UiT The Arctic University of Norway

Faculty of Bioscience, Fisheries and Economics

# Fishers’ effort allocation behavior and decision-making process in the Norwegian trawl fishery

Tannaz Alizadeh Ashrafi

A dissertation for the degree of *Philosophiae Doctor* in Natural Resource Economics, June 2021

# Fishers' effort allocation behavior and decision-making process in the Norwegian trawl fishery

PhD candidate: Tannaz Alizadeh Ashrafi

Supervisors: Prof. Arne Eide and Prof. Claire Armstrong

Affiliation: The Arctic University of Norway (UiT), The Norwegian College of Fisheries Science (NFH)

## Acknowledgement

This work was carried out at The Norwegian College of Fisheries Science (NFH), The Arctic University of Norway (UiT). I owe my deepest gratitude to my supervisors Prof. Arne Eide and Prof. Claire Armstrong, who provided an opportunity for me to study for a PhD. Without their continuous help and support, this study would not have been completed. I also express my warmest gratitude to Øystein Hermansen at The Norwegian Institute of Food, Fisheries, and Aquaculture Research (Nofima AS), who provided multiple data sets. Thanks to Assoc. Prof. Roger Larsen and Prof. Jahn Petter Johansen, who helped me to become familiar with the Norwegian quota management system. I am also exceptionally grateful to Prof. Øystein Myrland, who has never let me down. I would also like to acknowledge my co-authors Dr. Shaheen Syed and Dr. Keita Abe for their contributions to my PhD.

To my parents, especially my mom, thank you for encouraging me in all of my pursuits and inspiring me to follow my dreams and for supporting me emotionally and financially throughout these years. Thanks to my sister Elnaz, and my brother in-law Babak, who constantly reminded me and demonstrated that all I had to do was to say the word and they would be always here for me. Many thanks to my brother Reza and his wife Neda for providing precious academic guidance. I express my deepest love to my sweet nephew and niece Surush and Nila, whose cuteness refreshed me during my difficult times.

I am indebted to my closest friend Mona Bayat. Her support was worth more than I can express on paper. I am fortunate enough to have Yana Zykova and Suthamaty Nadarajah as my friends, who always have my back. Thanks to Arnt Otto Østland, Samira Saheb Alzamani, Babak Sarabi, Dejene Gizaw, Furug Garbalchi, and Mustafa Selcuk Uzmanoglu for giving me friendship, putting up with my odd hours and providing me with lifts and practical help.

*Dedicated to my amazing mom and dad: Susan and Hamid*

## Summary of the articles

The aim of this dissertation is to investigate the economic impacts of seasonality in fish abundance on Norwegian trawler fishing effort allocation, with respect to quota constraints. Recognition of how fishing effort is allocated to exploit fish stocks in response to changes in the marine environment, market conditions, and regulations is a prerequisite for the attainment of successful management of fisheries.

In the first paper, we investigated the presence of seasonality in cod fishery, in two regions, the west coast of northern Norway, and the high sea areas of the Arctic (i.e., Svalbard and Bear Island). We further investigated how trawlers adjust the allocation of fishing effort and utilize the cod quota in relation to the economic consequences stemming from the seasonality of cod fishery. The results of the study show that seasonality in cod fishery is only present in the fishing grounds along the north-west coast of Norway, and the spawning migration of North-East Arctic (NEA) cod shapes the seasonal pattern. The spawning aggregation of NEA cod in this region during wintertime encourages both trawlers and coastal fishers to increase the landings of cod, which in turn reduces the price of cod. Hence, trawlers withdraw from cod fishery and partake in other available fisheries (e.g., saithe and haddock). In other words, trawlers reserve the cod quota for the ensuing months towards the end of the year, when NEA cod swim back to the Artic area to feed. At this time, cod fetch higher prices due to less cod being landed as coastal fishers have already largely fished their cod quota during Lofoten fishery.

In the second paper, we studied the harvesting behavior of trawlers in minimizing revenue risk in their fishing portfolio, consisting of cod, saithe, and haddock fisheries over the course of a year, while adhering to quota restrictions. These fisheries follow different patterns of seasonality, and the economic consequences from the variation in stock abundance are different. We concluded that holding a diverse fishing portfolio to reduce revenue risk is an irrational and untenable strategy for trawlers as it leads to inefficient allocation of fishing effort and fishing rights. We also found that profit generation is a more important business objective compared to revenue risk reduction. We speculate that the vertical integration of the trawl industry and the advanced technical specifications of trawl vessels could explain the prioritization of revenue enhancement over minimizing revenue risk. We further found that the seasonality in cod fishery dictates the dynamics of trawl fishery to generate and increase fishing revenue.

In the third paper, we investigated the profit-maximizing behavior of trawlers targeting cod, saithe, and haddock. In essence, we studied how trawlers re/allocate effort over time and space across three fisheries and three regions including the southern and northern parts of the west coast of Norway, and the high sea areas of the Arctic including Svalbard and Bear Island. These areas are heterogeneous in terms of fish availability, prices of fish species, fuel cost to travel to the fishing grounds in these regions and availability of coastal fleet. We found that locational attributes play a significant role in shaping the harvest strategy that maximizes the profit of the fishing portfolio. The results of the study also show that trawlers are capable of identifying the economic benefits and costs associated with the selected regions, and thus the re/allocation of fishing effort across regions over the course of a year is consistent with rational choice theory.

# Table of contents

## List of Tables

## List of Figures

# Abstract

The empirical investigation of fishers' harvest behavior is an important but neglected strand of fishery science. In this thesis, we fill some of this gap by developing empirical models to investigate trawlers' harvest behavior over time and space in codfish fisheries, managed using individual vessel quotas (IVQs).

Fishers' harvest behavior is reflected in the decision-making processes underlying effort allocation: when and where to fish, what species to target, and how much to fish in each haul to avoid over- and underutilization of quotas. Effort allocation is a challenging task, especially in multi-species fisheries as the fish stocks in the fishing portfolio may differ in feeding, breeding, and migration patterns. This biological heterogeneity together with constant movement of different fish stocks across various locations influences economic conditions such as market prices and operation costs. What adds more complication to optimal allocation of fishing effort is the constantly changing environmental conditions such as food availability and sea temperature, which influence fish behavior. Another complication arises from the inherent uncertainties and external disturbances such as abrupt oceanographic changes, which affect the catch size and profitability. On top of what has been mentioned, institutional regulations such as quota restrictions further complicate the decisions underlying effort allocation.

Understanding how trawlers behave and why they behave the way they do reveals valuable information about marine resource status, as well as evaluating fisheries management options to anticipate the possible responses of fishers to changing regulatory schemes. Moreover, recognition of the fishing effort allocation of the trawl fleet enables fisheries managers to evaluate the status of the benthos and seafloor as dragging heavy nets across the ocean can be environmentally destructive.

This thesis focuses on codfish; that is, cod, saithe, and haddock fisheries as this portfolio includes economically important species in terms of volume and total revenue. These fish species are seasonally migratory and constantly swim over a vast geographical area to spawn and/or feed. The thesis aims to empirically investigate the fishing behavior of Norwegian trawlers in response to the economic changes stemming from the migratory behavior of these fish stocks, and to show how this could affect harvest attributes such as location choice, timing of production, preference in target species, and quota utilization.

This study employs and combines multiple data sources for the empirical analysis of spatiotemporal allocation of fishing effort in trawl fishery. Our comprehensive data set covers the relevant information of trawl fishery during 2011–2016 to conduct empirical investigations of trawlers' adopted harvest strategy and explain the drivers behind the chosen harvest strategy. The outcomes of this thesis are believed to be useful to fisheries managers in the policy-making process as well as for fishers' communities to enhance the efficiency of their fishing activities.

# 1 Introduction

Constant movement across different regions of the marine environment is among the most profound features of fish behavior. Fish move and adapt to the changing conditions of aquatic systems to grow, survive, and reproduce (Olsen et al., 2010; Schlosser, 1991; Wilson et al., 1994).

Different fish species may exhibit a variety of movement patterns with different dispersal scales (Schlosser, 1991; Sundby & Nakken, 2008). Spatial and temporal fish movement is driven by various factors such as ecological conditions (e.g., substrate type, disturbance status, and food availability), biological factors, life-history traits of the fish species (e.g., recruitment dynamics, feeding, and spawning migrations), predator–prey interactions and environmental factors (e.g., sea temperature, light, and water flow) (Hersoug, 2005; Olsen et al., 2010; Schlosser, 1991; Shimadzu et al., 2013; Sundby & Nakken, 2008).

The dispersal scale of fish species is influenced by their age, size, and type of movement (Nakken, 1994; Schlosser, 1991; Sundby & Nakken, 2008). For instance, larger and more mature fish species are capable of undertaking larger migrations as they have more energy to swim farther, while younger fish are less mobile. At the same time, the type of movement affects the migration range. For example, the North-East Arctic (NEA) cod (*Gadus morhua*) travels over a large geographical area from the Barents Sea, where it feeds, to the north-west coast of Norway to spawn (Jakobsen, 1987; Rose, 1993). In contrast to spawning and feeding migrations, movements driven by predator avoidance occur in a smaller range.

Fish movement affects the distribution and abundance of fish species and the dynamics of the population. In addition, regulations such as seasonal closure and quota constraints can also affect fish availability across space and over time as these managerial tools control fishing effort by limiting the amount of landed fish to a sustainable level ( Anderson et al., 2019; Casey

& Myers, 1998; Hersoug, 2005). Relative fish abundance is usually expressed as the catch per unit of fishing effort (CPUE) (Hilborn & Walters, 1992; Maunder et al., 2006; Myers & Worm, 2003).

The focus of this thesis is on the spawning and feeding migration of NEA cod (*Gadus morhua*), saithe (*Pollachius virens*) and haddock (*Melanogrammus aeglefinus*) fisheries. These fish species are migratory and migrate over a vast geographical area to spawn and to feed. The aim of this thesis is to investigate how migration of the aforementioned fish species influences economic considerations of the fisheries and shapes the harvest strategy of Norwegian trawlers, with respect to quota constraints.

Migration of fish affects species distributions and catch composition, which then consequently influence fish price and the cost of fishing (Asche et al., 2015; Birkenbach et al., 2020; Smith, 2012). Fishers are generally identified as rational economic agents, who opportunistically switch between species/fishing grounds to maximize profit (Gordon, 1953, 1954). Thus, following changes in the economic considerations, fishers reallocate their fishing effort to the locations and fisheries of maximum profit.

In the first paper, we therefore investigated how migration of NEA cod from the Barents Sea, where it feeds, to the spawning grounds along the north-west coast of Norway influences economic conditions (e.g., price of fish and cost of operation) and fishing effort allocation as well as quota utilization by Norwegian trawlers. In this paper, we have used CPUE as a proxy for the change in the relative abundance of cod in two selected regions. Thereafter, we use Fast Fourier Transform (FFT) to detect seasonality patterns in these regions. The outcome of FFT analysis shows that seasonality is only present in cod fishery along the north-west coast of Norway during Lotofen fishery. Once we confirm the presence of seasonality, we use Fourier series to build trigonometric regression to obtain estimation results.

As the catch composition varies by fluctuations in fish availability, so does the fishing revenue. Fishing revenue is generated by catch level and market price. Production at sea is prone to a large degree of uncertainty in terms of the quantity and quality of landed fish. Each time a fisher puts out to sea, the catch is unpredictable as the constant movement of fish stocks, assemblage, and dispersion exert overwhelming uncertainty on the expected catch. Furthermore, besides the inherent uncertainty in the general market condition at the time of landing, price fluctuations, induced from changes in fish availability, quality of the landed fish, and variability on the demand side can add further uncertainty to the fishing revenue (Asche, Flaaten, et al., 2002; Birkenbach et al., 2020; Kasperski & Holland, 2013; Sethi et al., 2014). Another source of uncertainty that influences the catch size and fishing revenue is the weather conditions at sea.

With fluctuating catch size and prices, fishers may pursue strategies to minimize revenue fluctuations over the fishing season, given quota constraints. One of the most common firm-level strategies to buffer revenue risk is to diversify catch by targeting multiple fish species (Kasperski & Holland, 2013; Sethi et al., 2014). This strategy was theoretically postulated in Markowits' (1952) portfolio theory, showing that portfolio diversification can attenuate the total risk of portfolio return.

An industry-level strategy to reduce risk is vertical integration, where one firm takes control over the adjacent stages of the production process (Porter, 1980; Riordan, 1990). A large part of the Norwegian trawl fleet is vertically integrated and targets multiple fish species (i.e., cod, saithe, and haddock) (Dreyer et al., 2006; Isaksen, 2007). In the second paper, we therefore investigated whether holding a diversified fishing quota portfolio is a rational and tenable strategy to reduce fishing revenue risk for a vertically integrated trawl company. The quota portfolio includes cod, saithe, and haddock fisheries, whose seasonal migration patterns and potential impacts on prices differ. This study employs revenue per unit of effort (RPUE) to proxy expected fishing revenue and uses coefficient of variation (CV) to capture risk of RPUE. A decision-making frame work is used to evaluate the available options in terms of what and when to fish and how much to fish to minimize the risk of revenue.

Similar to the effect of seasonal variation of fish stocks on fishing revenue, the constant change in relative fish abundance across different regions affects the relative profitability of the fishing grounds. Along with continual change in population dynamics and species interactions across habitats, location-specific characteristics such as proximity to the shore, availability of other fishing fleets and climatic conditions influence the relative attractiveness of different fishing grounds, and subsequently their relative profitability. A system of individual vessel quotas (IVQs) allows fishers to plan harvesting activities throughout the fishing year to maximize the profitability of the fishing quota portfolio. However, to do so fishers need to identify the economic benefits and costs of when and where to fish, and how much of a quota to fish at any given point in time. In this regard, in the third paper we investigated how spatial heterogeneity among different fishing locations influences the profit maximization behavior of the trawl fleet, which targets cod, saithe, and haddock. This study uses a Heckman's (1976) selection model to identify the influential factors on trawlers' effort allocation decisions.

Despite the importance of investigation of the effort allocation in the codfish fishery by trawl fleet, little attention has been given to this strand of literature (Birkenbach et al., 2020; Eide et al., 2003). Unlike coastal fishery, trawl fishery is a year-round activity, which could secure a steady supply of codfish (Hersoug, 2005). Moreover, since trawl fleet target economically important species, identifying how the effort is allocation could improve the economic rent (Birkenbach et al., 2020). In addition, as investigation of effort allocation gives us insight about heavily trawled areas and times, implementation of proper management plans could preclude the destruction of aquatic ecosystems.

# 2 A brief historical background on the Norwegian fishery

Throughout history, fishing has occupied an important place in Norwegian society, economy, and culture (Årland & Bjørndal, 2002; Armstrong et al., 2014; Eide et al., 2013; Holm, 2001). Owing to its geographical characteristics such as extensive coastlines and large areas of marine and coastal waters, Norway is extremely well suited for fishing.

The NEA cod stock is the most economically important species in the Barents Sea (Armstrong et al., 2014; Eide et al., 2013; ICES, 2012). Along with cod, other commercially important species such as saithe and haddock are abundant and available for fishers in Norwegian waters (Birkenbach et al., 2020; Cojocaru et al., 2019; Eide et al., 2013; Guttormsen & Roll, 2011).

The history of commercial cod fisheries along the north Norwegian coast, and the international trade of this community dates back more than a thousand years (Årland & Bjørndal, 2002; Eide et al., 2013; Hallenstvedt, 1982; Solhaug, 1976). For thousands of years, codfish has been an important source of food, playing an important role in shaping livelihoods and settlements, particularly along the western coast of Norway (Hallenstvedt, 1982; Solhaug, 1976).

Besides food provision and survival purposes, codfish fisheries have created a foundation for commerce, employment, and money generation in coastal communities (Årland & Bjørndal, 2002; Hannesson et al., 2010; Maurstad, 2000; Solhaug, 1976). For example, for centuries Hanseatic merchants in Bergen, the largest city in Norway at that time, traded dried and unsalted cod from northern Norway with grains from merchants from other parts of Europe, in particular southern Europe (Solhaug, 1976). This has reinforced commercialization of the Norwegian cod fishery and international trade (Hallenstvedt, 1982; Hannesson et al., 2010; Solhaug, 1976). In other words, cod fisheries in northern Norway have benefited the economy of southern Norway, and have contributed to wealth distribution throughout the country (Drivenes et al., 1994; Holm, 2001).

By the beginning of the 20th century, the export of cod fish had increased considerably and constituted a large part of the foreign trade (Hallenstvedt, 1982). Today, most of the harvested cod is exported in several different product forms such as dried, salted, salted and dried, whole, and fillets (fresh and frozen). Southern Europe, and especially Portugal, is still an important market for Norwegian cod. The Norwegian fish market has extended to all the continents (Asche, Flaaten, et al., 2002; Asche, Gordon, et al., 2002; Gordon & Hannesson, 1996; Nielsen et al., 2009).

# 3 General description of the codfish fishery

NEA cod is a seasonally migratory fish species (Godø & Michalsen, 2000; Olsen et al., 2010). It feeds in the high sea areas of the Barents Sea as well as the eastern part of the Barents Sea and waters around Svalbard and Bear Island. NEA cod is abundant in sub-Arctic areas and is by far the most commercially valuable species of the Barents Sea (Armstrong et al., 2014; Holm, 2001). It is reported that NEA cod stock lies within safe biological limits (Armstrong et al., 2014).

Annually, the NEA cod stock undertakes spawning migration further south to spawn in the shallow waters along the north-west coast of Norway during winter from January to April (Garrod, 1967; Godø & Michalsen, 2000; Neuenfeldt et al., 2013; Olsen et al., 2010). The spawning cod stock remains in the coastal areas until around April–May (Olsen et al., 2010; Rose, 1993). The migration direction from the feeding areas of the Arctic to the spawning areas off the north-west coast of Norway is shown in Figure 1.

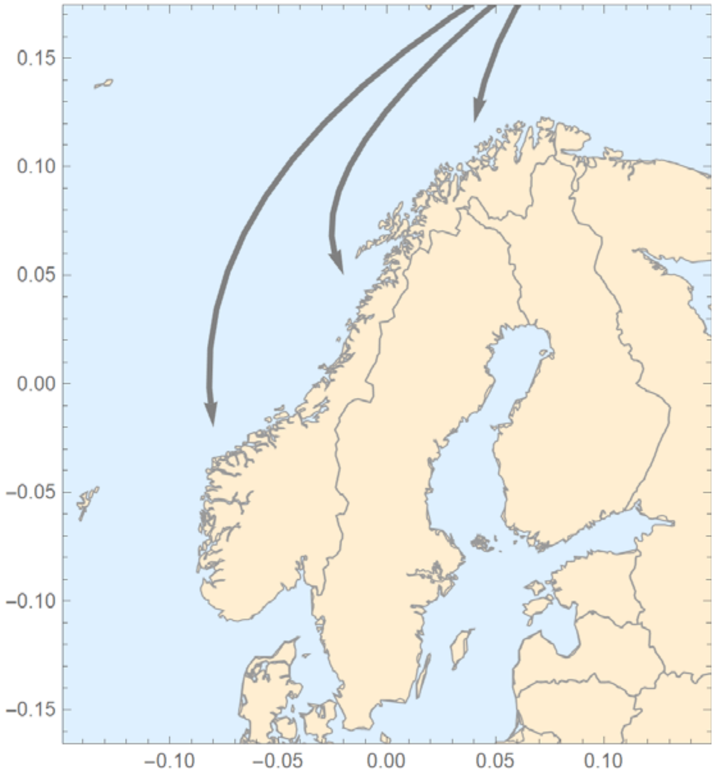

Figure 1. Map of the migration routes of NEA cod from feeding areas of the Arctic to the spawning grounds along the north-west coast of Norway

As can be seen from the map in Figure 1, the amplitude of migration patterns can vary considerably. The amplitude of NEA cod migration is influenced by the age and size of the fish. Larger NEA cod have more energy to swim greater distances to reach spawning grounds relative to that of younger fish (Nakken, 1994; Sundby & Nakken, 2008).

Unlike NEA cod, coastal cod spend their entire life span, including feeding and breeding, in the fjords and coastal areas of Norway. Hence, coastal cod is available to fishers throughout the year along most of the Norwegian coast (Hannesson et al., 2010; Jakobsen, 1987).

During wintertime and the spawning season, cod availability and catchability increase in areas along the north-west coast of Norway (Godø & Michalsen, 2000). This gives rise to the winter fishery known as the Lofoten fishery (Hannesson et al., 2010; Hermansen & Dreyer, 2010). The Lofoten fishery is seasonal, based on the migration of NEA cod at the beginning of the year (Hannesson et al., 2010; Hermansen & Dreyer, 2010). After spawning, cod swim back to the sub-Arctic areas to feed (Bergstad et al., 1987; Trout, 1957), which gives rise to the fishery in the Barents Sea and around Svalbard.

Similar to NEA cod, saithe, and haddock are migratory species. They aggregate to spawn in wintertime, with a peak in February (saithe) and March–June (haddock) (Olsen et al., 2010; Pethon, 2005). Saithe spawning takes place from the coastal banks of the Lofoten Islands and south to the North Sea. After winter spawning, young saithe are carried northwards by the ocean currents. Hence, saithe larvae are available in the north-east part of the Norwegian economic zone as late as August (Pethon, 2005). Adult saithe exhibit recurring migrations between spawning and feeding areas (Jones & Jónsson 1971; Olsen et al., 2010). Despite being a commercially valuable species, the migration pattern of saithe is poorly studied (Homrum et al., 2013).

The migration and spawning pattern of haddock is more similar to that of NEA cod. Haddock aggregate along the slope between the continental shelf and the Norwegian Sea during winter to spawn. Similar to NEA cod, haddock swim northwards to the Barents Sea to feed after spawning in the winter months (Bergstad et al., 1987; Olsen et al., 2010).

# 4 Participant fleets in the Norwegian codfish fishery

## 4.1 Coastal fleet

Historically and traditionally, fishers with small boats and conventional gears such as handlines, longlines and gillnets participate heavily in the Lofoten fishery (Hannesson et al., 2010; Holm, 2001; Maurstad, 2000). Since small commercial boats are constrained in relation to moving offshore, aggregation of NEA cod along the west coast of northern Norway provides an important opportunity for employment and revenue generation for the coastal fishers (Årland & Bjørndal, 2002; Holm, 2001; Maurstad, 2000).

The Norwegian fisheries management has allocated 65–80% of the codfish quota to coastal vessels (Asche et al., 2014; Hersoug, 2005; Holm & Rånes, 1996; Standal & Hersoug, 2015). Hence, during a short period of the winter, a large amount of fish, in particular cod, is landed (Birkenbach et al., 2020; Hermansen & Dreyer, 2010; Holm et al., 2000).

Figure 2 depicts weekly cod landings by the coastal fleet in thousand tons over 2011–2016. As shown in Figure 2, landings of cod by the coastal fleet are concentrated during the winter months when NEA cod congregates along the west coast of northern Norway to spawn. This implies that the coastal fleet rigidly follows the cyclical pattern of spawning migration of cod.

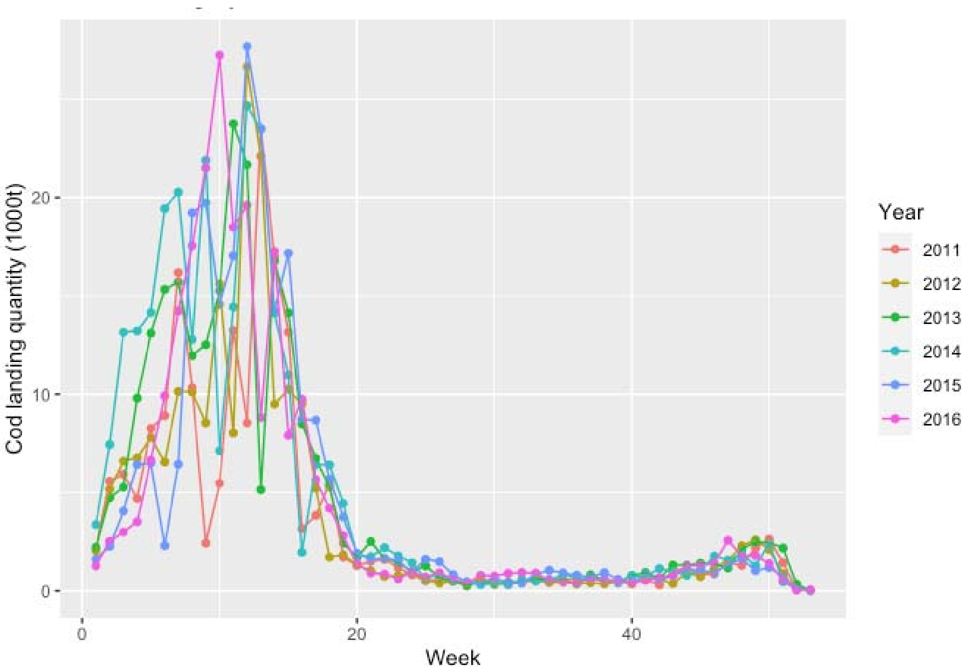

Figure 2. Weekly total landings of cod in thousand tons, caught by coastal vessels during 2011–2016. Source: The Norwegian Directorate of Fisheries

The lack of a processing deck and limited capacity of the small boats necessitate taking shorter fishing trips (i.e., daily basis) in comparison to the fishing trip duration of large industrial vessels. Therefore, coastal fishers mainly land fresh codfish.

## 4.2 Bottom trawling

The bottom-trawl fleet consists of large ocean-going ships that are able to cover vast and distant areas of ocean to target multiple fish stocks (Birkenbach et al., 2020; Guttormsen & Roll, 2011).

Prior to the advent of trawl technology, codfish fisheries (cod, saithe, and haddock) were operated solely by the coastal fleet along the west coast of Norway (Hersoug, 2005; Holm, 2001). After industrialization, particularly in the second half of the 20th century, technological improvement in fishing gears and the rapid growth of fishing power led to the appearance of English trawl vessels in the Barents Sea to utilize NEA cod and haddock for the first time in 1903 (Christensen & Nielssen, 1996; Grekov & Pavlenko, 2011; Popov & Zeller, 2019).

However, despite the availability of new technologies, there was limited Norwegian trawl fishery development. There are three possible reasons behind this. The first obvious reason is that it was still possible for Norwegian fishers to catch cod using other conventional gears such as longlines and gill nets. The second reason is insufficient financial capital to invest in new trawl vessels and required equipment (Grekov & Pavlenko, 2011). The third reason is that the authorities were critical of trawl fishing as it can adversely affect coastal fishers' catch and revenue in an open access fishery (Eide et al., 2013; Holm, 2001). Indeed, in the presence of trawl fisheries in Norwegian waters during both the Lofoten and offshore fisheries, coastal fishers saw themselves as losers because trawl vessels had better production possibilities. In essence, small boats were left with smaller catch sizes and revenues under an open access fishery. Both coastal and trawl fishers already had interest in the cod stock, and competing interests would naturally be seen as in opposition. There was also apprehension among coastal fishers that trawlers destroyed fish habitats and disturbed the fish (Hersoug, 2005; Johansen, 1972). As a result, the Trawler Acts of 1936 and 1939 were introduced to limit the operation of the trawl fleet (Eide et al., 2013; Holm, 2001). Thus, initially the cod stock was harvested along the coast of Norway and little or no offshore cod fishery was conducted in the Barents Sea by Norwegian fishers.

However, economic growth, particularly after the great depression during the 1930s, contributed to the development of the Norwegian offshore fishery in the Barents Sea, mainly operated by trawlers. In 1939, licensed trawlers became active in the Norwegian fisheries (Hersoug, 2005; Johansen, 1972; Standal & Hersoug, 2015). The development of a trawl fishery to target NEA cod and haddock in the Barents Sea continued after a period of limited fishing activity during World War II (1940–1945) (Nakken, 1994; Standal & Hersoug, 2015).

The technological developments in designing Norwegian trawl vessels enabled trawlers to cover vast areas; from south in the North Sea to the north-west coast of Norway to participate in the Lofoten fishery, and extending into Arctic regions to target NEA cod and haddock. Powerful engines together with advanced technical characteristics make trawl vessels less susceptible to the harsh climatic conditions of the Arctic (Flaaten & Heen, 2004; Standal & Hersoug, 2015). This means that, unlike coastal fishers that rigidly follow the spawning aggregation of NEA cod and largely operate in the Lofoten fishery, the advanced technology of large industrial vessels dilutes the seasonality of the Lofoten fishery. Hence, large industrial vessels have the opportunity to spread landings over the course of a year to take advantage of fluctuations in market price and availability of cod fish—unlike coastal boats.

The current trawl fleet is equipped with onboard freezing facilities, and trawlers primarily deliver frozen products (Flaaten & Heen, 2004; Standal & Hersoug, 2015). The availability of modern freezing facilities over the last couple of decades has, to some extent, resolved the problem of perishability of fish. Hence, trawlers can take longer trips relative to coastal boats. Furthermore, supplying frozen cod provides an additional advantage for trawlers in the marketplace as they are not obliged to sell the fish immediately, unlike coastal boats that land fresh cod (Gordon & Hannesson, 1996).

### 4.2.1 Gear specifications of bottom trawling

Bottom trawling is classified as a fishing practice involving active/mobile gear where marine organisms are swept up from the seabed or get entangled in the net when the gear is dragged over the seafloor (Gabriel et al., 2005). A bottom trawl employs funnel-shaped nets, consisting of a belly, codend, trawl doors/boards, and ground gear (see Figures 3 and 4). The mouth of the net is held open vertically during towing by the use of trawl doors/boards and trawl floats to chase fish (Gabriel et al., 2005). Depending on the habitat and target species, the towing speed is adjusted along the seabed (Gabriel et al., 2005).

In the Norwegian trawl fishery, due to the availability of strong engine power and modern technology, double-rig trawling is also used. Double-trawl gear involves two trawl nets connected together so that they can be dragged side by side across the surface of the seabed from the same boat (see Figure 4).

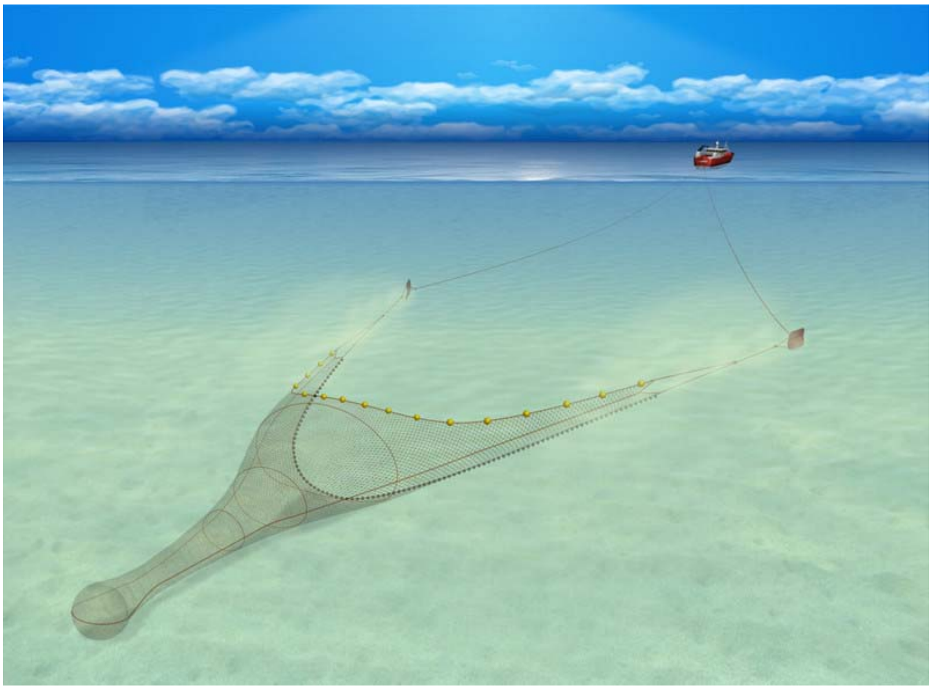

Figure 3. Single net bottom trawl. Source: https://www.seafish.org/

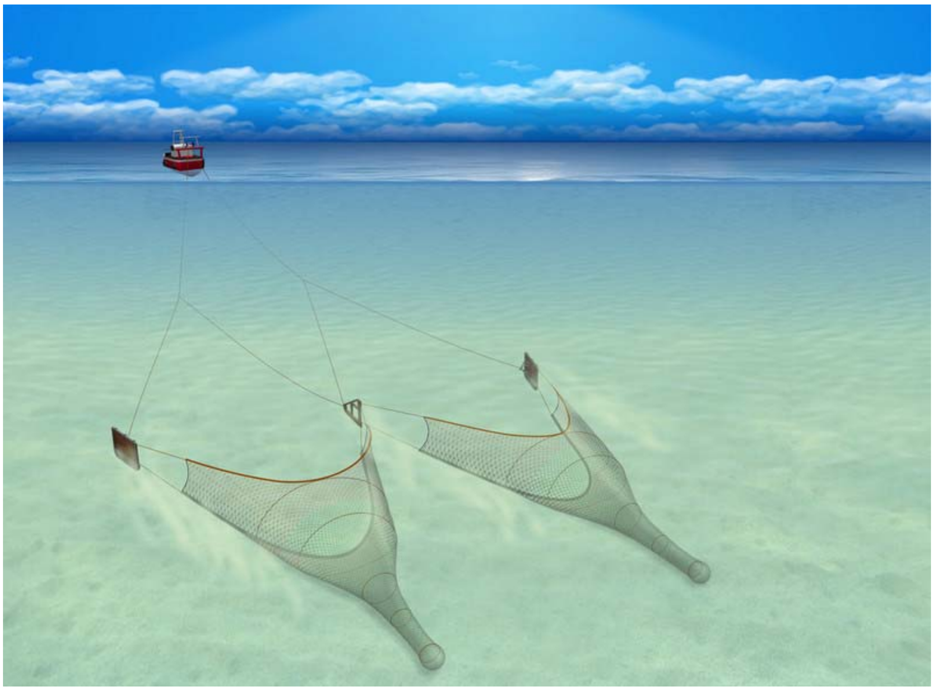

Figure 4. Double net bottom trawl. Source: https://www.seafish.org/

Trawlers constantly monitor the seabed to avoid rocky surfaces to protect the gear against abrasion by the uneven sea bottom (Jørgensen et al., 2016). In addition, ground gear is placed under the trawl net to facilitate movement across rough seabed terrain and at the same time to protect the fishing line and netting from damage (Larsen et al., 2018). Furthermore, to lessen the potential environmental damage due to the physical and direct contact of heavy nets with the seafloor, trawlers seek to circumvent sponge areas and oyster beds. Based on Norwegian fisheries regulations, bottom trawling is prohibited within 12 nautical miles off the coast (Hersoug, 2005).

A number of gear modifications have contributed to reduce the bycatch of trawling such as a minimum mesh size in the codend and placement of larger meshes in the belly of the net so that non-target species can escape from the net as they move across the belly meshes of the net (Gabriel et al., 2005; Stergiou et al., 1997). Despite all these modifications, the removal of some non-target species is unavoidable in trawl fisheries when the net is towed across the sea (Gabriel et al., 2005; Stergiou et al., 1997).

### 4.2.2 Industry characteristics of the trawl fleet

Even though the coastal fleet has been the backbone of Norwegian codfish fisheries in terms of socioeconomic considerations, especially along the north-west coast of Norway (Armstrong et al., 2014; Holm, 2001; Maurstad, 2000), after World War II Norwegian politicians highlighted the fact that the coastal fleet is largely confined within the short season of the Lofoten fishery (Hersoug & Leonardsen, 1979; Standal & Hersoug, 2015) (see also Figure 2).

As discussed earlier, coastal boats are smaller in size and have less powerful engines in comparison to trawl vessels. This limits coastal fishers in allocation of fishing effort over time and space. The limited fishing activities of coastal boats means that they cannot provide a stable supply of codfish over the course of a year, thus reliance on the coastal fleet limits Norwegian fisheries' potential for mass production and industrialization (Dreyer et al., 2006; Hersoug & Leonardsen, 1979; Holm, 2001; Standal & Hersoug, 2015).

Norwegian politicians have highlighted the role of the trawl fishery in 1) building a modern and sustainable consumer market for codfish, where consumers are willing to pay higher prices for better quality products, and 2) to turn the entire supply value chain into a year-round industry to provide a steady supply to cover the demand from consumers, primarily in Europe and in the United States of America (USA) and 3) economic efficiency considerations (Årland & Bjørndal, 2002; Asche, Gordon, et al., 2002; Gordon & Hannesson, 1996; Hersoug & Leonardsen, 1979; Isaksen, 2007).

