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A bioeconomic perspective on the Barents Sea snow crab (*Chionoecetes opilio*, Majidae) fishery

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Abstract

The focus of this thesis is the Barents Sea snow crab (*Chionoecetes opilio*, Majidae) fishery. The crab was first observed in the area in 1996, and a fishery for the crab commenced in 2012. Both the crab population and the fishery are still expanding. The main objective of this thesis is to develop research that contributes to an improved utilization of the crab. For this purpose, a spatial bioeconomic model was developed and used. Initially, the crab was treated as a fishery resource and vessels from Norway, Russia and EU-countries were participating in the fishery in an area of high seas, but in 2015 the crab was established as a sedentary species. This resulted in a new management regime in which Norway and Russia manage and harvest the crab on their respective parts of the continental shelf. Because of this, in 2017 Norwegian vessels were excluded from previously available lucrative harvest grounds on Russian territory and had to fish elsewhere. Paper I focuses on the effect of this regime change on the Norwegian fleet. In Paper I it was found that the regime change is likely to have had a negative effect on the fleet. It was also highlighted that measures may have to be taken to avoid a *race-to-fish* from developing and overcapacity from emerging. Paper II focuses on the role of fleet dynamics on the geographical expansion of the fishery. The findings suggest that during the initial phase of the fishery – when the focus is on identifying lucrative harvest grounds – the fleet dynamics may affect which areas are explored. Paper III takes the international perspective of the fishery. The results of Paper III suggest that the effect of management measures implemented on a national level may be hampered by the interventions made by the other nation on its share of the fishery. It was also found that there may be gains to be made by implementing a regime of mutual access to harvesting grounds.

Acknowledgements

Many thanks to my family, friends and colleagues. You have all helped me in different ways. However, some of you deserve extra attention.

I am very grateful to my supervisors Arne Eide and Bent Dreyer. I highly value your expertise and kindness. This work would not have been completed without you. A major thanks to Arne for the countless hours you have spent time on reading through my incorrect spelling and bad formulations, while you have greeted me with a smile afterwards. I guess being good at[1] English prepositions ("in", "at", "on", "of", etc.) is just not my thing.

Last but not least, I want to thank my family. First and foremost, my dear Silje for your patience and support. I know this has not been easy on you. With this work out of the way, we will have more time for each other ♡.

Regarding my daughter Thea. On the surface, it appears that you haven't made this task any easier on me. You made me take breaks at times when I wouldn't if it had been up to me. In itself, this has led to the work taking longer. However, I have a feeling that these involuntary breaks may have had an unintended effect. Often, I think, these breaks occurred at times of frustration when there was a subconscious need for them and in this way you have contributed to my productivity. I haven't reached a conclusion about the overall effect just yet. Anyway, you have given me a new perspective on what are the important things in life.

[1] Or is it being good *with* prepositions? Or, perhaps, both are wrong.

Abbreviations

CA Cellular automata

CCA Continuous Cellular automata

CPUE Catch per unit effort

EBS Eastern Bering Sea

EEZ Exclusive Economic Zone

ERS Electronic Reporting Systems

EU European Union

ITQs Individual transferable quotas

MPAs Marine Protected Areas

NEAFC North-East Atlantic Fisheries Commission

NOU Official Norwegian Report

POM Pattern-oriented modelling

RFMOs Regional Fisheries Management Organizations

TAC Total Allowable Catch

UNCLOS United Nations Convention on the Law of the Sea

Declaration of contributions

Papers

The following papers are included in this PhD thesis:

I Hogrenning, E., Henriksen, E. (2021). En kvantitativ studie av lønnsomhet i det norske snøkrabbefisket. *Økonomisk fiskeriforskning, 31*, 29–41.

II Hogrenning, E., Eide, A. (2021). Environmental constraints, biological growth and fleet dynamics of a developing fishery: A model study of the Barents Sea snow crab (*Chionoecetes opilio*, Majidae) fishery. *Fish and Fisheries*, 23, 324– 341. https://doi.org/10.1111/faf.12618.

III Hogrenning, E., (2022). Oh crab, don't forget to explore the effects of potential management regimes of the Barents Sea snow crab (*Chionoecetes opilio*, Majidae) fishery: A simulation study using a spatio-temporal bioeconomic model. (Manuscript)

Contributions

Paper I was prepared by Egil Hogrenning and Edgar Henriksen, whereas Paper II was prepared by Egil Hogrenning and Arne Eide. In these two papers, each author contributed to developing the research questions, constructing the research design, gathering the data, modelling, interpreting, and writing. Paper III was prepared by Egil Hogrenning.

Other declarations

Parts of Chapters 3 and 6 have been recycled/adjusted from the author's examination delivery titled "From non-spatial to spatial biecononmic models" in the subject SVF-8809 'Spatial distribution of marine animal species' in May 2021.

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1 Background

The topic of this thesis is the Barents Sea snow crab (*Chionoecetes opilio*, Majidae) fishery. This crab recently entered the Barents Sea and was first observed in this area in the 1990s. A fishery for the crab commenced in 2012 and is currently in an early stage of development. Globally, however, snow crab fisheries are well established in several regions. The snow crab is naturally distributed in the North Pacific, the Sea of Japan, and the Northwest Atlantic (Alvsvåg et al., 2009), and crab fisheries are found in these regions. These fisheries are of varying sizes and were established at different times.

Hvingel et al. (2021) studied the global development of snow crab fisheries up to 2020. They state that fishing for the snow crab has taken place in the Sea of Japan since at least the 18th century. They found that this fishery peaked in the late 1960s, and landings have declined since then. They further presented a figure depicting the global landings of snow crab over the last decades (1970–2020) by region. This figure is included in this thesis as Figure 1. Based on the figure, we will now describe how these fisheries have developed.

In the late 1960s, fisheries for the crab began in the Eastern Bering Sea (EBS) and along the Atlantic coast of Canada (Hvingel et al., 2021). In subsequent years, these two fisheries grew significantly, and in the 1990s they accounted for the majority of the global landings of snow crab. However, the picture has changed since then. The landings from the EBS fishery are now notably less than during the peak(s) in the 1990s. The landings from the Canadian Atlantic coast have remained large, although declining in the last couple of decades. In the 1990s, a snow crab fishery also developed on the coast of Greenland, but this fishery has remained considerably smaller than the two aforementioned ones. It should be

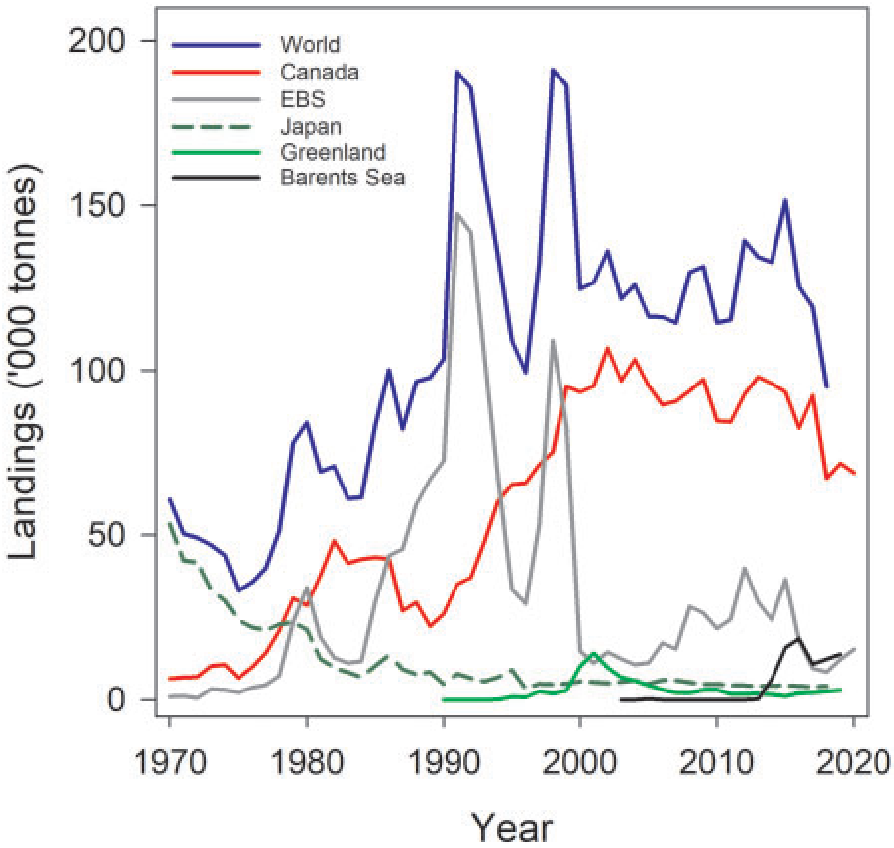

Figure 1: Global snow crab landings from 1970 to 2020. (EBS = domestic United States + Japan until 1981, Barents Sea = Russia + Norway). The figure was originally published by Hvingel et al. (2021)

noted that additional snow crab landings occur (e.g. in the Okhotsk Sea), but the landings are believed to be mixed with other *Chionoecetes* species in the statistics or not reported at all (Hvingel et al., 2021). At the end of the time period covered by the figure, we observe landings of snow crab originating from the Barents Sea.

The Barents Sea is located between Norway and Russia, and is a part of the Arctic. The area is about 1.4 million km^2, and is located between the Svalbard Archipelago on its west and Novaya Zemlya on its east (Institute of Marine Research, 2020). When the work on this thesis started in 2017, fishing for the snow crab in the Barents Sea had only been going on for 5 years. At the time, the fishery accounted for around 10 percent (10,847 tons) of the global landings (115,302 tons) (FAOSTAT, 2022), but there were expectations of a significant growth in the years to come (Eira & Lundgren, 2015).

Initially, vessels from Norway, Russia and European Union (EU) nations participated in the fishery, but for reasons that will be covered in detail later, vessels from the EU no longer do so. The fishery now involves only vessels from Russia and Norway, which fish on their nation's share of the continental shelf in the Barents Sea. Much is still not known about the crab population and the ongoing fishery. The crab is still invading new areas in the Barents Sea: how large the crab population will become and its spatial extent is unknown. The same goes for the crab fishery. In parallel with this, the management regime must be continually developed if the crab resource is to be well utilized.

2 Objectives

In this thesis, bioeconomic theory is applied to study the emerging snow crab fishery in the Barents Sea. From a societal perspective, the snow crab represents income from the crab fishery, but at the same time the crab may have a significant impact on the ecosystem. Other currently ongoing studies have the perspective of the latter[2], while the focus of this thesis is on the former. The purpose of this thesis is to develop research that can contribute to an improved utilization of the crab.

This thesis comprises three papers. Something that will become apparent as the research questions are presented, is how closely linked they are with *space*. While the temporal dynamics are often explicitly accounted for in bioeconomic models, this applies more rarely to the spatial dynamics. Spatial dynamics and the modeling of these dynamics are strongly emphasized in this thesis, and the reason for this is twofold.

First, a geographical expansion of both the crab population and the fishery is currently ongoing in the Barents Sea. Hence, the present structure of the fishery, such as its geographical location, may change with this expansion. Second, this expansion is taking place on the continental shelf of both Norway and Russia. Therefore, each of these two nations can implement nation-specific management measures that apply only within its jurisdiction. These two aspects must be taken into account when models are to be developed to answer the research questions. The matter then becomes *how* the spatial dynamics should be accounted for in the models developed and at what level of detail, not *if* the spatial dimension needs to

[2] For example the project EISA – Snow (https://www.akvaplan.niva.no/en/projects-networks/eisa/)

be accounted for.

Because modeling the spatial dynamics is given a high priority, we rewrite the aim of the thesis somewhat: The purpose of this thesis is to develop research that contributes to an improved utilization of the crab and to do so by developing spatial bioeconomic models of general value. Accordingly, the implications from the thesis will also be twofold. An outcome can be knowledge about the current situation in the fishery or what can be expected in the future, information which can be useful when management decisions are to be made, but an outcome can also be a general suggestion on how to model a fishery. The remaining parts of this document are organized as follows:

Chapter 3 gives a brief introduction to the research field of bioeconomics. The information presented in this section is not explicitly linked to the work in the papers; the purpose of the chapter is rather to provide the reader with the necessary information to understand the work presented in the sections to come. This chapter also illustrates how a practical implementation of bioeconomic theories in management regimes can be challenging.

In Chapter 4, a brief review of the system for managing Norwegian fisheries is provided. The intention of the chapter is to illustrate how Norwegian fisheries are often managed and how the crab fishery fits into this system.

In Chapter 5 attention is focused on the Barents Sea snow crab fishery and key events in the development of the fishery up to now are presented. The development in the fishery forms the basis for the research questions. At the end of the chapter the research questions are presented.

In Chapter 6 the research design and data are presented. Here the focus is on providing a rationale for the methodological choices made, which requires a comprehensive description of the methods used and some of those which were not chosen.

In Chapter 7 the main findings are presented and discussed in light of the limitations and weaknesses of the study. In addition, some time has already passed since parts of this thesis were completed, and aspects of developments since then are commented on.

In Chapter 8 a summary of the thesis is presented.

3 Bioeconomics – Theory and implementation

Bioeconomics is an interdisciplinary research field, which integrates theories from biology and economics. More specifically, it is a combination of fish population dynamics (biology) and the economic activity of exploiting a fish stock resource (economics). The origin of the research field is usually[3] traced back to the seminal papers of Schaefer (1954), Gordon (1954), and Scott (1955).

Gordon (1954) pointed out that the majority of analyses of fisheries had a foundation in biology, while economists had given the field limited attention at the time. According to Gordon (1954), biologists essentially treated the actions of the fishers as an exogenous factor impacting the biological system through the removal of fish. He regarded this view as insufficient and proposed that analyses of fisheries should include the actions of the fishers' in a system of mutual interdependence. Gordon demonstrated that the rent will be dissipated in an open-access fishery due to the fact that the fish are common property.

In his model, this corresponded to the situation where the total value of the landings minus the total cost is zero. Gordon attributes this to the free and competitive nature of common-property resources, and used the following example to illustrate why:

> "the fish in the sea are valueless to the fisherman, because there is no assurance that they will be there for him tomorrow if they are left behind today." (Gordon, 1954, p. 135)

[3]Note that we do find contributions to the field several decades earlier. In 1911, Warming (1911) published a paper in the Danish language focusing on the inefficiency of open-access fisheries. His work did not receive international recognition at the time, which may be attributed to its language of publication (Eggert, 2009).

Furthermore, when considering equilibrium conditions, Gordon argued that the open-access situation deviates from the social optimum. He further contrasted the open-access situation with the socially optimal situation, namely, one where the net economic yield is optimized. In his model, the social optimum is achieved when the total value of the landings minus the total cost is maximized, a situation, he argued, which can only be attained under some sort of social control. According to Gordon, this explains why fishers' taking part in unregulated fisheries are generally not wealthy.

At about the same time as Gordon published his influential paper, a paper by Schaefer (1954) was published. Schaefer studied the dynamics between the fish population and the fishing fleet. He formulated the population dynamics as a function of a growth model, represented by the logistic growth model (Verhulst, 1838), and the activity of exploiting it, represented by a harvest function. The latter was constructed as a function of the size of the fish stock, units of fishing effort, and a constant q (commonly referred to as the coefficient of catchability). The work of Gordon (1954) and Schaefer (1954) has resulted in a model commonly referred to as the *Gordon–Schaefer model*.

An important piece is missing in the theory of Gordon, namely the capital theoretical perspective of a fishery. The work of Scott (1955) can be seen as a response to the work of Gordon. While Gordon favored the management position of the sole owner to that of competing fishers, Scott added a distinction to this picture by contrasting the short-run and long-run dynamics of the two management regimes. According to Scott, the short-run decisions in the fishery need not differ under the two regimes, but when the sole owner expects to have property rights over time, it is likely that they will differ. In this situation, the aim of the sole owner is to maximize the present value of the fishery, making the best use of the factors of production and the fishery over time (Scott, 1955). Hence, according to Scott, fish stock resources should be considered in terms of investment theory. Clark and Munro (1975) later formalized the capital theoretical stance mathematically using optimal control theory.

In response to the theory outlined above, fisheries are often managed in line with a Total Allowable Catch (TAC), limiting the harvest allowed to be extracted from the stock over a time period, which, if set correctly, protects the stock from being overfished (Asche et al., 2008), and Individual transferable quotas (ITQs), which in theory can maximize the net economic rent (Copes, 1986). In ITQ regimes, the holders are provided with a transferable and exclusive right to fish a share of the TAC (Sumaila, 2010). It places its faith in the market mechanism to ensure an efficient allocation of these shares (Standal et al., 2016).

The theory reviewed so far provide us with knowledge about how to manage a fishery for the good of society. But a practical implementation of these theories as management regimes is not necessarily straightforward. The theories often assume that there is a *social planner* in a position to implement the desired management regime. This role can be assumed to be represented by a governmental entity, but its presence may not be sufficient in some cases.

The ability of the social planner to implement a management regime is restricted by, e.g. the rights of the nation in question. In this area, there have been major changes over the past decades. According to the United Nations Convention on the Law of the Sea (UNCLOS), a coastal state has the right to establish a 200 nautical mile Exclusive Economic Zone (EEZ) off its coast (United Nations, 1982), to attain a sovereign right to the fishery resources encompassed by it (Munro, 2009). Prior to this, the jurisdiction of a coastal state over its fishery resources only extended to a maximum of 12 nautical miles off its coast (Grønbæk et al., 2018). Hence, with this extension, it was made possible for the social planner of each coastal state to establish management regimes within the areas covered by the EEZ.

However, some stocks, referred to as straddling fish stocks, are found both within EEZs and on the adjacent high seas (Munro, 2009). In areas of the high seas, Regional Fisheries Management Organizations (RFMOs) – consisting of the coastal and distant water fishing states – are the management bodies of straddling fish stocks (Munro, 2009). The commercial fishing fleet of these nations must comply with the RFMO regulations to be able to participate in a fishery in the region (Cullis-Suzuki & Pauly, 2010).

However, for sedentary species, EEZs and high seas regimes are of no importance. Such species can be defined as follows: "organisms which, at the harvestable stage, either are immobile on or under the seabed or are unable to move except in constant physical contact with the seabed or the subsoil" (United Nations, 1982, p. 54). Sedentary species are subject to the legislation for the continental shelf and not the bodies of water above (Kvalvik, 2021).

4 Fishery management put into practice – Norwegian fisheries in general

A number of management measures are used in the management of Norwegian fisheries. The use of the various measures depends on the type of vessel and species being managed, which contributes to the complexity of the management system in Norway (Årland & Bjørndal, 2002). A detailed description of the system is given in an Official Norwegian Report (NOU) (St.meld. nr. 32, 2018–2019). The mentioned report represents a starting point of identifying important characteristics of this system.

First, a national TAC is set with the aim of preventing the fish stock from being overfished. The TAC may be an outcome of international agreements if the stock is shared with other nations. Second, the fishery is closed to new entries, where mainly the fishers who participated before the closing are allowed to participate. Third, the TAC is distributed among groups of vessels. These groups consist of vessels that may be aggregated together on the basis of factors such as gear and vessel size. There may also be subgroups to which the group quota is further distributed. Forth, the group quotas – or the TAC if there are no groups established – are distributed further on a vessel level as (guaranteed) individual quotas, maximum quotas, or a combination of the two. Fifth, a structural quota scheme is implemented with the aim of adapting the capacity in the fishery to the fish stock. An excessive capacity in the fishery can occur if the capacity was too large at the time of the closure, but may also emerge with technological progress. The scheme makes it possible, given certain conditions, to accumulate several quotas in the same fishery on one vessel.

According to Hannesson (2013), the quota system in Norway shares similarities with the theoretical idea of ITQs, but they differ in terms of the transferability and tenure of the quotas. There may be several reasons for these differences. Social changes are associated with ITQ-regimes; e.g. quotas may be moved out of some communities and concentrated in a few (Branch et al., 2006). In Norway, one aim of the management system is to maintain employment and settlement in coastal communities (Havressurslova, 2008, §1), meaning that an efficient allocation of resources at the harvesting stage is not the only emphasis of the management system.

In most[4] Norwegian fisheries, one or several of these steps are implemented. The differences between the fisheries are probably due to the authorities considering different measures as appropriate in different fisheries. New fisheries may for example have different needs and challenges than well established ones. In the snow crab fishery, which we will cover in depth in the next chapter, only step one is currently implemented, but other steps may be implemented as the fishery develops. Hence, the snow crab fishery is managed by a TAC, but without quotas being allocated at a vessel level.

[4]One exception is the open-access fishery for the red king crab west of 26° E, where the aim of the management is to limit the westward expansion of the crab (Sundet & Hoel, 2016)

5 The Barents Sea snow crab fishery – The newcomer

The snow crab species was first observed in the Barents Sea in 1996, more precisely in the area of the Goose Bank (Institute of Marine Research, 2017) and since then the crab population has expanded and a fishery for the crab has evolved. There are many knowledge gaps regarding the crab population. How it arrived in the Barents Sea and where it came from[5] is unknown, as is the size of the current and future population (Institute of Marine Research, 2017). However, the snow crab population is expected to continue to spread across the Barents Sea and settle in suitable areas.

The snow crab fishery in the Barents Sea commenced in 2012. The fishery was initiated in an area of the Barents Sea referred to as *the Loophole*, and vessels from Norway, Russia and EU-countries took part. The Loophole is an area outside of EZZs, and the water column encompassed by it is therefore an area of high seas. The area is formally under the jurisdiction of North-East Atlantic Fisheries Commission (NEAFC)[6], however the snow crab fishery started out as an open-access one (Kaiser et al., 2018). Figure 2 shows a visualization of the Barents Sea area, including the area of the Loophole. The continental shelf in the Barents Sea is the sovereign resource of the coastal shelf states Norway and Russia, and the area that constitutes the Loophole is shared between the two. In this early phase of the fishery, most of the crab was harvested on the Russian part of the continental shelf in the Loophole (Institute of Marine Research, 2019).

[5] Recent research finds it likely that the crab wandered from the Chukchi Sea (Institute of Marine Research, 2022)

[6] the Regional Fisheries Management Organisation (RFMO) of the North East Atlantic

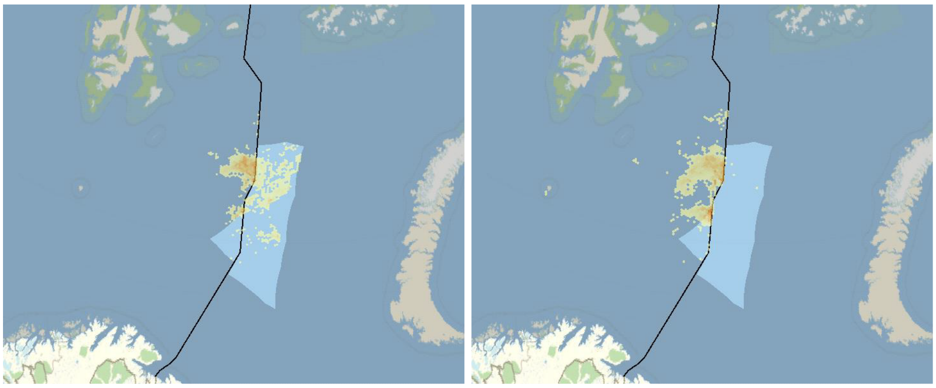

Figure 2: The harvest locations of Norwegian vessels in the Barents Sea during 2016 (left) and 2017 (right) shown by shades of yellow. The figure also shows the area of the Loophole (light blue). We see that the line of delimitation (black) divides the continental shelf of the the Loophole in two areas, one belonging to Russia and one belonging to Norway. Additionally, parts of the mainland of Norway and Russia are shown in the lower-left corner, Svalbard in the upper-left corner, and Novaya Zemlya to the right. The figure was originally published in Paper I. A more comprehensive map of the Barents Sea is shown in Figure A.1 in the appendices.

In 2015, Norway and Russia established, in accordance with UNCLOS, the crab as a sedentary species (Joint Norwegian Russian Fisheries Commission, 2015)[7], and with this, the crab shifted from being managed as a fish stock in the water column to a natural resource located on the continental shelf, similar to oil and minerals (Hansen, 2016). According to the definition of sedentary, Norway and Russia have sovereign rights to manage and harvest the crab on their respective parts of the continental shelf in the Barents Sea (Hansen, 2016). The definition enabled the two nations to exclude foreign vessels from harvesting crab from the territory of the nation. Consequently, as of the autumn of 2016, Russia excluded

[7] This status has not been questioned by other nations (Hansen, 2016)

foreign vessels, apart from Norwegian ones, from harvesting the crab on the Russian part of the continental shelf in the Loophole. This comes into view in the catch statistics as presented in Table 1[8]. The table shows that catches from EU vessels generally do not occur after 2016[9].

Table 1: Established quotas, and landings of snow crab (in tonnes) in the Barents Sea in the period 2012 to 2021 divided by each nation. This table is based on Table 1 in Institute of Marine Research (2021).

Year	Quotas (tonnes)		Landings (tonnes)			Total landings (tonnes)
	Norway	Russia	Norway	Russia	EU	
2012	-	-	2	0	0	2
2013	-	-	189	62	0	251
2014	-	-	1800	4104	2300	8204
2015	-	1100	3482	8895	5763	18140
2016	-	1600	5290	7520	3690	16500
2017	4000	7840	3153	7780	2	10847
2018	4000	9840	2804	9728	-	12532
2019	4000	9840	4038	9840	-	13878
2020	4500	13250	4362	13202	-	17564
2021	6500	14575	6545	13800*	-	20345*

*per 23 November 2021

Internally, Norway and Russia agreed to allow their vessels to have mutual access

[8]The values for the total landings in this table appear to differ from what is shown in Figure 1, originally presented in Hvingel et al. (2021). Judging by how the crab fishery is presented in the mentioned article, it may be the case that landings from EU nations are not included in the figure.

[9]A small proportion of crabs were landed by EU-vessels in 2017, but the author has no knowledge of why.

to harvest grounds on the continental shelf in the area of the Loophole (Joint Norwegian Russian Fisheries Commission, 2015). However, in 2017 the agreement was not extended and this has been the status ever since (Joint Norwegian Russian Fisheries Commission, 2016, 2017, 2022). Because of this, the vessels of each nation may only harvest the crab on the territory of its own nation. This reorganization of the Norwegian–Russian management regime, which took place in 2017, will from now on be referred to as the *regime change*. Figure 2 shows the adaptation the Norwegian fleet made from 2016 to 2017. We observe no harvesting by Norwegian vessels on the Russian continental shelf in 2017.

The cooperation between Norway and Russia on the management of the stock is currently limited to biological aspects. The two nations have decided to cooperate on research in order to ensure the biological sustainability of the crab stock (Joint Norwegian Russian Fisheries Commission, 2015). Since 2017 both nations have managed their fishery given an annual TAC – a limit on the amount of crabs that are allowed to be harvested each year – on their respective parts of the continental shelf (Table 1).

We also observe an increase in the annual quotas and the landings from 2017 and onward, consistent with the assumption of a further geographical expansion and growth of the crab population in the Barents Sea. Access to participate in the Norwegian crab fishery is restricted to vessels having a permit. In 2021, 63 vessels had obtained a permit, but only 12 of these vessels used the opportunity to participate in the fishery (Institute of Marine Research, 2021).

In Paper I, the consequence of the regime change on the Norwegian fleet is studied: The harvest grounds on the Russian continental shelf in the Loophole were the ones considered to provide the highest catch rate at the time when the regime change took place. In the wake of this event, a concern arose that it would have a negative effect on the Norwegian fleet. More specifically, the concerns were that it would lead to lower catch rates and hence have a negative impact on the profitability of the fleet. The paper studies the effect of the regime change on the Norwegian fleet and discusses ways in which the profitability can be improved and obstacles that may counteract improvements.

In Paper II, fleet dynamics that can shape the further geographical expansion of the snow crab fishery are explored: Because of the regime change, the Norwegian vessels were limited to harvesting the crab on the Norwegian continental shelf – given that the vessels still wanted to participate in the fishery. We observe from Figure 2 that the fishing activity on Norwegian grounds was taking part over a larger area after the regime change. This indicates that exploratory fishing for the crab was taking place in areas of the Barents Sea at the time. This observation was the point of departure for Paper II, where the effect of the fleet dynamics on the geographical expansion of the fishery is studied.

In Paper III, the effect of potential nation-specific management measures and the efficiency of the current international regime are studied: The Barents Sea snow crab population can be considered a shared stock, i.e. a fishery resource exploited by two or more nations (Grønbæk et al., 2018). It is suggested that Norway and Russia may have different incentives when it comes to managing the snow crab (Kaiser et al., 2018), which may lead the two nations to choose diverging management strategies for their domestic fisheries. The first object of the paper is to study the effect of several potential nation-specific management measures under the assumption that the current international management regime will prevail.

However, it is not clear whether the current international regime – where sovereign rights determine where the vessels of the two nations are allowed to fish – is preferred from an economic perspective. A reintroduction of the agreement of mutual access to harvest grounds has repeatedly been a subject of discussion during the annual Joint Norwegian–Russian Fisheries Commission meetings, but no agreement has been reached (Joint Norwegian Russian Fisheries Commission, 2017, 2022). The second objective of the paper is to study the economic outcome of the regime where the fleet of each nation exploits the crab on its own territory (the current regime) versus a regime where mutual access to the harvest grounds (the suggested alternative) is allowed. Here we assume that the two nations aim to maximize the rent from the fishery.

6 Research design and data

6.1 Accounting for spatial diversity in models of the snow crab fishery

In this context, spatial diversity can be understood as the dimensions associated with the crab fishery leading to the fishing activity not being homogeneously distributed across the Barents Sea. The theory reviewed so far does not provide us with guidelines on how to model spatial diversity in the crab fishery. However, spatial diversity has been considered; in his model, Gordon (1954) defined the area where the fishing activity was ongoing – the fishing ground – as a location, separated from other locations by barriers that prevented (fish) movement between locations. Gordon (1954) developed his model with demersal fish in mind, acknowledging that other species (e.g. species that have a more migratory nature) may need a different modeling approach[10].

If we were to treat the crab fishery as one fishing ground, we would simply be aggregating location-specific information. From an economics perspective, Sanchirico and Wilen (1999) motivate the use of disaggregated models for two reasons. First, assuming that the resource is heterogeneously distributed[11], the fisher's choice of fishing grounds is determined by opportunities in other areas, and second, management measures can be location specific.

Spatial diversity in the crab fishery has various sources, of which the following sources may be the important ones. Differences in the characteristics of the environment may result in some areas providing a better habitat for the crab than oth-

[10]Note that Gordon (1954) argues that it does not change the conclusion of his work.

[11]There may be other reasons: The costs of fishing may vary over space.

ers. The crab is found to have preferences for sea temperature and depth, among other things (Institute of Marine Research, 2017). The crab is also able to move within and between areas of various characteristics. The crab is now assumed – if not in economically viable sizes – to be found in every area in the Barents Sea considered to fulfill the criteria of being a crab habitat (Institute of Marine Research, 2019). The fishers' – who are assumed to be rational economic actors – are not fishing in every area in an equal amount, but their choices of fishing grounds are likely to depend on the harvest potential of different grounds. Therefore the fishing activity is also likely to be heterogeneously distributed over the Barents Sea. Hence, there may be environmental, biological and economic reasons for the crab fishery to be spatially diversified.

Many research topics in fisheries are well studied without taking into account the reasons and consequences of spatial diversity (and thus the need for a spatial model), such as the rent-dissipation associated with open-access fisheries put forward by Gordon (1954), but when turning to the research questions at hand it becomes evident that this is not the case in this thesis. Given the various research questions, we identify the following minimum conditions of a spatial dimension that the models in the various papers must fulfill.

In Paper I, there is a need to determine estimates of location-level Catch per unit effort (CPUE) allowing us to compare the harvest potential of different areas. Paper II addresses the process of exploring new fishing grounds, making it necessary to divide the Barents Sea into regions at some scale. This also applies to Paper III, where regions must be assigned Norwegian or Russian ownership if an investigation of the effects of potential nation-specific management measures is to be made possible. With these requirements in mind, the focus shifts from *whether* the spatial dimension needs to be included in the models to *how* it may be implemented.

6.2 Paper I

The effect the regime change had on the Norwegian fleet is studied in Paper I. Two data sources were used in the study. The first source was the Electronic Reporting Systems (ERS) (Directorate of Fisheries, n.d.-b). The second source was the data collected for the purpose of being used in the Profitability survey of the Norwegian fishing fleet (Directorate of Fisheries, n.d.-a) – an annual survey conducted on a sample of Norwegian fishing vessels. Both sources are administrated by the Norwegian Directorate of Fisheries. The former data describes the harvest operations and the latter the annual income and cost structure for vessels taking part in the Norwegian snow crab fishery.

An annual measure of CPUE was calculated for each vessel participating in the fishery in the year before (2016) and after the regime change (2017). The measure was constructed as the ratio of catch, measured in kilos, and effort, measured by the amount of pots used in the fishing operation. Initially, we intended to include the length of the harvest operation, but the reporting of this variable was incomplete and the degree of reporting varied among the vessels. This may be a weakness of the approach. If harvest expectations vary between the areas, the fishers may operate with different soak time depending on which area they exploit. To investigate if the expected value of CPUE differed between the years, a paired t-test was applied.

