanic Carbon cycle

Figure 4.4 presents the oceanic carbon cycle sub model. The oceanic carbon cycle is modelled using three stocks representing the carbon levels in the surface, deep ocean, and the ocean sediment. The model includes other carbon fluxes besides the carbon flux via vertical migration. However the fluxes related to vertically migrated carbon are modelled most elaborately, since these are most relevant for assessing the impact of mesopelagic harvesting.

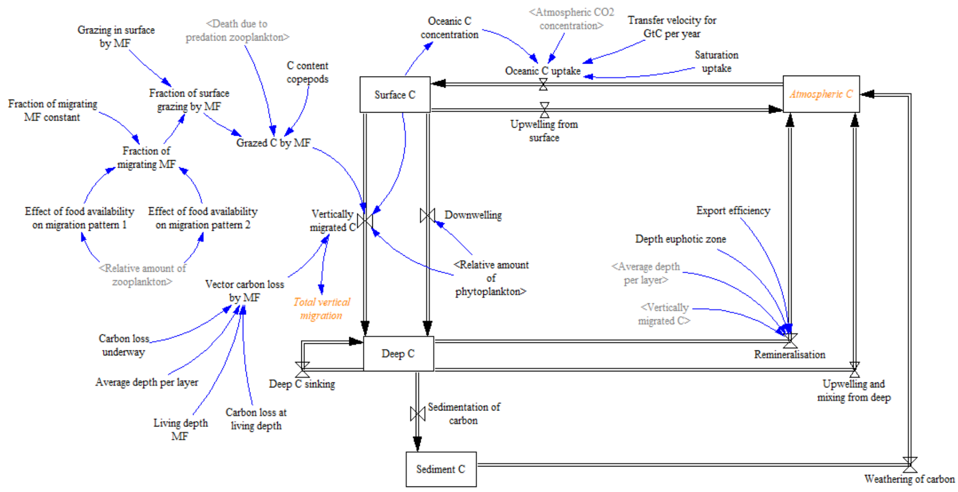

Figure 4.4: *Main structure of the carbon sequestration sub model, outcomes are in orange italics*

For the component of the oceanic carbon cycle driven by mesopelagic fish, three distinctions in processes can be made that represent the carbon flow from the atmosphere to the ocean and back again. These processes are air-sea exchanges, vertically migrated carbon, and remineralisation.

Carbon ends up in the ocean due to air-sea exchange fluxes. These are calculated using the difference between carbon concentrations in the air and water, and the gas transfer velocity (k), using the formula below (Liss & Slater, 1974).

$$F_{uptake} = k[C_{air} – C_{water}]$$

After carbon is taken up in the ocean, many different carbon fluxes take place. Of these fluxes, mesopelagic fish have the most influence on the vertical migration of carbon. Vertically migrated carbon is a flux driven by mesopelagic fish that graze in the surface during the night and respire, defecate and excrete at greater depths during the day. The zooplankton they eat contains carbon, which is stored longer in the ocean when it is released at greater depths, extending the time it reappears at the surface (Davison et al., 2013; Kwon et al., 2009; Saba et al., 2021). Vertically migrated carbon is therefore assumed to be a function of mesopelagic biomass, the fraction of migrating mesopelagic fish, carbon content of zooplankton, and the amount of carbon in the surface. A part of the carbon grazed by the fish is released above the thermocline (Anderson et al., 2019) and therefore not successfully sequestrated.

In addition, the vertical migration of carbon is subscripted into ten different layers between 150-1000m since this is the depth range mesopelagic fish migrate towards when leaving the surface (Catul et al., 2011). The fish release most carbon in their habitation layer, and some carbon in the layers they migrate through (Davison et al., 2007).

The carbon that is deposited at greater depths by the mesopelagic fish, sinks down and is respired back to CO2 due to a process called remineralisation. The carbon flux due to remineralisation is often represented as a function of the carbon flux out of the euphotic zone (Fz), the depth of the euphotic zone (zc), the depth below the euphotic zone at which carbon is released by for example fish (z) and the efficiency of the downward transfer of carbon (b) using the formula below (Kwon et al., 2009). Since the amount of remineralisation differs highly on depth, the model is subscripted so that in contains different layers of depth. In other words, formula 2 is applied at different depth layers. The model is subscripted so that it contains ten layers between 100 to 1000 meters depth.

$$F_{remineralisation} = F_z(z/zc)^b$$

As can be seen in Figure 4.4, the model includes other carbon fluxes as well. Downwelling and upwelling are the two major carbon flows in the ocean (Bice, n.d.). They influence the carbon levels in the surface and the deep ocean and therefore vertically migrated carbon. Thus, it is important to incorporate this process in the model dynamically. Downwelling is dependent on the concentration of carbon in the surface, and the water flow downwards (Bice, n.d.), resulting in the formula below. There are other carbon fluxes as well, for example inorganic carbon fluxes (Raven et al., 2005). These fluxes are not modelled dynamically but included as a standard factor of carbon flux added to the downwelling stream. Carbon within the deep ocean stock sinks down from layer to layer, or mixes upwards. Upwelling and mixing happens from both the surface as well as the deep ocean (Raven et al., 2004). Also, the model includes sedimentation towards the ocean sediment and weathering flows out of the sediment.

$$F_{downwelling} = carbonconcentration * waterflow + othercarbonfluxes$$

Lastly, the amount of carbon in the surface is dependent on primary net production via phytoplankton (Anderson et al., 2019). This feedback is modelled by computing the availability of phytoplankton relative to the initial amount of plankton. The vertically migrated carbon and downwelling fluxes are dependent on this factor (Anderson et al., 2019).

4.2.3 Decision making on harvesting quotas

The sub model describing the decision making process on the harvesting quota is based on the conclusions drawn from the governance analysis. The resulting sub model is presented in Figure 4.5. Considering existing conventions, the assumption that the harvesting quota is set every 2 years seems realistic. This is modelled with a pulse train. The magnitude of the quota is defined with support of the EMA workbench.

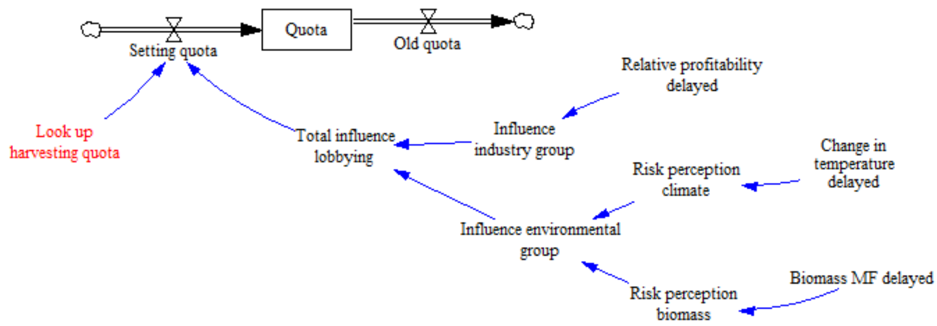

Figure 4.5: *Main structure of the decision making sub model, the parameter in red is optimised in the EMA workbench*

The decision maker can be influenced by the two main lobbying groups: the industry group and the environmentalist group. The quota preference of the industry group depends on the relative profitability of mesopelagic fish. The higher the profitability, the higher the influence of this lobbying group. The quota preference of the environmentalist group is dependent on risk perception in biomass reduction and climate change risk perception. As described by Beckage et al. (2018), risk perception is highly determined by the frequency of extreme climate change events. The frequency of extreme events is represented by changes in temperature, which in turn depends on atmospheric carbon levels. The higher the risk perception on both these factors, the higher the influence of the environmentalist lobbying group on the decision makers. This structure assumes that decision makers and the environmentalist group are aware of the link between mesopelagic harvesting and carbon sequestration. The described factors influencing the lobbying groups (i.e. profitability, change in biomass, change in temperature) are delayed since it is assumed the information will not instantly influence preference of the lobbying groups, but only after a longer consecutive trigger.

4.2.4 Harvesting & fishery capacities

The fishery capacity sub model is presented in Figure 4.6. Harvesting is a function of effort (f), catchability (q), and the mesopelagic biomass (B), defined as the formula below (FAO.org, n.d.). This structure can be found in Figure 4.3.

$$Y = q * f * B$$

Effort is dependent on the global fisheries capacity and is limited by the harvesting quota. The capacity in turn is dependent on the profitability of fish meal and the harvesting quota.

The capacity of fisheries is important to include since it cannot be assumed that harvesting capacity and thus effort is equal to the quota in place. Oftentimes the

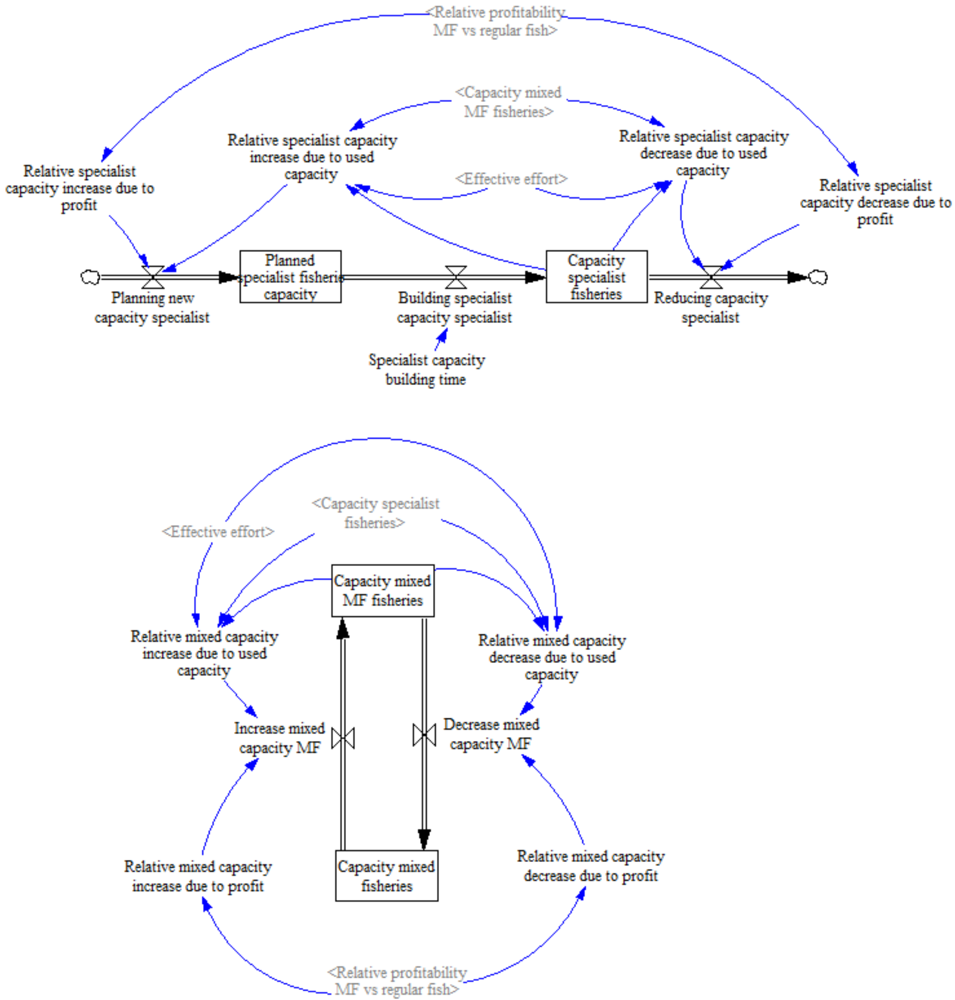

Figure 4.6: *Main structure of the harvesting sub model.*

total fisheries capacity is higher than the total quota allowed because fisheries are not aware of the capacity of other fisheries, causing overfishing (FAO.org, n.d.). Another reason the magnitude of harvested fish is not equal to the quota is because of fisheries discarding fish. For these reasons it is important to include the dynamics of fisheries capacity to realistically represent harvesting dynamics.

The main structure of the fisheries capacity sub model is presented in Figure 4.6. Two different fisheries are considered, namely fisheries specialised in mesopelagic fish and mixed fisheries. The latter represents fisheries that convert from regular fishing to mesopelagic fish if this is assumed more profitable. The converting time of mixed capacity is therefore quicker for mixed capacity than the building time of specialist capacity.

Capacity increase as well as decrease is driven by profit and capacity underuse (FAO.org, n.d.). Fisheries are not fully knowable about the amount of capacity, and do not know if other fisheries are planning to increase capacity. Therefore, decisions based on capacity underuse are not considering capacity in planning, possibly causing an overshoot in capacity due to what is called a procurement delay. Capacity decrease in turn is driven by a low profitability and capacity overuse (FAO.org, n.d.). Since the governance analysis clarified that effort can be best assumed to be managed by harvesting quotas, the fisheries are less inclined to buy new vessels or more efficient vessels or stay longer at sea when profits are low, simply because they are not allowed to catch more (FAO.org, n.d.).

Fishmeal profitability is naturally dependent on costs and sale price, which are influenced by profitability change and demand, respectively. The costs of mesopelagic fishing are extremely high currently, since there are still a lot of challenges in developing fisheries, and fuel costs are much higher compared to fisheries closer to the coast (Blue Marine Foundation, 2020). The model therefore includes two scenarios concerning changing profitability driving the costs down. These scenarios are handled as uncertainties. They are defined in Table 4.2.

Profit or loss is calculated using the price change caused by differences in supply and demand of fishmeal. Demand is determined by the annual fish consumption per capita and the predicted population size. For the population size three different scenarios are modelled, representing low, medium, and high population growth scenarios as defined by the UN (United Nations, 2019). Of the total global fish demand, about 50% is assumed to be aquaculture demand (Fisheries.noaa.gov, n.d.), which needs fishmeal as input. Fish meal supply naturally depends on harvesting levels, and influences the demand. Finally, the effort is limited by the regulations set in place, which in this case is a harvesting quota since open sea harvesting regulations mainly come in the form of quotas.

4.2.5 Global Carbon model

The oceanic carbon cycle is modelled as an extension of a global carbon cycle. Representing the entire global carbon cycle instead of solely the ocean cycle allows for a more realistic representation, especially of atmospheric carbon levels. The model is build using the description as stated in Chapter 3 of TAR-03 by the IPCC (2001) (W. Auping, personal communication, February, 2020).

4.3 KEY UNCERTAINTIES OF THE MODEL

Uncertainties can be classified into different categories. This model contains structural uncertainties as well as scenario and parametric uncertainties. This section presents and explains these uncertainties.

4.3.1 Structural uncertainties

Several structures in the model are uncertain or can be modelled in different ways. Table 4.1 presents the structural uncertainties that are included in the exploratory model. Table A.2 in Appendix A.2 presents all structural uncertainties of the SD model.

Table 4.1: Structural uncertainties in the SD model

Uncertainty	Switch	Reference
Switch risk reward mechanism	asymptotic, linear (and more influence) & constant	Assumption & Aksnes et al., 2017; Kaartvedt et al., 2017
Switch profitability change MF fisheries	linear & asymptotic	Assumption
Switch price change	asymptotic high & asymptotic low	Assumption

Risk & reward mechanism mesopelagic fishes
One of the conclusions from the interview with ecologists was that there is a high variability within the mesopelagic zone on both the harvesting side as well as the ecological side. One source of this variability is the migration pattern of the fish. Since this pattern has a high influence on the amount of carbon sequestrated, this structural uncertainty is incorporated in the model. It is thought the migration patterns are based on a risk and reward mechanism. Mesopelagic fish have a higher risk of predation when light levels are higher, which is the case in the ocean surface (Aksnes et al., 2017). If there is a high amount of food in the surface, the reward is high enough to swim upwards, and vice versa.

Price change
The sale price change of mesopelagic fish is modelled in order to determine the profitability of mesopelagic fish and therefore the amount of harvesting effort. It can be assumed that the sale price of mesopelagic fish changes if the demand for fish meal changes, however the magnitude of that effect is unclear since it is still a nearly non-existing market (Prellezo, 2019). The model therefore includes two different structures representing the effect of demand on the sale price, in which the magnitude of this effect is different, as well as the form of the relation.

4.3.2 Scenario uncertainties

Profitability of mesopelagic fisheries
The incentive for fisheries to harvest mesopelagic fish depends on profitability of harvesting. Harvesting is currently unprofitable (Prellezo, 2019). Future developments however, like technological innovation but also upcoming effort limitations on regular fisheries and expanding markets, are triggers that make harvesting in the mesopelagic zone more profitable. This uncertainty is high. These factors are therefore incorporated into the model as a combined scenario uncertainty for profitability of mesopelagic fish. Of the two scenarios, one presents a rather optimistic profitability scenario from 2030 onwards, to ensure at least one scenario produces enough incentive for fisheries to harvest in the mesopelagic zone.

4.3.3 Parametric uncertainties

There are many parametric uncertainties in the mesopelagic system. The uncertainties are divided into two categories: medium uncertain and highly uncertain. These have an uncertainty range of 80%-120% and 60%-140%, respectively. Some uncertainty ranges were altered after the open exploration to gain a more realistic representation of behaviour. The most relevant uncertainties were selected by analysing Kernel Density and Feature Scoring plots. These uncertainties were included in the exploratory model. Table 4.2 shows these uncertainties. In the table in Appendix A.2 presents all uncertainties that were originally included in the model.

Table 4.2: Parametric uncertainties in the SD model

Parameter	Default value	Deviation around default	Reference
Grazing in surface by MF	0.37 dmnl	40%	Anderson et al., 2019
C content copepods	0.51 GtC/GtZoo	20%	Omori, 1969
Surface ocean	3.63e14 m2	10%	Kwon, 1994
Depth euphotic zone	100 m	10%	Kwon et al., 2009
Transfer velocity for GtC per year	1.12169 Dmnl	20%	Bender et al., 2011
Initial surface C	600 GtC	5%	Raven et al., 2005
Initial sediment C	3390 GtC	20%	Shaffer & Wallace et al., 2000
Downwelling water	1.7e15	20%	Assumption
Residence time deep carbon	1000 years	10%	Raven et al., 2005
Upwelling delay surface	8 years	10%	Raven et al.,2005
Consumption by MF in bodyweight	7 GtZoo/Year	20%	Koz, 1995
Initial weight juvinile MF	9 GtMF	20%	Assumption; Jones et al., 2014; StJohn et al., 2020
Initial weight adult MF	1 GtMF	20%	Assumption; Jones et al., 2014; StJohn et al., 2020
Initial zooplankton	4 GtZoo	20%	Assumption; Falkowski, 2012
Consumption by zooplankton in bodyweight	3 Gt/Year	20%	Assumption
SWITCH lanternfish to mauriculus	1	0.4-1	Catul et al., 2011; Proud et al. 2018
Spawning fraction	0.18 dmnl	20%	Sassa, 2019
Fraction spawning mauriculus vs myctophidae	0.75dmnl	10%	Assumption & Armstrong & Prosch, 1991
Female fraction	0.515dmnl	20%	Dalpadado, 1988
Catchability myctophidae	0.14 dmnl	40%	Hidaka et al., 2001
Fishmeal to fish factor	4 dmnl	20%	StJohn et al., 2020

4.4 VALIDATION OF THE SYSTEM DYNAMICS MODEL

During and after developing the model the quality of the model was tested. Evaluating the quality of a model can be done using verification and validation. Verification refers to the models correctness, for example whether the model results are consistent with reality. Validation refers to the question whether the model is valid (Oreskes et al., 1994). Validation should therefore reveal if the model is suited for answering the research question. It is crucial to evaluate the model on these aspects, since it clarifies in what range of situations the model is useful, and even more importantly in which ways is it not useful.

Verification of the model largely takes place implicitly during the modelling cycle. For example, the model was build using existing historical or predicted data, and the model runs were compared with current real life behaviour of the system. Also, several types of debugging were used for verification, for example XIDZ, MIN and MAX functions, and adapting equations, look ups or parameters if they produced unrealistic behaviour.

Validation of the model entails evaluating whether the model is fit for purpose. The purpose of the model is to analyse how the mesopelagic system might evolve over possible futures given certain policy interventions. Whether the model is the right tool for this depends on whether the model includes the right structures (e.g. boundaries and aggregation levels) and behaviour.

4.4.1 Structural validation

First of all, the structure of the model was verified iteratively during the conceptualisation of the model by aiming to include all relevant structures for answering the research question. The model entails several sub models: These sub models together are expected to be adequate enough to capture the dynamics between the mesopelagic ecosystem, the fishery industry, decision making arena, and the global carbon cycle.

Structural validation also includes incorporating structural uncertainties relevant for analysing the behaviour of the mesopelagic system under harvesting policies. The structure of the model is based mostly on literature. Additionally, consultations with experts in the field of mesopelagic fish found place, in order to check assumptions, the validity of the structure and the boundaries of the model. This for example led to including the Maurolicus muelleri specie instead of only representing lanternfish in the model. This was recommended because harvesting this specie is currently more economically viable and since more literature exists on this specie. These consultations also clarified the boundaries of the models validity. The model does not include the effects of light attenuation on migration patterns, for example (Kaartvedt et al., 2017).

The boundaries of the model have a crucial impact on the validation (Oreskes, 1994). The boundaries of the model help defining in what range the model still makes sense. It is crucial to be aware of the demarcations, because it clarifies whether the model is suitable for answering the research question; it helps understanding what the model can and most importantly cannot give insight on. For example, the model build in this study does not take into account behavioural changes of mesopelagic fish. It has been shown that factors like light levels and harvesting might have an impact on the migration patterns of fish (Aksnes et al., 2017; Kaartvedt et al., 2017; Peña, 2019). These dynamics however are not taken into account in the model.