Stability in the supply of fish not only requires regular fish landings over the course of a fishing year but also demands the year-round operation of processing plants. One way that processing plants could secure a stable supply of raw fish is to get control over fish exploitation and landings. In order to achieve this goal, the owners of processing plants need to buy into fishing vessels. In this way, the owner of a processing plant can decide how the catch should be spread over the course of a fishing year to better utilize the capacity of the processing plants while ensuring a stable supply of fish (Hersoug & Leonardsen, 1979; Isaksen, 2007).

Political support for the industrialization of Norwegian fisheries has gradually shifted the large part of the trawl industry into vertically integrated businesses, where different stages in the supply chain—from the supply of raw material (e.g., fish) to the processing of raw material and to release of final products into the market—are conducted by the same firm. Figure 5 shows the business model of the Norwegian trawl industry with integrated adjacent stages of the supply chain. The direction of the arrows indicates the flow of goods and/or services between successive stages of the supply chain.

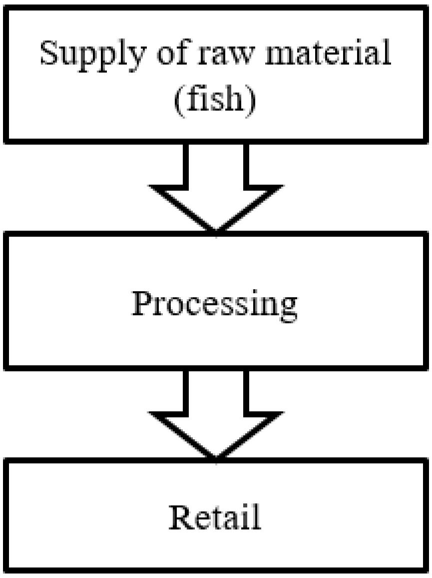

Figure 5. Schematic diagram of vertical integration of the trawl industry with successive stages of the supply chain

Vertical integration is thought of as a means to better cope with the competitive environment as the integration of different stages of the supply chain generates profound business advantages (Porter, 1980; Riordan, 1990). For example, the total cost of vertically integrated business is lower as inputs (e.g., fish) are provided by the same firm. Purchasing inputs for processing constitute a large part of the total production costs (Porter, 1980; Riordan, 1990). Moreover, lack of proprietary boundaries in different stages of the value chain facilitates information flow and reduces obstacles to obtaining new information about markets, which in turn increases administrative and operational efficiency. These characteristics again generate market power and lessen the risk exposure of the integrated business (Isaksen, 2007; Porter, 1980; Riordan, 1990).

# 5 Decision-making process underlying effort allocation of the trawl fleet

The decision-making process underlying the effort distribution reflects the adopted harvest strategy and fishing behavior that aim to achieve specific business objective(s) (e.g., minimizing risk, dis/investment, and/or maximizing profit) with respect to the constraint(s) (e.g., physical and non-physical capital such as quotas) (Béné, 1996; Béné & Tewfik, 2001; Christensen & Raakjær, 2006; Vestergaard et al., 2005). The selection of fishing location and harvest time, and the decision underlying what proportion of fishing quota to utilize in each haul as well as shifts in the targeted species, are components of fishing effort allocation that are governed by fishers' goals and/or constraints (Béné & Tewfik, 2001; Branch & Hilborn, 2008; Christensen & Raakjær, 2006; Opaluch & Bockstael, 1984).

Allocation of fishing effort in multi-species trawl fishery is a complex task as the decisions depend on a set of factors such as managerial, economic, environmental, and biological considerations, and their complex interactions (Asche et al., 2015; Birkenbach et al., 2020; Smith, 2012).

It is conventionally assumed that commercial fishers take into account the expected profit when they make their choices about the location and time of harvest as well as target species (Gordon, 1953, 1954). However, in reality it is not straightforward to optimally and rationally allocate fishing effort across various species and different locations as fishers need to simultaneously identify changes in biological, economic, and environmental conditions as well as their complex interactions. This difficulty could result in deviation from making rational choices regarding effort allocation. Aberration from rationality in allocation of fishing effort has been identified in several fisheries articles (Jacobson & Thomson, 1993; Lane, 1988; Opaluch & Bockstael, 1984; Smith & Hanna, 1993; Wilen et al., 2002).

The patterns of fishing effort allocation are influenced by fish movement and seasonality in fish abundance as well as by managerial rules such as quota constraints. As mentioned earlier, cod, saithe, and haddock are migratory species and perform a vast migration over a wide area. In this thesis, our focus is on how seasonality patterns of fish availability and quota regulations influence the adopted harvest strategy and allocation of fishing effort.

Fishing involves a high degree of uncertainty. Fish move across space constantly with unpredictable patterns. The constantly changing marine environment, abrupt oceanographic changes (e.g., sea temperature and food availability), fluctuation in market conditions and changes in regulatory schemes can add more complexity to the decisions underlying effort allocation (Asche et al., 2015; Birkenbach et al., 2020; Eales & Wilen, 1986; Holland & Sutinen, 1999; Smith, 2012).

Additionally, species in the quota portfolio differ in habitat requirements and may differ in their congregational and/or dispersion behavior across different fishing grounds over the course of the year. Population dynamics affect the economic considerations (e.g., relative market price and cost of operation), and the magnitude of the economic effects might be different from one species to another (Asche et al., 2015; Birkenbach et al., 2020).

Besides variation in the relative abundance of fish stocks and species composition, fishing locations are heterogeneous in their availability of other fleet groups, weather conditions, and proximity to the shore (Eales & Wilen, 1986; Holland & Sutinen, 1999, 2000).

For instance, NEA cod moves across a sub-Arctic area where it feeds after the winter months and the north-west coast of Norway where it spawns during wintertime. Fishing cod in the sub-Artic area is associated with higher transportation cost due to the longer traveling distance as well as the higher cost per unit of fishing as cod is less congregated in this period (Bergstad et al., 1987; Trout, 1957). Less desirable climatic conditions in the Barents Sea, in particular in wintertime, can also increase the risk of fishing operation. However, the market price of cod is higher out of the winter months as coastal fishers have already fished their cod quota, and landings of cod are smaller (Hermansen & Dreyer, 2010).

In contrast, less transportation cost is ascribed to cod fishing during Lofoten fishery, because of proximity to the shore and a lower cost per unit of fishing effort due to the congregated cod stock (Hannesson, 2007b; Kvamsdal, 2016; Sandberg, 2006). Reduced cost motivates fishers including trawlers and coastal fishers to utilize the cod quota. 65-80% of the Total Allowable Catch (TAC) of cod is allocated to the coastal fleet (Asche et al., 2014; Hersoug, 2005; Holm & Rånes, 1996; Standal & Hersoug, 2015). The limited geographical mobility of the coastal fleet encourages them to fish the cod quota. As a result of large landings of cod, the price of cod declines (Hermansen & Dreyer, 2010).

At this time, a complication arises for the trawl fleet in terms of effort allocation as reduced cost is an encouraging factor to fish cod, while reduced price is a demotivating factor. If the magnitude of reduction in price is more than the reduction in cost during Lofoten fishery, then trawlers substitute cod fishery with other fisheries (e.g., saithe and haddock) available in their quota portfolio.

Another source of complication is related to catch quotas. The Norwegian trawl fishery is quota-regulated. The introduction of catch quotas has thrown up new challenges regarding the allocation of fishing effort. First of all, the Norwegian quota system only allows for the transfer of a small portion of the unused quota to the next year (Hersoug, 2005). This means that trawlers need to utilize the quota portfolio by the end of the fishing year to avoid underutilization of quota and economic loss. Moreover, under a quota-regulated fishery, fishers need to constantly match the catch size and remaining quota to benefit from the fluctuation in fish availability and prices, while avoiding over-quota or under-quota catches (Branch &

Hilborn, 2008; Copes, 1986; Squires et al., 1998). This means that fishers need to identify economically favorable conditions for fishing (e.g., high prices, low costs and dense stock) to utilize the quota—a task that can be notoriously difficult to implement optimally.

Empirical investigation of effort allocation reflects the characteristics of fleet dynamics and their impacts on exploited stocks (Anderson et al., 2019; Christensen & Raakjær, 2006; Vignaux, 1996). For instance, if heavy exploitation of a particular stock is detected at a specific time within a fishery year in certain areas, appropriate managerial regulations (e.g., season or area closure) can be undertaken for biological conservation. At the same time, knowledge of the spatial and temporal distribution of fishing effort contributes to a better understanding of fishers' potential responses to various changes in managerial, biological, and economic conditions (Eales & Wilen, 1986; Hilborn & Walters, 1992; Wilen et al., 2002).

Moreover, correct evaluations of temporal and spatial allocation of fishing effort across various species contribute to the economic prosperity of fishers, subsequently leading to an economically sustainable fishing industry (Christensen & Raakjær, 2006; Hilborn & Walters, 1992). Related to this, Eales and Wilen (1986), and Hart and Pitcher (1998) mention that the degree of accuracy of decisions underlying spatiotemporal allocation of fishing effort and shifts between the available alternatives with respect to the constraint(s) and the business objective(s) identify either a good or a bad fisher.

## 5.1 Empirical studies of effort allocation in the Norwegian cod fishery

Despite the importance of investigating effort allocation and the fact that codfish fishery has been under intensive investigation for almost a century, the empirical literature of effort allocation is yet inadequate (Birkenbach et al., 2020; Eide et al., 2003; Flaaten, 1987; Hannesson, 1983a).

Hannesson (1983a), Flaaten (1987) and Eide et al. (2003) estimated a variety of harvest functions for NEA cod with the Cobb–Douglas specification. Hannesson (1983a) and Flaaten (1987) emphasized the analysis of technical efficiency. Eide et al. (2003) concluded that the fishing effort in cod fishery is elastic, meaning that one unit increase in fishing effort increases the cod catch by more than one unit. These studies lack the spatial aspect of the effort allocation.

Birkenbach et al. (2020) studied profit-maximizing effort allocation in codfish fishery, caught by the trawl fleet. They concluded that fishing effort should be spread over the course of a year for cod, while for the less commercially important species (saithe in their study) effort should be congregated over a short period during winter.

With the above considerations in mind, in this dissertation we have undertaken empirical analysis of the spatiotemporal effort allocation of the codfish caught by the trawl fleet. As stated earlier, the migratory behavior of the fish and seasonality patterns in fish abundance together with quota regulations influence effort allocation. Hence, in the following sections we cover these two aspects of fisheries.

# 6 Seasonality: an important but neglected aspect of cod fishery

Due to the commercial, socioeconomic, and cultural importance of cod fishery, literature abounds on this study subject. A wide range of studies have investigated different aspects of cod fishery, including work on productivity and efficiency (Asche, 2009; Bjørndal & Gordon, 1993, 2000; Eide et al., 2003; Flaaten, 1983; Guttormsen & Roll, 2011; Hannesson, 1983a, 1983b, 2010; Kumbhakar et al., 2013; Salvanes & Squires, 1995), design of catch quotas (Hannesson & Steinshamn, 1991), cannibalism (Armstrong & Sumaila, 2001; Wikan & Eide, 2004), age-differentiated and multi-cohort management (Diekert et al., 2010a, 2010b), multi-species aspects (Asche et al., 2015; Birkenbach et al., 2020), effects of climate change (Eide, 2007; Hannesson, 2006), resource rent (Asche et al., 2009), gear selectivity (Brinkhof et al., 2018; Diekert et al., 2010a, 2010b; Graham et al., 2007), market and price analysis (Asche, Flaaten, et al., 2002; Asche, Gordon, et al., 2002; Asche et al., 2007; Gordon & Hannesson, 1996; Nielsen et al., 2009), the effect on stock of spawning aggregation (Hannesson, 2007b; Kvamsdal, 2016; Sandberg, 2006), allocation of fishing effort (Birkenbach et al., 2020; Flaaten, 1987; Hannesson, 1983a), the history of technological transformations (Standal & Hersoug, 2015), controversial issues regarding oil exploration and petroleum activities in codfish spawning areas (Misund & Olsen, 2013), managerial negotiations about Norway–Russia cooperation in cod fishery (Armstrong & Flaaten, 1991; Eide et al., 2013; Hammer & Hoel, 2012; Hannesson, 1997, 2006; Stokke et al., 1999; Sumaila, 1997) and co-management advocates in Lofoten fishery (Holm et al., 2000).

Even though fisheries scientists recognized the seasonal aggregation of NEA cod along the north-west coast of Norway a long time ago, little attention has been paid to the seasonality phenomenon from an economic point of view, or its impacts on fishers' decision-making process underlying spatiotemporal effort allocation and quota utilization. What we mean by seasonality is the systematic variation in fish density between and within various geographical locations throughout the year.

For the most part, the existing literature on the seasonality of cod fish investigates this phenomenon from a biological perspective, for example, how seasonal migration affects the physiological features of cod (Johannesen et al., 2015; Mello & Rose, 2005; Neuenfeldt et al., 2013; Schwalme & Chouinard, 1999).

A handful of applied studies have been carried out, analyzing the effect of seasonal spawning migration of NEA cod from an economic perspective. Eide et al. (2003) confirmed the presence of seasonality in cod fishery through estimation of a harvest function using data from the time that the Norwegian cod fishery was still open access. Thus, the possible effect of quota regulation could not be analyzed. Moreover, a lack of vessel monitoring systems (VMSs), to gather the data on geospatial positions at the time of the study, has confined this study to include the spatial dimension of effort allocation.

Recently, Birkenbach et al. (2020) have investigated temporal effort allocation in codfish fishery, caught by the trawl fleet. Even though this study uses data from the time that codfish fishery has become quota-regulated, it lacks the consideration of quota regulations. Moreover, this study does not consider the spatial dimension of effort allocation.

Indeed, spatiality and temporality are interlinked as fish movements over the year influence the relative attractiveness of different fishing areas. This being said, consideration of spatiality is of critical relevance to the decisions underlying effort allocation, in particular for migratory species as in the case of cod, saithe, and haddock fisheries. Migration and constant movement across specific locations influence species distributions, which in turn affect the catch composition, quota utilization, and relative profitability of different fishing locations (Asche et al., 2015; Eales & Wilen, 1986; Hermansen & Dreyer, 2010). Moreover, migration patterns shape locational heterogeneity. This means that different fishing regions are characterized by different biological (e.g., fish abundance) and economic (e.g., cost of fishing operation and price) features over the course of a year, and fishers need to identify the costs and benefits associated with these features to optimally allocate effort (Asche et al., 2015; Flaaten, 1983; Hannesson, 2007b; Sundby & Nakken, 2008).

## 6.1 Measurement of seasonality patterns of fish stock

Fish move constantly across space, hence the abundance and distribution of fish continually vary. This shapes seasonal patterns in fish abundance. For many fish populations, obtaining abundance and distribution information is a complex and costly task to evaluate changes in fish stocks (Campbell, 2004; Hilborn & Walters, 1992). In the absence of information of fish abundance, fisheries scientists use commercial data such as catch and effort records from fisheries to assess stock abundance (Hilborn & Walters, 1992; Myers & Worm, 2003). This is a reasonable way to assess stock abundance as fish exploitation patterns can give insight about relative fish availability (Campbell, 2004). The relationship between stock abundance and commercial catch and effort data is captured by Schaefer's (1954) harvest function. Schaefer (1954) introduced a standard harvest equation (H) in linear form, consisting of two input factors, namely fishing effort (E) and fish availability (B):

$$H(t) = q\,E(t)B(t) \tag{1}$$

This equation specifies that total catch at time $t$ depends on both the level of fishing effort and the average stock or biomass at any point in time. Assume that catch size and stock abundance are measured in tons and let fishing hours per haul be the measurement of fishing effort. The parameter $q$ is a positive constant, known as the catchability coefficient, which indicates the efficiency of the technology that is used to harvest fish (Hilborn & Walters, 1992; Maunder et al., 2006).

The positive first derivatives with respect to the fishing effort and stock size imply that as effort and stock size increase so does the catch size. Moreover, under this specification, output elasticities in stock and effort are unitary, meaning that the production technology is increasing returns to scale and its quantity is equal to 2.

We re-cast Equation (1) to obtain the total harvest per number of fishing hours as a measurement of fishing effort. This will yield catch per unit of effort (CPUE):

$$CPUE(t) = H(t)/E(t) = q\ B(t) \tag{2}$$

The value of CPUE represents the total amount of harvested fish in tons per hour of trawling. As seen in Equation (2), CPUE is proportional to the average level of the fish stock at time $t$, having the catchability coefficient $q$, the factor of proportionality. Hence, CPUE can be used as an index of population abundance, which reflects seasonal aggregation and/or dispersion of fish stock at a particular point in time in a certain region. Higher values of CPUE reflect the availability of denser fish stock and vice versa (Hilborn & Walters, 1992; Maunder et al., 2006; Myers & Worm, 2003).

In fisheries, where independent measurements of stock abundance are lacking due to the difficulty of stock assessment, CPUE is a commonly employed index to provide an estimate of the average stock size, as data on total harvest and measures of the level of effort are more readily available to the researchers (Maunder et al., 2006; Myers & Worm 2003).

Besides the seasonality implication of CPUE, from an economic point of view, CPUE reflects the productivity of fishing activity. Higher values of CPUE imply that the harvest level has enhanced without any additional increase in fishing effort and operation cost (Cooke & Beddington, 1984; Cunningham & Whitmarsh, 1980; Hanchet et al., 2005).

## 6.2 Seasonality patterns of the codfish fishery

The radar plot in Figure 6 depicts the average monthly variation in CPUE of cod, saithe, and haddock during 2011–2016 in Norwegian waters, including the west coast of Norway and the Barents Sea. For this purpose, we obtained CPUE values from Equation (2), where the monthly total catch of 61 trawl vessels, measured in tons, is divided by the corresponding effort measured in trawling hours. The monthly values of CPUE are represented on the radial axis, ranging from 0 to 8 tons per hour of trawling (i.e., 8: most dense fish stock, 0: least dense fish stock). The months are assigned to the outer axis in a clockwise direction. It should be noted that the amount of bycatch of other species is considered in the calculation of total catch and CPUE for each fishery.

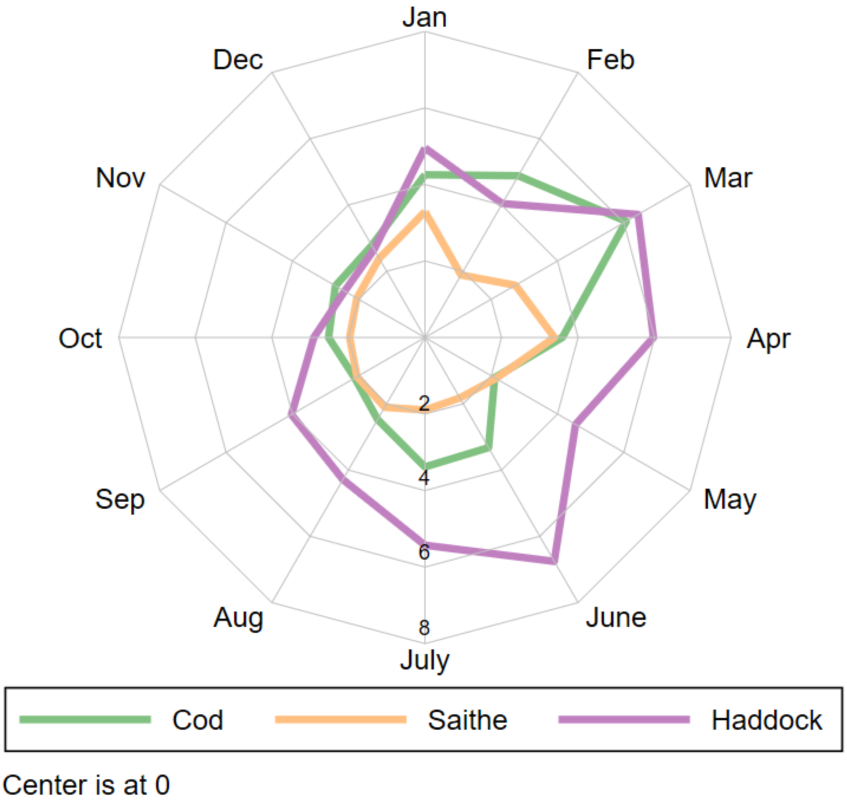

Figure 6. Variation in monthly average CPUE, measured in tons per hour for cod, saithe, and haddock fisheries based on the fishing activities of 61 registered trawl vessels in Norwegian waters including the west coast and the Barents Sea. Source: The Norwegian Directorate of Fisheries 2011–2016

From Figure 6, we see that the values of CPUE vary within and between the selected fish stocks over the course of a fishing year. The temporal variations in cod and haddock abundance follow similar patterns, with the first peak in March. The second peaks for these fisheries occur in the summer season, in July and June, respectively. Another resemblance between the temporal variations of cod and haddock is that after summer, the CPUE of these fisheries declines as time elapses towards the end of the year.

The temporal variation of saithe fishery shows a different pattern, with its peaks in January and April. If we put these two months aside, the CPUE values of saithe are almost steady and remain around 2 tons per hour of trawling.

The high values of CPUE in the three fisheries during the winter months are primarily due to spawning aggregation along the west coast of northern Norway. The congregated stock requires less fishing effort (Hannesson, 2007b; Kvamsdal, 2016; Sandberg, 2006), resulting in increased CPUE (see Equation 2). After the winter months, cod and haddock swim dispersedly northwards to feed in the Barents Sea. At this time of the year, the Arctic weather is more suitable (e.g., ice-free sea and less windchill) (Årthun et al., 2012; Kvingedal, 2005). Hence, the high values of CPUE for cod and haddock fisheries in the summer are ascribed to fishing in Arctic areas.

# 7 Overview of managerial changes in Norwegian fisheries management

The current form of Norwegian fisheries management has evolved over the past century, often in response to some crisis in marine resources (Årland & Bjørndal, 2002; Hersoug, 2005). The imposed regulations and regulatory reforms are based on research and scientific advice from the Directorate of Fisheries and the Institute of Marine Research, both established in 1900 (Årland & Bjørndal, 2002). Since most of the commercially important species such as cod are shared between Norway and other countries, Russia being the most important, the Norwegian authorities are in close cooperation with other neighboring countries (Årland & Bjørndal, 2002; ICES, 2012).

The current fisheries management regime is diverse and constitutes of a mixture of regulatory instruments including the setting of annual Total Allowable Catch (TAC) quotas and licensing requirements. Today, almost all commercially valuable species are regulated through TAC and licensing (Årland & Bjørndal, 2002).

The aim of the managerial regulations is to 1) boost the profitability of the fishery industry and avoid rent dissipation, 2) conserve marine organisms, 3) secure and maintain employment opportunities and 4) sustain settlement along the coast (Flaaten & Heen, 2004; Guttormsen & Roll, 2011; Salvanes & Squires, 1995). The first two objectives emphasize maximum resource rent and a biologically sustainable fisheries sector. The latter two goals of Norwegian fisheries management are closely connected as employment opportunities are prerequisite to sustain the livelihood of fishing communities along the coast.

Throughout history, there have been many shifts and reformations in regulations governing marine resources, the most profound of which was the transformation from pure open access fishery to regulated open access, and eventually to rights-based fishery (Årland & Bjørndal, 2002; Hersoug, 2005). These management schemes are ascribed varying degrees of harvesting property rights. Figure 7 shows the evolution of Norwegian fisheries management and the corresponding exclusiveness in harvest rights. Pure open access fishery and rights-based fishery lie at the two ends of the spectrum. In pure open access fishery, fish is communal property, whereas in rights-based management only fishers with allocated quotas have the right to fish. We will discuss this evolutionary process in detail in the following sub-sections.

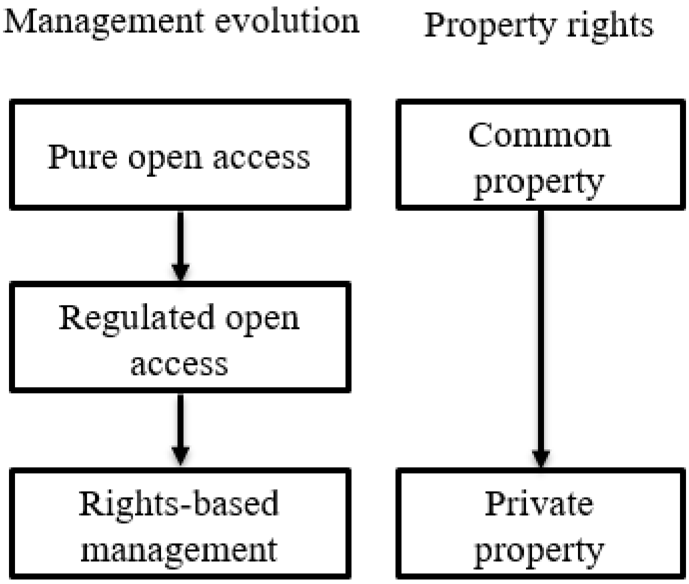

Figure 7. Evolution of Norwegian fisheries management

## 7.1 Pure open access and regulated open access fisheries

Initially, the Norwegian fishery was purely open access (Årland & Bjørndal, 2002; Johnsen & Jentoft, 2017): there were no managerial constraints imposed on fishery, hence harvesters had equal and free access to exploit fish stocks (Anderson et al., 2019; Hersoug, 2005). Pure open access fisheries are often characterized by biological overexploitation and dissipation of potential economic rent (Gordon, 1954). There is a surplus of fish, and this encourages too many fishers to maximize their profit by exploiting as much marine resources as they can (i.e., as long as unit revenue minus unit cost is positive) because if he/she does not, somebody else will (Anderson et al., 2019; Copes, 1986). Under this circumstance, increasing allocation of fishing effort to race for fish is unavoidable, resulting in overfishing and reduced profitability (Anderson et al., 2019; Hersoug, 2005).

However, during early periods, the negative impacts were not very considerable due to the lack of technology to extract resources. Advances in fishing technology (e.g., large and decked boats, the advent of power blocks and modern fish-finding equipment such as sonar and navigational aids, and so forth) have increased fishing capacity which, in turn, has indelibly exacerbated the competition among fishers under open access fisheries (Bjørndal & Gordon, 2000; Hannesson, 2007a).

As fish stocks become more scarce, pure open access institutions transit to regulated open access, where access to a resource is still open (i.e., no exclusive fishing rights), but managerial regulations are also in place to implement and enforce regulations on fishers to avoid biological overexploitation (Anderson et al., 2019; Hersoug, 2005).

The Norwegian cod fishery is a good example of a fishery that operated under regulated open access institutions. Prior to 1980s when the mortality of cod was increased, there was no comprehensive and coherent management scheme in the Norwegian fisheries (Årland & Bjørndal, 2002; Johnsen & Jentoft, 2017; Mikalsen & Jentoft, 2003), although some regulatory tools were available, long before the collapse of cod. For example, the Limited Entry Act was enacted in 1972 as a capacity reduction tool (Hersoug, 2005; Johnsen & Jentoft, 2017). Another management tool is TAC, known as total quota. TAC is determined on an annual basis for each fish stock for the coming year. To avoid overfishing, the total catches should not exceed the agreed TAC.

The increased mortality of cod was attributed to the feeding of young herring (*Clupea harengus*) on capelin (*Mallotus villosus*) larvae (Hamre, 2003). The Norwegian herring fishery collapsed in the 1960s (Lorentzen & Hannesson, 2004). One of the consequence of the collapse of the herring was that fishers switched to capelin fishery (Lorentzen & Hannesson, 2004). Herring fishery eventually recovered in the 1980s (Lorentzen & Hannesson, 2004). Overfishing of capelin together with predation by herring eventually led to the collapse of capelin fishery (Hamre, 1985, 2003).

The reduction in capelin biomass affected cod stock as a capelin predator. A lack or inadequacy of capelin has resulted in cannibalism in the cod stock (Hamre, 1985, 2003). Moreover, the growth rate of the cod stock has declined and the maturation process has experienced a delay (Hamre, 1985, 2003).

In 1989, a moratorium was imposed on the coastal fleet and fishing was prohibited from April until the end of the year (Årland & Bjørndal, 2002; Maurstad, 2000). Relatedly, the TAC of cod was reduced considerably by the fisheries authorities. The consequence of the daunting crisis was a reduction in the landings of cod from over 340,000 tons in 1981 to 125,000 tons in 1990 due to overfishing of cod. Figure 8 shows the immediate and short-term impacts of this situation on cod fishery.

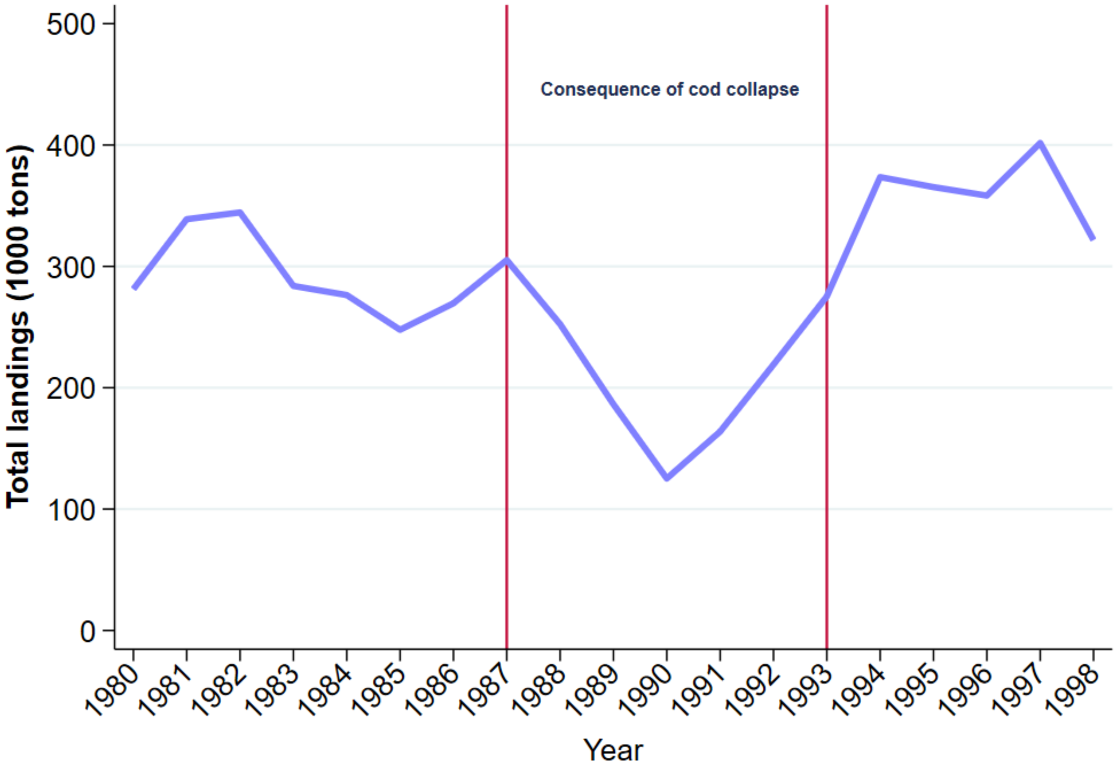

Figure 8. Annual landings of cod in thousand tons during 1980–1997. Source: The Norwegian Directorate of Fisheries

Vanishing cod and subsequent degradation of Lofoten fishery have brought severe environmental and socioeconomic consequences to Norwegian society. The negative impacts of increased mortality of cod were market failure, low profitability, maldistribution of capital and resources (i.e., existence of excess capacity), and decreasing quantity and quality of landed cod (Årland & Bjørndal, 2002; Gullestad et al., 2014; Hersoug, 2005; Holm, 2001; Maurstad, 2000). This has threatened income sources, employment opportunities, and overall the settlement of coastal communities and indigenous groups (Armstrong et al., 2014; Holm, 2001; Maurstad, 2000). Due to the inadequacy of regulations and poor definition of harvesting property rights, overfishing and rent dissipation persisted under regulated open access (Hersoug, 2005). Thus, Norwegian authorities have advocated the need for further regulations and stringent management regimes to prevent overexploitation, and to replenish the threatened stocks.

## 7.2 Rights-based fishery and the introduction of individual vessel quotas (IVQs)

In order to resolve the existing problem in Norwegian fisheries, IVQs were introduced. IVQs grant fishers the right to fish a certain proportion of the TAC from a commercial fish stock (Årland & Bjørndal, 2002; Gullestad et al., 2014; Holm, 2001). IVQs are essentially one form of output control, which circumscribe the catch size that every active fisher can harvest to prevent fish stocks from being overfished (Johnsen & Jentoft, 2017).

Traditionally, fisheries management has almost always implemented regulations with the purpose of preventing biological overexploitation and ignored regulatory rules that can trigger the economic motivations of fishers (Reimer & Wilen, 2013; Wilen et al., 2002).

A secured share of catch corrects fishers' incentives and ceases the race to fish. In other words, this prevents capital-stuffing and provides fishers with incentives to operate at the least cost by choosing the minimum levels of fixed and variable inputs that maximize returns per unit of quota (Copes, 1986; Nøstbakken et al., 2011; Squires et al., 1998). Another economic advantage of the introduction of quotas is that it allows fishers to take their time, and spread fishing effort optimally and catch better quality products across the entire fishing year to increase the value of the landed products and revenue (Dupont et al., 2005; Scott & Neher, 1981; Squires et al., 1998). This indeed highlights the importance of spatiotemporal effort allocation under quota regulations.

In order to transform from a regulated open access fishery to a rights-based fishery, some institutional preconditions must be present. The initial step to privatize fish stock was to establish Exclusive Economic Zones (EEZs) in Norwegian waters to deprive foreign vessels, to reserve commercial fish stocks for Norwegian fishers (Anderson et al., 2019; Hersoug, 2005).

Cod quotas for trawl fleet were enacted in 1976 and applied to this vessel group in 1982, followed by the establishment of Norwegian EEZ (Eide et al., 2003; Holm, 2001). After almost

10 years, due to the dire state of cod, coastal vessels were made to adhere to quota regulations (Armstrong et al., 2014; Hersoug, 2005). The reluctance and hesitance to impose quota restrictions on the coastal fleet was because this segment has been the backbone of Norwegian fisheries in terms of settlements and employment, particularly in coastal regions (Armstrong et al., 2014; Hersoug, 2005; Holm, 2001). The authorities postponed quota imposition for regional considerations to prevent coastal communities from confronting economic hardship (Holm, 2001; Maurstad, 2000). However, after the cod crisis, quota imposition on the coastal fleet could no longer be avoided.

When the quota system was put in place for the first time, the initial allotment of quota among fishers was based upon historical catch levels and intensity of participation over the previous 5 years (Armstrong et al., 2014; Maurstad, 2000). One explanation for this was to ensure that only active fishers are entitled to the rent from the fisheries (Armstrong et al., 2014; Maurstad, 2000).

Even though the implementation of a quota system has increased the effectiveness of the activities, it has brought some challenges to the fishers and concerns for fisheries managers. Regulation through a quota system not only involves fishers but also politicians and foreign countries. Hence, fishing quotas are very vulnerable to political and economic changes and conflicts (Årland & Bjørndal, 2002; Lazkano & Nøstbakken, 2016).

Moreover, the imposition of IVQs can further complicate the decisions underlying effort allocation. This means that fishers need to constantly balance catch and remaining quota in each haul to maximize the expected profit from holding a fishing portfolio, a task that is arguably difficult to do (Copes 1986; Squires et al. 1998). For instance, if a fisher is left with a relatively low quota for a fish stock that it is favorable to catch (i.e., dense abundance and/or high prices), the ability to constantly adjust catch with remaining quota becomes poor and decisions about when and where to fish what are not necessarily optimally made.

Furthermore, as quotas restrict fishers' access to different fisheries, fishers' ability to diversify and target multiple species is undermined. Catch diversification is a common strategy in response to a changing marine environment to stabilize revenue (Kasperski & Holland, 2013; Sethi et al., 2014). Under IVQs, diversification might not be a valid harvest strategy to reduce revenue risk, and fishers need to develop a new strategy to lessen the revenue risk.

### 7.2.1 Setting TAC and quota allocation among different fleets

The annual TAC for fish stocks is set based on the inter-temporal stock assessments provided by fisheries biologists (Diekert et al., 2010a; Hannesson & Steinshamn, 1991; ICES, 2012). Since NEA cod is shared between Norway, Russia, and third parties which include the European Union (EU), Iceland, and Greenland, the regulatory chain for determining and sharing TAC starts with advice and recommendations from scientists from the member countries of the International Council for the Exploration of the Sea (ICES) through international negotiations (ICES, 2012). Usually, Norway and Russia are entitled to approximately 43% of NEA cod, and 14% is allocated to the third parties (ICES, 2012).