Initially, the intention was to apply the same approach to study if the profitability[12] differed between the years, but it was asserted that the number of vessels included in the Profitability survey both years were too few[13]. If this approach

[12] e.g. using the profit margin

[13] Only 5 vessels were included in the sample in 2016 and 2017, and the vessels in the sample differed between the years.

had been used, it would have resulted in the test having a low statistical power. Therefore an alternative approach was performed to study the effect of the regime change on the profitability. A profit equation based on the economic model of Gordon (1954) and the harvest equation of Schaefer (1954) was constructed, and evaluated using data on the ex-vessel price of crab and the cost structure of a fictitious average Norwegian snow crab vessel as presented in Tabell G 22 in the mentioned Profitability survey (Directorate of Fisheries, 2019, p. 96)[14]. With the profit equation, the effect on the profitability was evaluated using estimates of the CPUE. Additionally, some estimates of the CPUE were calculated on a regional basis and evaluated in the profit equation.

There is one important limitation associated with the approach. If overfishing was taking place on the Russian part of the continental shelf in the Loophole prior to the regime change, the ability of this area to produce a high CPUE may have been reduced from 2016 to 2017. Whether local overfishing had occurred at the time was discussed (Institute of Marine Research, 2017). Hence, it may be that the Norwegian fleet would not have achieved a higher CPUE in 2017 even if it had retained access to the Russian areas in the Loophole. We have no observations of the CPUE of Russian vessels in this area in 2017 and thus have no basis for comparison. The consequence is that the chosen approach may falsely indicate that the regime change had a negative effect on the Norwegian fleet.

[14]The fictitious vessel represents an average of the snow crab vessels included in the Profitability survey.

6.3 Paper II & Paper III

The approach used in Paper II and Paper III is very different from the one used in Paper I. In order to be able to study the research questions of the two papers, a model of the Barents Sea crab fishery was needed. In the modelling approach, the aim was to construct a model that created an output adequately resembling the crab fishery as it unfolded in time and space. In the process, a framework proposed by Grimm et al. (2005) was used.

For Grimm et al. (2005), the aim was to establish a framework, Pattern-oriented modelling (POM), for tying a (bottom-up) model to the fundamental aspects of the system it tries to model, and thereby making the model more capable of studying *real* problems. In their approach, multiple patterns – e.g. found in the spatial distribution – are used as a point of departure. According to Grimm et al. (2005), a *pattern* is a property of the system and can be interpreted as an indicator of its important underlying structures and processes. With this in mind, they argue that a modeller may ask themselves the following question during the process of developing a model:

> "What observed patterns seem to characterize the system and its dynamics, and what variables and processes must be in the model so that these patterns could, in principle, emerge?"
> (Grimm et al., 2005, p. 987)

The author had access to observations of the CPUE in the area of the Loophole and a graphical visualization of the distribution of the crab stock in 2013. The latter can be thought to reflect the invasion frontier of the crab expansion. Both were interpreted as patterns of the underlying dynamics and were used in the modelling approach. The two patterns can be considered to be on different levels within a hierarchy. The former can be argued to be at a community level (the CPUE observations are an indirect measure of crab abundance in the *Loophole community*, observations that occur as a result of human exploitation), while the latter is at a population level (the spatial distribution of the crab population in the Barents Sea). The two were used to evaluate the model. The benefit of using patterns from different levels of the hierarchy is that it provides a link between low-level processes of a system to those occurring on higher levels (Gallagher et al., 2021).

However, according to Grimm et al. (2005), there are potential pitfalls associated with the use of the approach. On the one hand, if the model is too simple, it is likely to ignore some fundamental mechanism of the system and it may not provide a sufficient solution. On the other hand, if the model is too complex, analysing its outcome may be hard and perhaps too detailed. According to Grimm et al. (2005), the solution is to identify the zone of the optimal complexity, a zone referred to as the *Medawar zone*, sufficient to answer the research question at hand. Hence, neither a too simple nor too detailed model is to be preferred. With this in mind, the next step was to decide upon how the spatio-temporal dynamics might be formulated.

A fundamental methodological question is to decide if the object of study is to be represented continuously or discretely. According to M. D. Smith et al. (2009), the former can be represented by a Fisher reaction–diffusion equation describing how a substance spreads over space as a function of diffusion and density-dependent growth at each point. Combined with a harvest equation, a population that develops over time and space can be described, a development that will be determined by the harvest rate at each point.

However, M. D. Smith et al. (2009) motivate the use of discrete methods when modelling spatio-temporal dynamics for the following reasons. First, populations are often distributed discretely due to environmental factors, e.g. because of varying carrying capacity. Second, management measures often are discret, e.g. zonal access. Third, discrete approximation of a sufficient scale are often preferred because continuous models may be mathematically challenging to solve. With these motivations and the research questions of study in mind, it was chosen to proceed with a discrete model. It was further decided that the model was to be made up of three sub-models: an environmental, a biological, and an economic one.

The crab has preferences for environmental conditions. It is therefore necessary to account for the effect of the environmental conditions in the Barents Sea on the crab population. Data describing the environment in the Barents Sea were provided by the SinMod model (Slagstad et al., 2015), which has a spatial resolution of 20 times 20 km. To take advantage of the data on this scale, the model of the crab fishery was chosen to have the same resolution. Hence, the (spatial) resolution of the model was determined by the structure of the environmental data. The environmental model was constructed on an $i \times j$ lattice representing the Barents Sea, where each cell represents a specific sub-area within the Barents Sea[15]. The suitability of a cell for being a crab habitat was fully determined by the bottom temperature and ocean depth in the sub-area the cell represents. The modelled carrying capacity is visible in Figure 3.

[15]In the model, the Barents Sea area is made up by in total 8100 (90 times 90) cells (including some land area).

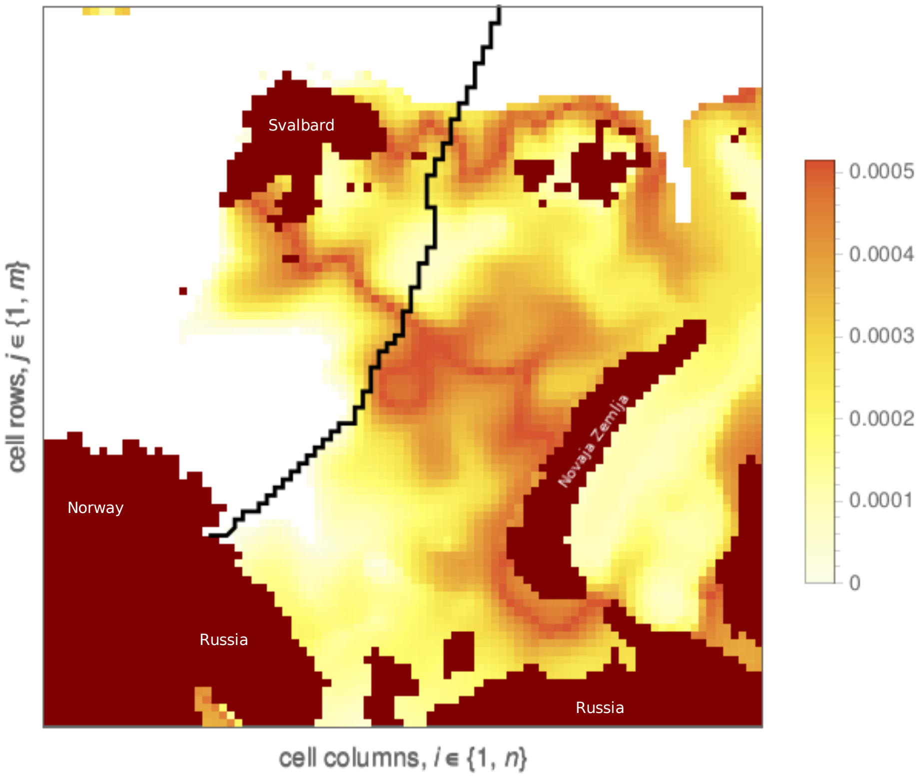

Figure 3: The modelled distribution of normalised carrying capacities of snow crab in the Barents Sea as estimated in Paper II. Dark brown indicates land areas. The legend to the right refers to the normalised carrying capacity of one cell. Also shown is how the environmental model is constructed by cells defined by the value of (i, j). The black line divides the sea areas into a Norwegian (left) and Russian part (right). The figure was originally published in Paper III.

As for modelling the population dynamics, metapopulation models constitute a way of approximating a continuous space and are frequently used to represent bioeconomic systems (see e.g. (Sanchirico & Wilen, 1999, 2005; M. D. Smith et al., 2009)). The term 'metapopulation' was coined by Levins (1969) to describe a population of populations (Hastings & Harrison, 1994). More specifically, a metapopulation can be seen as a population of sub-populations, distributed on patches linked over space through some dispersal mechanism (Sanchirico & Wilen, 1999). However, metapopulation models are not spatially explicit models, as they do not include spatial arrangement[16]. Therefore, it is not possible to account for the effect of the spatial arrangement on the population being studied (Vinatier, Tixier, Duyck, & Lescourret, 2011). Hence, such an approach would not enable us to take into account the spatial arrangement of the Barents Sea as it emerges in Figure 3.

In contrast, in spatially explicit models, the location of each object (e.g. a habitat patch or a local population) within a heterogeneous landscape is defined (Dunning Jr et al., 1995). Consequently, there will be a spatial relationship between habitable locations and other characteristics of the area, such as spatial barriers (Dunning Jr et al., 1995). Cellular automata (CA) models are spatially explicit models (Hastings & Harrison, 1994) and therefore constitute a way of accounting for this relationship.

The concept of CA originates from the work of John von Neumann in the 1940s (Chopard & Droz, 1998). He envisioned a machine having the complexity of the (human) brain with the ability for self-control and self-repair in order to solve complex problems (Chopard & Droz, 1998). Formally, his approach was about defining the characteristics of a system that enabled it to replicate itself (Chopard & Droz, 1998). According to Kari (2005), von Neumann imagined a universe made up of a two-dimensional mesh of locally interconnected cells, each having a finite number of states.

In this universe, the discrete state of each cell is updated synchronously at discrete time steps as a function of the states of the cells in its neighbourhood[17] and

[16]At least not as they appear in the classical concept of Levins (1969).

[17]*Moore* – or *von Neumann* neighbourhood are commonly used neighbourhoods. An illustration

a universal rule (i.e. the same rule for every cell) (Kari, 2005). This discrete universe is known as a CA. Continuous Cellular automata (CCA) versions of CA have evolved. In a CCA, the state of each cell is continuous (e.g. values in [0,1]). Wolfram (2002, pages 155–161) gives an example of a CCA model where the value of the state of each cell in each period is given as the fractional part of a real number.

A benefit of using CA models is that they require a relatively low amount of data to be parametrized (White et al., 2018). Additionally, CA models are found especially suitable to model the interactions between neighbours (e.g. habitat patches) in cases when the dispersal is low relatively to the size of the area being modelled (Vinatier et al., 2011).

CA models have previously been used in studies of fisheries, e.g. by Eide (2012). He used a CCA model to study the effect of Marine Protected Areas (MPAs) as a management tool. As for modelling the snow crab fishery, the CCA was assumed to have the potential to adequately represent the structure and processes of the crab population by a rule describing its growth, spread and mortality at the cellular level.

What remained then was to include the economic dynamics in the model. The economic model included the economic model of Gordon (1954) and the harvest equation of Schaefer (1954). The fishery was modelled as an open-access fishery – which also was the case in the initial phase of the fishery (Kaiser et al., 2018) – where the evolution of (fishing) effort was implemented according to the principles of V. L. Smith (1969). The spatial distribution of effort was assumed to be proportional to the distribution of the crab biomass in the cells, in line with the reasoning of Caddy (1975). Accordingly, we assumed the fishers to be able to

of the two neighbourhoods is available in Figure A.2 in the appendices.

target areas of high biomass with more fishing activity than areas of low biomass, but not in a way that was likely to maximize the harvest level each period.

After deciding upon the variables and process assumed necessary to include in the model of the crab fishery, the next step was to parametrize the model. A large number of simulations were run where the values of the different parameters of the model were chosen arbitrarily from a distribution of potential values. The parameter values with the best fit to the observed patterns were chosen to represent the fishery and used to study the research questions of Paper II and Paper III. In these papers, the research questions were studied by simulations carried out using the model.

In the modeling approach, data from different sources were used, some of which have already been specified in the previous paragraphs. One source was the ERS data which describes the harvest operations. This includes where, when and how the crab was harvested, in addition to the effort used in the operation. Hence, the ERS data provided valuable information about the fishing activity that had taken place. Economic data were present in the Profitability survey of the Norwegian fishing fleet. Other information about the crab was available through fishery-independent data such as research surveys. Some information was obtained from studies of well-established snow crab populations elsewhere in the world, such as movement rates and habitat preferences. These bits and pieces of data were utilized with the aim of developing a model of the Barents Sea crab fishery. Despite the data available in the aforementioned sources, the authors were faced with many uncertainties during the modelling exercise (see Section 5).

In Paper II, the model was applied to study how the characteristics of the fleet may affect the further geographical expansion of the fishery. The exploration dynamics was inspired by models put forward by Allen and McGlade (1986) and Hilborn and Walters (1987). In our approach, the fishing activities of the fleet were divided into fishing on previously used grounds and fishing on as yet unexplored grounds. Further, the fleet was assumed to expand the fishery by exploring areas bordering the areas it was already exploiting. However, the fleet did not explore areas unconditionally; an area subject for exploration was explored only if it satisfied certain criteria depending on the harvest opportunities in the already explored areas, and the behaviour and ability of the fleet.

Several simulations were carried out where the fleet differed in its behaviour, in terms of the willingness to take risks, and the ability to determine the lucrativeness of an area subject for exploration. For every simulation, the percentage of the crab habitat the fleet explored and the equilibrium values of harvest and effort were calculated. These values were then compared between the simulations to study how the fleet characteristics affected the geographical expansion.

In Paper III, the international management of the crab fishery was studied. The model developed in Paper II was applied, although modified somewhat. To study the research questions posed, it was assumed to be necessary to include sovereign rights and sea ice conditions in the model. As a starting point for the simulations, both the crab and the crab fishery were assumed to have fully expanded across the Barents Sea.

In research question 1, the effect of potential nation-specific management measures was studied. Specifically, it was investigated how several nation-specific management measures – one with the aim of limiting the ecosystem impact of the crab stock, another of keeping it as a reserve stock, and a third of allowing a fishery to take place – can affect the snow crab fishery both on the territory of the nation executing the measure (represented by Russia in the model) and on the territory of the other nation (represented by Norway in the model).

In research question 2, the efficiency of the current international regime was studied given the assumption that the two nations aimed at maximizing the rent from the fishery. Consequently, the open-access dynamics were detached from the model and replaced with a rent-maximizing procedure applying the golden section search method. The economic outcome of the regime where the fishing fleet of each nation exploited the crab on its own territory independently of the other (the current) was compared to that of mutual access to harvest grounds (the suggested alternative).

7 Discussion

The snow crab fishery in the Barents Sea is the topic of this thesis. In 2012, the fishery started out in an area of the high seas in the Barents Sea, called *the Loophole*. How it arrived in the Barents Sea, where it came from, and the size of the population, were unknown at the time (Institute of Marine Research, 2017). When the work on this thesis started, in 2017, these questions remained unanswered. In addition, there was also uncertainty about what the future would bring: Where the crab would settle in the Barents Sea, where it would be found in economically viable densities, how the management of the fishery would materialize and how the fishery would both be shaped by and shape these dimensions were all unanswered questions.

The aim of this thesis has not been to come up with absolute answers to these questions. Rather, with the help of the research questions, it has been simply to shed light on the fishery, how it may develop along the different dimensions, what may influence its development, and the choices that may have to be made along the way if the crab is to be efficiently managed. The main findings – which will be presented in the sections to come – can be of particular importance when management plans that lay the foundation for an efficient utilization of the crab are to be drawn up. The information can also be of special interest for the fishers making plans for a (further) participation in the fishery, but may also be beneficial for scientists and the larger society in general.

When a new fishery develops, it is important to identify the lucrative harvest grounds. In Paper II, we studied how a further geographical expansion of the fishery in the areas outside of the Loophole may come about. Here, the model was utilized to provide a map (Figure 3) of the areas likely to be suitable crab habitats and thus potential harvest areas. The model suggest that there are many areas outside of the Loophole that have the capacity of being harvest grounds for snow crab. However, according to the map, they are likely to be heterogeneously distributed over the Barents Sea.

Under such circumstances, we find that the fleet dynamics can affect which areas are explored. It appears that areas of low crab carrying capacity, separating areas of high crab carrying capacity, can serve as barricades against exploration. We find that limited information of the density of crabs in the unexplored grounds and irrational behaviour contribute to the identification of new fishing grounds.

The two forces appear to make the fleet explore non-lucrative grounds, potentially leading them to more lucrative grounds. Consequently, these forces appear to improve the long-term utilization of the crab. However, their presence does not by any means guarantee that all lucrative fishing grounds are discovered: the fishers' are likely to be in need of information from other sources to ensure a more complete exploration of the fishery. One such source could be publicly funded research surveys studying the spatial distribution of the crab.

Effort made to facilitate a new fishery needs to be balanced with a necessary level of regulations. Branch et al. (2006) claim that when a new fishery evolves, a manager may find it desirable to implement a low level of regulation to motivate fishers to join and take part in exploring the fishery. A consequence may be that the fishing effort in the fishery ends up exceeding the necessary level (Branch et al., 2006). The large number of licenses granted in the snow crab fishery may indicate a desire on the part of the management to facilitate an expansion of the crab fishery.

In Paper I it was pointed out that because the crab fishery is regulated without individual vessel quotas, these (licensed) fishers may end up in a *race-to-fish*[18] situation where they are competing with each other over shares of the annual TAC. This situation may have two major consequences.

First, the situation may lead the vessels to make capacity investments to increase their fishing power (Clark, 2010). Therefore, a *race-to-fish* situation is found to be associated with economic overcapacity (Clark, 2010; Gordon, 1954). This may increase the cost of fishing, and consequently the cost associated with harvesting the TAC. Second, the situation may facilitate a different set of products than what would be the case if the fishers' had catch rights and their activity were not dictated by a *race-to-fish* situation (Casey et al., 1995) [19]. Potential consequences of the current Norwegian management regime facilitating a *race-to-fish* was highlighted in Paper I.

The object of Paper I was to study the effect of the exclusion from the Russian areas in the Loophole on the Norwegian fleet. It was found that it probably had a negative effect on the catch rates and profitability of the Norwegian fleet in the period after the exclusion took place. It was found that the profitability could improve if the crab becomes available in economically viable sizes in new areas in the future – e.g. in the area around Svalbard as the model developed in Paper II suggest might be an option (Figure 3) or because of product development. However, it was pointed out that a *race-to-fish* regime may counteract developments

[18] also commonly called *Olympic* or *Derby fishing*

[19] When studying the British Columbia halibut fishery, Casey et al. (1995) found that following a transition into a regime with individual vessel quotas, the landings were spread out over the season opening new market opportunities for new products. The situation differed from what was the routine prior to the transition, when huge amounts of fish were landed during short seasons facilitated by a *race-to-fish* situation. Hence, the products made from the fish changed with the regime change.

that, all else being equal, can improve the profitability.

Note, however, that it was argued in the paper that a *race-to-fish* probably had not developed at that time because the fishery simply was not profitable enough. In general, as long as the profitability in the fishery is not sufficient to justify participation, the fishery is not likely to expand in terms of participating vessels. Since Paper I was published, the fishery has developed and some of the changes will therefore be commented on in the forthcoming sections.

The latest profitability study on the Norwegian crab vessels indicates that the vessels overall experienced negative operating profit in 2020 (Directorate of Fisheries, 2022a). However, the situation may very well have changed since 2020. Importantly, there was a large increase in the number of vessels participating in the Norwegian crab fishery in 2022. Whether this was because the profitability had improved or because the vessels expected the fishery to become closed[20] is unknown to the author.

The Norwegian crab landings approximately equalled the Norwegian quota in 2019 and 2021, while in 2020 it was slightly below (Table 1.). In 2022 and 2023 the TAC was also being exploited and the fishing season has become shorter (Directorate of Fisheries, 2022b, 2023). Consequently, the vessels may currently find it necessary to increase their fishing power in the fight for shares of the TAC – i.e. a *race-to-fish* may currently be evolving.

The crab is mainly processed into frozen clusters after harvest. In an early phase of the fishery, effort was made on exporting the crab alive at a higher price, and

[20]Showing activity in the form of harvesting crabs may be a criterion for being awarded a license in a potentially closed crab fishery, a licence that may prove to become valuable over time. A closure of the fishery was up for discussion at the time (Martinussen, 2022).

the share of crabs exported live was expected to increase as live storage methods improved (Lorentzen et al., 2018). However, this share is still infinitesimal. With the observations of Casey et al. (1995) in mind, one may question if processing the crab into frozen clusters is the rational thing to do given the current *race-to-fish* regime and if a regime with catch rights would have resulted in a larger share of the crabs being exported alive. There may obviously be reasons other than the management regime for the expected product changes not having taken place. The live storage methods may for instance still be insufficient.

However, the question posed in the previous section is undoubtedly important. The choices made at the harvesting stage may impact the decisions made further down the value chain and have socio-economic consequences. Different products may for example have different effects on the further value chain and differ in their demand for employment [21].

Ultimately, there is no basis for claiming that the current Norwegian management regime is ineffective – given the circumstances, it may be the optimal balance between regulations and encouragement of fishing activities. However, it cannot be ruled out that the product composition is sub-optimal and that a different regime could have led to a better utilization of the crab, or that overcapacity is being built up.

The domestic management regime is certainly an important factor in facilitating a profitable fishery. However, the domestic management regime must adhere to the principles of the international management regime. The current international regime for the snow crab fishery is made possible by the establishment of the sedentary definition of the crab, which has given Norway and Russia the right

[21] As for the halibut fishery, Casey et al. (1995) also found that the processor sector was impacted by the regime change in the halibut fishery.

to manage and harvest the crab on their respective parts of the continental shelf in the Barents Sea. In Paper III the crab fishery is studied from an international perspective.

It is well known that in many fisheries involving shared stocks, the individual actions taken by a nation on its share of the fishery may affect the fishery of the other(s) (see e.g. (Gulland, 1980; Munro, 1986)). A simulation study was carried out to investigate whether this may be the case for the snow crab fishery. In the simulations, the management measures carried out by one nation on its share of the fishery (in the scenarios, this was Russia) made the fleet of the other nation (in the scenarios, Norway) adapt its fishing activity. The results indicate that a management measure applied by one nation on its share of the fishery may have a significant impact on the fishery of the other nation. For example, if one nation aims for biological sustainability by implementing a TAC, but fails to take into account the impact of the action of the other nation, the aim may not be reached.

Additionally, the efficiency of the current international management regime was investigated in Paper III. The hypothesis was that a management regime where sovereign rights dictate where the vessels of the two nations are allowed to fish, does not need to be optimal from an economic perspective. A simulation study was conducted with the aim of comparing the economic outcome of the scenario where the two nation exploited the crab each on its own territory independently of the other (the current regime) to that of mutual access to harvesting grounds (the suggested alternative). We assumed fishing to be ongoing for 50 years and a realistic scenario of environmental change to take place, provoking changes in the crab habitat and harvest potential of each nation. The results suggest that the latter regime generates a larger rent. Hence, there may be gains to be made by implementing a new international management regime allowing for mutual access to harvest grounds.

This finding supports Gulland (1980) and Munro (1986), who claim that the optimal international management regime will depend on the population dynamics. However, because the two nations are likely to be self-interested, any gains from cooperation must be corrected by the cost of achieving and maintaining an agreement between the two nations. In situations where environmental changes are expected to occur but in a manner that cannot be accurately predicted, it is argued that any agreement must be flexible to avoid destructive conflicts (Miller & Munro, 2004).

The uncertainty associated with the model is well discussed both in this thesis and in the papers. However, some points needs to have some more light shed on them. Even though the model did reproduce some important characteristics of the fishery fairly well, it can neither be ruled out that other models would have been better nor that the model was built on wrong or inadequate assumptions. This includes the resolution of the model: A different resolution of the model (in time and space) could have provided different outcomes, all else equal. Additionally, there may be errors in the data used in the model. For example, some data are self-reported by fishers and subject to human errors.

That said, we have found the modelling approach promising. For example, in Paper III it was shown that the model generated a fair reproduction of the observed spatial distribution of fishing activities, outside of the scope (time and space) it was calibrated for. However, an inclusion of variables and processes for age structure was identified as potentially the next step forward in order to further improve the model. Consequently, with reference to the reasoning put forward in Chapter 6.1, perhaps spatial diversity in crab distribution associated with age structure should have been emphasized in the modeling process.

Therefore, the model should not be considered a final product, but rather work in progress. Further studies should therefore continually refine the model by applying additional patterns. Potentially, the model might be rejected in favour of an alternative model based on alternative theories. Ultimately, however, we see no reason why the POM approach should not be used to study other fisheries. In general, we see no obstacles to including additional dimensions to study, e.g. multiple-fleets fishing on multiple-species.

It is important to note that there are several aspects of the crab fishery that are not taken into account in this thesis. First of all, the sedentary definition of the crab is assumed to be maintained. It is neither studied what the effect would be if the sedentary definition were to be withdrawn nor the probability of this event taking place, but it would likely be a game-changer, changing which nations are allowed to exploit the crab and thereby complicating the management of the fishery. There are also different interpretations of the Svalbard Treaty regarding which nations have the right to exploit the crab in the areas around Svalbard, which could lead to similar outcomes[22]. In both cases, an EU vessel was arrested by the Norwegian authorities for not following the regulations. The two cases were taken to court (Kaiser et al., 2018) and are therefore disputed.

An existence of fleet diversity is given little attention[23]. A diversity may arise due to differences in physical characteristics, quota portfolio (alternative costs) or skipper effect[24] that may materialize in a diversified cost and income structure

[22]In 2017, the EU decided to distribute crab licenses to EU vessel which applied in the maritime zones around Svalbard (Østhagen & Raspotnik, 2019), something Norway considered the EU was not in a position to do.

[23]Aspects of fleet diversity in terms of behaviour and aptitude are implicitly included in Paper II, but this diversity is not explicitly modelled on a vessel-level.

[24]defined by Thorlindsson (1988) as “the amount of variation in the catch that can be attributed

among the vessels. The fact that a minority of the licensed vessels participate in the fishery is probably a response to and an indication of fleet diversity in the snow crab fishery. Ghost fishing[25] has been reported as a problem in the snow crab fishery (Institute of Marine Research, 2022), but is not taken into account. To protect the crab during molting, the fishery is managed by seasonal closures (Institute of Marine Research, 2022). In itself, this means that the fishing vessels are granted a shorter time-frame to harvest the annual quota during the year. Fleet diversity, ghost fishing and seasonal closures are undeniably important features of the fishery, but are not believed to have an impact on the main findings of this thesis.

The scope of the study has been limited to studying the crab fishery using bioeconomic theory. Apart from the theories on how fishing effort responds to profit opportunities outside the fishery (Gordon, 1954; V. L. Smith, 1969), the reviewed theory considers the fishery in isolation from the outside world. However, fisheries are related to each other both in terms of biological (for example predator–prey relationships) and economic interactions (many of the crab vessels participate in other fisheries). This means that what would be considered an optimal management regime for the crab fishery in itself, might not be optimal when taking into account potential interactions.

When it comes to biological interaction, there is limited knowledge on the role of the crab in the ecosystem and to which extent the crab population will be interlinked with other species. One exception to this is recent research suggesting a predator–prey dynamic between the cod and the snow crab. The spatial distribution of snow crab and cod overlaps and the degree of overlap may increase

to the skipper" (Thorlindsson, 1988, p. 200).

[25]defined by Smolowitz et al. (1978) as "the ability of fishing gear to continue fishing after all control of that gear is lost by the fisherman" (Smolowitz et al., 1978, p. 3).

with the crabs' expansion and with climate change (Institute of Marine Research, 2022), and therefore the cod have the potential to regulate the crab population and its expansion (Holt et al., 2021). If this relationship had been included in the model developed in this thesis, it could have affected the results. For example, the modelled distribution of crab put forward in Paper II could have become different.

As for economic interaction, it is related to the fact that many vessels have a wide portfolio of quotas in other fisheries in addition to having a crab license. For now, it is difficult to assess which of the licensed vessels will make up the future crab fleet and thus what links there will be between the snow crab fishery and other fisheries. These effect are therefore intentionally left out.

In Norway, fisheries are managed according to a regime where employment in coastal areas are important (Havressurslova, 2008, §1). However, we have paid limited attention to socio-economic impact, besides pointing out that is should not be ruled out that different management regimes may have different socio-economic impacts (e.g. the effect of the fishers' choice of products made from the crab may propagate further down the value chain).

The focus of this thesis has been on the income from exploiting the crab but as highlighted in the Introduction of this thesis, the crab fishery and the crab itself may have a negative effect on the ecosystem. Currently, little is known of ecosystem impacts and consequently including such effects in an appropriate manner in bioeconomic models would have been difficult. Nevertheless, in Paper III the effect of a management measure with the aim of eradicating the snow crab in certain areas is explored. Even though the cost of the presence of the crab is unknown, this does not change the fact that this cost (or perhaps benefit, something which can not be ruled out as the crab constitutes a new food item in the ecosystem) must be continually weighed against the benefits from the fishery as time goes by. Since there are management measures in place for a (biologically) sustainable fishery for the crab, it must be assumed that the latter currently is found beneficial.

8 Summary

The focus of this thesis is the Barents Sea snow crab fishery. The crab was first observed in the area in 1996, and a fishery for the crab commenced in 2012. The crab population is still developing and with it also the fishery. The object of the thesis has been, through the research questions asked, to shed light on the fishery, what can affect its further development, and the choices that may have to be made if the crab is to be well utilized.

In the thesis, a bottom-up model was established and calibrated using a pattern-oriented approach. Simulation studies were then carried out with the model with the aim of answering some of the of research questions asked. Other research questions were studied using statistical approaches.

In Paper I it was found that the regime change made possible by the definition of the crab as sedentary is likely to have had a negative effect on the Norwegian fleet. In the paper it was also highlighted that because the Norwegian fishery is managed without catch rights, a *race-to-fish* may evolve. This may facilitate overcapacity and thus an inefficient utilisation of the crab. However, doubts were raised as to whether a *race-to-fish* had developed at the time the paper was written, probably due to a lack of profitability in the fishery.

The findings of Paper II extend the findings of Paper I, by suggesting that not only does the utilization of a fishery depend on the use of traditional management measures, such as fishing licenses or a TAC, but during the initial phase of the fishery – when the focus is on mapping the spatial distribution and potential harvest areas of the species of target – the fleet dynamics may affect which areas are explored. However, it was asserted that information from other sources (e.g.

research surveys) may be important to ensure a more complete exploration of the fishery.

The results from Paper III extend the findings of Papers I and II by taking into account the international perspective of the crab fishery. The results of Paper III suggest that it cannot be ruled out that a management measure carried out by one nation can have a significant effect on the fishery of the other. Hence, it may be that the effect of management measures implemented on a national level may be hampered by the interventions made by the other nation on its share of the fishery. It was also found that the current international regime may be ineffective. It was found that there may be gains to be made by implementing a regime of mutual access to harvesting grounds.

The development of the crab fishery should be carefully monitored in the time to come; measures may have to be taken to avoid a *race-to-fish* from developing and overcapacity from emerging. In this regard, individual vessel quotas, which already exist in several other Norwegian fisheries, is one way of eliminating a competition for the TAC. The international perspective of the crab fishery should also be a subject for further studies.

As for the model developed of the crab fishery, the object of further studies should be to refine the model, perhaps through investigating if it is able to reproduce significant patterns not used in the study. In this regard, it cannot be ruled out that the model developed in this thesis will be rejected in favour of an alternative model based on alternative theories.