Another structural aspect of the model that influences the validation is the aggregation level of the model. The system was chosen to be modelled globally since this makes the most sense when analysing impacts on carbon sequestration and atmospheric carbon levels. However, the model therefore ignores the high variability levels that exists between for example different regions and species (Boyd et al., 2019; Saba et al.,2021). The entire mesopelagic biomass is modelled as one sink, only distinguishing between juvenile fish and adult fish. This has many consequences for the behaviour of the model. For example, the model then assumes that harvesting effort is spread equally over all regions and species, while it is much more realistic that certain regions and species undergo more intense effort. In addition, it could be that some species are much more vulnerable for harvesting than others. Also, it takes much longer for the fish stock to collapse, because it is modelled as one massive biomass. In addition, in reality fish species or schools impacted by harvesting effort might disappear entirely, which is not included in the model. Because of those reasons, it can be expected that the resilience of the biomass is much higher when modelled as one large connected sink. This underscores the importance to represent several different species in the model, like the Maurolicus muelleri and myctophidae.

4.4.2 Behavioural validation

Behavioural validation is another method to test the model's validity. According to Forrester & Senge (1980), behavioural validation means that the behaviour of the model is tested on its representativeness of the system. This type of validation has been done throughout the modelling cycle. Since this model is run using EMA and therefore takes into account deep uncertainty, this means the model should be able to produce a wide range plausible futures and behavioural pathways. Therefore, different perspectives should be represented in the behaviour. The open exploration plots demonstrated that the model indeed produces a wide range of behaviour, a random selection of the variety of behaviours of mesopelagic biomass can be seen in Figure 4.7. This makes the model suitable to take into account multiple possible futures and multiple perspectives.

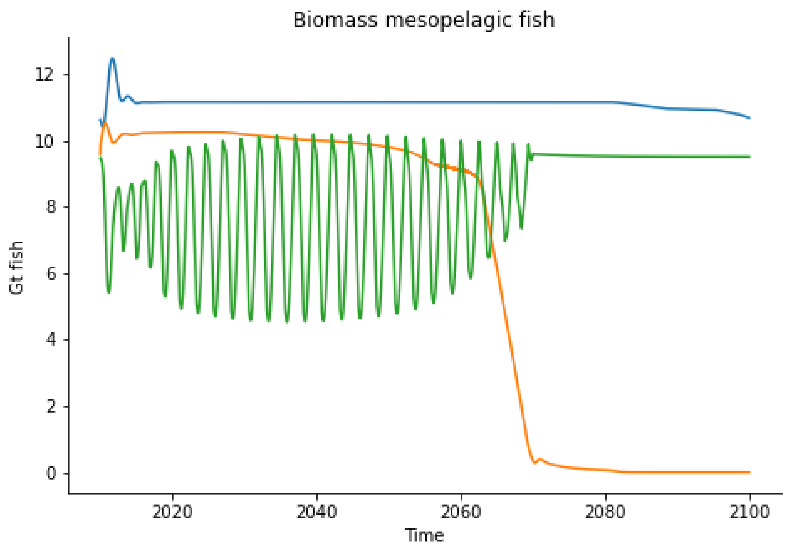

Figure 4.7: *Random selection of behaviour of the biomass of mesopelagic fish over time, under limitless harvesting. As can be seen, different types of behaviour are produced, and in some cases a biomass collapse occurs.*

At the same time, the behavioural validation illustrates that the model provides qualitative insights rather than quantitative insights. For the amount of harvesting for example, the model shows behaviour that is in accordance to expected behaviour; after a certain threshold of harvesting the biomass collapses, see Figure 4.7. However, the consecutive magnitude of this threshold is not realistic. In other words, the model can provide insight under which conditions and policies certain behaviour takes place, however it cannot be used to provide information on actual values of these factors.

All in all, it can be argued that the different levels of validation show that the model includes the right set up, structures, and behaviours for evaluating how the mesopelagic system might evolve over plausible futures given policy interventions. Nevertheless, the role of the model is restricted to providing a qualitative analysis rather than a quantitative analysis; the model can convey what behaviour policies produce, and most importantly what impact uncertainties have on those behaviours, though it cannot provide understanding on precise values. With regards to the fact that the model is used as a proof of concept for MORDM, it should be taken into account that during the modelling cycle a trade-off had to be made between the time scope and producing realistic behaviour.

4.5 MODEL SETTINGS OF THE SYSTEM DYNAMICS MODEL

The SD model runs from 2010-2100. 2100 is chosen as the end time because current discussions about atmospheric carbon levels mostly use 2100 as a reference point. 2010 is chosen so that the first part of the runs can be compared with historical data. The units of time were set to a year. The time step was set to 0.0078125, which is the smallest time step. Larger time steps caused different behaviour and were thus not small enough to catch all changes over time. The integration method that is used is Euler, since the model includes discrete functions like look ups.

4.6 EXPERIMENTAL SET UP MORDM

The following section clarifies how the SD model is used for performing MORDM. It presents the experimental set up that is used for MORDM, including the objectives, decision variables, reference scenario, and the experimental set up of the different steps in MORDM. The scripts used can be found here: *https://github.com/julievandeelen /Thesis-final*.

4.6.1 Step 1: Problem formulation

Uncertainties

The most influential uncertainties are selected using feature scoring over time for the base case. That case represents the scenario in which the system experiences no policy interventions. Table 4.2 presents which uncertainties are included in the MORDM cycle.

Decision variables

One decision variable is formulated for MORDM, namely the magnitude of the harvesting quota. This is the harvesting quota proposed by decision makers in Gt mesopelagic fish per year. This lever is set every 2 years, sampled out of a range between 0 and 6 GtMF/Year. The total set of quota values over the range of the run time is one policy.

Table 4.3: Objectives used for MORDM

Objective	Definition	Optimised direction	Units
Average vertical migration of carbon	The average amount of carbon (GtC) that is sequestrated by mesopelagic fish annually.	maximised	Gtc/Year
Average food provision by mesopelagic fish	The average amount of food that is provided annually by harvesting mesopelagic fish in Gt: the amount of harvesting mesopelagic fish translated to actual food provision using a factor of approximately 4 Gt fish/Gt Mesopelagic fish (StJohn et al., 2020).	maximised	Gt fish/Year
10th percentile of mesopelagic biomass	The 10th percentile of the global biomass of mesopelagic fish in Gt. This means that 10% of the time the biomass was lower than this number, 90% of the time the biomass was higher than this value.	maximised	Gt mesopelagic fish
Atmospheric carbon level in 2100	This outcome represents the levels of GtC in the atmosphere in 2100.	minimised	GtC
Inertia	The fraction of years where the absolute change in quota exceeds 0.1 Gt.	minimised	%

Objectives

Five outcomes are chosen to optimised, which are presented in Table 4.3. These outcomes are chosen because they are deemed most adapt to analyse a relevant scope of effects of harvesting in the mesopelagic zone for supporting decision making. Additionally it has been aimed to choose objectives which are expected to have a low correlation to each other.

For the outcome *Average food provision by mesopelagic fish*, this quantification is chosen because mesopelagic fish are most likely to be used as fish meal for aquaculture (Hildago & Browman, 2019). Since in this study food provision by mesopelagic fish is researched, this outcome is not measured as the amount of harvested mesopelagic fish, but the amount of aquaculture fish it could produce. In other words, it is the amount of harvesting mesopelagic fish translated to actual food provision using a factor of approximately 4 Gt fish/Gt Mesopelagic fish (StJohn et al., 2020).

Inertia is included as an objective to optimise over since it would be preferred if the harvesting quota would not take largely differing values per time step. This would simply not be pragmatic, since fishery fleets would then need to change their capacity by tremendous amounts every two years.

The quantification of the objective *Atmospheric carbon level in 2100* is chosen because most policy discussions are about atmosphere levels at 2100. Therefore, this value is deemed most relevant and easy to compare with other research.

Reference scenario

A reference scenario is used for the sake of reproducibility. The reference scenario is determined by running the model without any policy interventions, and then by finding the worst case scenario in terms of the highest value in atmospheric carbon levels in 2100. This is done because the carbon level in 2100 is one of the most relevant outcomes in the study. A worst case scenario is chosen as reference case because there is a lot of uncertainty involved.

4.6.2 Step 2: Searching for candidate solutions

In step 2, optimal candidate solutions were searched. This was done by searching over the lever over 800.000 runs. This high number of function evaluations has been chosen iteratively, aiming to reach convergence. Epsilon progress was tracked. An epsilon value of 0.05 was used. This value was chosen iteratively by finding a balance between accuracy and computing effort.

4.6.3 Step 3: Generating scenarios

In step 3 the candidate solutions from step 2 are analysed for their robustness. The policies from step 2 were tested over 3000 scenarios. This is a relatively low number of runs compared to step 2. 3000 Scenarios however seem to suffice for convergence of the robustness scores, since rerunning step 3 with 3000 scenarios several times showed to produce nearly the same scores.

Then, two robustness metrics were computed for all four outcomes for all policies. This was done by computing a signal to noise ratio as well as a maximum regret scores. This means that per policy, 2x4 scores were obtained. Aggregation of these scores was prevented by selecting policies that scores in the best 80% percentage of signal to noise scores for each outcome, as well as in the best 80% percentage of maximum regret scores for each outcome. Best refers to the highest and the lowest percentage, respectively. The robustness scores for the outcome inertia were not taken along in this selection, since these scores where already remarkably high relative to the other four outcomes.

4.6.4 Step 4: Scenario discovery

Lastly, scenario discovery is performed using PRIM and dimensional stacking. The policies selected in step 3 were run over 10.000 scenarios. Scenario discovery is applied to several best and worst case scenarios. For example, a worst case scenario that was analysed was a 10th percentile of mesopelagic biomass of lower than 9 Gt. Since the biomass originally oscillates around 10 Gt, 9 Gt would be undesirable. The coverage was set to 0.8, meaning there should be a prevalence of 80% of cases where the 10th percentile of biomass is lower than 9 Gt. From the trade-off plot, a box was selected that had the best density and coverage trade-off in order to find the causes of the outcome performance of interest.

5 RESULTS

This chapter presents the most relevant decision making insights on mesopelagic harvesting that were found by performing MORDM. The chapter is structured as follows. The first section presents the results of exploring the model's outcome-, decision- and uncertainty spaces, which was done prior to MORDM. The second section illustrates the most optimal policies found by the MORDM approach. Lastly, the performances of these policies are presented.

5.1 EXPLORATION

This section explores the outcome-, decision- and uncertainty spaces prior to starting the MORDM. This is done to understand how the four model objectives behave in relation to each other under different harvesting scenarios and uncertainties.

5.1.1 Exploration of the outcomes

The exploration of outcomes showed that the mesopelagic biomass produces unexpectedly robust behaviour. An open exploration was done for four different situations: a base case, a case without any harvesting, a static policy, and a high static policy. These four situations were run over 1000 different scenarios. The base case represents the system without any harvesting quotas. The static policy is defined by a harvesting quota of 0.3 Gt mesopelagic fish/Year, assuming a harvesting quota of 3% of the stock is realistic. The high static policy represents a harvesting quota 4 Gt fish/year. This an unusual high quota for such a long period. It was nevertheless explored since the static quota of 0.3 Gt/Year did not seem to affect the biomass as expected, as explained further in this section.

Before performing the open exploration, single runs in Vensim already showed that the variable *profitability of MF relative to regular fish* was not high enough to give fisheries an incentive to start harvesting. Therefore, the harvesting levels did not make significant impact on the outcomes. Thus, harvesting quotas will not have any impact on the outcomes either. In other words, there was no room for policies to govern harvest effort. Therefore, after the first open exploration, the profitability scenarios were altered so that mesopelagic harvesting profitability becomes high enough from 2030 onwards to induce levels of harvesting that impact the outcomes.

Firstly, the exploration of the outcomes illustrates that for the case without any harvesting there seems to be no relation between the biomass and harvesting, which is expected. However, for the harvesting policy of 0.3 Gt/year, the same is true. See Figure B.1 in Appendix B.1. This indicates that a harvesting quota of 0.3 Gt/Year has no noticeable negative effects on biomass in any of the scenarios. Moreover, a high food provision is related to lower biomass and a lower level of vertically migrated carbon. No apparent influences on atmospheric carbon levels can be deducted from the visualisation.

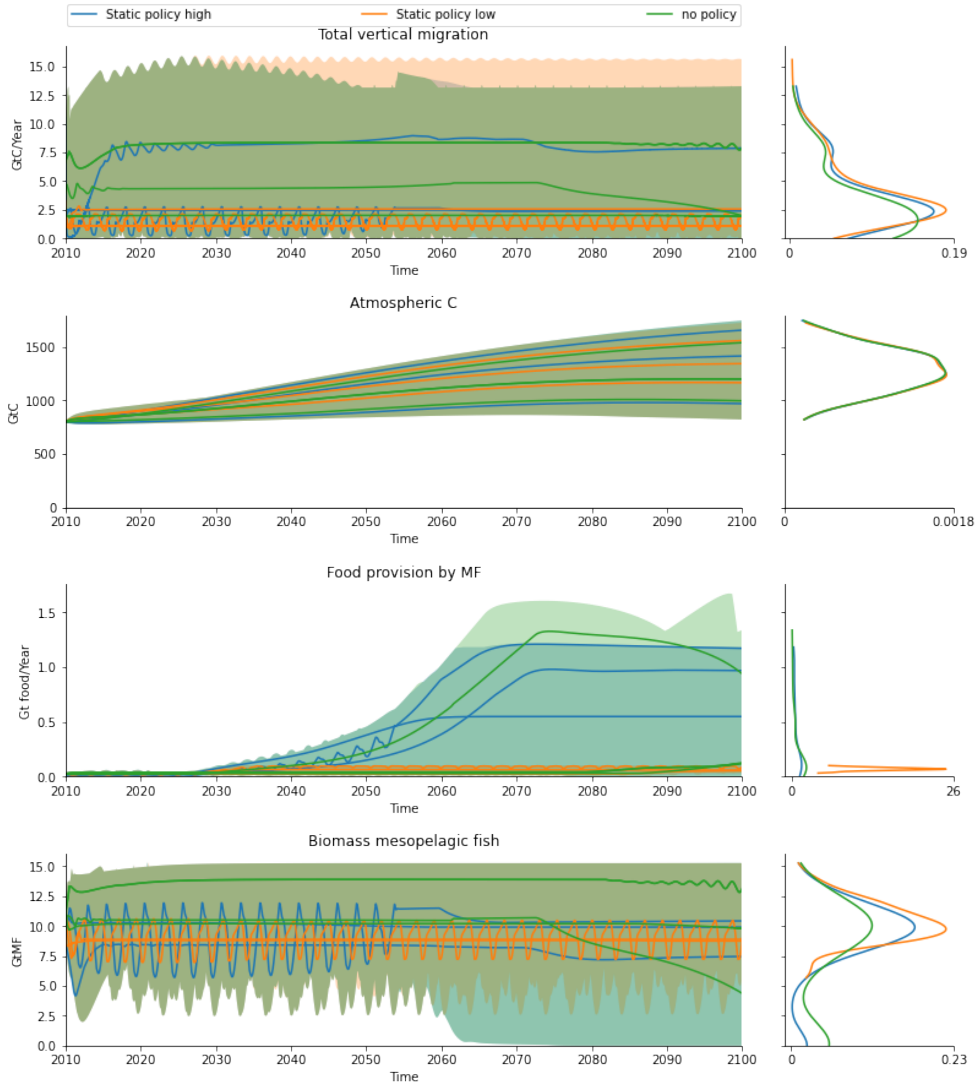

Figure 5.1: *Line plots for the outcomes during the base case, static policies, and unlimited harvesting. The different lines represent runs to showcase some different types of behaviours, which were randomly selected from the ensemble. The backgrounds show the entire range of all runs per corresponding policy in a lighter shade. The plots on the right show the distribution of the end state of the four different harvesting situations.*

Plotting the behaviour of the outcomes over time illustrated even more clearly that the low static policy produces relatively low food provision and does not seem to influence the biomass. See Figure 5.1. The high static policy has the highest food provision of all three cases, presumably since the case with no policy in place experiences biomass collapses in some scenarios. There are also clusters of runs demonstrating a lower food provision. Figure B.4 in Appendix B.1 illustrates that these runs start rising in the last decade as well, probably because these clusters are produced by a different profitability scenario. It additionally shows that there is a cluster of runs that provides an almost completely stable amount of food from the beginning. From Figure 5.1 it seems that there are no apparent differences in effects on atmospheric carbon between the four cases.

5.1.2 Exploration of the decision space

Exploring the effect of different decision ranges revealed that the range from [0,6] Gt/Year allows for finding multiple policy options. From the previous exploration, it seems only at an unexpectedly high quota, outcomes are influenced negatively. Additional exploration of the time step harvesting quota optimised in step 2 is performed to check the effect hereof on the decision space. This showed that optimising over a range of [0,0.3] Gt/Year produces policies that stay at 0.3 Gt/Year over the entire time, with little to no deviation, see Figure B.2 in Appendix B.1. Only the first third of the run time shows deviation, which makes sense considering in that period it is not yet profitable enough to harvest, therefore the quota is less relevant. The same behaviour was found for ranges between [0,2], [0,4], and [0,5] Gt/Year. However, a range of [0,6] Gt/Year produced multiple policies. A range of [0,20] Gt/Year was explored as well; this gave the same type of policy, see Figure B.3 in Appendix B.1.

It can be concluded that solely at a certain harvesting quota magnitude the biomass is influenced negatively. This magnitude is relatively high, higher than deemed realistic. This can be explained by the fact that the biomass is modelled as one sink. The most interesting space for governing the mesopelagic is the space where the level of food provision is high, while the biomass is not decreased permanently. In the field of harvesting such a value is referred to as the Maximum Sustainable Yield (MSY). The open exploration shows that the biomass is only influenced negatively at a harvesting quota of around 4 Gt/Year or higher. A quota should per definition be a limit that is expected to cause a decrease in biomass if it is crossed. For this model, this is not the case for 0.3 Gt/Year. Therefore, this exploration showed that a higher decision lever space needs to be taken along into the following steps in order to do a relevant analysis.

5.1.3 Exploration of the most prevalent model behaviours over time and the corresponding uncertainty space

Under deep uncertainty, analysing the most prevalent behaviours and most influential uncertainties helps narrow down the system's behaviour. Kernel density estimation (KDE) and feature scoring figures help exploring the effect of uncertainties on the outcomes over time. The plots also clarify the most prevalent bifurcations of the outcomes, the bandwidth of outcomes, and the uncertainty responsible for this behaviour. The figures were plotted for the base case of the system, meaning there are no harvesting policies in place. This helps understanding the varieties of behaviour decision makers can expect with no harvesting in place. The model was run 1000 times for these plots.

Most prevalent model behaviour over time

First of all, the KDE plots for the mesopelagic biomass illustrate that the most dominant behaviour is a stable biomass, however, a cluster of runs shows a biomass collapse towards the end. See Figure B.5 in Appendix B.2, which shows a density plot over time. The bandwidth of the biomass throughout the run time can be explained by the many parametric uncertainties differing per run and the oscillating behaviour of the biomass. Depending on predation and food availability, the biomass oscillates over time, which is expected behaviour as the related sub model has the structure of a predator-prey model (Lotka, 1920). In the last few decades, there is a bifurcation in the behaviour of the biomass over time - for a cluster of runs the biomass collapses. This can be explained by the base case presenting the mesopelagic system without any policy interventions. Therefore, it is logical that in some cases the biomass collapses. Not all runs show this type of behaviour, because the model considers different profitability scenarios of mesopelagic fish, which influences the harvesting effort. For all scenarios, mesopelagic harvesting is barely profitable initially, as Prellezo (2019) described. After 2030, this profitability is assumed to increase due to for example innovation, lower fuel costs, or harvesting quotas on the shelf seas (Prellezo, 2019). It seems that there is a certain threshold of harvesting which induces the biomass to collapse completely or nearly completely.

Secondly, almost the same behaviour can be seen for the amount of vertically migrated carbon since this relates to the mesopelagic biomass. The plot additionally shows that there is a high variability in the amount of carbon that is sequestrated. This makes sense since the model takes into account the variability between for example regions in its uncertain parameters, representing the large regional differences between sequestrated carbon (Boyd et al., 2019; Saba et al.,2021).

Thirdly, in the first few decades the most prevalent behaviour patterns for the amount of food provision by mesopelagic harvesting are all relatively low. At a certain point, a bifurcation arises, where a cluster of runs produce a relatively high amount of food provision, and a group of runs stay at the same low value, although with a higher variability than initially. The same reasoning can be applied for this bifurcation as the bifurcation for the biomass: a difference in profitability. The cluster of runs producing high food provision, either collapses quite soon, or stabilises. The collapse can be explained by a consequential collapse of biomass.

Lastly, Figure B.5 also shows the behaviour of atmospheric carbon levels over time. As could be expected this outcome shows a wide range of carbon levels, and does not bifurcate for different runs. The range of possible carbon levels logically becomes wider over time. In the first iteration, the range of atmospheric carbon levels in 2100 ranged unrealistically high. Therefore, the ranges of the most relevant uncertainties for this outcome were lowered slightly, so more realistic scenarios became more dominant.

Most influential uncertainties over time

Overall, the feature scoring plots over time illustrate that the two most influential uncertainties seem to be the profitability of mesopelagic fish versus regular fish and the risk reward mechanism. Feature scoring plots over time provide understanding about which uncertainties are most influential for each outcome, at a certain time in the run. At each time step, the two most influential uncertainties are selected. See Figure 5.2 for the resulting plots. Only the uncertainties that were selected for plotting the feature scoring plot are included as uncertainties in the following analyses, also see Table 4.2.