Once the international negotiations are finalized, the Norwegian Directorate of Fisheries sets domestic regulations for quota allocation among various fleet groups including costal and trawl fleets. Later, the allocated TAC is broken down and further distributed within the Norwegian-registered vessel groups with license permits to participate. The larger part of TAC (i.e., between 65% and 80%) is allocated to the coastal fleet with conventional gears (Hersoug, 2005; Holm, 2001). Accordingly, smaller vessels of the coastal fleet, whose range is between 10 and 28 meters, receive the largest part of the allocated quota. The rationale behind this division is to alleviate economic hardship of the smaller boats during years when the catch is highly volatile. This matter is comprehensively explained in the next sub-section.

Establishment of the TAC and quotas for saithe and haddock fisheries follows a similar procedure to that for cod stock (Birkenbach et al., 2020). The IVQs of the trawl fleet are allocated according to the size or tonnage of trawlers as well as the type of trawler license (Birkenbach et al., 2020).

### 7.2.2 The trawl ladder

The coastal fleet has been backbone of Norwegian cod fisheries. From the 1930s, licensed trawlers started to fish cod in Norwegian water (Hersoug, 2005; Johansen, 1972; Standal & Hersoug, 2015). Until the 1980s, when the quota regulations were put into place, there was a constant conflict between coastal and trawl fishers about exploitation of fish stocks, especially cod fish (Holm, 2001; Hersoug, 2005; Johnsen & Jentoft, 2017).

Prior to the introduction of quota regulations, costal fishers considered trawling as a major threat to the sustainability of fish stocks and the livelihood of coastal communities as trawl vessels have spatial and temporal freedom, thus they can land more fish. In essence, there was apprehension that small boats were left with smaller catch size and revenues (Hersoug, 2005; Johansen, 1972).

The introduction of IVQs has resolved this historical conflict to some extent. The division of TAC between coastal and trawl fleets is based on a tool known as the “trawl ladder” (Asche et al., 2014; Hersoug, 2005; Holm & Rånes, 1996). Based on this management tool, a larger part of TAC is allocated to smaller and coastal vessels to protect them against fluctuations in TAC, and consequently variations in annual income (Asche et al., 2014; Hersoug, 2005; Holm & Rånes, 1996; Standal & Hersoug, 2015).

Fluctuations in the biological condition of fish and oceanographic characteristics (e.g., food availability and sea temperature) lead to variation in the abundance of fish stock and annual TAC. For example, assume a vessel holds a 1% share in the cod fishery (i.e., this 1% share is fixed for the trawl vessel). If the biomass of cod shrinks, so does the TAC as well as the potential landings of this fisher, because 1% of a smaller TAC will yield a smaller catch size, leading to less annual income.

The trawl ladder specifies that in years with modest biomass (e.g., total cod quota is 100,000 tons or smaller), the coastal fleet is granted a larger part of TAC (approximately 80%) to lessen the large variation in revenue and alleviate economic hardships for smaller vessels (see Table 1). In years with higher biomass and TAC, the coastal fleet gets a smaller share to a maximum of 65% of TAC (which is approximately equal to 300,000 tons) (Asche et al., 2014; Hersoug, 2005; Holm & Rånes, 1996). This division rule aligns with the objective of Norwegian fisheries management, which is to sustain employment and livelihood along the coast of Norway. Similar to cod fishery, coastal boats get a larger share of saithe and haddock in comparison to trawlers.

Table 1. The trawl ladder rule for cod quota allocation between coastal and trawl fleets based on annual fluctuations in cod biomass

| **Cod quota in tons** | **Percentage share of coastal fleet** | **Percentage share of trawl fleet** |
|---|---|---|
| < 100,000 | 80% | 20% |
| 100,000–150,000 | 75% | 25% |
| 150,000–200,000 | 72% | 28% |
| 200,000–300,000 | 69% | 31% |
| > 300,000 | 65% | 35% |

### 7.2.3 Transferability of IVQs

As stated earlier, one of the goals of fisheries management is to increase economic efficiency in the exploitation of fisheries resource. Even though the implementation of IVQs in the 1990s has prevented rent dissipation and reduced excess capacity (Årland & Bjørndal, 2002; Lazkano & Nøstbakken, 2016), there was still room for further improvement in terms of achieving higher profitability and efficiency by undertaking further regulation reforms in the quota scheme.

Initially, quotas were by law non-transferable and non-divisible, and hence a competitive market did not exist for selling/purchasing the right to fish a certain quota stock (Årland & Bjørndal, 2002; Johnsen & Jentoft, 2017).

The evident advantage of transferability of quota is that it can prevent rent dissipation and improve the economic efficiency of the fleet through a capacity adjustment process (Agnarsson et al., 2016; Årland & Bjørndal, 2002; Johnsen & Jentoft, 2017). More precisely, this means that transferability enables more efficient vessels to buy out the quota entitlements of less efficient ones. Thus, by the withdrawal of less efficient vessels (i.e., fishers with less return per unit of quota), quota rights are aggregated in the hands of the most efficient fishers. With transferability of quotas, remaining large boats adjust their level of production to maximize economic rent (Agnarsson et al., 2016; Asche et al., 2009; Copes, 1986; Salvanes & Squires, 1995). Another benefit of transferability is that it creates the potential for fishers to switch between target species. Fishers who cannot manage to fish their entire quotas may sell their fishing rights to willing buyers (Hersoug, 2005; Johnsen & Jentoft, 2017).

Recognition of the benefits of transferability has encouraged the Norwegian fisheries management system to gradually move towards buying and selling quotas within the same vessel group, fish stock and geographical area of the country (i.e., within the same district of the country) (Årland & Bjørndal, 2002; Armstrong et al., 2014; Asche, 2009; Birkenbach et al., 2020). For instance, based on the transferability rules it is not allowed to scrap a cod trawler operating in northern Norway and transfer the quota to a cod trawler operating in the southern part. Moreover, in order to hinder a great concentration of quotas in the hands of larger and more efficient vessels, there are restrictions on how much quota each vessel owner can hold.

The implementation of an individual transferable quota (ITQ) system has improved the situation after major drops in total landings of cod in the late 1980s (Årland & Bjørndal, 2002).

# 8 Regulatory changes and subsequent alternation in harvest strategy

Environmental regulations are often subject to modifications and reforms to achieve public interest and promote social welfare towards sustainable development (Gullestad et al., 2014; Holm, 2001). As legislation regarding fish exploitation changes, so do patterns of effort allocation and adopted harvest strategy (Greaker et al., 2017; Quirijns et al., 2008). In the following sub-sections, we will discuss how the shift from open access fishery to quota-regulated fishery has changed the allocation of fishing effort and harvest strategy in codfish fishery.

## 8.1 Harvest strategy of codfish under an open access fishery

Under an open access fishery, the only major constraint that fishers confront is environmental conditions such as weather unsuitability and fish availability (Maurstad, 2000). Under this circumstance, a wide range of aquatic organisms are available for the fishers, hence they can freely alternate fishery in response to the changing marine environment and climatic conditions, and fish as much as possible to increase fishing revenue.

Under an open access fishery, it is rational to think that the race to catch cod encourages trawlers to start fishing as soon as the fishery opens to outdo other appropriators (including both other trawlers and coastal fishers) to reap bigger profits. This is because if fishers do not start catching cod as early as possible, their counterparts will exploit cod and nothing or little will be left for them. Put differently, latecomers have very little chance of catching anything as the cod stock has already been exploited by the incumbent fishers. Similarly, the incentive to pre-empt cod before other competitors would encourage capital investment in the trawl fleet. In the fishing race between coastal and trawl fleets, it is rational to believe that the trawl fleet will get a bigger catch due to the availability of stronger engine power.

Since the opening of the fishing year coincides with the spawning migration of NEA cod along the west coast of northern Norway, one would expect to see that fishing effort is aggressively concentrated during the winter months along the coast. At this time, it is likely that the cod price will go down due to the large supply of cod, landed by both coastal boats and trawlers. However, it is less likely or unlikely that trawlers will withdraw from cod fishery because of the low price of cod and switch to other species such as saithe or haddock. The rationale is that cod is the most economically valuable fish stock and if trawlers do not utilize this opportunity, then the cod stock will be pre-empted by other fleets. This implies that under open access fisheries, trawlers would probably not respond to the supplied quantity and price fluctuations in the cod fishery. Once the cod stock is fished, it is expected that trawlers would switch to haddock and later to saithe fishery as haddock is commercially more valuable than saithe.

In addition, from a spatial point of view, allocation of fishing effort in distant areas of the Arctic when NEA cod swim back to the Barents Sea to feed seems to be an untenable and foolish harvest strategy as the majority of this stock has already been fished earlier in the year during Lofoten fishery. Under this scenario, there will be little cod in the Barents Sea after the winter months of spawning. In essence, trawling in the Arctic area will be considerably costly because of the transportation cost as well as increased cost per unit of effort due to low fish abundance. Under this circumstance, it is expected that the total cost cannot be covered by the expected revenue, which leads to negative marginal profitability. Even if we assume that the market price of cod is better at the end of the year due to lower landings (i.e., if we assume that some trawlers fish in the Arctic and there is still a supply of cod out of the winter months), we cannot expect that the increase in price on its own could motivate trawlers to participate in the fishery in the Arctic area due to the high cost of fishing there. Hence, there will be no or little codfish fishery in the Arctic area. Related to this, the onboard freezing capacity of trawl vessels will be underutilized as trawlers fish during the winter months close to the shore and no freezing is needed.

## 8.2 Harvest strategy of the codfish fishery under quota regulations

The limited catch size together with assignment of property rights has brought some major economic considerations for fishers that have created the necessity to change their fishing strategy (Branch & Hilborn, 2008; Copes, 1986; Quirijns et al., 2008; Squires et al., 1998).

Since IVQs assign fishing rights to eligible fishers, the race for fish has ceased. This means that unlike in an open access fishery, fishers do not need to act hastily and fish as soon as the fishery season starts.

Moreover, the limited nature of harvest under the quota system encourages fishers to harvest in a cost-minimizing way while increasing revenue from fishing by correctly choosing when and where to fish what, and how much to harvest to take advantage of variations in stock abundance (i.e., CPUE) and in the prices of different fish stocks over the course of a fishing year (Anderson et al., 2019; Asche et al., 2015; Dupont et al., 2005). Fish prices fluctuate due to the quantity and quality of landings as well as variation on the demand side (Arnason et al., 2004; Asche, Gordon, et al., 2002; Birkenbach et al., 2020). There may also be seasonal variations in price (Birkenbach et al., 2020; Hermansen & Dreyer, 2010). Having a secured share of fish enables fishers to plan their activities throughout the season and respond to fluctuations in stocks and prices to maximize profit.

In essence, fishers shift the target species when available alternative fishery is economically and/or biologically more favorable (i.e., higher market prices and/or higher CPUE) to maximize profit. This highlights the importance of recognizing the spatiotemporal allocation of fishing effort, in particular for migratory species like cod, saithe, and haddock. In short, under a quota management system, the production possibilities (capacity) of fishers depend on quota size and how well fishers can utilize their fishing rights in terms of optimally allocating fishing effort over time and space. The chosen strategy should be in accordance with quota regulations. This means that fishers cannot fish more than the assigned quota, otherwise overfished quotas are forfeited, or highly penalized (Hersoug, 2005).

For a more comprehensive review on how the introduction of IVQs has affected the adopted harvested strategy and effort allocation, in Figure 9, we depict the effort allocation of trawlers operating in cod, saithe, and haddock fisheries over 2011–2016 on a fortnightly basis. Fishing effort is measured in thousand hours of trawling. As it is evident from Figure 9, unlike open access fishery, effort is spread over the course of a year.

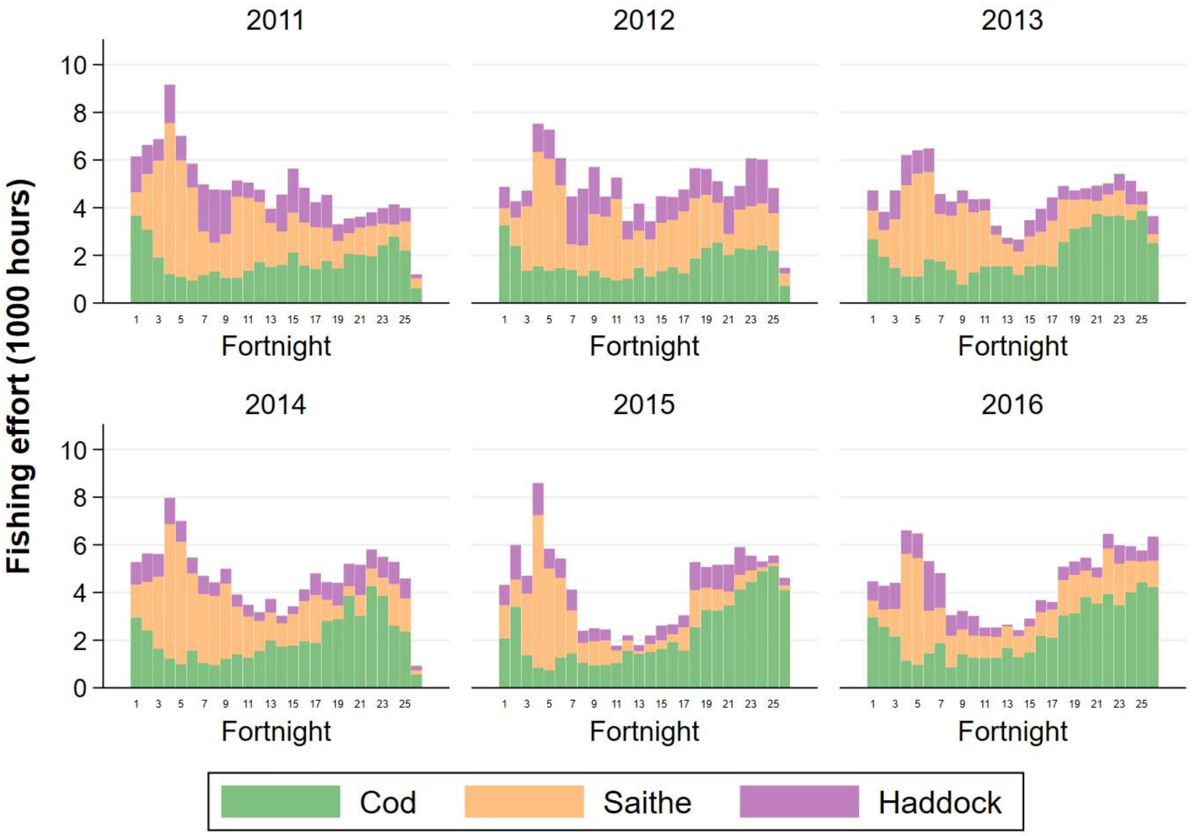

Figure 9. Fortnightly allocated fishing effort, measured in thousand hours of trawling for cod, saithe, and haddock fisheries, caught by 61 registered trawl vessels over 2011–2016. Source: The Norwegian Directorate of Fisheries

Relatedly, in Figure 10 we show catch patterns of cod, saithe, and haddock, measured in thousand tons, caught by the trawl fleet over the course of a year on a fortnightly basis. In the calculation of catch, incidental catch of other species is also considered as trawling inevitably comes with bycatch.

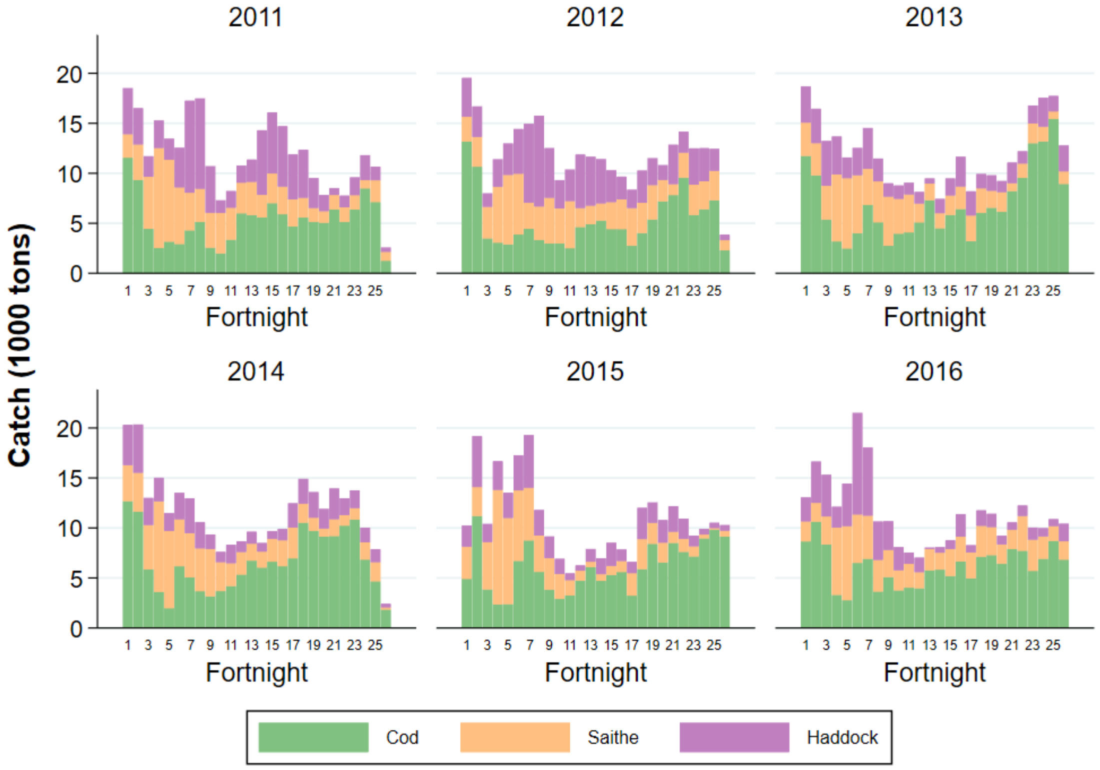

Figure 10. Fortnightly catch, measured in thousand tons for cod, saithe, and haddock fisheries, caught by 61 registered trawl vessels over 2011–2016. Source: The Norwegian Directorate of Fisheries

The patterns of allocation of fishing effort and catch are similar. At the beginning of the year, shortly after the fishing year starts, there is a noticeable drop in both fishing effort allocation and the catch of cod fishery, despite the CPUE for cod fishery still being high (see Figure 6). Concurrently, at this time there is a rise in fishing effort and catch of saithe fishery. This means that during this time interval, trawlers withdraw from the cod fishery and start targeting saithe and haddock.

As stated earlier, higher CPUE indicates higher productivity and less cost per unit of effort. One relevant explanation for refraining from cod fishery while CPUE is still high could be due to the price effect. As soon as the fishing year starts, coastal boats target NEA cod, which migrates from the Barents Sea to the fishing grounds along the coast of north-west Norway to spawn. Coastal boats hold 65–80% of cod quotas, and since they are geographically less mobile relative to trawlers, they exhaust their cod quotas (Birkenbach et al., 2020; Hermansen & Dreyer, 2010). Excess supply of cod lowers the price. The spatial freedom of the trawl vessels, together with being less susceptible to the harsh climatic conditions of the Arctic, makes them capable of catching cod in Arctic areas when NEA cod swim back to the Barents Sea to feed. Hence, the low price of cod during wintertime encourages trawlers to shift to saithe fishery and reserve the cod quota for the time when the price of cod is higher. As is evident in Figures 9 and 10, the sudden drop in fishing effort and landings of cod is followed by a rise towards the end of the year. This means that trawlers utilize the reserved quota in this period in the Arctic, where NEA cod is available in this area to feed. At this time, it is rational to think that cod fetches higher prices as the trawl fleet is the only source of cod landings from the Arctic area.

In agreement with the catch patterns in Figure 10, Birkenbach et al. (2020) concluded that Norwegian trawlers should spread cod landings over the course of a year while targeting saithe in a short period during winter to maximize profit. This is observable in Figure 10, where saithe is fished approximately between the 2nd and 11th fortnights. The catch pattern in Figure 10 on its own gives the insight that trawlers are profit-oriented and seek to maximize profit.

In order to support our argument about the responsiveness of trawlers to the price fluctuations under quota regulations, in Figure 11 we illustrate the monthly average prices of these three fisheries during 2011–2016. The prices are in Norwegian Krone (NOK) and ascribed to the frozen products of cod, saithe, and haddock as the trawl fleet is equipped with freezing facilities and it mostly delivers frozen products.

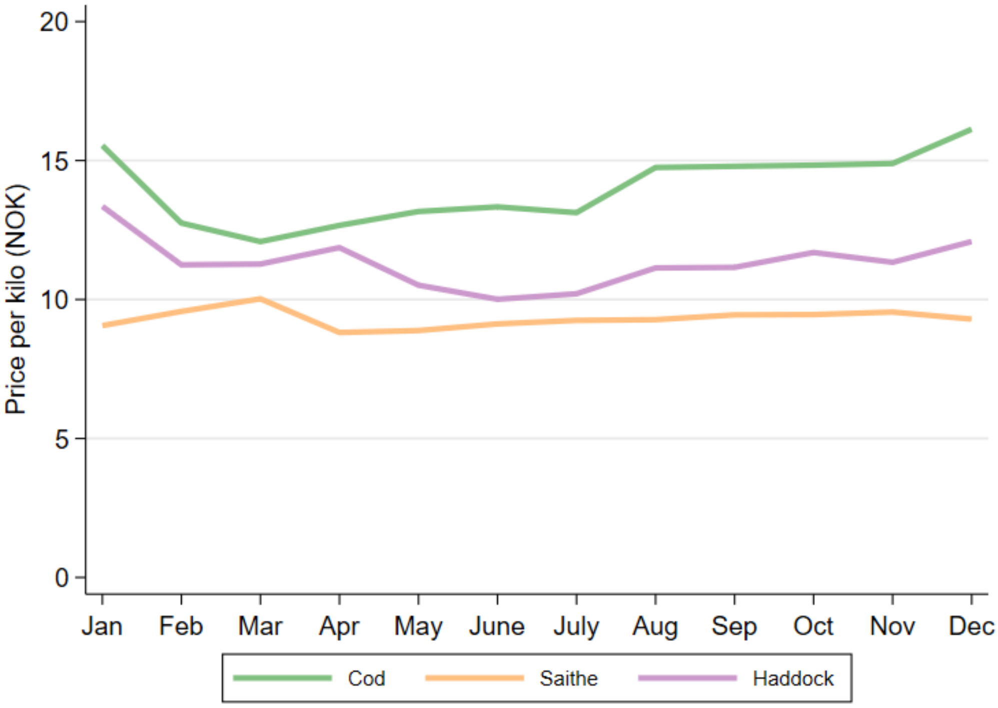

Figure 11. Monthly average price for landed frozen products of cod, saithe, and haddock caught by the trawl fleet during 2011–2016. Source: Norwegian Fishermen's Sale organization (Norges Råfisklag)

As is evident from Figure 11, cod and saithe are the most and least commercially valuable fish stocks, respectively. The prices of cod and haddock show more fluctuations relative to those of saithe fishery. One reason for observing more fluctuation in cod price is that Norwegian trawlers face a downward-sloping demand schedule, meaning that price responds to the changes in quantity (Arnason et al., 2004; Birkenbach et al., 2020). This is because the cod market is effectively segmented from that of other white fish, while saithe and haddock are more integrated into the global white fish market (Arnason et al., 2004; Birkenbach et al., 2020). Therefore, seasonality in cod fishery and fluctuations in landings of cod may be reflected in prices. Similarly, saithe price does not fluctuate as much as the prices of cod and haddock, probably because the CPUE of saithe does not fluctuate considerably either, if we disregard January and April (see Figure 6). Another explanation could be that the demand for saithe is very limited (Birkenbach et al., 2020; Hersoug, 2005).

At the beginning of the year, cod and haddock fetch lower prices. The rationale behind this pattern is related to the intensive participation of the coastal fleet during Lofoten fishery.

Proximity to the shore and lower cost per unit of effort because of the availability of congregated stocks (Hannesson, 2007b; Kvamsdal, 2016; Sandberg, 2006) provide a good opportunity for the fishers, especially the coastal fleet, to fish their quotas, in particular cod and haddock as these species are commercially more valuable. As stated earlier, excess supply leads to the lowering of prices (Birkenbach et al., 2020; Hermansen & Dreyer, 2010).

As is shown in Figure 11, the prices of cod and haddock are higher towards the end of year, which motives trawlers to target these species in the Arctic areas, in particular cod.

Interestingly, the price of saithe is highest in March (around 10 NOK per kilo) when the CPUE of cod and haddock is high as well. This could indicate that during Lofoten fishery the landings of saithe are lower as fishers fish cod and haddock. The reduced supply of saithe could be the reason behind the higher price of saithe in March. The price of saithe starts to decline in April, the time at which CPUE is the highest (see Figure 6). The price of saithe remains almost steady until the end of the fishing year.

With the above considerations in mind, we see that under a quota-managed fishery, trawlers adopt a different harvest strategy in comparison to that in an open access fishery. Under rights-based fishery, trawlers spread their catch over the course of a year and respond to the fluctuations in CPUE of different stocks and its potential effect on prices.

# 9 Contribution: a gradual shift from conventional fisheries management

Fishing is a process which is built upon constant interactions between fish and fisher. Hence, fisheries management on the one side should be concerned about fish dynamics, and on the other——an equally important side—the need to investigate fishers' behavior as fishers are part of, depend on, and affect the ecology and population dynamics of fish stocks (Fulton et al., 2011; Hilborn, 2007). This means that an integrated management scheme, in which fish and fisher behaviors and their interactions are incorporated, is needed to sustain a biologically and economically sustainable fishing industry (Charles, 1995; Fulton et al., 2011; Hilborn & Walters, 1992).

However, traditionally, fisheries management places greater prominence on fish population dynamics and conservation of target species, and focuses on the biological management of fish (Hilborn, 1985, 2007; Wilson et al., 1994). In other words, fishers' behavior and the motivations governing the patterns of effort allocation have rarely been taken into account in developing and implementing regulatory schemes (Charles, 1995; Reimer & Abbott, 2020).

For instance, notable among the early managerial criteria to hinder overfishing is the traditional maximum sustainable yield (MSY), introduced in 1954 (Hersoug, 2005). MSY supports the largest possible annual fish production while ensuring sustainability of the fish population. When the fish population falls below the MSY, overfishing occurs (Hersoug, 2005). Larkin (1977) and Ludwig et al. (1993) argue that the attainment of biological and economic sustainability based upon merely biologically founded criteria such as MSY is impossible as it overlooks how fish is caught and how fishing effort is distributed. In agreement with the aforementioned scholars, Wilson et al. (1994) stated that the use of biological research results for implementing policies leads to inefficient fisheries management, and improving the efficacy of fishing management requires an understanding of fishers' behavior and the spatial and temporal distribution of fishing effort.

Related to the inefficiency of fisheries management, the failure of strictly regulated fisheries where overfishing and excess capacity are still present has been abundantly reported by scholars (FAO, 2012; Fulton et al., 2011; Hilborn et al., 2001; Kelleher et al., 2009; Lazkano & Nøstbakken, 2016; Miranda & Brandon, 2017).

NEA stock lies within safe biological limits (Armstrong et al., 2014). Despite meeting conservation objectives and having a biologically well-managed stock, fisheries researchers have found that the management of cod fisheries is still inefficient (Arnason et al., 2004; Asche, 2009; Bertheussen & Dreyer, 2019; Diekert et al., 2010a, 2010b; Ottersen, 2008). For example, Diekert et al. (2010a, 2010b) revealed that overfishing still exists in cod fishery and economic rent could be improved. Similarly, Asche et al. (2009) have identified considerable overcapacity in the Norwegian trawl fleet. Additionally, Bertheussen and Dreyer (2019) have detected a market failure in cod fishery. Moreover, Arnason et al. (2004) and Ottersen (2008) have shown that the harvest pattern of cod is inefficient and the rent could be enhanced by redistribution of fishing effort.

However, it is difficult to pinpoint a single prevailing reason for the inefficiency of management policies; human ecologists, anthropologists, and maritime social scientists argue that excluding fishers' harvesting behavior, their motivations, and factors influencing the choice of adopted harvest strategies in designing policies has led to the failure of fisheries management and non-sustainability of fisheries (Béné & Tewfik, 2001; Hilborn, 1985, 2007; Hilborn & Walters, 1992; Ludwig et al., 1993; Opaluch & Bockstael, 1984; Wilson et al., 1994). Scientists believe that pecuniary and non-pecuniary factors can drive fishers to allocate fishing effort in a way that is not necessarily in accordance with the biological conservation goals (Béné &

Tewfik, 2001; Branch & Hilborn, 2008; Bucaram & Hearn, 2014; Fulton et al., 2011; O'Farrell et al., 2019; Salas & Gaertner, 2004).

Related to this, Hilborn (1985) and Ludwig et al. (1993) mentioned that managing fisheries is indeed managing fishers. They argue that the inefficiency of fisheries management such as the problem of overfishing is not because of an inadequate amount of fish in the sea but rather it is attributed to the inability of managers to understand how fishing practices are conducted to catch fish, and what motivates such strategies.

More than half a century ago, for the first time Gordon (1953) combined fishers' effort allocation behavior with the biophysical characteristics of fish and introduced a bio-economic model. Even though the investigation of fishers' behavior dates back to the 1950s, its incorporation in designing fisheries policies is neglected. Hilborn and Walters (1992), Charles (1995) and Wilen et al. (2002) claim that our understanding of fishers' harvest behavior is at best rudimentary. Moreover, Heal (2007) claims that the current gap between potential and actual performance of fisheries management is the largest in comparison to other areas of environmental economics.

Some scholars claim that one of the main reasons for this negligence is because of the complexity of fishers' behavior (Deporte et al., 2012; Fulton et al., 2011). Maurstad (2000) agrees that in realistic settings human behavior is no less complex than fish behavior. However, she claims that unlike fish that constantly move across sea, and which are not directly observable to researchers, fishers are accessible to researchers. She suggested that, for instance, interviewing fishers can reveal valuable information about fishing effort allocation and the motivation behind the behavior of fishers.

The contribution of this thesis is to improve the efficiency of fisheries management by investigating fishers' behavior in allocation of fishing effort across space and over time.

# 10 Research questions and empirical methods

As conventional fisheries management with a focus merely on fish population dynamics falls short in solving existing problems in Norwegian fisheries, the main aim of this thesis is to bring attention to trawlers' harvest behavior and investigate how they allocate fishing effort and utilize quotas over time and across space, governed by trawlers' goals and quota constraints. Since the fishing portfolio of cod, saithe, and haddock is among the most valuable quota portfolios, investigation of the spatiotemporal allocation of fishing effort in trawl fishery can contribute to enhancement of the industry's profitability (Birkenbach et al., 2020; Cojocaru et al., 2019; Guttormsen & Roll, 2011).

There are three relevant explanations behind choosing the trawl fleet in this thesis. First, the spatial and temporal freedom of trawl vessels and their capability to cope with the harsh climatic conditions could influence their fishing strategy. The reason is that these features could dilute the consequences of seasonal spawning aggregation of fish stocks during wintertime along the north-west coast of Norway (Asche et al., 2014; Hersoug & Leonardsen, 1979; Standal & Hersoug, 2015). Moreover, these features enable trawlers to steadily supply white fish over the course of a year to reinforce Norwegian fisheries (Hersoug & Leonardsen, 1979).

Second, the Norwegian trawl industry is vertically integrated (Dreyer & Grønhaug, 2004; Hersoug & Leonardsen, 1979; Isaksen, 2007), and this on its own might affect the way trawlers behave in comparison to non-integrated coastal fishers. As stated earlier, in section 3.2.2, vertically integrated industries are able to operate at lower cost in comparison to non-integrated businesses. At the same time, they are exposed to less risk due to an integrated supply chain and increased control over the market (Isaksen, 2007; Porter, 1980; Riordan, 1990).

Third, as mentioned earlier, investigation of how fishing effort is allocated across space and over time reveals information about exploitation patterns and stock status. This information is of critical relevance to the trawl fishery as this fishing practice might harm the marine environment. If intensive and damaging trawling is identified at a specific time and location, managerial policies could be developed to prevent the destruction of ecosystems and marine resources, such as the designation of trawl-free zones.

The empirical investigation of fishers' behavior is a less developed area of fisheries research. Thus, the outcome of this thesis contributes to fill the gap in empirical literature concerning fishers' behavior.

## 10.1 First article

In this article, first we investigated the presence of seasonality in the cod fishery in two distinct areas, namely the fishing grounds off the west coast of northern Norway and the high sea areas of the Arctic including Bear Island and Svalbard. Furthermore, we examined how seasonality affects economic considerations such as the price and cost of fishing as well as the utilization of quotas and allocation of fishing effort in the two aforementioned regions.

We approximate seasonality in the cod stock by obtaining CPUE in the selected areas. Thereafter, Fast Fourier Transformation (FFT) and Fourier series are used to detect and model seasonality. Our analysis detects seasonality in the cod stock along the west coast of northern Norway due to the spawning aggregation of NEA cod. The congregated stock in this area during wintertime reduces cost per unit of effort, which in turn encourages both trawlers and coastal fishers to target cod. As a result of a large supply of cod, the price of cod declines. Furthermore, our results suggest that the magnitude of the reduction in price outweighs the reduction in cost, hence it would then no longer be in the interests of trawlers to utilize the cod quota. At this time, trawlers withdraw from cod fishery and participate in available fisheries such as saithe or haddock and reserve the cod quota for a time when the price of cod goes up. The price of cod starts to increase when NEA cod returns back to the Barents Sea to feed. The increased price of cod is due to the limited landings of cod as coastal fishers are not able to fish in the Arctic areas.

Based on the outcomes of this study, we conclude that Norwegian trawlers respond to changes in cod abundance and the market price of cod in an economically rational way. More precisely, this means that trawlers redirect fishing effort to other available fisheries in the winter months when the price of cod is lower. Trawlers start cod fishery when the price of cod starts to rise after Lofoten fishery. This result indicates that effort allocation and quota utilization of trawlers are consistent with the theory of rational choice.

## 10.2 Second article

In the second article, we examined whether diversification in terms of catching multiple species functions as a revenue risk reduction mechanism in Norwegian trawl fishery. Revenue from the fishing portfolio is characterized by considerable risk, stemming from fluctuations in population abundance, changes in the relative prices of fish stocks, and possible reforms in regulations. Hence, trawlers seek to minimize revenue risk and obtain a stabilized revenue over the fishing year, while adhering to quota constraints.

Our quota portfolio consists of cod, saithe, and haddock fisheries. The seasonality patterns of these fish stocks and price reactions to the fluctuations in relative fish availability are different, hence trawlers need to constantly reallocate fishing effort across these species over the course of a year to accomplish revenue risk minimization.

Bycatch considerations are also included in this study, as during wintertime the spatial distribution of cod, saithe, and haddock coincides along the north-west coast of Norway, hence big incidental catches are expected, which could constitute a considerable part of the fishing revenue.

This study uses coefficient of variation of revenue per unit of effort (RPUE) as a revenue risk measure. A decision-making framework, which incorporates the alternatives about when to fish what, and how much to fish, is used to assess the revenue risk-minimizing behavior of the trawl fleet under two different scenarios. In the first scenario, we assume that a risk-minimizing trawler has only one business objective, which is to allocate fishing effort in a way that minimizes the revenue risk of the fishing portfolio. In the second scenario, the decision maker (i.e., representative trawler) has two simultaneous objectives: minimizing revenue risk and generating a sufficient level of revenue. The results from the first scenario show that minimizing revenue risk comes at a greater cost, and that is the underutilization of the cod quota. Since cod is the most commercially valuable species in this portfolio, it is unlikely that trawlers would forgo the revenue that could have been generated from cod fishery for the sake of minimizing revenue risk. This provides an insight that lowering risk by the means of diversification is economically irrational in trawl fishery, and an untenable strategy to adopt. The results of the second scenario show that trawlers manage to fully exhaust the quota portfolio by the end of the fishing year. Moreover, our findings prove that enhancing revenue is more important than minimizing revenue risk for the trawlers. Relatedly, we found that the seasonality in cod fishery plays an important role in shaping the adopted harvest strategy to enhance fishing revenue.

Despite the fact that diversification has long been a strategy to stabilize revenue, we found that trawlers hold a diverse portfolio to enhance revenue, and not necessarily to reduce revenue risk. We speculate that the vertical integration of the trawl industry together with the spatiotemporal freedom of trawl vessels and their ability to cope with unsuitable climatic conditions secure trawlers against revenue fluctuations.