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Appendices

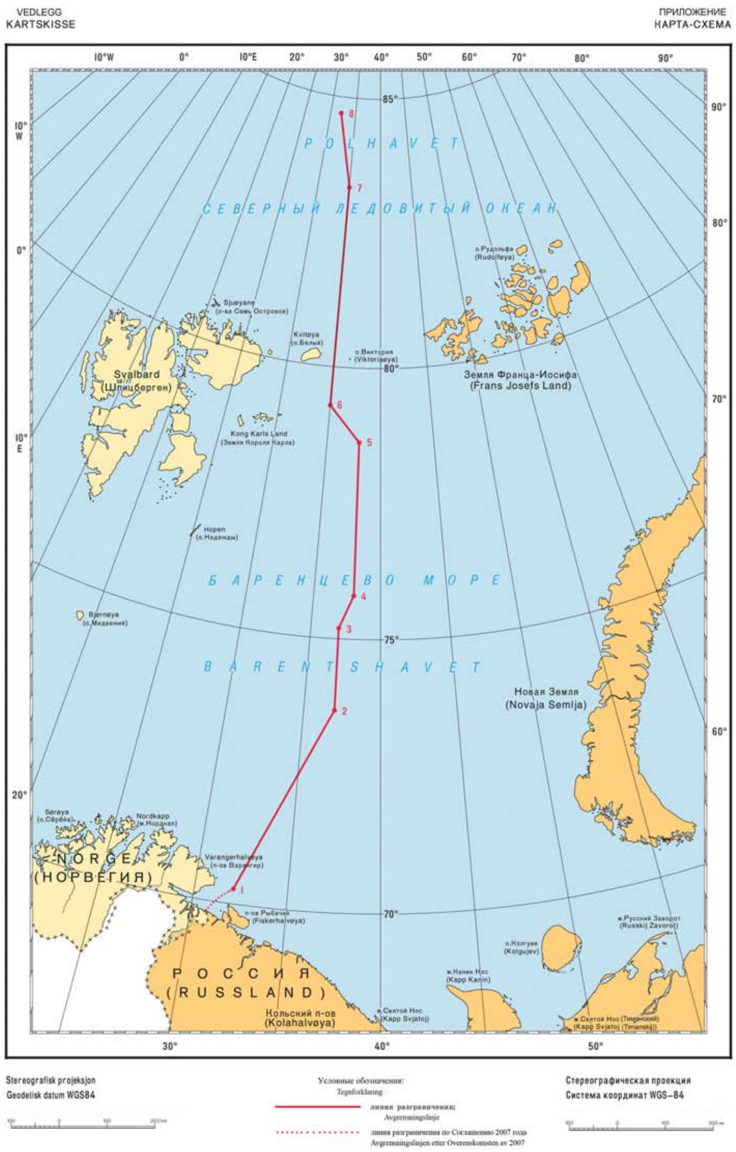

Figure A.1: Map sketch with the delimitation line according to the Agreement of 15 September 2010 (Delelinjeavtalen, 2010)

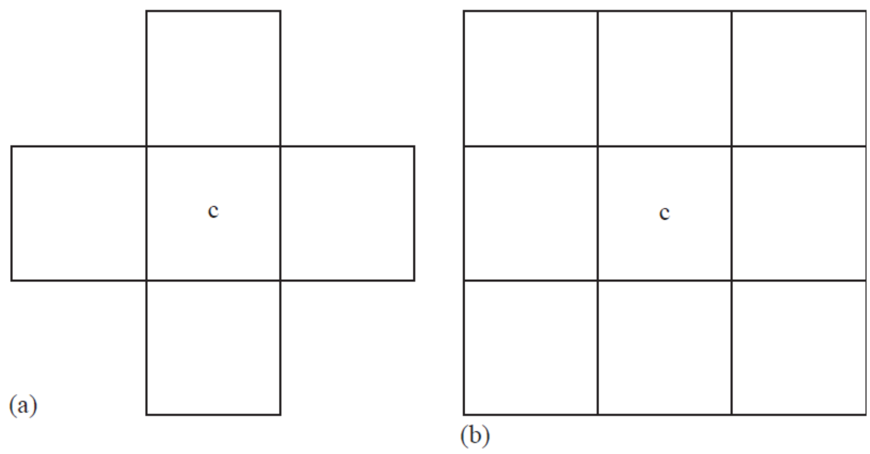

Figure A.2: Two-dimensional (a) von Neumann and (b) Moore neighborhood of cell *c* (Kari, 2005)

Papers

En kvantitativ studie av lønnsomhet i det norske snøkrabbefisket

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Sammendrag:
I denne artikkelen studerer vi lønnsomheten til den norske snøkrabbeflåten. Inntil 2017 hadde flåten adgang til de antatt attraktive fangstområdene på den russiske delen av kontinentalsokkelen i Smutthullet. Russland bestemte deretter at den norske flåten ikke fikk adgang til disse områdene. Vi estimerer CPUE for tiden før og etter utestengelsen for å undersøke effekten av denne forvaltningsendringen. Sammen med inntekt - og kostnadsdata for flåten, antyder estimatene at forvaltningsendringen har hatt en betydelig negativ økonomisk effekt. Videre analyserer vi realistiske fremtidsscenarioer for snøkrabbefisket, og i lys av scenarioene identifiserer vi faktorer som kan påvirke den fremtidige lønnsomheten til flåten.

Abstract in english:
This article discusses the profitability of the Norwegian snow crab fleet. Until 2017 the fleet was allowed to fish in the Russian part of the Continental Shelf in Smutthullet, at grounds believed to be the most attractive ones. However, from 2017 Russia denied Norwegian vessels to fish in this area. We calculate estimates of CPUE for the time before and after the exclusion to investigate the effect of this change in management. Supplementing these estimates with data describing the revenue and cost structure of the fleet, our findings suggests that the exclusion has had a substantial negative effect on the fleet's economic performance. Further, we put forward and analyze what is in our opinion, realistic scenarios for the future of the Norwegian snow crab fishery and identify factors that may affect the future profitability of the fleet.

Introduksjon

Snøkrabben er en ny art i Barentshavet, og ble første gang observert i 1996. De første kommersielle fangstene ble landet i 2013, og i de påfølgende årene bygget det seg opp et betydelig fiskeri, hovedsakelig lokalisert på den russiske delen av kontinentalsokkelen i Smutthullet. Smutthullet er internasjonalt farvann, der kontinentalsokkelen er delt i to geografiske områder, et tilhørende Norge og et tilhørende Russland. Fisket etter snøkrabbe foregår med teiner, og fartøy fra Norge, Russland og EU-land har deltatt i fisket.

Norske fartøy leverte i rekordåret 2016 fangster på 5406 tonn snøkrabbe med en førstehåndsverdi på 191 millioner NOK (Fiskeridirektoratet, 2018; Tabell 1 og 2). I startfasen av fisket ble arten forvaltet på grunnlag av fiskerisoner. I 2015 ble snøkrabben definert som en sedentær art[i] og dermed omfattet av lovgivingen for kontinentalsokkelen (Nærings- og fiskeridepartementet, 2015). Ifølge denne er det opp til kyststatene, Norge og Russland, å bestemme hvordan de ønsker å forvalte snøkrabben på sine kontinentalsokler. Etter en periode med gjensidig enighet om tilgang til å fiske snøkrabbe på hverandres kontinentalsokler, bestemte Russland seg for å endre sin strategi. Med virkning fra 2017 av, besluttet Russland å ikke tillate norske fartøy å fiske snøkrabbe på den russiske delen av kontinentalsokkelen i Smutthullet. De antatt beste fangstområdene ligger i dette området. Etter dette har det norske fisket foregått på norsk kontinentalsokkel (se Figur 1) (Havforskningsinstituttet, 2018).

Endringen i forvaltningen antas å ha fått store konsekvenser for det norske snøkrabbefisket. Mange redere har investert tungt for å kunne delta i fisket, og fangstinntektene er trolig påvirket av forvaltningsendringen. Studerer man regnskapstallene til flåten i Tabell 6e (Fiskeridirektoratet, 2019a, s. 57) ser man at fartøyene som deltar i snøkrabbefisket i gjennomsnitt har hatt negativt driftsresultat. Dette indikerer at den norske flåten møter betydelige økonomiske utfordringer i snøkrabbefisket.

I denne studien anvender vi bioøkonomisk teori for å undersøke de økonomiske konsekvensene den norske snøkrabbeflåten er påført ved å ikke lenger ha tilgang til den russiske delen av sokkelen i Smutthullet. Deretter analyserer og diskuterer vi økonomiske effekter av det vi mener er realistiske fremtidsscenarioer for det norske snøkrabbefisket. Ettersom det norske fisket etter snøkrabbe er relativt nytt er datamaterialet som beskriver fisket begrenset og tidsseriene relativt korte.

Markante forskjeller i fangstrater mellom ulike områder indikerer at populasjonen er heterogent fordelt over sitt utbredelsesområde. Sanchirico & Wilen (1999) presenterer en bioøkonomisk modell som inkorporerer en romlig dimensjon som ofte oversees i bioøkonomiske modeller. Forfatterne begrunner modellen med at det er vanlig å anse populasjoner som uniformt fordelt over sitt utbredelsesområde, og ved å utelate den romlige dimensjonen ignorerer man også hvordan fiskeflåten tilpasser seg denne heterogeniteten. De ser på fiskefartøyene som profittsøkende, og på grunn av dette vil fartøyene fiske i områder som antas å gi høyest profittmulighet. Det finnes også empiriske observasjoner som støtter Sanchirico & Wilen sin teoretiske modell. Caddy (1975) studerte kamskjellfiske på Georges Bank over en lengre tidsperiode, og finner at noen områder av banken står for brorparten av fangsten. Caddy knytter denne fangstfordelingen opp mot artens rekrutteringsområder, og påpeker at fiskeflåten tilsynelatende er dyktig i å lokalisere og drive fiske på områder som har stor biomasse. Funnene i disse studiene kan benyttes til å forklare hvorfor vi har observert en konsentrasjon i fisket etter snøkrabbe på den russiske delen av Smutthullet. Profittsøkende fartøyer fisker i områder de antar har høyest tetthet av snøkrabbe. Tettheten av snøkrabbe i et område avhenger av dybde, temperatur og tilgang til mat (Havforskningsinstituttet, 2019).

Catch per unit effort[ii] (CPUE) blir ofte benyttet som et indirekte mål på populasjonstetthet. Vi forutsetter at CPUE er proporsjonal med bestanden det fiskes på i henhold til Schaefer (1957). Dette betyr at forskjeller i biomassetetthet vil reflekteres i CPUE, og at en sammenligning av CPUE-estimater mellom områder vil indikere om noen fangstområder er bedre enn andre. For et fartøy er CPUE et mål på hvor mye fangst fartøyet får per innsats. Gitt konstant pris og konstante innsatskostnader er en høyere CPUE å foretrekke, siden det gir en større fortjeneste. Ved å sammenligne CPUE for fangst tatt før og etter utestengelsen får man et mål på effekten forvaltningsendringen har hatt for flåtens CPUE. For å studere effekten som utestengelsen har hatt på lønnsomheten bruker vi CPUE-estimatene i en bioøkonomisk modell som også inkluderer inntekts- og kostnadsstrukturen for flåten.

I snøkrabbefisket råder det stor usikkerhet knyttet til langsiktig lønnsomhet. Snøkrabben er fortsatt i ekspansjon i Barentshavet og det antas en fremtidig spredning av snøkrabbe nord- og vestover i Barentshavet (Havforskningsinstituttet, 2019). Dette kan føre til at nye områder på norsk kontinentalsokkel oppnår en krabbetetthet av kommersiell interesse i fremtiden. Det er også stor usikkerhet knyttet til fremtidig forvaltning av fisket. Både fra norsk og russisk side er det uttrykt intensjoner om å diskutere adgang til hverandres deler av kontinentalsokkelen, uten at det har ført til konkrete tiltak hittil (Nærings- og fiskeridepartementet, 2019). Fartøy som ønsker å delta i det norske snøkrabbefisket må søke om tillatelse fra Fiskeridirektoratet. Det er satt en totalkvote for fisket, uten at denne er fordelt på individuelle kvoter til deltagerne. Fravær av individuelle kvoter er kjent for å kunne føre til en situasjon der deltagerne konkurrerer om totalkvoten, en situasjon omtalt som *kappfiske* som ikke er samfunnsøkonomisk optimal (Clark, 2010) . Det er derfor sannsynlig å forvente endringer i forvaltningen på dette punktet.

Forskningsspørsmålene vi ønsker å undersøke i denne studien kan formuleres på følgende måte:

1) Hvilke økonomiske konsekvenser er den norske flåten påført som følge av Russlands beslutning om å ekskludere norske fartøy fra å fiske snøkrabbe på den russiske kontinentalsokkelen i Smutthullet?
2) Hva kreves for å oppnå et lønnsomt norsk snøkrabbefiske? Under dette punktet analyserer vi tre realistiske fremtidsscenarioer for dette fisket:
   – En videreføring av det nåværende russisk-norske forvaltningsregimet med uendret CPUE
   – Krabben sprer seg videre nord- og vestover norsk kontinentalsokkel, under et uendret forvaltningsregimet.
   – Lovendringer i dagens forvaltningsregime.

Vi analyserer hva som kreves for å oppnå et lønnsomt norsk snøkrabbefiske under disse omstendighetene. Beslutningen om å bli med eller gå ut av et fiske kan sees i sammenheng med lønnsomheten til fartøyene som er involvert i fisket (Smith, 1969). Scenarioene vil dermed gi oss en indikasjon på hvordan fisket kan utvikle seg.

Datagrunnlag og metode

Datamaterialet

I dette studiet har vi gjort bruk av data fra to ulike kilder, elektronisk fangst- og aktivitetsdata (ERS) og Fiskeridirektoratet sin lønnsomhetsundersøkelse for fiskeflåten. Tidsperioden i datasettene er henholdsvis for årene 2016–2017 og for året 2017. ERS er innsamlet av Fiskeridirektoratet og alle fartøy over 15 meter er pålagt å rapportere denne informasjonen (Fiskeridirektoratet, 2019b). Datamaterialet inkluderer dermed hele populasjonen av norske snøkrabbefartøy. Observasjonene omfatter hver fiskeoperasjon[iii] fartøyene har utøvd i perioden. Dette datamaterialet beskriver dermed fiskeaktiviteten til fartøyene som er involvert i snøkrabbefisket.

Fra lønnsomhetsundersøkelsen bruker vi regnskapsdata på fartøynivå for å kunne beskrive fangstinntekter og fangstkostnader. Dette datamaterialet inneholder ikke data for alle norske fartøy som deltok i snøkrabbefiske, men for et utvalg av disse basert på visse kriterier som for eksempel at fartøyet har oppnådd en viss fangstinntekt i året som undersøkelsen gjelder for (Fiskeridirektoratet, 2019a). Vi har benyttet gjennomsnittsdata for å definere et gjennomsnittsfartøy. Dette fartøyet er identisk med gjennomsnittsfartøyet slik det fremstår i lønnsomhetsundersøkelsen i Tabell G 22 (Fiskeridirektoratet, 2019a, s. 96). Dette gjennomsnittsfartøyet er beregnet ut fra et utvalg bestående av kun 5 fartøy og aktiviteten til hvert enkelt fartøy i utvalget har dermed stor påvirkning på de kalkulerte verdiene som beskriver dette fartøyet. Dette forholdet, samt at fisket er nytt og under utvikling, innebærer at det er betydelig usikkerhet forbundet med modeller basert på datamaterialet.

Metode

Den kortsiktige fangsten *h* i et fiske antas å kunne formuleres som en funksjon av en konstant tilgjengelighetskoeffisient, *q*, fiskeinnsatsen *E* og bestandens biomasse *X* (Schaefer, 1957):

$$h = q \cdot E \cdot X \qquad (1)$$

I ligning (2) formulerer vi CPUE gjeldende for det geografiske området *s* ved en omskrivning av fangstfunksjonen (1). Vi ser at *CPUE* er proporsjonal med biomassen *X*, hvor proporsjonalitetsfaktoren er *q*. Konstanten *q* kan tolkes som sannsynligheten for at et individ av populasjonen i område *s* blir fisket.

$$CPUE_s = \frac{h_s}{E_s} = \mathrm{q}\mathrm{X}_s \qquad (2)$$

For å kunne svare på våre forskningsspørsmål er vi avhengige av å operasjonalisere et uttrykk for CPUE. Til dette formålet har vi benyttet data på fiskeoperasjoner fra Elektronisk fangst – og aktivitetsdata (ERS).

For hver fiskeoperasjon er variablene *fangst* som mål på oppnådd fangst i kg (rundvekt), *innsats* som mål på antall teiner benyttet og *varighet* som mål på teinenes ståtid målt i minutter oppgitt. Fiskeoperasjonen er i tillegg knyttet til et geografisk område. Studerer vi datamaterialet finner vi at noen observasjoner ikke er fullstendige. I noen tilfeller (ca. 2 %) er det ikke opplyst hvor mange teiner som har blitt benyttet i fiskeoperasjonen. I slike tilfeller blir antall teiner erstattet med gjennomsnittsverdien av antall teiner som fartøyet har operert med over perioden. I noen tilfeller er varigheten av fiskeoperasjonen oppgitt til å være usannsynlig lav, i noen tilfeller lik 0 minutter. Andelen fangstoperasjoner som har oppgitt en varighet som ikke er forenelig med hvordan vi anser at fisket utføres i praksis, utgjør rundt 10 % av alle observasjonene, og er ulikt fordelt mellom fartøyene. Dette kan indikere at det har forekommet en ulik praksis mellom fartøyene i forhold til hvordan de måler ståtiden, noe som skaper usikkerhet knyttet til tolkningen av denne informasjonen. En ulik praksis antar vi kan forklares med at fisket var nytt i tidsperioden som observasjonene gjelder for. Dette gjør at det er vanskelig å definere et godt mål for CPUE som tar høyde for varigheten en teine fisker, for eksempel fangst per time per teine, som vi i utgangspunktet hadde ønsket. Vi har derfor valgt å utelate tidsaspektet og definerer CPUE som fangst per teine.

$$CPUE = \frac{Fangst}{Antall\ teiner} \tag{3}$$

Vi vil undersøke om den forventede CPUE-verdien som snøkrabbefartøyene opplever er lavere etter utestengelsen fra den russiske delen av Smutthullet. Vi sammenligner dermed CPUE mellom 2016 og 2017 på grunn av at utestengelsen fant sted ved årsskiftet 2016–2017. For flåten representerer denne utestengelsen en innskrenkning av de tilgjengelige fiskeområdene. Vi mener derfor at det kun er hensiktsmessig å undersøke om utestengelsen har hatt en negativ effekt på CPUE. Dette gjør at vi har valgt en ensidig parvis t-test for å undersøke om forventningsverdien for CPUE er lavere i 2017 enn i 2016. En konsekvens av metodevalget er at vi ikke vil kunne påvise et eventuelt høyere forventet CPUE i 2017 enn i 2016. Vi formulerer dermed følgende hypotese:

H_0 Det er ikke forskjell i fangstrater (CPUE) mellom 2016 og 2017[iv].

H_1 Fangstraten (CPUE) er større i 2016 enn i 2017[v].

I denne testen ser vi på differansen som hvert fartøy opplever i CPUE mellom de to årene. Det gir mulighet for å kontrollere for eventuell heterogenitet i flåten som gjør at fartøyene kan oppnå ulik CPUE. Et eksempel på en slik heterogenitet kan være at fartøyene har forskjellige fangststrategier, for eksempel knyttet til bruk av agn. For hvert fartøy har vi derfor kalkulert en årlig CPUE etter ligning (3) basert på årlig aggregerte verdier for fangstmengde og antall teiner. Siden t-testen undersøker endringer i CPUE mellom årene, er vi avhengige av at fartøyene deltar i fisket begge årene, noe som ikke er tilfelle for alle fartøyene i datamaterialet. I datamaterialet registrerer vi fangster fra 14 og 16 unike fartøy i henholdsvis 2016 og 2017, men bare 10 av disse fartøyene er aktive begge årene. Disse 10 fartøyene utgjør dermed vårt utvalg i den parede t-testen. For å utøve en paret t-test er det en forutsetning at fordelingen av differansen av de parvise observasjonene av CPUE er normalfordelt. Dette ble testet ved hjelp av en Skewness Kurtosis test. Med 5 % signifikansnivå kan vi ikke forkaste hypotesen om at fordelingen er normalfordelt.

For å undersøke effekten CPUE har på lønnsomhet må vi inkludere CPUE estimatene i en sammenheng som beskriver lønnsomheten i næringen. Profitten i år *t* er differansen mellom inntekten fra fiskeoperasjonene gitt ved produktet av enhetsprisen *p* og fangstmengde *h* og enhetskostnaden *c* forbudet med å produsere innsatsnivået *E* i år *t*.

$$Profitt_t = p_t \cdot h_t - c_t \cdot E_t \tag{4}$$

Ved å anvende ligning 1, kan vi skrive profittligningen som:

$$Profitt_t = p_t \cdot q \cdot E_{t\cdot} \cdot X_t - c_t \cdot E_t \tag{5}$$

For å kunne se CPUE i relasjon til profitt skriver vi om ligning (5) ved hjelp av ligning (2).

$$Profitt = (p_t \cdot CPUE_t - c_t)E_t \qquad (6)$$

Ligning (6) viser sammenhengen mellom CPUE og profitt. For å knytte den teoretiske fremstillingen til snøkrabbefisket benytter vi data fra lønnsomhetsundersøkelsen. Regnskapspostene som beskriver kostnadsstrukturen i 2017 vil være identisk med gjennomsnittfartøyet som er presentert i Tabell G 22 (Fiskeridirektoratet, 2019a). I tillegg benytter vi data på fiskeoperasjoner fra Elektronisk fangst – og aktivitetsdata som er basert på det samme utvalget av fartøy for det samme året. Dette materialet benytter vi for å kalkulere gjennomsnittsfartøyet sin årlige bruk av teiner, E_t. Denne verdien er gjennomsnittet av det totale antall teiner hvert fartøy i utvalget benyttet i løpet av året. Det er så langt ikke etablert en tariff[vi] i snøkrabbefisket, så avlønning av mannskapet blir bestemt på fartøynivå, hvor noen benytter lottbasert avlønning, andre fastlønn eller en kombinasjon av begge deler. I denne studien har vi antatt at mannskapets avlønning kun er avhengig av driftsnivået og ikke fangstnivået. Kostnaden per teine c_t har vi beregnet som summen av fartøyets driftskostnader inklusive avskrivninger dividert på E_t. Prisen p_t som fartøyet mottar for sin fangst er satt til den gjennomsnittlige kiloprisen som snøkrabbefartøyene oppnådde, slik den er oppgitt i lønnsomhetsundersøkelsen. Denne verdien er også presentert i Tabell G 22 (Fiskeridirektoratet, 2019a). Av ligning (6) ser vi at profitten per teine er $p_t \cdot CPUE - c_t$.

Basert på ligning (6), heretter omtalt som profittligningen, gjør vi en scenarioanalyse der vi evaluerer hvordan en endring i pris, kostnad per teine og CPUE påvirker fartøyets profitt. Ved å evaluere ligningen for forskjellige verdier, måler vi hvordan profitten til et fiktivt gjennomsnittsfartøy reagerer på disse endringene og antar at dette fartøyets prestasjon er beskrivende for flåtens prestasjon. Vi vil benytte profittligningen i diskusjonene rundt de økonomiske effektene av de tre fremtidsscenarioene vi har presentert.

Resultater og diskusjon

I dette kapittelet presenterer vi både resultater og diskusjon. Vi gransker effekten på fangst per innsatsenhet (CPUE) forbundet med forvaltningsendringen. Deretter undersøker vi de økonomiske konsekvensene av denne endringen og vi diskuterer økonomiske framtidsutsikter i tråd med scenarioene presentert i introduksjonsdelen.

Fangsteffekt av utestengelsen

En paret t-test ble, som nevnt ovenfor, utført for å undersøke om forventningsverdien til CPUE var lavere i 2017 (etter endring av forvaltningsregime) enn for fangst tatt i 2016 (før endring av forvaltningsregime). I vår hypotesetest har vi benyttet et signifikansnivå på 5 %. I 2017 var gjennomsnittlig CPUE lik 1,37 (SD = 0,98), signifikant lavere enn i 2016, hvor gjennomsnittlig CPUE var 2,76 (SD = 2,06)[vii]. Dette betyr at fartøyene har en statistisk signifikant lavere CPUE etter at de mistet tilgangen til russisk kontinentalsokkel i Smutthullet. I 2017 var CPUE for den norske snøkrabbeflåten halvert sammenliknet med året før. Funnet antyder at tapt tilgang til fangstområdene i russisk sone i Smutthullet har hatt en negativ påvirkning på oppnådd CPUE.

For å sammenligne CPUE estimatene fra t-testen med hele fartøypopulasjonen, har vi lagt ved Tabell 1 som beskriver fangststatistikk kalkulert på bakgrunn av fangstoperasjonene til alle fartøyene, gruppert etter fangstsone og fangstår. Tabell 1 viser forskjellige CPUE verdier enn den parede t-test viser for de to årene. For det første skyldes dette at Tabell 1 er beregnet på grunnlag av alle fangster, mens verdiene fra t-testen er beregnet fra fangstene til utvalget av fartøy som deltok i fisket begge årene. For det andre er gjennomsnittsverdiene som kommer frem ved t-testen kalkulert på bakgrunn av hvert enkelt fartøy sin CPUE. Disse verdiene er vektet like mye uavhengig av antall fangstoperasjoner fartøyet utøvde, mens CPUE verdiene i Tabell 1 viser de årlige aggregerte verdiene. I den videre diskusjonen i dette avsnittet vil vi diskutere resultatene av t-testen i lys av observasjonene i Tabell 1. Dette gir en mer helhetlig forståelse av effekten av utestengelsen fra Smutthullet.

Tabell 1 *Beskrivende statistikk – Alle fartøy. Fangstår er året fiskeoperasjonene foregikk, Fangstsone viser hvor fangstene ble tatt. Rundvekt angir total fangst av snøkrabbe målt i tonn, Innsats viser antall teiner brukt. CPUE er kalkulert som Rundvekt per Innsats. Varighet viser den gjennomsnittlige ståtiden til en teine.*

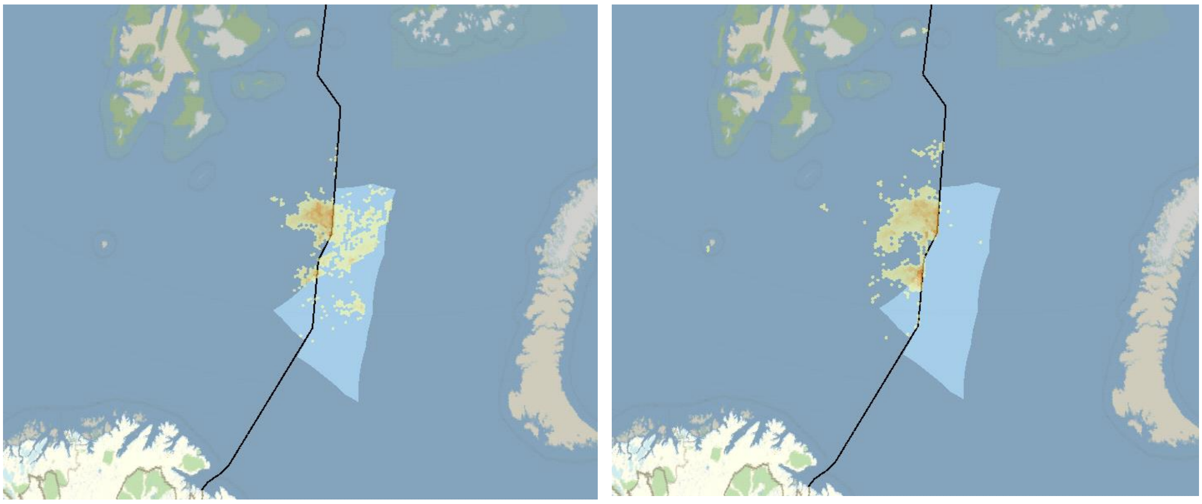
Fangstår	Fangstsone	Rundvekt (tonn)	Innsats[d] (teiner)	CPUE (kg/teine)	Varighet (min)
2016	SMUTTHULLET [a]	2 140,51	331 151,09	6,46	3 124,08
2016	NORSK [b]	2 481,91	826 341,61	3,00	11 677,45
2016	SMUTTHULLET [a] og NORSK [b]	4 622,42	1 157 492,71	3,99	7 400,76
2017	NORSK [c]	2 876,04	159 0019,2	1,81	8 315,22

[a] Fangster som er tatt i Smutthullet, i all hovedsak på Russisk sokkel

[b] Fangster på norsk kontinentalsokkel utenfor Smutthullet

[c] Fangster på norsk kontinentalsokkel

[d] Grunnet at manglende observasjoner er erstattet med gjennomsnittsverdier, summeres teinene opp til desimaltall her.



Figur 1 *Kart som viser fordelingen av fangstområder i Barentshavet i 2016 (til venstre) og 2017 (til høyre) for norske fartøy. Det lyseblå området viser Smutthullet. Den svarte linjen viser avgrensningslinjen mellom norsk og russisk kontinentalsokkel. Vi ser at avgrensningslinjen deler kontinentalsokkelen i Smutthullet i to områder, et tilhørende Russland og et tilhørende Norge. Punkter i gulnyanser viser fangstaktivitet. Illustrasjonene av fangstaktiviteten er basert på datamaterialet fra elektronisk fangst – og aktivitetsdata og fremstilt ved hjelp av programvaren Matematica.*

En overraskende observasjon fra Tabell 1 er at det ble fanget mer snøkrabbe av norske fartøy utenfor Smutthullet enn i Smutthullet i 2016 - på et tidspunkt hvor fartøyene fortsatt hadde adgang til den russiske delen av kontinentalsokkelen. Dette tyder på at det fantes gode fangstområder også utenfor Smutthullet i 2016. Figur 1 viser den geografiske fordelingen av fangstområdene for de to årene. Sammenligner man derimot CPUE for de to områdene i 2016, ser man at CPUE for fangst tatt i Smutthullet er over dobbelt så stor som for fangst tatt utenfor Smutthullet. Om vi antar at fangstkostnadene er uavhengig av fangstområde, står denne observasjonen i motstrid til teorien til Sanchirico & Wilen (1999) og Caddy (1975) hva angår en distribusjon av fartøy som følger fangstpotensial, siden mye fangst er tatt på mindre attraktive fangstområder. Et berettiget spørsmål å stille er om vi her observerer en opptreden som ikke er i samsvar med hva økonomisk rasjonalitet tilsier. Tar man hensyn til at dette er et nytt fiskeri, kan Allen & McGlade (1986) sin teori forklare denne observasjonen. Forfatterne ser på sammensetningen av fiskefartøy, og definerer to ekstremer. På den ene siden har vi fartøy som er risikoaverse, og dermed kun fisker på områder som gitt den informasjonen som fartøyet besitter, vil gi høyest fangst. Motsatsen er fartøy som er risikovillige, og dermed er villige til å utforske nye områder i forhåpning om at disse uutforskede områdene vil kunne bringe dem gode fangster. Allen & McGlade (1986) sin teori kan dermed forklare hvorfor vi observerte dette valget av fiskefelt. En annen forklaring kan vi finne ved å ta hensyn til at det ikke nødvendigvis er utelukkende CPUE som er viktig når flåten velger hvor det skal fiskes. I 2016 var det mange fartøy fra Norge, Russland og EU som fisket snøkrabbe i Smutthullet. Teinene var dermed plassert tett i de mest attraktive fangstområdene. Dette indikerer at valget kan ha vært påvirket av risiko forbundet med å ikke få tilgang til de beste områdene i Smutthullet i konkurranse med andre fartøy, og potensielle kostnader grunnet tap eller skade på redskap som følge av den store fiskeaktiviteten i området. Siden mye av fangsten i 2016 er tatt utenfor Smutthullet, betyr dette at Smutthullets fangstattraktivitet ikke kommer fullstendig frem i estimatene i t-testen, gitt at fangstdistribusjonen til utvalget av fartøy i t-testen er representativt for observasjonene i Tabell 1 som gjelder for alle fartøy.

Kolonnen *Varighet* viser at det er vesentlige ulikheter i gjennomsnittlig ståtid mellom fangstår og fangstområde. Gjennomsnittlig ståtid i Smutthullet var mindre enn 1/3 av gjennomsnittlig ståtid for områder utenfor Smutthullet i 2016. Dette tyder på at når CPUE ikke inkluderer ståtiden til teinene, underestimeres fangstattraktiviteten i Smutthullet relativt til områder utenfor. Effekten av utestengelsen kan derfor være underestimert. Observasjonen indikerer også at flåten opererer med forskjellige fangstrategier i sonene i forhold til hvor lenge en teine blir stående å fiske. Dette kan tyde på at tiden en teine blir stående kan være avhengig av fangstpotensialet i området det fiskes. Forventninger om høy CPUE fører til kortere ståtid. I metodedelen påpekte vi usikkerhet rundt hvordan fartøyene måler ståtiden, vi kan derfor ikke utelukke at ulikhetene i ståtiden mellom områdene kun skyldes dette.

En siste observasjon fra Tabell 1 er at CPUE for fangster tatt på norsk kontinentalsokkel er lavere i 2017 enn i 2016. Det har vært diskutert om det har forekommet lokalt overfiske i denne perioden (Havforskningsinstituttet, 2017). Sammenligningen av CPUE kan tyde på at det har vært en nedgang i den fangstbare populasjonen i områdene fra 2016 til 2017, og at det har blitt drevet overfiske på norsk kontinentalsokkel. Dersom man antar at den samme tendensen også fant sted på russisk sokkel i Smutthullet, så vil CPUE i dette området også være lavere i 2017 enn i 2016. En nedadgående trend vil i så fall være med på å overestimere effekten av utestengelsen. Gitt en tilstrekkelig nedgang i den fangstbare populasjonen på den russiske delen av kontinentalsokkelen i Smutthullet fra 2016 til 2017, er det mulig at CPUE i disse områdene i 2017 ikke er høyere enn hva flåten opplevde på norsk kontinentalsokkel i 2017. Dette vil eventuelt bety at utestengelsen ikke har hatt en effekt på CPUE som flåten opplevde i 2017. Fravær av observasjoner fra norske fartøy på russisk del av Smutthullet i 2017 gjør at det ikke kan anslås sammenlignbar CPUE innenfor og utenfor området i 2017.