As can be seen in Figure 5.2, the most influential uncertainty for the 10th percentile of biomass is the consumption of mesopelagic fish in the first half of the runs. In the last third of the run time, the impact of consumption by the fish is gradually overruled by the impact of profitability of mesopelagic fish versus regular fish and the price change of mesopelagic fish. This dynamic is likely correlated with the rising profitability in 2030.

For food provision, the profitability of mesopelagic fish versus regular fish was found by far the most influential, mainly during the middle 50 years of the runs. This confirms the clusters of behaviour for food provision in Figure B.5. A lower influence of the uncertainty towards the end of the run time might be correlated to the stabilisation of profitability.

The risk reward mechanism was most influential for vertically migrated carbon throughout the whole run, mainly in the first two-thirds of the run time. Combining this insight with the Kernel Density Estimation in Figure B.5, the decreased influence towards the end might correlate with a decreased vertical migration.

For the atmospheric carbon levels in 2100, the conversion factor to ppm had the most impact initially, after which downwelling water followed through the rest of the run time.

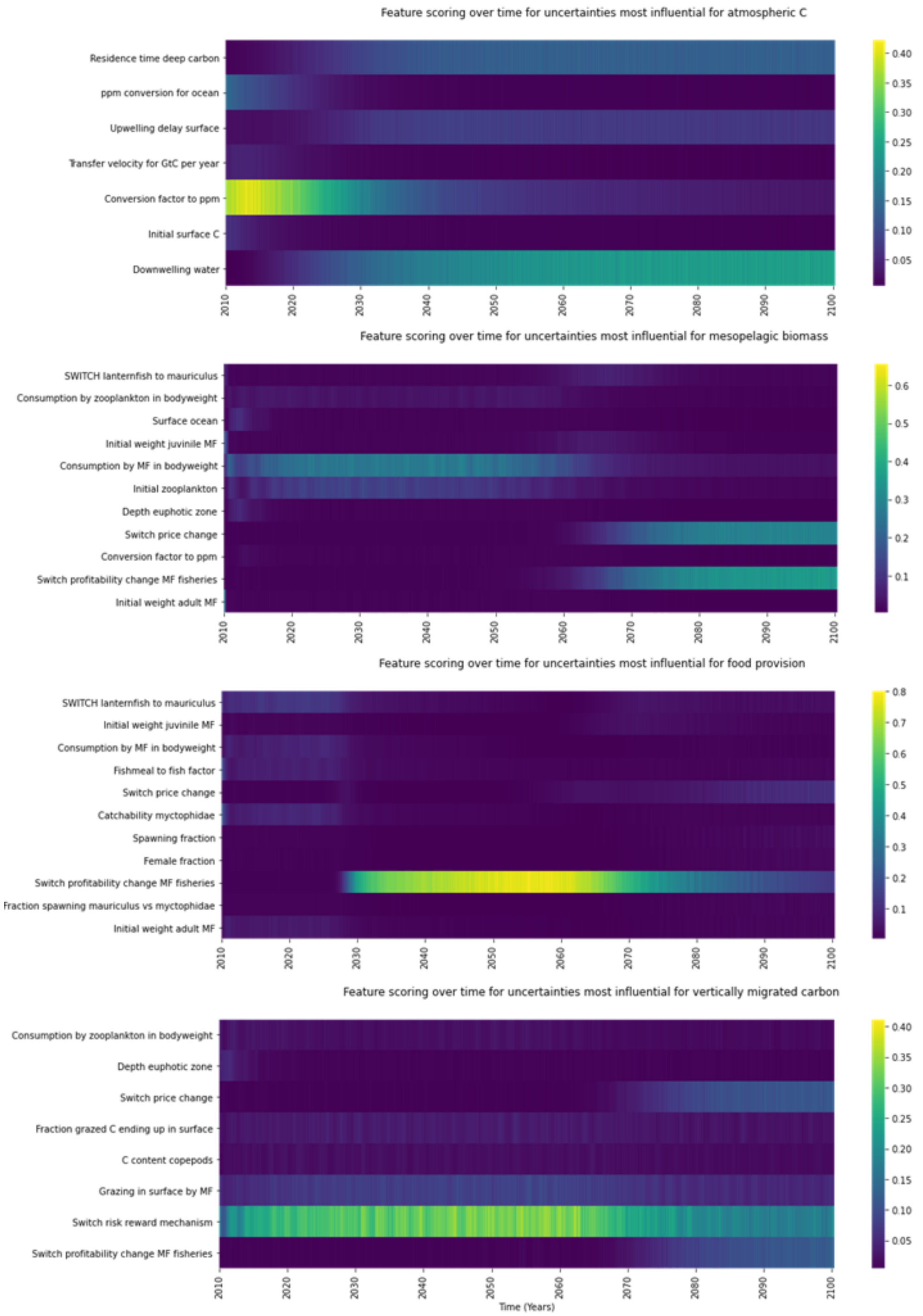

Figure 5.2: *Feature Scoring over time for the four outcomes. Uncertainties are included if they were found to be in the top 2 influential uncertainties in at least one time step. A light colour indicates a high influence. The plots on the right show the feature score corresponding to the colour.*

5.2 DEFINING OPTIMAL HARVESTING POLICIES

In this section, the policies found most optimal by the MORDM approach are presented, and the reasons why these policies were found to be most optimal.

5.2.1 Searching for candidate solutions

Out of the 800.000 runs performed in step 2, ten optimal policies were found. Figure B.6 in Appendix B.3 shows the policies over time that resulted from the optimisation. The ten policies are diverse in their performance on outcomes. This is reflected in Figure B.7, which presents the different trade-offs in outcomes per policy. In order to check the completeness of the optimisation process executed in step 2, a convergence metric was measured. Epsilon convergence was not completely reached, indicating that more dominant solutions could still be found if more runs were done, see Figure B.8 in Appendix B.3. Additionally, a seed analysis for five different seeds was done to check if MORDM found a convergent set of policies. The results still show slight variation over the different seeds, indicating that convergence was not fully reached, the plot can be found in Figure B.9 in Appendix B.3.

5.2.2 Assessing robustness by generating scenarios

Evaluating the ten selected policies on their robustness showed the outcome inertia produces extremely high signal to noise scores, while food provision without exception scores relatively low. A high score for all outcomes is ideal. This finding illustrates that food provision has a notably high variation over the scenarios and is thus the least robust outcome in terms of signal to noise. This might be explained by the fact that when the biomass collapses, food provision goes to zero. However, the biomass scores indicate a much higher robustness. Therefore, this variable behaviour is presumably induced by uncertainties affecting food provision solely. All other outcomes score above one and therefore experience less noise than signal over the 3000 scenarios. The trade-offs between the signal to noise ratio scores for each outcome are illustrated in Figure B.10 in Appendix B.4.

Evaluating the robustness of the ten policies in terms of maximum regret, showed that overall, the outcomes concerning food provision, vertically migrated carbon, and mesopelagic biomass have relatively the highest frequency of high scores over all scenarios. A low score for all outcomes is ideal. The maximum regret scores of the atmospheric carbon levels are high in trade-off with a low score for these three outcomes. This might partly be explained by considering the oscillating behaviour of the biomass as illustrated during the open exploration. In conclusion, there is no ideal policy in the sense that it is robust for all five outcomes in terms of maximised regret. The scores per outcome per policy are visualised in a heat map in Figure B.11 in Appendix B.4.

Data on robustness was obtained by running the ten policies selected in step 2 over 3000 scenarios. This was done in step 3 of MORDM. Based on both robustness metrics, the most robust candidate policies found in step 2 were selected. This was done by selecting the policies that score in the best 80% for each outcome, for both metrics. This selection method resulted in selecting two most robust policies.

5.2.3 Optimal policies over time

Figure 5.3 illustrates the two quotas that were found most optimal and robust after performing step 2 and 3 of MORDM. Despite optimising over inertia, the policies

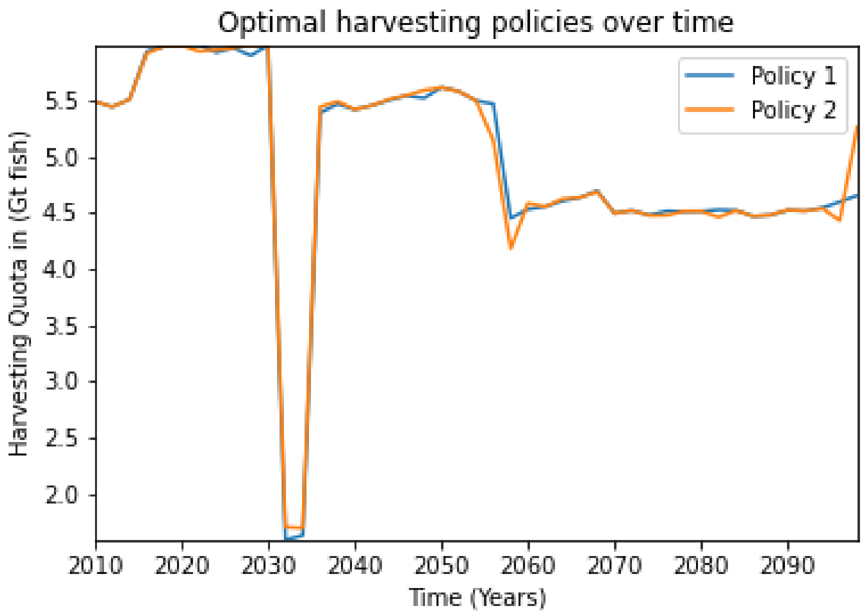

Figure 5.3: *The two selected policies plotted over time.*

take remarkably large jumps. Apparently, these significant differences in quota are beneficial for the other outcomes at specific points in time. Since it is not immediately clear why this is the case, the behaviour of several model parameters was explored to clarify these jumps.

Exploration of system behaviour in relation to selected policies

The exploration of system behaviour illustrated that the shape of the optimal policies can at least partly be explained by the parameter concerning the profitability of mesopelagic fish versus regular fish. Figure 5.4 shows the behaviour of this model parameter over time. Looking back at Figure 5.3, it can be implied that the sudden jumps are presumably linked to profitability. The similarity between the two figures suggests a relation between the optimal harvesting quota and the relative profitability of mesopelagic fish. This relation seems to be inverse. The quota steeply decreases while the profitability steeply rises. This might be because the profitability induces high levels of effort, while the quota balances out this trigger.

Figure 5.4 shows that as soon as mesopelagic harvesting becomes relatively more profitable in 2030, the peak collapses after a variable delay. This can be explained by the fact that due to profitability fisheries are modelled to expand their fleet exponentially. Consequentially the profitability goes down since the demand for mesopelagic fish is lower. It stabilises towards a relative profitability of around one. A cluster of runs rises from 2060 onwards, again with a variable delay. Presumably, this is caused by the second profitability scenario, which might only then cause mesopelagic harvesting to be profitable enough. Interestingly, these clusters show more stable behaviour the clusters of the other profitability scenario. This might be explained by a less steep rise in profitability and therefore a less explosive growth of fisheries capacity. The steep rise in profitability is a result of an extreme profitability scenario.

The behaviour of the system was explored under the two policies that were deemed optimal after completing MORDM. The two policies were run over 1000 scenarios to explore the the mesopelagic system's behaviour over time over different possible

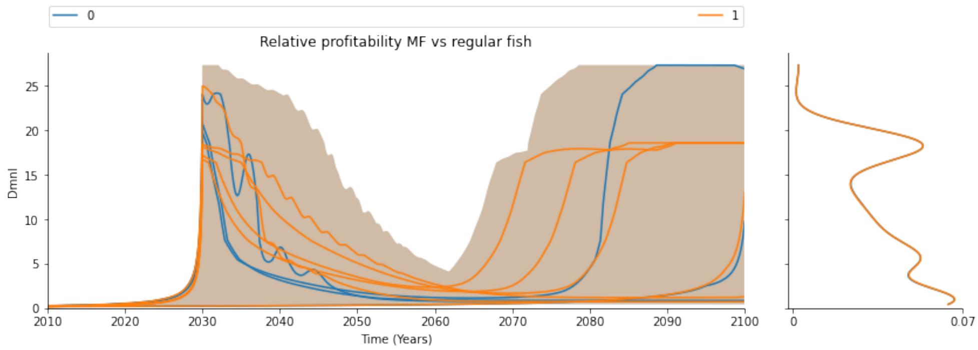

Figure 5.4: *Relative profitability overtime under selected policies. Blue lines indicate runs from policy 1, orange from policy 2. The different lines represent randomly selected runs to showcase some different types of behaviours. The background shows the entire range of all runs per policy in a slighter lighter colour. The plots on the right show the distribution of the end state of the two different policies.*

futures. The system was explored for several outcomes and parameters that were thought to have notable influence on the policies (i.e. mesopelagic biomass, effort, harvested fish, and the relative profitability of mesopelagic fish).

5.3 PERFORMANCE OF OPTIMAL HARVESTING POLICIES

In this section, the performance of the optimal policies is evaluated. This is done by performing scenario discovery to understand in which scenarios the policies perform desirably or undesirably. Secondly, the outcomes the policies produce are benchmarked against the outcomes of a situation with zero harvestings.

5.3.1 Discovery of a worst case scenario for the mesopelagic biomass

Scenario discovery was applied to the two policies selected in step 3. The two policies were run over 10.000 scenarios. In this research, an unsatisfactory outcome would be a low 10th percentile of mesopelagic biomass. Therefore, the PRIM method is applied to analyse the uncertainties that have the most influence in causing the 10th percentile of biomass lower than 9 Gt. Coverage of 0.8 was chosen for all following PRIM analyses.

The most influential uncertainties for low mesopelagic biomass

The two outcomes that were selected by the PRIM analysis as most influential uncertainties were the switch in profitability and the switch in price change. The scattering plot clarifies that when the Switch price change is set to 2 and Switch profitability change MF fisheries is set to 1, this causes lower biomass. This makes sense because these two scenarios trigger harvesting. The plot shows that profitability seems to have the most profound impact on producing a worst case scenario in terms of mesopelagic biomass. The corresponding figure can be found as Figure B.15 in Appendix B.5.

The trade-off between density and coverage of the PRIM analysed solutions illustrated that of the ten uncertainty dimensions the last two cover most of the uncertainty space and have a relatively high trade-off between density and coverage. The corresponding figure can be found as Figure B.14 in Appendix B.5.

The most influential combinations of uncertainties for a low mesopelagic biomass

High consumption by MF in body weight combined with low initial zooplankton and high profitability (scenario 0 is high), always causes an occurrence of a biomass 10th percentile smaller than 9 Gt, according to Figure 5.5. The dimensional stacking plot shows combinations that cause the 10th percentile of biomass of lower than 9 Gt. With the profitability switch set for the less profitable scenario, the occurrence of this undesirable outcome is also notably high. This is interesting since this implies that independently of harvesting profitability, the biomass in the model is more vulnerable if the fish are linked to a high consumption rate but are provided a low food availability.

Vice versa, a high to medium initial zooplankton combined with a low profitability causes a notably low prevalence of a low mesopelagic biomass, according to this plot. A similar dynamic is found for the combination of a low price change and low consumption by MF in body weight.

Dimensional stacking is another way to visualise subspace partitioning. It is a tool to visualise multi-dimensional data in 2D (LeBlanc et al., 1990). The dimensional stacking plot in Figure 5.5 shows which combination of uncertainties cause a particular outcome to perform undesirably or desirably.

5.3.2 Discovery of other scenarios

The worst case scenarios for food provision were influenced most by the uncertainties concerning the switch between myctophidae and Maurolicus muerelli, and the fishmeal to fish factor. The latter directly relates to the magnitude of food provision, however, the relation between food provision and the former uncertainty is not as straightforward. The dimensional stacking plot, Figure B.17, clarifies that solely the combination of a high percentage of myctophidae, high profitability, and a low price change guarantees a food provision higher than 0.4 Gt/Year. Additionally, uncertainties like a high female fraction, a high initial weight of juvenile mesopelagic fish, and a high magnitude of initial zooplankton positively influence success in food provision as well.

The best case scenario for vertical migration of carbon was found to be influenced most by the switch between the risk and reward mechanism, as well as grazing in the surface by mesopelagic fish. The magnitude of grazing seems to roughly have a linear effect on the amount of vertically migrated carbon. The risk reward mechanism set to 2 represents a linear and more substantial relation between food availability and migration, and therefore causes a notably high prevalence of vertical migration of carbon of higher than 3 Gt/Year.

These results were found by doing a PRIM analysis was for the worst case scenario for food provision and a best case scenario for vertical migration. The resulting figures from these analyses can be found in Appendix B.5 as Figures B.16 & B.17, and Figures B.18 & B.19, respectively.

5.3.3 Trade-off between food provision & carbon sequestration

Benchmarking the performance of the policies found by MORDM against a zero harvesting case illustrates that the greatest difference, naturally, is that no harvesting produces zero food provision. See Figure 5.6. Furthermore, there is a trade-off between harvesting and average vertical migration of carbon of about averagely 0.11 GtC/Year. Also, the atmospheric carbon level in 2100 shows an average trade-off of

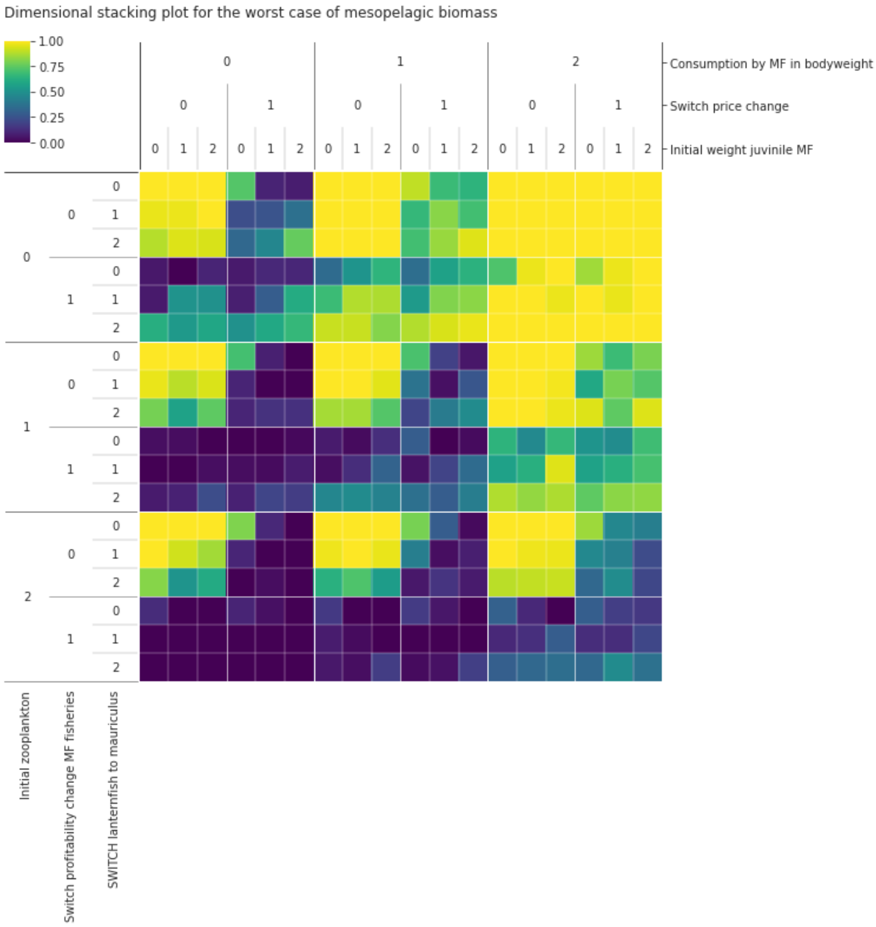

Figure 5.5: *Dimensional Stacking Plot of Candidate Policies. A lighter colour indicates a higher prevalence of the 10th percentile of mesopelagic biomass lower than 9 Gt. The plot shows which combination of uncertainties causes this undesirable outcome. The subplot on the left upper corner indicates the prevalence of the worst case scenario corresponding to the colours. 0 refers to the lowest interval of the corresponding uncertainty, 2 refers to the highest interval.*

1.85 GtC. The most prominent trade-off is seen for the 10th percentile of mesopelagic biomass, which is reduced by more than 2 Gt, and also has a much higher standard deviation. This implies an unstable biomass. Additionally, Figure 5.6 shows that the performance of the two selected policies differs little in outcomes. More statistics can be found in Table B.1 in Appendix B.6.

Furthermore, the box plots of all four outcomes show that the outcomes are distributed over a notably high range, even though the policies were optimised for robustness. Especially the distribution of the biomass reaches remarkably low, which is undesirable. However, it has to be noted that the mesopelagic biomass reaches to less than 2 GtMF without harvesting as well.