## 10.3 Third article

Having confirmed that revenue enhancement is a more important business objective for the trawl fishers, in the third article we investigated the profit maximization behavior of the Norwegian trawl fleet under quota restrictions. Our quota portfolio includes cod, saithe, and haddock. Precisely, we examine intra- and inter-temporal allocation of fishing effort across three regions, namely the northern and southern parts of the west coast of northern Norway and the high sea areas of the Arctic, which include the Barents Sea area and Svalbard. In the southern part of the west coast of Norway, saithe fishery is dominant, while in the northern part of the west coast and in the sub-Artic areas, cod and haddock fisheries prevail.

These three locations are heterogeneous in terms of the availability of different fish stocks and the corresponding prices, the fuel cost to travel to the fishing grounds (i.e., proximity to shore) and the presence of the coastal fleet. The relative attractiveness of these locations varies over the course of the year, hence trawlers need to constantly evaluate the economic benefits and costs associated with the selected regions.

This study employs a Heckman's two-step selection model and incorporates the aforementioned spatial features through a two-step procedure. In the first step, a probit regression model is used to determine whether trawlers allocate fishing effort at a specific location and time. The second step develops a distinct regression model to specify the factors influencing the allocation of fishing effort.

The results of the proposed two-step Heckman's selection model reveal that location-specific costs have a great impact on how trawlers displace effort across the three different regions and over time.

From intra-temporal analysis, we found that the presence of the coastal fleet during Lofoten fishery along the north-west coast of Norway increases the cost of fishing for the trawlers, hence they refrain from cod fishery and reserve the cod quota for a time when NEA cod swim back to the Arctic regions to feed. Moreover, our analysis shows that with higher fuel prices, trawlers would allocate fishing effort in saithe fishery in the southern parts of the west coast of Norway.

Based on our results from inter-temporal analysis, we found that trawlers react to the congestion of the coastal fleet during Lofoten fishery during wintertime. Once the negative effect of stock congestion fades away (i.e., low market price for cod), trawlers utilize their quota in this region. Furthermore, trawlers respond to changes in fuel price and try to even out the rise in fuel price by constantly redistributing the fishing effort over the course of a year.

# 11 Data

The data used in this thesis are extracted from a combination of sources. We used vessel monitoring system (VMS) data for 61 trawl vessels engaged in cod, saithe, and haddock fisheries over 2011–2016. These data are collected by the Norwegian Directorate of Fisheries (Norwegian: Fiskeridirektoratet). Almost all of the vessels had fished the previous years and were active over the 6 years of observation.

Based on Norwegian fisheries management, all vessels more than 15 meters in length are obligated to be equipped with a VMS for surveillance of vessel sailing and enforcement (Pramod, 2018). The trawl vessels in this study range in size from 40 to 75 meters and are equipped with onboard freezing facilities. Data recorded by the VMS include haul-based observations of geographic coordinates on net set location (Loran) and time of set, location and time of lift, the depth at which trawling has occurred and the size of the towed area. A total of 86,418, 67,071, and 38,928 haul-based observations were recorded for cod, saithe, and haddock fisheries, respectively. The application of spatial and temporal data recorded by VMS enabled us to investigate the spatial and temporal distribution of fishing effort.

Another major source of data is the logbooks kept by fishers. We obtained the logbooks of the corresponding vessels from the Norwegian Directorate of Fisheries, which include haul-based records of fishing date, target species (e.g., cod, saithe or haddock fisheries), estimates of catch weights of the main target together with bycatch species, and soaking time. This data set contains information on vessels' identity as well as technical characteristics of the vessels such as engine specifications. The vessels had the same identification numbers during the period of 6 years. Using catch, measure in tons, and effort, measured in trawling hours, we can obtain CPUE to investigate the possible effect of variation in fish abundance (see Equation 2) on trawlers' re/allocation of effort across space and over time.

The third data set was obtained from the Norwegian Fishermen's Sales Organization (Norwegian: Norges Råfisklag), which includes weekly price data for frozen products of cod, saithe, and haddock over 2011–2016. The sales organization was established in 1939 (Hersoug, 2005; Holm, 2001). Ex-vessel and minimum prices of fish stocks (Norwegian: Råfiskloven) are set by the Fishermen's Sales Organization through negotiation with fish buyers. Trawlers have refrigeration facilities on board and they usually deliver frozen products (Hersoug, 2005; Holm, 2001). Hence, we used price information for the frozen fish products. Using this data set shows how trawlers react to price movements in terms of effort allocation.

In the third article, in order to investigate the effect of fuel cost on trawlers' effort allocation, we utilized the data from two different sources. First, the annual average fuel price per liter for the trawl fleet was obtained from The Guarantee Fund for Fishers (Norwegian: Garantikassen for fiskere). We then obtained the monthly gasoline price per liter from Statistics Norway (Norwegian: Statistisk sentralbyrå; SSB). In order to capture the fuel price variation over the course of a year, we obtained the monthly fuel price of the trawlers by normalizing gasoline prices based on the annual average price (i.e., we used 2011), and multiplied the standardized price to the monthly data.

It is worth mentioning that fishery data are affected by noise. Any interference from the environment (e.g., bad weather conditions), gear failure, or simply good/bad luck affects the size of the catch (Durrenberger & Pálsson, 1983; King, 2011; Thorlindsson, 1994). In order to eliminate noise from our data set to have meaningful features, we have aggregated the data on a fortnightly basis in the first and second articles, consisting of 26 fortnights over 6 years (i.e., 156 fortnights in total). However, in the third article, we have used weekly and monthly data for the intra- and inter-temporal analysis of fishing effort, respectively. We have used weekly data to enhance the number of observations to get reliable empirical estimates. The reason for application of monthly data in the estimation of inter-temporality is to avoid collinearity caused by fuel price data.

# 12 Conclusion

The empirical investigation of fishers’ harvest behavior has received little attention in fisheries literature. As a result of this, including fishers’ behavior when designing policies for fisheries management has been neglected. In recent years, fisheries researchers have put forward the view that fisheries management requires further understanding of the fishers and their motivations behind choices for effective management.

In this regard, the present work seeks to shed light on the spatiotemporal effort allocation of Norwegian trawlers, with special emphasis on the migratory behavior of codfish and quota regulations. The reason behind the choice of cod, saithe, and haddock fish stocks is that this portfolio constitutes economically important species in terms of volume and total revenue, caught by trawlers.

Accessibility to comprehensive and detailed data sets, obtained from several sources, allows us to empirically investigate the choices regarding when and where to fish what, and how much to fish, to accomplish the considered business objective(s), while adhering to quota constraints.

Making optimal decisions underlying the effort allocation of the trawl fleet can be notoriously difficult due to several reasons. First of all, the bottom-trawl fleet operates in multi-species fisheries (here, cod, saithe, and haddock). These species have heterogeneous biological characteristics (i.e., feeding and breeding patterns) and their habitat requirements might vary as well. Hence, they exhibit different seasonal patterns across different locations over the course of a year. As a result of heterogeneous patterns of seasonality in these fish stocks, the potential economic consequences and the magnitude of these consequences might be different.

Besides the unpredictability of fish behavior, the varying states of the ocean in terms of temperature and food, inherent uncertainty related to the price fluctuations and market conditions, and abrupt reformations in regulations add more complication to the allocation of fishing effort.

Another source of complexity is that the Norwegian trawl fleet is quota-regulated and trawlers need to constantly track catch sizes and remaining quotas to take advantage of variations in stock abundance and price over the course of a fishing year to attain the considered goal(s). Moreover, based on the Norwegian quota system, only a small percentage of unused quota can be granted in the subsequent year. Hence trawlers need to fully utilize the quota portfolio by the end of the fishing year, otherwise underutilization is considered an economic loss.

The results of the three articles are in line with each other. In summary, our analysis suggests two major conclusions. One of the common take-away messages from the three articles is that trawlers are profit-oriented and swiftly redistribute fishing effort in response to changes in fish availability and prices to obtain the highest level of possible profits. This implies that the selections of where, when, and what to fish are in accordance with the theory of rational choices. The second common outcome among all papers is related to the cascading effect of spawning migration of NEA cod and intensive participation of the coastal fleet in shaping the harvest strategy adopted by trawlers.

The outcomes of this study aim to shift the focus of fisheries management from fish behavior to fishers' behavior. Recognition of how trawlers allocate fishing effort contributes to the refinement and improvement of fisheries management as this enables us to compare how fishers might respond to alternative regulations as well as changes in biological and economic conditions.

## References

Agnarsson, S., Matthiasson, T., & Giry, F. (2016). Consolidation and distribution of quota holdings in the Icelandic fisheries. *Marine Policy, 72*, 263-270.

Anderson, C. M., Krigbaum, M. J., Arostegui, M. C., Feddern, M. L., Koehn, J. Z., Kuriyama, P. T., . . . Fiamengo, C. (2019). How commercial fishing effort is managed. *Fish and Fisheries, 20*(2), 268-285.

Årland, K., & Bjørndal, T. (2002). Fisheries management in Norway—an overview. *Marine Policy, 26*(4), 307-313.

Armstrong, C. W., Eide, A., Flaaten, O., Heen, K., & Kaspersen, I. W. (2014). Rebuilding the Northeast Arctic cod fisheries–economic and social issues. *Arctic Review, 5*(1).

Armstrong, C. W., & Flaaten, O. (1991). The optimal management of a transboundary fish resource: the Arcto-Norwegian cod stock. In R. Arnason & T. Bjørndal (Eds.), *Essays on the economics of migratory fish stocks* (pp. 137-151). Berlin Springer.

Armstrong, C. W., & Sumaila, U. R. (2001). Optimal allocation of TAC and the implications of implementing an ITQ management system for the North-East Arctic cod. *Land Economics, 77*(3), 350-359.

Arnason, R., Sandal, L. K., Steinshamn, S. I., & Vestergaard, N. (2004). Optimal feedback controls: comparative evaluation of the cod fisheries in Denmark, Iceland, and Norway. *American Journal of Agricultural Economics, 86*(2), 531-542.

Årthun, M., Eldevik, T., Smedsrud, L., Skagseth, Ø., & Ingvaldsen, R. (2012). Quantifying the influence of Atlantic heat on Barents Sea ice variability and retreat. *Journal of Climate, 25*(13), 4736-4743.

Asche, F. (2009). Adjustment cost and supply response in a fishery: A dynamic revenue function. *Land Economics, 85*(1), 201-215.

Asche, F., Bjørndal, M. T., & Bjørndal, T. (2014). Development in fleet fishing capacity in rights based fisheries. *Marine Policy, 44*, 166-171.

Asche, F., Bjørndal, T., & Gordon, D. V. (2009). Resource rent in individual quota fisheries. *Land Economics, 85*(2), 279-291.

Asche, F., Chen, Y., & Smith, M. D. (2015). Economic incentives to target species and fish size: prices and fine-scale product attributes in Norwegian fisheries. *Ices Journal of marine science, 72*(3), 733-740.

Asche, F., Flaaten, O., Isaksen, J. R., & Vassdal, T. (2002). Derived demand and relationships between prices at different levels in the value chain: a note. *Journal of Agricultural Economics, 53*(1), 101-107.

Asche, F., Gordon, D. V., & Hannesson, R. (2002). Searching for price parity in the European whitefish market. *Applied Economics, 34*(8), 1017-1024.

Asche, F., Menezes, R., & Dias, J. F. (2007). Price transmission in cross boundary supply chains. *Empirica, 34*(5), 477-489.

Béné, C. (1996). Effects of market constraints, the remuneration system, and resource dynamics on the spatial distribution of fishing effort. *Canadian Journal of Fisheries and Aquatic Sciences, 53*(3), 563-571.

Béné, C., & Tewfik, A. (2001). Fishing effort allocation and fishermen's decision making process in a multi-species small-scale fishery: Analysis of the conch and lobster fishery in Turks and Caicos Islands. *Human Ecology, 29*(2), 157-186.

Bergstad, O., Jørgensen, T., & Dragesund, O. (1987). Life history and ecology of the gadoid resources of the Barents Sea. *Fisheries Research, 5*(2-3), 119-161.

Bertheussen, B. A., & Dreyer, B. M. (2019). Is the Norwegian cod industry locked into a value-destructive volume logic? *Marine Policy, 103*, 113-120.

Birkenbach, A. M., Cojocaru, A. L., Asche, F., Guttormsen, A. G., & Smith, M. D. (2020). Seasonal Harvest Patterns in Multispecies Fisheries. *Environmental and Resource Economics, 75*(3), 631-655.

Bjørndal, T., & Gordon, D. V. (1993). The opportunity cost of capital and optimal vessel size in the Norwegian fishing fleet. *Land Economics*, 98-107.

Bjørndal, T., & Gordon, D. V. (2000). The economic structure of harvesting for three vessel types in the Norwegian spring-spawning herring fishery. *Marine Resource Economics, 15*(4), 281-292.

Branch, T. A., & Hilborn, R. (2008). Matching catches to quotas in a multispecies trawl fishery: targeting and avoidance behavior under individual transferable quotas. *Canadian Journal of Fisheries and Aquatic Sciences, 65*(7), 1435-1446.

Brinkhof, J., Olsen, S. H., Ingólfsson, Ó. A., Herrmann, B., & Larsen, R. B. (2018). Sequential codend improves quality of trawl-caught cod. *PLoS One, 13*(10), e0204328.

Bucaram, S. J., & Hearn, A. (2014). Factors that influence the entry–exit decision and intensity of participation of fishing fleet for the Galapagos lobster fishery. *Marine Policy, 43*, 80-88.

Campbell, R. A. (2004). CPUE standardisation and the construction of indices of stock abundance in a spatially varying fishery using general linear models. *Fisheries Research, 70*(2-3), 209-227.

Casey, J. M., & Myers, R. A. (1998). Near extinction of a large, widely distributed fish. *Science, 281*(5377), 690-692.

Charles, A. T. (1995). Fishery science: the study of fishery systems. *Aquatic Living Resources, 8*(3), 233-239.

Christensen, A.-S., & Raakjær, J. (2006). Fishermen's tactical and strategic decisions: A case study of Danish demersal fisheries. *Fisheries Research, 81*(2-3), 258-267.

Christensen, P., & Nielssen, A. R. (1996). Norwegian fisheries 1100–1970: main developments. *The North Atlantic Fisheries*, 1100-1976.

Cojocaru, A. L., Asche, F., Pincinato, R. B. M., & Straume, H.-M. (2019). Where are the fish landed? An analysis of landing plants in Norway. *Land Economics, 95*(2), 246-257.

Cooke, J., & Beddington, J. (1984). The relationship between catch rates and abundance in fisheries. *Mathematical Medicine and Biology: A Journal of the IMA, 1*(4), 391-405.

Copes, P. (1986). A critical review of the individual quota as a device in fisheries management. *Land Economics, 62*(3), 278-291.

Cunningham, S., & Whitmarsh, D. (1980). Fishing effort and fisheries policy. *Marine Policy, 4*(4), 309-316.

Deporte, N., Ulrich, C., Mahévas, S., Demaneche, S., & Bastardie, F. (2012). Regional métier definition: a comparative investigation of statistical methods using a workflow applied to international otter trawl fisheries in the North Sea. *Ices Journal of marine science, 69*(2), 331-342.

Diekert, F. K., Hjermann, D. Ø., Nævdal, E., & Stenseth, N. C. (2010a). Non-cooperative exploitation of multi-cohort fisheries—The role of gear selectivity in the North-East Arctic cod fishery. *Resource and Energy Economics, 32*(1), 78-92.

Diekert, F. K., Hjermann, D. Ø., Nævdal, E., & Stenseth, N. C. (2010b). Spare the young fish: optimal harvesting policies for North-East Arctic cod. *Environmental and Resource Economics, 47*(4), 455-475.

Dreyer, B., & Grønhaug, K. (2004). Uncertainty, flexibility, and sustained competitive advantage. *Journal of business research, 57*(5), 484-494.

Dreyer, B., Isaksen, J. R., Bendiksen, B. I., & Rånes , S. A. (2006). *Evaluering av leveringsplikten.* Fiskeriforskning. Tromsø.

Drivenes, Einar-Arne og Ragnar Jernsletter (1994), “Det gjenstridige nord-norge: Religiøs, politisk og etnisk mobilisering 1850-1990”. In Einer Arne Drivenes, Marit Anne Hauan og Helge A. Wold (eds), *Nordnorsk kulturhistorie*. Oslo.

Dupont, D. P., Fox, K. J., Gordon, D. V., & Grafton, R. Q. (2005). Profit and price effects of multi-species individual transferable quotas. *Journal of Agricultural Economics, 56*(1), 31-57.

Durrenberger, E. P., & Pálsson, G. (1983). Riddles of herring and rhetorics of success. *Journal of Anthropological Research, 39*(3), 323-335.

Eales, J., & Wilen, J. E. (1986). An examination of fishing location choice in the pink shrimp fishery. *Marine Resource Economics, 2*(4), 331-351.

Eide, A. (2007). Economic impacts of global warming: The case of the Barents Sea fisheries. *Natural Resource Modeling, 20*(2), 199-221.

Eide, A., Heen, K., Armstrong, C., Flaaten, O., & Vasiliev, A. (2013). Challenges and successes in the management of a shared fish stock–the case of the Russian–Norwegian Barents Sea cod fishery. *Acta Borealia, 30*(1), 1-20.

Eide, A., Skjold, F., Olsen, F., & Flaaten, O. (2003). Harvest functions: the Norwegian bottom trawl cod fisheries. *Marine Resource Economics, 18*(1), 81-93.

FAO. (2012). *The state of the world fisheries and aquaculture*. FAO. Rome.

Flaaten, O. (1983). The optimal harvesting of a natural resource with seasonal growth. *Canadian Journal of Economics*, 447-462.

Flaaten, O. (1987). Sesongvarierende bestandstilgjengelighet og produktfunksjoneri i Lofotfisket [Seasonal catchability variations and production functions in the Lofoten fishery] (in Norwegian). Report 7005/1-87. Forut. Tromsø.

Flaaten, O., & Heen, K. (2004). Fishing vessel profitability and local economic link obligations—the case of Norwegian trawlers. *Marine Policy, 28*(6), 451-457.

Fulton, E. A., Smith, A. D., Smith, D. C., & van Putten, I. E. (2011). Human behaviour: the key source of uncertainty in fisheries management. *Fish and Fisheries, 12*(1), 2-17.

Gabriel, O., Lange, K., Dahm, E., & Wendt, T. (2005). Fishing with Bottom Trawls. In O. Gabriel, K. Lange, E. Dahm, & T. Wendt (Eds.), *Fish Catching Methods of the World* (pp. 392-412). Oxford: Blackwell Publishing Ltd.

Garrod, D. (1967). Population dynamics of the Arcto-Norwegian cod. *Journal of the Fisheries Board of Canada, 24*(1), 145-190.

Godø, O. R., & Michalsen, K. (2000). Migratory behaviour of north-east Arctic cod, studied by use of data storage tags. *Fisheries Research, 48*(2), 127-140.

Gordon, D. V., & Hannesson, R. (1996). On prices of fresh and frozen cod fish in European and US markets. *Marine Resource Economics, 11*(4), 223-238.

Gordon, H. S. (1953). An economic approach to the optimum utilization of fishery resources. *Journal of the Fisheries Board of Canada, 10*(7), 442-457.

Gordon, H. S. (1954). The economic theory of a common-property resource: the fishery. *Journal of political economy, 62*, 178-203.

Graham, N., Ferro, R. S., Karp, W. A., & MacMullen, P. (2007). Fishing practice, gear design, and the ecosystem approach—three case studies demonstrating the effect of management strategy on gear selectivity and discards. *Ices Journal of marine science, 64*(4), 744-750.

Greaker, M., Grimsrud, K., & Lindholt, L. (2017). The potential resource rent from Norwegian fisheries. *Marine Policy, 84*, 156-166.

Grekov, A. A., & Pavlenko, A. A. (2011). *A Comparison of Longline and Trawl Fishing Practices and Suggestions for Encouraging the Sustainable Management of Fisheries in the Barents Sea*. WWF Technical Report, Murmansk.

Gullestad, P., Aglen, A., Bjordal, Å., Blom, G., Johansen, S., Krog, J., . . . Røttingen, I. (2014). Changing attitudes 1970–2012: evolution of the Norwegian management framework to prevent overfishing and to secure long-term sustainability. *Ices Journal of marine science, 71*(2), 173-182.

Guttormsen, A. G., & Roll, K. H. (2011). Technical efficiency in a heterogeneous fishery: the case of Norwegian groundfish fisheries. *Marine Resource Economics, 26*(4), 293-307.

Hallenstvedt, A. (1982). *Med lov og organisasjon: organisering av interesser og markeder i norsk fiskerinæring*. Tromsø: Universitetsforlaget.

Hammer, M., & Hoel, A. H. k. (2012). The development of scientific cooperation under the Norway–Russia fisheries regime in the Barents Sea. *Arctic Review, 3*(2).

Hamre, J. (1985). Assessment and management of Barents Sea capelin. Institute of Marine Research. Bergen.

Hamre, J. (2003). Capelin and herring as key species for the yield of north-east Arctic cod. Results from multispecies model runs. *Scientia Marina, 67*(S1), 315-323.

Hanchet, S. M., Blackwell, R. G., & Dunn, A. (2005). Development and evaluation of catch per unit effort indices for southern blue whiting (Micromesistius australis) on the Campbell Island Rise, New Zealand. *Ices Journal of marine science, 62*(6), 1131-1138.

Hannesson, R. (1983a). Bioeconomic production function in fisheries: Theoretical and empirical analysis. *Canadian Journal of Fisheries and Aquatic Sciences, 40*(7), 968-982.

Hannesson, R. (1983b). Optimal harvesting of ecologically interdependent fish species. *Journal of Environmental Economics and Management, 10*(4), 329-345.

Hannesson, R. (1997). Fishing as a Supergame. *Journal of Environmental Economics and Management, 32*(3), 309-322.

Hannesson, R. (2006). Sharing the Northeast Arctic cod: possible effects of climate change. *Natural Resource Modeling, 19*(4), 633-654.

Hannesson, R. (2007a). Buyback programs for fishing vessels in Norway. In R. Curtis & D. Squires (Eds.), *Fisheries Buybacks* (pp. 177-190). California: Blackwell.

Hannesson, R. (2007b). A note on the" stock effect". *Marine Resource Economics, 22*(1), 69-75.

Hannesson, R., Salvanes, K. G., & Squires, D. (2010). Technological change and the tragedy of the commons: the Lofoten fishery over 130 years. *Land Economics, 86*(4), 746-765.

Hannesson, R., & Steinshamn, S. I. (1991). How to set catch quotas: Constant effort or constant catch? *Journal of Environmental Economics and Management, 20*(1), 71-91.

Hart, P. J., & Pitcher, T. J. (1998). Conflict, consent and cooperation: an evolutionary perspective on individual human behaviour in fisheries management. In *Reinventing fisheries management* (pp. 215-225): Springer.

Heal, G. (2007). A celebration of environmental and resource economics. *Review of Environmental Economics and Policy, 1*(1), 7-25.

Heckman, J. J. (1976). The common structure of statistical models of truncation, sample selection and limited dependent variables and a simple estimator for such models. In *Annals of economic and social measurement, volume 5, number 4* (pp. 475-492): NBER.

Hermansen, Ø., & Dreyer, B. (2010). Challenging spatial and seasonal distribution of fish landings—The experiences from rural community quotas in Norway. *Marine Policy, 34*(3), 567-574.

Hersoug, B. (2005). *Closing the commons: Norwegian fisheries from open access to private property*. Utrecht: Eburon Academic Publishers.

Hersoug, B., & Leonardsen, D. (1979). *Bygger de landet? : distriktspolitikk og sosialdemokrati 1945-1975*. Oslo: Pax Forlag.

Hilborn, R. (1985). Fleet dynamics and individual variation: why some people catch more fish than others. *Canadian Journal of Fisheries and Aquatic Sciences, 42*(1), 2-13.

Hilborn, R. (2007). Managing fisheries is managing people: what has been learned? *Fish and Fisheries, 8*(4), 285-296.

Hilborn, R., Maguire, J.-J., Parma, A. M., & Rosenberg, A. A. (2001). The precautionary approach and risk management: can they increase the probability of successes in fishery management? *Canadian Journal of Fisheries and Aquatic Sciences, 58*(1), 99-107.

Hilborn, R., & Walters, C. J. (1992). *Quantitative fisheries stock assessment: choice, dynamics and uncertainty*. New York: Chapman and Hall.

Holland, D. S., & Sutinen, J. G. (1999). An empirical model of fleet dynamics in New England trawl fisheries. *Canadian Journal of Fisheries and Aquatic Sciences, 56*(2), 253-264.

Holland, D. S., & Sutinen, J. G. (2000). Location choice in New England trawl fisheries: old habits die hard. *Land Economics*, 133-149.

Holm, P. (2001). *The invisible revolution: The construction of institutional change in the fisheries.* (PhD thesis), The Arctic University of Norway (UiT), Tromsø.

Holm, P., Hersoug, B., & Rånes, S. (2000). Revisiting Lofoten: Co-managing fish stocks or fishing space? *Human Organization, 59*(3), 353-364.

Holm, P., & Rånes, A. S. (1996). *The Individual Vessel Quota System in the Norwegian Arctic Coastal Cod Fishery*. Paper presented at the The Sixth Annual Conference of the International Association for the Study of Common property, California.

Homrum, E. í., Hansen, B., Jónsson, S. Þ., Michalsen, K., Burgos, J., Righton, D., . . . Hátún, H. (2013). Migration of saithe (Pollachius virens) in the Northeast Atlantic. *Ices Journal of marine science, 70*(4), 782-792.

ICES. (2012). *The Barents Sea and the Norwegian Sea*. Technical Report, International Council for the Exploration of the Sea (ICES), Copenhagen.

Isaksen, J. R. (2007). *Upstream vertical integration and financial performance: the case of the Norwegian fish processing industry.* (PhD thesis), The Arctic University of Norway (UiT), Tromsø.

Jacobson, L. D., & Thomson, C. J. (1993). Opportunity costs and the decision to fish for northern anchovy. *North American Journal of Fisheries Management, 13*(1), 27-34.

Jakobsen, T. (1987). Coastal cod in northern Norway. *Fisheries Research, 5*(2-3), 223-234.

Johannesen, E., Johansen, G. O., & Korsbrekke, K. (2015). Seasonal variation in cod feeding and growth in a changing sea. *Canadian Journal of Fisheries and Aquatic Sciences, 73*(2), 235-245.

Johansen, J. (1972). *Trålfiske og trålerdebatt i 1930-årene.* (Hovedoppgåve i historie), Universitetet I Trondheim, Trondheim.

Johnsen, J. P., & Jentoft, S. (2017). Transferable qoutas in Norwegian fisheries. In M. G. Winder (Ed.), *Fisheries, quota management and quota transfer; Rationalization through bio-economics* (pp. 121-139). Cham: Springer.

Jones B. W., Jónsson J.. Coalfish tagging experiments at Iceland, *Rit Fiskideildar*, 1971, vol. 5 (pp. 1-27).

Jørgensen, L. L., Planque, B., Thangstad, T. H., & Certain, G. (2016). Vulnerability of megabenthic species to trawling in the Barents Sea. *Ices Journal of marine science, 73*(suppl_1), i84-i97.

Kasperski, S., & Holland, D. S. (2013). Income diversification and risk for fishermen. *Proceedings of the National Academy of Sciences, 110*(6), 2076-2081.

Kelleher, K., Willmann, R., & Arnason, R. (2009). *The sunken billions: the economic justification for fisheries reform*. Washington D.C: The World Bank and The Food and Agriculture Organization of the United Nation (FAO).

King, T. J. (2011). The" skipper effect": riddles of luck and rhetorics of individualism. *Human Organization*, 387-396.

Kumbhakar, S. C., Asche, F., & Tveteras, R. (2013). Estimation and decomposition of inefficiency when producers maximize return to the outlay: an application to Norwegian fishing trawlers. *Journal of Productivity Analysis, 40*(3), 307-321.

Kvamsdal, S. (2016). Technical change as a stochastic trend in a fisheries model. *Marine Resource Economics, 31*(4), 403-419.

Kvingedal, B. (2005). *Sea-ice extent and variability in the Nordic Seas, 1967—2002.* (PhD thesis), University of Bergen, Bergen.

Lane, D. E. (1988). Investment decision making by fishermen. *Canadian Journal of Fisheries and Aquatic Sciences, 45*(5), 782-796.

Larkin, P. A. (1977). An epitaph for the concept of maximum sustained yield. *Transactions of the American fisheries society, 106*(1), 1-11.

Larsen, R. B., Herrmann, B., Brinkhof, J., Grimaldo, E., Sistiaga, M., & Tatone, I. (2018). Catch Efficiency of Groundgears in a Bottom Trawl Fishery: A Case Study of the Barents Sea Haddock. *Marine and Coastal Fisheries, 10*(5), 493-507.

Lazkano, I., & Nøstbakken, L. (2016). Quota enforcement and capital investment in natural resource industries. *Marine Resource Economics, 31*(3), 339-354.

Lorentzen, T., & Hannesson, R. (2004). *The collapse of the Norwegian herring fisheries in the late 1950s and 60s: crisis, adaptation, and recovery*. Bergen: Institute for Research in Economics and Business Administration.

Ludwig, D., Hilborn, R., & Walters, C. (1993). Uncertainty, resource exploitation, and conservation: lessons from history. *Ecological applications*, 548-549.

Markowits, H. (1952). Portfolio selection. *Finance, 7*, 77-91.

Maunder, M. N., Sibert, J. R., Fonteneau, A., Hampton, J., Kleiber, P., & Harley, S. J. (2006). Interpreting catch per unit effort data to assess the status of individual stocks and communities. *Ices Journal of marine science, 63*(8), 1373-1385.

Maurstad, A. (2000). To fish or not to fish: small-scale fishing and changing regulations of the cod fishery in northern Norway. *Human Organization*, 37-47.

Mello, L., & Rose, G. (2005). Seasonal cycles in weight and condition in Atlantic cod (Gadus morhua L.) in relation to fisheries. *Ices Journal of marine science, 62*(5), 1006-1015.

Mikalsen, K. H., & Jentoft, S. (2003). Limits to participation? On the history, structure and reform of Norwegian fisheries management. *Marine Policy, 27*(5), 397-407.

Miranda, J. J., & Brandon, C. (2017). *The sunken billions revisited: Progress and challenges in global marine fisheries*. Washington, D.C.: The World Bank.

Misund, O. A., & Olsen, E. (2013). Lofoten–Vesterålen: for cod and cod fisheries, but not for oil? *Ices Journal of marine science, 70*(4), 722-725.

Myers, R. A., & Worm, B. (2003). Rapid worldwide depletion of predatory fish communities. *Nature, 423*(6937), 280-283.

Nakken, O. (1994). *Causes of trends and fluctuations in the Arcto-Norwegian stock.* Paper presented at the ICES Marine Science Symposia, Reykjavik.

Neuenfeldt, S., Righton, D., Neat, F., Wright, P., Svedäng, H., Michalsen, K., . . . Pampoulie, C. (2013). Analysing migrations of Atlantic cod Gadus morhua in the north-east Atlantic Ocean: then, now and the future. *Journal of Fish Biology, 82*(3), 741-763.

Nielsen, M., Smit, J., & Guillen, J. (2009). Market integration of fish in Europe. *Journal of Agricultural Economics, 60*(2), 367-385.

Nøstbakken, L., Thebaud, O., & Sørensen, L.-C. (2011). Investment behaviour and capacity adjustment in fisheries: a survey of the literature. *Marine Resource Economics, 26*(2), 95-117.

O'Farrell, S., Chollett, I., Sanchirico, J. N., & Perruso, L. (2019). Classifying fishing behavioral diversity using high-frequency movement data. *Proceedings of the National Academy of Sciences, 116*(34), 16811-16816.

Olsen, E., Aanes, S., Mehl, S., Holst, J. C., Aglen, A., & Gjøsæter, H. (2010). Cod, haddock, saithe, herring, and capelin in the Barents Sea and adjacent waters: a review of the biological value of the area. *Ices Journal of marine science, 67*(1), 87-101.

Opaluch, J. J., & Bockstael, N. E. (1984). Behavioral modeling and fisheries management. *Marine Resource Economics, 1*(1), 105-115.

Ottersen, G. (2008). Pronounced long-term juvenation in the spawning stock of Arcto-Norwegian cod (Gadus morhua) and possible consequences for recruitment. *Canadian Journal of Fisheries and Aquatic Sciences, 65*(3), 523-534.

Pethon, P. (2005). *Aschehougs store fiskebok: Norges fisker i farger* (B. O. Nyström Ed.). Oslo: Aschehoug & Co.

Popov, S., & Zeller, D. (2019). Reconstructed Russian fisheries catches in the Barents Sea: 1950-2014. *Frontiers in Marine Science, 6*.

Porter, M. E. (1980). *Competitive strategy: Techniques for analyzing industries and competitors*. New York: Free Press.

Pramod, G. (2018). Norway-Country report, In: Policing the Open Seas: *Global Assessment of Fisheries Monitoring Contorl and Surveillance in 84 countries*, IUU Risk Intelligence-Policy Report No.1, Canada.

Quirijns, F., Poos, J., & Rijnsdorp, A. (2008). Standardizing commercial CPUE data in monitoring stock dynamics: accounting for targeting behaviour in mixed fisheries. *Fisheries Research, 89*(1), 1-8.

Reimer, M. N., & Abbott, J. K. (2020). Structural Behavioral Models for Rights-Based Fisheries. *Available at SSRN 3582502.*

Reimer, M. N., & Wilen, J. (2013). Regulated open access and regulated restricted access fisheries. *Encyclopedia of Energy, Natural Resource, and Environmental Economics, 2*, 215-233.

Riordan, M. (1990). What is vertical integration? In M. Aoki, B. Gustafsson, & O. E. Williamson (Eds.), *The firm as a nexus of treaties* (pp. 94-111). London: Sage.

Rose, G. A. (1993). Cod spawning on a migration highway in the north-west Atlantic. *Nature, 366*(6454), 458.

Salas, S., & Gaertner, D. (2004). The behavioural dynamics of fishers: management implications. *Fish and Fisheries, 5*(2), 153-167.

Salvanes, K. G., & Squires, D. (1995). Transferable quotas, enforcement costs and typical firms: an empirical application to the Norwegian trawler fleet. *Environmental and Resource Economics, 6*(1), 1-21.

Sandberg, P. (2006). Variable unit costs in an output-regulated industry: the fishery. *Applied Economics, 38*(9), 1007-1018.

Schaefer, M. B. (1954). Some aspects of the dynamics of populations important to the management of the commercial marine fisheries. *Inter-American Tropical Tuna Commission Bulletin, 1*(2), 23-56.

Schlosser, I. J. (1991). Stream fish ecology: a landscape perspective. *BioScience, 41*(10), 704-712.

Schwalme, K., & Chouinard, G. (1999). Seasonal dynamics in feeding, organ weights, and reproductive maturation of Atlantic cod (Gadus morhua) in the southern Gulf of St Lawrence. *Ices Journal of marine science, 56*(3), 303-319.

Scott, A., & Neher, P. A. (1981). *The public regulation of commercial fisheries in Canada*. Ottawa: Economic Council of Canada.

Sethi, S. A., Reimer, M. N., & Knapp, G. (2014). Alaskan fishing community revenues and the stabilizing role of fishing portfolios. *Marine Policy, 48*, 134-141.

Shimadzu, H., Dornelas, M., Henderson, P. A., & Magurran, A. E. (2013). Diversity is maintained by seasonal variation in species abundance. *BMC biology, 11*(1), 98.

Smith, C. L., & Hanna, S. (1993). Occupation and community as determinants of fishing behaviors. *Human Organization, 52*(3), 299-303.

Smith, M. D. (2012). The new fisheries economics: incentives across many margins. *Annual Review of Resource Economics, 4*(1), 379-402.

Solhaug, T. (1976). *De norske fiskeriers historie 1815-1880*. Bergen. Universitetsforlaget.

Squires, D., Campbell, H., Cunningham, S., Dewees, C., Grafton, R. Q., Herrick Jr, S. F., . . . Shallard, B. (1998). Individual transferable quotas in multispecies fisheries. *Marine Policy, 22*(2), 135-159.

Standal, D., & Hersoug, B. (2015). Shaping technology, building society; the industrialization of the Norwegian cod fisheries. *Marine Policy, 51*, 66-74.

Stergiou, K., Politou, C.-Y., Christou, E., & Petrakis, G. (1997). Selectivity experiments in the NE Mediterranean: the effect of trawl codend mesh size on species diversity and discards. *Ices Journal of marine science, 54*(5), 774-786.

Stokke, O. S., Anderson, L. G., & Mirovitskaya, N. (1999). The Barents Sea Fisheries. In O. R. Young (Ed.), *The effectiveness of international environmental regimes: causal connections and behavioral mechanisms* (pp. 91-154). Cambridge: MIT Press.