I lys av observasjonene vi har gjort i dette delkapitlet er det tydelig at ståtiden bør inkluderes i CPUE-estimatet når datamaterialet tillater dette. I tillegg vil en modell som kontrollerer for både fartøy- og fangstsonekarakteristika trolig være bedre egnet for å studere endringer i CPUE mellom årene. I t-testen benyttet vi verdier for CPUE som var gruppert etter år og fartøy. Vi har vurdert fremgangsmåten med å benytte aggregerte verdier som egnet for å undersøke vår problemstilling, men modeller som benytter de individuelle observasjonene for CPUE vil i høyere grad utnytte informasjonen i datamaterialet og bør derfor vurderes.

Økonomisk effekt av utestengelsen

I dette kapittelet har vi frem til nå studert effekten av utestengelsen på flåtens fangstrater (CPUE) målt i fangst per teine. Vi finner en statistisk signifikant lavere CPUE etter utestengelsen. For å studere den økonomiske effekten må man se CPUE i sammenheng med andre elementer som påvirker lønnsomheten; pris for krabben og kostnaden forbundet med fiskeaktiviteten.

I den økonomiske analysen er det nødvendig å ta hensyn til at datamaterialet vi har tilgjengelig på lønnsomhetsdata er for et utvalg av fartøy som er med i lønnsomhetsundersøkelsen. Vi har derfor kalkulert verdier basert på fangstaktiviteten til dette utvalget. Disse verdiene er presentert i Tabell 2.

Tabell 2 viser at fartøyene i 2017 totalt fisket 1774 tonn med snøkrabbe med en CPUE på 1,79. Det er 5 fartøy med i fartøyutvalget som fisket i gjennomsnitt 355 tonn snøkrabbe hver med i gjennomsnitt 198452 teiner. Fartøyene fikk 50 kr per kilo for fangsten, og vi har beregnet kostnaden per teine til 193 kroner. Sammenligner vi observasjonene fra Tabell 2 med observasjonene for år 2017 i Tabell 1, ser vi at verdiene i de overlappende kolonnene (Rundvekt, Innsats og CPUE) er forskjellige. F.eks. finner vi et CPUE i Tabell 1 på 1,81, mens tilsvarende i Tabell 2 er 1,79. Grunnen til dette er at vi i Tabell 2 kun inkluderer fangst fra fartøyene i lønnsomhetsundersøkelsen, mens Tabell 1 er beregnet med basis i alle fartøy som deltok i fisket. En sammenligning av disse to gjennomsnittsverdiene indikerer at CPUE fartøyene i utvalget oppnådde ikke skiller seg vesentlig fra CPUE som hele fartøymassen oppnådde.

Ved å bruke profittligningen og verdier for CPUE, pris, kostnad per teine og Innsats per fartøy har vi gitt et anslag for den økonomiske prestasjonen til flåten. Resultatet er presentert i Tabell 3, hvor vi også presenterer en scenarioanalyse for verdiene. Kolonnen *Scenario* benevner hvilket sensitivitetsscenario som analyseres og kolonnen *Profitt* viser scenarioets profitt.

Scenario Base viser den profitten fartøyet oppnår ved å evaluere profittligningen på verdiene for CPUE, pris, kostnad per teine og Innsats per fartøy som er oppgitt i Tabell 2. Base beskriver dermed modellens beregning av den økonomiske prestasjonen i 2017. Vi ser at fartøyet går med et underskudd på i overkant av 20 millioner. Funnet indikerer at fartøyene i snøkrabbefisket er i en krevende økonomisk situasjon, og at vesentlig bedre økonomiske resultater trolig vil være nødvendig for at fartøyene blir værende i fisket. De resterende scenarioene kan ses på som en endring i base-caset, hvor tomme celler indikerer at verdiene er uendret fra base-caset.

Tabell 2 Beskrivende statistikk – Utvalg av fartøy basert på Lønnsomhetsundersøkelsen. Rundvekt er total fangst målt i tonn. Innsats er antall teiner benyttet. CPUE er kalkulert som rundvekt/teine. Antall Fartøy viser antall fartøy i utvalget. Rundvekt per fartøy og Innsats per fartøy viser henholdsvis gjennomsnittlig rundvekt fartøyene fisket og gjennomsnittlig antall teiner benyttet. Pris og Kostnad per teine viser henholdsvis den gjennomsnittlige prisen fartøyene oppnådde og den estimerte kostnaden per teine.

Fangst-år	Fangst-sone	Rundvekt (tonn)	Innsats (teiner)	CPUE (kg/teine)	Antall fartøy	Rundvekt per fartøy (tonn)	Innsats per fartøy (teiner)	Pris (kr/kg)	Kostnad per teine
2017	Norsk	1 774	992 261	1,79	5	355	198 452	50	193

Tabell 3 Terskelverdier og scenarioanalyse for CPUE, pris og kostnad per teine.

Scenario	Pris (kr/kg)	CPUE (kg/teine)	Kostnad per teine (kr/teine)	Teiner	Profitt (kr)
Base	50	1,79	193	198 452	-20 539 782
TCPUE		3.86			0
SCPUE_2016		3,99			1 289 938
SCPUE_2016S		6.46			25 798 760
Tp	108				0
Tc			90		0

Tabellelementer uten verdi indikerer at verdiene for Scenario *Base* er nyttet.

Scenario TCPUE viser hvilket CPUE-nivå som vil være tilstrekkelig for at gjennomsnittsfartøyet skal drive i balanse (0 profitt) og det fremkommer at en CPUE på 3,86 vil være tilstrekkelig, et CPUE-nivå som er over dobbelt så høyt som flåten hadde i 2017. Det er interessant å sammenligne dette scenarioet med scenario SCPUE_2016. I scenario SCPUE_2016 bruker vi estimatet på CPUE fra 2016 fra Tabell 1 (som er kalkulert med basis i all fangst fra både norsk og russisk sokkel). Med CPUE i 2017 som i 2016 ville gjennomsnittsfartøyet fått et overskudd i 2017 på i overkant av 1 million. I scenario SCPUE_2016_S bruker vi estimatet på CPUE fra 2016 fra Tabell 1 for fangst kun tatt i Smutthullet. Vi finner at gjennomsnittsfartøyet kunne ha oppnådd en profitt på i overkant av 25 millioner i 2017 med en slik CPUE. Disse anslagene indikerer at utestengelsen fra områdene med høyest fangstrate har hatt en markant negativ effekt på flåten sin lønnsomhet. Noen fartøy er derimot trolig mer påvirket enn andre siden mye fangst også ble tatt utenfor Smutthullet i 2016. Det er imidlertid viktig å ta med i betraktningen som tidligere nevnt, at det kan ha forekommet et overfiske i tiden før utestengelsen. Dersom dette er tilfelle betyr det at et CPUE-nivå sammenfallende med scenarioet SCPUE2016 og SCPUE_2016S ikke vil være bærekraftig over en lengre tidshorisont og at den negative effekten på lønnsomheten som følge av at norske snøkrabbefartøy ikke har tilgang til russisk sokkel vil være overestimert.

I scenario Tp evaluerer vi base-caset med en terskelverdi for pris som gjør at gjennomsnittsfartøyet driver i balanse. Vår modell indikerer at en pris over 108 kr per kilo vil være tilstrekkelig for at flåten går i overskudd. Dette er i så fall mer enn en dobling av den faktiske prisen som flåten oppnådde i 2017. I scenario Tc evaluerer vi base-caset med en terskelverdi for kostnad per teine som gjør at gjennomsnittsfartøyet driver i balanse. Vi finner at en kostnad på under 90 kr per teine vil være tilstrekkelig for at flåten går i overskudd. Gitt 2017 priser vil et kostnadsnivå som er under 50 % av den kalkulerte kostnaden i base-caset være nødvendig for at flåten oppnår overskudd.

I Base-caset fant vi at fartøyet går med et underskudd på i overkant av 20 millioner i 2017. Denne beregningen er ikke så ulik driftsresultatet for 2017 presentert i Tabell G 22 (Fiskeridirektoratet, 2019a), men vår modell viser imidlertid en noe høyere negativ profitt. Dette betyr at vår modell ikke produserer et profittestimat som er helt i samsvar med den observerte verdien. Dette kan være grunnet begrensningene i datamaterialet som gjør at vi har gjort noen nødvendige forenklinger. En forenkling er at vi har gjort alle kostnadene variable og avhengige av driftsnivået. Faste kostnader er gjort variable ved å bruke den årlige avskrivningskostnaden av fartøyet. Dette gjør at kostnadene undervurderes ved lav fiskeinnsats og overvurderes ved høy. I mangel på tariffavtaler for flåten har vi antatt at avlønningen er proporsjonal med driftsnivået og uavhengig av fangstnivået. I forhold til regulær lottavlønning betyr dette en undervurdering av arbeidsgodtgjørelsen ved høy CPUE, og en overvurdering ved lav CPUE. Vi mener at med de begrensinger og usikkerheter som er gjort rede for, er vårt anslag det best tilgjengelige. I tillegg indikerer våre funn at fartøyene opererer med forskjellig ståtid avhengig at antatt fangstpotensial. Dette kan påvirke kostnaden forbundet med fiskeaktiviteten, men er ikke noe vår kostnadsstruktur tar høyde for. Vår modell benytter verdier som representerer et gjennomsnittsfartøy, men i realiteten er fartøyene ulike både i forhold til kostnadsstruktur og fangstmønster. Elementene som er nevnt i dette avsnittet kan føre til at et profittestimat for et gitt scenario avviker fra den faktiske profitten som er sammenfallende med scenarioet.

Økonomiske framtidsutsikter

I den resterende delen av artikkelen vil fokuset være på hvordan flåten sin lønnsomhet kan forbedres i lys av resultatene. I de neste tre delkapitlene vil vi diskutere tre fremtidsscenarioer som vi anser å kunne påvirke flåtens lønnsomhet.

En videreføring av det nåværende russisk-norske forvaltningsregimet med uendret CPUE

I dette scenarioet antar vi at det nåværende russisk-norske forvaltningsregimet blir videreført, samtidig som en fremtidig utbredelse av krabben ikke fører til at det oppstår nye fangstområder av kommersiell interesse. I dette scenarioet anser vi at CPUE-nivået som flåten oppnådde i 2017 vil være det bærekraftige nivået, og at en forbedring i lønnsomheten følgelig må være en konsekvens av enten økt pris per kg eller reduserte kostnader per fangstinnsats.

Våre funn i scenarioanalysen viser at et prisnivå på over 108 kroner per kilo skaper overskudd for gjennomsnittsfartøyet. Hovedsakelig blir snøkrabben foredlet ombord og hovedproduktet fra denne prosessen er fryst cluster[viii], mens restråstoffet i høy grad ikke omsettes (Lorentzen *et al.,* 2017). Det finnes dermed et potensial i å utnytte biproduktet fra denne foredlingsprosessen til kommersielle formål som kan gjøre at fartøyene øker inntektene. Et annet alternativ er å endre hovedproduktet. Levende krabbe har historisk sett oppnådd en høyere kilopris i markedet enn fryst cluster, men denne produktformen fører også med seg utfordringer. Det er kvalitetsutfordringer med levendelagring av snøkrabbe i prosessen frem til den når sluttmarkedet (Lorentzen *et al.,* 2017). En endring i produktform og/eller en bedre utnyttelse av restråstoffet kan bidra til at fartøyene oppnår en høyere kilopris, men hvorvidt dette vil bidra til økt lønnsomhet er avhengig av kostnadene som en endret strategi medfører. Våre funn i scenarioanalysen for kostnad per teine viser at et kostnadsnivå under 90 kroner per teine gir overskudd for gjennomsnittsfartøyet. Fiske etter snøkrabbe er nytt for mange av aktørene, og de fleste har dermed en begrenset erfaring med fisket. Det er trolig at fisket er preget av en viss prøving og feiling i fangstoperasjonene. Denne prosessen kan føre med seg innovasjoner som kan gjøre at kostnaden forbundet med fangstaktiviteten blir redusert på sikt. Akkar blir i dag primært benyttet som agn, men det jobbes med å fremstille et mer kostnadseffektivt agn, og det har blitt forsøkt å nytte restråstoff med begrenset alternativ anvendelse. Siikavuopio *et al.,* (2018) brukte innmat fra torsk som agn, og fant at man kan oppnå like god fangst som med bruk av akkar. Agn utgjør en stor kostnadspost i regnskapet og dermed har innovasjoner på dette feltet potensielt en stor effekt på kostnaden forbundet med fiskeaktiviteten.

Krabben sprer seg videre nord- og vestover norsk kontinentalsokkel, under et uendret forvaltningsregime

I dette scenarioet er observasjonene fra forrige scenario fortsatt gjeldende, men en videre utbredelse av snøkrabben nord – og vestover gir også en mulighet for at det oppstår nye fangstområder med høyere CPUE enn hva flåten oppnår med nåværende utbredelse. Det er funnet at store deler av norsk sokkel egner seg som habitat for snøkrabber (Havforskningsinstituttet, 2020). Disse områdene er i ferd med å bli kolonisert, men om fangstområdene vil være profitable er fortsatt usikkert (Havforskningsinstituttet, 2019). Vi beregnet at dersom gjennomsnittsfartøyet hadde hatt en CPUE i 2017 som var i samsvar med hva flåten opplevde i Smutthullet i 2016, ville fartøyet snudd et underskudd på over 20 millioner til et overskudd på 25 millioner. I vår modell har CPUE dermed en stor effekt på lønnsomhet, noe som indikerer et potensial for store forbedringer i lønnsomheten under forutsetning av at det oppstår nye fangstområder som gir fangstrater i samme størrelsesorden som flåten opplevde i Smutthullet.

Endringer i dagens forvaltningsregime

En endring i dagens forvaltningsregime kan skje på bilateralt nivå mellom Norge og Russland, eller i det norske forvaltningsregimet.

På bilateralt nivå kan en avtaleendring føre til at norske og russiske fartøy får gjensidig tilgang til å fiske på hverandres kontinentalsokler. En tilgang til russiske områder vil dermed føre til at flåten igjen får tilgang til de attraktive fangstområdene i Smutthullet. Våre funn tilsier at den norske kontinentalsokkelen per i dag er preget av mindre lukrative fangstområder enn hva som finnes på den russiske delen. Om man utlukkende vurderer den relative attraktiviteten til fangstområdene på norsk – og russisk sokkel, kan en avtale om gjensidig tilgang virke usannsynlig. Derimot er det trolig andre faktorer som kan påvirke dette, som for eksempel tradisjon for samarbeid. Norge og Russland samarbeider i dag om forvaltning av flere fellesbestander i Barentshavet (Nærings- og fiskeridepartementet, 2019).

Norske fartøy som ønsker å delta i fisket etter snøkrabbe må søke Fiskeridirektoratet om tillatelse til å bli med i fisket etter snøkrabbe (Konsesjonsforskriften, 2006 § 1-2 og § 6-1). Med en slik tillatelse kan et fartøy delta i fisket etter en totalkvote (Forskrift om forbud mot fangst av snøkrabbe 2014,§ 3). Gitt at totalkvoten ikke er satt for høyt sikrer den totalbestanden mot overfiske. En slik forvaltning legger derimot ikke nødvendigvis til rette for en optimal økonomisk utnyttelse av ressursen. I en situasjon med totalkvoter uten begrensinger på fartøynivå, ligger det til rette for et *kappfiske*, herunder fare for lokalt overfiske. Et kjennetegn på et slikt fiske er at det fører til en høyere fangstintensitet i en kortere periode i fiskesesongen enn hva som er i samsvar med det som minimerer fartøyets kostnader (Clark, 2010). Grunnen til dette er at fartøyene investerer for å kunne konkurrere om å sikre seg en størst mulig andel av den tilgjengelige totalkvoten. Dette resulterer i at kostnadene forbundet med å ta en viss andel av totalkvoten kan bli høyere enn det mest kostnadseffektive nivået. En slik situasjon er ikke samfunnsøkonomisk optimal ettersom det sløses med ressursens potensielle avkasting og innsatsfaktorene er ineffektivt allokert (Ward *et al.,* 2004). Havressursloven er styrende for forvaltningen av marine ressurser, og en målsetting er at ressurser skal forvaltes på en måte som skaper samfunnsøkonomisk lønnsomhet (Havressursloven, 2008 § 1). De nevnte effektene av et kappfiske står i strid med denne målsettingen og kan dermed fremprovosere forvaltningsendringer i fisket som legger bedre til rette for samfunnsøkonomisk lønnsomhet. Eierrettigheter til fartøykvoter innenfor totalkvoten er ofte sett på som et alternativ for å unngå kappfiske. Med en slik forvaltning kan hvert fartøy fokusere på å fiske sin årlige forutbestemte kvote på en profittmaksimerende måte fremfor å måtte konkurrere med andre fartøy om andeler av totalkvoten (Wilen, 2000). Ved å studere fisket i British Columbia etter kveite finner Casey *et al.* (1995) at sesongprofilen i landinger endret seg fra få markante topper ved åpninger i fisket til en lengre og jevnere fordelt profil etter at fisket endret seg fra et kappfiske til et fiske med fartøykvoter. I tillegg finner de også at førstehåndsprisen for fisken er markant høyere etter innføringen av fartøykvoter. Forfatterne setter dette i sammenheng med at store deler av fisken som tidligere ble solgt fryst nå ble solgt fersk, til nye markedsmuligheter som ble gjort mulig via den nye landingsprofilen. Endringer i kvotesystemet kan dermed gi en positiv effekt på prisen fartøyene oppnår og redusere fartøyenes kostnader i fisket.

I snøkrabbefisket finnes det i dag en betydelig høyere andel fartøy som har tillatelse til å fiske enn fartøy som faktisk fisker. En aktørs avgjørelse om å delta i et fiske eller ikke, kan ses i sammenheng med lønnsomheten til de allerede deltagende fartøyene (Smith, 1969). Man kan dermed forvente at flere av disse fartøyene vil involvere seg i fisket dersom de forventer at aktiviteten fra fisket vil gi høyere avkastning enn hva fartøyene kan få ved alternative aktiviteter, eller at fartøyene strategisk posisjonerer seg i forhold til et antatt framtidig nytt rettighetsregime (Bertheussen *et al.,* 2020). Bertheussen *et al.* (2020) diskuterer om norske rederier posisjonerer seg for å oppnå gratis og potensielt verdifulle rettigheter i et framtidig lukket snøkrabbefiske ved å vise til historisk aktivitet i fisket. Dette kan føre til at fartøyene blir med/værende i fisket til tross for dårlig lønnsomhet.

Totalkvoten var på 4000 tonn i årene 2017 til 2019, men studerer vi fangststatistikken presentert i tabellen *Rundvekt (tonn) fordelt på art* (Fiskeridirektoratet, 2020) ble totalkvoten ikke tatt i hverken 2017 eller 2018. Dette betyr at totalkvoten ikke har vært en begrensning på fartøyenes samlede fangstmengde. Dette indikerer at den dårlige lønnsomheten i fisket har hindret et kappfiske i å utvikle seg. I 2019 ble totalkvoten derimot tatt, dette kan være grunnet en større bestandstetthet i fangstområdene og dermed en forbedret fangstøkonomi. Man kan anta at kostnaden per teine kan øke dersom et kappfiske oppstår i fremtiden.

Konklusjon

Ved å sammenligne fangstrater (CPUE) fra perioden før og etter norske snøkrabbefartøy ble nektet å fiske på den russisk kontinentalsokkel i Smutthullet, finner vi at fangstraten har blitt signifikant lavere etter utestengelsen. Funnet antyder at utestengelsen fra den russiske kontinentalsokkelen i Smutthullet har hatt en negativ påvirkning på flåtens CPUE. Men ettersom vi ikke vet hvilket CPUE fartøyene ville oppnådd om de hadde hatt tilgang til å fiske i disse områdene i 2017, kan vi ikke trekke slutningen at utestengelsen har hatt en negativ påvirkning.

Ser vi CPUE estimatene i lys av inntekts- og kostnadsdata indikerer våre resultat at utestengelsen har snudd et overskudd til et kraftig underskudd. Datamaterialet har vært begrenset, noe som har gjort at enkle analyser har blitt utført. Vi har estimert CPUE uten å inkludere ståtiden og betraktet kostnadene som variable og kun avhengige av driftsnivået. Det er derfor knyttet stor usikkerhet til estimatene av både CPUE og kostnad. Dette kan ha påvirket profitt-estimatene.

Vi finner at lønnsomheten på kort sikt først og fremst kan forbedres ved høyere fangstrater (økt CPUE) og selvsagt også ved høyere pris og lavere kostnader. Vi har kalkulert verdier som indikerer hvilket nivå disse må ligge på for at driften skal gå i balanse. Videre har vi pekt på hva som kan gjøre at lønnsomheten bedrer seg. Vi finner at den nåværende forvaltningen kan være til hinder for endringer som påvirker lønnsomheten positivt, siden den tilrettelegger for et kappfiske gitt en tilstrekkelig fangstøkonomi. Avslutningsvis identifiserer vi forvaltningsendringer som kan hindre ett slikt fiske fra å oppstå.

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Sluttnoter

[i] Sedentære arter sitter fast på havbunnen (som muslinger), eller må ha stadig kontakt med havbunnen for å kunne bevege seg.

[ii] Fangst per innsatsenhet (fangstrate)

[iii] En fiskeoperasjon er lenke med et antall teiner som er satt på havbunnen over en tidsperiode.

[iv] H_0 Differansen i forventningsverdien for CPUE for de parvise observasjonene i 2016 og 2017 er lik 0 ($CPUE_{2016} = CPUE_{2017}$)

[v] H_1 Differansen i forventningsverdien for CPUE for de parvise observasjonene i 2016 og 2017 er større enn 0 ($CPUE_{2016} > CPUE_{2017}$)

[vi] Mannskaps- og båteierseksjonen i Norges Fiskarlag har inngått et sett av tariffavtaler avhengig av fiskeri og mannskapsstørrelse som regulerer hvordan kostnader foreles og andel av korrigerte fangstinntekter (Delingsfangst) som tilfaller fisker.

[vii] vilkår; $t(10) = 2{,}29$, $p = 0{,}023$

[viii] skulder, fire bein og ei klo

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ORIGINAL ARTICLE

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Environmental constraints, biological growth and fleet dynamics of a developing fishery: A model study of the Barents Sea snow crab (*Chionoecetes opilio*, Majidae) fishery

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Abstract

The snow crab (*Chionoecetes opilio*, Majidae) has recently entered the Barents Sea, and a crab fishery is developing. Information on how the crab appeared and where it is moving is limited. We study how the characteristics of the fleet may affect the further development of the fishery. A spatial model is constructed as a grid of cells given a carrying capacity for crab determined by environmental data, assumed to reflect crabs' preferences. The biological dynamics are modelled using cellular automata, describing the growth and movements of the crabs. The fleet dynamics is represented by scenarios of fleet behaviour and aptitude, using standard theories of harvest production and economics. Pattern-oriented modelling is used to calibrate the model. The fishery started in the Loophole, but is anticipated to expand as the crabs populate adjacent areas. We use simulations to explore a potential geographical expansion of the fishery. The fleet is assumed to continually expand the current fishing area by initiating fishing in adjacent areas, relying only on their own judgement to locate promising fishing grounds. We find an inability to successfully quantify the amount of crabs in the areas subject to exploration and the willingness to take risks to be two forces contributing to a long-term utilization of the stock. Both forces appear to make the fishers explore non-lucrative grounds, potentially leading them to lucrative grounds. However, information from other sources indicating the presence of crabs at various locations appears to be necessary to ensure a more complete exploration of the fishery.

KEYWORDS

bioeconomics, cellular automata, fleet behaviour, new fisheries, pattern-oriented modelling, spatial bioeconomic dynamics

1 | INTRODUCTION

Recently, the snow crab (*Chionoecetes opilio*, Majidae) has invaded the Barents Sea, and a fishery has developed. The first observation of snow crabs in this area was in 1996, in the Goose Bank. The existence of this snow crab population, in terms of where it came from and how it got here, remains uncertain (Anon., 2017). There is extensive uncertainty concerning the current and the potential size of the population (Anon., 2017), but the population is anticipated to spread throughout suitable parts of the Barents Sea area, depending on factors such as depth and temperature (Anon., 2019a).

In a well-established fishery, fishers tend to have extensive information, learned through fishing activities, about which fishing areas are the most valuable. However, in a new fishery, such information simply does not exist. This raises some interesting questions regarding how the behaviour of the fishers and their aptitudes shape the biological and economic dynamics of the fishery. Such information is needed in order to establish an adequate management plan for the fishery. To study these questions, a spatio-temporal model could be constructed, representing the biological, economic, and environmental components of the crab fishery.

Marine biological systems are based on physical laws (e.g. oceanography) and biological processes (e.g. growth, mortality, predation) that often lead to extensive models expressed by complicated systems of differential equations, where extrapolation may be difficult (Ermentrout & Edelstein-Keshet, 1993). A cellular automaton (CA) mimics a complex system by the use of simple rules. A CA may be used with a simple 1D model, where each cell could have one of two states (e.g. 0 or 1) (Wolfram, 1984). The state of each cell develops over time through discrete time steps by applying predefined rules.

Models using continuous cellular automata (CCA) have been developed. In these, the state of each cell is given by a continuous quantity, for example by introducing the fractional part of a real number as the state value of each period (Wolfram, 2002). A feature of CAs is their ability to incorporate cell-specific characteristics (Eide, 2012). For instance, this allows us to model how some fishing grounds are more successful than others at providing a habitat for the crab. Eide (2012) bioeconomic developed a 1D model where the population dynamics was expressed by CCA rules, combining this with a harvest function in order to estimate the possible effects of marine sanctuaries. Further use of CCA for fisheries includes a two-dimensional CCA model inspired by the Northeast Arctic cod fishery (Eide, 2011) and a simulation study of the same fishery (Eide, 2014).

There is a need for models addressing the rational development of a new fishery (Branch et al., 2006). This has led us to focus on the economic and biological dimensions in a spatially diversified environment, something common to all fisheries. This is a necessary focus in the management of fisheries. Therefore, in this study, a pure open access fishery of the snow crab is assumed, without any other constraints on the harvesting other than those imposed by Nature. This corresponds to the initial phase of the snow crab fishery. The fishery started out as an open access fishery located in the high sea areas of the Barents Sea, referred to as the *Loophole* (Henriksen, 2020). New fisheries generally have a development phase where regulations are minimized to motivate entrepreneurs to explore the fishery (Branch et al., 2006) or simply because the catch sizes are too low to have a significant effect on the sustainability of the fishery.

It is now well known from simple models following (Gordon, 1954) that in pure open access fisheries, rent is dissipated. However, such models only consider states of biological and economic equilibria in a self-sustaining, uniformly distributed, fishing ground and do not include the possible effects of spatial diversity. Some argue that models that take into account spatial heterogeneity will be more successful than more aggregated and simplified models in studying economic activities (such as economically motivated fleet behaviour) (Sanchirico & Wilen, 1999).

The development of fishing effort over time can be seen as a function of the economic performance of the fleet (Smith, 1969). However, within a shorter time frame, when the level of effort is fixed, the fleet needs to decide how to use the fishing capacity, as well as when and where to carry out fishing activities (Hilborn, 1985). A fleet does not deploy an uniform distribution of effort: in order to maximize its benefits (Caddy, 1975), a fleet efficiently targets areas believed to contain larger biomasses. In multi-patch frameworks, effort has been modelled heterogeneously over the fishing ground as proportional to local catch per unit of effort (CPUE) (Caddy, 1975), sequential allocation of effort to the unit with the highest catch rate (Hilborn & Walters, 1987), and using a concentration parameter linked to catch rates, fishers' objectives, economic factors, and available information (Walters et al., 1993).

When modelling the spatial distribution of effort, the process of discovering fishing grounds is sometimes explicitly included. Allen and McGlade (1986) identify two types of fishers, differing in their appetite for risk. A *Cartesian* will only consider fishing at fishing grounds known to be the valuable, while a *stochast* will take the risk of exploring new fishing grounds (Allen & McGlade, 1986). In a scenario with only *Cartesians*, Allen and McGlade, (1986) find that the fleet will end up exploiting only a small fraction of the total area, resulting in a relatively small fleet and low catches, while the behaviour of a *stochast* in the long run will be beneficial for all. Hilborn and Walters (1987) allocate the lesser part of the fleet's annual fishing effort to the exploration of unknown areas, in order to uncover the potential of different fishing grounds, using the new information when allocating the remaining effort to the most promising fishing grounds.

This paper presents several simulations inspired by the developing snow crab fishery. In the simulations, we enter at an early stage of the crab invasion and thereby also the fishery. The aim of the simulations is to examine how the fleet dynamics affect the biological and economic dynamics of the fishery. The method applied is presented in the next section along with the model including environmental, biological and economic factors affecting the habitat of the snow crab, the development of its population and the dynamics of the fishing fleet.

2 | METHODS AND DATA

2.1 | Environmental carrying capacity for the snow crab

The environmental model employed in this study is constructed in order to map the suitable habitat for the snow crab population in the Barents Sea. A crucial element of the modelling process has been to take into account the fact that the Barents Sea seabed is not homogeneous, that is, recognizing that some areas are more suitable than others for the snow crab. The model is built upon an $i \times j$ lattice where each cell represents a specific geographic area within the Barents Sea. Each cell may sustain a snow crab biomass up to a cell-specific carrying capacity level.

The suitability of a habitat for the snow crab is a function of its preferred ocean depths and temperature range (Agnalt et al., 2011; Anon., 2017). We assume that the suitability of a habitat, that is an area providing a positive snow crab carrying capacity, is fully determined by these two variables. Thus, for a cell to provide a positive carrying capacity for the snow crab, it has to be within a certain range of both ocean depth and average temperature.

The bottom temperatures and ocean depths are provided by the SinMod model (Slagstad et al., 2015), which has a spatial resolution (grid) of 20 times 20 km in the Barents Sea. The average depth of the ocean in cell (i,j) will be denoted by $D_{i,j}$, and its average temperature by $T_{i,j}$. The depth function $\text{depth}_{i,j}(D_{i,j})$ represents a binary number assumed to be a habitat switch factor for the possible presence of crab (1) and its absence (0), depending on the average depth (in metres) of cell (i,j), as illustrated in Figure 1. The annual average bottom temperature $T_{i,j}$ of cell (i,j) is calculated from the monthly averages of 2016 and measured in degrees Celsius. We consider a scale for the suitability of this habitat, from a minimum of 0 (not suitable) to a maximum of 3 (perfect), as illustrated in Figure 1.

The carrying capacity of cell (i,j) is defined as a function of the habitat factors depth and temperature. It is a normalized product of $\text{depth}_{i,j}$ and $\text{temp}_{i,j}$. With m and n representing the maximum number of cells in each direction, it can be expressed as follows:

$$\text{cap}_{i,j}(T_{i,j}, D_{i,j}) = \frac{\text{temp}_{i,j}(T_{i,j}) \cdot \text{depth}_{i,j}(D_{i,j})}{\sum_{i=1}^{n} \sum_{j=1}^{m} \text{temp}_{i,j}(T_{i,j}) \cdot \text{depth}_{i,j}(D_{i,j})} \tag{1}$$

The normalization arranges that the sum of the carrying capacities of all cells $\sum_{i=1}^{n} \sum_{j=1}^{m} \text{cap}_{i,j} = 1$. Cell (i,j) is defined as habitable when $\text{cap}_{i,j} > 0$, with a relative carrying capacity given by the value of $\text{cap}_{i,j}$. In Section 2.6, the normalized carrying capacities are scaled by a factor K (the environmental carrying capacity of the snow crab in the Barents Sea in terms of crab biomass) to reflect the carrying capacities in terms of the maximum crab biomass each cell can sustain. Figure 2 displays how the distribution of cell carrying capacities within the geographical area is based on bathymetrics and the average bottom temperatures in 2016. The figure illustrates how the local carrying capacities are heterogeneously distributed over the area.