The data used for the boxplots in Figure 5.6 was obtained by running the three cases over 10.000 scenarios. This was done in order to evaluate the trade-off that these four outcomes experience with and without harvesting. The box plot of inertia can be found in Appendix B.6 as well.
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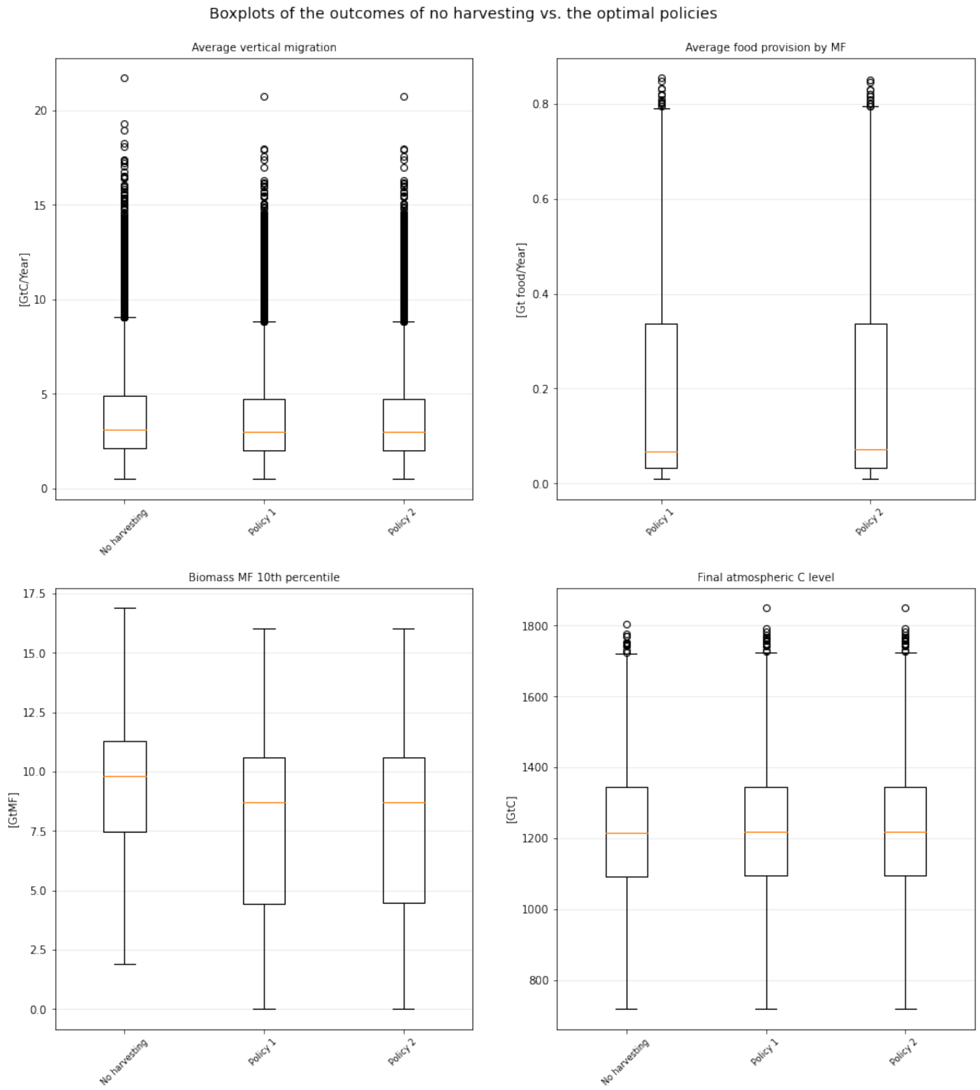

Figure 5.6: *Box plots of outcomes produced by the two selected policies, compared with a zero harvesting case. The line depicts the median. The box shows the upper and lower quartiles, and the whiskers the range of the data. The dots represent outliers.*

6 DISCUSSION

This chapter firstly places the studies' most critical results into the context of existing literature. Moreover, it presents the results' implications from a governmental, industrial, environmental and societal perspective, and its reflections on methodology. Additionally, it discusses the limitations of the research and presents recommendations for future work.

Firstly, assessing the performance of the policies over different futures demonstrated that several (combinations of) uncertainties have a crucial impact on the mesopelagic system's best and worst case behaviour. It seemed that profitability scenarios of mesopelagic harvesting relative to regular fishing and price changes are the most prominent indicators for collapses of the mesopelagic biomass. Finding these uncertainties to be profound indicators implies that they might be useful for computations of adaptive quotas or stock assessment. Research of Fryxell et al. (2017) seems to confirm that profit is related to overharvesting.
Additionally, it uncertainties concerning food availability profoundly impact the ability of the mesopelagic biomass to endure harvesting. A high food availability causes a lower prevalence of biomass collapse, and vice versa, independently of the profitability scenario. This finding is noteworthy since it confirms that harvesting quotas must take into account the carrying capacity of the biomass, which might differ greatly per region (e.g., Morel et al., 2010). This finding is in agreement with the fact that food availability positively influences metabolism and thus growth, as well as reproduction rates (Yoneda & Wright, 2005).
Other notable uncertainties influencing worst case behaviour, in this case for food provision, are the type of specie that is represented in the model and factors concerning reproductive parameters of the mesopelagic fish, like the female fraction. Additionally, the workings of the risk reward mechanism have a profound effect on the best case scenarios for vertically migrated carbon, which is in line with the findings of Davison et al. (2013).

Secondly, the optimisation for optimal policies showed that profitability is related to the shape of the optimal harvesting quotas. It seemed that an optimal harvesting quota acts as a balancing tool for profitability. The same dynamic is in line with earlier research. For example, Sethi et al. (2010) demonstrate that profit is a good indicator for fishery development. Fryxell et al. (2017) also imply that optimal bioeconomic profit and biomass conservation can be reached by calculating targets using price and harvest statistics. Moreover, explosive profitability caused an explosive growth of fishery capacity, which seems negatively correlated with a stable magnitude of food provision. Costello et al. (2016) confirm this finding. They found that globally, stock recovery in the long term increases biomass conservation, profit, and food provision.

Thirdly, the exploration of the uncertainty space clarified which uncertainties have the greatest influence on the objectives when no harvesting limits are in place and in what situation their impact is the highest. The two most significant uncertainties are the profitability of mesopelagic fish versus regular fish and the type of risk reward mechanism. The finding that uncertainty in migrational patterns is of strong influence on the objectives is in line with Davison et al. (2013), who already noted the relevance of migration patterns of mesopelagic fish for carbon export. As mentioned, previous literature has also shown profitability to negatively influence the objectives (e.g., food provision and biomass).

Fourthly, by applying MORDM on the resulting model it was found that there is indeed a trade-off between food provision and carbon sequestration. The model implies that harvesting according to the selected policies produces an average increase of about 1.85 GtC in atmospheric carbon levels in 2100. This is a substantial value when considering global anthropogenic emissions were about 49 GtC in 2010 (IPCC, 2014). Although the value of the results produced by this study lies in the qualitative aspect rather than the quantitative, this still indicates a trade-off significant enough to consider in decision making. Averagely the vertically migrated carbon decreased by 0.11 GtC/Year for the estimated 0.175 Gt/Year of food provision. This reduction in vertically migrated carbon would mean the biological carbon pump is compromised by at least 1%, since it is estimated to export 5 to 12 GtC/Year (Boyd and Trull, 2007; Henson et al., 2011; Siegel et al., 2016). The magnitude of food provision might seem unrealistically high since the total fish and seafood production currently is about 0.155 Gt/Year globally (Ritchie, 2019). However, it must be noted that the mesopelagic biomass comprises 90% of the total fish biomass (SUMMER, 2019). All in all, these findings strengthen the call for considering climate change as well as biomass conservation when thinking about mesopelagic governance.

6.1 IMPLICATIONS FOR GOVERNANCE

Firstly, the findings in this research imply that current marine governance is far from adequate to manage the revealed magnitude and variety of the impacts harvesting can have on mesopelagic biomass, the service of carbon sequestration, and consequentially atmospheric carbon levels. There are currently no conventions considering both biomass conservation and climate change in place in the governance arena (Elsler et al., n.d.). For mesopelagic harvesting specifically, there are no targeted international conventions in place at all yet. Meanwhile, profitability presumably rises in the future (Prezello, 2019), and some species have been economically viable for a while (Armstrong & Prosch, 1991) and thus targeted for harvesting. Moreover, oceanic carbon sequestration's functioning becomes more and more uncertain under climate change (IPCC, 2019), while atmospheric carbon levels rely heavily on this service (Passow & Carlson, 2012). Not having adequate policies in place can have immense financial consequences. Research has shown that the expected reduction of 17-43% in oceanic carbon sequestration for the current century converts to a monetary value of US$193-3401 billion for the Atlantic Ocean alone (Barange et al., 2017). The mesopelagic system sequesters 15-17% of total carbon export (Davison et al., 2013), and would thus contribute substantially to such costs. Concluded, current developments combined with the findings in this research thus stress that current conventions like the UNFCCC, CBD, and UNFSA urgently need to start considering mesopelagic harvesting in their decision making processes.

Secondly, this research implies that the management tools currently used most often by international conventions like the UNFSA for managing fisheries (i.e., static harvesting quotas and marine protected areas) might improve significantly by considering several uncertainties. Taking into account profitability and food availability for mesopelagic fish when deciding on fisheries management, showed to mitigate most of the risk of biomass collapse. The same goes for a high rate of food provision when accounting for reproductive parameters. Factors like these consequentially might be useful to include in computations of harvesting control rules. Harvest control rules calculate allowable catch values based on indicators (Pewtrusts, 2016).

This is used for many quota systems such as that of Atlantic cod (ICES, 2017; MFRI, 2020). The most dominant and furthermore practical parameter to consider for determining harvesting quotas showed to be the profitability of mesopelagic fish versus regular fish in addition to ecological parameters. This finding is more pressing because Voss et al. (2014) indicated that species with a low market value have a higher risk of collapse when they are managed based on profit maximisation strategies. However, since trends for this parameter could be estimated, this might be a practical and effective factor for setting an optimal harvesting quota, according to this research. Additionally, since this research showed that the two most influential uncertainties are the migrational patterns of mesopelagic fish and profitability, a major uncertainty space can be reduced by focusing future research on migration patterns and expected profitability.

Finally, when speculating about what would happen if these policies would be implemented, it is clear that success is not guaranteed. The effect of high uncertainty in the mesopelagic system is reflected in the set of policies; none of the policies turned out to be completely robust. The variety and range of outcome behaviour over different scenarios confirmed this. Moreover, managing regular fisheries has been very unsuccessful the last few decades - most fish stocks are depleted (Worm et al., 2009). It goes without saying that a remote environmental system beyond national legislation like the mesopelagic can be expected to be an even greater challenge. When thinking about implementing policies, decision makers should thus aim for precautionary governance considering the current developments for coastal fisheries and the findings on the policies' robustness and outcome behaviour.

6.2 implications for the industry & environmental stakeholder groups

With little to no mesopelagic governance in place, the industry currently has a carte blanche for harvesting in the mesopelagic zone. However, this research illustrates that the profitability of the mesopelagic fish yet has to rise dramatically before becoming a viable market. The success of mesopelagic harvesting has also shown to be a risky investment for players in the industry - food provision showed to be overall the least robust objective. However, this research found several factors that could reduce the risk for the industry. For example, explosive fishery capacity growth showed to induce biomass collapses which consequentially destabilised food provision. Also, the success of food provision is higher if the majority of the fish are assumed to be more similar to myctophidae rather than Maurolicus muerelli. In practice, this shows that it might be beneficial to model different species to see what influence the type of species has on food provision. All in all, the industry has a free hand in mesopelagic harvesting, however, players are expected to await much higher profitability levels, and even then, mesopelagic harvesting will be a risky investment. Changes in profitability are likely to occur in the future when harvesting quotas for regular fisheries change, or due to innovations in high sea fishing and growing aquaculture markets (Prelezzo, 2019).

For the stakeholders focused on the environmental impacts of mesopelagic harvesting, this study strengthens the argument to take into account climate change in mesopelagic governance by underscoring that there is indeed a noteworthy link between harvesting and a reduced carbon sequestration and eventually atmospheric carbon levels. The high occurrence of biomass collapse, even with policies in place, stresses the need for a careful approach when large-scale mesopelagic harvesting is initiated.

6.3 implications for society

Food security is one of the pressing challenges humanity is currently faced with. Considering another main challenge, namely climate change, food systems should not only secure healthy diets but also avoid threatening key environmental processes. This study is not adapt for providing exact quantitative values, however, according to this study the mesopelagic biomass could provide a significant amount of food, provided that harvesting is found profitable enough by fisheries. The global current fish demand is about 0.12 Gt/Year (York & Gossard,2004), and presumably rises to more than 0.16 Gt/Year as the population grows (United Nations, 2019). The magnitude of food provision that this study found (averagely 0.175 Gt product/year) might be overestimated, nonetheless, it can be concluded that the biomass has the potential to resolve at least a considerable portion of the global fish demand. The carbon intensity of harvesting mesopelagic fish showed to be about 0.63 GtC/Gt product, while for other sources of proteins like meat this value is 25.51 GtC/Gt product (Foa.org, 2017). It has to be noted this mesopelagic carbon intensity only considers the effect on carbon sequestration, and does not include transportation and production emissions.

However, these implications need to be considered while keeping in mind other adverse effects the aquaculture industry might have on society as well. Aquaculture plants cause local fish markets to collapse and cause disturbance for the local community by for example generating high levels of waste that deteriorate the local environment (Yokoyama, 2000), inducing deoxygenation (Nishimura, 1982) and unwanted phytoplankton blooming (Hirata et al., 1994). Moreover, farmed fish often contain high levels of antibiotics and hormones (Romero et al., 2012) and can threaten local fish when escaping from the farm (Taranger et al., 2015).

6.4 implications for robust decision making

This study shows that MORDM has the potential to find an interesting set of policies optimal within a complex decision arena containing multiple opposing objectives. These policies need to be re-evaluated but are promising starting points for learning about the mesopelagic governance arena. It has to be noted that the types of insights gained in this study are strategic insights for global governance, while the conventions present in the arena consider governance to be implemented nationally. Therefore, the strategic and global character of the insights are presumably most valuable for the agenda-setting stage in the policy cycle (May & Wildavsky, 1978), and not for actual policy designing yet.

Apart from the set of policies, it is shown that MORDM is suited for providing a valuable understanding of the mesopelagic system, its behaviour over possible futures, and revealing vulnerabilities of policies. This is also valuable information since public perceptions of marine harvesting and its risks determine the corresponding political decision making (Gelcich et al., 2014; Lotze et al., 2018). As little is known about the remote mesopelagic system, public understanding and connection to this environment is low, while this is essential for sustainable ocean governance (Kaikkonen & van Putten, 2021). In particular, scenario discovery showed to be apt to summarise the vast set of information produced by the high amount of computational runs, like Parker et al. (2015) illustrated as well. These revealed triggers consequentially cause undesirable scenarios and therefore reveal the principal points of attention during decision making (e.g., peaks in profitability, low food availability, and low reproduction rates of the targeted fish) so that such points can be ameliorated in further iterations.

Moving away from this particular model, this study confirmed that MORDM can be used to facilitate learning by stakeholders about a promising set of policies and their trade-offs (Liebman, 1976; Reed & Kasprzyk, 2009) to help place this environmental issue on the political agenda (van Daalen et al., 2002), and providing insights useful to facilitate relevant discussions between stakeholders within the decision arena (Singh et al., 2015). For example, by illustrating the fishing industry their impact and demonstrating what possible contribution they can make to prevent such impact. Such a discussion between stakeholders was previously impossible due to the deeply uncertain character of the mesopelagic zone. This added value of MORDM has been shown before by applying it to water management issues (Singh et al. 2015; Herman et al. 2014; Kasprzyk et al. 2013), but here its added value is demonstrated for a novel field.

6.5 LIMITATIONS

This study shows several limitations in different areas, primarily in the model and the exploration of the model. This section discusses the main limitations and their effects per area.

6.5.1 Limitations in the exploration of the model

The SD model was used to explore behaviour of the mesopelagic system over plausible futures by using MORDM. This study has the following limitations in that area.

This study shows some limitations in its robustness assessment. The selection method for robust policies resulted in selecting policies that were most robust for each outcome. However, this method therefore assumes that robustness is of equal importance for each outcome, and also caused a loss of policies which in total scored higher robustness. The selected policies had a high maximised regret in terms of mesopelagic biomass, and therefore there was a high prevalence of collapsed biomass nonetheless. Another caveat in terms of robustness is that the robustness metric signal to noise metric might not have been suited to assess the robustness of the mesopelagic biomass, since this outcome naturally oscillates highly over time. The same is true for the vertical migration of carbon.

Moreover, a critical limitation of the set up of MORDM is that epsilon convergence was not completely reached in the optimisation in step 2. This implies that there might be more optimal policies that were not found in step 2 due to computational time limits. Related to this limitation is the choice of an epsilon value in step 2. The value of 0.05 has caused the optimisation to find only 10 candidate solutions out of 800.000 runs. If the epsilon value had been lower, more candidate solutions could have been found, and consequentially this would have resulted in more policies to select from in the successive steps. In conclusion, a trade-off between accuracy and computational effort had to be made, which resulted in a smaller and less optimal group of candidate policies than needed.

6.5.2 Limitations of the model

The SD model served to prove the added value of MORDM for a system like the mesopelagic. Due this research's the proof of concept nature, several simplifications were made in the SD model. Most limitations of the SD model were already discussed for the validation of the model. However, some of these proved to be of significant influence on the results of this study. The prime limitation of the model is that the mesopelagic biomass proved highly resilient for harvesting. The effect this had on the optimisation is that the optimal harvesting quota is high for an implausibly long and consecutive period. There are several reasons for this limitation.

First of all, resilience is caused by the omission of regions and separate species in the model. This has presumably caused the mesopelagic system to be more resilient than it should be since this implies the biomass acts as one large sink with an equal distribution of harvesting effort. Such a sink is only reduced permanently when the entire biomass disappears, while actually schools of fish or species of fish could disappear permanently. In reality, harvesting causes effects like range contraction behaviour (e.g., schooling). This has been modelled before, and has shown to have significant impact on enabling harvesting to extinction (Burgess et al., 2017)

Additionally, the mesopelagic biomass has been exposed to comparative little changes in the environment, so the emergence of vessels and trawling nets can be expected to influence the mesopelagic fish. Peña (2019) has already shown that vessel lights have changed the fish's migration patterns. Moreover, climate change has shown to affect the ocean in terms of for example pH, temperature, phytoplankton, light attenuation, and oxygen levels (Doney et al., 2017). These changing environmental factors can be expected to affect an ecosystem as pristine as the mesopelagic negatively. Some of these factors are known to link to migration patterns of the fish already, like light levels and oxygen (Aksnes et al., 2017; Kaartvedt et al., 2017). However, this aspect is not included in the SD model, which has caused the biomass to behave more resilient than realistically can be expected.

Finally, harvesting as well as lobbying was modelled quite simplistically in the model. Harvesting was assumed to be spread equally over the entire biomass. Also, lobbying was modelled by assuming lobbyists and decision makers were aware of the state of the mesopelagic biomass, however, in real life this is not directly measurable. Additionally, the decision making model assumes that decision makers and environmentalists are aware of the link between mesopelagic fish and carbon sequestration.

6.6 RECOMMENDATIONS FOR FUTURE WORK

First of all, an addition to advance this study would be performing Directed Policy Search (DPS) to support decision making. For DPS, decisions are made based on a function that describes the state of the system. The state variables within that function are optimised instead of a set of consecutive decisions. The latter has been done in this study. Therefore, by using DPS the optimisation produces an optimised decision rule, which is often a more pragmatic result when the aim is to support decision making. Such a decision rule can take different forms; it could for example lower the harvesting quota as soon as a parameter like the estimation of biomass reaches a certain threshold. Some fisheries (e.g., in Iceland) already compute the harvesting quota using environmental and reproduction parameters. These approaches could be used as the basis for the decision rule used in DPS. Using DPS, aspects like delays in decision making could be taken into consideration as well. Governance systems are often resilient; decisions are taken with a delay rather than precautionarily. Taking this into account when optimising a decision rule, might then result in finding triggers to change the quota even before causing any noticeable damage.

Secondly, this study could be ameliorated by including multiple problem framings. A decision problem such as mesopelagic harvesting can be formulated in variable ways, for example from different stakeholders perspectives. As Quinn et al. (2017) clarify, rival problem formulations with differing objectives, constraints, and computations of these objectives can produce quite different results. Analysing several formulations allows finding unexpected and unwanted consequences that alternative formulations might bring about. MORDM would therefore presumably produce more holistic insights when multiple framings are incorporated in future work.

Moreover, for future work, it might be interesting to optimise a quota using an adaptive range, depending on the Maximum Sustainable Yield (MSY). The range that the harvesting quota is sampled from now is a static range. The MSY is defined by the estimation of the maximum level of the biomass. This would be more realistic since this strategy is actually used in fisheries management; quotas set by the RFMO are often the MSY divided by two. Recent research has even shown that catch-quota balancing systems, which thus use adaptive quotas, show to help balance economic and ecological goals in fisheries management, and might therefore be a promising dynamic to include (Oostdijk et al., 2020). Including adaptive ranges would require an expansion of the SD model that represents how the mesopelagic biomass is estimated.

Furthermore, a recommendation for future work would be to rectify simplifications of the mesopelagic system that were made in the SD model. First of all, it would be recommended to model the vulnerability of the mesopelagic biomass more explicitly. This can be done in several ways; for example by modelling a biomass of which compartments (i.e. regions, species or schools of species) might be reduced permanently. Also, the fact that the biomass presumably has a low resilience for environmental changes could be incorporated by including scenarios of climate-induced oceanic changes, like changes in temperature, pH, light attenuation, phytoplankton biomass, and oxygen levels (Doney et al., 2017), and their effects on the mesopelagic system. Also, the lobbying sub model might be ameliorated by using measurable state variables for lobbying, instead of for example the exact biomass. Moreover, in terms of harvesting, it might have been more realistic if harvesting levels differ per region. Finally, it would be more plausible including a phase where fisheries harvest while no quota is yet in place, regarding the current governance situation. All in all, these additions to the model might add to a more interesting and plausible exploration of harvesting in the mesopelagic zone.