Sumaila, U. R. (1997). Cooperative and non-cooperative exploitation of the Arcto-Norwegian cod stock. *Environmental and Resource Economics, 10*(2), 147-165.

Sundby, S., & Nakken, O. (2008). Spatial shifts in spawning habitats of Arcto-Norwegian cod related to multidecadal climate oscillations and climate change. *Ices Journal of marine science, 65*(6), 953-962.

Thorlindsson, T. (1994). Skipper science: a note on the epistemology of practice and the nature of expertise. *Sociological quarterly, 35*(2), 329-345.

Trout, G. (1957). *The Bear Island Cod: Migrations and Movement*. Ministry of Agriculture and Food Fisheries Investigations Series **2, 21**.

Vestergaard, N., Jensen, F., & Jørgensen, H. P. (2005). Sunk cost and entry-exit decisions under individual transferable quotas: why industry restructuring is delayed. *Land Economics, 81*(3), 363-378.

Vignaux, M. (1996). Analysis of vessel movements and strategies using commercial catch and effort data from the New Zealand hoki fishery. *Canadian Journal of Fisheries and Aquatic Sciences, 53*(9), 2126-2136.

Wikan, A., & Eide, A. (2004). An analysis of a nonlinear stage-structured cannibalism model with application to the Northeast Arctic cod stock. *Bulletin of Mathematical Biology, 66*(6), 1685-1704.

Wilen, J. E., Smith, M. D., Lockwood, D., & Botsford, L. W. (2002). Avoiding surprises: incorporating fisherman behavior into management models. *Bulletin of Marine Science,*

Wilson, J. A., Acheson, J. M., Metcalfe, M., & Kleban, P. (1994). Chaos, complexity and community management of fisheries. *Marine Policy, 18*(4), 291-305.

# Paper 1

Alizadeh Ashrafi, T., Eide, A. & Hermansen, Ø.

**Spatial and temporal distributions in the Norwegian Cod fishery**

Manuscript.

Now published in *Natural Resource Modeling, 33*(4), 2020, e12276.
https://doi.org/10.1111/nrm.12276

# Spatial and temporal distributions in the Norwegian Cod fishery

Tannaz Alizadeh Ashrafi, The Arctic University of Norway (UiT), Norwegian College of Fishery Science, Muninbakken 21, 9019, Tromsø, Norway, Email address: tannaz.alizadeh@uit.no, 0047- 77620824

Arne Eide, The Arctic University of Norway (UiT), Norwegian College of Fishery Science, Muninbakken 21, 9019, Tromsø, Norway, Email address: arne.eide@uit.no, 0047- 77645583

Øystein Hermansen, The Norwegian Institute of Food, Fisheries and Aquaculture Research (NOFIMA), Muninbakken 9, 9019 Tromsø, Norway, Email address: oystein.hermansen@nofima.no, 0047- 77629109

# Abstract

Fisheries are characterized by variations in space and time. This study investigates the characteristics of seasonality in cod trawl fisheries in two distinct areas: the coast along the northern Norway and the high sea area of the Barents Sea. Catch per unit of effort (CPUE) is used to proxy variation in stock abundance. A CPUE function has been estimated in the frequency-domain framework, to detect the presence of seasonality. Our analysis reveals that seasonality in stock abundance is only present in the northern coast of Norway. We conclude that as a consequence of seasonality in stock aggregation during the first quarter of the fishing year, possible economic losses caused by reduced prices -stemming from a large supply of cod- is larger than the economic benefits from cost reduction per unit of harvest. We speculate that declined price and consequently potential economic losses encourage trawlers to substitute cod by other high value fisheries during the winter months. As the price of cod starts to rise after the first quarter, trawlers begin to target cod in the high sea areas, a region with less seasonality.

Keywords: Seasonality; spatiality; Frequency domain; Trawl fishery; Cod fishery

# Recommendations for resource managers

Taking into account findings, policy formations and management considerations may include:

- Improving understanding of the spatial and temporal distribution of CPUE. This allows for better long- and medium term planning of vessel capacity and technology.
- Allowing also for better planning of the distribution of fishing effort across the year, which improves economic yield.
- Sharing the result of the study will improve short-term utilization and economic yield among the fishing fleet.
- Information on variations in CPUE over time and space may be relevant for authorities and researchers in evaluation of stock abundance.

# 1. Introduction

Almost all fisheries are subjected to constantly changing marine environment and various biological responses by fish stocks (e.g., migration pattern) conditioned by environmental fluctuations (Godø & Michalsen, 2000; Maslov, 1972; Mello & Rose, 2005a, 2005b). When fluctuations are repeated annually, seasonality may become a significant and persistent characteristic of fisheries utilizing such resources, as in the fishery of migratory cod (*Gadus morhua*) (Bartolino et al., 2012; Garrod, 1967; Godø & Michalsen, 2000; Maslov, 1972; Mello & Rose, 2005a, 2005b). The seasonality is defined by systematic fish density variations between and within various geographical areas throughout the year. Seasonality in fish behavior could influence harvest pattern and fisher's decision about how to allocate fishing effort (Flaaten, 1987). Perhaps the best known example of seasonal harvest is the Lofoten cod fishery (Hannesson et al., 2010; Hermansen & Dreyer, 2010; Standal & Hersoug, 2015).

The seasonality of the cod fishery is described in a vast number of studies (Eide et al., 2003; Flaaten, 1987, Godø & Michalsen, 2000; Maslov, 1972; Sundby & Nakken, 2008; Trout, 1957; and more). However, the seasonality studies on cod is mainly dominated by biological literature, posing questions such as how seasonal cycles affect the physiological conditions of cod (Johannesen et al., 2015; Mello & Rose, 2005a, 2005b; Neuenfeldt et al., 2013; Sundby & Nakken, 2008; Schwalme & Chouinard, 1999). While this focus remains important, it is only a part of the wider issue of seasonality in cod fisheries. A neglected but important dimension is to see how seasonality affects market conditions as well as fishers' behavior in terms of redirecting fishing effort over time and space, and how it affects quota utilization in regulated fisheries.

Changes in environmental and oceanographic conditions leading to biological aggregation, could affect economic considerations such as price and cost per unit of harvest (Asch et al., 2015; Flaaten, 1983; Sanchirico & Wilen, 1999; Sundby & Nakken, 2008). For instance, Asche et al., (2015) have detected that market price of cod varies with harvest attributes such as when and where the fish was caught over the course of a year, which in turn could influence the effort allocation. Moreover, according to bioeconomic theory the cost per unit of harvest is inversely proportional to fish density, hence it might be advantageous to take large catches when the stock is dense (Hannesson, 2007; Sandberg, 2006). However, immediate drop in unit prices of harvest during periods of large catches works in the opposite direction (Flaaten, 1987; Hannesson, 2007; Hilborn & Walters, 1992; Larkin & Sylvia, 1999). These economic consequences could affect fisher's harvest behavior.

Eide et al., (2003) investigated and detected the existence of seasonality in the Norwegian trawl fishery of cod through fitting a harvest function while this fishery still was an open access fishery (1971-1985). However, this study lacks the spatial dimension and it is not obvious how the seasonal pattern affects the fishing behavior after the introduction of quota regulations. In fact, spatial dimension of fishery is not distinguishable from its temporality as different fishing grounds feature different biological and economic condition to catch fish over the course of a year (Asche et al., 2015; Béné & Tewfik, 2001; Flaaten, 1983; Sanchirico & Wilen, 1999).

Bottom trawling is a common method of fishing cod. The trawlers are ocean going vessels, reasonably homogenous in terms of length (size) and engine power, with the possibility of combining cod quota with quotas for other species such as saithe, haddock and shrimp (Johnsen & Jentoft, 2017; Standal & Hersoug, 2014; Flaaten & Heen, 2004; Salvanes & Squires, 1995). Trawlers have an advantage in coping with the rough climate condition in the high sea area (e.g., Svalbard) as well as providing fresh seafood throughout the year due to availability of advanced technology and equipment (e.g., processing deck and slurry ice machine or freezing capacity) (Flaaten & Heen, 2004; Standal & Hersoug, 2015). Technical characteristics of the trawl fleet together with flexibility of shifting from cod to other species , when cod is not favorable economically (e.g., low price) and/ or biologically (e.g., low abundance cod stock), could provide opportunity for the trawlers to mollify the potential adverse effect of seasonality (e.g., low prices) in the cod fishery (Salvanes & Squires, 1995). Despite voluminous literature on productivity studies of Norwegian trawl fleet (Asche et al., 2009; Bjørndal & Gordon, 1993, 2000; Guttormsen & Roll, 2011; Salvanes & Squires, 1995; Sandberg, 2006), the effect of seasonality on trawler's harvest pattern is far less researched.

Given the homogeneous structure of the fleet (e.g., size and length), here we assume equal technology among 54 active cod trawlers over 6 years (2011-2016). The ratio between catch and fishing effort; catch per unit effort (CPUE) therefore is assumed to reflect variation in stock abundance and possible seasonal pattern as well as partial productivity of the trawlers at a certain time in a certain location (Cooke & Beddington, 1984; Cunningham & Whitmarsh, 1980; Hanchet et al., 2005). Using fortnight CPUE values -catches per time (each haul is measured in hours)-, the first objective of this paper is to detect possible seasonality in the two areas: 1) along the northern coast Norway and 2) the high sea area of the Barents Sea. Using the CPUE values, we estimated a CPUE function through Fast Fourier Transformation (FFT) and Fourier series. The second objective is to provide a description of underlying causes of seasonality and the possible effect of seasonal cycles on the market conditions, fisher's decision-making process about reallocation of fishing effort and quota utilization. In addition, the present paper investigates whether the introduction of quota regulation has any effect on observed fishers' behavior and decision criteria in response to seasonality in cod stock.

It is worth mentioning that the behavioral researchers of fisheries believe that failure to incorporate fisher's behavior, even when fishery is biologically well-managed, leads to inefficiency of management (Charles, 1995; Hilborn, 1985, 2007; Hilborn & Walters, 1992; Wilen et al., 2002). Related to the preceding point, Diekert et al., (2010) claim that in spite of strict regulations on Norwegian cod fishery, overfishing is still detectable. Similarly, Asche et al., (2009) have identified substantial overcapacity in the Norwegian trawl fleet. Hence, understanding the extent of seasonality and its potential effect on fishing strategies, the decisions that trawlers make in deciding when, where and what to fish could lead to more efficient fisheries management. Moreover, as bottom trawling damages the seafloor and its habitat, recognition of intense trawling pressure in certain areas at certain times, could mitigate negative effects of trawling by implementing proper management practices (Bergman & Van Santbrink, 2000; He & Winger, 2010).

# 2. Method

## 2.1 Theoretical framework

Assume a fishery where the harvest of a given stock is a function of two variables: (1) the amount of fishing effort applied and (2) the stock's biomass. Using the canonical harvest model, which was introduced by Schaefer (1954), we have:

$$H(t,\gamma) = q\,E(t,\gamma)B(t,\gamma) \tag{1}$$

where $H(t,\gamma)$ is the harvest (here measured in tonne) at time $t$ and location $\gamma$, $E(t,\gamma)$ is the amount of fishing effort allocated at the same time and location (here measured as trawling hour per haul) and $B(t,\gamma)$ is the corresponding biomass of the exploited stock, e.g. total weight of the stock present at time $t$ in location $\gamma$. The parameter $q$ is the catchability coefficient, e.g. the portion of the available stock captured by one unit of effort. $q$ reflects the efficiency of the effort in catching fish (Hilborn & Walters, 1992). The output elasticities of the two variables in Equation (1) are equal to one and the elasticity of scale is two. Equation (1) can be rearranged to express the catch per unit of effort:

$$CPUE(t,\gamma) = H(t,\gamma)/E(t,\gamma) = q\,B(t,\gamma) \tag{2}$$

Since the CPUE is proportional to stock abundance by “catchability coefficient" $q$, CPUE may be used to detect seasonality, given that Equation (1) provides a reasonable description of catch production. The CPUE values presented here are measured in tonnes of cod caught per trawling hour for each haul.

## 2.2 Frequency domain analysis

If a periodic function is represented by a single sine function it provides a consistent repetition and regular periodicity over all time. However, real-world signals, such as CPUE, come with noises of different frequencies (Bloomfield, 2004; Oppenheim & Schafer, 1983; Proakis & Manolakis, 2001). When graphing such a signal in the time domain it is difficult to detect the periodicity, as the cycles may not be regular. Even though a real signal oscillates over time, the lengths of the cycles cannot be determined easily in the time domain, as peaks of signal are not evenly distributed (Bloomfield, 2004; Oppenheim & Schafer, 1983; Proakis & Manolakis, 2001).

Another limitation of analyzing a signal in the time domain is that noises are not separable from desirable signal (Bloomfield, 2004; Oppenheim & Schafer, 1983; Proakis & Manolakis, 2001). One solution to detect the periodicity of signals containing noise is to represent the signal of interest in the frequency domain. In the frequency domain, a particular signal is characterized by its fundamental periodicity, $T$, or fundamental frequency $f$ and angular frequency $\omega$. The reciprocal relation between the period $T$ and the frequency yields $f = \frac{1}{T}$, furthermore, $\omega = \frac{2\pi}{T}$ or $\omega = 2\pi f$.

The Fourier transformation decomposes any arbitrary signal with periodicity $T$, into a weighted sum of infinite sets of sinusoidal series of frequencies with $f = 0, 1, 2,3, \dots n$, which are called the $nth$ harmonics of the signal. The continuous Fourier transform of the signal $x(t)$ is defined by the following (Oppenheim & Schafer, 1983; Proakis & Manolakis, 2001):

$$X(f) = \int_{-\infty}^{+\infty} x(t)\, e^{-j2\pi ft} dt \tag{3}$$

where $X(f)$ shows the signal representation in the frequency domain. As can be seen, Fourier transform basically exhibits the signal with a bunch of complex exponential functions, each with its own frequency. The relationship between the exponential and the sine/cosine is given by Euler's Formula (Oppenheim & Schafer, 1983; Proakis & Manolakis, 2001):

$$e^{jx} = \cos(x) + j\sin(x)$$

This allow us to modify the Fourier transformation to

$$X(f) = \int_{-\infty}^{+\infty} x(t)(\cos(2\pi ft) - j\sin(2\pi ft))dt \tag{4}$$

Note that in our analysis, Fast Fourier Transform (FFT) has been employed, which is a more efficient algorithm to compute the Fourier transform of the input signal. The output of the FFT is complex data points in the frequency spectrum showing the amplitude of the signal at different frequency components present in the signal. The output of FFT helps us to identify the sufficient number of harmonics to reconstruct our signal.

Based on the Fourier series representation, it is known that the original periodic signal can be approximately generated by the sum of infinite sinusoidal functions (Bloomfield, 2004). Once we identified the number of relevant harmonics from output of FFT, we can build our trigonometric regression model (Fourier series), presented by

$$f(t) = \bar{a}_d + \sum_{n=1}^{N}[\alpha_n \cos(\omega nd) + b_n \sin(\omega nd)] + \varepsilon_t,\ d = 1,2,\dots 26 \tag{5}$$

with $\bar{a}_d$ representing the periodic mean, $\alpha_n$ and $b_n$ being the coefficients of the cosine and sine functions in the series, $n$ the current number of harmonics and $N$ the maximum number of harmonics. $\omega$ is angular frequency while $d$ represents the fortnight number running from the beginning of 2011 to the end of 2016. $\varepsilon_t$ represents random error in the model. We determine $\bar{a}_d$, $\alpha_n$ and $b_n$ using the following equations (Bloomfield, 2004; Oppenheim & Schafer, 1983; Proakis & Manolakis, 2001):

$$\bar{a}_d = \frac{1}{T}\sum_{d=1}^{T} a_d \tag{6}$$

$$\alpha_n = \frac{2}{T}\sum_{d=1}^{T} a_d \cos(2\pi nd/T) \tag{7}$$

$$b_n = \frac{2}{T}\sum_{d=1}^{T} a_d \sin(2\pi nd/T) \tag{8}$$

Model (5) above theoretically estimates and supports the entire real numbers for CPUE. However, we know that CPUE is non-negative. To constrain the estimated values of CPUE to be non-negative, we square our regression equation in model (5) to obtain only feasible range for CPUE. The Fourier coefficients are designed to minimize the square of the error from the actual observation to acquire the best fitting components.

# 3. Data

## 3.1 Fishery areas and geographical distinction

Cod (*Gadus morhua*) is a commercially valuable fish species found throughout the shelf seas of the North Atlantic (Godø & Michalsen, 2000; Maslov, 1972). It is a population-rich species that exhibits migratory behavior (Neuenfeldt et al., 2013; Rose, 1993; Sundby & Nakken, 2008). In Norwegian waters cod is traditionally classified into two types: coastal and Northeast Arctic (NEA) cod. NEA cod, the cod considered here, migrates from the Barents Sea, aggregating during the period of mid-January to late February at particular geographical locations, mainly along the northern coast of Norway, to spawn (Mello & Rose, 2005b; Neuenfeldt et al., 2013; Rose, 1993). The migratory pattern and congregation in the same spawning field occurs every year in succession, representing a seasonal distribution pattern (Godø & Michalsen, 2000). Spawning migrations of NEA cod towards the coastal areas of Norway gives rise to a winter fishery. After spawning, NEA cod swim to offshore areas where it is available to the high seas cod fisheries. Figures 1 and 2 show the spatial and temporal distribution of trawling activities over a period of six years (2011-2016), including a total of 64,747 single trawl hauls (including both single and double trawls).

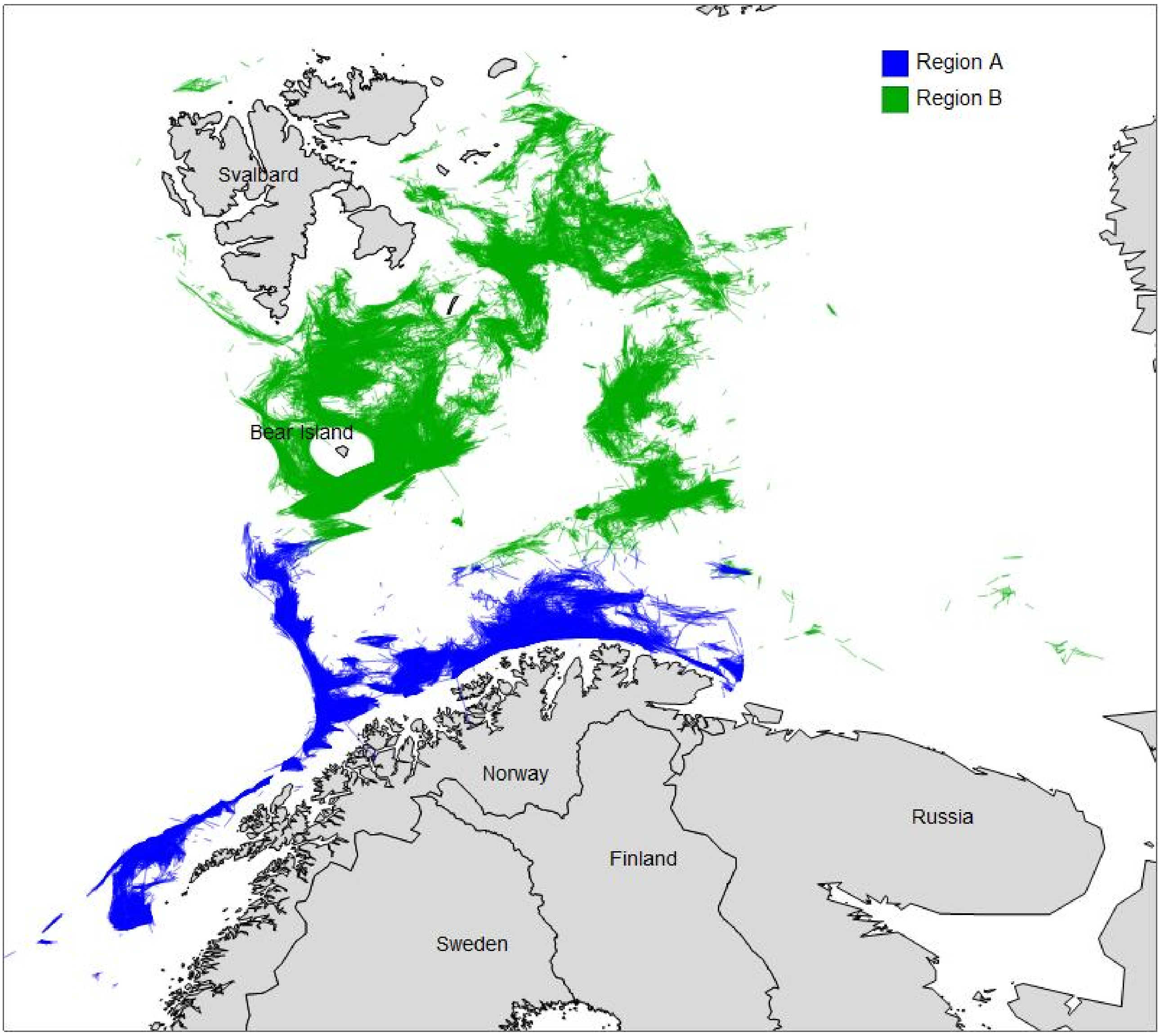

Figure 1. Positions (geolocations) of 64747 individual tows by 54 Norwegian registered trawl vessels 2011-2016 (Figure 1. excludes exceptionally short or long hauls and abnormal catch sizes) - Source: Norwegian Directorate of Fisheries

As it can be seen from Figure 1, fishing activity is concentrated in the fishing grounds off the northern coast of Norway (region A) and high north areas of northern Norway (region B). These arbitrary areas are chosen to reflect spatial heterogeneity such as level of resource availability, climate condition and proximity to shore. It should be noted that some of region A is not close to coast, rather following the slope down to deeper water. Since this constitutes a continuum with the near-coast activities, which southern part also is defined by the slope, it is included in region A. Figure 2 shows how trawlers allocate their fishing effort (thousand trawling hours) in the two regions over the course of a year on fortnightly basis.

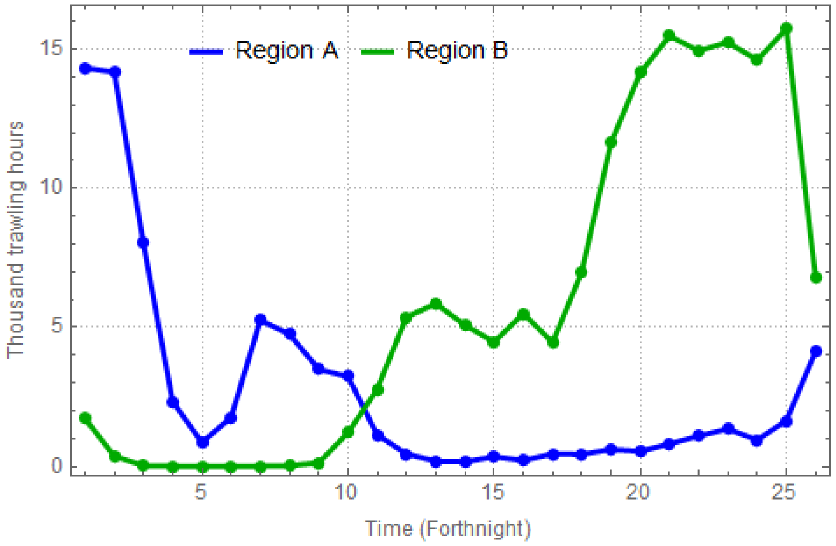

Figure 2. Total trawling time per fortnight spent on targeting cod in the two regions during the period 2011-2016. Source: Norwegian Directorate of Fisheries

As it can be seen from figure 2, effort allocation shows opposite patterns in the two regions. At the beginning of fishing season, effort is concentrated in region A, with its peak in January. The pattern is followed by a sudden drop in the fifth fortnight (March), and then it displays a plateau towards the end of the year. Whereas fishing effort in region B is dominantly concentrated at the end of the annual fishing season with its peak in December. A complete halt of production and effort allocation in the winter months for region B is observable, probably due to the harsh climate with extreme wind chill. Lack of fishing activities during the first quarter could be also attributed to the fact that trawlers are more attracted to region A due to cod assemblage and lower cost of fishing.

The economic benefits of stock aggregation (i.e., lower cost per tonne of catch) is even more highlighted for the coastal fleet using gears such as long lines, gillnets and Danish seine, as they are not able to traverse to distant areas to fish their quota (Asche et al., 2014; Hermansen & Dreyer, 2010; Maurstad, 2000). In the Norwegian cod fishery, it is the coastal fleet that takes the largest share of the total quota (approximately 65%), hence 80% of the Norwegian cod is landed in the first quarter of the fishing year along the northern coast of Norway (Asche et al., 2014; Hermansen & Dreyer, 2010; Standal & Hersoug, 2015).

In figure 3, we graph cod catches in thousand tonnes per fortnight broken down by years (2011-2016). The catch also includes cod that incidentally was caught as bycatch in fisheries targeting, for example, saithe or haddock. The pattern of catch is reasonably similar to the pattern of fishing effort evident in Figure 2. Not surprisingly, for region A, monthly catch is highest in at the beginning of the year (January) due to high densities of cod. Similar to the pattern of effort allocation in graph 2, there is a sudden drop in catch in February and March, even though cod stock density is still high. Comparable with Figure 2, catch size starts to rise in region B by May (fortnight number 10). Trawling is predominant in this region until the end of the fishing year.

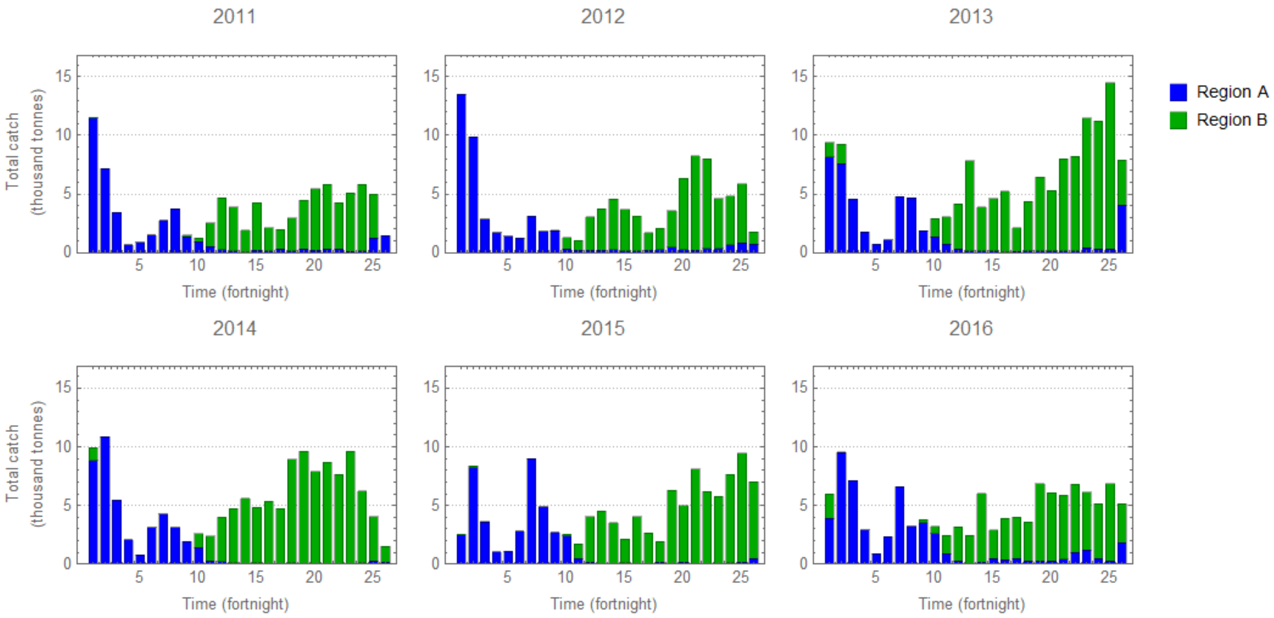

Figure 3. Fortnight cod catches (thousand tonnes) in the two areas during 2011-2016. Bycatch of cod when targeting other species is also included. Source: Norwegian Directorate of Fisheries

Figure 4 shows monthly average CPUE pertaining to regions A and B over the course of a year. The scores on the radar plot are on the scale of 0 to 8 in steps of 2, showing values of CPUE. From Figure 4, it can be seen that there is substantial variation in the magnitude of CPUE between the two regions. CPUE in region A displays a significant degree of variation where it reaches its peak in March. Looking at Figure 3, we see that even though in March (5th and 6th fortnight) catch size is considerably low, CPUE has the highest value of approximately 6 tonnes per hour of trawling, on average. The high value of CPUE arises because trawlers require less amount of fishing effort to catch cod when the stock is dense. Hence, reduction in trawling hour determines high CPUE in March. By April, when NEA cod migrates back to the high sea areas to feed, CPUE starts to decline considerably in region A. Since higher/ lower values of CPUEs are related to the time when the stock is congregated/ dispersed, this could offer some insight about the reason for seasonality in region A.

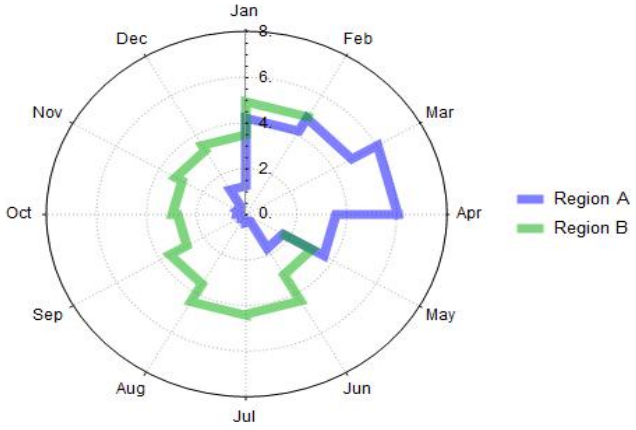

Figure 4. CPUE (tonne/ hour) in the selected areas (2011-2016) with radial axes representing different months with center at zero in steps of 2- Source: Norwegian Directorate of Fisheries

It is worth mentioning that initially we split the high sea area into two separate regions, a western and an eastern region. Since it was detected a strong resemblance between the level of CPUEs in the two regions, the regions were merged, recognizing them as one (region B). The rise in CPUE in region B occurs when NEA cod swims back to the Barents Sea. At this point in time, sea ice melts and weather becomes suitable in high north areas, encouraging fishers to redirect their fishing effort from region A to B. Productivity reaches its highest score in July and January with approximately 4 tonnes of cod per one hour of operation in region B. If we leave winter months (February and March) aside, CPUE is almost steady for the rest of the year. As pointed out earlier, when assuming a bi-linear catch equation, CPUE is proportional to stock (see Equation 2). Invariability in CPUE could drive the lack of seasonality in the high sea areas.

Figure 5, provides a richer description of the underlying distribution of CPUE and its variability in fortnight units in two regions.

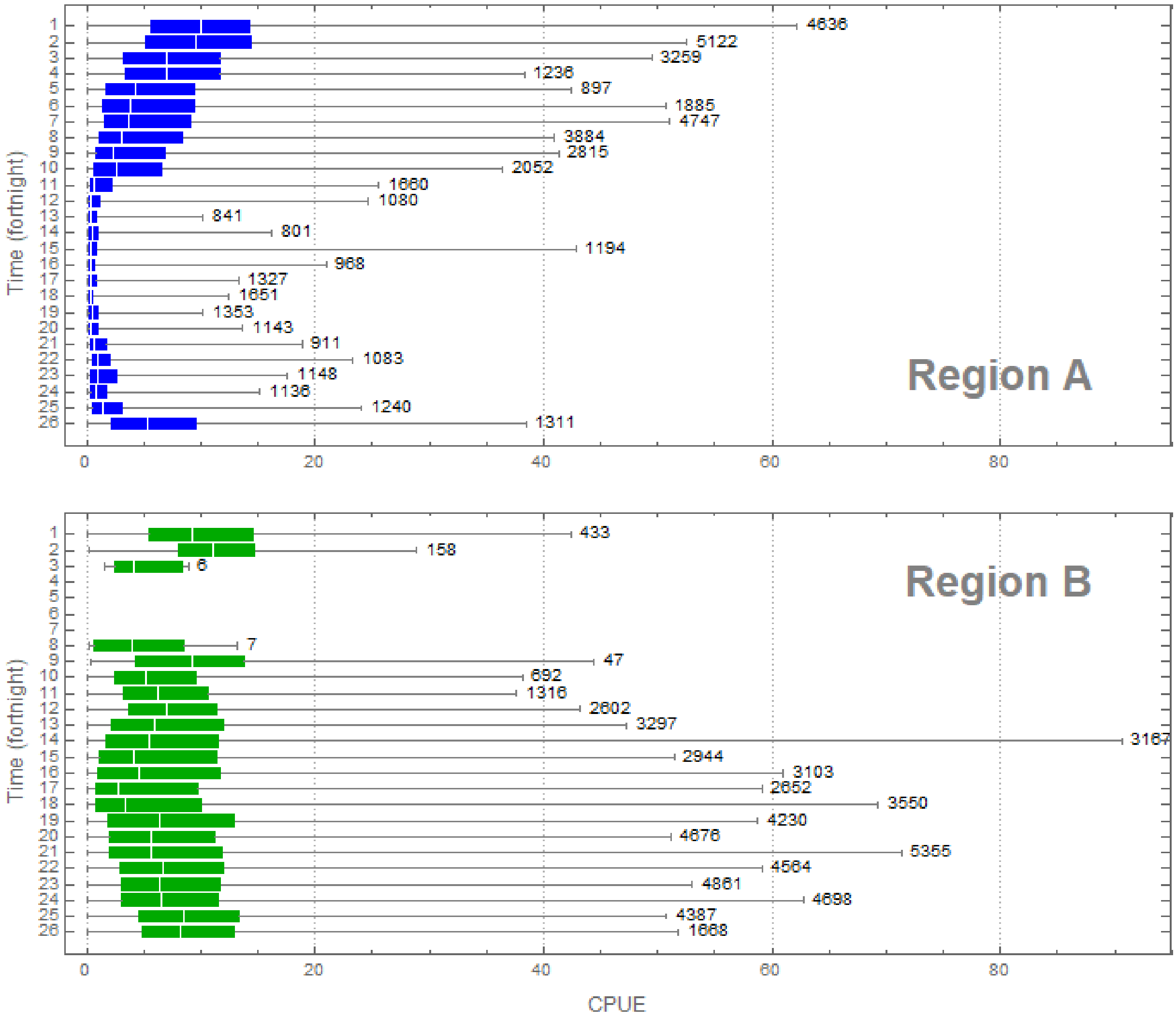

Figure 5. Comparative Box plot of fortnight distribution of CPUE (tonne/ hour) in the selected areas (2011-2016) with the corresponding number of trawling operations- Source: Norwegian Directorate of Fisheries

Figure 5 shows that the average CPUE and the number of trawling operations in the first quarter in region A is greater than that of those in region B. The opposite pattern is discernible for region B out of winter months. Excluding fortnights four to seven, we see that average values and interquartile ranges are reasonably similar in region B.

Seasonality in fish behavior could play an important role on price movement due to possible fluctuation in supply volume. Figure 6 shows the percentage change in the ex-vessel price of cod with respect to an average price of 15.92 NOK (per kilo) for trawl catches in 2016. From the figure, it is evident that the cod price is characterized by strong seasonal fluctuations. The price drops at the beginning of the year and stays below the average price until May, probably due to large cod supply in the market (Standal & Hersoug, 2015). As stated earlier, coastal fishing vessels, which holds a large share of cod quota, fish a significant part of their quota during the first quarter of the year, thus fishing industry has a good supply of fresh cod, leading to decline in the first-hand price. During the same period, it is rational to expect that trawlers switch to other fisheries –if these fisheries are available and profitable- as trawl fishery is multispecies fishery (Flaaten & Heen, 2004; Salvanes & Squires, 1995). When the busy winter season is over, the price of cod starts to rise and reach higher values in comparison to average price due to low landings as a small share of cod quota is left for the low seasons towards the end of the year (Hermansen & Dreyer, 2010). The monthly ex-vessel price data for cod caught by trawl fleet in 2016 is obtained from The Norwegian Directorate of Fisheries.