2.2 | Biological growth and spatial distribution

We assume the biological dynamics of the Barents Sea snow crab population to be described by a surplus production model that includes biomass diffusion, providing the spatial distribution of biomasses in the $i \times j$ lattice. A constant per period growth rate g is assumed, while natural mortality triggers a local collapse when the specific maximum biomass level of each cell is exceeded. The discrete redistribution of biomasses assumes a Moore neighbourhood

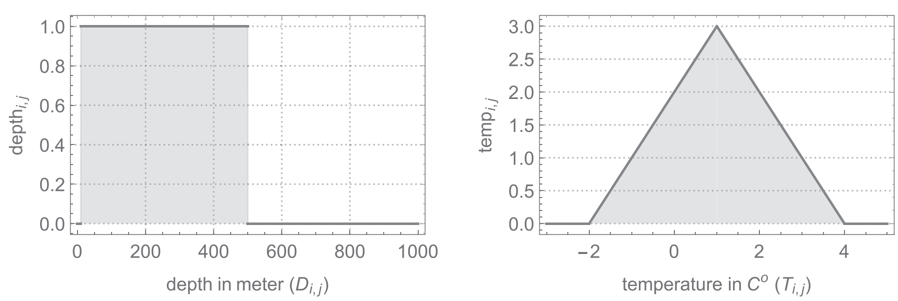


FIGURE 1 The values for depth (to the left) and temperature (to the right) that are assumed to be suitable to be a habitat for snow crab. For a cell to provide a positive carrying capacity for snow crab, it has to be within both ranges

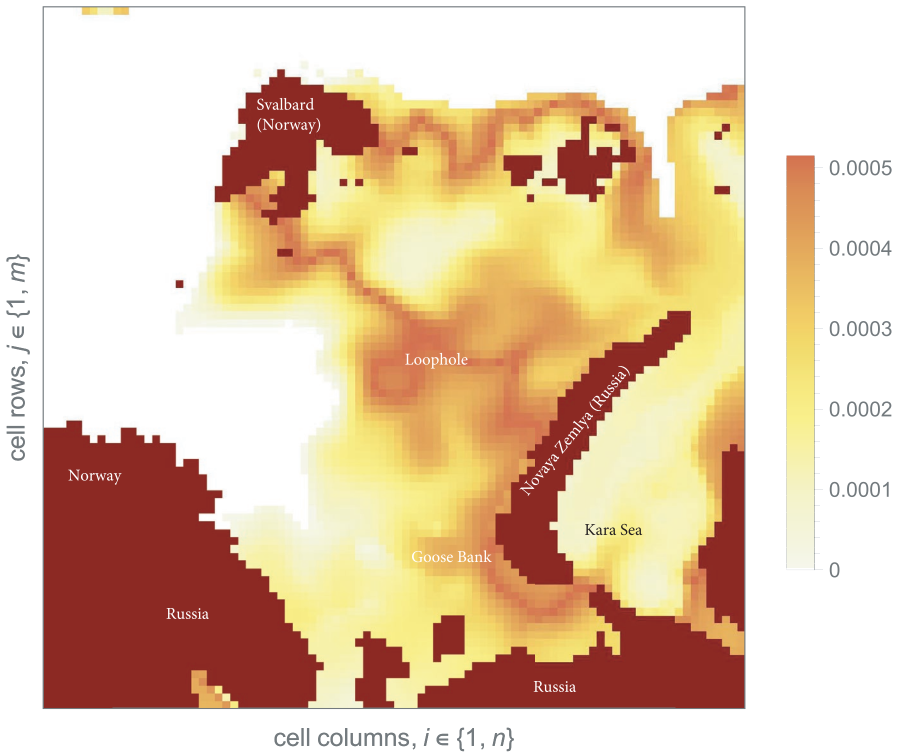


FIGURE 2 Distribution of normalized carrying capacities of snow crab in the Barents Sea, according to Equation (1) on the basis of SinMod data from 2016. Dark brown indicates land areas. The legend to the right refers to the value of the normalized carrying capacity of one cell. Also shown is how each cell's coordinate is defined by the value of (i, j). Note that some areas outside the Barents Sea that belong to the Kara Sea are also included and have positive carrying capacities given the assumption of the model

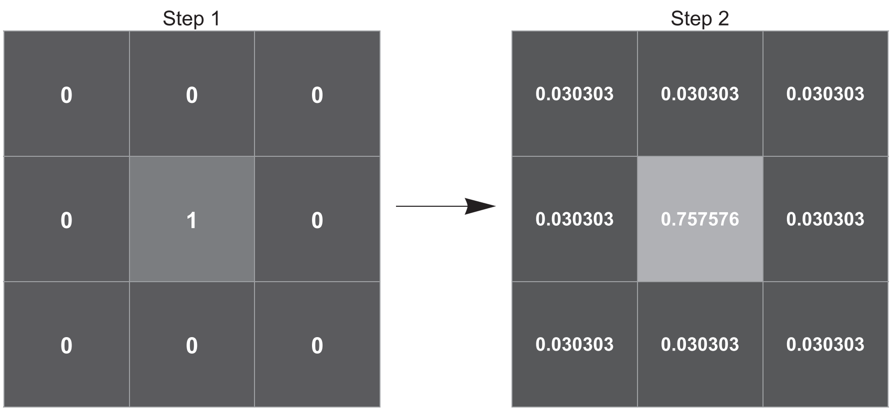


FIGURE 3 With one biomass unit in the middle cell to the left (step 1), the biomass distribution to the neighbouring cells in the next time step (assuming a Moore distribution of range 1) follows a diffusion matrix, M, calibrated by the POM approach, as shown by the value of each cell to the right (step 2)

of range 1, as indicated in Figure 3. The redistribution of the biomass $b_{i,j,t}$ contained in cell (i,j) at time t is modelled by CCA rules. Each period includes a surplus growth of biomass before the new biomass is redistributed between the neighbouring cells and the cell itself, as indicated in the right-hand panel of Figure 3.

After the redistribution of cell biomass, the fractional part of the ratio $b_{i,j,t}/\text{cap}_{i,j}$ is retained in the cell. Hence, when $b_{i,j,t}$ exceeds the capacity level $\text{cap}_{i,j}$, the biomass is reduced accordingly, reflecting how natural mortality is implemented in the CCA model. The combined growth, recruitment, mortality and distribution determine the crab biomass of each cell at time $t + 1$. Hence, the biomass is given as a function of (1) the cell's biomass at time t, (2) the biomasses of the neighbouring cells, (3) the diffusion properties, (4) the growth rate and (5) the carrying capacities of each cell. This study assumes an absorbing boundary, meaning that the biomass dispersed from a habitable area into a non-habitable area will disappear, that is it will experience 100% mortality.

During the early benthic stages, the snow crab is presumed to be stenothermic, where early juvenile instars are found to prefer temperatures in the range between 0°C and 1.5°C (Dionne et al., 2003). This sensitivity can affect the ability of the species to reproduce in an area. Therefore, growth is only implemented in cells with temperatures between 0°C and 1.5°C.

The total crab biomass within all cells in period t, B_t, is given by summing

$$B_t = \sum_{i=1}^{n} \sum_{j=1}^{m} b_{i,j,t} \tag{2}$$

where $b_{i,j}$ is the biomass of cell (i,j).

2.3 | Spatial distribution of fishing activity

Fishers must continually decide how the fishing effort is to be spatially distributed. In this developing crab fishery, we assume the fishing effort to be distributed both in areas where earlier fishing activities have taken place and in new fishing grounds. Hence, there are two distinctly different sets of lattice cells exposed to fishing effort: one where earlier fishing has occurred, and another set of previously unexplored cells.

Let H_t and U_t be two binary $i \times j$ matrices representing previous fishing activities in the $i \times j$ lattice at time t. If effort was distributed in cell (i,j) of matrix H_t earlier, the entry $h_{i,j,t}$ of H_t equals 1, but 0 if not. Similarly, with reference to U_t, $u_{i,j,t}$ equals 1 if this is the first time period, fishing takes place in the cell, but 0 if not.

The total number of cells where fishing takes place at time t is therefore given by the sum of the two matrices, ($\sum_{i=1}^{n} \sum_{j=1}^{m} (u_{i,j,t} + h_{i,j,t})$).

We assume the fleet assigns a certain share, a_t, of its total fishing effort, E_t, at time t to exploratory fishing. The remaining share of effort, (1-a_t), is allocated to already explored grounds. Fishing effort in previously explored cells is assumed to be distributed according to the first case of Equation (3):

$$e_{i,j,t}(h_{i,j,t}, u_{i,j,t}) = \begin{cases} \dfrac{b_{i,j,t}^{d} \cdot h_{i,j,t}}{\sum_{i=1}^{n} \sum_{j=1}^{m} b_{i,j,t}^{d} \cdot h_{i,j,t}} \cdot (1-a_t) \cdot E_t \text{ when } h_{i,j,t}=1 \\ \dfrac{a_t \cdot E_t}{\sum_{i=1}^{n} \sum_{j=1}^{m} u_{i,j,t}} \text{ when } u_{i,j,t}=1 \\ 0 \text{ otherwise} \end{cases} \tag{3}$$

The fishing effort placed in previously explored cells (defined by H) depends on (1) the density of biomass in each cell, (2) the value of the concentration parameter d, (3) the share of fishing effort placed in previously unexplored cells a and (4) the total fishing effort allocated to the crab fishery E. If $d = 0$, the total fishing effort of these cells, $(1 - a)E$, is uniformly distributed in the cells defined by H. If $d = 1$, the distribution of effort is proportional to the distribution of biomass in the cells; and if $d > 1$, the concentration in cells with the highest biomass density increases by the value of d, in agreement with Caddy (1975) and Walters et al. (1993).

The second rule provided in Equation (3) expresses how fishing effort is distributed in previously unexplored cells. We assume that the expectation of obtaining a harvest in an unexplored area, defined by U , is equal for all these cells. Hence, the total fishing effort allocated to exploratory fishing, $a \cdot E$, is assumed to be uniformly distributed over those cells where fishing is taking place for the first time.

2.4 | Dynamics of exploring new fishing grounds

We assume that the crab fleet has the necessary basic knowledge about the crab's habitat preferences to exclude all cells without living conditions for crabs. We further assume that as long as the fishery is still developing, there will always exist unexplored areas. Hence, the fishers must choose which of these areas they want to explore at any time during the development.

Let R_t be a binary $i \times j$ matrix reflecting the remaining unexplored cells in the $i \times j$ lattice at time t. If the cell (i,j) remains unexplored at time t, $r_{i,j,t}$ equals 1, 0 if not. R_t therefore defines the cells remaining unexplored at time t. Initially, at time $t = 0$, all cells having positive crab carrying capacity remain unexplored, as expressed by Equation (4)

$$r_{i,j,t=0}(\text{cap}_{i,j}) = \begin{cases} 1, & \text{when cap}_{i,j} > 0 \\ 0, & \text{otherwise} \end{cases} \tag{4}$$

The fishers are assumed to expand the fishing ground by expanding the already explored area at any time. Hence, we assume that only cells adjacent to already explored cells are considered for exploration. The rationale behind this is the assumption that fishers continually perceive the potential of unexplored fishing grounds next to the area they already are exploiting. These cells define the binary $i \times j$ matrix R'_t, where each cell with value 1 is a subject for exploration at time t. If the cell (i,j) at time t remains unexplored (defined by R_t) and is located next to an already explored area (defined by H_t), $r'_{i,j,t}$ takes the value 1 and 0 otherwise.

The number of cells subject to exploration selected by the fishers will depend on the anticipated potential of each cell relatively to the assumed potential in the already explored areas, in addition to the aptitude of the fleet and its willingness to take risks. In order to operationalize the exploration process, we introduce a measure of the assumed potential in the already explored area, referred to as the *Threshold Level of Biomass* (*TLOB*), defined by

$$\begin{aligned} \text{TLOB}_t &= \sum_{i=1}^{n} \sum_{j=1}^{m} \left(b_{i,j,t} \cdot \frac{b_{i,j,t}^{d} \cdot h_{i,j,t}}{\sum_{i=1}^{n} \sum_{j=1}^{m} b_{i,j,t}^{d} \cdot h_{i,j,t}} \right) \\ &= \sum_{i=1}^{n} \sum_{j=1}^{m} \frac{b_{i,j,t}^{1+d} \cdot h_{i,j,t}}{\sum_{i=1}^{n} \sum_{j=1}^{m} b_{i,j,t}^{d} \cdot h_{i,j,t}} \end{aligned} \tag{5}$$

where n is the total number of rows and m is the total number of columns in the lattice. Equation (5) expresses TLOB as the sum of the biomass $b_{i,j,t}$ in every cell within set H at time t raised to the d th power, corresponding to Equation (3), where increasing values of d increase the fleet's ability to identify cells of high biomass density in the already explored areas. By including the term $h_{i,j,t}$, we specify that only explored cells are given positive weights, that is, have an effect on *TLOB*. Hence, *TLOB* represents the density of crabs the fleet expects to find when fishing in an explored area.

We define two types of exploration strategies, one rational and one irrational, reflecting different scenarios for the fleet's willingness to take risks. In the rational strategy, a cell subject to exploration will be explored if the anticipated size of the crab biomass in the cell exceeds TLOB. In the irrational strategy, the cell will be explored if the anticipated biomass level exceeds 50 per cent of TLOB. We also specify two branches of each strategy, assumed to reflect different scenarios of the fleet's aptitude.

In the *Rational FI* and *Irrational FI* strategies, the fleet receives full information of the state of the crab stock in the adjacent unexplored cells: they are able to successfully determine the biomass level in an adjacent unexplored cell. The strategies where the fleet only has limited information are denoted by *Rational LI* and *Irrational LI*, where the fishers are, with equal probability, able to anticipate the biomass level in an adjacent unexplored cell to be in the interval of ±100 per cent of the actual biomass level.

These strategies enable us to specify under which circumstances exploration is allowed to take place, by linking the decision to the available biomass in the explored areas, taking into account the fact that it is not a forgone conclusion that the fleet will carry out any exploration. The aim is to add credibility to the fleet's reasoning in the exploration process by preventing clearly unrealistic behaviour.

Hence, for a given strategy, $u_{i,j,t}$ is given the value 0 or 1 in period t according to the following rules:

$$u_{i,j,t}\left(r'_{i,j,t}, b_{i,j,t}\right) = \begin{cases} \begin{cases} 1, \text{ when } r'_{i,j,t} \cdot b_{i,j,t} > \text{TLOB}_t \\ 0, \text{ otherwise} \end{cases} & \text{for RationalFI} \\ \begin{cases} 1, \text{ when } r'_{i,j,t} \cdot b_{i,j,t} > \dfrac{\text{TLOB}_t}{2} \\ 0, \text{ otherwise} \end{cases} & \text{for IrrationalFI} \\ \begin{cases} 1, \text{ when } r'_{i,j,t} \cdot X \cdot b_{i,j,t} > \text{TLOB}_t \\ 0, \text{ otherwise} \end{cases} & \text{for RationalLI} \\ \begin{cases} 1, \text{ when } r'_{i,j,t} \cdot X \cdot b_{i,j,t} > \dfrac{\text{TLOB}_t}{2} \\ 0, \text{ otherwise} \end{cases} & \text{for IrrationalLI} \end{cases} \tag{6}$$

where X is a random number between 0 and 2.

If $u_{i,j,t}$ equals 1, then cell (i,j) in the lattice is chosen by the fishers to be explored at time t. The term $r'_{i,j,t}$ specifies that only cells subject to exploration at time t may be chosen. When the fleet has decided which areas to explore, it also needs to set aside a share of effort for the exploratory fishing. We assume that the proportion of effort used for exploratory fishing at time t is given by the ratio between the number of cells where exploratory fishing will be performed and the total number of cells where all fishing activities will be performed. a_t is therefore defined by

$$a_t = \frac{\sum_{i=1}^{n}\sum_{j=1}^{m} u_{i,j,t}}{\sum_{i=1}^{n}\sum_{j=1}^{m} h_{i,j,t} + \sum_{i=1}^{n}\sum_{j=1}^{m} u_{i,j,t}} \tag{7}$$

where n is the total number of rows and m is the total number of columns in the lattice. If no cells subject to exploration are found to meet the criterion for being explored ($\sum_{i=1}^{n}\sum_{j=1}^{m} u_{i,j,t} = 0$), the total fishing effort will be distributed over the already explored cells. This criterion may cause some cells to remain unexplored at the end of the simulation period.

The number of remaining unexplored cells (defined by R) diminishes over time by cell exploration according to

$$R_t = R_{t-1} - U_{t-1} \tag{8}$$

The percentage of the carrying capacity the fleet has revealed at time t is expressed as

$$rev\_cap_t = \left(\sum_{i=1}^{n}\sum_{j=1}^{m} cap_{i,j,t} \cdot (h_{i,j,t} + u_{i,j,t})\right) \cdot 100 \tag{9}$$

where n is the total number of rows and m is the total number of columns in the lattice.

One last scenario is added for the sake of comparison: The *Fully Explored* scenario assumes the fleet to have explored all cells in advance and therefore do not need to start exploration.

2.5 | Harvesting economics

The harvest, $y_{i,j,t}$, captured in cell (i,j) at time t, when the density of biomass is $b_{i,j,t}$ and the fishing effort equals $e_{i,j,t}$, is given by the Cobb–Douglas equation

$$y_{i,j,t}(e_{i,j,t}, b_{i,j,t}) = \begin{cases} q \cdot e_{i,j,t} \cdot b_{i,j,t}^{\beta} & \text{when} \quad b_{i,j,t} \geq q \cdot e_{i,j,t} \cdot b_{i,j,t}^{\beta} \\ b_{i,j,t} & \text{when} \quad b_{i,j,t} < q \cdot e_{i,j,t} \cdot b_{i,j,t}^{\beta} \end{cases} \tag{10}$$

where q is the catchability coefficient while β is interpreted as the output elasticity of biomass. Thus, a change of one per cent in the biomass b results in a corresponding β per cent change in the harvest. Eide et al. (2003) argue that active gears or gears attracting fish by bait will have a value of β below one, and found that the β of the Barents Sea cod trawl fishery was just above 0.4. In the snow crab fishery, pots are applied, designed to lure crabs with bait into the pots, suggesting a β below one.

The total harvest at time t is given by

$$Y_t = \sum_{i=1}^{n}\sum_{i=1}^{m} y_{i,j,t} \tag{11}$$

where n is the total number of rows and m is the total number of columns in the lattice. The abnormal profit π_t in period t is given by

$$\pi_t = p \cdot Y_t - c \cdot E_t \tag{12}$$

where the price p is the unit price of harvest (Y_t), and the unit cost of effort E_t, including opportunity cost, is c. Economic performance is measured in terms of abnormal profit, π, which determines the evolution of effort. When $\pi > 0$, more participants are encouraged to join the fishery and when $\pi < 0$, fishers will start leaving the fishery. The evolution of effort over time (increasing, decreasing, or steady state) is modelled according to the principles used by Smith (1969), defined by

$$\Delta E_t = \gamma \cdot \pi_{t-1}, \tag{13}$$

γ being a constant stiffness parameter controlling the speed of changes in fishing effort due to changes in the abnormal profit.

Equation (13) shows that the change in effort in period t is proportional to the abnormal profit in period $(t-1)$.

2.6 | Model validation and parameter settings

In order to make a representative model of the developing snow crab fishery, the model and the model parametrization have to be in line with the observed characteristics of the fishery. Therefore, the model has been calibrated using a pattern-oriented modelling (POM) approach. In general, the main object of POM is to use the observed patterns (in the actual fishery) to guide the design of the model describing the system (Grimm et al., 2005). A *pattern* is a characteristic of the system and can be interpreted as an indicator of the underlying structure and processes of the system (Grimm et al., 2005). In our study, two patterns have been used to calibrate the model.

The first pattern consists of the observed CPUEs revealed during the fishing activity in the Loophole from 2014 to 2016. The snow crab fishery started in the Loophole, and to a large extent, all fishing activities took place in this area during this period of time (Hogrenning & Henriksen, 2021). The observed CPUEs are calculated using the same data material and method as outlined in Hogrenning and Henriksen (2021). The data are based on the electronic reporting systems and are publicly available (Anon., 2019c), administrated by the Norwegian Directorate of Fisheries. In Hogrenning and Henriksen (2021), the CPUE is calculated as the ratio of the annual harvest with the number of pots used in the harvest operations. Hence, the number of applied pots is used as a measure of effort. The same method has been adopted here in calculating the CPUE, while the calculations are monthly instead of annual.

The data material only covers observations of harvest operations carried out by Norwegian vessels and therefore only represents a share of the total operations carried out by the vessels from all the nations involved. We therefore assume the calculated values of the CPUE for 2014–2016 to be valid for all vessels and the harvest and effort levels of the Norwegian vessels to be proportional to the total harvest and effort levels of each month. In the following, the coefficient of proportionality is denoted by pp.

Table 1 (Table A1) in Anon. (2019a, p. 6) shows the total annual harvest, grouped by the different nations involved in the fishery. For the years 2014–2016, we calculate the annual *pp* as the ratio between the annual Norwegian harvest and the annual total harvest, using the values in the table. We calculate the annual *pp* s in the absence of monthly observations of the total harvest levels. The observed $\mathrm{CPUE}_{y,mo}$ for month *mo* in year *y* is therefore given by

$$\widehat{\mathrm{CPUE}}_{y,mo} = \frac{\widehat{\mathrm{harvest}}_{y,mo}}{\widehat{\mathrm{effort}}_{y,mo}} = \frac{\mathrm{pp}_y \cdot \mathrm{harvest}_{N,y,mo}}{\mathrm{pp}_y \cdot \mathrm{effort}_{N,y,mo}} \tag{14}$$

where the subscript *N* refers to the harvest and effort levels of Norwegian vessels only. The hat operator indicates that the value is an estimate of the actual value. The value of $\widehat{\mathrm{effort}}$ in month *mo* in year *y* is given by

$$\widehat{\mathrm{effort}}_{y,mo} = \mathrm{effort}_{N,y,mo} \cdot \mathrm{pp}_y \tag{15}$$

In the simulation, we instruct the fleet to execute the observed effort levels in an area designed to be a discrete spatial representation of the Loophole area. The simulated CPUE subsequently were compared to the observed CPUE. The Euclidean distance between the two was calculated based on the periodic differences of the two time series. A relatively low absolute value of the Euclidean distance suggests a good fit. Note that there were some fishing activities within the Loophole area before 2014, and some fishing activities outside of the Loophole in 2016, but only to a modest extent. This implies that the simulated level of effort executed in the Loophole does not fully reflect the actual fishing activities within the area during the given period. This is also visible in Figure 4, which shows the fishing activities by the Norwegian vessels during 2014–2016 and the geographical range of the Loophole.

TABLE 1 Parameter values for the selected simulation providing the best fit

Parameter	Value	Description	Section	POM
g	0.05	Growth rate	2.2, 2.6	Yes
d	1	Concentration parameters	2.3	No
K	950,000	The total capacity (tonnes)	2.6	Yes
M	(Figure 3)	Diffusion matrix	2.2, 2.6	Yes
q	0.0001	Catchability coefficient	2.5, 2.6	Yes
β	0.9	Output elasticity of biomass	2.5	Yes
p	50	Unit price of harvest (NOK)	2.5	No
c	193	Unit cost of effort (NOK)	2.5	No
γ	0.00015	Stiffness parameter	2.5	No
pwh	758	Number of periods conducted before the harvest started	2.6	Yes
T	2,000	The total number of periods conducted	2.6	Yes

Note: The POM column specifies if the parameter value is an outcome from the POM procedure (Yes) or obtained from another source (No). The column section gives a reference to the section(s) in the paper where the parameter is described.

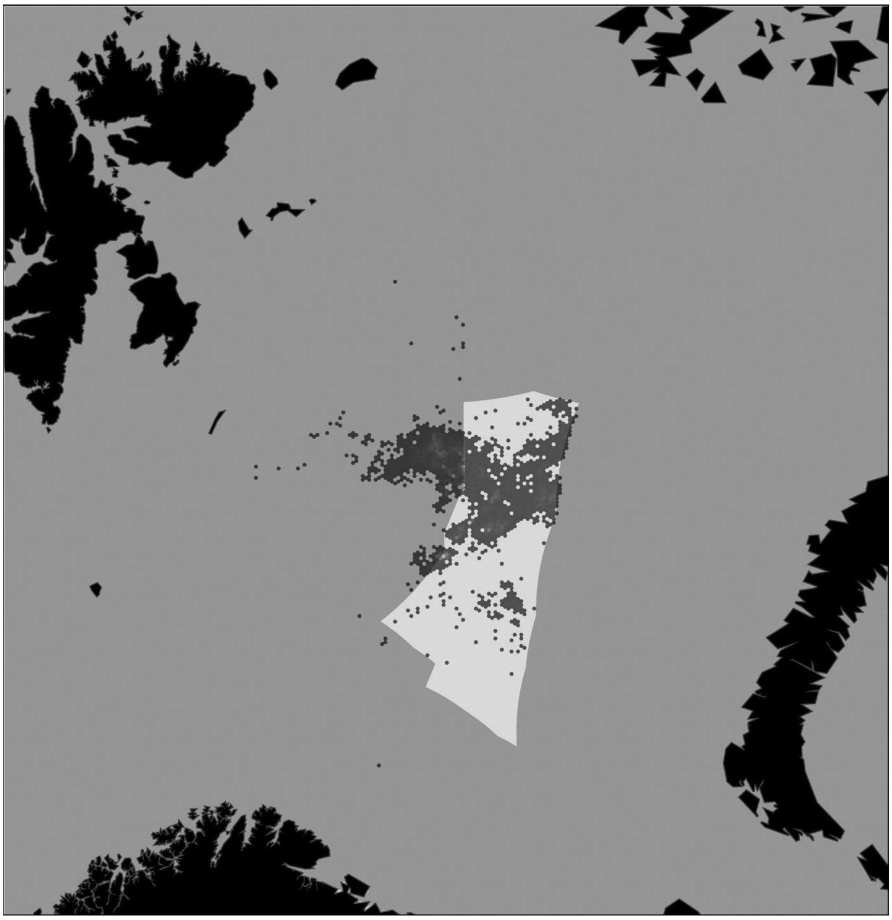


FIGURE 4 The observed distribution of fishing effort from the Norwegian vessels up to 2017. The Loophole is the area represented by light grey. Black colour indicates land areas. We observe that fishing is taking place both inside and outside of the Loophole. The Norwegian vessels only amount to a minority of the total fishing activities

The second pattern used in carrying out the POM is a map representing the spatial distribution of crabs at a specific point in time. The map is based on an ecosystem survey performed in 2013, illustrated in figure 3.4.2 (Figure A.1) in Anon. (2016, p. 74). This figure was visually compared with the simulated spatial distribution of crabs for the same time period. The simulated spatial distribution of crabs is depicted in the panel $t = 758$ in Figure 5. The visual evaluation was performed by searching for the simulation that had the best fit to the observed pattern.

The POM approach was operationalized to calibrate the model:

1. A random sample from a distribution of reasonable values was drawn for each of the following ranges of parameter values:
   - *Growth rate:* $0.01 < g < 0.2$. The net growth is determined by the spatial diversity in the growth, diffusion, local collapses, and an absorbing boundary. Hence, the lump-based growth rate represented by g is not easily identified, and therefore, a relatively wide range was used. The lower limit is the lowest growth rate found to facilitate a sustainable level of biomass in the absence of fishing mortality.
   - *Catchability coefficient:* $0.0001 < q < 0.01$. q can be interpreted as the probability of any crab in a given cell being caught by one pot during one time step. There are no good indications for the possible values of this parameter, and therefore, a relatively wide range has been investigated.
   - *The total capacity of the system:* $700,000$ tonnes $< K < 1,680,000$ tonnes. Estimated probability densities for the snow crab capacity in tonnes/km^2 based on the Canadian snow crab stock are presented in Figure 5 (Figure A2) in Anon. (2019a). The figure depicts values in the interval of 0.5–1.2 tonnes/km^2 as the most likely values. The values within this range are scaled according to the size of the Barents Sea (about $1,400,000$ km^2) and used as the range of possible values of the total carrying capacity.
   - *The diffusion matrix M* defines the redistribution of biomasses at the cell level. Observations of movements of the snow crabs are used as the basis for creating the diffusion matrix. Nichol et al. (2017) have estimated the rates of movement for a sample of snow crabs in the Bering Sea using data storage tags. The values in the column labelled 'Mean distance per day' (km) in Table 1 (Table A2) in the referred study is used. We further aggregate these values into monthly values. For each simulation, we randomly drew a subset of 50 per cent of these values. The sample was divided into two parts. The share of values below 20 km represents the share of crabs remaining in the cell, while the rest are equally divided between the neighbouring cells.
   - *The output elasticity of biomass:* $0.1 \leq \beta \leq 1$. From the arguments given above, β is expected to be a positive value below one and all realistic values are covered by the assumed range.
   - *Number of periods without a harvest:* $240 < \text{pwh} < 960$, from the start of the invasion until the observed effort levels were

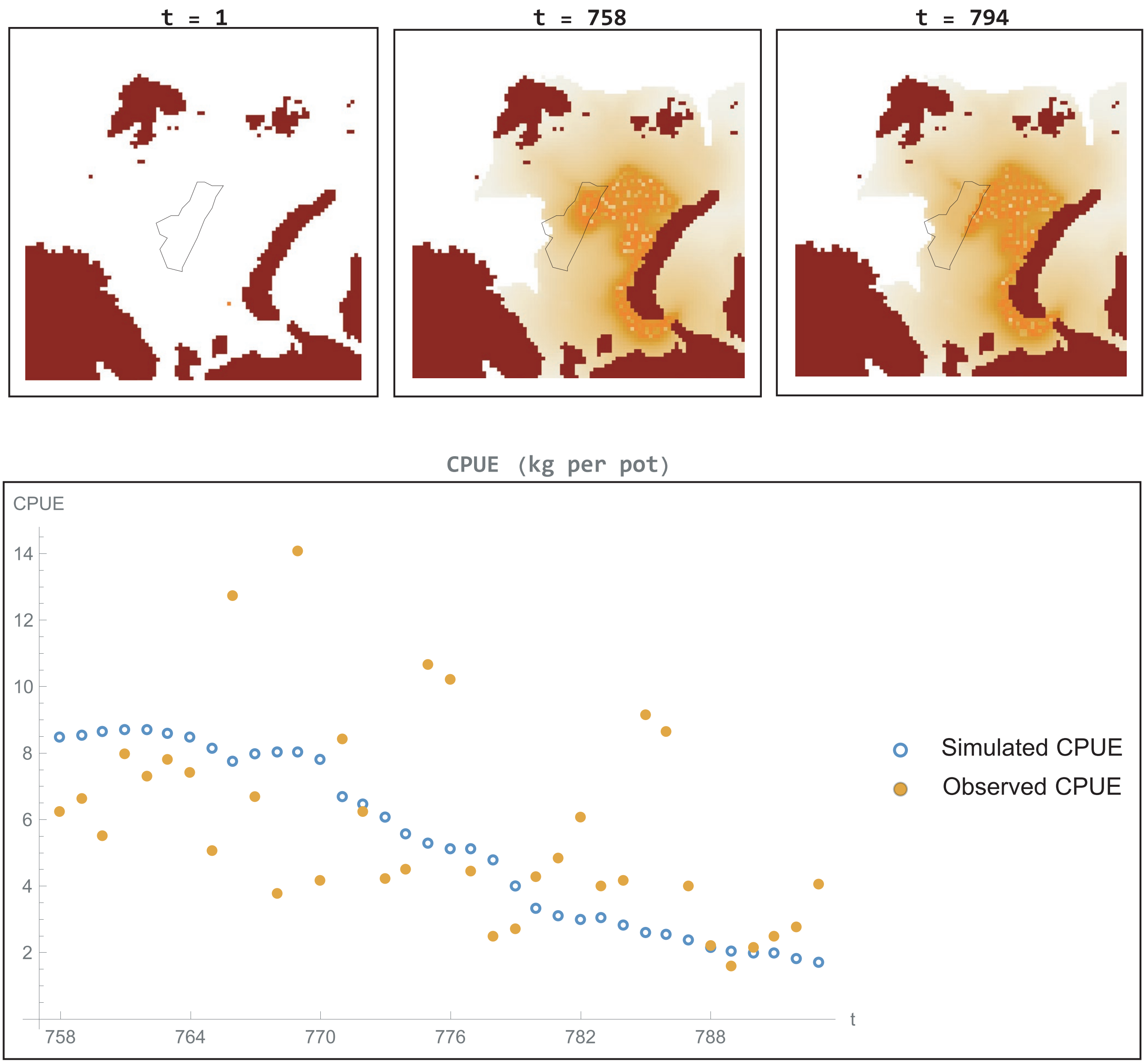


FIGURE 5 Snapshots of the distribution of snow crabs in the Barents Sea at different stages during the simulated invasion. Dark brown indicates land areas while white represents sea areas not occupied by the crabs. The remaining colours indicate the density of crab: more intense colours indicate higher densities. The representation of the Loophole is the polygon sketched by black lines. The lower panel shows the simulated and observed values of CPUE

implemented. The unit of time is the month, which is the unit used for the variable *t* throughout the present paper.

2. At time $t = 1$, one unit of biomass (1 kg) is released into the area of the Goose Bank, representing the start of the snow crab invasion, and a simulation is run based on a random sample of parameter values.
3. The number of simulated time periods without a harvest is defined by the value of *pwh*, after which the observed effort is implemented in the discrete spatial representation of the Loophole for the following 36 periods.
4. The Euclidean distance is calculated based on the periodic differences between the simulated and the observed CPUE.
5. Steps 1-4 were repeated 10,000 times and the 10 simulations providing the shortest Euclidean distance were selected for further inspection.
6. A subjective expert evaluation was conducted on the basis of the 10 selected simulations in order to identify the one with the best fit to the second pattern. The chosen simulation was selected as the base simulation for further studies of the development of the snow crab fishery.