Lastly, this study could be improved in future work by reiterating the MORDM cycle including some straightforward modifications. This might considerably ameliorate the outcomes of the MORDM method. In order to find a more complete and larger set of candidate solutions it would be recommended to improve this study by increasing the number of runs in step 2 of MORDM, and lower the epsilon value. Secondly, the robustness selection method should prioritise the robustness score of the 10th percentile of the biomass since the policies selected in this study still caused biomass collapse in many scenarios. It might be best to include this as a constraint in future work since this is an unacceptable outcome. Thirdly, since the optimal policies show enormous jumps in harvesting quotas, it could be recommended to include inertia as a constraint rather than an objective. A policy that advises imposing an harvesting quota that takes 4 Gt/Year jumps over a range of 2 years is not quite pragmatic. Also, choosing less correlated outcomes might reveal a more interesting trade-off, since the three outcomes 10th percentile of mesopelagic biomass, average vertical migration of carbon and average food provision are all related quite directly.

7 CONCLUSION

The recently discovered harvesting potential of the mesopelagic zone has sparked interest from the fishing industry and governments. At the same time, this immense biomass is of great value to the planet's ecosystem and the oceanic carbon cycle and it is uncertain what effects harvesting might have on such a pristine ecosystem. This research therefore aimed to gain governance relevant insights on decision making for harvesting in the mesopelagic by analysing the current governance arena, the working of the mesopelagic zone, and finally applying these findings to model the global mesopelagic system and its role in the global carbon cycle to explore the behaviour of the system over different plausible futures.

7.1 THE CURRENT & FUTURE MESOPELAGIC GOVERNANCE ARENA

The governance analysis demonstrated that the mesopelagic zone is ignored in current marine management negotiations (Blue Marine Foundation, 2020), despite the thriving interest in harvesting mesopelagic fish. The weak regulation, ambiguity of the ecosystem and climate change cause the decision arena to be highly complex. Governance challenges lie in the vastness of the source and its location beyond national borders. Furthermore, existing conventions like the UNFCCC, CBD, and UNFSA omit considering the link between carbon sequestration and harvesting. The most commonly used tools for harvesting management are Marine Protected Areas and quotas. Exploring the model demonstrates a high range of possible futures and consequentially high uncertainty. It illustrates that there is a high chance of collapse with and without harvesting policies in place. This implies that this current state of governance is far from ready to take on large-scale mesopelagic exploitation. Initiatives like the Blue Growth Strategy set up by the European Commission should therefore be more hesitant in pushing for exploitation without any adapt management in place.

7.2 THE WORKING OF THE MESOPELAGIC ZONE

In order to gain insights on governing the mesopelagic zone, the system needed to be appropriately modelled. The model development required comprehension of the mesopelagic zone. There are naturally multiple ways to model the mesopelagic system. This study resulted in developing a model on a global level, that not only captures the mesopelagic workings but also its connections to other areas, like fisheries and the global carbon cycle. The insights obtained from the model imply that a model consisting of sub models on the oceanic carbon cycle, mesopelagic biomass, fisheries capacity, and decision making processes are adequate to at least partly capture the impacts of global harvesting and its cumulative effects on the carbon cycle. Unification of these perspectives, like called for by previous studies (Saba et al., 2021), indeed provided novel and holistic insights relevant for the mesopelagic governance arena.

7.3 BEHAVIOUR OF THE SYSTEM OVER POSSIBLE FUTURES

Exploring the behaviour of the model over uncertainties and policies demonstrated the main dynamics across different possible futures. With and without harvesting, the most dominant dynamic is a mesopelagic biomass that produced more stable behaviour than expected. Solely in the case high profitability and high harvesting effort, the biomass is noticeably affected. Even in such circumstances in combination with limitless harvesting, biomass collapse occurs only for a cluster of runs.

Under governance of the policies found my MORDM, all outcomes produced wide ranges and variety of dynamics. Nonetheless patterns can be identified. Again, the mesopelagic biomass produces stable behaviour in the beginning, though in some cases it seems to reach a certain threshold afterwards the biomass still collapses. This is reflected in the fact that the set of policies are not ideally robust, however this is to be expected for a deeply uncertain system like the mesopelagic. Vertical migration of carbon shows identical behaviour to that of the mesopelagic biomass, due to their strong link. Dynamics of food provision depend on profitability scenario as well as biomass, and therefore primarily shows steep rises at two different moments, and some collapsing runs towards the end of the run, presumably because of biomass collapse. Atmospheric carbon levels show to be substantially influenced by harvesting, though its behaviour over time is not influenced as much as the other outcomes. Lastly, despite optimising over inertia, the policies take remarkably large jumps. These large differences in quota are beneficial for the other outcomes at certain points in time, and are caused by the strong inverse influence of profitability on the ideal harvesting level.

7.4 INSIGHTS FOR GOVERNING THE MESOPELAGIC ZONE

Despite deep uncertainty and a complex governance arena, a set of policies and behaviour was found that first of all contribute simply by improving understanding of the system. Such understanding is valuable for understanding the high range and behaviour of the system, which for example showcases that precautionary governance is needed. Findings on which combinations of uncertainties cause worst and best case behaviour illustrate that management tools can improve greatly by accounting for a few dominant uncertainties like reproductive parameters and food availability, for example by including those in quota computations. These insights also reveal principal points of attention for decision makers to focus on (e.g. peaks in profitability). Moreover, understanding of the mesopelagic zone in general is crucial for decision making. Public understanding and connection to this remote environmental system is extremely low, while public perceptions of marine harvesting substantially determine corresponding political decision making (Gelcich et al., 2014; Lotze et al., 2018; Kaikkonen & van Putten, 2021).

Due to the deep uncertainty linked to the mesopelagic system, a discussion between stakeholders about mesopelagic harvesting was formerly difficult. The found ensemble of behaviour and set of policies serve as a promising starting point for such a discussion (Singh et al., 2015). For instance by clarifying the negative impacts stakeholders can have and how they can mitigate these. The profitability and subsequent explosive fishery capacity for example seems to cause a less stable food provision, which is in none of the stakeholders' interest. In turn, this showed to be possibly partly mitigated by taking into account regional differences in food provision for the mesopelagic fish, and differentiating management per specie based on the reproductive parameters and magnitude of food consumption.

Lastly, the governmental insights have the potential to placing this environmental issue on the political agenda. The substantial contribution of mesopelagic harvesting both on reduced carbon sequestration and increased food provision, confirm the two-sided potential of the mesopelagic zone to contribute to food security as well as as climate change. The high variety of behaviour and low robustness of the policies underscores that targeted mesopelagical governance will be challenging, but crucial for sustainable ocean governance. Such insights gained from this study have a global and strategic character which makes them primarily suitable for the agenda-setting stage in the policy cycle (May & Wildavsky, 1978).

In conclusion, when the profitability of mesopelagic harvesting rises, the mesopelagic system has the potential to play a part in food security, while at the same time, this will threaten the critical role it has in oceanic carbon sequestration. The majority of fish stocks worldwide still need to be rebuilt (Worm et al., 2009). If mesopelagic fisheries are to be managed similarly as coastal systems, the same disastrous developments are bound to occur. Added upon that, the consequences of mesopelagic overfishing will defect part of the oceanic carbon pump. Even higher pressure on the climate is the very last thing needed. This study underscores the call for more careful strategies to successfully make use of the food provision potential of the mesopelagic and avoid extra climate pressure. Risks like biomass collapse and reduced carbon sequestration are critical to take into account when designing such harvesting policies. Awareness of how highly uncertain this system is and where its vulnerabilities lie is paramount to governing the mesopelagic zone. The set of policies found within this complex decision arena provides an understanding of the system and its key vulnerabilities and facilitates a promising starting point for successful mesopelagic harvesting.

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A SYSTEM DYNAMICS MODEL

This appendix presents background material concerned with the system dynamics model.

A.1 MAUROLICUS MUELLERI VS. MYCTOPHIDAE

Table A.1 presents the parameters that are included to model the distinction between Myctophidae and Maurolicus muelleri.

Table A.1: Parameters of the SD model that distinguish between Myctophidae & Maurolicus muelleri

Parameter	Value	Reference
Catchability (Dimensionless)		
Catchability myctophidae	0.14	Hidaka et al., 2001
Catchability mauriculus	0.28	Assumption based on Hidaka et al., 2001
Growth period (Years)		
Growth period myctophidae	0.583	Catul et al., 2011
Growth period mauriculus	1	Armstrong & Prosch, 1991
Life expectancy (Years)		
Life expectancy myctophidae adult	4	Catul et al., 2011
Life expectancy mauriculus	2	Armstrong & Prosch, 1991
Spawning (Dimensionless)		
Spawning myctophidae	13.6269	Dalpadado, 1988; Sassa, 2019
Spawning mauriculus	10.2202	Assumption & Armstrong & Prosch, 1991
Living depth (meters)		
Living depth myctophidae	950	Catul et al., 2011
Living depth mauriculus	350	Armstrong & Prosch, 1991
Costs status quo ($/GtMF)		
Costs status quo myctophidae	4.5e+11	Prelezzo, 2018
Costs status quo mauriculus	3e+11	Assumption based on Prelezzo, 2018

A.2 UNCERTAINTIES

A.2.1 Structural Uncertainties

Table A.3 presents all structural uncertainties that are included in the SD model.

Table A.2: Structural uncertainties in the SD model

Uncertainty	Switch	Included	Reference
Switch risk perception climate	linear, cubic & logistic	no	Beckage et al., 2018
Switch risk perception biomass	linear & asymptotic	no	Assumption
Switch risk reward mechanism	asymptotic, linear (and more influence) & constant	yes	Assumption & Aksnes et al., 2017; Kaartvedt et al., 2017
Switch influence sunlight on phytoplankton	linear & asymptotic	no	Charalampous et al., 2018; Edwards et al., 2016
Switch influence CO_2 on phytoplankton	linear & asymptotic	no	Schippers et al., 2004
Switch profitability change MF fisheries	linear & threshold	yes	Assumption
Switch price change	asymptotic high & asymptotic low	yes	Assumption

Risk perception climate change & Biomass Change
Since more extreme events in the public memory lead to altered emission behaviour (Beckage et al., 2018), it could be argued the lobbying for higher harvesting regulations increase with higher risk perception of climate change. In this model, risk perception of climate change is influenced by changes in temperature, which in turn depends on atmospheric carbon levels. Beckage et al. represent perceived risk for climate change as either a logistic, linear or cubic function. The same theory is applied in this study. Additionally, the same theory is used for the risk of biomass reduction, with linear and asymptotic forms. To make this structure more realistic, mesopelagic biomass and temperature changes as input for the risk perception functions are delayed by five years.

Influence of sunlight & CO2 concentration on phytoplankton growth
CO2 concentrations and sunlight are two factors that have an influence on phytoplankton growth. The minimal and maximal influence of both these factors are known (Charalampous et al.,2018; Edwards et al., 2016; Schippers et al.,2004), the shape of the relationships however are not. Therefore, both these relationships are modelled in different shapes; linear and asymptotic.

Population growth
Population growth for the coming century is another scenario uncertainty that is incorporated into the model. This factor not only influences the fish(meal) demand, but also the magnitude of anthropogenic fossil fuel use, and change in terrestrial biomass due to land use change. The population growth scenarios are based on the predictions of the UN (United Nations, 2019), and include low, medium, and high growth scenarios.

A.2.2 Parametric uncertainties

Table A.3 presents all parametric uncertainties that are included in the SD model.

Table A.3: Uncertainties in the model

Parameter	Type	Default value	Deviation around default	Included	Reference
Oceanic carbon cycle sub model					
Fraction of migrating MF constant	parametric	0.4 dmnl	40%	no	Anderson et al., 2019
Grazing in surface by MF	parametric	0.37 dmnl	40%	yes	Anderson et al., 2019
C content copepods	parametric	0.51 GtC/GtZoo	20%	yes	Omori, 1969
Surface ocean	parametric	3.63e14 m2	10%	yes	Kwon, 1994
Depth euphotic zone	parametric	100 m	10%	yes	Kwon et al., 2009
Total atmospheric volume	parametric	3.99e18 m3	20%	no	Kwon & Schnoor, 1994
Export efficiency	parametric	0.97 dmnl	40%	no	Kwon et al., 2009
Transfer velocity for GtC per year	parametric	1.12169 Dmnl	20%	yes	Bender et al., 2011
Initial surface C	parametric	600 GtC	5%	yes	Raven et al., 2005
Initial sediment C	parametric	3390 GtC	20%	yes	Shaffer & Wallace et al., 2000
Conversion factor to ppm	parametric	2.0619	10%	no	IPCC, 2001
Other carbon fluxes	parametric	5 Gtc/year	10%	no	Assumption
Carbon loss underway	parametric	0.04	40%	no	Assumption
Carbon loss at living depth	parametric	0.4	40%	no	Assumption
Average sinking time	parametric	380 years	20%	no	Raven et al.,2005
Delay sedimentation	parametric	10.000 years	20%	no	Raven et al., 2005
Delay weathering	parametric	10.000 years	20%	no	Raven et al., 2005
ppm conversion for ocean	parametric	2.1	10%	no	ldeo.columbia.edu, n.d.
Downwelling water	parametric	1.7e15	20%	yes	Assumption
Residence time deep carbon	parametric	1000 years	10%	yes	Raven et al., 2005
Upwelling delay surface	parametric	8 years	10%	yes	Raven et al.,2005
Mesopelagic ecology sub model					
Average weight per juvenile MF	parametric	0.07e-6 GtMF/GMF	20%	no	Karuppasamy & Menon, 2008
Average weight per adult MF	parametric	1e-6 GtMF/GMF	20%	no	Karuppasamy & Menon, 2008

Life expectancy myctophidae adult	parametric	4 years	20%	no	Catul et al., 2011
Life expectancy mauriculis	parametric	2 years	20%	no	Armstrong & Prosch, 1991
Growth period myctophidae	parametric	0.583 years	10%	no	Catul et al., 2011
Growth period mauriculus	parametric	1 years	10%	no	Armstrong & Prosch, 1991
Consumption by MF in bodyweight	parametric	7 GtZoo/Year	20%	yes	Koz, 1995
Living depth myctophidae	parametric	550-950 m		no	Catul et al., 2011
Living depth mauriculus	parametric	250-350 m		no	Armstrong & Prosch, 1991
Initial weight juvinile MF	parametric	9 GtMF	20%	yes	Assumption; Jones et al., 2014; StJohn et al., 2020
Initial weight adult MF	parametric	1 GtMF	20%	yes	Assumption; Jones et al., 2014; StJohn et al., 2020
Initial juvinile predator weight	parametric	6 GtPred	20%	no	Assumption
Initial predator weight	parametric	4 GtPred	20%	no	Assumption
Average weight per predator	parametric	0.3 GtPred/GPred	20%	no	Assumption; Colossal Squid. (n.d.)
Average weight per predator juvinile	parametric	0.08 GtPred/GPred	20%	no	Assumption; Colossal Squid. (n.d.)
Initial zooplankton	parametric	4 GtZoo	20%	yes	Assumption; Falkowski, 2012
Initial phytoplankton	parametric	1 GtPhyto	20%	no	Falkowski, 2012
Growth period predator	parametric	3 years	20%	no	Pauly, 1998
Other food sources	parametric	2 GtMF	20%	no	Assumption
Turnover time phytoplankton	parametric	0.077 years	20%	no	Kirchman et al., 1991
Consumption by zooplankton in bodyweight	parametric	3 Gt/Year	20%	yes	Assumption
SWITCH lanternfish to mauriculus	paramteric	1	0.4-1%	yes	Catul et al., 2011; Proud et al. 2018

Annual consumption predator	parametric	1.6 GtMF/Year	20%	no	Koz, 1995
Predator life expectancy	parametric	6 Years	20%	no	Assumption & Pauly, 1998
Survived larvea	parametric	147	10%	no	Dalpadado, 1988
Spawning fraction	parametric	0.18 dmnl	20%	yes	Sassa, 2019
Fraction spawning mauriculus vs myctophidae	parametric	0.75 dmnl	10%	yes	Assumption & Armstrong & Prosch, 1991
Female fraction	parametric	0.515 dmnl	20%	yes	Dalpadado, 1988
Harvesting sub model					
Catchability myctophidae	parametric	0.14 dmnl	40%	yes	Hidaka et al., 2001
Catchability mauriculus	parametric	0.28 dmnl	20%	no	Assumption
Fishmeal to fish factor	parametric	4 dmnl	20%	yes	StJohn et al., 2020
Annual fish consumption per capita	parametric	1.7e-05 GtMF/MPerson/Year	20%	no	York & Gossard, 2004
World population	structural			no	United Nations, 2019
Efficiency factor fisheries	parametric	7 dmnl	20%	no	Retrieved from model
Harvest information delay	parametric	3 years	20%	no	Assumption
Costs regular fish	parametric	3.39e+11 $/Gt		no	Prellezo, 2018
Sale price regular fish	parametric	3.1e+12	$/Gt	no	Prellezo, 2018
Costs status quo myctophidae	parametric	450e9$/Gt	40%	no	Prelezzo, 2018
Costs status quo mauriculus	parametric	300e9$/Gt	20%	no	Assumption & Prelezzo, 2018
Information delay risk perception	parametric	5 years	20%	no	Assumption
Share of aquaculture	parametric	0.5dmnl	20%	no	Aquaculture (n.d.)
Share of irreplaceable aquaculture	parametric	1dmnl	10%	no	Assumption
Percentage discarded fish	parametric	0.08dmnl	20%	no	
Specialist capacity building time	parametric	5 years	20%	no	Assumption

A.3 SD MODEL

This section presents the total model.

Figure A.5 presents the sub model on the oceanic carbon cycle. It shows the major flows that are associated with carbon sequestration by mesopelagic fish. The *vertically migrated C* flow is connected to the biomass model in Figure A.2. The *Atmospheric C* stock is connected to the global carbon cycle in Figure A.5. the *Deep C* stock is subscripted, just as most of the flows connected to it.

Figure A.2 presents the predator prey model concerned with the mesopelagic fish biomass. This sub model contains four parts: phytoplankton on the upper left corner, mesopelagic predators in the upper right corner. Zooplankton in the lower left corner, and the mesopelagic fish in the lower right corner. The mesopelagic biomass connects back to the amount of sequestrated carbon.

Figure A.3 present the decision making model. Quotas are changed every 2 years, based on a input from the EMA workbench, and are slightly influenced by two lobbying groups: an environmental and industry group.

Figure A.4 depicts the fisheries capacity. There are two types of capacity: existing capacity that converts to mesopelagic capacity, and newly build capacity. Building and termination of capacity is influenced by profitability and the percentage of capacity actually in use.

Figure A.5 presents the global carbon cycle. It shows the main carbon sinks and their interdependencies. The *Atmospheric C* stock is connected to the oceanic carbon cycle in Figure A.1.