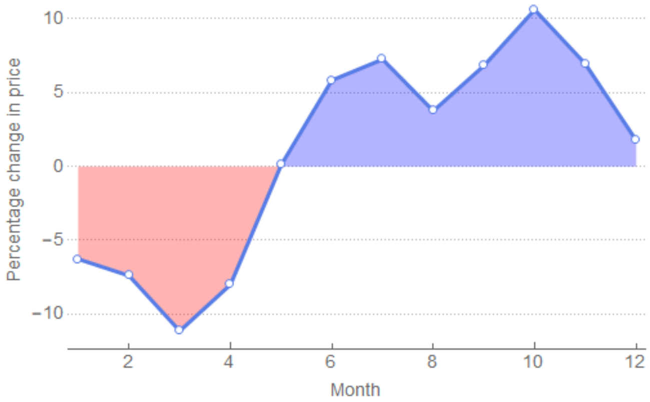

Figure 6. Percentage change in the frozen cod price in comparison to average price caught by trawl fleet in 2016

Source: Norwegian Directorate of Fisheries published data

### 3.2 Fortnightly basis for estimation of CPUE

Time series data of fisheries are inherently noisy. When the trawlers leave port they do not know with any degree of certainty, whether the catch will be good or poor. Unexpected failures in equipment, good or bad luck, weather conditions and other factors can introduce random variation into the magnitude of the catch (Kirkley et al., 1995; Salvanes & Steen, 1994; Squires & Kirkley, 1999; Thorlindsson, 1994). One way to reduce the random variation in CPUE is to aggregate CPUE data by fortnight. The rationale behind choosing fortnight data resolution is to cancel out most of the positive and negative randomness in the CPUE. We believe that a-14 day- period is long enough duration to offset positive and negative shocks of random occurrences in fishing activities. In this regard, our original data of 23,256 and 41,491 observations for CPUE for region A and B, obtained from individual tows of 54 active vessels over 2011-2016, are reduced to 157 fortnight datasets over 2011-2016 for each of the two regions. The effort component of CPUE is measured in trawling hours while catch is measured in tonnes. The CPUE values encompass fishing by single and double trawl operations. It is worth mentioning that since the chosen time resolution is fortnightly, fundamental periodicity $T$ has fortnight units, hence fundamental frequency $f$ shows the cycles made in a two-week time resolution.

Furthermore, it should be noted that, even though we have zero observations for catch and effort during fortnights four to seven (see Figure 2 and 3) in region B, which yields no CPUE, we conduct linear interpolation to obtain values for CPUE to fill the observations. The rationale behind this is that by doing so, our assumption that CPUE is taken as an estimate of stock size is still valid as no values for CPUE confound indexes of abundance (see Equation 2). Secondly, interpolation enhances the fit of our model.

## 4. Empirical results

Figure 7 shows the output of the FFT, which is the result of running a Fourier transform on the fortnightly CPUE signals for region A and B in the time domain after converting these signals to the frequency domain. Note that the frequency spectrum starts at zero, which is basically a constant, demonstrating the time average of the signal. For convenient frequency analysis, the absolute value of the FFT, which renders real-valued magnitudes, is employed. Figure 7 connects the magnitude of FFT points of the CPUE signals in region A and B to two line plots.

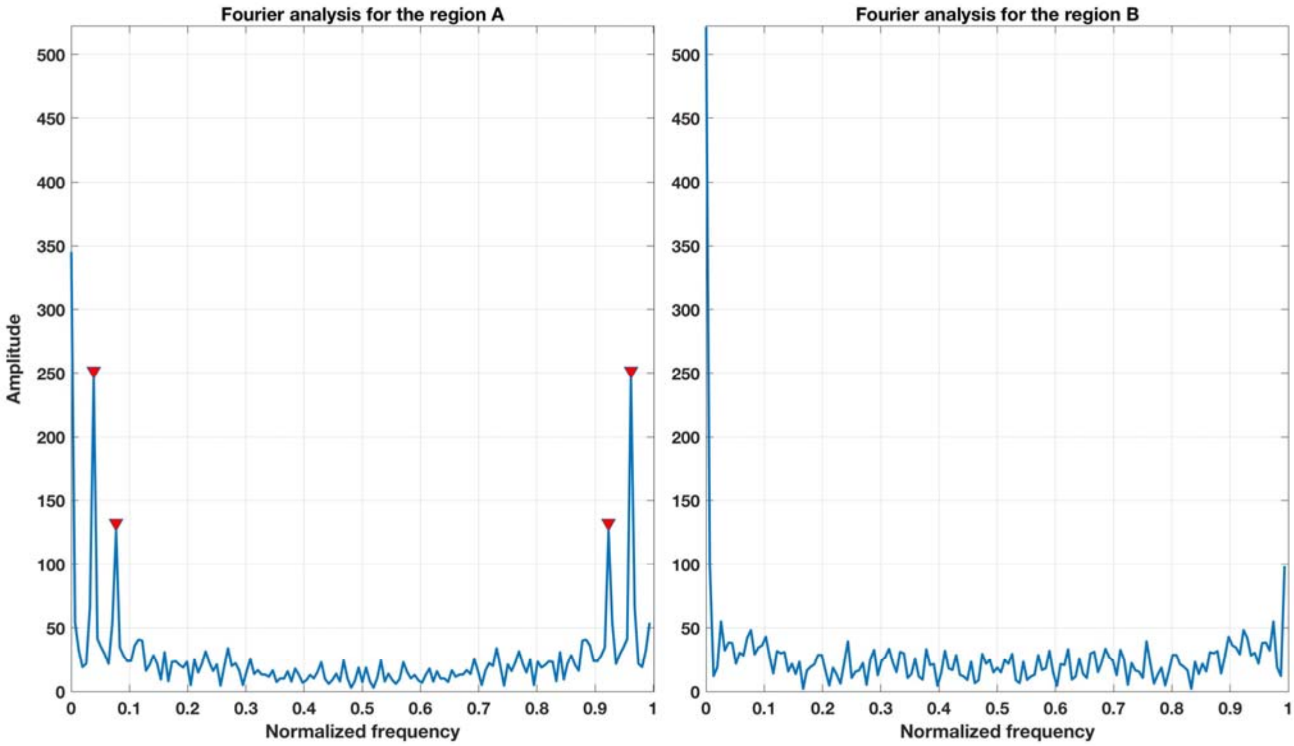

Figure 7. FFT of fortnight time-series of CPUE in region A and B- It extracts dominant frequency ($\frac{1}{fortnight}$) components in CPUE signal- Two detectable spikes are marked in region A, indicating seasonal behavior while no distinguishable spike is observed or marked for region B

Figure 7 carries important information on the existence of seasonality by detecting dominant frequencies and corresponding periods. What we mean by dominant frequencies are frequencies with the highest and most distinguishable spikes (amplitudes), as the frequencies with the highest amplitude represent the dominant periodic components in the original signal.

As it can be seen from Figure 7 the output of FFT in two regions are different. The CPUE spectrum for region A exhibits two strong peaks marked with triangles whereas no distinguishable spike is detected for region B. The existence of two conspicuous spikes in the signal in region A demonstrates the presence of seasonality in this region. For region A the first and highest spike is at the frequency 0.03822 and the second at a frequency of 0.07643, corresponding to the first and second harmonics. The corresponding period cycles for these frequencies for region A in terms of fortnights are $T_1 = 1/0.03822 = 26.16$ (annual) and $T_2 = 1/0.07643 = 13.08$ (semi-annual). The fundamental period of the signals for region A is $T = 26.16$, which corresponds to approximately one calendar year ($26.16 \times 14 = 366.24$ days). The spectrum displayed in Figure 7 shows no more distinct spikes in higher frequencies and remaining bumps are interpreted as random noise. Since seasonality in stock abundance through CPUE is only detected in region A, we estimate the CPUE function for region A.

After having identified the two harmonics from the FFT output, we run a trigonometric regression model (Fourier series) as described by model (5). The estimation results and corresponding $P$-values for region A are provided in Table 1.

Table 1. Estimated Fourier coefficient from aggregated fortnight hauls for region A

| Parameters | Fourier coefficient | $P$-value |
|---|---|---|
| $\bar{a}_d$ | 1.211 | 0.001 |
| $\alpha_1$ | 0.712 | 0.001 |
| $b_1$ | 0.845 | 0.001 |
| $\alpha_2$ | -0.251 | 0.001 |
| $b_2$ | 0.39 | 0.001 |
| $\omega$ | 0.2386 | 0.001 |
| $R^2$ | 0.6478 | - |

$\bar{a}_d$ in the Table 1 shows the periodic mean while $a_n$, $b_n$ and $\omega$ represent the estimated coefficients for the period functions of cosine and sine, and angular frequency, respectively. Based on the $P$-values, it can be concluded that the estimated coefficients are statistically significant. The estimated angular frequency for region A is $\omega = 0.2386$, which yields a period of 26.33 in fortnight units. This means that the cyclic pattern in cod stock aggregation repeats itself approximately every 26 fortnights, which is equal to one year. This result is consistent with the duration of the fishing year.

Figure 8 displays the scatterplot of observed data for fortnightly CPUE versus nonlinear regression line, obtained from model (5) with two harmonics. We also include the CPUE of individual hauls (gray dots) for a better visualization. Upon visual inspection in Figure 8, we could see that the reconstructed signal for region A (red line) satisfactorily follows the original observation CPUE data (blue dots).

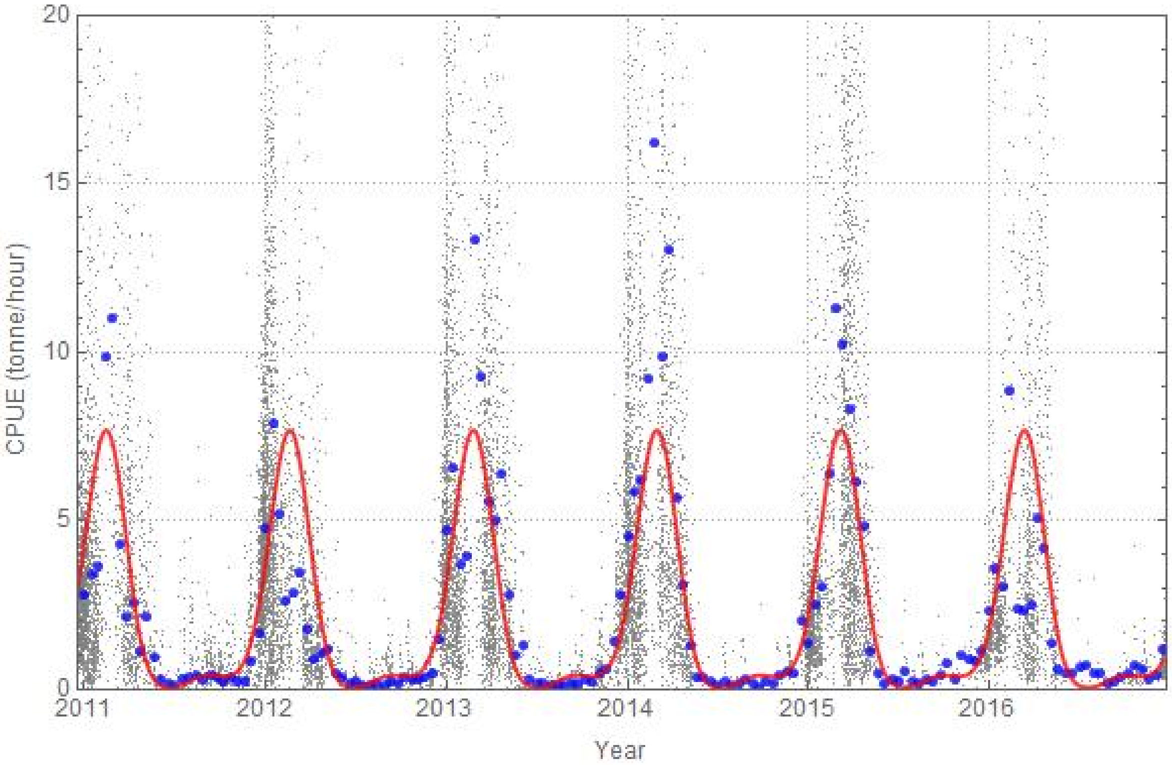

Figure 8. Scatter plot of fitted (red line) and actual observation of fortnightly CPUE (blue dots) in region A derived from model (5) by two harmonics * Gray dots represent actual observation of CPUE for each individual haul

Oscillation with almost regular and detectable cycles are evident over 6 years, implying that seasonality in cod stock recurs every year in succession. As can be seen in Figure 8, CPUE peaks in the beginning of the calendar year when NEA cod migrate from the Barents Sea southward to shallow waters of the northern coast of Norway. After the winter months are over, they swim back to the Barents Sea to feed. At this time the stock is less concentrated in this region, which results in lower CPUE.

# 5. Discussion

CPUE is used to show the variation in cod stock abundance over the course of a year in two regions; 1) shallow waters of the northern coast of Norway and 2) the high seas area. Migration of NEA cod to spawn in shallow waters (region A) and subsequently stock aggregation lead to high values of CPUE at the beginning of the fishing year. After the winter season, when NEA cod swim back to the Barents Sea to feed, the value of CPUE declines because the stock is less dense. The association of high/ low values of CPUE during first quarter of the year/ remaining months with dense/ dispersed stock availability reflects the presence of seasonality in region A. However, trawlers do not rigidly follow the seasonal pattern of stock abundance due to some economic considerations, which will be discussed below.

In contrast, in further offshore areas during winter months, there is almost no trawling activity probably due to high productivity of region A and/ or the harsh climate condition in the Arctic. If we relinquish winter months, there is no considerable variation in CPUE over the course of a year in region B, indicating that the cod stock does not follow a seasonal pattern.

We confirmed our primary assertion about the existence of seasonality in region A and lack of seasonality in region B by conducting FFT. The outcome of FFT shows two dominant frequencies for region A while no distinguishable peaks are detected for region B. The satisfactory fit for region A based on the trigonometric regression, using average values of fortnightly CPUE resulted in a fairly high $R^2$, meaning that, leaving other influential factors on CPUE aside, 64.78% of variation in CPUE is due to seasonal variation in cod distribution. This finding is *"partially"* consistent with the result from study of Eide et al., (2003) where they conclude that the availability of cod stock is seasonal. We use the term "partially" as their study lacks the geographical distinction.

What seems interesting is that despite the seasonality in the cod stock in region A, trawlers and their harvest patterns do not follow the seasonal pattern of the stock. This may be due to the fact that high CPUE creates two opposite effects through price and cost reduction. The availability of dense stock during winter months in region A reduces cost per tonne of catch (Hannesson, 2007; Sandberg, 2006). Therefore, from an economic point of view, it is advantageous to take large catches when the stock is dense. Lower cost of fishing per unit of harvest, also encourages coastal vessels with conventional gears, such as gillnet, to operate strictly during winter months (Hermansen & Dreyer, 2010; Maurstad, 2000; Standal & Hersoug, 2015). In addition, due to the limited mobility and simpler technology of coastal vessels, fishing near the northern coast during winter months is a great opportunity for them to utilize (Hermansen & Dreyer, 2010; Maurstad, 2000; Standal & Hersoug, 2015). The influx of cod supply in the marketplace in relatively short period results in price reduction (Asche et al., 2015; Norges Råfisklag; Standal & Hersoug, 2015). Reductions in the price of cod may offset or even reverse the advantages of fishing on an aggregated stock. This situation confines trawlers' time preferences to either fish during winter months at lower cost and lower price (region A) or to fish out of winter season at slightly higher cost and significant higher price (region B).

In order to find out which of the aforementioned strategies is chosen by the fishers, we need to know which of the strategies, pays off better. Considering trawl companies as rational agents, they would only continue participating in the cod fishery in region A during winter season if the magnitude of reduction in the cost per tonne of catch is big enough to offset the reduction in sales price. If we look at Figure 3 where there is a sudden drop in catch during winter season, we could conclude that the reduction in price outweighs the reduction in cost. In this situation, it is expected that trawlers redirect their fishing effort to the alternative fisheries with higher market value and reserve their cod quota for when the winter season ends and price of cod starts to rise (see Figure 3 and 6). To support our speculation, comparing the productivity level from radar plot in Figure 4, we see that the productivity of the cod fishery in region B out of winter season could be almost as high in region A during the winter fishery. Logically, while trawlers can achieve high productivity in region B and get higher sales price (see Figure 6) out of the winter season (Asche et al., 2015; Norges Råfisklag), it would be irrational for them to utilize the cod quota with low market price during first quarter of the calendar year in region A.

From a management point of view, the flexibility to combine quotas of different species together with readiness to switch among various target species plays an important role for the trawlers to cope with adverse effect of seasonality (price drop) in the cod fishery.

In addition, one of the underlying reasons for why fishers catch part of their cod quota at the beginning of the year while price is low and then withhold it in the hope of getting a better price, is that fishers have to make the most economical configuration of the quota portfolio. This means that by waiting too long until the price starts to rise (from May and after, see Figure 6), there is apprehension of not being able to catch the whole cod quota in the remaining part of the year. Under an open access fishery we would not expect to see this fishing pattern because the race for fish would compel fishers to commence harvesting as soon as the season opens and continue until the quota is exhausted irrespective of any financial advantages of distributing the catch over the year to take advantage of price swings and seasonal aggregations of cod.

## 6. Conclusion

The economic and managerial consequences of seasonality in the cod fishery have been overlooked by fisheries researchers. The purpose of the present paper is threefold: 1) to examine how the characteristics of seasonality vary between the west coast of northern Norway and the high seas areas under a regulated fishery, 2) to study the possible effect of seasonality on market conditions, fishers' harvest behavior and quota utilization, and 3) to investigate whether or not the introduction of quota has any effect on trawlers' fishing behavior.

In order to investigate the presence of seasonality, this study employs CPUE measures, as CPUE values reflect variation in fish availability. The analysis suggests that there is no seasonality in region B, where CPUE remains almost constant during fishing seasons. In contrast, in region A, CPUE exhibits large variation, indicating the presence of strong seasonality. Thereafter, the analysis of CPUE in frequency domain validated our initial speculation about presence and/ or lack of seasonality in the selected areas.

Seasonality in region A, induced from NEA cod aggregation in the northern coast of Norway has a ubiquitous effect on trawler’s fishing strategy and how they utilize their fishing quota. The availability of a dense cod stock has two opposite economic effects on harvest decision through a reduction in the cost of fishing per tonne caught and decreases price of fish. Trawlers are enticed by the reduced cost per tonne of catch. However, drop in price reduces their incentive to target cod.

Availability of a dense stock means lower unit cost of harvest encourages trawlers and fishers with passive gear to catch cod. This, in turn, leads to large cod landings and may reduce cod price. At this time, despite reduction in the cost per tonne of cod caught, trawlers may switch to targeting other species, which have higher market prices, suggesting that potential benefits from cost savings may not fully offset reductions. The crucial point to note, however, is that the promise of cost savings in the winter fishery in region A, by itself, may not be sufficient to encourage trawlers to remain in cod fishery. Later in May, when the cod price starts to rise, trawlers reallocate their effort to catch cod in the high seas areas where catch has better quality.

This shifting behavior indicates that trawlers are adaptive in their fishing strategies to overcome the adverse effects of seasonality. They switch to other fisheries when the payoff of the cod fishery falls below that available in the alternative fisheries. Any legislative change that could restrict the access to the different fisheries (e.g., area or seasonal closure) and readiness to bind quota will affect the adaptive behavior of the trawlers. This adaptive behavior further reveals that the collective behavior of trawlers is in accordance with economic theory of rational choice as they redirect fishing effort to a different fishery with higher expected profitability in comparison to other available alternatives. Surprisingly, our finding contradicts the outcome of several studies, which indicate that the fishers do not respond rationally to the changes in fishery conditions and that the economic man hardly exists in this sector (Béné & Tewfik, 2001; Holland, 2008).

As an additional contribution, investigating seasonality, its characteristics and potential effects could provide valuable information about destructive effect of intense trawling pressure at a certain time in a certain location including physical damage on seabed, benthic communities and reduction of populations being fished.

## Reference

Asche, F. (2009). Adjustment cost and supply response in a fishery: A dynamic revenue function. *Land Economics, 85*(1), 201-215.

Asche, F., Bjørndal, M. T., & Bjørndal, T. (2014). Development in fleet fishing capacity in rights based fisheries. *Marine Policy, 44*, 166-171.

Asche, F., Bjørndal, T., & Gordon, D. V. (2009). Resource rent in individual quota fisheries. *Land Economics, 85*(2), 279-291.

Asche, F., Chen, Y., & Smith, M. D. (2015). Economic incentives to target species and fish size: prices and fine-scale product attributes in Norwegian fisheries. *Ices Journal of marine science, 72*(3), 733-740.

Bartolino, V., Cardinale, M., Svedäng, H., Linderholm, H. W., Casini, M., & Grimwall, A. (2012). Historical spatiotemporal dynamics of eastern North Sea cod. *Canadian Journal of Fisheries and Aquatic Sciences, 69*(5), 833-841.

Béné, C., & Tewfik, A. (2001). Fishing effort allocation and fishermen's decision making process in a multi-species small-scale fishery: Analysis of the conch and lobster fishery in Turks and Caicos Islands. *Human Ecology, 29*(2), 157-186.

Bergman, M. J. N., & Van Santbrink, J. W. (2000). Mortality in megafaunal benthic populations caused by trawl fisheries on the Dutch continental shelf in the North Sea in 1994. *Ices Journal of marine science, 57*(5), 1321-1331.

Bjørndal, T., & Gordon, D. V. (1993). The opportunity cost of capital and optimal vessel size in the Norwegian fishing fleet. *Land Economics*, 98-107.

Bjørndal, T., & Gordon, D. V. (2000). The economic structure of harvesting for three vessel types in the Norwegian spring-spawning herring fishery. *Marine Resource Economics, 15*(4), 281-292.

Bloomfield, P. (2004). *Fourier analysis of time series: an introduction*. New York: John Wiley & Sons.

Charles, A. T. (1995). Fishery science: the study of fishery systems. *Aquatic Living Resources, 8*(3), 233-239.

Cooke, J., & Beddington, J. (1984). The relationship between catch rates and abundance in fisheries. *Mathematical Medicine and Biology: A Journal of the IMA*, 1(4), 391-405.

Cunningham, S., & Whitmarsh, D. (1980). Fishing effort and fisheries policy. *Marine Policy, 4*(4), 309-316.

Diekert, F. K., Hjermann, D. Ø., Nævdal, E., & Stenseth, N. C. (2010). Non-cooperative exploitation of multi-cohort fisheries—The role of gear selectivity in the North-East Arctic cod fishery. *Resource and Energy Economics, 32*(1), 78-92.

Eide, A., Skjold, F., Olsen, F., & Flaaten, O. (2003). Harvest functions: the Norwegian bottom trawl cod fisheries. *Marine Resource Economics, 18*(1), 81-93.

Flaaten, O. (1983). The optimal harvesting of a natural resource with seasonal growth. *Canadian Journal of Economics*, 447-462.

Flaaten, O. (1987). Sesongvarierende bestandstilgjengelighet og produktfunksjoneri i Lofotfisket [Seasonal catchability variations and production functions in the Lofoten fishery] (in Norwegian). Report 7005/1-87. Forut. Tromsø

Flaaten, O., & Heen, K. (2004). Fishing vessel profitability and local economic link obligations—the case of Norwegian trawlers. *Marine Policy, 28*(6), 451-457.

Garrod, D. (1967). Population dynamics of the Arcto-Norwegian cod. *Journal of the Fisheries Board of Canada, 24*(1), 145-190.

Godø, O. R., & Michalsen, K. (2000). Migratory behaviour of north-east Arctic cod, studied by use of data storage tags. *Fisheries Research, 48*(2), 127-140.

Guttormsen, A. G., & Roll, K. H. (2011). Technical efficiency in a heterogeneous fishery: the case of Norwegian groundfish fisheries. *Marine Resource Economics, 26*(4), 293-307.

Hanchet, S. M., Blackwell, R. G., & Dunn, A. (2005). Development and evaluation of catch per unit effort indices for southern blue whiting (Micromesistius australis) on the Campbell Island Rise, New Zealand. *Ices Journal of marine science*, 62(6), 1131-1138.

Hannesson, R. (2007). A note on the" stock effect". *Marine Resource Economics, 22*(1), 69-75.

Hannesson, R., Salvanes, K. G., & Squires, D. (2010). Technological change and the tragedy of the commons: the Lofoten fishery over 130 years. *Land Economics, 86*(4), 746-765.

He, P., & Winger, P. D. (2010). Effect of trawling on the seabed and mitigation measures to reduce impact. In P. He (Ed.), *Behavior of marine fishes: Capture processes and conservation challenges* (pp. 295-314). Ames Iowa: Wiley.

Hermansen, Ø., & Dreyer, B. (2010). Challenging spatial and seasonal distribution of fish landings—The experiences from rural community quotas in Norway. *Marine Policy, 34*(3), 567-574.

Hilborn, R. (1985). Fleet dynamics and individual variation: why some people catch more fish than others. *Canadian Journal of Fisheries and Aquatic Sciences, 42*(1), 2-13.

Hilborn, R. (2007). Managing fisheries is managing people: what has been learned? *Fish and Fisheries, 8*(4), 285-296.

Hilborn, R., & Walters, C. J. (1992). *Quantitative fisheries stock assessment: choice, dynamics and uncertainty*. New York: Chapman and Hall.

Holland, D. S. (2008). Are fishermen rational? A fishing expedition. *Marine Resource Economics, 23*(3), 325-344.

Johannesen, E., Johansen, G. O., & Korsbrekke, K. (2015). Seasonal variation in cod feeding and growth in a changing sea. *Canadian Journal of Fisheries and Aquatic Sciences, 73*(2), 235-245.

Johnsen, J. P., & Jentoft, S. (2017). Transferable quotas in Norwegian fisheries. In M. G. Winder (Ed.), *Fisheries, quota management and quota transfer; Rationalization through bio-economics* (pp. 121-139). Cham: Springer.

Kirkley, J. E., Squires, D., & Strand, I. E. (1995). Assessing technical efficiency in commercial fisheries: the mid-Atlantic sea scallop fishery. *American Journal of Agricultural Economics, 77*(3), 686-697.

Larkin, S. L., & Sylvia, G. (1999). Intrinsic fish characteristics and intraseason production efficiency: a management-level bioeconomic analysis of a commercial fishery. *American Journal of Agricultural Economics, 81*(1), 29-43.

Maslov, N. A., (1972). Migration of the Barents Sea cod. Fisheries Research Board of Canada, **21-29, 43**.

Maurstad, A. (2000). To fish or not to fish: small-scale fishing and changing regulations of the cod fishery in northern Norway. *Human Organization*, 37-47.

Mello, L., & Rose, G. (2005a). Seasonal cycles in weight and condition in Atlantic cod (Gadus morhua L.) in relation to fisheries. *Ices Journal of marine science, 62*(5), 1006-1015.

Mello, L., & Rose, G. (2005b). Using geostatistics to quantify seasonal distribution and aggregation patterns of fishes: an example of Atlantic cod (Gadus morhua). *Canadian Journal of Fisheries and Aquatic Sciences, 62*(3), 659-670.

Neuenfeldt, S., Righton, D., Neat, F., Wright, P., Svedäng, H., Michalsen, K., & Pampoulie, C. (2013). Analysing migrations of Atlantic cod Gadus morhua in the north-east Atlantic Ocean: then, now and the future. *Journal of Fish Biology*, 82(3), 741-763.

Norges Råfisklag, https://www.rafisklaget.no/portal/page/portal/NR/PrisogStatistikk

Oppenheim, A. V., & Schafer, R. W. (1983). *Digital signal processing. 1975*. New York: Englewood Cliffs.

Proakis, J. G., & Manolakis, D. K. (2001). *Digital signal processing: principles algorithms and applications*. London: Pearson Education India.

Rose, G. A. (1993). Cod spawning on a migration highway in the north-west Atlantic. *Nature, 366*(6454), 458.

Salvanes, K. G., & Steen, F. (1994). Testing for relative performance between seasons in a fishery. *Land Economics*, 431-447.

Salvanes, K. G., & Squires, D. (1995). Transferable quotas, enforcement costs and typical firms: an empirical application to the Norwegian trawler fleet. *Environmental and Resource Economics, 6*(1), 1-21.

Sanchirico, J. N., & Wilen, J. E. (1999). Bioeconomics of spatial exploitation in a patchy environment. *Journal of Environmental Economics and Management, 37*(2), 129-150.

Sandberg, P. (2006). Variable unit costs in an output-regulated industry: the fishery. *Applied Economics, 38*(9), 1007-1018.

Schaefer, M. B. (1954). Some aspects of the dynamics of populations important to the management of the commercial marine fisheries. *Inter-American Tropical Tuna Commission Bulletin, 1*(2), 23-56.

Squires, D., & Kirkley, J. (1999). Skipper skill and panel data in fishing industries. *Canadian Journal of Fisheries and Aquatic Sciences, 56*(11), 2011-2018.

Standal, D., & Hersoug, B. (2014). Back to square one? Fisheries allocation under pressure. *Marine Policy, 43*, 236-245.

Standal, D., & Hersoug, B. (2015). Shaping technology, building society; the industrialization of the Norwegian cod fisheries. *Marine Policy, 51*, 66-74.

Sundby, S., & Nakken, O. (2008). Spatial shifts in spawning habitats of Arcto-Norwegian cod related to multidecadal climate oscillations and climate change. *Ices Journal of marine science, 65*(6), 953-962.

Schwalme, K., & Chouinard, GA. (1999). Seasonal dynamics in feeding, organ weights, and reproductive maturation of Atlantic cod (Gadus morhua) in the southern Gulf of St Lawrence. *Ices Journal of marine science, 56*(3), 303-319.

Thorlindsson, T. (1994). Skipper science: a note on the epistemology of practice and the nature of expertise. *Sociological quarterly, 35*(2), 329-345.

Trout, G. (1957). *The Bear Island Cod: Migrations and Movement*. Ministry of Agriculture and Food Fisheries Investigations Series **2, 21**.

Wilen, J. E., Smith, M. D., Lockwood, D., & Botsford, L. W. (2002). Avoiding surprises: incorporating fisherman behavior into management models. *Bulletin of Marine Science, 70*(2), 553-575.

# Paper 2

Alizadeh Ashrafi, T., Syed, S. & Eide, A.

## Individual quotas and revenue risk of fishing portfolio in the trawl fishery

Manuscript.

Now published in *Fisheries Research, 241*, 2021, 105990.
https://doi.org/10.1016/j.fishres.2021.105990

# Individual quotas and revenue risk of fishing portfolio in the trawl fishery

Tannaz Alizadeh Ashrafi, The Arctic University of Norway (UiT), Norwegian College of Fishery Science, Muninbakken 21, 9019, Tromsø, Norway, Email address: tannaz.alizadeh@uit.no, 0047- 77620824

Shaheen Syed, The Arctic University of Norway (UiT), Department of Computer Science, Hansine Hansens veg 56, 9019 Tromsø, Norway, Email address: shaheen.a.syed@uit.no, 0047-77644162

Arne Eide, The Arctic University of Norway (UiT), Norwegian College of Fishery Science, Muninbakken 21, 9019, Tromsø, Norway, Email address: arne.eide@uit.no, 0047- 77645583

## Abstract

The revenue from fishing portfolio exhibits substantial intra-annual variation and carries a significant degree of risk due to the presence of intrinsic volatilities in marine environment such as seasonal fluctuations in stock size, changes in market conditions and varying management regulations over the course of a year. A classic harvest strategy to buffer revenue risk in the face of varying fishing environment is to catch a diverse fishing portfolio. Switching between target species to reduce revenue risk is a challenging task, as it embeds multiple interrelated decisions such as when to fish what and, how much to harvest to match the catch size and remaining quota, given the constraints set by the quotas. In this regard, a decision-making framework based on a bio-economic model is used to explore revenue risk minimization behavior of the Norwegian trawl fleet, targeting three different species (cod, saithe, and haddock). The study comprises trawl catches and fishing effort from 2011 to 2016 and two different scenarios of behavior have been investigated. The results indicate that catch diversification originates from different ways to enhance revenue, not necessarily to reduce the risk associated with the revenue. We argue that the advanced technology of the trawl vessels together with vertically integrated trawl industry may explain the prioritization of revenue enhancement over revenue risk minimization. The seasonal spawning aggregation of NEA cod and how this affects market prices, shape the trawlers’ harvest strategy on increasing fishing revenue. Furthermore, our findings indicate that a risk minimizing strategy could lead to inefficient allocation of fishing rights and fishing effort, and that potential economic losses from minimizing revenue risk outweighs its benefits.

Keywords: Revenue risk, Quota allocation, Trawl fishery, Diversification, Seasonality, Harvest strategy

**Highlights**

- Trawlers are profit-oriented and the main purpose of holding a diverse fishing portfolio is to increase fishing revenue, not necessarily to minimize revenue risk.
- The seasonal migration of North-east Atlantic cod predominantly determines the whole dynamics of the trawl fishery in generating profit.
- Vertical integration of the Norwegian trawl industry together with the advanced technology of the trawl fleet makes trawlers less vulnerable towards revenue fluctuations.
- Minimizing revenue risk leads to inefficient allocation of fishing effort and quota portfolio in the Norwegian trawl fleet.
- Since vessel and industry characteristics could sustain trawlers from revenue fluctuations, the implementation of enforcement rules such as season closure or area closure for conservation purposes might not considerably affect trawlers' revenue.

# 1 Introduction

Fishing is one of the most economically risky activities as fishers face high levels of revenue variability within a fishing year, particularly in the case of migratory fish species (Anderson et al., 2017; Kasperski & Holland, 2013; Sethi, 2010; Smith & Wilen, 2005). Revenues are generated by catch per unit of effort (CPUE) (reflecting fish availability (Hilborn & Walters,;Maunder et al., 2006)) and price, both of which could be affected by biological characteristics of fish species such as feeding and spawning migration patterns (Alizadeh Ashrafi et al., 2020; Asche et al., 2015; Birkenbach et al., 2020; Hermansen & Dreyer, 2010). The constant variation in fish availability and price together with possible changes in management schemes shapes revenue risk (Asche et al., 2015; Cline et al., 2017; Kasperski & Holland, 2013; Smith & Wilen, 2005).

Harvesting a diverse portfolio of fish stocks as a revenue risk reduction strategy has long been a critical feature of fisheries (Cline et al., 2017; Hilborn et al., 2001; Kasperski & Holland, 2013; Minnegal & Dwyer, 2008; Van Oostenbrugge et al., 2002). Analogous to portfolio effect (Markowits, 1952), the overall revenue risk of a fishing portfolio gets lower if the revenues from different fish stocks vary asynchronously (Kasperski & Holland, 2013; Schindler et al., 2010). Reducing revenue risk enables fishers to pay off the loans that were borrowed to purchase vessels and/or additional tangible (e.g., equipment) and non-tangible (e.g., fishing permits) capitals, which in the long-run leads to an economically viable fishing industry (Heady, 1952; Minnegal & Dwyer, 2008; Perruso et al., 2005; Sanchirico et al., 2008; Schindler et al., 2010; Sethi, 2010; Sethi et al., 2012).

Kasperski and Holland (2013), Sethi et al. (2014), Anderson et al. (2017), Finkbeiner (2015) and Cline et al. (2017) have acknowledged the inverse relationship between holding a diverse fishing portfolio and revenue risk in the small-scale fisheries. Although this is an important finding, they shed no light on the effect of seasonal migration of fish stocks on effort allocation and quota utilization to accomplish this objective, nor if the outcome of quota utilization to reduce revenue risk is efficient. Baldursson and Magnússon (1997) conclude that a diversification strategy by targeting different age cohorts of cod stock to buffer revenue risk in the Icelandic cod fishery, leads to inefficient effort allocation.

The Norwegian bottom-trawl fleet is quota-regulated and multi-species fisheries, targeting North-east Atlantic (NEA) cod (*Gadus morhua*) as the main species, together with large quantities of other economically important fish species, such as haddock (*Melanogrammus aeglefinus*) and saithe (*Pollachius virens*) (Asche, 2009; Flaaten & Heen, 2004; Salvanes & Squires, 1995).

Every winter, NEA cod, saithe and haddock aggregate and spawn along the north-west coast of Norway (Olsen et al., 2010; Rose, 1993). The stock aggregation could create two opposite effects on revenue through CPUE and price (Alizadeh Ashrafi et al., 2020; Eide et al., 2003; Flaaten, 1983, 1987), which might contribute to stabilization of revenue over the course of a year. The availability of dense stock increases CPUE (Hermansen & Dreyer, 2010; Maunder et al., 2006). However, the increased CPUE might encourage fishers (including coastal fishers) to increase landings, which in turn could lower the price (Alizadeh Ashrafi et al., 2020; Asche et al., 2015; Hermansen & Dreyer, 2010). In Norwegian fishery, coastal fleet gets a larger share of total quotas, and due to the confined geographical mobility coastal fishers almost exhaust their quotas during stock aggregation in winter (Asche et al., 2014; Hermansen & Dreyer, 2010). Hence their harvest behavior is expected to influence trawlers' adopted harvest strategy to stabilize revenue (Alizadeh Ashrafi et al., 2020; Asche et al., 2015; Hermansen & Dreyer, 2010). After spawning and out of the winter months, these fish stocks swim dispersedly (Olsen et al., 2010), leading to reduced CPUE. At this time, cod and haddock swim northward to the nutritious areas of The Barents Sea to feed (Olsen et al., 2010; Rose, 1993). The prices might increase due to the lower landings after the winter months. This is because, at this time, coastal fishers have already fished their quotas (Alizadeh Ashrafi et al., 2020; Birkenbach et al., 2020; Hermansen & Dreyer, 2010).