The economic parameters are not included in the POM approach but obtained from other sources. The unit price of harvest and explicit unit cost of effort have been estimated to be 50 NOK/kg and 193 NOK

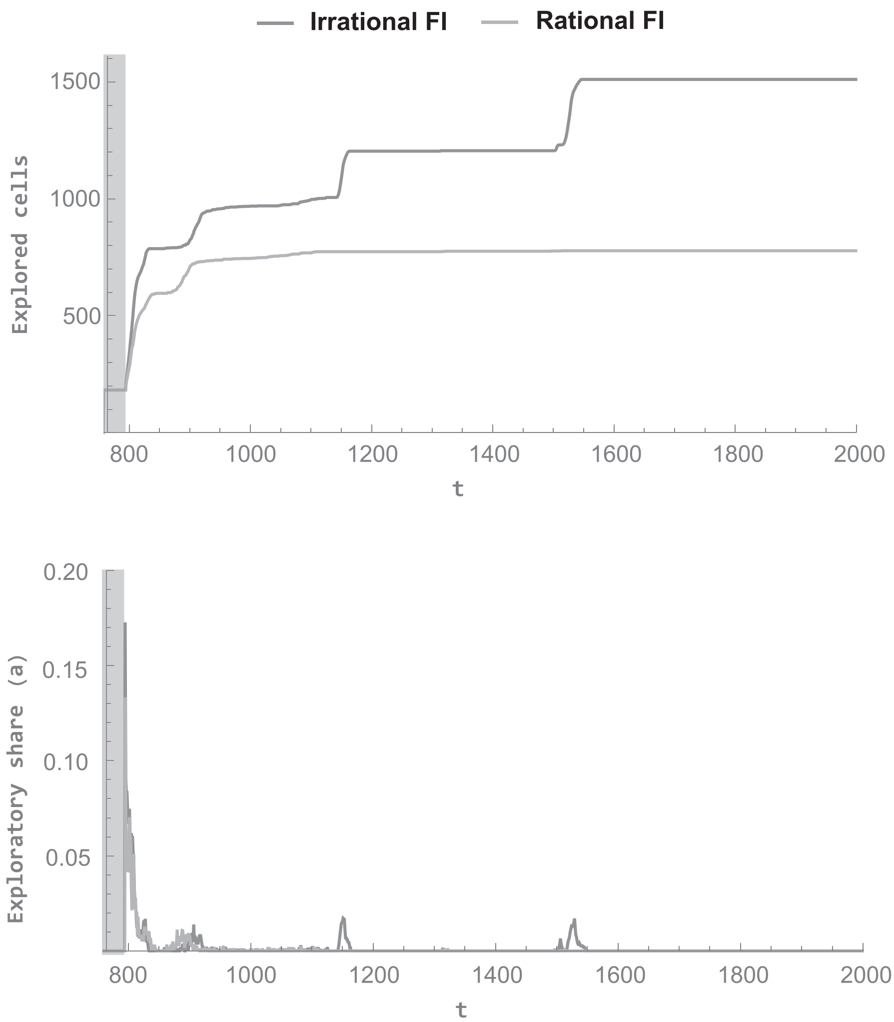


FIGURE 6 The top figure shows the cumulative number of explored cells $\sum_{i=1}^{n} \sum_{j=1}^{m} (u_{i,j,t} + h_{i,j,t})$ and the bottom figure shows the exploration rate (a_t) at time t. The figure shows the development from time period $t = 759$ and onwards. The grey background colour indicates the phase of the historic fishing activities taking place in the Loophole from 2014 until the end of 2016. The white background colour indicates the simulated further development of the fishery depending on the fleet's strategy. The dark colour indicates the *Irrational FI* scenario, and the grey colour represents the *Rational FI* scenario

per pot (Hogrenning & Henriksen, 2021), and we use these values for p and c. In the simulations, the stiffness parameter (see Equation 13) has been set to $\gamma = 0.00015$, determining the speed of fleet dynamics.

The parameter values of the selected simulation providing the best fit to the observed data are listed in Table 1. Figure 5 provides a visual representation of the chosen simulation in selected periods. We see that the fishing has affected the density of the crabs in the area where the fishing took place. The lower panel in Figure 5 shows the simulated and observed values of CPUE during the period of fishing.

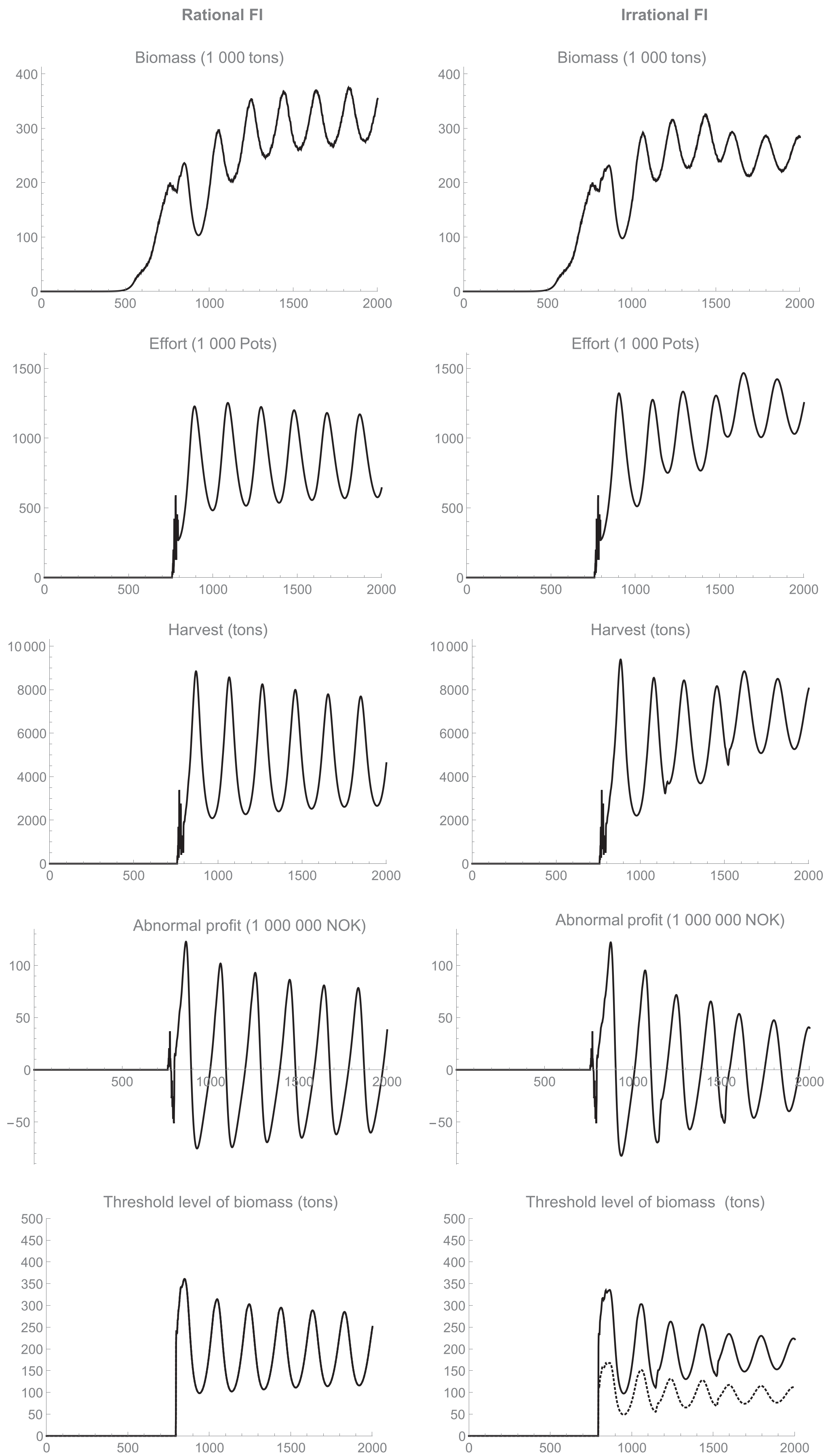
3 | RESULTS

Figure 6 displays the simulated development of effort devoted to exploratory fishing (a) and the number of explored cells for a fleet conducting a *Rational FI* and *Irrational FI* exploration strategy. Starting at time $t = 759$ and continuing for 36 time periods, fishing is allowed to occur in the model's discrete representation of the Loophole. The number of explored cells is shifted upwards by the number of habitable cells in this area. This event represents the historic fishing activities taking place in the Loophole from 2014 until the end of 2016. After this phase is finished, we allow the fleet to start exploring areas outside the Loophole. From time $t = 795$ and onward the different strategies are mapped by different scenarios, differing both in terms of the share of effort devoted to exploratory fishing and the development of explored cells.

In the *Irrational FI* scenario, we observe that a relatively large share of the fishing effort is placed into exploratory fishing during some stages of the development. Hence, a large number of new cells are being explored. The development in the number of explored cells is characterized by periods of intensive exploration, interrupted by periods of almost no exploration. The first occurs as exploration is allowed to be carried out; additionally, there are three phases of exploration occurring around times 900, 1,150 and 1,500, before exploration of new areas comes to an end.

In the *Rational FI* scenario, a relatively low number of cells are explored compared to the *Irrational FI* strategy. However, in the *Rational FI* scenario there are no further phases of exploration after

FIGURE 7 The solid lines represent the levels of biomass, fishing effort, harvest, abnormal profit and threshold level of biomass (TLOB) in the two scenarios. In the Irrational FI scenario, the figure representing TLOB also includes a dotted line. This line represents the biomass level required in an unexplored cell in order for it to be explored. In the *Rational FI* scenario, this level coincides with the level of TLOB and the line is therefore not visible


Rational FI
Irrational FI
Biomass (1 000 tons)
Biomass (1 000 tons)
Effort (1 000 Pots)
Effort (1 000 Pots)
Harvest (tons)
Harvest (tons)
Abnormal profit (1 000 000 NOK)
Abnormal profit (1 000 000 NOK)
Threshold level of biomass (tons)
Threshold level of biomass (tons)

the second phase. In order to verify that exploration did not restart after 2,000 time periods, we ran both simulations for another 3,000 time periods without obtaining any new areas being explored.

Figure 7 shows that both systems appear to approach a bioeconomic equilibrium as the simulations move towards the final period. The *Irrational FI* strategy appears to be stabilizing at a higher level of harvest and effort and at a lower level of snow crab biomass than the *Rational FI* strategy does. It also shows what appears to be a correlation between the aggregate levels of biomass and the TLOB, which is determined by the biomasses of the explored cells and consequently is a function of the combined biological and economic dynamics reflected in fluctuations over time. A correlation is therefore to be expected. A reduction in TLOB may change the status of an unexplored cell from not being qualified for exploration to being qualified, and vice versa, according to (6). The figure shows that the biomass level required in an unexplored cell in order for it to be explored is on average substantially lower in the *Irrational FI* scenario than in the *Rational FI* scenario.

The plots of *harvest*, *abnormal profit* and TLOB in Figure 7, show what appear to be irregular positive shifts in the *Irrational FI* scenario. These shifts coincide with periods of large scale exploratory fishing and are visible around times 1,150 and 1,500 and occur at low levels of TLOB. This indicates that exploratory fishing starts when the harvest potential in the explored areas is relatively low, and that newly explored areas contribute to increased harvest and profit.

We now include the *Fully Explored* scenario, where we assume the fleet to have explored all cells in advance and there is nothing more to explore. This unlikely scenario is added for the sake of comparison. Table 2 includes figures displaying the spatial distribution of the snow crab fishery in the Barents Sea area in the cases of the three scenarios. A much higher share of the habitat is explored by conducting an *Irrational FI* strategy (56.7%) than by a *Rational FI* strategy (31.2%) (Table 2). However, the *Irrational FI* strategy also leaves a large share of the cells unexplored. It should be noted that the *Fully Explored* strategy also leaves some habitable cells unexplored (0.8%). This is due to the fact that some habitable cells are disconnected from the main area and consequently could not be occupied by snow crab, given the assumptions in our model.

These differences in the explored shares of the habitat have consequences for the levels of the harvest and effort. The values do not differ substantially between the *Irrational FI* and the *Fully Explored* scenarios. The *Fully Explored* scenario achieves an annual harvest around 89,000 tonnes of biomass by employing around 16,500 thousand pots, while the *Irrational FI* scenario achieves an annual harvest around 79,000 tonnes of biomass by employing around 14,300 thousand pots. In the *Rational FI* scenario, the levels of effort and harvest are substantially lower. The annual harvest is around 51,500 tonnes obtained by applying around 9,700 thousand pots. The results from the simulations show that a fleet employing an *Irrational FI* strategy will explore a larger number of cells and exploit a higher share of the habitat than a fleet employing a *Rational FI* strategy. Hence, the results suggest that a larger share of the habitat will be explored when the fleet is willing to take risks.

Table 3 presents the descriptive statistics for both branches (*FI* and *LI*) of the *Rational* and the *Irrational* strategies. The table shows that the *LI* scenario covers a higher percentage of snow crab populated cells than the corresponding coverage of the *FI* scenario. The maximum values in Table 3 reveal that the *Rational LI* scenario is capable of obtaining a distribution corresponding to the values obtained in the *Irrational LI* scenarios. The results suggest that when the fleet is not able to fully determine the biomass level in adjacent unexplored cells, a larger share of the habitat will be explored.

4 | DISCUSSION

The model has been calibrated to represent the Barents Sea snow crab fishery by the use of a pattern-oriented approach. Although the model does not necessarily reflect all factors involved in the growth

TABLE 2 Final states of explored cells for the Rational FI, Irrational FI and Fully Explored scenarios

Rational FI	Irrational FI	Fully explored
		
Exploration rate: 31.2%	Exploration rate: 56.7%	Exploration rate: 99.2%
Effort = 9,703.6	Effort = 14,308.7	Effort = 16,422.1
Harvest = 51,524.1	Harvest = 79,128.6	Harvest = 89,414.2

Note: White indicates non-habitable cells. Light grey indicates habitable cells left unexplored in the scenario. Dark grey indicates explored habitable cells in the scenario. Black indicates land areas. The exploration rate refers to explored habitable cells as a percentage of all habitable cells in each scenario, calculated according to Equation 9. Effort (measured in thousands of pots per year) and harvest (measured in tonnes per year) are approximations of the equilibrium annual fishing effort and harvest. The two latter are averages over the last 500 time periods—in situations close to equilibrium.

TABLE 3 Descriptive statistics showing the exploration rates (percentage of the snow crab habitat explored by the fleet) in different scenarios

Scenario	Mean	SD	Min	Max	N
Rational FI	31.2		31.2	31.2	1
Irrational FI	56.7		56.7	56.7	1
Rational LI	49.1	5.05	45.2	63.1	20
Irrational LI	63.0	0.20	62.6	63.3	20

Note: The statistics are obtained by running each scenario the number of times specified in column N. The exploration rates are presented in terms of average values of the runs (Mean), standard deviation (SD), and minimum (Min) and maximum (Max) values of all runs.

and distribution of the snow crab, it seems to reproduce the observed patterns quite well. However, this is not a guarantee that the model will reflect future distribution patterns.

Our results confirm that different fleet strategies affect the fishery both in short- and long-term perspectives. In both the *Rational FI* and the *Irrational FI* scenarios, the fleet explores areas east of the Loophole towards Novaya Zemlya and some areas northwest, towards Svalbard, motivated by the potential harvest in these areas. The attractiveness of these areas is also apparent in Figure 2, reflecting the basic assumptions of habitat preferences. The majority of the cells with the largest capacities are located in an area of several interconnected cells. This area includes the Loophole, where the fishery was located when the process of exploration started.

In the *Rational FI* scenario, the fleet does not discover clusters of high capacity areas located further away from the initial area. It appears that the unfavourable areas separating the areas of high biomass carrying capacity might serve as barricades to exploration. This indicates that if the crabs are clustered together in areas separated by patches with lower amounts of crabs, the fleet might not identify these areas as long as the fleet behaves rationally. This will potentially leave profitable areas unexplored and thereby leave dense areas of crab biomass unexploited.

When introducing a riskier exploration behaviour, the fleet also explores other areas of high capacity located further away from the initial area. The *Irrational FI* strategy is consistent with the definition Allen and McGlade (1986) give of a *stochast*, because the fleet risks deploying effort into unexplored cells with significantly lower biomasses than in the already explored area. This may lead the fleet to explore cells acting as gateways to more valuable fishing grounds, which would not be explored by a fleet employing a *Rational FI* strategy. We also find that harvest and effort levels are closer to the levels found in the *Fully Explored* scenario. This supports the findings of Allen and McGlade (1986), suggesting that a fishery will benefit in the long run from the behaviour of a *stochast*. Additionally, our results indicate that the long-run gains from the *stochast*'s behaviour depend on the spatial heterogeneity in the distribution of the species of target.

In the *FI* strategies, we give the fleet the ability to know whether or not an adjacent unexplored cell has a crab density surpassing what the fleet on average would locate by fishing in the explored area. This is a very strict and unrealistic assumption. However, the fleet is likely to formulate hypotheses about crab densities both in the areas where they are currently fishing and in unexplored neighbouring areas, and explore accordingly. With the *LI* strategies, we allow the fleet to miscalculate the biomass level of unexplored adjacent cells by ±100 per cent. The *LI* scenarios, reflecting that these hypothesis are correct to a varying degree, find a larger percentage of the habitat than their counterparts, the *FI* scenarios. Because of the limited information about the density of crabs in the unexplored area next to the known fishing grounds, the fleet unintentionally explores areas of lower density than anticipated, leading as pathways to more prosperous fishing grounds.

Limited information of the density of crabs in the unexplored grounds next to the explored grounds and an irrational behaviour contribute to identifying new fishing grounds to be exploited. Because both forces appear to contribute to exploration, it is difficult to attribute causation to a specific force when exploration is observed. This is in line with Branch et al. (2006), stating that it is difficult to identify risk-taking behaviour in a fishery. They claim that fishers may also have made a bad decision, had insufficient information, or simply been unlucky. Of course, the two forces do not guarantee that all valuable fishing grounds will be explored, but our study suggests that both contribute to revealing larger parts of the dense area of snow crab. Different rules of irrational behaviour and fish-finding capabilities may change the magnitude of the effect of the particular force, without changing the implication of a combination of spatial heterogeneity and the two forces.

Our results emphasize the serious consequences of ignoring spatial diversity when modelling fisheries. The distribution of carrying capacities is defined by the average depth and annual temperature within an area of 20 by 20 km. There may be a significant heterogeneity within each area. Models based on different spatial resolutions may therefore find different distributions of the environmental carrying capacities for the snow crab. Modifications of the rules (Figure 1) defining the environmental carrying capacity will alter the distribution. The simulated development of the fishery could then change, but we still expect the interaction between the fleet dynamics and the spatial distribution of crabs to be important for its development.

In our model, we assume that once a fishing ground is explored the information describing the particular ground is common knowledge for the entire fleet the next period. Hence, we do assume that there are no competitive advantages for a particular vessel from discovering a fishing ground beyond the single period of the exploration. This is in conflict with Barney (1991), who argues that a firm can experience a sustainable competitive advantage by implementing a strategy that no other competitor is able to duplicate. However, the Norwegian statistics covering harvest operations (such as harvest rates and fishing locations) are with only few exceptions considered public information (Anon., 2019b). Therefore, it is reasonable to assume that a strategy of fishing on a newly explored, particularly lucrative fishing ground, can be followed by other vessels, and so it might be tempting for a vessel to refrain from exploratory activities and wait for others to explore an area. This observation may question to what extent we would expect to find vessels following the *Irrational* strategy. Therefore, we suggest that exploratory fishing is most prominent in times when the harvest rates in the explored areas are inadequate to facilitate profitability, leaving the vessels with no other options than exploring new areas if they want to earn profits (assuming the vessels to be reluctant to leave the fishery). If this is the case, the exploration of new areas will be a function of the profitability of the vessel. We have ignored differences in the cost of transportation to different fishing grounds, but we expect the fishers to explore fishing grounds minimizing the cost of transportation all else equal. The model can be adjusted to incorporate the effect of transportation costs given the existence of such cost estimates. Another, potentially important, factor in the snow crab fishery is that we do not consider the potential unavailability of some fishing grounds due to environmental conditions, for example, the presence of sea ice.

In this study, we focus on a fleet targeting a species expanding its presence in a new area. The habitat distribution is assumed fixed and therefore only needing to be explored once. However, habitats are likely to change over time, making the process of discovering lucrative fishing grounds a continuous effort for the fishers. Annual bottom trawl surveys on the eastern Bering Sea (EBS) shelf indicate that this may be the case in the Bering Sea snow crab fishery. In the EBS, a cold pool of bottom water is formed by the seasonal melting of ice (Stabeno et al., 2001). Recently, a reduction in the range of the distribution of the snow crab has been associated with a reduction of this pool (Fedewa et al., 2020). In the northern Bering Sea (NBS), observations of snow crabs have historically been of sizes outside the scope of commercial value; however, a substantial increase in large size crabs has recently been observed, indicating the potential for a future commercial fishery in the NBS (Fedewa et al., 2020). In general, any species having a shifting habitat distribution over time is likely to continually generate the exploration and exploitation dynamics we have examined in this study.

Decisions about the management of fisheries are often based on historical data and catch records (Hilborn, 2012). Our results suggest that fishery managers should be aware that the distribution of fishing effort only represents the discovered resource distribution. One implication of this is that any unexplored area could act as a unintended no-take zone and in this way decrease the risk of biological overexploitation. It also signifies the role surveys may play for fishers as a source of information. In the model specifications, we have considered areas available for exploration to be limited to neighbouring areas to those already explored. In practice, a non-adjacent unexplored area may be pinpointed for exploration due to by-catch observations or information from research activities, as was the case with the first observation of the snow crab in the Barents Sea in 1996 (Anon., 1997). Our model does not take into account the contribution of such events in identifying attractive fishing grounds. Hence, surveys can provide fishers with information that leads to a more complete exploration of a new fishery. However, observations from the Bering Sea snow crab fishery indicate that this role is not limited to new fisheries (Fedewa et al., 2020).

Management constraints could have influenced the development of the crab fishery in a number of ways. A regulation may limit both the exploitation area and the Total Allowable Catch (TAC). However, independently of the management regime, a spatial exploration of potential fishing grounds needs to take place. Our results suggest that exploration is often initiated when the biomass level is reduced in the explored areas. The TAC may serve to prevent biological overexploitation and hinder the exploration process at the same time as preventing biomass suppression in the explored areas. This shows how fishery management could alter the dynamics of exploration. Further studies should investigate the effect of different management regimes on spatial exploration and the long-term exploitation in the crab fishery.

The *Fully Explored* scenario provides the open access levels for the simulated crab fishery given that the whole area is explored. It suggests that the open access harvest level of the fishery is around 89,000 tonnes per year. This result depends heavily on the assumptions of the model. However, the estimated open access harvest level is within the range of future harvest rates estimated by the Norwegian Institute of Marine Research. Their estimate is within the range of 50,000 to 170,000 tonnes, acknowledging that this estimate is associated with a high degree of uncertainty (Anon., 2015). While this is a study of the Barents Sea snow crab fishery, our model also includes parts of the Kara Sea as a suitable habitat for the snow crab. This is consistent with recent findings of snow crabs in the Kara Sea (Anon., 2019a).

There are uncertainties related to the structure of the biological, environmental, and economic model, as well as its parameter values and initial conditions. Snow crabs have a life cycle involving a pelagic larval phase and may therefore also spread by larval drift due to ocean currents (Siikavuopio et al., 2019). If this kind of dispersion is an important factor in creating the patterns we observe, we might have omitted an important element describing the spread. Even if we had included important elements describing the system, a larger number of simulations would be necessary to explore the entire parameter space of the model. The pattern-oriented modelling approach seems to be promising, as it produces comparable estimates and allows the inclusion of more patterns in the calibration process as more knowledge is gained and more observations are obtained.

5 | CONCLUSION

By using a cellular automata approach, it has been possible to model spatial diversity on a rather detailed scale. The interaction between the fleet dynamics and spatial distribution of the snow crab appears to be of great importance. Our study suggests that the most lucrative fishing grounds for snow crab are heterogeneously distributed over the Barents Sea, separated by patches of lower densities. The fleet dynamics affects which fishing grounds are explored and exploited.

We consider the findings to also have implications for how to model other fisheries where the species are heterogeneously distributed. Further studies should aim at validating this finding by incorporating different scenarios of fleet dynamics. For instance, we suggest having the exploration dynamics depend on the profitability of the fishery, influenced by information from other sources and a spatially distributed cost structure. Further research should also look more closely at the development of a new fishery under various regulatory measures.

Although our model represents a new fishery, we anticipate the exploration and exploitation dynamics also to be present in mature fisheries where the species of interest reallocates itself over time. However, the fishers are likely to be in need of external information to ensure a more complete exploration of new fisheries and in order to stay updated on lucrative fishing grounds in existing fisheries. Information from surveys appears to be important.

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DATA AVAILABILITY STATEMENT

The data used in this study are openly available, and the sources are clarified within the article.

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APPENDIX 1

TABLE A1 Norwegian quota recommendation, established quotas, and landings of snow crab (in tonnes) in the Barents Sea in the period 2012 to 2020 divided by each nation. This table is the authors' own translation of table 1 originally published in Norwegian in Anon. (2019a, p. 6)

Year	Recommended Norwegian Quotas (tons)	Quotas (tons)		Landings (tons)			Total landings (tons)
		Norway	Russia	Norway	Russia	EU countries	
2012		-	-	2	0	0	2
2013		-	-	189	62	0	251
2014		-	-	1800	4104	2300	8204
2015		-	1100	3482	8895	5763	18140
2016		-	1600	5290	7520	3690	16500
2017	3600–4500	4000	7840	3153	7780	2	10847
2018	4000–5500	4000	9840	2804	9728	-	12532
2019	3500–5000	4000	9840	3775*	9840	-	13615*
2020	<5500						

*Data as of 19 November 2019.

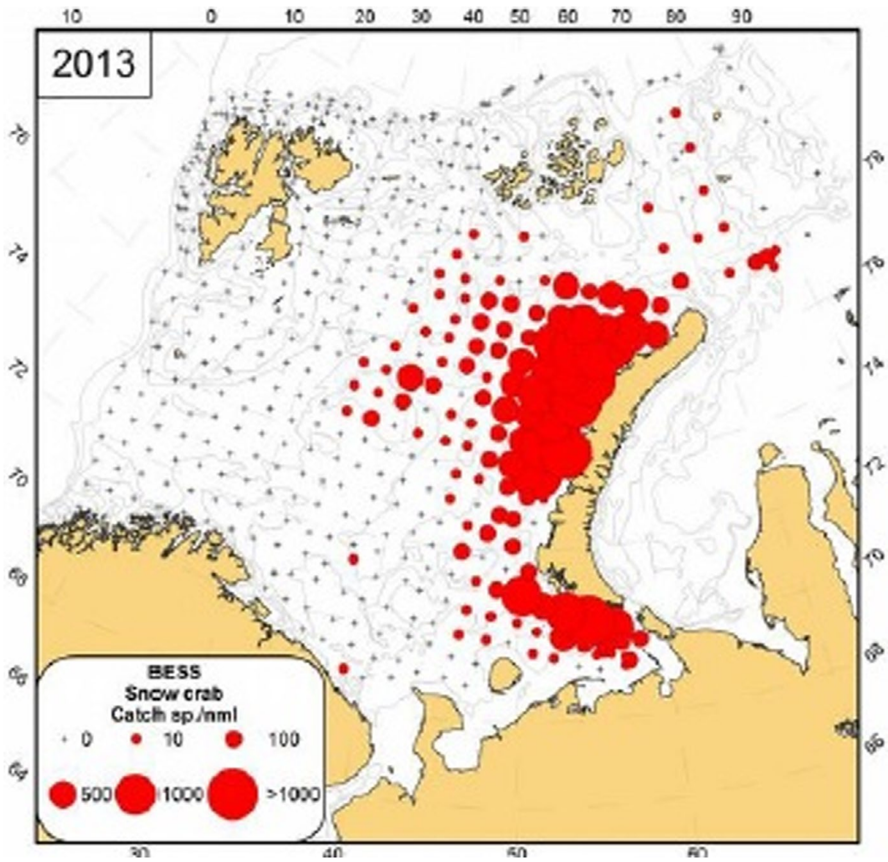

FIGURE A1 Map of snow crab distribution from the ecosystem survey reports for 2013 (Anon., 2016, p. 74).

TABLE A2 Summary of the distances moved by morphometrically mature (Large-clawed) male snowcrab (Chionoecetes opilio) released with data storage tags in the eastern bering sea. Distances reflect across-shelf movements only, estimated for each crab as the daily change in bottom depth divided by the bottom slope (Nichol et al., 2017).

Table 1.
Summary of the estimated distances moved by morphometrically mature (large-clawed) male snow crab (*Chionoecetes opilio*) released with data storage tags in the eastern Bering Sea. Distances reflect across-shelf movements only, estimated for each crab as the daily change in bottom depth divided by the bottom slope.

Crab identification number	Release date	Days recorded[1]	Carapace width (mm)	Mean overall temperature (°C)	Cumulative distance moved (km)	Mean distance per day (km)	Maximum distance per day (km)	Maximum distance per month (km)	Month/year of maximum distance[2]
5658	4/19/2010	309	119	3.6	63.2	0.2	3.5	19.2	5/2010
5660	4/19/2010	312	122	3.6	53.8	0.2	1.3	8.5	5/2010
5665	4/19/2010	255	126	3.2	107.9	0.4	1.9	26.7	11/2010
5749	4/19/2010	282	121	3.4	61.2	0.2	2.5	16.6	5/2010
5756	4/19/2010	296	116	3.1	267.2	0.9	5.1	38.0	5/2010
5770	4/20/2010	320	109	3.5	98.6	0.3	2.1	28.7	9/2010
5771	4/20/2010	286	115	3.6	28.8	0.1	1.1	6.5	5/2010
5776	4/20/2010	303	114	3.6	58.3	0.2	1.8	15.9	5/2010
5782	4/20/2010	286	125	3.5	101.0	0.4	2.8	21.3	7/2010
5786	4/20/2010	317	119	3.1	219.6	0.7	3.4	52.2	5/2010
5791	4/20/2010	93	111	2.5	71.9	0.8	5.6	28.6	4/2010 (8)
5792	4/20/2010	276	110	3.3	104.6	0.4	3.6	29.9	5/2010
5798	4/20/2010	293	100	2.6	260.7	0.9	8.4	47.3	9/2010
5809	4/20/2010	138	121	3.3	35.3	0.3	2.4	20.8	5/2010
5816	4/20/2010	316	123	3.6	47.9	0.2	1.4	9.7	5/2010
5819	4/20/2010	279	117	3.6	35.9	0.1	2.2	17.3	5/2010
5820	4/20/2010	279	119	3.6	48.0	0.2	1.4	8.9	5/2010
5845	4/21/2010	467	100`	3.2	416.8	0.9	8.5	97.6	4/2011
5846	4/21/2010	287	110	3.4	170.7	0.6	5.9	50.9	5/2010
5851	4/22/2010	318	102	2.9	255.4	0.8	6.0	57.6	5/2010
5854	4/22/2010	278	117	3.5	147.3	0.5	7.0	24.3	11/2010
5855	4/22/2010	296	112	3.1	338.3	1.1	6.3	83.8	12/2010
5859	4/22/2010	317	125	3.4	99.2	0.3	3.0	19.5	1/2011
5860	4/22/2010	277	115	3.2	126.7	0.5	6.5	32.7	9/2010
7340	3/08/2011	440	112	2.2	242.3	0.6	5.6	38.5	11/2011
7352	3/08/2011	299	120	2.6	89.4	0.3	1.4	14.3	5/2011
7368	3/08/2011	454	123	2.3	110.6	0.2	1.4	12.2	3/2012
7371	3/08/2011	426	100	2.2	210.8	0.5	3.3	28.7	4/2011
7387	3/08/2011	45	115	2.4	16.8	0.4	1.9	8.7	3/2011 (21)
7424	3/08/2011	441	119	2.4	118.9	0.3	1.9	14.7	3/2012
7425	3/08/2011	435	117	2.3	149.1	0.3	3.1	23.6	6/2011
7448	3/08/2011	34	123	2.4	15.5	0.5	2.2	11.6	3/2011 (21)
7456	3/08/2011	69	106	2.3	77.8	1.1	3.7	44.7	4/2011

[1] For crab identification numbers **5665, 5791, 5809, 5845, 7387, 7448, 7456**, the tag depth sensors failed after the indicated days recorded, and thus days recorded do not equal days at liberty.
[2] Number in parentheses indicates the total days of the month in which data was collected, for months that were not complete (i.e., the month of tag release).

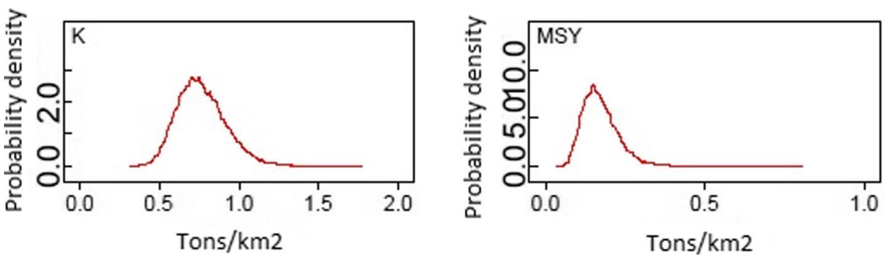

FIGURE A2 Probability densities for carrying capacity (*K*) and maximum sustainable yield (MSY) in tons/km^2 based on estimates for the snow crab population in Canada. This figure is the authors' own translation of figure 5 originally published in Norwegian in Anon. (2019a, p. 8).

Oh crab, don't forget to explore the effects of potential management regimes of the Barents Sea snow crab (*Chionoecetes opilio*, Majidae) fishery.

A simulation study using a spatio-temporal bioeconomic model.