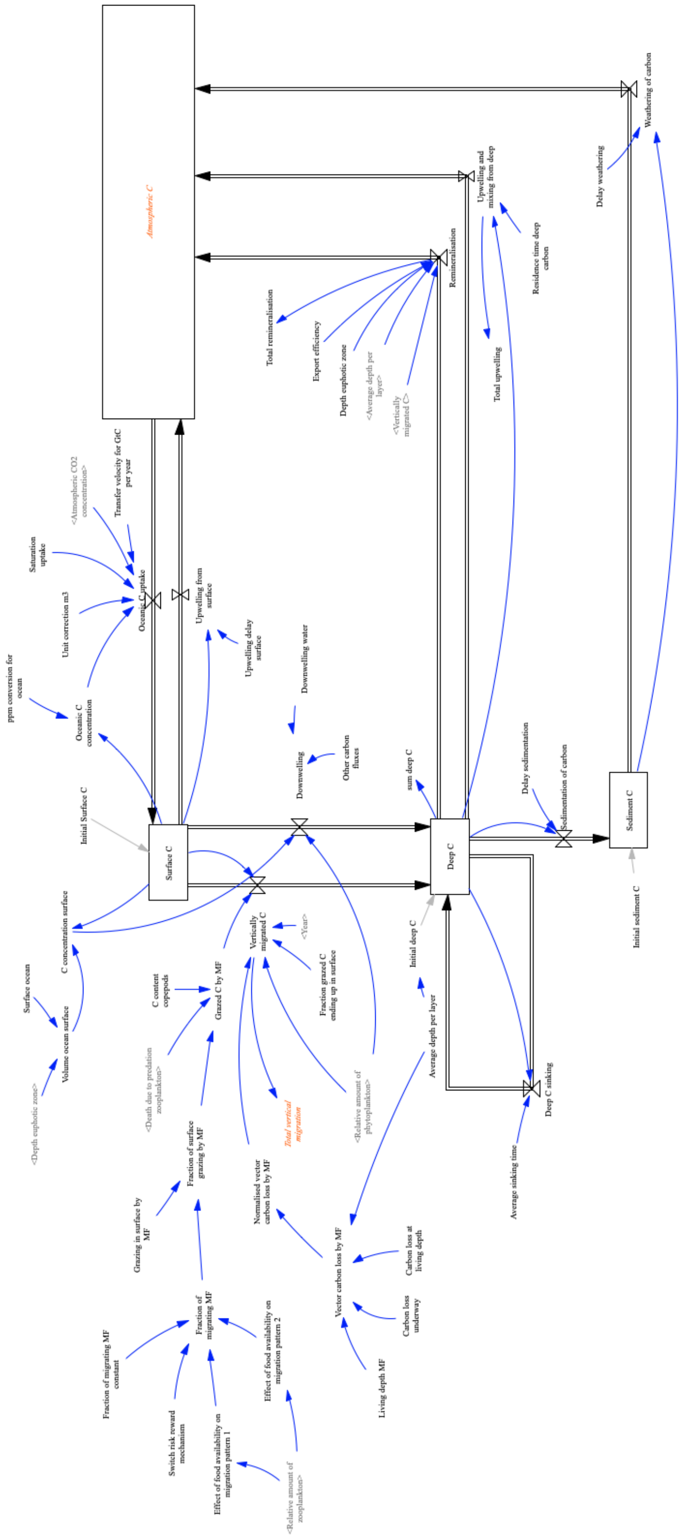

Figure A.1: *System Dynamics sub model of the oceanic carbon cycle*

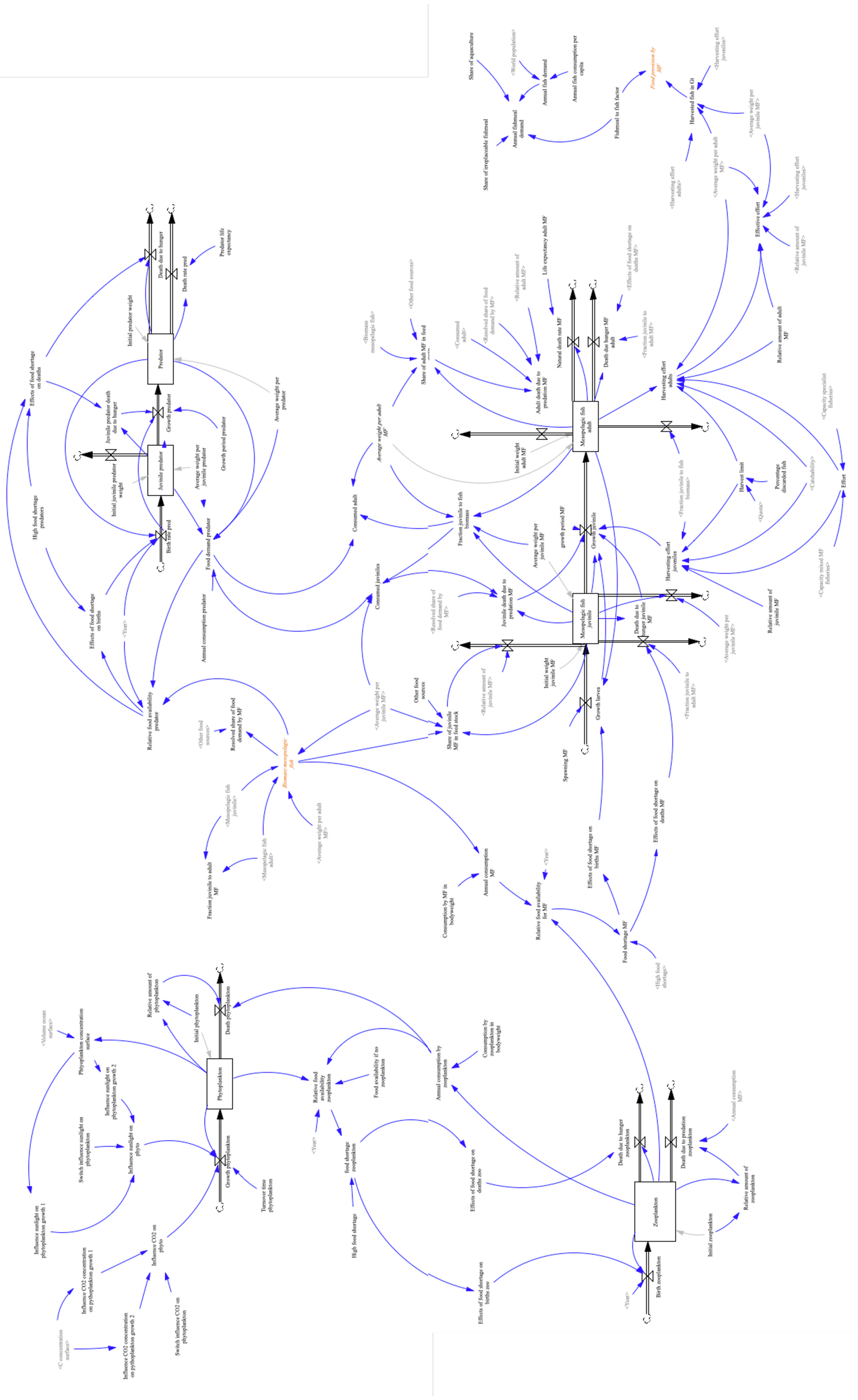

Figure A.2: *System Dynamics sub model of the predator prey model. This sub model contains four parts: phytoplankton on the upper left corner, mesopelagic predators in the upper right corner. Zooplankton in the lower left corner, and the mesopelagic fish in the lower right corner.*

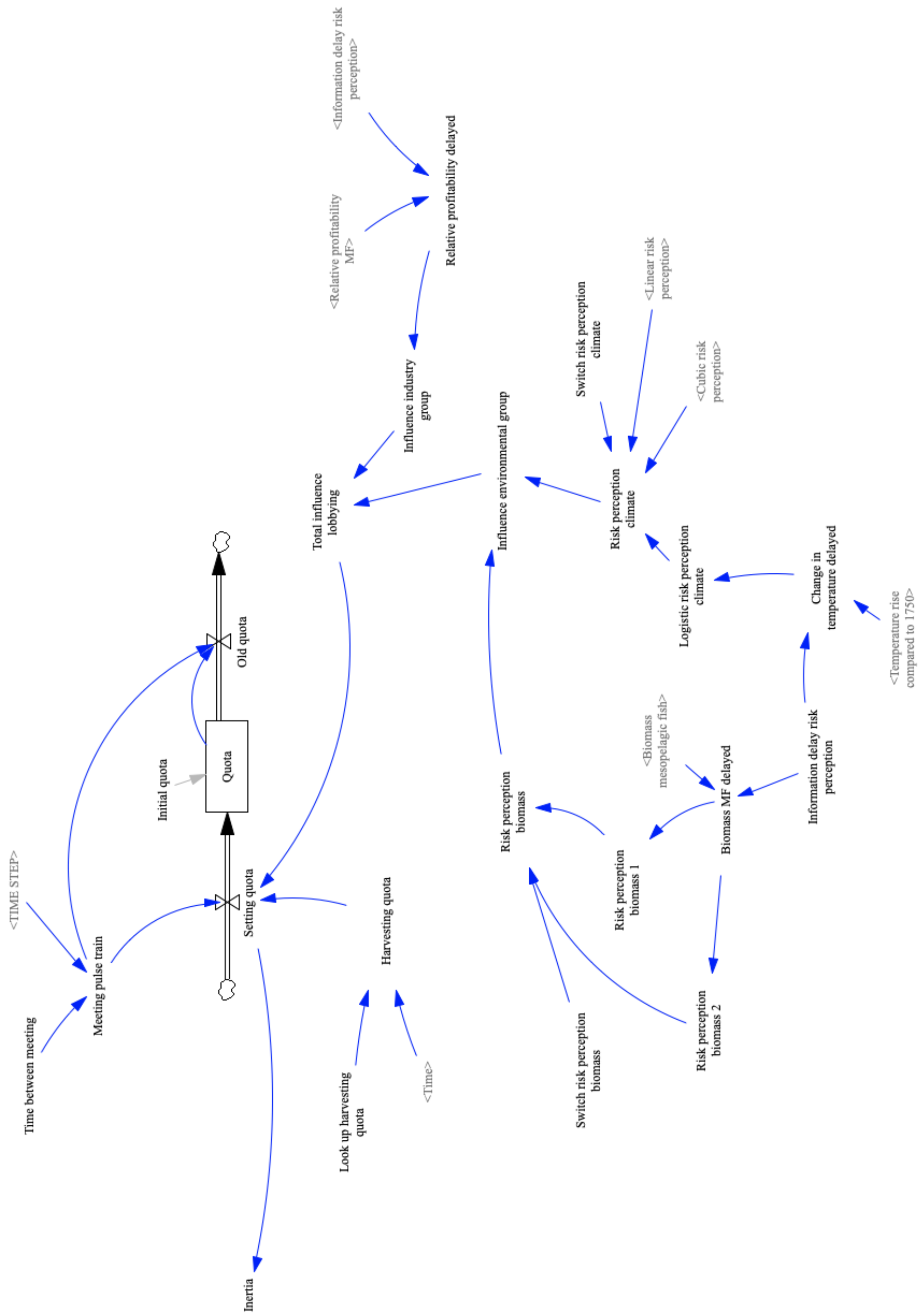

Figure A.3: *System Dynamics sub model of the decision making process on harvesting quotas*

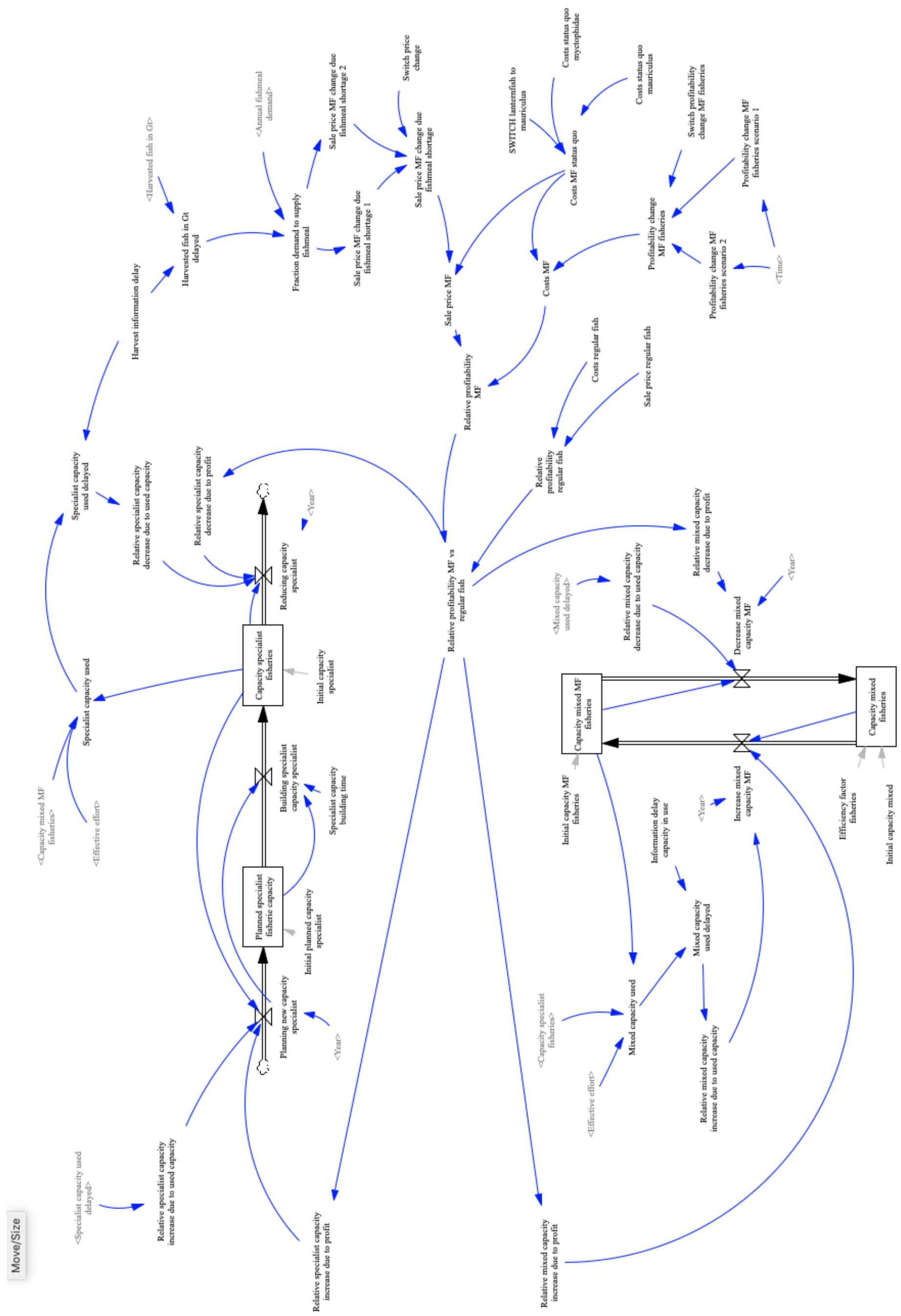

Figure A.4: *System Dynamics sub model of the fisheries capacities.*

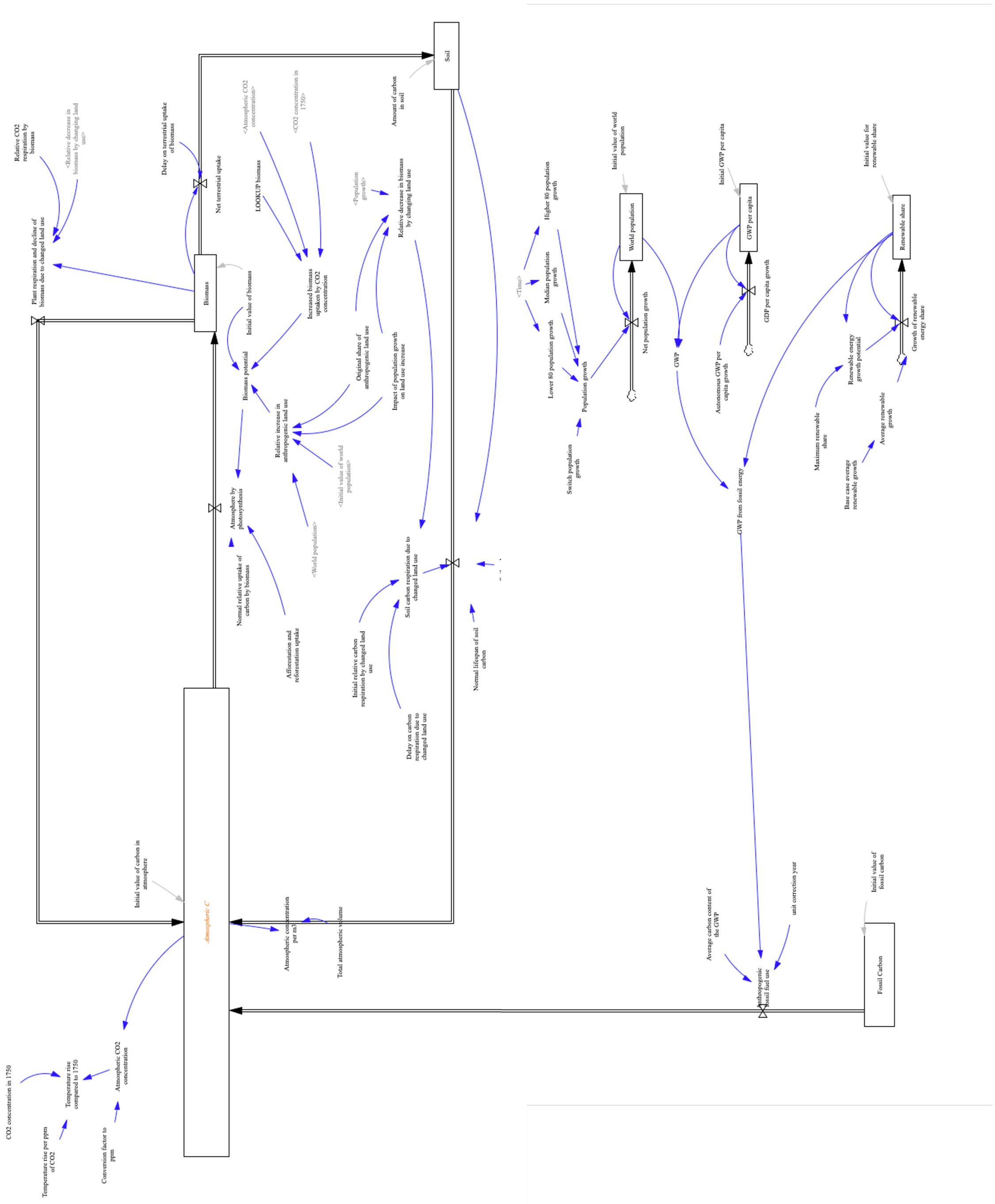

Figure A.5: *System Dynamics sub model of the global carbon cycle.*

B RESULTS APPENDIX

This section presents some background results.

B.1 OPEN EXPLORATION

Figure B.1 shows four outcomes and their correlation to each other for four different harvesting situations.

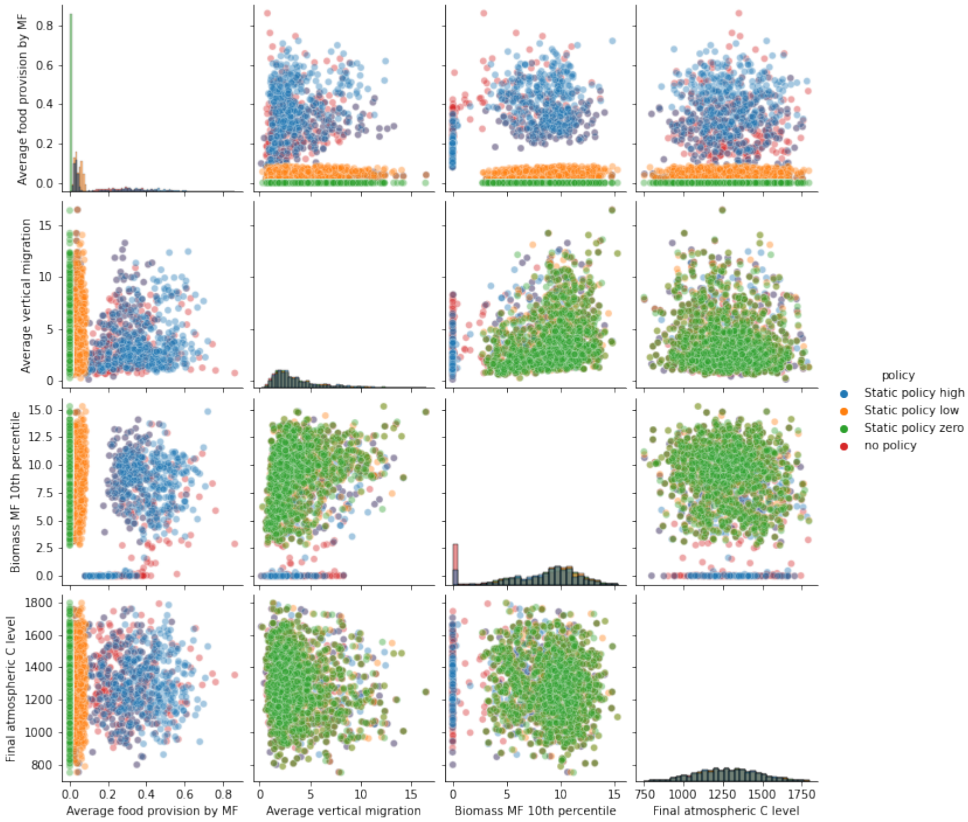

Figure B.1: *Pairsplot of base case & 3 static policies. The histograms show the distribution of one single outcome, while the scatter plot shows the correlation or lack of correlation between pairs of outcomes.*

The Figures B.2 & B.3 show the policies over time for different sample ranges. Figure B.4 zooms in on the lower clusters of the food provision.

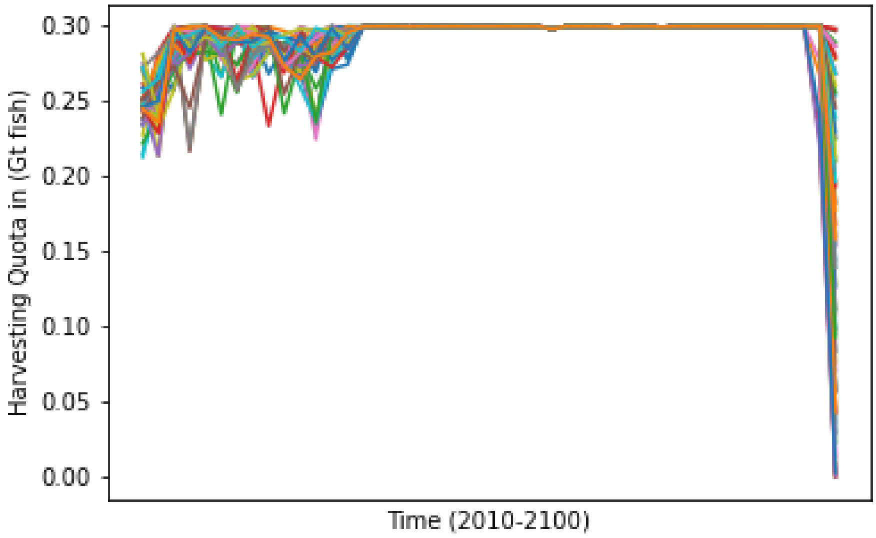

Figure B.2: *Exploration of harvesting quotas in realistic range over time*

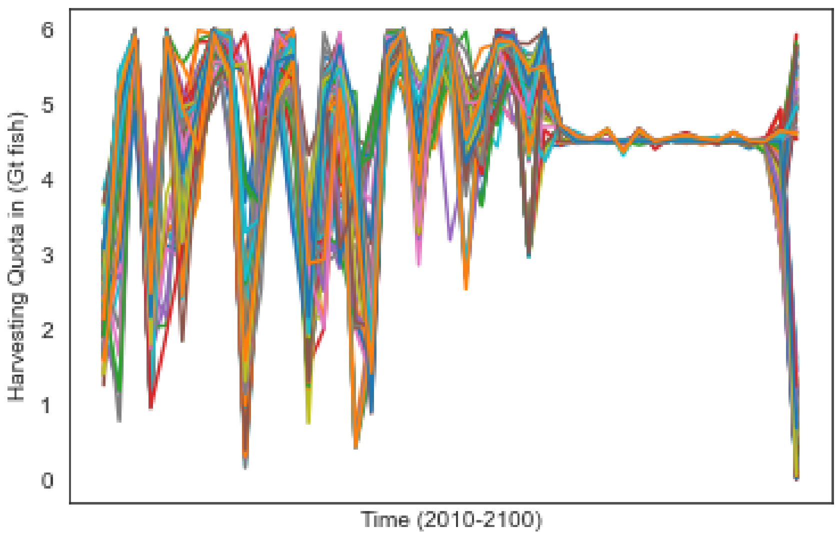

Figure B.3: *Exploration of harvesting quotas in high range over time*

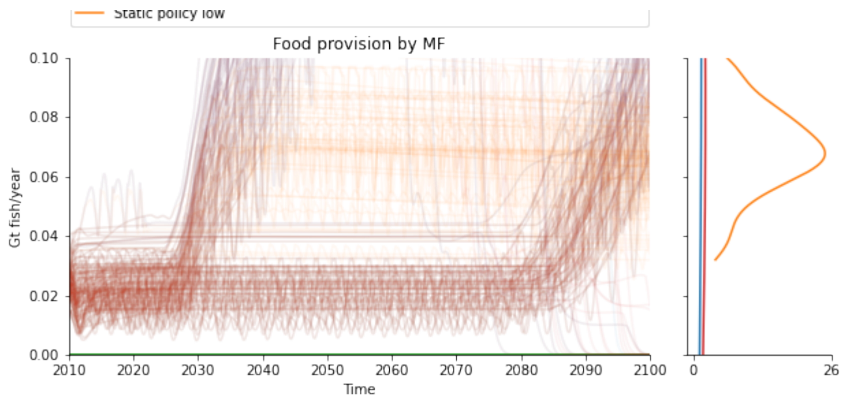

Figure B.4: *Food provision over 4 cases, zoomed in*

B.2 KERNEL DENSITY ESTIMATION

Figure B.5 shows the kernel density estimation of all four outcomes over time.