In essence, trawlers not only need to know how market reacts to stock dynamics over the course of a year but also need to recognize the magnitude of CPUE and price variabilities and their impacts on revenue fluctuations to choose the target species to stabilize revenue. This can be deceptively complicated given the contemporaneous spawning assemblages of these species in winter along the north-west coast and subsequently possible impact of the coastal trawlers' harvest strategy.

What adds more complication is that, under a quota management system shifting between target species involves considerations of how much to fish to match the catch size and quota, and to take advantage of possible seasonal aggregations of different stocks as well as price fluctuations, to buffer the risk of total revenue (Branch & Hilborn, 2008; Copes, 1986; Squires et al., 1998).

In this regard, the aim of this study is to address the sequential nature of decisions on when to target what (cod, saithe and haddock), and how much to fish, in order to minimize revenue risk in the Norwegian trawl fleet, respect to quota constraints. The empirical data from 2011 to 2016 have been used within a decision-making framework based on a bio-economic model. An important contribution of this paper is that revenue risk reduction has not been investigated for large-industrial fleet. In addition, this study explicitly considers two important aspects of fisheries: catch quotas and the effect of variability in stock availability in the decision-making process of trawlers, in relation to revenue risk minimization. Furthermore, since trawling practice often includes catch of non-targeted species, we take bycatch into consideration in our analysis.

The outcome of our analysis reveals trawlers' adaptive behavior in terms of allocating fishing effort towards revenue stability. Implementing fishers' behavior in fisheries management will promote the efficiency of regulatory systems (Charles, 1995; Hilborn, 1985, 2007; Hilborn & Walters, 1992; Opaluch & Bockstael, 1984; Wilen et al., 2002).

# 2 Theoretical framework

## 2.1 Measuring the risk of the portfolio revenue based on a bioeconomic model

Adopting Schaefer's (1954) harvest function to our framework, we have:

$$H_i(t) = q_i \cdot E_i(t) \cdot B_i(t) \tag{1}$$

where $H_i(t)$, $E_i(t)$ and $B_i(t)$ are measurements of total catch measured in tons, the amount of fishing effort expressed in trawling hours and, stock availability, expressed in tons at time $t$, respectively. $i$ refers to the available fisheries (here: cod, saithe and haddock). The constant factor $q_i$ refers to the catchability coefficient of each fishery, which addresses the efficiency of fishing operations (Hilborn & Walters, 1992; Maunder et al., 2006). Equation (1) shows unitary output elasticity in stock and effort, meaning that the production technology provides increasing returns to scale.

The CPUE is obtained by rewriting Equation (1):

$$CPUE_i(t) = \frac{H_i(t)}{E_i(t)} = q_i \, B_i(t) \tag{2}$$

CPUE is measured in tons of fish being caught per trawling hour. As it can be seen according to the underlying assumptions, $CPUE_i(t)$ varies proportionally with the stock biomass $B_i(t)$, with a constant proportionality factor of $q_i$. Hence, CPUE can be used as an indication for fish availability/ seasonality over the course of a year (Hilborn & Walters; Maunder et al., 2006). Higher/ lower values of CPUE address the availability of dense/disperse fish stock

((Maunder et al., 2006). Based on Equation (1) the revenue function for each fishery could be obtained by:

$$R_i(t) = p_i(t) \cdot H_i(t) \tag{3}$$

where $R_i(t)$ refers to the revenue generated from fishery $i$ at time $t$. $p_i$ shows the unit price of species $i$ caught by trawlers, in Norwegian currency (NOK). The Norwegian trawlers are equipped with processing and freezing facilities and mostly deliver frozen products (Flaaten & Heen, 2004; Standal & Hersoug, 2015). Hence, the price that trawlers receive may differ from the prices of fresh products caught by coastal vessels with conventional gears such as gillnet and long line. Equation (3) in terms of revenue per unit of effort (RPUE) is:

$$RPUE_i(t) = CPUE_i(t) \cdot p_i(t) \tag{4}$$

Since expected revenues of fishing trips could not be observed directly (i.e., when fishers leave the port, catch sizes and prices are uncertain), RPUE is utilized to approximate *expected* fishing revenue. Trawlers take longer trips, approximately two week, hence the prices at the time of landing may be different from the prices when fishers left the port. In order to capture revenue risk of fishing portfolio, we use coefficient of variation (CV) of RPUE for each fishery over the course of a year (Sethi, 2010; Sethi et al., 2014).

$$CV_{it}(CPUE_{it}, P_{it}) = \frac{\sigma_i(t)}{\mu_i(t)} \tag{5}$$

$CV_{it}$ captures the risk of RPUE of $i$th fishery at time $t$. $\sigma_i(t)$ and $\mu_i(t)$ are the standard deviation and mean of RPUE in fishery $i$ at time $t$, respectively. The greater the CV, the greater is the revenue risk.

Equation (4) indicates that risk of RPUE of fishing portfolio comes from the volatility in stock aggregation/ dispersion, measured by CPUE and prices. In Figure 1 and 2 we look at volatilities in the CPUE and prices for these fisheries over the course of a year.

The radar plot in Figure 1 display the temporal fluctuations of CPUE within and between the three species; cod, saithe and haddock. The spokes represent the average monthly values of CPUE, starting from zero. The values of CPUE are obtained from total catch and effort data of individual hauls of sixty-one active and registered trawlers in 2011-2016. A total of 86,414 cod hauls, 67,071 saithe hauls, and 38,928 haddock hauls were recorded over six years.

Figure 1 indicates that the temporal variation of the cod and the haddock fisheries follow similar patterns, reaching the highest peak levels in March. The second highest peak appears in the summer season for both cod and haddock, in July and June, respectively. The CPUE values of the cod fisheries decline and remain almost stable after July. Similarly, towards the end of the year also the CPUE values of haddock decline.

The saithe fishery shows lower catchability compared to the cod and haddock fisheries over the course of a year. In addition, the temporality exhibits a different pattern, with its peaks in January and April. Apart from these two months, the CPUE value of saithe is almost invariant and remains around two tons per hour of trawling.

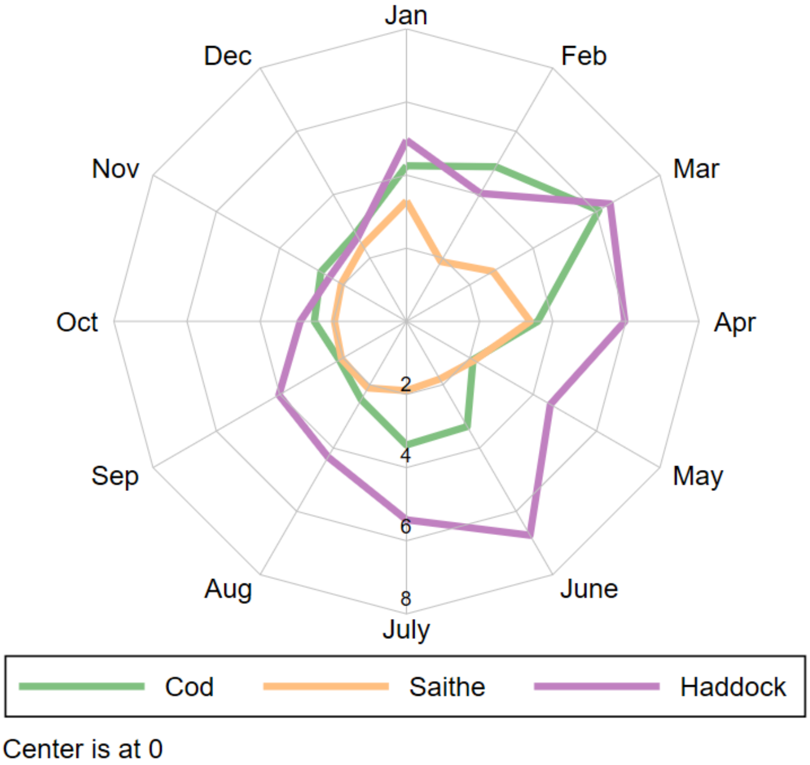

Figure 1. Monthly average of CPUE (tons per trawling hour) for cod, saithe and haddock fisheries based on individual hauls of 61 registered trawl vessels Source: The Norwegian Directorate of Fisheries 2011-2016.

Cod, saithe and haddock aggregate and spawn during wintertime along the north-west coast of Norway, with peak activities in March-April, February and March-June, respectively (Olsen et al., 2010). Hence, observing high values of CPUEs in the winter months is primarily due to the congregated fish stocks. After spawning in winter months, cod and haddock swims towards the high sea areas of sub-Arctic, while saithe does not undertake considerable migration (Olsen et al., 2010; Rose, 1993).

Figure 2 depicts the prices movements of these fisheries. This figure shows the average monthly prices for frozen products of cod, saithe, and haddock during 2011-2016, obtained from the Norwegian Fishermen’s Sale Organization (Norges Råfisklag).

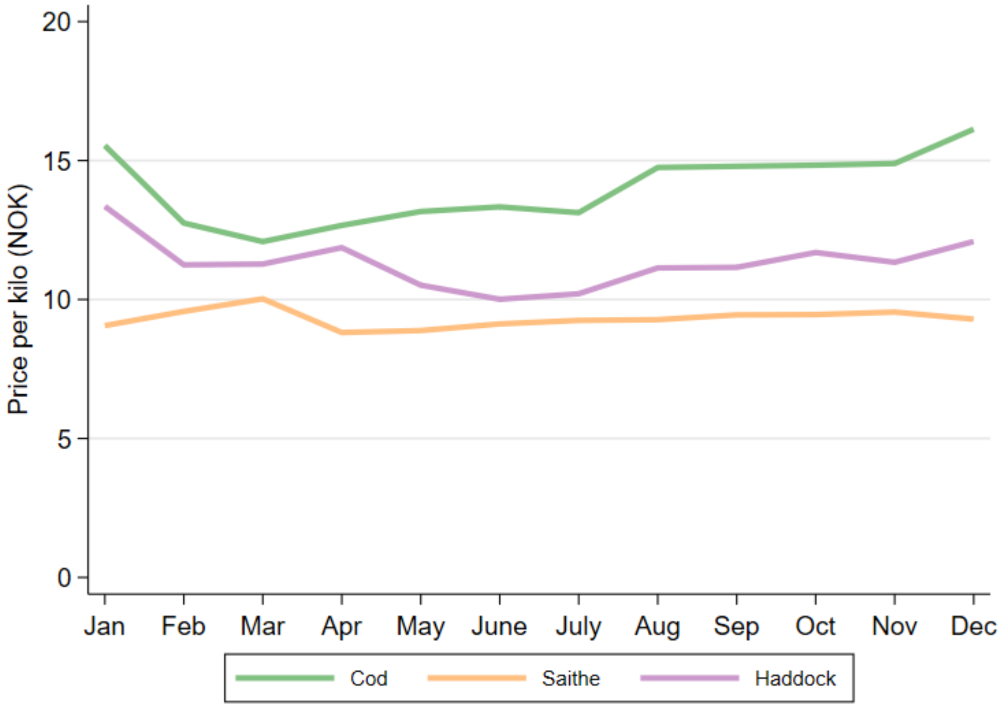

Figure 2. Monthly average price for the landed frozen products of cod, saithe and haddock caught by trawl fleet in 2016 Source: Norwegian Fishermen's Sale Organization (Norges Råfisklag)

As it is evident from Figure 2, cod and saithe are the most and the least valuable fish stocks in this portfolio, respectively. At the beginning of the year, the prices of cod and haddock decline. This is the time when these fish stocks aggregate along the coastal areas to spawn (higher CPUE). In contrast, towards the end of the year, cod and haddock fetch higher prices (lower CPUE).

Unlike the price patterns of cod and haddock, the first hand price of saithe is highest in March (around 10 NOK per kilo). From April, price starts to decline and remains almost constant until the end of the year. Generally, saithe price does not fluctuate as much as the prices of cod and haddock, probably because the CPUE of saithe does not vary considerably either, if we disregard January and April. Another explanation could be that the demand for saithe is very limited and saithe is preserved in different forms when landed (Birkenbach et al., 2020; Hersoug, 2005). Moreover, unlike the cod fishery, the processing capacity of the industry is not challenged by fluctuations in the saithe fishery (Hersoug, 2005).

# 3 Material and method

## 3.1 Proposed model

Here, we treat a representative holder of a quota portfolio as a decision-maker, aiming to minimize revenue risk by constantly making decisions about when to fish what, while adhering to the quota constraints.

The main assumptions used in the formulation of this problem are the following: Trawlers switch between target species every two weeks (i.e., we cannot target two different species during the same fortnight). The assumption is considered realistic due to the high cost of frequent switching between target species. Trawlers are assumed to operate at full capacity. The time resolution is fortnight and one fishing year is equal to maximum of 26 fortnights. Bycatch is not discard (Hersoug, 2005; Johnsen & Jentoft, 2017) (assuming a given trawler to act according to actual legalization). This assumption necessitates that trawlers adeptly match catch size and remaining quota and reserve part of their quota for *expected* bycatch in future hauling. For example, during the winter months, NEA cod, saithe and haddock aggregate along the north-west coast of Norway to spawn. The spatial overlay of these three species at this period causes landings of main catch to come with incidentally caught species (Olsen et al., 2010). Hence, the bycatch could constitute a profound share of the landings.

Furthermore, the following notations are used in the formulation of the proposed research question.

**Sets**

| | |
|---|---|
| $i \in \{1,2,3\}$ | Potential sets of fisheries; cod (1), saithe (2) and haddock (3) |
| $t \in \{1,2,\ldots,26\}$ | Sets of fortnights |

**Parameter**

$Q_i$ Initial quota allocation of a representaive trawl vessel for fishery $i$

**Decision variables**

$H_{it}$ Landing of species $i$ in tons at time $t$

$RQ_i$ Remianing quota of species $i$ over the course of a fishing year

**Business objective**

$$Min \sum_{i=1}^{3} \sum_{t=1}^{26} CV_{it}(CPUE_{it}, P_{it}) \qquad (6)$$

$CV_{it}$ indicates the revenue risk of the fishing portfolio. Equation (6) indicates that in a given year, a representative trawler seeks to minimize total risk of fishing portfolio revenue across species $i$ and time periods $t$.

**Constraints**

$$\sum_{t=1}^{t=26} H_{it} \leq Q_i \qquad \forall\, i \qquad (7)$$

$$\sum_{t=1}^{t=26} E_{it} \leq \bar{E} \qquad \forall\, t \qquad (8)$$

$$E_t \geq 0 \qquad \forall\, t \qquad (9)$$

Equation (7) ensures that the trawler's total landings of three species (including bycatch) over the course of a fishing year do not exceed the quota allocations. In addition, we use the smaller-than-or-equal sign to address the fact that misallocation of fishing effort and fishing right could lead to rest quotas at the end of the fishing year. Hence, there is a possibility that trawler is not able to fully exhaust their quotas. This constraint defines our first scenario. Equation (8) indicates the time and capacity constraint of the vessel. Equation (9) guarantees a non-negative effort.

In the second scenario, we assume that the representative fishing firm pursues a *set* of business goals, including minimizing revenue risk and generating *sufficient* and *reasonable* revenue from holding this fishing portfolio. Under such circumstance, the constraint expressed by Equation (7) becomes stricter in the cod fishery.

$$\sum_{t=1}^{t=26} H_{cod,t} = Q_{cod} \tag{10}$$

Since cod is the most economically valuable species in the portfolio (Asche, 2009; Flaaten & Heen, 2004; Salvanes & Squires, 1995), constraint (10) assures that the trawler will generate sufficient money by fully exhausting the cod quota by the end of the fishing year, while minimizing revenue risk.

### 3.1.1 Solution algorithm

Once the CV of RPUE is calculated for each fortnight and fishery from Equation (5), it is sorted from lowest to highest to acquire what species, in which fortnight and, in what catch proportion will result in the lowest risk of portfolio revenue. This does not mean that we exhaust the quota for species with the lowest CV, because if we do so, then we are left with no quota and no more fishing is allowed for that species in the future attempts. Put differently, we take expected catch and bycatch compositions in the future landings into account that contributes to the lowest risk. Hence, we constantly rebalance catch size (i.e., including bycatch) and remaining quota by tracking how much catch and bycatch the trawler might still get during the remaining fortnights, to minimize risk of RPUE of portfolio. Assume that a specific species that minimizes the risk is selected at a given time. If the remaining quota for this species is small, given the remaining fortnights; we choose the second best option, as the trawler is likely to exhaust the remaining quota of first option with the bycatches of future hauls. Thus, the risk minimization strategy is affected not only by catch size and quota size but also by expected bycatch.

In the second scenario, since we articulate the exhaustion of cod quota to generate enough revenue, we perform the same as above but then twice. We first go over each CV value, from lowest to highest, but skip any CV from a different species than cod. By doing so, we prioritize catching cod to generate money while minimizing portfolio revenue risk. We then perform the same procedure with all three species. When we do that, we basically skip any CV for cod, since we already have utilized the cod quota.

## 4 Construction and utilization of data

We employ two different data sets to explore the risk minimizing harvest strategy of the trawl fleet. Fortnightly prices for cod, saithe, and haddock, caught by trawlers during the six years (2011-2016) are obtained from the Norwegian Fishermen's Sales Organization (Norges Råfisklag). Since the trawlers mostly deliver frozen products the prices are associated with frozen products.

Haul-based catch and effort data of sixty-one trawlers, including single and double trawls, targeting cod, saithe and haddock over the period (2011-2016), are derived from The Norwegian Directorate of Fisheries to obtain CPUE (see Equation 2). Almost all of the sixty-one vessels, were active in all three fisheries over the six years period. The total numbers of single trawl hauls targeting cod, saithe and haddock are 86,418, 67,071, and 38,928, respectively. Multiplying fortnightly prices and CPUEs per haul in each fortnight yields the corresponding RPUE (see Equation 4).

The CVs of RPUEs are obtained by the aggregated standard deviation and mean of the fortnightly RPUEs of the three fisheries for 26 fortnights (see Equation 5). The choice of time resolution is that the fortnightly data enables to levels out random noises in harvest attributed to luck, weather conditions, and stochastics in general. Additionally, due to the availability of freezing facilities on board, trawlers take longer fishing trips – about two weeks on average – including running time to and from the fishing grounds.

In order to see how the catch composition looks in revenue risk minimization strategy, we obtain the total of main catch and bycatch of three species per vessel over 26 fortnights, to implement it in our model. To account for the quota constraints in shaping the adopted harvest strategy, and to investigate whether or not the allocation of quotas are efficient, we use total landings of each species to approximate the allocated quotas. The Norwegian trawl fishery is strictly regulated through catch quotas, and fishers cannot fish more than the allocated catch shares, otherwise overfished quotas are confiscated, or highly penalized (Hersoug, 2005). Hence, total catch could be a reasonable approximation for the quota size. Table 1 shows the average annual quota allocation per trawl vessel in tons for three species over 2011-2016. Cod quota constitutes the largest part of quota portfolio and the catch entitlements have increase over six years. Quota allocation of saithe and haddock fisheries is almost stable.

Table1. Calculated average annual allocation of quota per vessel in tons for cod, saithe, and haddock over 2011-2016

| **Species** | **2011** | **2012** | **2013** | **2014** | **2015** | **2016** |
|---|---|---|---|---|---|---|
| **Cod** | 2912.749 | 3230.679 | 3650.051 | 3522.420 | 3353.478 | 4121.903 |
| **Saithe** | 1588.563 | 1802.133 | 1414.457 | 1547.285 | 1334.687 | 1794.641 |
| **Haddock** | 1857.306 | 2077.503 | 1066.616 | 1076.089 | 1052.776 | 1500.121 |

In order to obtain the *initial* quotas for a given vessel, which operates in three fisheries and aims to minimize revenue risk, we find the average of annual quota allocations for each species over six years, presented in Table 1. By doing so, we obtain quota sizes of 3465.21, 1580.29 and 1438.4 tons for cod, saithe and haddock, respectively. The adopted harvest strategy should be consistent with these quotas.

# 5 Results

Figure 3 shows how CV of RPUE of three species varies over the course of a fishing year. The CV of RPUE of cod varies in wider range in comparison to saithe and haddock fisheries. This could indicate that cod fishery is riskier than saithe and haddock fisheries.

Haddock shows the least fluctuation in RPUE, probably because increase/decrease in CPUE offsets decrease/increase in price. Cod exhibits less volatility at the beginning of the fishing year, probably due to the opposite effect of high values of CPUE and low prices. After the seventh fortnight (April), when the price starts to rise, CV of RPUE of cod increases. In contrast, saithe shows more fluctuations at the beginning of the year with its peak in January due to high values of CPUE (See Figure 1). After May, the CV of RPUE of saithe shows less fluctuations in comparison to cod. One possible explanation is that at this period both CPUE and price of saithe remain almost stable (See Figures 1 and 2).

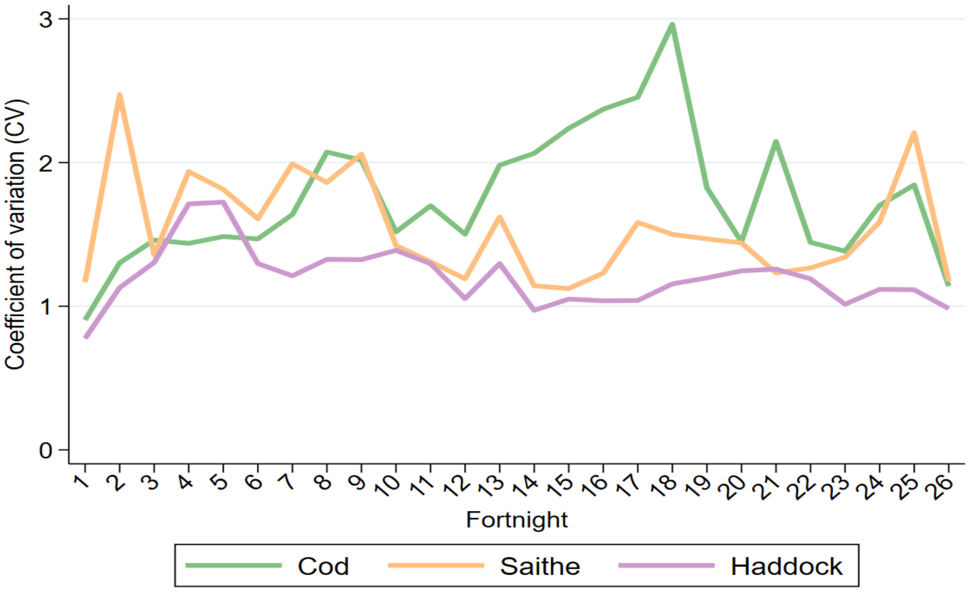

Figure 3. Fortnightly values of coefficient of variation of RPUE of three species (cod, saithe, and haddock) over the course of a fishing year, caught by trawl fleet

## 5.1 Scenario 1

Figure 4 reveals catch composition (upper panel), quota utilization (middle panel) and generated revenue from the adopted harvest strategy (lower panel) to minimize revenue risk under the scenario that minimizing revenue risk is the only business objective for the trawlers.

Since CV of RPUE of cod fluctuates within a wider range (See Figure 3), a trawler whose aim is to minimize volatility of portfolio revenue, redirects fishing effort on haddock and saithe fisheries. The middle panel of Figure 4, shows how the quotas are allocated to accomplish this business objective. Here, trawlers only use half of the allocated cod quota, but fully exhaust saithe and haddock quotas as the revenues from saithe and haddock fisheries carry less fluctuations (See Figure 3). Cod quota is utilized in March-May and July-August. The unused cod quota means that minimizing revenue risk leads to inefficient allocation of fishing effort. This is not expected to be the case in real fishing practice as quotas are markedly expensive, notably the cod quota, and having leftovers of cod quota is a big economic loss. Moreover, in the lower panel of Figure 4, we show how these three fisheries contribute to the total revenue from the risk minimizing harvest strategy. The total revenue from this harvest strategy is around 60 million Norwegian krone (NOK).

Figure 4. Catch composition, quota utilization, and revenue of fishing portfolio of the first scenario over 26 fortnights

## 5.2 Scenario 2

Figure 5 shows the results of the second scenario where the trawler aims to minimize revenue risk while generating a *sufficient* and *reasonable* amount of revenue. The upper, middle, and lower panels of Figure 5 show catch composition, quota utilization and generated revenue of this harvest strategy. The upper panel of the figure shows that trawlers use the cod quota early in the fishing year (January-mid April) as well as towards the end of the year. From fortnights 10 to 13, trawlers partake in saithe fishery when both CPUE and price are almost stable (See Figure 1 and 2). Busy time for haddock fishery is winter time when CPUE is high and price is low. However, a part of haddock quota is used in July (fortnight 14-15-16) when CPUE is still high and prices are still low (See Figure 1 and 2). The middle panel shows that the representative trawler can fully exhaust the fishing quota portfolio. This is a win-win situation for fishing firm as the trawler meets two important business objectives simultaneously. The lower panel of the Figure 5 shows how revenue of the fishing portfolio, decomposed by target species. The total revenue of the adopted harvest strategy is around 80 million krone.

Figure 5 . Catch composition, quota utilization, and revenue of fishing portfolio of the second scenario over 26 fortnights

# 6 Discussion

## 6.1 First scenario

In the first scenario we assume that the only business objective of the trawlers is to minimize revenue risk. Under such circumstance, the results show that trawlers give up on cod fishery and operate in haddock and saithe fisheries as CV of RPUE of these two fisheries show less fluctuation over the time. The Norwegian quota systems are built upon "use-it-or-lose-it" principle and if trawler cannot manage to fully exhaust cod quota, the unfished quota will not be awarded in the subsequent years (Hersoug, 2005). Hence, in reality fishers would not forgo utilization of cod quota for the sake of minimizing revenue risk as refraining from cod fishery is considered as a huge economic loss. The revenue attributed to this harvest strategy is 60 million NOK. The trawler could have enhanced the potential revenue by taking a more risky harvest strategy by partaking in cod fishery (See Figure 3).

Moreover, the un-used cod quota implies that diversification through targeting multiple species to minimize revenue risk leads to inefficient allocation of fishing effort in the trawl fishery. This finding is somehow in line with the results from Baldursson and Magnússon (1997), which reveal that the optimal fishing pattern through diversification in Icelandic cod fishery to attenuate risk is inefficient. They define diversification in terms of age cohorts of cod stock.

## 6.2 Second scenario

As the results of the first scenario are incompatible with rationality in conducting business, in the second scenario, we adopt a more realistic approach where trawler aims to simultaneously minimize revenue risk and generate a sufficient and reasonably good amount of revenue. Since the cod fishery is the most economically valuable in this portfolio (see Figure

2), in this scenario, we articulate that trawlers fully exhaust cod quota by the end of the fishing year to reach a satisfying and adequate level of revenue, while minimizing revenue risk.

The result from this scenario shows that not only trawlers minimize revenue risk but also they manage to fully exhaust quota portfolio, which addresses the fact that the trawler generate *satisficing* (i.e., combination of *satisfy* and *suffice*) revenue. As shown in the lower panel of Figure 5, adopting this strategy, enhances the total revenue by 20 million krone, in comparison to the strategy that was merely based on revenue risk reduction. Additionally, comparing the lower panels of Figure 4 and 5 reveals that increasing expected return and minimizing revenue risk are two antagonistic business objectives. In the first scenario, trawlers sacrifice some of the expected return by refraining from cod fishery — which is associated with higher risk — in order to lower the variability of gain (i.e., RPUE of portfolio), whereas in the second scenario they generate more revenue by partaking in cod fishery at the cost of higher risk of revenue. This is consistent with financial theories, which imply that the greater/less the risk, the greater/less the potential for gain (i.e., expected returns) (Markowits, 1952).

## 6.3 Illustration of the real adopted harvest strategy

In Figure 6, we depict the real harvest pattern of the trawlers, obtained from our data to compare it with the harvest pattern from the second scenario. In the second scenario the representative trawler follows two business objectives; to minimize revenue risk and to generate satisficing revenue. We relinquish the first scenario as it is an untenable strategy to be adopted. Figure 6 displays the total catch of cod, saithe and haddock, harvested by sixty-one trawlers on fortnightly basis over the period 2011-2016. Bycatch of other species is also included in the calculation of total catch of each fisheries.

As it is evident from Figure 6, the cod catch is the largest in the first and second fortnights, followed by a sudden drop in the cod landings (starting from fortnight 3). Interestingly, during the same period catch of saithe has increased.

After the winter months and toward the end of the year the cod catches increase. This is probably due to the higher cod prices towards the end of the year (See Figure 2). Similarly, catches of haddock and saithe decrease as the fishing year gets closer to the end.

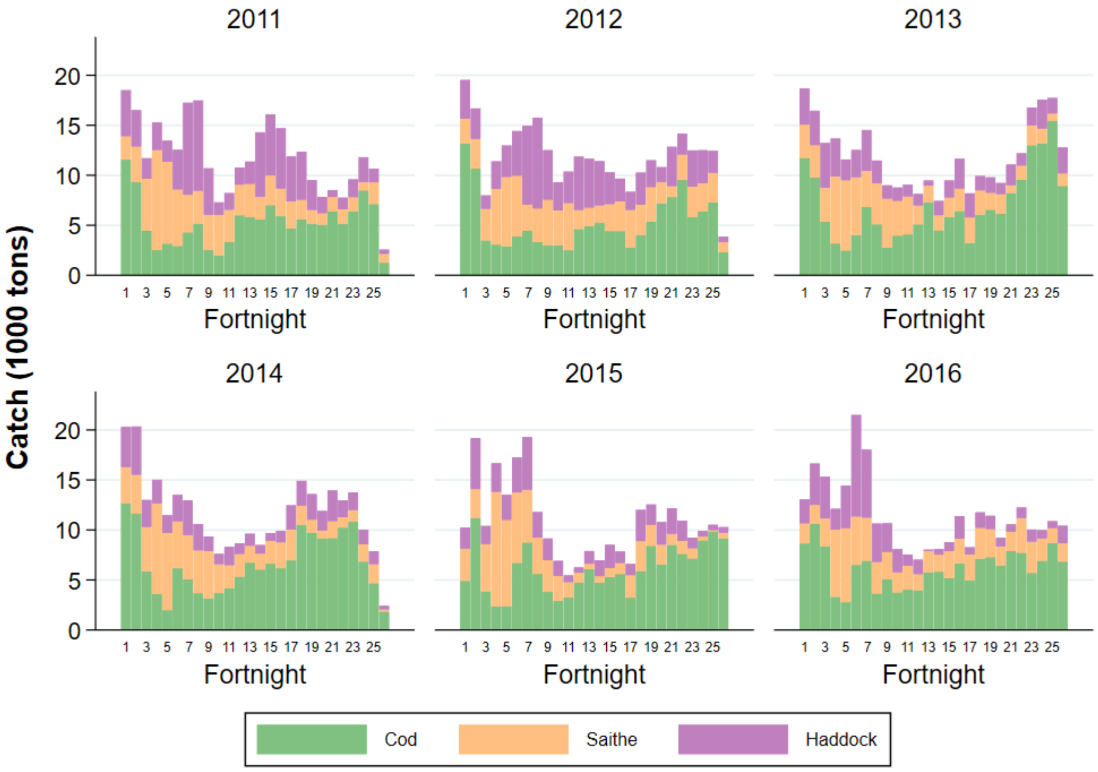

Figure 6. Fortnightly total catch of cod, saithe and haddock, caught by the 61 registered trawl vessels Source: The Norwegian Directorate of Fisheries 2011-2016

The comparison of the harvest patterns in the upper panel of Figure 4 with Figure 6 reveals some degree of resemblance. Similar to the observed harvest strategy in Figure 6, from Figure 4 we see that the cod catch is also largest at the beginning of the year. Another conspicuous resemblance is the sudden drop in the cod landings at the beginning of the fishing year (i.e., fortnights 8-13 and 3-11 in Figure 4 and 6, respectively), and substitution of cod fishery with other available fisheries. The other similarity is that the cod landings increase toward the end of the year.

One justification for observing large landings of cod at the beginning of the year is due to the effect of stock aggregation on reducing cost per unit of effort (Hannesson, 2007; Kvamsdal, 2016; Sandberg, 2006). Proximity to the shore and higher fish densities provide opportunities for both the coastal and the high sea fleet to operate at lower cost (Hannesson, 2007; Kvamsdal, 2016; Sandberg, 2006).

The sudden drop in cod landings at the beginning of the year and shifting from the cod fishery to other available fisheries, despite the high values of CPUE of the cod fishery (see Figure1) and lower cost per unit of effort, could be explained by the impact of the behavior of coastal fishers. Cod fishery is the most important fishery during winter (Lofoten fishery). 65% up to 80% of the cod quota is granted to the coastal fishers (Asche et al., 2014; Hermansen & Dreyer, 2010). The less advanced technology of the coastal boats limits their geographical mobility. This means that coastal fishers cannot chase NEA cod after spawning when the stock swims back to the high sea areas of the Barents Sea. Hence, the spawning migration along the north-west coast of Norway during winter months is an unprecedented opportunity to exhaust the cod quota (Asche et al., 2014; Hermansen & Dreyer, 2010; Maurstad, 2000; Standal & Hersoug, 2015). The large supply of cod lowers its price (See Figure 2) (Alizadeh Ashrafi et al., 2020, Asche et al., 2015; Birkenbach et al., 2020). The declined price of cod motivates trawlers to adjust fishing effort by reallocating to more profitable fisheries (saithe and haddock) and reserve the cod quota for the periods at the end of the year as the price is higher (See Figure 2).

From Figure 6, we see that, in reality the shift from cod fishery to other fisheries takes place earlier in the year in comparison to what we have found from the second scenario (fortnights 8-13 and 3-11 in Figure 4 and 6, respectively). This could mean that, in real cases, trawlers react to price reduction in the cod fishery more swiftly, underpinning that trawlers are more concerned about increasing profit than reducing revenue risk. All the above argument provides an insight that trawlers are responsive to the fluctuations of CPUE of the cod fishery and its effect on price, indicating that trawlers adjust fishing effort to enhance revenue.

One may argue that the increased landings of cod at the beginning/ end of the year in Figure 5 and 6, may be stemmed from risk minimization motives as the high/low values of CPUE might offset low/high prices. This cannot be the case as we would have seen the increased landings of cod at the beginning/ end of the year in the harvest pattern obtained in the first scenario (See the upper panel of the Figure 4), where we focus only on risk minimization.

In short, dissimilarity between harvest patterns obtained from the first scenario —where the only focus is on minimizing revenue risk— and the second scenario—where trawlers aim to minimize revenue risk and enhance revenue—together with similarities between the harvest patterns of the real case and the second scenario, could confirm that generating and enhancing revenue outweighs minimizing revenue risk.

## 6.4 Industry structure and fleet characteristics

Norwegian trawl fishery is a vertically integrated seafood industry, meaning that a single fishing firm owns and coordinates various adjacent stages of the supply chain from harvesting fish to processing the catch, distributing, and selling the products (Dreyer & Grønhaug, 2004; Dreyer et al., 2006; Hersoug & Leonardsen, 1979). This combinatory process works as a hedging mechanism and lessens the risk exposure for the trawl fleet relative to non-integrated businesses (e.g., small-scale fishers) (Porter, 1980; Riordan, 1990). The reason is that with vertical integration trawlers have higher control over the industry and markets as the combinatory process provides them better knowledge and information (e.g., what is selling well at which time period) (Dreyer et al., 2006; Hersoug & Leonardsen, 1979). The integrated nature facilitates information flows and exchange across supply chain since there are no proprietary boundaries encountered (Porter, 1980; Riordan, 1990). These characteristics generate some potential market power for the integrated industry, which could lessen the revenue fluctuation faced by trawlers (Dreyer et al., 2006; Hersoug & Leonardsen, 1979).