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Abstract

The snow crab (*Chionoecetes opilio*, Majidae) recently entered the Barents Sea and subsequently a fishery for the crab evolved. The crab was defined as a sedentary species in 2015, and the crab stock is shared between Russia and Norway. Currently, both nations manage their crab fishery on their respective parts of the continental shelf, and cooperation is largely limited to the research front to ensure biological sustainability. The management of the fishery has been given limited attention; the extent to which one nation's management measures may affect the fishery of the other and whether there may be economic reasons for increasing the level of cooperation are still open questions. We make use of an existing spatial bioeconomic model of the crab fishery. The model was further modified so that a simulation study could be initiated to investigate the aforementioned questions. It is found that it can not be ruled out that a management measure executed by one nation can have a substantial effect on the fishery of the other, nor can it be ruled out that a regime of mutual access to harvest grounds would be preferable. Rather, our results indicate that this may be the case.

1 Introduction

This paper studies the management of the Barents Sea snow crab (*Chionoecetes opilio*, Majidae) fishery. This crab was first observed in the area in 1996, and the stock is still expanding (Institute of Marine Research, 2021). Following the definition of Grønbæk et al. (2020), this crab stock can be defined as an internationally shared stock, i.e. a fishery resource exploited by two or more nations. The crab stock is shared between Norway and Russia.

In 2012, an unregulated fishery on the snow crab stock started. Since then, the crab has evolved from an ungovernable to a governable resource, a process involving research, legislation, inputs from fishers, politics and legal proceedings (Kvalvik, 2021). An outcome of this process has been an agreement between Norway and Russia to define the crab as a sedentary species and to cooperate on research to ensure a biological sustainable crab stock (Joint Norwegian Russian Fisheries Commission, 2015).

Because the crab is defined as sedentary, Norway and Russia have sovereign rights to harvest and manage the crab on their respective parts of the continental shelf, and the two nations are not constrained to cooperate on management aspects (Hansen, 2016). The two nations did however discuss whether to allow their vessels to have mutual access to the harvest grounds, but no agreement resulted (Joint Norwegian Russian Fisheries Commission, 2020). In this perspective, the international management of the fishery can be characterised as a non-cooperative one, where each nation manages the crab on its own territory – independently of the other – according to its own goals. The management regime has been given limited attention; to what extent a nation may affect the fishery of the other nation through management measures, and whether the current international regime is preferable from an economic perspective, are two unanswered questions of primary importance.

Regarding the first question, when two or more nations share a common stock, there may be or evolve different views among the involved parties on how the stock should be managed. Studies on the optimal management of internationally shared resources have included differences in preferences of the social rate of discount, the cost of fishing, and consumer preferences (Munro, 1979, 1986). In the snow crab fishery, we have identified two situations that may evolve into conflicting management views.

On the one hand, Kaiser et al. (2018) argue that Russia also harvests snow crab in the Far East – an area geographically closer to the major end market for live snow crab – where exploiting the crab is assumed to be more cost efficient than in the Barents Sea. They argue that in order to have a better control of the global supply and capitalize on a high price for the crab, Russia may be less willing to facilitate a snow crab fishery in the Barents Sea, and thus may instead treat the stock as a reserve stock. A management goal corresponding to the reserve-stock argument would allow the crab to spread and grow within the limit of the capacity of the habitat on the Russian part of the continental shelf.

On the other hand, the impact of the crab on the ecosystem is not yet fully understood, and its existence may damage the ecosystem (Kaiser et al., 2018). Hence, there may evolve conflicting views on how to value the ecosystem in the Barents Sea and/or on how the crab impacts it. Here, a conflicting scenario may be that one nation wants to encourage an extermination fishery for the crab, while the other wants to facilitate a long-term commercial fishery[1].

It is well known that in many situations the individual actions taken by one nation on an internationally shared stock cannot be seen in isolation (Gulland, 1980; Munro, 1986). Gulland (1980) states that (fish) individuals move across the boundaries of national jurisdiction and therefore individual actions on the fish stock taken by one nation can affect the other(s). Thus, the choices made by one nation on its share of the crab stock may have an effect beyond its own fishery.

Regarding the second question, even though there may exist incentives that could evolve into diverging management views, the current position is that the two nations have found the benefits of facilitating a long-term commercial fishery on the snow crab to outweigh the cost: both nations have said that they are aiming for a sustainable exploitation of the stock (Joint Norwegian Russian Fisheries Commission, 2015). In practice, this aim is often assumed to be met by a combination of a total allowable catch (TAC), providing an upper limit on the harvest allowed to be extracted from the stock over a time period, which, if set accurately, prevents the stock from being overfished (Asche et al., 2008), and individual transferable quotas (ITQs)[2], which in theory can lead to the generation of the maximum net economic rent (Copes, 1986). Hence, a likely scenario is that both nations manage their (domestic) fishery on the crab using management measures similar to those mentioned above as the fishery matures[3].

However, the ability of the domestic regimes to realize the potential rent in the fishery may depend on the international regime. An international regime allowing for mutual access to harvest grounds has, as already mentioned, been up for consideration, and is therefore a natural regime to contrast with the current international regime. In this

[1]Currently, a combination of the two is being implemented in the Norwegian fishery for the red king crab: west of the 26° east meridian – with the aim of restricting a further westward expansion of the crab – the crab can be harvested by anyone, while east of that meridian a quota-regulated fishery is ongoing (Lorentzen et al., 2018).

[2]although there may be modifications, e.g. of the transferability of ITQs, reflecting additional management goals shaped by history and politics (Hannesson, 2013), often related to the potential social impacts of the ITQs (Branch et al., 2006).

[3]Note that, for the time being, this is not the case: as far as the Norwegian crab fishery is concerned, it is regulated without individual vessel quotas, circumstances under which a *race to fish* may develop (Hogrenning & Henriksen, 2021).

alternative regime, the fleet of each nation would be free to fish independently of any sovereign rights, while in the current regime, the fleet of each nation is restricted to the territory of its own nation.

Clearly, both topics should be studied in light of the crab's mobility, bearing in mind the observations of Gulland (1980) and Munro (1986) and the ability of both nations to enforce their sovereign rights within their territories. A spatial bioeconomic model of the Barents Sea snow crab fishery taking into account the ability of the crab to move between areas of varying carrying capacity for the crabs – including across territorial borders – would be an appropriate model to use to study the two topics.

A spatial model of the Barents Sea snow crab fishery was constructed in Hogrenning and Eide (2022) and applied to study the role of the fleet on the geographical expansion of the fishery. Hogrenning and Eide (2022) used the rates of movement observed on a sample of snow crabs to guide the modelling process, and evaluated the model by, among other criteria, its ability to provide an acceptable reproduction of the monthly rates of CPUE observed in a minor area of the Barents Sea where the fishery for the crab started out. However, the model of Hogrenning and Eide (2022) neither includes sovereign rights to harvest grounds nor takes into account the presence of sea ice in the Barents Sea. Both components determine where the fleet of each nation can fish and are therefore needed to be taken into account when studying the two topics.

More specifically, these two topics can be formulated as two research questions:

- RQ1: Assuming the current international regime to prevail, what would be the effects of the potential national-specific management regimes?
- RQ2: Is the current international management regime efficient?

2 Method

The model presented in this study extends the model developed in Hogrenning and Eide (2022). Their model consists of three submodels: an environmental, biological, and economic model. The environmental model is constructed as a two-dimensional lattice representing the Barents Sea. Each cell in the lattice represents a geographical area within the Barents Sea and is given a carrying capacity for crabs determined by the observed bottom temperatures and depths in the area. The biological model is based on a cellular automata method representing the periodic growth, mortality and movement of crabs at the level of the cells of the cellular automaton, the movement being restricted to adjacent cells. The economic model is that of Gordon (1954) and the harvest equation of Schaefer (1954) implemented in an open-access crab fishery. The fleet is assumed to distribute its (spatial) fishing activities over the areas of the Barents Sea in proportion to the crab biomass. Hogrenning and Eide (2022) put forward several scenarios of the expansion of the crab stock and fishery, of which the scenario where the crab stock and fishery had fully expanded was used in this study. A more detailed summary is available in the appendices, while Hogrenning and Eide (2022) can be consulted for an in-depth derivation of the model, from now on referred to as the base model.

2.1 Extensions of the base model

To be able to answer the research questions at hand, some modifications were made to the base model. An ownership (either Norwegian or Russian) was given to each cell. In this procedure, a map (Figure S.1) depicting the sovereign rights in the Barents Sea presented in Delelinjeavtalen (2010), was used as a point of departure. The ownership of the cells in the area of the border was given to the nation owning the largest area of the cell. A map of the modelled ownership is presented in Figure 1.

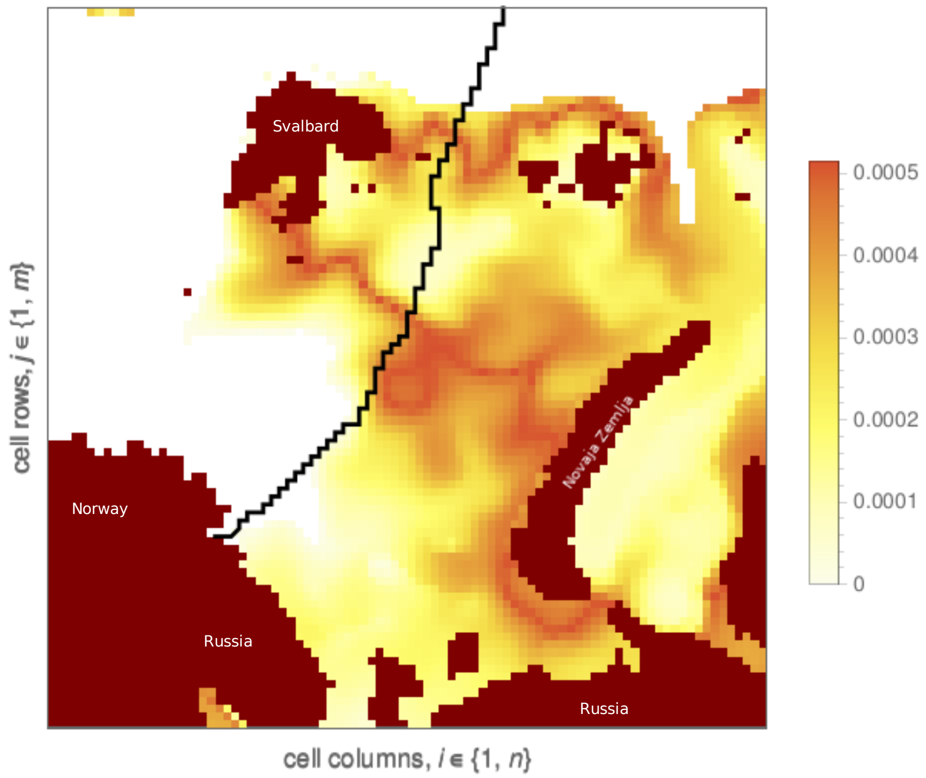

Figure 1: The modelled distribution of normalised carrying capacities of snow crab in the Barents Sea as defined in the base model of Hogrenning and Eide (2022). Dark brown indicates land areas. The legend to the right refers to the normalised carrying capacity of one cell. Also shown is how the environmental model is constructed by cells defined by the value of (i, j). The black line divides the sea areas into a Norwegian (left) and Russian part (right).

Further, a Russian and Norwegian fishing fleet was created, allowed to fish on Russian and Norwegian territory respectively. The two fleets were assumed to operate under equal market conditions with identical harvest dynamics, except for some scenario-specific differences to be introduced in Section 2.2.

It is asserted that some potential harvest grounds are unavailable for fishing due to the formation of sea ice (Institute of Marine Research, 2021), but the base model does not take this into account. Therefore, it was extended to include monthly schedules of sea ice formation. The schedule was constructed with the aim of mimicking the maps of monthly frequency of sea ice [4] in the Norwegian Arctic during 1990–2019 (Figure S.2), as presented by The Norwegian Polar Institute (The Norwegian Polar Institute, 2022). A cell was assumed to be unavailable for fishing activity if the monthly frequency of sea ice in it exceeded 30 percent, and available otherwise. Note however that the tolerance for ice probably differs among the fishers – e.g. due to differences in the physical characteristics of their vessels – and that there in practice are likely to be individual differences making a common threshold value hard to define. Figure 2 shows the modelled monthly schedules of the formation of sea ice. We observe that many areas with modelled carrying capacity for crabs are partly or fully unavailable for fishing activities over the year.

The model presented in the last section was used to study RQ1 and RQ2. The model was used to run several simulations representing different scenarios. These scenarios will be presented in the two sections to come.

[4] a measure of how often the ice cover is more than 15 percent in a given period within a given area (The Norwegian Polar Institute, 2022)

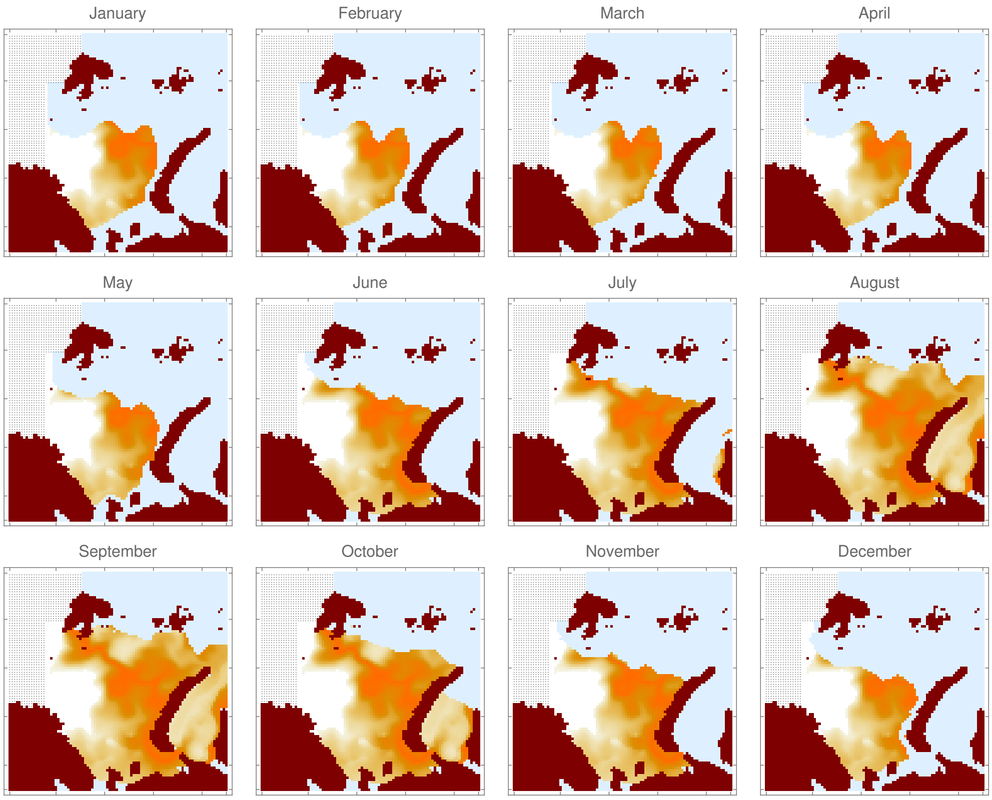

Figure 2: The figure shows how the modelled monthly sea ice conditions (blue) partly or fully cover some cells of modelled carrying capacity of crabs during the year. The cells coloured white with black dots represent areas where we have not included the sea ice conditions. This is because the area – for all practical purposes – is outside the area of modelled carrying capacities for crabs.

2.2 Scenario setup (RQ1)

Three scenarios represented by three simulations were constructed. In the scenarios, Norway was assumed to operate an open-access (OA) fishery, while the Russian management regime varied between an open-access (OA), inactive (I), and subsidized open-access (OA_S) fishery.

In the $OA - OA$ scenario, both nations were assumed to operate an open-access fishery. The open-access regime was used to represent the scenario where a nation facilitates a long-term commercial fishery on the snow crab, even though the regime is characterized by overcapacity and rent dissipation, and thus contrasts with a rent maximizing regime. It was chosen because of its simplicity and availability in the base model. In the $I-OA$ scenario, the Russian fleet was assumed to be inactive, consistent with the reserve stock argument of Kaiser et al. (2018). In the $OA_S - OA$ scenario, Russia was assumed to operate a heavily subsidised open-access fishery. Here a subsidized price per kilo of 500 NOK – ten times the market price used in the open-access scenario – was assumed. The scenario represents a situation where Russia finds the cost to the ecosystem of the crab to exceed the benefits from facilitating long-term commercial fishing of the snow crab, and because of this, arranges for an extermination fishery on the crab aiming to significantly reduce the stock.

The open-access values of effort and biomass estimated in Hogrenning and Eide (2022) were used as the initial values in these scenarios. However, the effort needs to be distributed amongst the two nations. Here, we let the share of the carrying capacity on the territory of each nation define its initial share of effort, except in the $I - OA$ scenario, where the Russian fleet is inactive and the Russian effort is thus set to zero. The scenarios were simulated over 600 time periods and then the average biomass, effort and harvest level of the two nations' fisheries were calculated. The percentage differences in these values between the scenarios were then calculated using the $OA-OA$ scenario as a baseline.

2.3 Scenario setup (RQ2)

Two scenarios were created: the cooperation scenario and the non-cooperation scenario. The former represents the regime where the two nations allow mutual access to harvest grounds, while the latter represents the regime where each nation exploits the crab in its own territory. The fishery was assumed to be ongoing for 600 time periods (50 years). Further, it was assumed that both nations aimed at maximizing the rent from the fishery over a finite time horizon and, for simplicity, the time value of money was ignored. Therefore, the open-access dynamic was detached from the model and replaced with a rent-maximizing procedure.

The environment in the Barents Sea is likely to change over a period of 50 years, which may affect the potential rent from the fishery. Therefore, before the setup for the cooperation and non-cooperation scenarios are further outlined, the scenario of environmental change assumed to take place over this time period is presented.

In this scenario, sea temperatures change according to short-term variability, long-term variability, and a long-term trend. Observations of sea temperatures in the Barents Sea, as presented in Institute of Marine Research (2022), were used as the starting point for modelling these different effects (trend and variability). The short-term variability was represented by a sine curve with an amplitude of 0.5 and a wavelength of a year. The curve was phase shifted to reflect the assumed pattern of seasonality. The long-term variability was represented by the same sort of curve with a wavelength of 50 years. At present, the temperature in the Barents Sea appears to in a phase of cooling associated with natural variation (Institute of Marine Research, 2020), suggesting that the chosen shape may be representative. The trend was represented by a linear increase of 0.5 degrees over 50 years, assumed to reflect a long-term increase in the temperatures.

The changes in the temperature affect the carrying capacity of each cell, following the configuration depicted in Figure A.1. Figure 3 illustrates these effects separately and collectively over a period of 50 years (600 periods) and their collective impact on the share of the carrying capacities located on the territory of each nation.

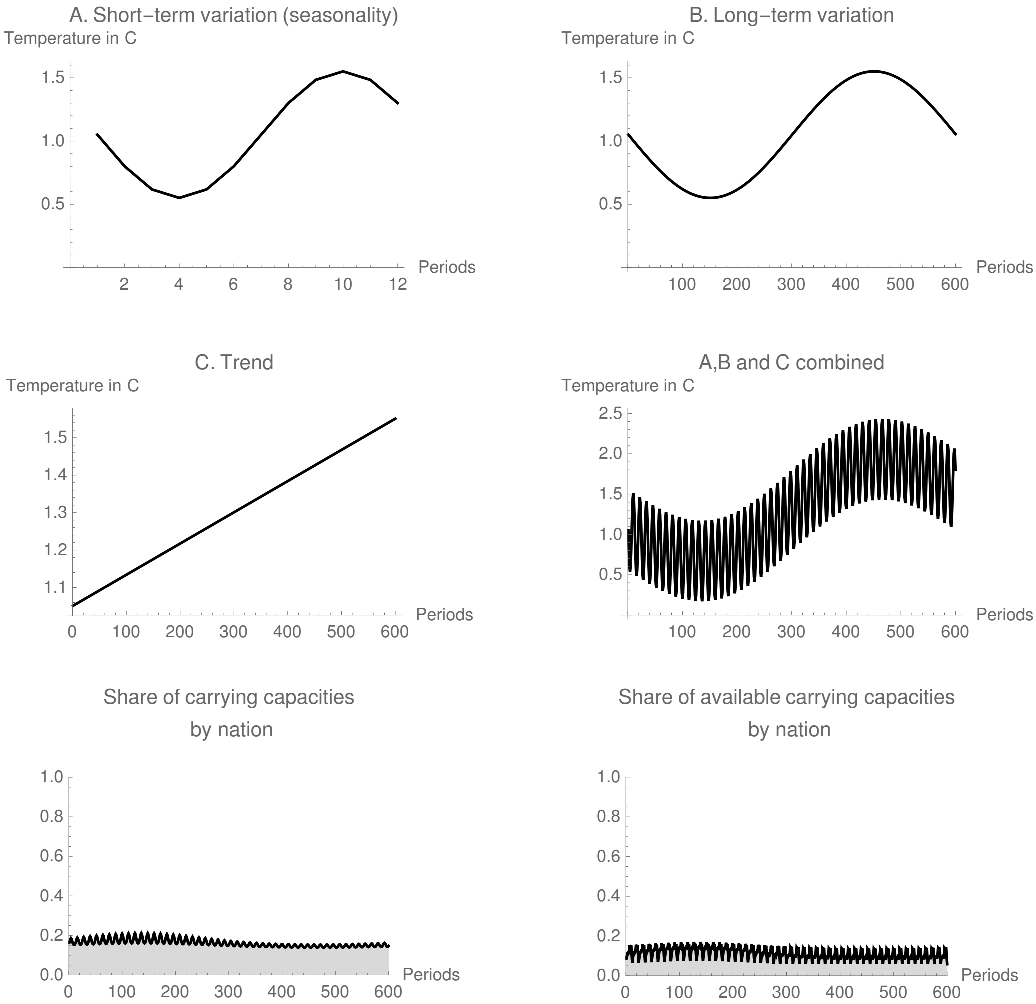

Figure 3: The subfigures in the upper and middle rows show the modelled development of temperatures as a result of seasonality (A), a long-term natural variablity (B), a time trend (C) and their collective effect. The subfigures in the bottom row show the effect of the temperature changes on the share of modelled carrying capacity on the territory of each nation over the 600 time periods. The left figure includes every area and the right figure only includes areas free of sea ice. In these figures the grey area represents the Norwegian share, while the white area represents the Russian share.

Temperature changes are also likely to provoke changes in the sea ice conditions – an increasing temperature trend is accompanied with a downward trend in ice coverage in the Barents Sea (Institute of Marine Research, 2022), but for simplicity we have assumed the schedules of sea ice, depicted in Figure 2, to be fixed.

We now proceed to present the cooperative and non-cooperative scenarios. First, the cooperation scenario was constructed. Here the Norwegian and Russian fishing fleet are combined into one fleet free to fish independently of sovereign rights. In order to calculate the economic outcome, the golden section search method was used. This method is an approach that, through a rule-based sampling of a function having one optimum within an interval, quickly reduces the width of the interval in which the optimum is located, until a predefined sufficient accuracy in the solution is reached (Keane & Nair, 2005). This method was used to search for the fixed level of effort maximizing the rent over the 600 time periods under the assumption that the rent, as a function of effort, was a unimodal distribution. The method was implemented as follows:

1. First the initial interval of the Golden section search method was set. The lower limit of effort was set to zero and the upper limit to the open-access value of effort as estimated in Hogrenning and Eide (2022). The latter is, by design, rent-dissipating. Hence, all levels of effort in this interval were believed to provide rent and therefore treated as potential rent-maximizing effort levels.

2. A simulation was carried out where a fixed level of effort, dictated by the golden-section search method, was deployed for 600 periods. In each period, the fleet was assumed to fish in the 100 cells with the highest harvest potential in the Barents Sea.

3. At the end of the simulation, the total rent from the fishing activities was calculated.

4. The search interval was recalculated according to the golden-section search method given the rent obtained in the simulation.

5. Steps 2–4 were repeated until the search interval was narrowed to below 1000 pots – a limit assumed to be close enough to the rent-maximizing effort level – being the terminating condition of the golden-section search algorithm.

6. The simulation with the effort level obtaining the largest rent was chosen to represent the *cooperation* scenario.

Second, the non-cooperation scenario was constructed. Here, two nation-specific fleets (a Russian and a Norwegian) were established, with each one only allowed to fish on the territory of its own nation. The golden-section search method could potentially be implemented separately on the fishery of each nation. However, because the harvest strategies of one nation may (according to the results that we will present in Section 3.1 *they will*) affect the fishery of the other nation, this would be a misspecification[5]. Instead, simulations were carried out in which the level of effort and the number of cells fished in were kept at the same level as in the *cooperation* scenario, but distributed between the two fleets in a proportion that varied between the simulations. The procedure was implemented as follows:

1. 101 simulations, denoted in the range of $non-cooperation_0$ (nc_0) to $non-cooperation_{100}$ (nc_{100}) were constructed, each representing one scenario.

2. In each scenario, y denotes the percent of effort applied by the Norwegian fleet and $100-y$ denotes the percent of effort applied by the Russian fleet. Similarly, y also denotes the number of cells fished by the Norwegian fleet in Norwegian grounds, and likewise, $100-y$ denotes the number of cells fished by the Russian fleet in Russian grounds. For example, in the $non-cooperation_{25}$ scenario, 25 percent of the effort was applied by the Norwegian fleet to the 25 cells with the highest harvest potential on Norwegian grounds, and the remaining 75 percent was applied by the Russian fleet to the 75 cells with the highest harvest potential in the Russian grounds.

3. The simulations were carried out for 600 time periods and the total rent of each simulation was calculated.

[5] Multi-objective optimization approaches could have been used, however the author considered such methods to be too computationally challenging to carry out.

3 Results

3.1 Results (RQ1)

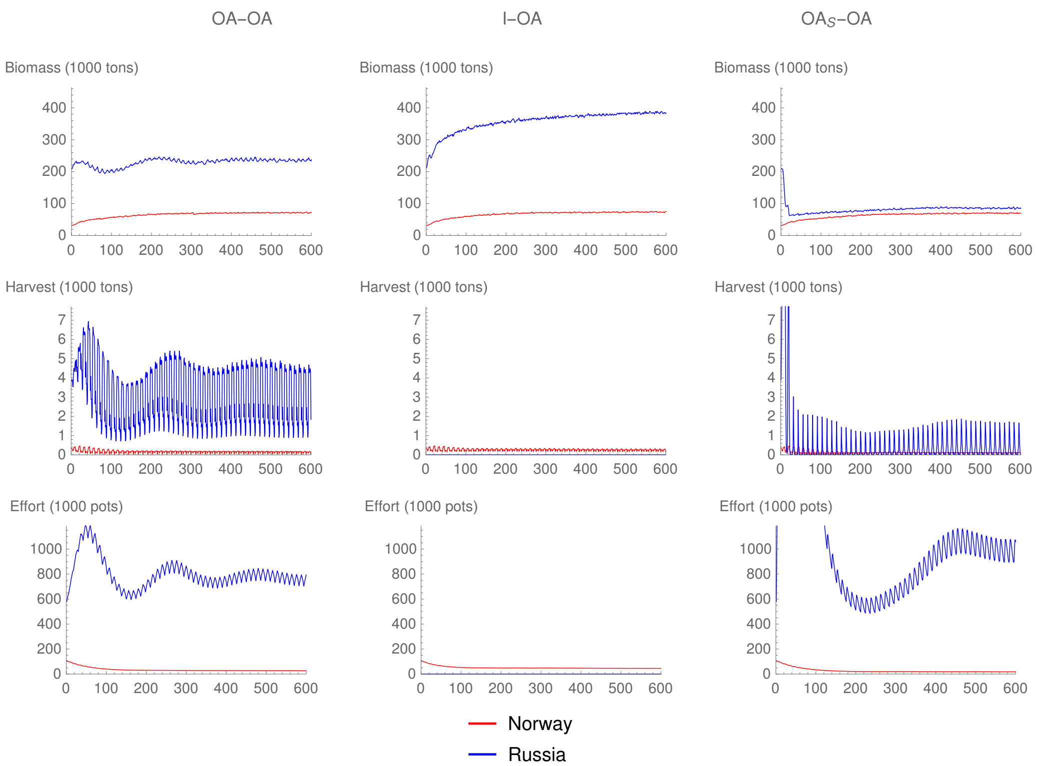

Figure 4: The results in the $OA - OA$, $I - OA$ and $OS_S - OA$ scenarios. The line plots show the Norwegian (red) and Russian (blue) development of biomass, harvest and effort over 600 time periods.

Table 1 shows the results of RQ1, while the development of biomass, harvest and effort corresponding with each scenario are shown in Figure 4. The large variation in the harvest rates from period to period are probably because of the schedule of sea ice formation, which changed the harvest grounds available. The table shows the average level of biomass (B), harvest (H) and effort (E) corresponding to each nation, denoted by the subscript R for Russia and N for Norway. The value in parentheses in the $I - OA$ and $OA_S - OA$ scenarios represents the percentage change in comparison with the $OA - OA$ scenario.

In the $OA - OA$ scenarios the structures of the fisheries of the two nations were the

Table 1: The average values of the biomass available in Russian ($\bar{B_R}$) and Norwegian ($\bar{B_N}$) grounds, the effort applied by the Russian ($\bar{E_R}$) and Norwegian ($\bar{E_N}$) fleets and the harvest obtained by the Russian ($\bar{H_R}$) and Norwegian fleets ($\bar{H_N}$) during the 600 time periods for each scenario. The value in parentheses represents the change in percent compared with the $OA - OA$ scenario.

Scenario	$\bar{B_R}$	$\bar{H_R}$	$\bar{E_R}$	$\bar{B_N}$	$\bar{H_N}$	$\bar{E_N}$
$OA - OA$	229.35 (0)	3.22 (0)	799.97 (0)	65.17 (0)	0.17 (0)	35.01 (0)
$I - OA$	357.04 (56)	0 (-100)	0 (-100)	67.35 (3)	0.26 (58)	51.41 (47)
$OA_s{-}OA$	82.35 (-64)	0.65 (-80)	1658.38 (107)	63.38 (-3)	0.12 (-27)	27.19 (-22)

same except for the harvest grounds at their disposal. In these scenarios, we observe that the Russian levels of biomass, effort and harvest are larger than the Norwegian ones. This can be explained by the distribution of carrying capacities (Figures 1 and 2). We observe that the majority of the capacity is located on Russian grounds. Figure 5 shows the areas where the majority of fishing effort was deployed during the 600 time periods. We observe that many of these areas – about every area in the Norwegian fishery – are relatively close to the territorial border.

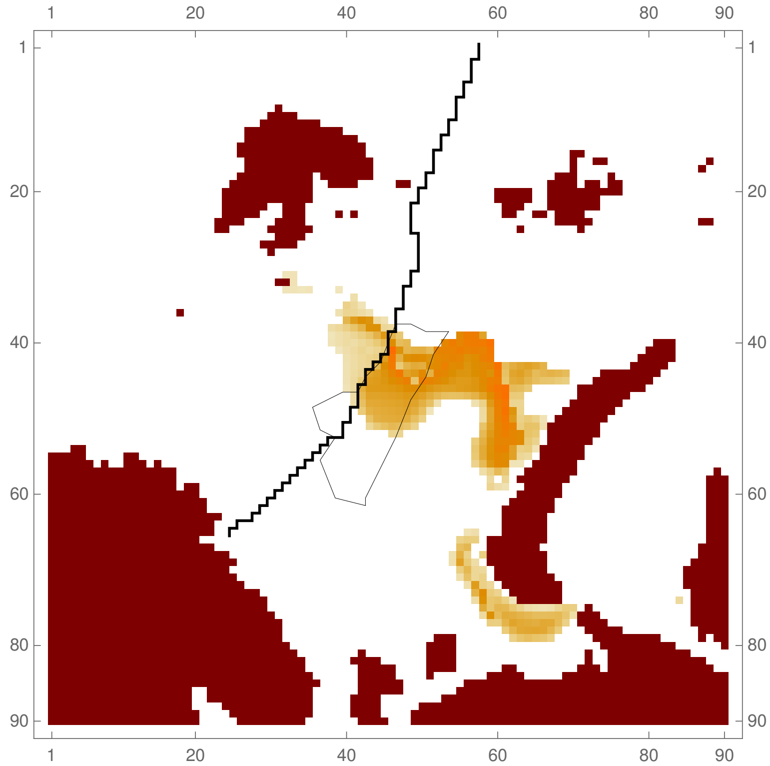

Figure 5: Dark brown indicates land areas and white indicates sea areas. The black line divides each sea area into a Norwegian (left) and Russian sea area (right). The remaining cells show where the majority of the fishing activities were distributed during the $OA - OA$ scenario, where increasing intensity of red indicate a higher level of activity. The area of the Loophole is represented by the polygon sketched by black lines.

In the $OA-OA$ scenario the biomass level averaged at 229.35 thousand tons on Russian grounds and at 65.17 thousand tons on Norwegian grounds. The harvest level on the Russian grounds averaged at 3.22 thousand tons by applying on average 799.97 thousand pots. The corresponding values for the Norwegian fleet was a harvest level of 0.17 thousand tons by applying on average 35.01 thousand pots.