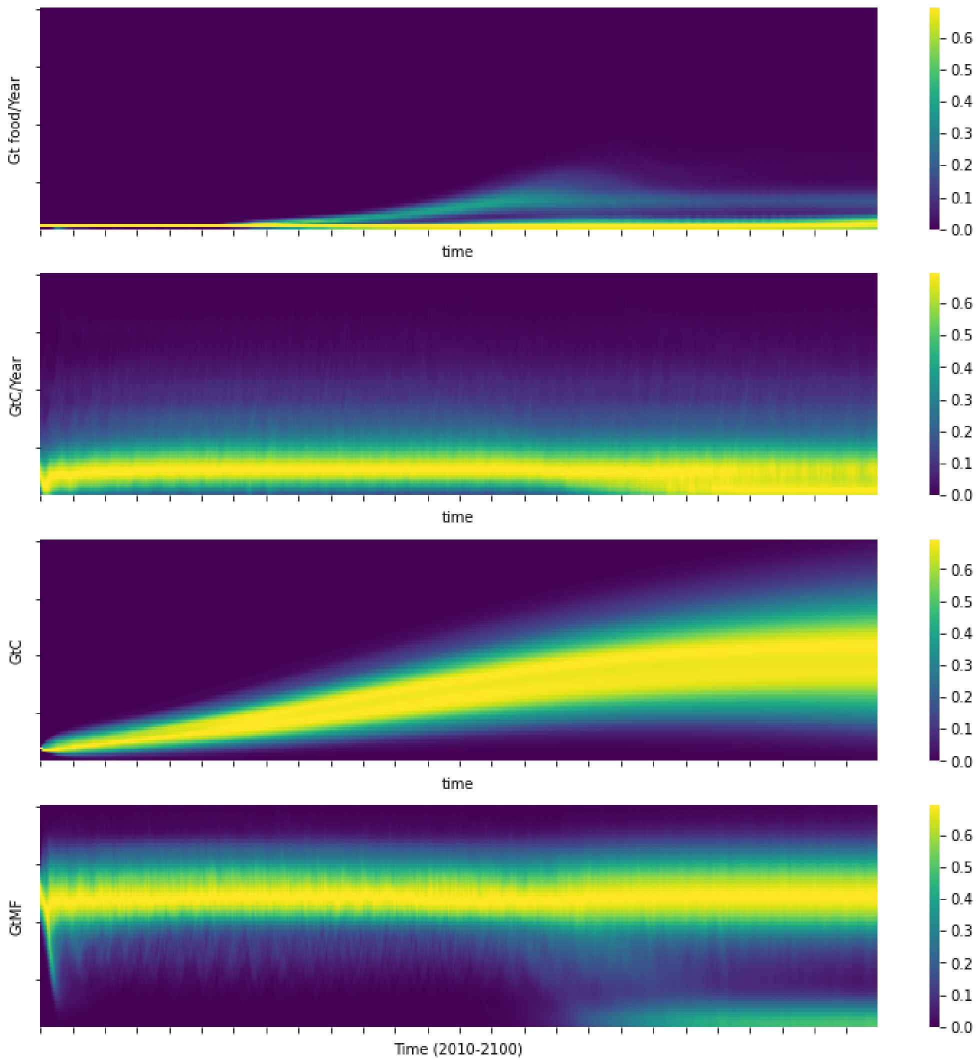

Figure B.5: *Kernel Density Plot for the outcomes over Time*

B.3 STEP 2 MORDM

Figure B.6 illustrates the 10 optimal policies over time as found in step 2.

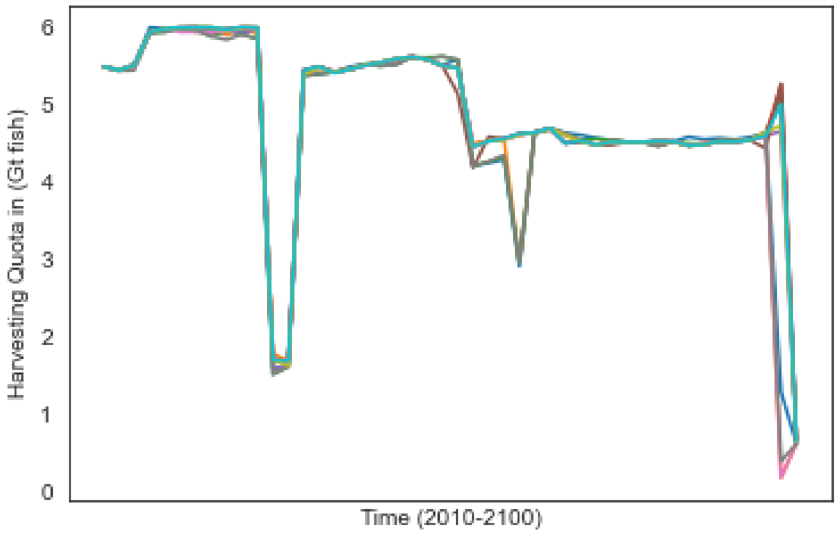

Figure B.6: *Policies of quotas over time as found in step 2. Each line represents a policy.*

Figure B.7 presents the 10 policies found in step 2, and their trade-offs in outcomes.

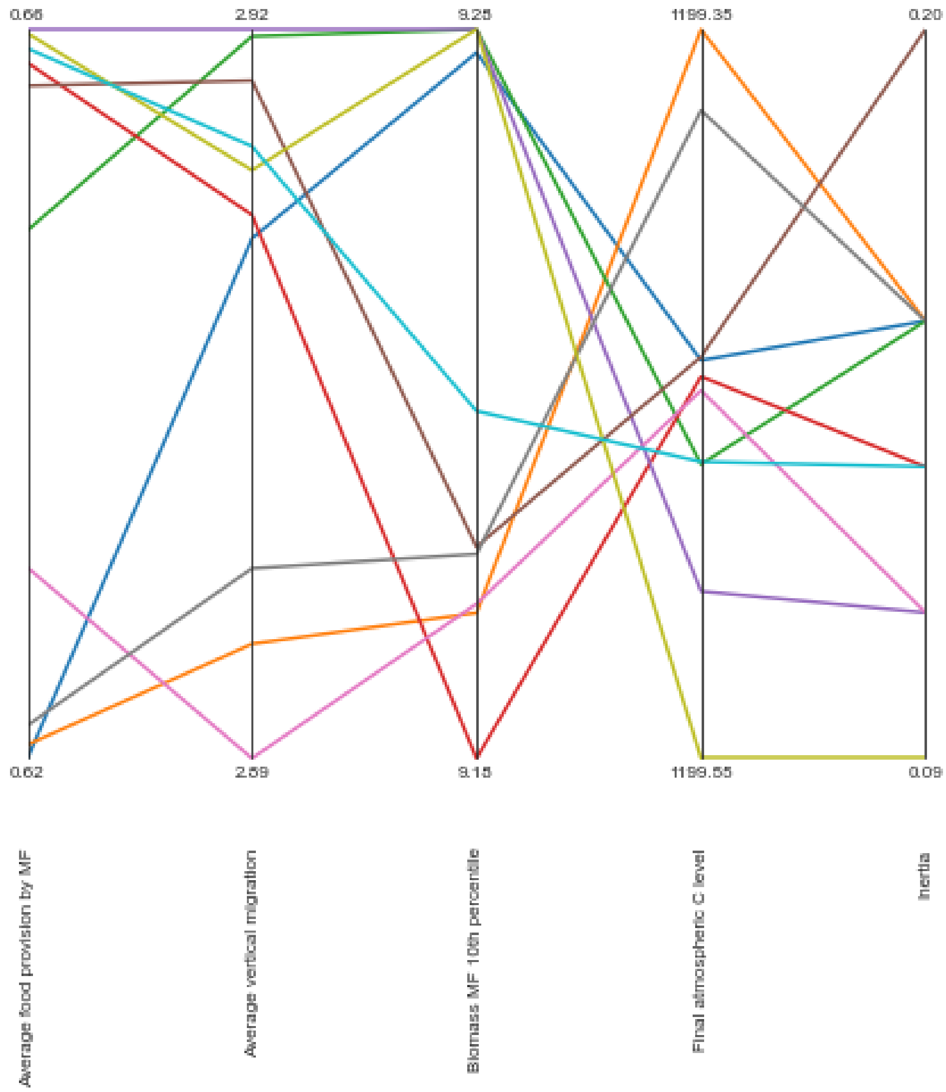

Figure B.7: *Trade-offs between Outcomes for Candidate Policies. Each line represents a policy, while each vertical axis represents an outcome.*

Figure B.8 shows the convergence of the epsilon progress from the optimisation performed in step 2 of MORDM. Epsilon convergence is reached when the curve is flattened, indicating that there are no new dominant policies to be found when a higher amount of runs would be performed.

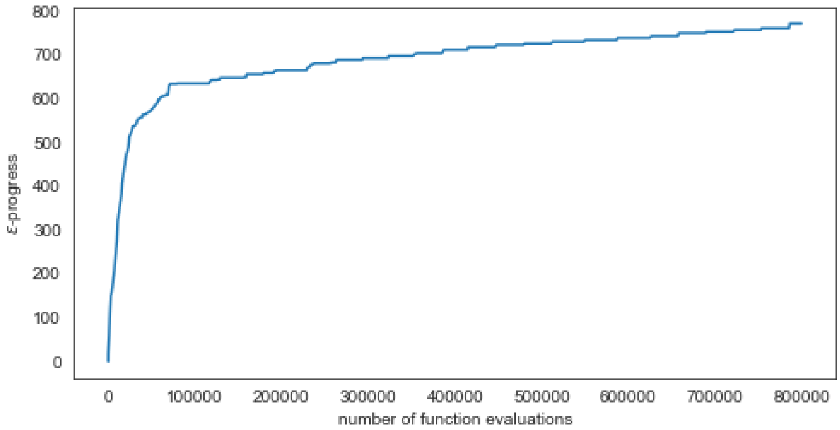

Figure B.8: *Convergence of Candidate Policies from Step 2*

Figure B.9 shows the different sets of found policies from five different seeds. Each set of policies found by a corresponding seed is visualised in a separate colour. As can be seen, the sets of results still vary slightly.

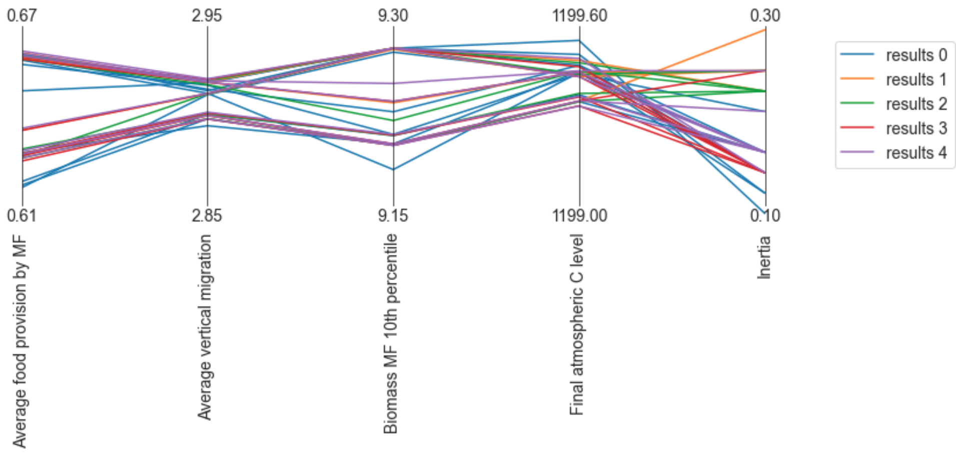

Figure B.9: *Sets of Candidate Policies from Step 2 of five different seeds*

B.4 STEP 3 MORDM

Figure B.10 presents the trade-offs between the signal to noise ratio scores for each outcome.

Figure B.11 shows the heat map of the maximum regret scores per candidate policy. Figure B.12 presents the trade-offs between maximum regret scores of candidate policies.

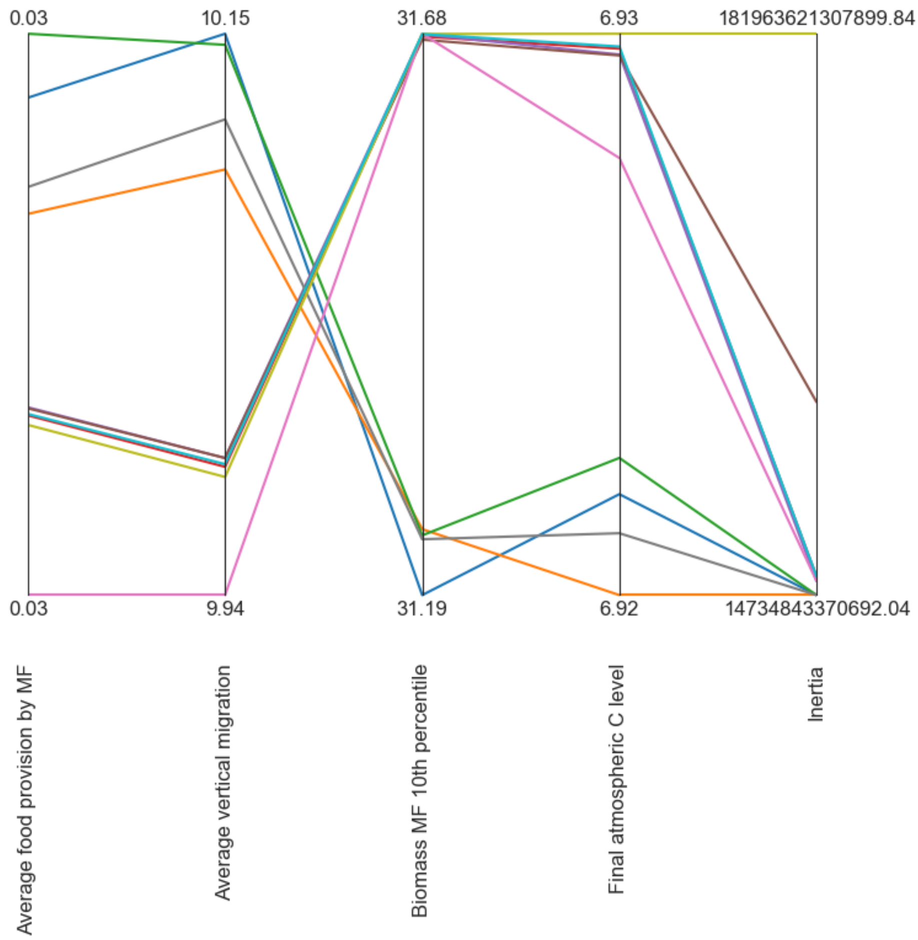

Figure B.10: *Trade-offs between Signal to Noise of Candidate Policies. Each line represents a candidate policy. A high score for all outcomes is ideal.*

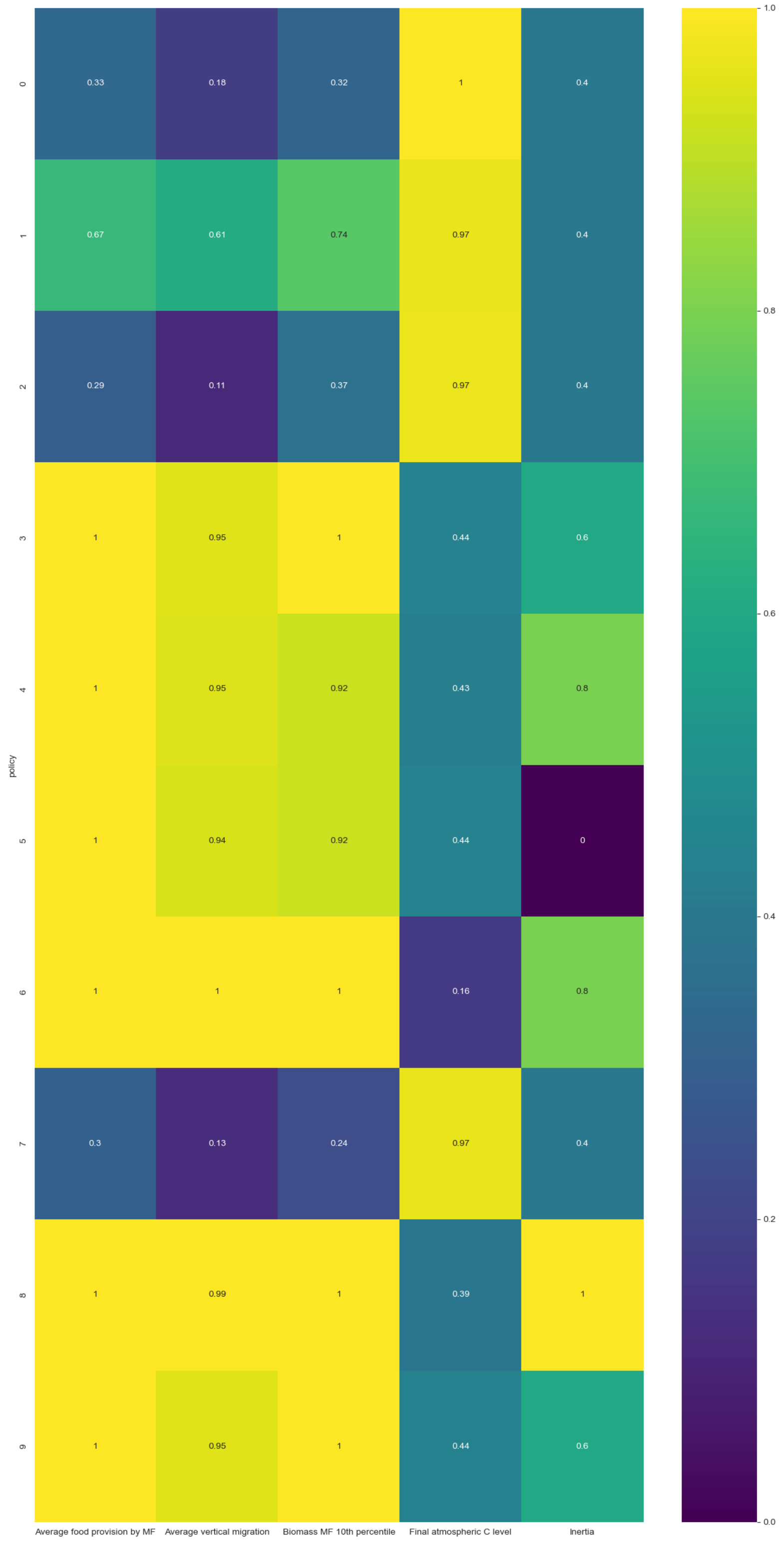

Figure B.11: *Heat map of Maximum Regret Scores for Outcomes of Candidate Policies. A low score for all outcomes is ideal. A dark colour refers to a low score.*

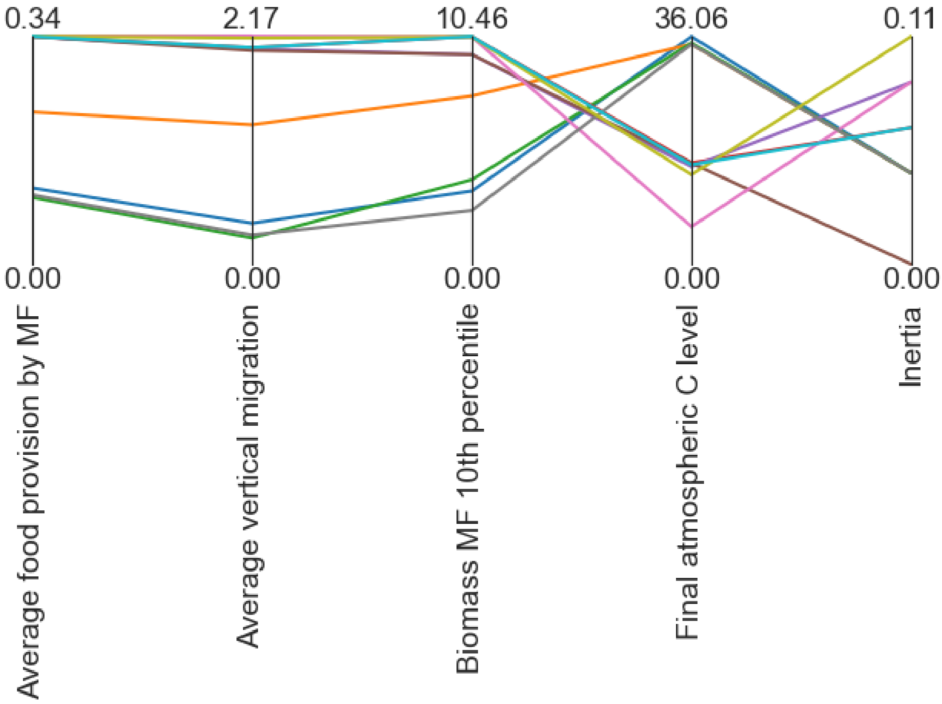

Figure B.12: *Trade-offs between Maximum Regret Scores of Candidate Policies*

B.5 STEP 4 MORDM

Figure B.13 was plotted to choose values for the exploration of worst and best case scenarios to be analysed using PRIM. By exploring the distribution of the outcome values over these scenarios, worst or best cases of interest per outcome can be defined.