In the $I - OA$ scenario the Russian fleet was inactive. In this scenario, the average biomass on Russian grounds increased by 56 percent compared with the $OA - OA$ scenario, while the average values of biomass, harvest and effort on Norwegian grounds increased by 3, 58 and 47 percent respectively. Hence, when the Russian fleet is inactive, the Norwegian fishery expands both in terms of harvest and effort.

In the $OA_S - OA$ scenario, the Russian fishery is highly subsidized. Figure 4 shows that the subsidised price immediately attracts large levels of Russian effort. In this scenario, the average biomass on Russian grounds is reduced by 64 percent, the harvest by 80 percent, while the effort increases by 107 percent, when compared to the $OA - OA$ scenario. Although the average Russian harvest was reduced compared to the $OA - OA$ scenario, Figure 4 shows that large harvest rates were achieved early in the simulation, which subsequently reduced the crab biomass. The average values of biomass, harvest and effort on Norwegian grounds were reduced by 3, 27 and 22 percent. Hence, when the Russian fishery is highly subsidized, the Norwegian fishery is reduced both in terms of harvest and effort.

3.2 Results (RQ2)

Figure 6 shows the results from the rent-maximizing procedures in the $cooperation$ and $non - cooperation$ scenarios.

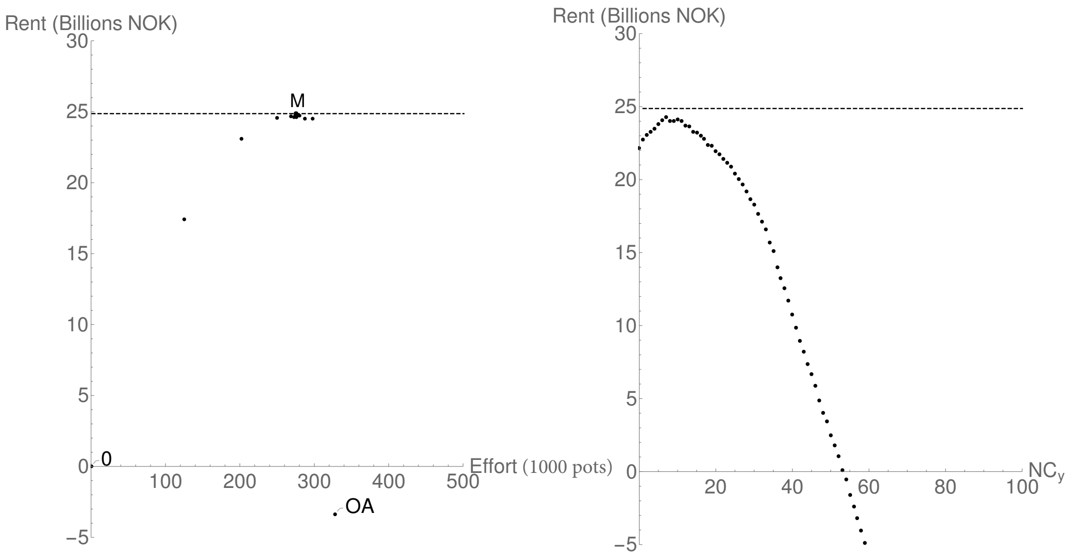

Figure 6: The figure to the left shows the rent obtained by the rent-maximizing procedure when the fleet operates as one unit free to fish independently of any sovereign rights. The points denoted 0 and OA (open-access) – not to be confused with the OA scenario in RQ1 – represent the range within which the rent-maximizing effort was expected to be present. M denotes the simulation where the maximum rent was found, and the simulation chosen to represent the *cooperation* scenario. The figure to the right shows the rent obtained in scenarios nc_0–nc_{100}. In an attempt to ease the visualization of the results, scenarios producing a total rent below -5 billion are not included.

The subfigure to the left shows the result for the *cooperation* case. The point denoted M corresponds to the simulation with the effort level found to maximize the rent and thus the simulation chosen to represent the *cooperation* scenario. The maximum rent was found to be around 25 billion NOK, obtained by employing a fixed level of effort slightly beneath 300 thousand pots in each time period.

The subfigure to the right shows the outcome of scenarios NC_0–NC_{100}. We observe that scenario NC_8 maximizes the rent. Hence, the rent has its maximum when 8 percent of the effort is applied by the Norwegian fleet on Norwegian grounds each time period, and the remaining 92 percent of the effort is applied by the Russian fleet on Russian grounds each time period. We observe that the rent obtained in the NC_8 scenario is lower than the rent obtained in the *cooperation* scenario.

4 Discussion

Using simulations we have studied the management of the snow crab fishery in the Barents Sea. The first research question (RQ1) was how different nation-specific management measures can affect the snow crab fishery both on the territory of the nation executing the measure (represented by Russia in the model) and on the territory of the other nation (represented by Norway in the model). The second research question (RQ2) is about the efficiency of the current international management regime. We compared the economic outcome where each nation exploited the crab in its own territory independently of the other (the current regime), with the outcome where the two nations allow mutual access to the harvest grounds (the proposed alternative regime).

The results for RQ1 indicate that the management measures are effective in achieving the aim of the executing nation. Compared to the case when the fishers are paid the market price, it has been found that paying the fishers a price above the market price will encourage more fishing activity and thereby lower the amount of crab on the territory of the nation, whilst prohibiting any fishing is found to have the opposite effect on the crab biomass. These findings are in line with what standard bioeconomic theory (see, e.g. Anderson and Seijo (2010, p. 28-29)) would predict. We also find that these measures have an effect on the fishery of the other nation, causing a substantial adaptation – measured by the change in the effort and harvest level – in the fishery of the other. This indicates that the management measures applied by one nation may affect whether the management objective of the other is reached.

The results for RQ2 indicate that it may be beneficial to operate with a combined fleet with no restriction on how to spatially distribute the fishing activity. Being able to allocate a varying proportion of the fishing effort to the grounds of each nation over time appears to be favorable, assuming environmental change to take place altering the distribution of carrying capacities for the crab in the Barents Sea in the manner modelled[6]. Hence, the results suggest that there may be economic gains to be made if the two nations allow their vessels to have mutual access to harvest grounds.

The adaptations that the Norwegian fleet makes in the scenarios in RQ1 are a response to changes in the Russian management regime. Fundamentally, they are due to the differences in the amount of crab biomass arriving from Russian territory. The results are in agreement with the reasoning of Gulland (1980). According to Gulland (1980), when the mixing of individuals between the territories is only moderate, the stock abundance will correspond to the abundance preferred by the nations involved, except in areas close to the border if their preferences of abundance differ. The mixing of crabs between the two nations can be of this type, and the adaptation made by the Norwegian fleet from one scenario to another can thus be explained by the Norwegian fishery being situated near the Russian border (Figure 5). Note however, that the effect of the management measures studied appears to be shaped by the environmental conditions. Because some areas are partly or fully covered by sea ice during the year, the crab biomass in these areas is not subject to fishing activities. This suggests that only in certain areas, partly or fully free from sea ice, are the management measures effective, which also may affect the amount of crab departing for the territory of the other nation.

Essentially, the results obtained in RQ1 suggest that when implementing a management measure in the Norwegian fishery, e.g. a TAC with an aim of biological sustainability, the management measure taken in the Russian fishery should not be ignored, since it may affect whether the Norwegian aim is reached. However, two aspects must be emphasized. First, only the Russian management measures were altered between the

[6] A study by Fedewa et al. (2020) on the snow crab in the Bering Sea suggests that the crab is sensitive to environmental changes, supporting the results from our model. In the Bering Sea, the fishery for the crab has taken place in the South Bering Sea. However, Fedewa et al. (2020) recently found masses of snow crab of exploitable sizes in the North Bering Sea – an area where no commercial fishing has taken place – suggesting that a future fishery may develop there. They further associate this discovery with temperature changes, which is the parameter we altered when modelling the scenario of environmental changes.

scenarios. If modeled in the opposite direction, Norwegian management measures would be likely to have had a different effect on the Russian fishery, because the spatial structures of the two fisheries are different. Second, the management measures we have studied can be considered as two extremes: an eradication fishery and no fishing at all. If more moderate management measures (e.g. reflecting small differences in the social rate of discount) had been chosen, the effect on the other nation would probably have been less. Additionally, an open access fishery was used to represent a long-term commercial fishery, which is an unlikely outcome. If a more appropriate representation had been used, the effect on the other nation of moving from a long-term commercial fishery – assuming it to give rise to a higher biomass level and more departing crabs than the open access representation would – to a subsidized open fishery (inactive fishery) would be likely to have been greater (less) that those based on the $OA - OA$ scenario.

The results about RQ2 need some additional clarification. In Figure 6 we observe that the OA scenario did not generate zero rent over the 600 time periods. Quasi (temporary) rent typically occurs outside of equilibrium when the effort adapts to the biomass, and may be substantial in an open-access fishery (Eide, 2012, 2016). Hence, some positive or negative rent is to be expected. This did not appear to have an impact on the profit-maximizing procedure. A profit-maximizing effort level was found within the range anticipated to generate positive rent and the output of the golden section search method, shown the left sub-figure of Figure 6, appear to form the shape expected.

Several assumptions made on the economics in the rent-maximizing approach in RQ2 need a discussion. First, in the $non - cooperation$ scenario, we have only studied the rent obtained when the Norwegian and Russian fleet in total use the same level of effort as the one optimizing the rent in the cooperation scenario: there may exist other levels of effort obtaining a rent surpassing the rent obtained in the $cooperation$ scenario. Then again, supporting our results is the fact that the lower rent obtained in the $non - cooperation$ scenario can only be attributed to the restriction on the locations available for fishing for each fleet due to the sovereign rights, whereas in the $cooperation$ scenario the combined fleet has no restriction on where to fish. This is the only difference between the $non-cooperation$ and $cooperation$ scenario.

Second, in both the $cooperation$ and $non-cooperation$ scenarios, the level of effort is assumed constant and to be fully utilized in the fishery every time period. Hence, the capacity of the fleet is assumed fixed (e.g. ignoring the possibility that vessels are traded or withdrawn from the fishery for the purpose of being used in another) and to be fully applied in the fishing activities every time period regardless of profit expectations. Such a procedure would have been characterized as inadequate by Clark (2010). However, because the assumption applies in both scenarios, the author sees no reason why this should affect the result, but nevertheless it cannot be ruled out and further research should address whether the result depends on these assumptions. A sensible adjustment to the model would be to allow a fixed level of effort to serve as the available capacity, and the effort used each period to be an outcome of a profit maximizing problem constrained by the capacity, its alternative use, and the state of the stock (e.g. by a TAC).

Third, the assumption that both nations are only interested in maximizing the rent from the fishery is highly questionable. The participants are likely to be self-interested and care more about maximizing their own benefits from the fishery (Munro et al., 2004). Therefore, any benefits from cooperation need to be adjusted for the potential cost of achieving and maintaining an agreement making the outcome from a cooperation scenario possible (Munro, 1986). Seen in relation to environmental changes, Miller and Munro (2004) argue that an agreement on cooperation needs to be flexible to avoid destructive conflicts. They argue that environmental changes can be anticipated to occur but not accurately predicted, neither in time nor in magnitude, e.g. causing a stock to reallocate over time and thereby altering the bargaining power of the participants. Hence, besides being identified as a reason for why it may be feasible to cooperate in the crab fishery in the first place, environmental changes may also be what makes an agreement hard to maintain.

We believe the validity of the model depends on three important assumptions made on the movement, habitat, and the exploitation of the crab. These assumptions relate both to the base model and the extensions made to it in this study. First, even though Hogrenning and Eide (2022) found their model to reproduce important features of the crab fishery, it cannot be ruled out that other models would have been better. When it comes to the effect of the management regimes studied in RQ1, the results are particularly vulnerable to misspecification of the crab movement. The modeled crab movement is based on observations of movement rates made of crabs in the benthic life stage. However, the snow crab has a relatively long planktonic phase, enabling long-distance movement by water masses (Hardy et al., 2011) that may affect the pattern of movement[7]. In general, the crab movement can be determined by a vast number of structures and processes, such as local barriers to movement or potential predators. Collectively, these elements may create a predominant movement pattern which may be sufficiently imitated by the model, but an entirely different model may also be needed. Hence, the mixing of crabs between the two nations might be both higher or lower, or be of a more unidirectional nature (e.g. due to the directions of the ocean currents or ontogenetic movement), and the effect of the management measures studied for RQ1 may therefore be different than our model suggests.

Second, the modelled distribution of carrying capacity determining the distribution of the crabs may differ from their actual distribution. If, for example, the crab biomasses on the territories of the two nations make up two self-sustaining populations with little or no exchange of crabs between them, the effect of a management measure on the non-executing nation is likely to be none or negligible. Third, we have assumed the fishers to choose harvest grounds exclusively on the basis of harvest potential. However, they are likely to consider other components than just harvest potential when determining where to fish. The cost of fishing may be higher in some areas, due to, e.g. the distance to shore or weather conditions, making some areas more attractive than others. Similarly, some harvest grounds may be unavailable for fishing because of management decisions not taken into account by the model.

One way to evaluate the aforementioned assumptions of the model is using patterns[8]

[7] In an earlier version of this paper, the author attempted to include this type of movement in the model. However, due to the little research performed on the early life-stage population dynamics of the crab stock (the work of Hjelset et al. (2021) being one exception) the attempt was put aside because of the many uncertain factors involved.

[8] i.e. indicators of essential underlying processes and structures of the real system(Grimm et al., 2005).

(Gallagher et al., 2021). The reported harvest locations may represent such a pattern. Figures 3 (Figure A.3) and 5 (Figure A.4) in Institute of Marine Research (2021) show the reported harvest locations in the Norwegian and Russian fisheries, respectively. When comparing these figures with the modelled harvest locations depicted in Figure 5, we observe a fair degree of similarity, suggesting that the assumptions made are reasonable. However, the model suggests a cluster of harvest locations on the south coast of Novaya Zemlya and in the Loophole, two areas where no harvest has been reported recently.

As for the former, it can be related to the preferences of the crab for habitat. A study of the Barents Sea snow crab reported large concentrations of juvenile crabs in shallow waters in coastal areas, while large crabs appeared in deeper waters (Sundet & Bakanev, 2014). Hence, the area south of Novaya Zemlya may be an area well suited for being a crab habitat as suggested by our model, but perhaps not as an habitat for crabs of exploitable sizes and because of this not subject to harvest activity.

As for the latter, the lack of fishing activities in the Loophole – being the hotspot of the fishery from 2012 to 2016 – may originate both from management and biology. There were concerns about local overfishing in the area during this period (Institute of Marine Research, 2017). Therefore, the lack of harvest activity in this area may be due to anticipations of low catch rates or simply because the area is closed for fishing due to these concerns. The area can also be kept unexploited for strategic reasons, which may indicate that Russia has implemented a reserve-stock management regime in this area. If the crab biomass in this area close to the Norwegian border is not subject to fishing mortality by the Russian fleet and instead remains unexploited, a management measure executed on the Russian side, such as those studied for RQ1, might have a significantly lower effect on the Norwegian fishery.

The fact that the observed and modelled harvest locations do not completely coincide indicates that one or several processes are absent from the model. For example, a model allowing for life-stage dependent crab preferences for habitat conditions might be a necessary correction to the present model. In relation to the results for RQ2, it may still be favourable to allow mutual access to harvest grounds even if the modelled harvest locations deviate from the observed ones.

As thoroughly evaluated in the last sections, there are many uncertainties in the biological, economic and environmental dimensions of the model. Consequently our results can only be considered as an exploration of the potential effects of management regimes in the snow crab fishery, and rather illustrate how crab movement and environmental changes may influence the outcome. Future research should improve the model in line with the inadequacies identified.

5 Conclusion

A fishery on the expanding snow crab stock, shared by Russia and Norway, is evolving in the Barents Sea. In this study we have taken advantage of a spatio-temporal bioeconomic model assumed to represent the fishery on a fully developed scale. We extended the model for the purpose of studying the management of the fishery.

Two major findings can be drawn from this study. One can neither rule out that a management measure executed by one nation have a substantial effect on the fishery of the other nor that the current international regime is inefficient. Rather, our results indicate that this may be the case.

The implications are that the fishery management of each nation may need to pay attention to the management measures applied by the other, as it may impact whether their management aims are met, and that there may be economic gains to be made by introducing a regime of mutual access to harvest grounds. Both topics should be studied more closely.

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Data Availability Statement

The data used in this study are openly available, and the sources are clarified within the article.

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Appendices

The base model

The model of Hogrenning and Eide (2022) consists of three submodels. An environmental model represents the crab habitat within the Barents Sea, a biological model represents the growth, mortality and movement of the crabs in the habitat, and an economic model represents the open-access and harvest dynamics of the fishery. The environmental model is constructed as an $i \times j$ lattice representing the Barents Sea. Each cell in the lattice represents a geographical area within the Barents Sea and is given a carrying capacity for crabs determined by the observed bottom temperatures and depths in the area in 2016, given assumptions of crab preference for temperature and depth, as depicted in Figure A.1.

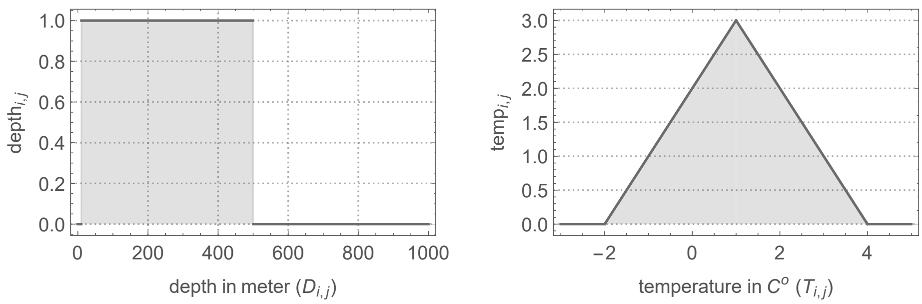

Figure A.1: The values for depth (to the left) and temperature (to the right) assumed to provide a habitat for snow crab. For a cell to be assumed appropriate to provide carrying capacity for snow crab it has to be within both temperature and depth range. All depth values found appropriate are assumed to be equally suitable, while within the temperature range, a value of one C^0 is assumed to provide the highest suitability. The figure was originally published in Hogrenning and Eide (2022).

These assumptions resulted in the distribution of carrying capacities in the Barents Sea presented in Figure 1. The spatial resolution of each cell is 20 times 20 km, and the total number of cells is 8100 (90 times 90).

The biological model is based on a cellular automaton representing the periodic growth, mortality and movement of crabs on a cell level. The growth of the biomass within each cell is added to the biomass already present in the cell. However, if the biomass exceeds the carrying capacity of the cell, a collapse takes place and only the fractional part of the biomass is retained in the cell. The rates of movement have been calibrated using empirical observations and are assumed to take place between neighbouring cells according to Figure A.2.

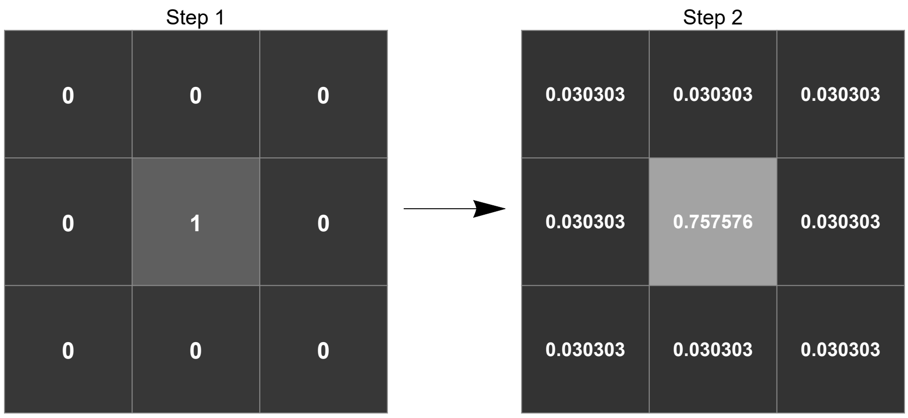

Figure A.2: With one biomass unit in the middle cell to the left (step 1) the biomass distribution to the neighbouring cells in the next time step (assuming a Moore distribution of range 1) follows a diffusion matrix, as shown by the value of each cell to the right (step 2) (Hogrenning & Eide, 2022).

The economic model is that of Gordon (1954) and the harvest equation of Schaefer (1954) implemented in an open-access crab fishery. Here the evolution of effort, measured in crab pots, over time is modelled according to the principles of Smith (1969). Thus, the current level of activity in the fishery is seen in relation with the previous profitability in the fishery. The fleet is assumed to distribute its fishing activities in proportion to the crab density of the areas in the Barents Sea. Therefore, a cell with a high density of crabs will be the aim of more fishing activity than a cell with a low density. The model was calibrated based on observations of catch per unit effort (CPUE) and a map of the observed geographical distribution of the crab at an early stage of the invasion. In the model the unit of time is the month. Hogrenning and Eide (2022) can be consulted for an in-depth derivation of the model. The parameter values of the model are presented in Table A.1.

Table A.1: Parameter values of the model. The column *Section* gives a reference to the section(s) where the parameter is described, where the superscript a signifies a section in Hogrenning and Eide (2022) where the base model is described.

Param.	Value	Description	New	Section
g	0.05	Growth rate	N	2.6[a]
d	1	Concentration parameters	N	2.3[a]
K	950,000	The total capacity (tons)	N	2.1[a], 2.6[a]
	(Fig. A.2)	Diffusion Matrix	N	2.1[a], 2.6[a]
q	0.0001	Catchability coefficient	N	2.5[a], 2.6 [a]
β	0.9	Output elasticity of biomass	N	2.5[a], 2.6[a]
p	50	Unit price of harvest (NOK)	N	2.5[a]
c	193	Unit cost of effort (NOK)	N	2.5[a]
γ	0.00015	Stiffness parameter	N	2.6[a], 2.7[a]

[a](Hogrenning & Eide, 2022)

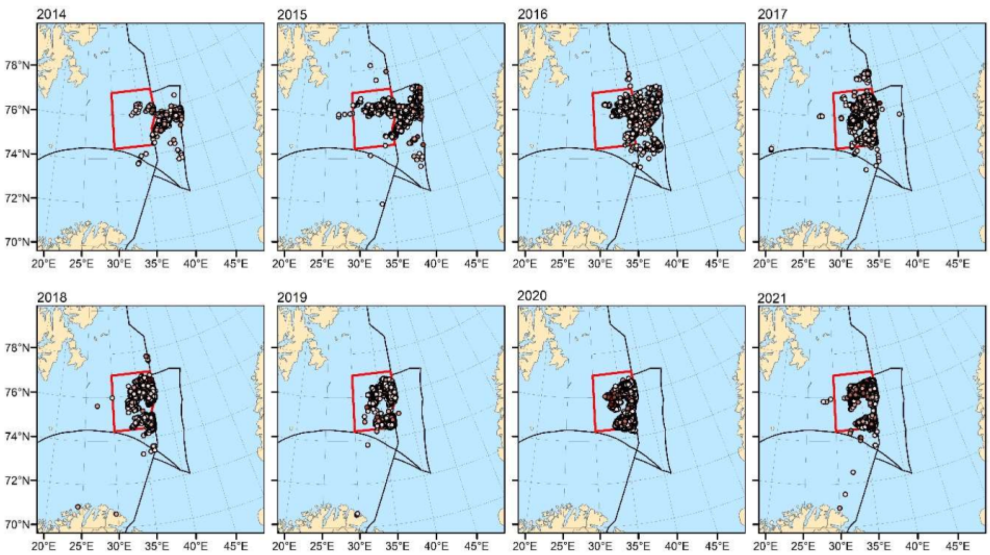

Figure A.3: The locations of harvesting in the Norwegian snow crab fishery during 2014–2021. Initially the fishery was ongoing in the area of the Loophole (see Figure 5 for an illustration of the area), however, in 2017, the Russian part of the area was closed to Norwegian vessels by Russia. Therefore we observe no harvest activity in this area from 2017 on. The figure was originally published in Norwegian in Institute of Marine Research (2021, p. 6).

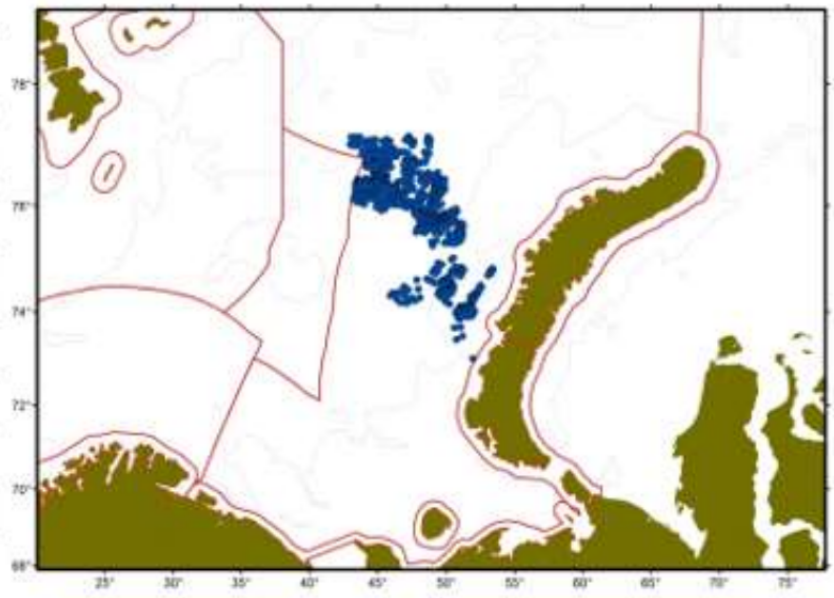

Figure A.4: The locations of harvesting in the Russian snow crab fishery during 2020. The figure was originally published in Norwegian in Institute of Marine Research (2021, p. 7).

Supplementary material

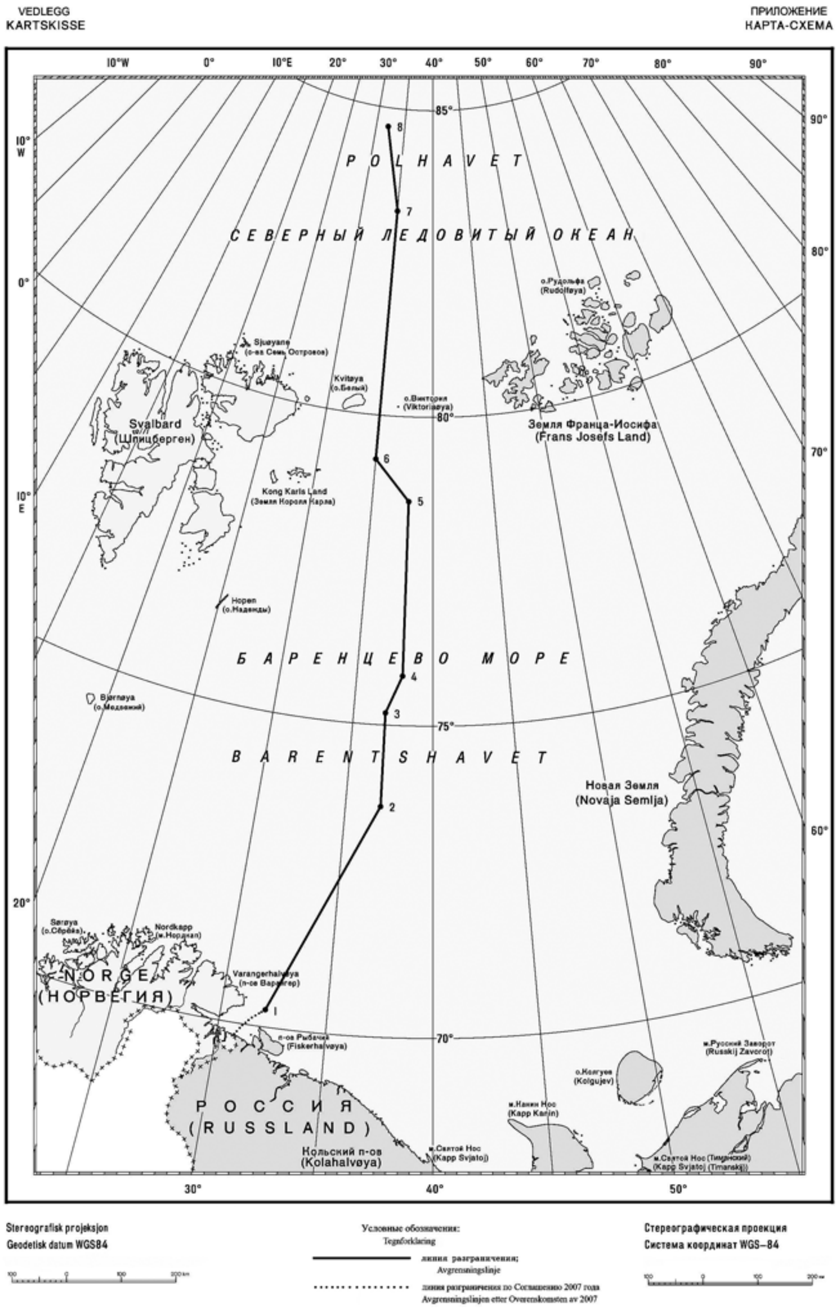

Figure S.1: The delimitation line in the Barents Sea Delelinjeavtalen (2010)

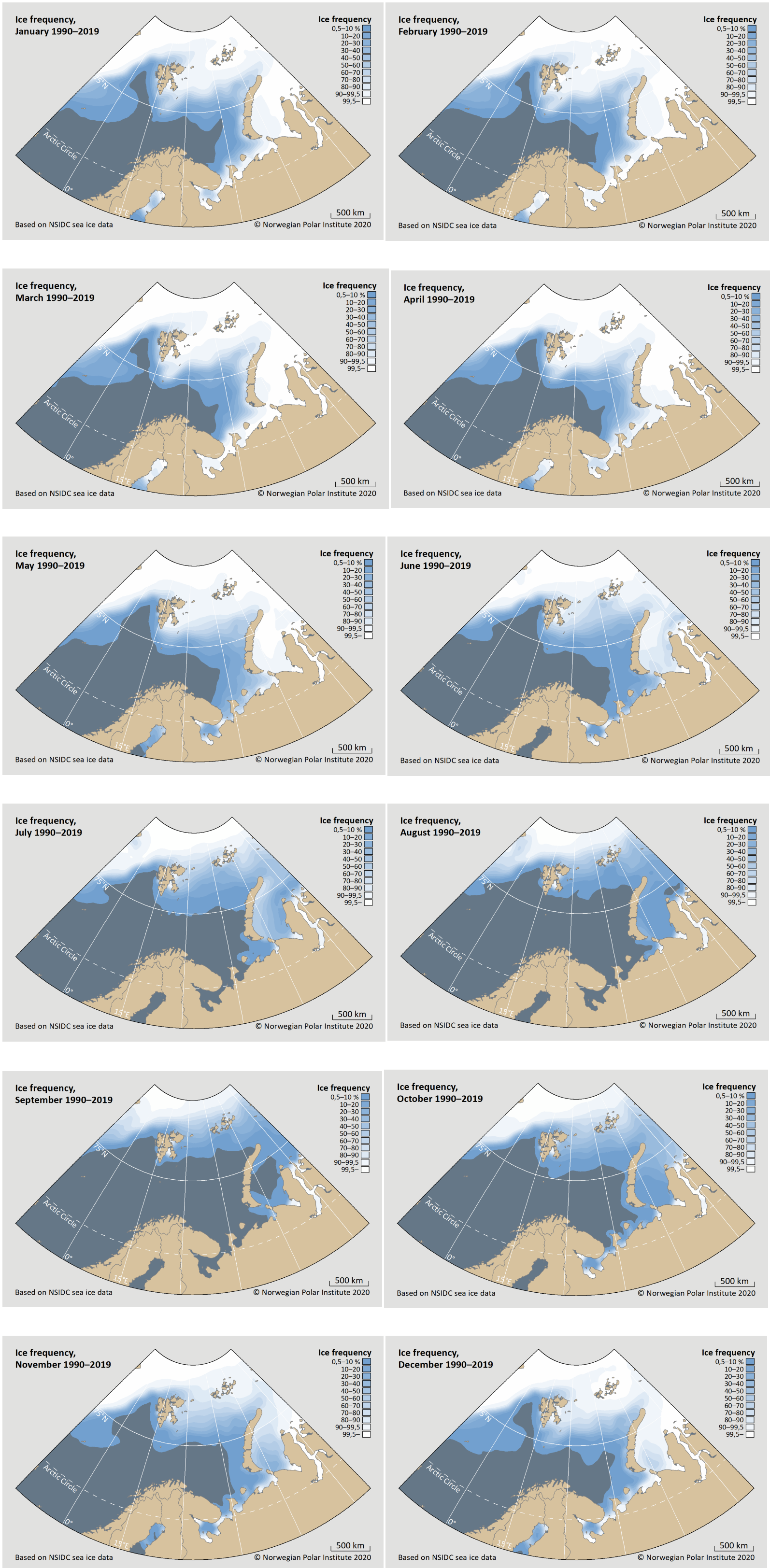

Figure S.2: The monthly frequency of sea ice in the Norwegian Arctic, 1990–2019. The figure was originally published in The Norwegian Polar Institute (2022).