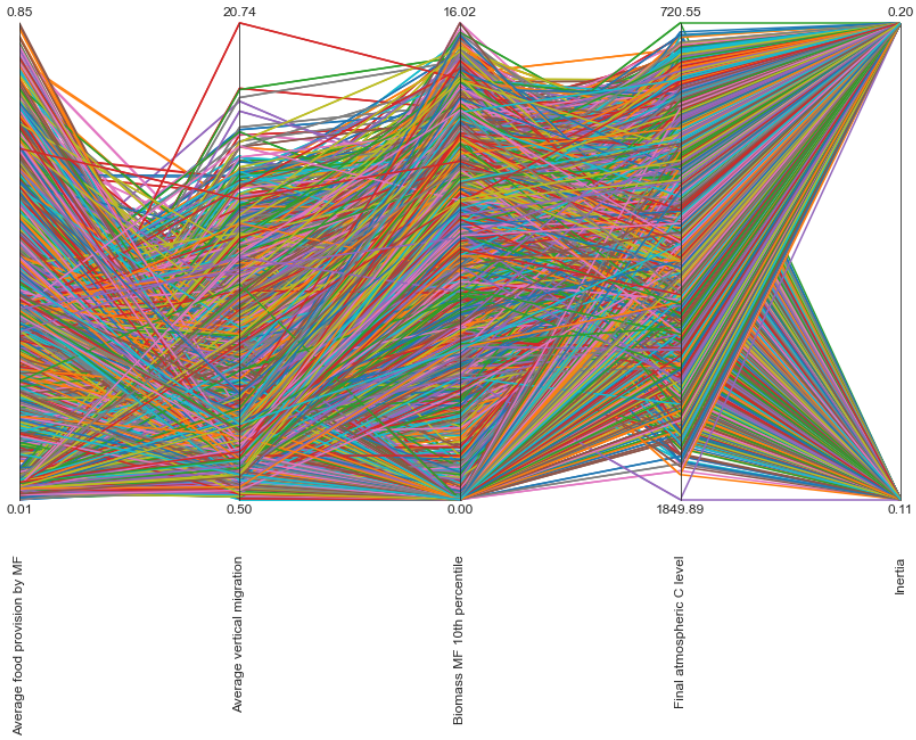

Figure B.13: *Exploration of ranges of outcomes in step 4*

Figure B.14 shows the trade off plot between coverage and density for the worst case scenario concerning the mesopelagic biomass. For further analysis a box is selected that has at least a density of 0.8, high coverage and uncertainties with a quasi p-value of at least lower than 0.05. These criteria resulted in selecting box 2, for which the scatter plot in Figure B.15 was plotted.

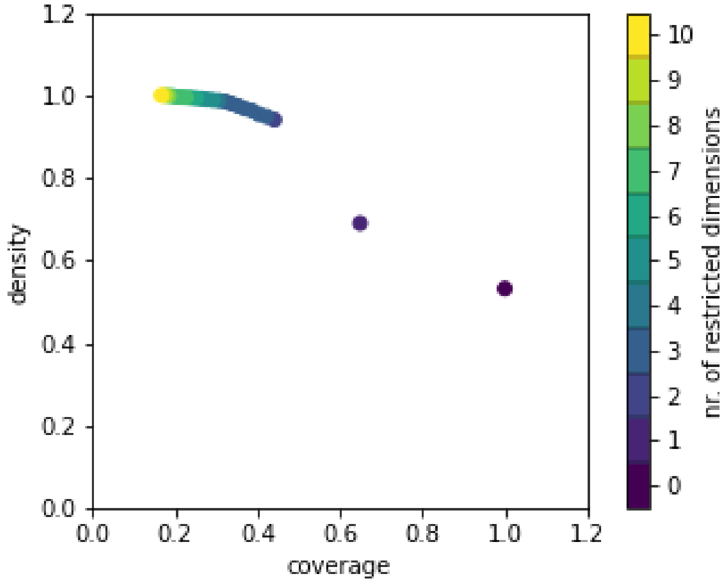

Figure B.14: *Prim Trade off between Coverage vs. Density of Candidate Policies*

Figure B.15 shows the scatter plot for the worst case scenario for the mesopelagic biomass.

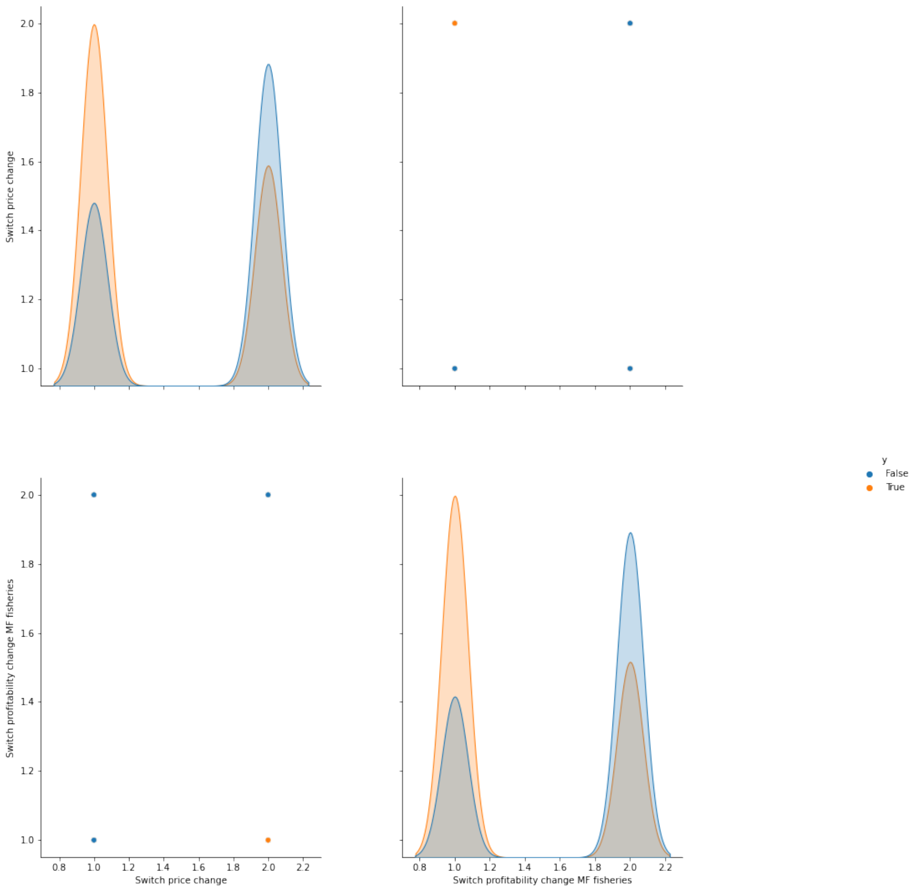

Figure B.15: *Scatter plot PRIM Candidate Policies. The 'True' cases refer to cases which produce a 10th percentile of mesopelagic biomass of less than 9 Gt.*

Figure B.16 shows the scatter plot for the worst case scenario for food provision. Figure B.17 shows the dimensional stacking plot for this scenario. The scenario refers to a food provision lower than 0.4 Gt/Year.

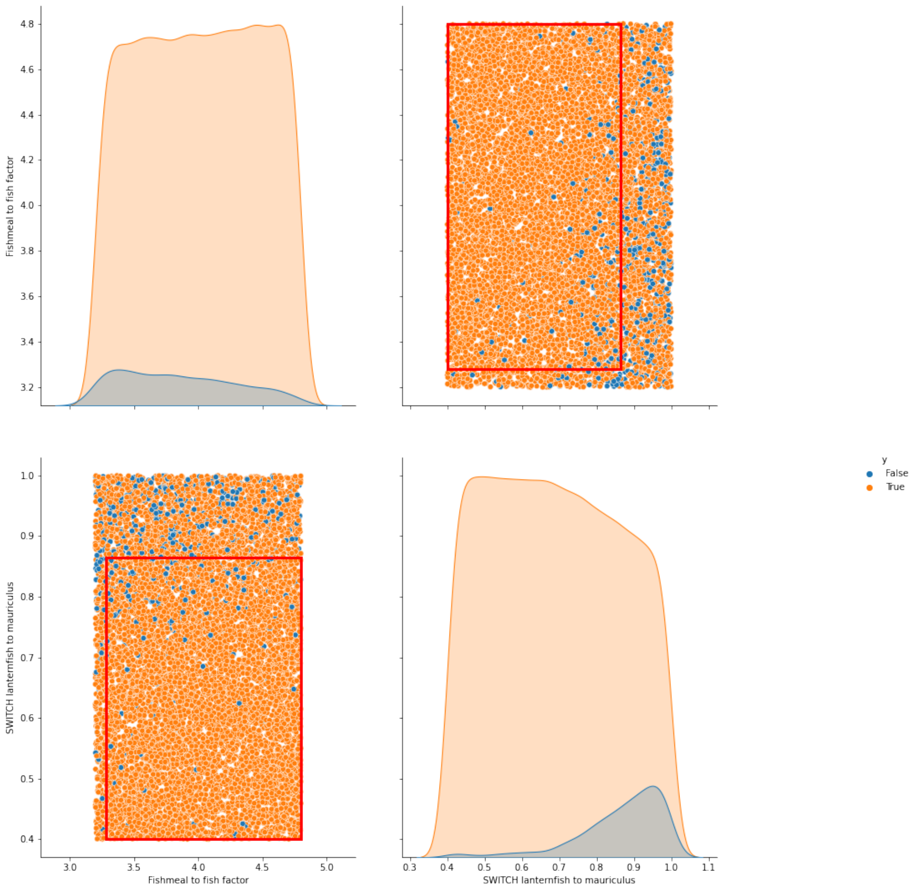

Figure B.16: *Scatter plot PRIM worst case scenario food provision*

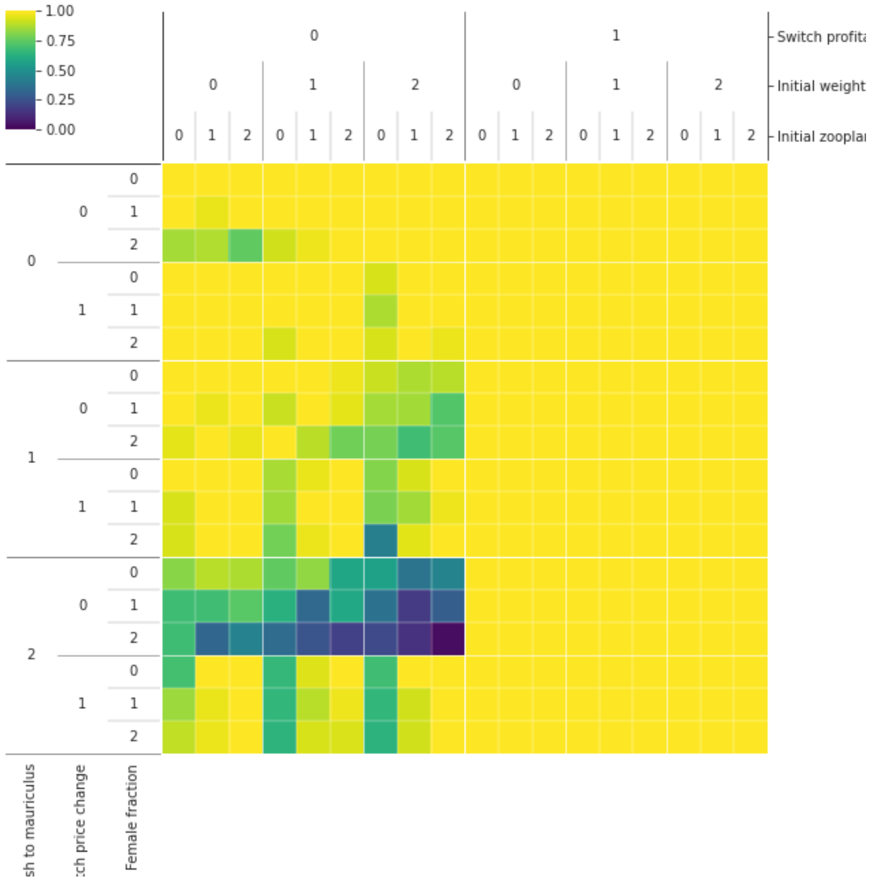

Figure B.17: *Dimensional stack plot worst case scenario food provision*

Figure B.18 shows the scatter plot for the best case scenario for vertically migrated carbon. Figure B.19 shows the dimensional stacking plot for this scenario. The scenarios refers to vertical migration of carbon higher than 3 Gt/Year.

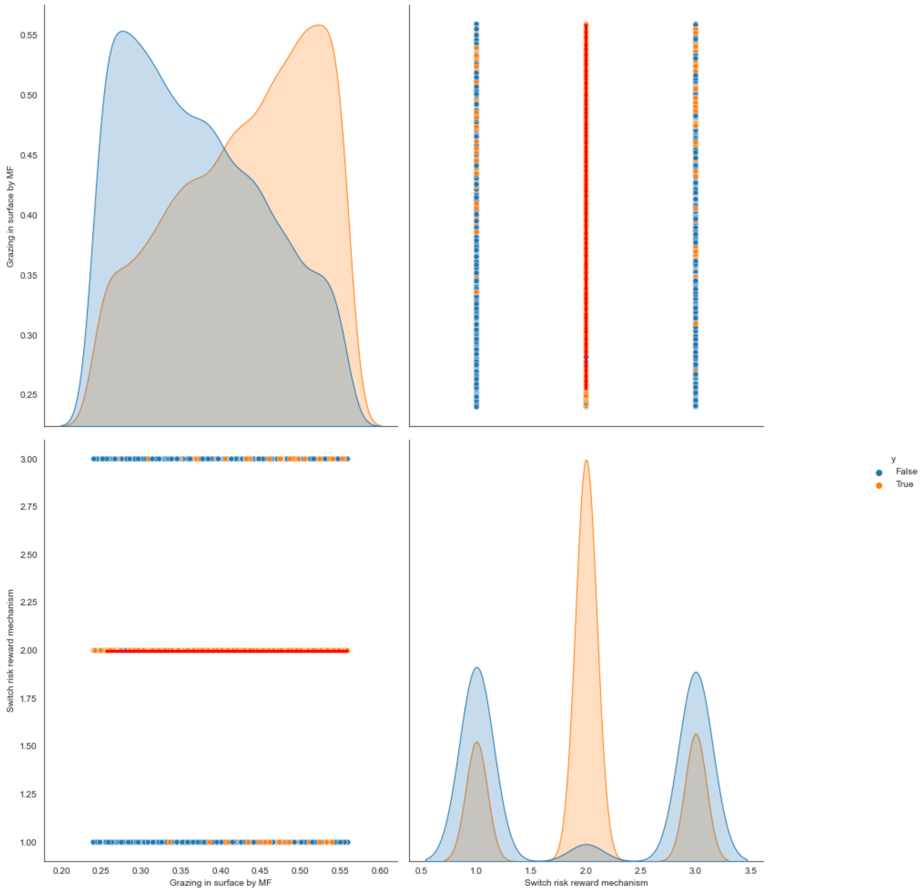

Figure B.18: *Scatter plot PRIM best case scenario vertical migration of carbon*

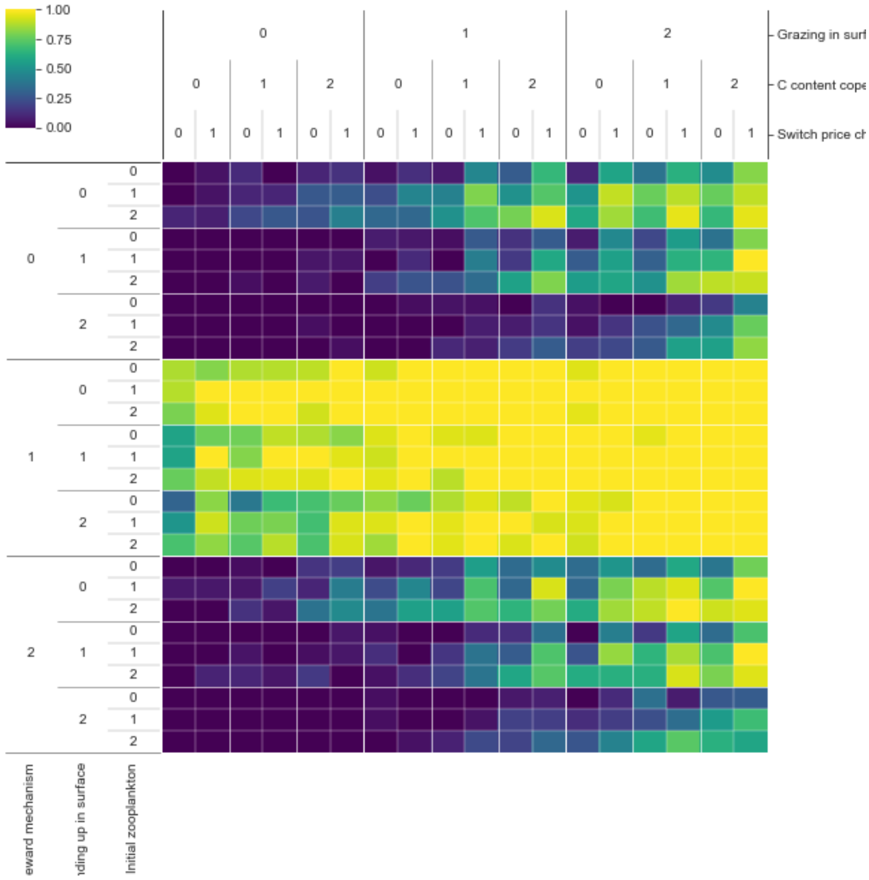

Figure B.19: *Dimensional stack plot best case scenario vertical migration of carbon*

B.6 EXPLORATION SELECTED POLICIES

Table B.1 presents some statistics of a situation without harvesting and with harvesting according to the candidate policies.

Table B.1: Trade-offs between no harvesting vs. selected policies

	mean	**std**	**min**	**max**
Average food provision by MF [Gt food/Year]				
No harvesting	0.000000	0.000000	0.000000	0.000000
Policy 1	0.174798	1.688285e-01	9.026754e-03	0.854984
Policy 2	0.174870	1.689028e-01	9.026754e-03	0.851322
Average vertical migration of Carbon [GtC/Year]				
No harvesting	3.955524	2.654082	0.529747	21.733540
Policy 1	3.844915	2.603290e+00	4.993319e-01	20.736193
Policy 2	3.845130	2.603084e+00	4.993319e-01	20.736193
Biomass MF 10th percentile [GtMF]				
No harvesting	9.325691	2.735981	1.920625	16.898184
Policy 1	7.243803	4.381679e+00	5.140374e-22	16.017002
Policy 2	7.246787	4.379413e+00	5.140374e-22	16.017002
Final atmospheric C level [GtC]				
No harvesting	1218.725240	179.269152	718.458000	1803.309300
Policy 1	1220.376449	1.772799e+02	7.205523e+02	1849.894200
Policy 2	1220.366984	1.772717e+02	7.205523e+02	1849.894200

Figure B.20 shows the box plot of the outcome inertia for the two selected policies.

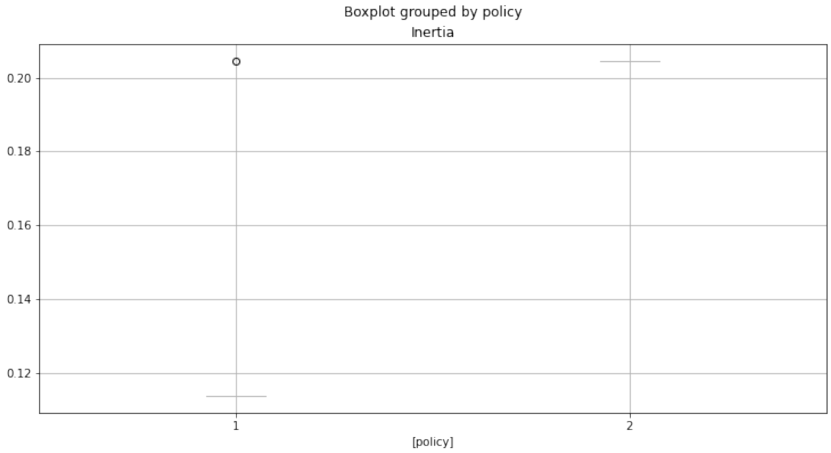

Figure B.20: *Selected policies box plot inertia*