Unlike small-scale fishers that rigidly follow seasonality of fish stocks and operate along the coast during winter months when fish stocks are aggregated, trawl vessels possess progressive technology (e.g., processing plants and freezing facilities on board), enabling them to run a year-round operation. Moreover, trawlers are less vulnerable to the harsh climate and can move freely to explore vast geographical areas –from southern Norway to Svalbard and Bear Island- at greater depths to extract fish (Flaaten & Heen, 2004; Standal & Hersoug, 2015).

In short, the industry and vessel characteristics provide multiple useful tools for the trawlers to cope with revenue fluctuations. While trawlers have many tools to attenuate fluctuations, they do not need to diversify catch to buffer revenue risk.

# 7 Conclusion

The fishing revenue is highly volatile due to uncertainties about prices, seasonal and cyclical fluctuations in stock size and, possible changes in regulatory schemes over the course of a year. Given the extreme economic risk, catch diversification has been identified as one of the common fishing strategies to reduce revenue risk and stabilize yield. The inverse relationship between holding a diverse fishing portfolio and revenue risk has been confirmed in small-scale fisheries. However, the existing studies have ignored how efficient this strategy is in terms of allocating fishing effort and quota utilization.

Switching between fisheries is not a single and straightforward decision to make, as the fish species in the portfolio have different seasonality patterns and the effect of seasonality on species prices might be different as well.

Our study complements and extends this literature by jointly considering the intricately related decisions about switching between species (e.g., when to fish what and how much), with respect to quota constraints and the possible effects of seasonality in fish stocks to minimize revenue risk of the trawl fleet. We further investigate whether the revenue risk minimization is an efficient strategy.

Thus, the main objective of this paper is to determine harvest strategy in terms of revenue stabilization in the Norwegian trawl fishery targeting 3 species; namely cod, saithe and haddock. On this basis, we build a decision-making framework of a highly complex decision problem where fishers are faced with wide range of choices about when and what to target as well as considering quota constraints to minimize revenue risk.

There are at least three motives for choosing risk minimizing behavior of the trawl fleet. First, unlike small-scale fishers who are rigidly confined with fish seasonality and inshore fishing, bottom trawling is a year-round fishing practice (Asche et al., 2014; Hersoug & Leonardsen, 1979; Standal & Hersoug, 2015). Second, owing to the progressive technology and capability to cope the harsh climatic conditions of the sub-Arctic areas, trawl vessels can exploit fish stocks in the high sea areas of the Barents Sea and Svalbard. Third, the industry structure of Norwegian trawl is based on vertical integration whereas the business strategy of small-scale fishers is non-integrated.

The results from our model reveal that minimizing revenue risk in the trawl fishery leads to inefficient allocation of fishing effort and quota, which is in a sharp contrast with economic rationality. In addition, our results suggest that the Norwegian trawler fleet holds diverse fishing portfolio to increase profitability rather than minimizing revenue risk. We further conclude that trawlers are profit oriented, where the seasonal pattern in cod aggregation/dispersion and its economic consequences (e.g., price fluctuations based on supply) shapes the trawlers' fishing strategy. We speculate that the industry and fleet structure could explain the prioritization of generating revenue over minimizing risk. These features make trawlers less susceptible towards revenue fluctuations. This could be a valuable information for the fisheries managers when implementing and/or enforcing the rules and regulations.

## References

Alizadeh Ashrafi, T., Eide, A., & Hermansen, Ø. (2020). Spatial and temporal distributions in the Norwegian cod fishery. *Natural Resource Modeling*, e12276.

Anderson, S. C., Ward, E. J., Shelton, A. O., Adkison, M. D., Beaudreau, A. H., Brenner, R. E., . . . Williams, B. C. (2017). Benefits and risks of diversification for individual fishers. *Proceedings of the National Academy of Sciences, 114*(40), 10797-10802.

Asche, F. (2009). Adjustment cost and supply response in a fishery: A dynamic revenue function. *Land Economics, 85*(1), 201-215.

Asche, F., Bjørndal, M. T., & Bjørndal, T. (2014). Development in fleet fishing capacity in rights based fisheries. *Marine Policy, 44*, 166-171.

Asche, F., Chen, Y., & Smith, M. D. (2015). Economic incentives to target species and fish size: prices and fine-scale product attributes in Norwegian fisheries. *Ices Journal of marine science, 72*(3), 733-740.

Baldursson, F. M., & Magnússon, G. (1997). Portfolio fishing. *Scandinavian Journal of Economics, 99*(3), 389-403.

Birkenbach, A. M., Cojocaru, A. L., Asche, F., Guttormsen, A. G., & Smith, M. D. (2020). Seasonal Harvest Patterns in Multispecies Fisheries. *Environmental and Resource Economics, 75*(3), 631-655.

Branch, T. A., & Hilborn, R. (2008). Matching catches to quotas in a multispecies trawl fishery: targeting and avoidance behavior under individual transferable quotas. *Canadian Journal of Fisheries and Aquatic Sciences, 65*(7), 1435-1446.

Charles, A. T. (1995). Fishery science: the study of fishery systems. *Aquatic Living Resources, 8*(3), 233-239.

Cline, T. J., Schindler, D. E., & Hilborn, R. (2017). Fisheries portfolio diversification and turnover buffer Alaskan fishing communities from abrupt resource and market changes. *Nature communications, 8*, 14042.

Copes, P. (1986). A critical review of the individual quota as a device in fisheries management. *Land Economics, 62*(3), 278-291.

Dreyer, B., & Grønhaug, K. (2004). Uncertainty, flexibility, and sustained competitive advantage. *Journal of business research, 57*(5), 484-494.

Dreyer, B., Isaksen, J. R., Bendiksen, B. I., & Rånes , S. A. (2006). *Evaluering av leveringsplikten.* Fiskeriforsking. Tromsø:

Eide, A., Skjold, F., Olsen, F., & Flaaten, O. (2003). Harvest functions: the Norwegian bottom trawl cod fisheries. *Marine Resource Economics, 18*(1), 81-93.

Finkbeiner, E. M. (2015). The role of diversification in dynamic small-scale fisheries: Lessons from Baja California Sur, Mexico. *Global Environmental Change, 32*, 139-152.

Flaaten, O. (1983). The optimal harvesting of a natural resource with seasonal growth. *Canadian Journal of Economics*, 447-462.

Flaaten, O. (1987). Sesongvarierende bestandstilgjengelighet og produktfunksjoneri i Lofotfisket [Seasonal catchability variations and production functions in the Lofoten fishery] (in Norwegian). Report 7005/1-87. Forut. Tromsø

Flaaten, O., & Heen, K. (2004). Fishing vessel profitability and local economic link obligations—the case of Norwegian trawlers. *Marine Policy, 28*(6), 451-457.

Hannesson, R. (2007). A note on the" stock effect". *Marine Resource Economics, 22*(1), 69-75.

Heady, E. O. (1952). Diversification in resource allocation and minimization of income variability. *Journal of Farm Economics, 34*(4), 482-496.

Hermansen, Ø., & Dreyer, B. (2010). Challenging spatial and seasonal distribution of fish landings—The experiences from rural community quotas in Norway. *Marine Policy, 34*(3), 567-574.

Hersoug, B. (2005). *Closing the commons: Norwegian fisheries from open access to private property*. Utrecht: Eburon Academic Publishers.

Hersoug, B., & Leonardsen, D. (1979). *Bygger de landet? : distriktspolitikk og sosialdemokrati 1945-1975*. Oslo: Pax Forlag.

Hilborn, R. (1985). Fleet dynamics and individual variation: why some people catch more fish than others. *Canadian Journal of Fisheries and Aquatic Sciences, 42*(1), 2-13.

Hilborn, R. (2007). Managing fisheries is managing people: what has been learned? *Fish and Fisheries, 8*(4), 285-296.

Hilborn, R., Maguire, J.-J., Parma, A. M., & Rosenberg, A. A. (2001). The precautionary approach and risk management: can they increase the probability of successes in fishery management? *Canadian Journal of Fisheries and Aquatic Sciences, 58*(1), 99-107.

Hilborn, R., & Walters, C. J. (1992). *Quantitative fisheries stock assessment: choice, dynamics and uncertainty*. New York: Chapman and Hall.

Johnsen, J. P., & Jentoft, S. (2017). Transferable qoutas in Norwegian fisheries. In M. G. Winder (Ed.), *Fisheries, quota management and quota transfer; Rationalization through bio-economics* (pp. 121-139). Cham: Springer.

Kasperski, S., & Holland, D. S. (2013). Income diversification and risk for fishermen. *Proceedings of the National Academy of Sciences, 110*(6), 2076-2081.

Kvamsdal, S. F. (2016). Technical change as a stochastic trend in a fisheries model. *Marine Resource Economics, 31*(4), 403-419.

Markowits, H. (1952). Portfolio selection *Finance, 7*, 77-91.

Maunder, M. N., Sibert, J. R., Fonteneau, A., Hampton, J., Kleiber, P., & Harley, S. J. (2006). Interpreting catch per unit effort data to assess the status of individual stocks and communities. *Ices Journal of marine science, 63*(8), 1373-1385.

Maurstad, A. (2000). To fish or not to fish: small-scale fishing and changing regulations of the cod fishery in northern Norway. *Human Organization*, 37-47.

Minnegal, M., & Dwyer, P. D. (2008). Managing risk, resisting management: Stability and diversity in a southern Australian fishing fleet. *Human Organization*, 97-108.

Olsen, E., Aanes, S., Mehl, S., Holst, J. C., Aglen, A., & Gjøsæter, H. (2010). Cod, haddock, saithe, herring, and capelin in the Barents Sea and adjacent waters: a review of the biological value of the area. *Ices Journal of marine science, 67*(1), 87-101.

Opaluch, J. J., & Bockstael, N. E. (1984). Behavioral modeling and fisheries management. *Marine Resource Economics, 1*(1), 105-115.

Perruso, L., Weldon, R. N., & Larkin, S. L. (2005). Predicting optimal targeting strategies in multispecies fisheries: a portfolio approach. *Marine Resource Economics, 20*(1), 25-45.

Porter, M. E. (1980). *Competitive strategy: Techniques for analyzing industries and competitors*. New York: Free Press.

Riordan, M. (1990). What is vertical integration? In M. Aoki, B. Gustafsson, & O. E. Williamson (Eds.), *The firm as a nexus of treaties* (pp. 94-111). London: Sage.

Rose, G. A. (1993). Cod spawning on a migration highway in the north-west Atlantic. *Nature, 366*(6454), 458.

Salvanes, K. G., & Squires, D. (1995). Transferable quotas, enforcement costs and typical firms: an empirical application to the Norwegian trawler fleet. *Environmental and Resource Economics, 6*(1), 1-21.

Sanchirico, J. N., Smith, M. D., & Lipton, D. W. (2008). An empirical approach to ecosystem-based fishery management. *Ecological Economics, 64*(3), 586-596.

Sandberg, P. (2006). Variable unit costs in an output-regulated industry: the fishery. *Applied Economics, 38*(9), 1007-1018.

Schaefer, M. B. (1954). Some aspects of the dynamics of populations important to the management of the commercial marine fisheries. *Inter-American Tropical Tuna Commission Bulletin, 1*(2), 23-56.

Schindler, D. E., Hilborn, R., Chasco, B., Boatright, C. P., Quinn, T. P., Rogers, L. A., & Webster, M. S. (2010). Population diversity and the portfolio effect in an exploited species. *Nature, 465*(7298), 609.

Sethi, S. A. (2010). Risk management for fisheries. *Fish and Fisheries, 11*(4), 341-365.

Sethi, S. A., Dalton, M., & Hilborn, R. (2012). Quantitative risk measures applied to Alaskan commercial fisheries. *Canadian Journal of Fisheries and Aquatic Sciences, 69*(3), 487-498.

Sethi, S. A., Reimer, M., & Knapp, G. (2014). Alaskan fishing community revenues and the stabilizing role of fishing portfolios. *Marine Policy, 48*, 134-141.

Smith, M. D., & Wilen, J. E. (2005). Heterogeneous and correlated risk preferences in commercial fishermen: The perfect storm dilemma. *Journal of Risk and Uncertainty, 31*(1), 53-71.

Squires, D., Campbell, H., Cunningham, S., Dewees, C., Grafton, R. Q., Herrick Jr, S. F., . . . Shallard, B. (1998). Individual transferable quotas in multispecies fisheries. *Marine Policy, 22*(2), 135-159.

Standal, D., & Hersoug, B. (2015). Shaping technology, building society; the industrialization of the Norwegian cod fisheries. *Marine Policy, 51*, 66-74.

Van Oostenbrugge, J. A., Bakker, E., van Densen, W. L., Machiels, M. A., & van Zwieten, P. A. (2002). Characterizing catch variability in a multispecies fishery: implications for fishery management. *Canadian Journal of Fisheries and Aquatic Sciences, 59*(6), 1032-1043.

Wilen, J. E., Smith, M. D., Lockwood, D., & Botsford, L. W. (2002). Avoiding surprises: incorporating fisherman behavior into management models. *Bulletin of Marine Science, 70*(2), 553-575.

# Paper 3

Alizadeh Ashrafi, T. & Abe, K.

## Intra and inter-temporal effort allocation and profit maximizing strategy of the trawl fishery

Submitted manuscript.

# Intra and inter-temporal effort allocation and profit maximizing strategy of the trawl fishery

Tannaz Alizadeh Ashrafi, The Arctic University of Norway (UiT), Norwegian College of Fishery Science, Muninbakken 21, 9019, Tromsø, Norway, Email address: tannaz.alizadeh@uit.no, 0047- 77620824

Keita Abe, The Norwegian School of Economics (NHH), Department of Economics, Helleveien 30, 5045 Bergen, Norway, Email address: keita.abe@nhh.no, 0047-55 95 94 35

# Abstract

The Norwegian bottom trawlers are profit-oriented and operate over a vast geographical area. Allocation of the fishing effort in multi-species trawl fishery to maximize profit is a complex and multi-facet process. The available fish species in the fishing portfolio might exhibit different feeding and spawning migration patterns as well as congregation and/or dispersion behavior. Hence, the magnitude of economic consequences stemmed from the constant variation in fish abundance might be different across different fish species. In addition, the spatial heterogeneity among different fishing areas in terms of fuel costs and travel distance from port, and availability of other fishing fleets further complicates decisions underlying effort allocation such as when and where to fish what and how much to fish to obtain the highest level of profits. In this regard, the purpose of this article is to identify the key drivers of intra and inter-temporal effort allocation of the trawl fleet targeting cod, saithe and haddock, where the aim is to maximize fishing profit within the quota constraints. We have developed a two-step Heckman estimator that incorporates the relative attractiveness of three heavily trawled areas including southern and northern parts of the west coast of Norway, and the high sea areas of the Arctic. The relative attractiveness is specified by catch per unit of effort (CPUE), prices of the target species, fuel cost and the intensity of coastal fleet participation over 2011-2016. Our results show that region-specific costs have a profound impact on intra-temporal and inter-temporal allocation of fishing effort to maximize profit. Furthermore, we have found evidence of economically rational behavior of the Norwegian trawlers in constantly reallocating fishing effort in response to the changes in the relative attractiveness of the selected regions.

Keywords: Bottom Trawl, Profit maximization, effort allocation, multispecies fisheries, Heckman estimator, intra-temporal, inter-temporal

# 1 Introduction

Large-industrial vessels like bottom trawlers are profit-oriented and seek to maximize profit by constantly redistributing fishing effort across multiple species over time and space (Abernethy et al., 2007; Asche et al., 2009; Birkenbach et al., 2020). The Norwegian bottom trawl fleet is quota-regulated and targets commercially valuable species including Northeast Arctic (NEA) cod (*Gadus morhua*) as the main target together with saithe (*Pollachius virens*) and haddock (*Melanogrammus aeglefinus*) (Birkenbach et al., 2020; Cojocaru et al., 2019; Guttormsen & Roll, 2011).

Particular interest lies in identifying the effort allocation of the trawl fleet, which leads to profit maximizing harvest strategy. One reason is that, cod, saithe, and haddock fisheries constitute one of the most economically valuable fishing portfolios (Asche, 2009; Asche et al., 2015; Cojocaru et al., 2019; Guttormsen & Roll, 2011). The spatial and temporal freedom of trawlers as well as capability to cope with less desirable climatic conditions of the sub-Arctic areas (Flaaten & Heen, 2004; Standal & Hersoug, 2015) could secure a steady supply of codfish throughout the year (Alizadeh Ashrafi et al., 2020; Asche et al., 2014; Hersoug & Leonardsen, 1979). This in return could ensure a long-term economically sustainable fishery (Birkenbach et al., 2020; Cojocaru et al., 2019; Guttormsen & Roll, 2011). The investigation of fishing effort allocation in codfish fishery has received little attention (Alizadeh Ashrafi et al., 2020; Birkenbach et al., 2020; Eide et al., 2003). In this regard, the aim of this paper is to identify the influential drivers of the effort allocation of the codfish trawl fishery to maximize annual profit.

Under a quota-managed fishery, allocation of fishing effort consists of multiple interlinked decisions including when and where to fish what, and what proportion of quotas to consume to match the catch size and remaining quotas (Birkenbach et al., 2020; Branch & Hilborn, 2008; Copes, 1986; Squires et al., 1998).

The interplay between spatial and temporal dimensions is primarily ascribed to the different habitat requirements for the fish stocks to feed and/or breed over the course of a year (Alizadeh Ashrafi et al., 2020; Birkenbach et al., 2020). Cod, saithe, and haddock undertake spawning migration and aggregate along the west coast of Norway during wintertime (Garrod, 1967; Hannesson et al., 2010; Olsen et al., 2010). After spawning, cod and haddock migrate dispersedly to the sub-Arctic areas of the Barents Sea and Svalbard to feed (Bergstad et al., 1987; Trout, 1957). Saithe is dispersed along the south-west of Norway as well as in the northern part of the west coast as late as August (Pethon, 2005).

The constant movements, congregational and/or dispersion of fish stocks across different fishing locations over the course of a year shape locational heterogeneity in terms of relative population abundance measured by catch per unit of effort (CPUE) (Hilborn & Walters, 1992; Maunder et al., 2006) and economic considerations such as relative prices of fish species and cost of fishing operation (Asche et al., 2015; Hannesson, 2007; Sandberg, 2006).

Additionally, different fishing locations have different attributes that is specific to that location, which could affect profit of trawling. For example, less fuel consumption and less required travel time might make nearshore areas economically more desirable relative to the high sea areas of the Arctic, all else being equal.

The harvest strategy of trawl fishers is intimately related to the behavior of coastal fleets (Alizadeh Ashrafi et al., 2020; Asche et al., 2015). Cod, saithe, and haddock are jointly fished by coastal fleets using conventional gears such as gill nets and longlines. Coastal boats cannot venture into the off-shore fishing due to the limitation in technical specifications (i.e., limited engine power and smaller size) (Flaaten & Heen, 2004; Standal & Hersoug, 2015). As a result, they are heavily reliant on nearshore fisheries such as Lofoten fishery (Hannesson et al., 2010;

Hermansen & Dreyer, 2010). 65-80% of Total Allowable Catch (TAC) of codfish quotas belong to the coastal fleets (Asche et al., 2014; Standal & Hersoug, 2015). Hence, large landings of fish by the coastal fleet during spawning aggregation in wintertime could affect prices, which would then influences the effort allocation decisions of the trawlers (Alizadeh Ashrafi et al., 2020; Birkenbach et al., 2020). Considering the argument above, the constant variation in the relative attractiveness of different fishing areas affects the spatio-temporal effort allocation and the way trawlers utilize fishing quotas (Alizadeh Ashrafi et al., 2020; Asche et al., 2015; Holland & Sutinen, 1999, 2000).

The recent work by Birkenbach et al. (2020) investigates the profit maximizing harvest strategy of the Norwegian trawl fleet. However, this study lacks the consideration of spatial dimension. Effort allocation cannot be comprehensively analyzed without considering the interrelation between temporality and spatiality, in particular for the migratory species as the constant movements of fish influence the profitability of different locations.

This article employs Heckman's (1976) two-step estimator to scrutinize the drivers of intra-temporal and inter-temporal effort allocation respect to the changes in the attractiveness of different fishing areas in the Norwegian trawl fleet to maximize annul profit. The model emphasizes on locational heterogeneity and incorporates fish abundance measured by CPUE, market prices of the fish species, fuel cost and availability of coastal fishers in three heavily trawled regions including the northern and, southern parts of the west coast of Norway, and the high sea areas of the Barents Sea. What we mean by intra-temporal effort allocation is that how fishers reallocate fishing effort across three selected areas within the same time period. Inter-temporality refers to the reallocation of fishing effort over time within the same location.

The investigation of fisher’s behavior underlying effort allocation reveals important information about the possible responses of fishers to the changes in biological, economic, environmental, and regulatory conditions, which ultimately contributes to the improvement of the present management scheme (Béné & Tewfik, 2001; Charles, 1995; Hilborn, 1985, 2007; Holland & Sutinen, 1999; Maurstad, 2000; Opaluch & Bockstael, 1984; Wilen et al., 2002).

## 2 Data description

### 2.1 A description of fishery area, its sub-regions and the corresponding attributes

Figure 1 shows the predominant areas of the trawl fishery where cod, saithe, and haddock fisheries are conducted. The area consists of the Norwegian west coast, from south in the North Sea to the shallow shelf along the northern parts of the west coast, extended towards the deep-sea areas of the Arctic (including Svalbard and Bear Island). We divide the fishing area into three arbitrary sub-regions A, B and C based on the relative availability of fish species according to the feeding and spawning migration patterns over the course of a year.

Region A attributes to the high sea areas of the Barents Sea where predominantly cod fishery and to a lesser extent haddock fishery are conducted. After spawning in the winter months, cod and haddock swim to the sub-Arctic areas to feed.

Region B corresponds to the west coast of northern Norway, where three fisheries overlap mostly during winter. Every winter mature NEA cod and haddock perform an extensive migration from the Arctic sub-areas, where they feed to the shallow waters of north-west coast of Norway to spawn, with peak activities in March-April and March-June, respectively (Korsbrekke, 1999; Olsen et al., 2010; Rose, 1993). Similar to NEA cod and haddock, saithe spawns in winter during February-April, with its peak in February along the coastal banks of west of Norway (Olsen et al., 2010). The congestion of NEA cod, saithe, and haddock to spawn along the west coast of northern Norway leads to an intensive trawling in this area.

Region C depicts the southern part of the west coast of Norway, where saithe fishery is dominant. Spawning of saithe occurs over a wider area than for NEA cod and haddock towards southern parts of Norway in the North Sea. Feeding migration of saithe takes place across a narrower area towards northern parts (Jakobsen & Olsen, 1987; Olsen et al., 2010).

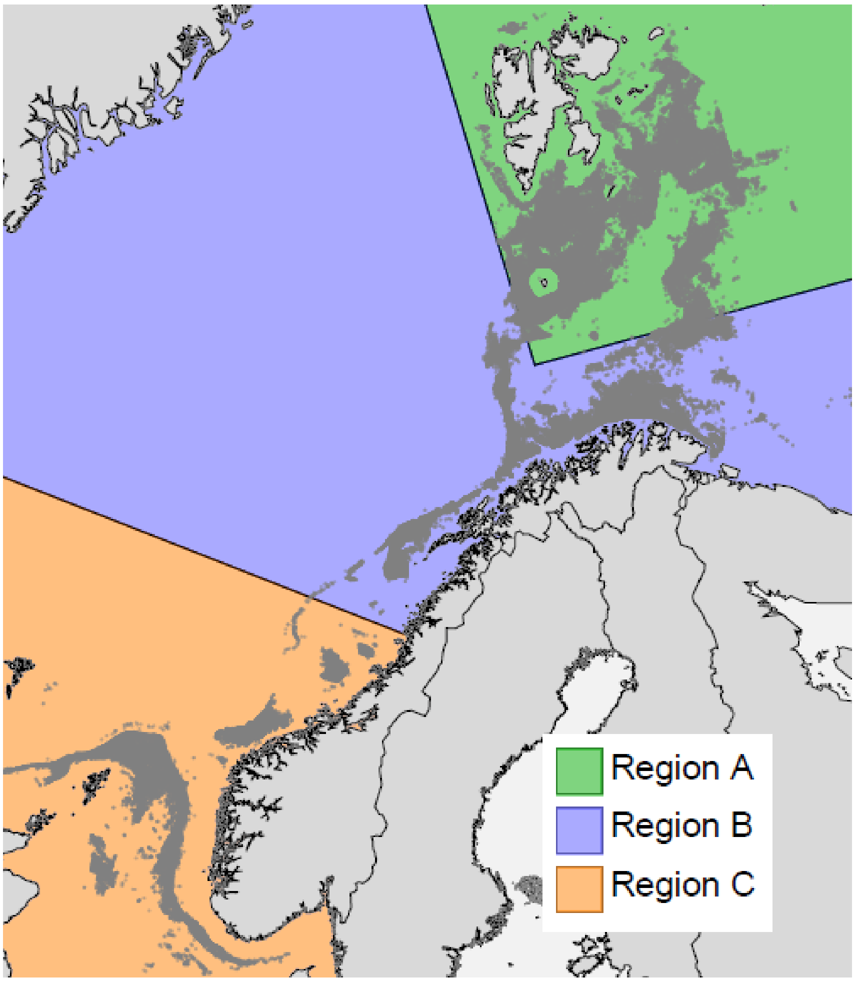

Figure 1. Map shows three arbitary regions where cod, saithe, and haddock fisheries are conducted. Cod and haddock fisheries are prevailing in regions A and B, while saithe fishery is dominant in region C. The map also shows the location of trawling based on the individual hauls in the selected areas over 2011-2016. Trawl vessels dominate fishing along the west coast of Norway and the sub-Arctic areas

Figure 2 shows the average monthly variation in CPUE within and between these three fisheries in the selected regions over 2011-2016. Monthly CPUE is calculated by dividing the total catch by the corresponding trawling hours. Incidental catches of other species are also included in the calculation of CPUEs of these three fisheries.

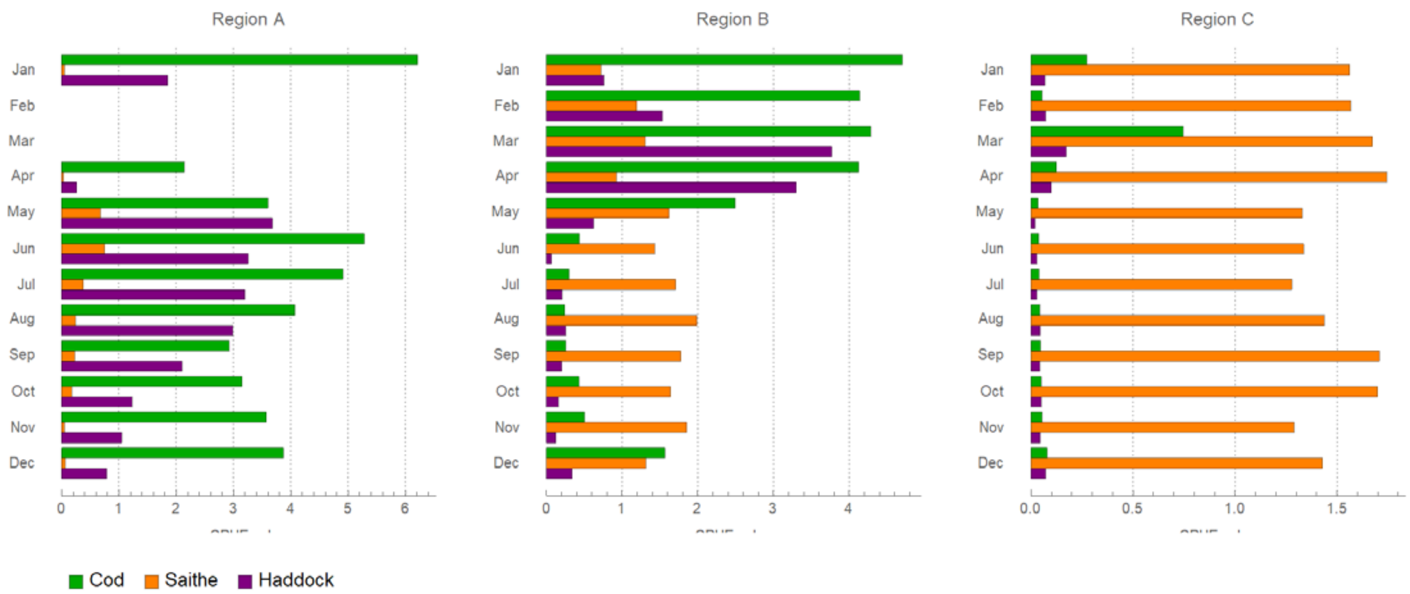

Figure 2. Temporal variation of CPUE, measured in tones per hour of traveling in cod, saithe, and haddock fisheries in the selected regions on monthly basis. Source: The Norwegian Directorate of Fisheries.

As it is shown in Figure 2, cod and haddock fisheries are prevailing in region A and B, while saithe fishery is dominant in region C. In area B, the CPUEs of cod and haddock are high at the beginning of the fishing year. This is probably related to the spawning aggregation of cod and haddock along the north-west coast of Norway. After May, there is a sudden reduction in CPUEs of these fisheries in region B. Concurrently from May, the CPUE of these two fisheries start to rise in region A. As it is evident from Figure 2, there are no fishing activities in February and March in region A. This is probably because of the unsuitable weather conditions in region A (i.e., Arctic area). CPUE of saithe fishery exhibits a stable trend in regions B and C.

Figure 3 shows the average monthly variation in allocation of fishing effort in cod, saithe, and haddock fisheries over 2011-2016. The fishing effort is measured in thousand trawling hours.

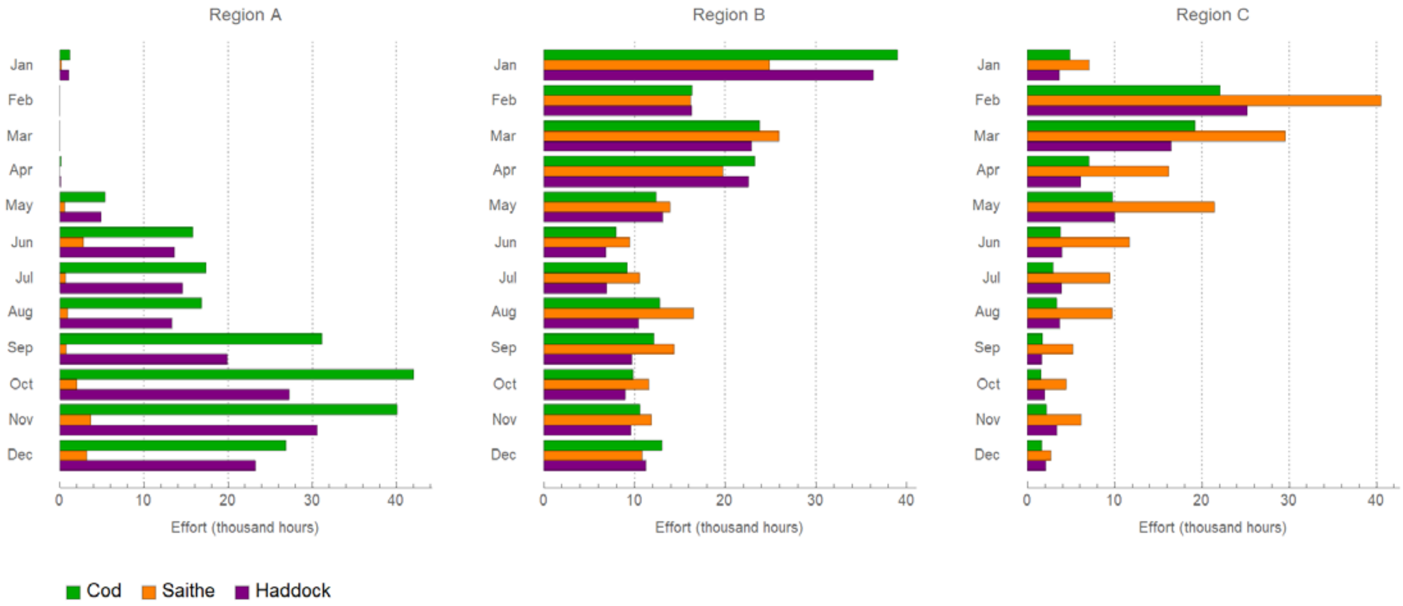

Figure 3. Fishing effort allocation of the Norwegian trawlers in cod, saithe, and haddock fisheries, measured in thousand trawling hours in the three selected regions on monthly basis over 2011-2016. Source: The Norwegian Directorate of Fisheries.

The highest concentration of effort in region A in cod and haddock fisheries takes place towards the end of the year. This is the time when cod and haddock are available in the Arctic waters to feed. The patterns of fishing effort allocation in cod and haddock fisheries in region B follow a declining trend over the course of a year. A sharp drop is obvious at the beginning of the fishing year in these two fisheries in region B. Concurrent to the drop in fishing effort in cod and haddock fisheries, the effort allocation in saithe fishery has increased in region C in February. The effort allocation in saithe fishery in region C follows a decreasing pattern towards the end of the year.

Figure 4 depicts the average monthly catch, measured in thousand tons in the cod, saithe and haddock fisheries in the three selected regions over 2011-2016. It should be noted that bycatches of other species are considered in the calculation of total catch.

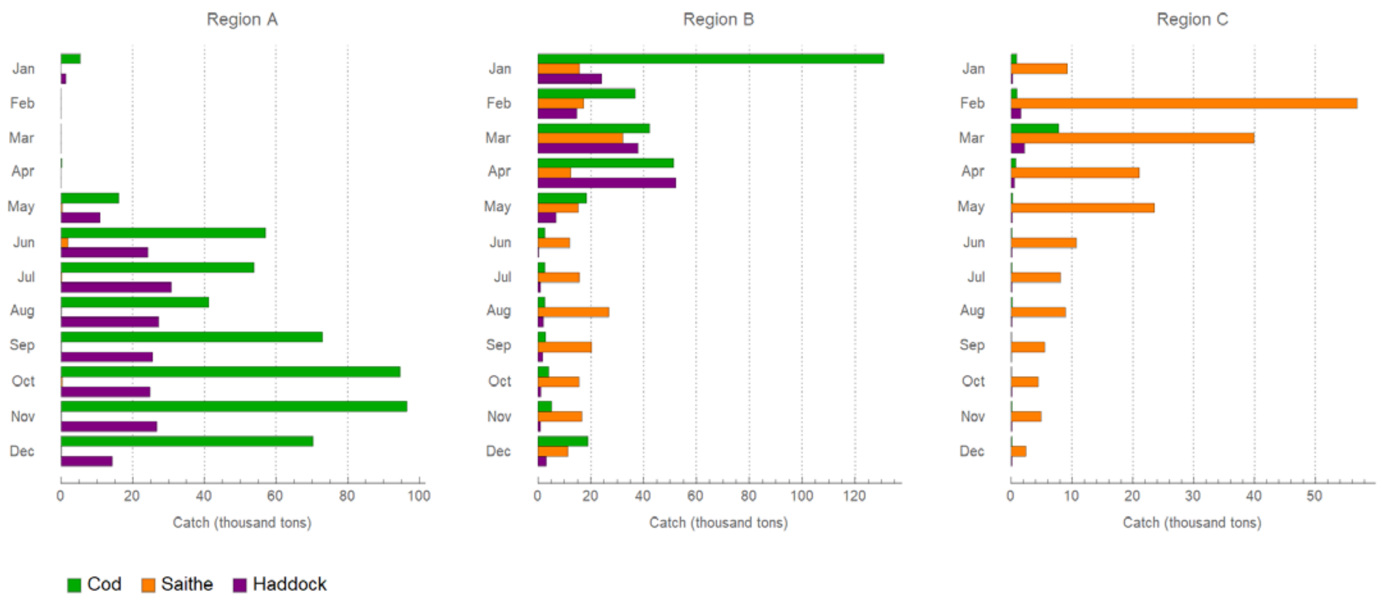

Figure 4. Distribution of the total catch of cod, saithe and haddock fisheries, measured in thousand tons in the three regions on monthly basis over 2011-2016. Source: The Norwegian Directorate of Fisheries.

In region A the catch of cod and haddock is highly concentrated towards the end of the year. In region B, the largest landing of cod takes place in January, followed by a considerable and sudden decline towards the end of the year. Right after this drop, the catch of saithe in area C has increased. This might indicate that trawlers redirect fishing effort from cod fishery in region B to saithe fishery in region C. The catch of saithe declines after the winter months.

In order to investigate the possible impact of the availability of coastal fishers during winter fishery in region B on trawlers' harvest strategy, in Figure 5, we depict the average of total weekly cod catch of coastal vessels measured in thousand tons during 2011-2016. Since cod fishery is the most important element of the winter fishery (i.e., Lofoten fishery), Figure 5 shows the total catch of cod.

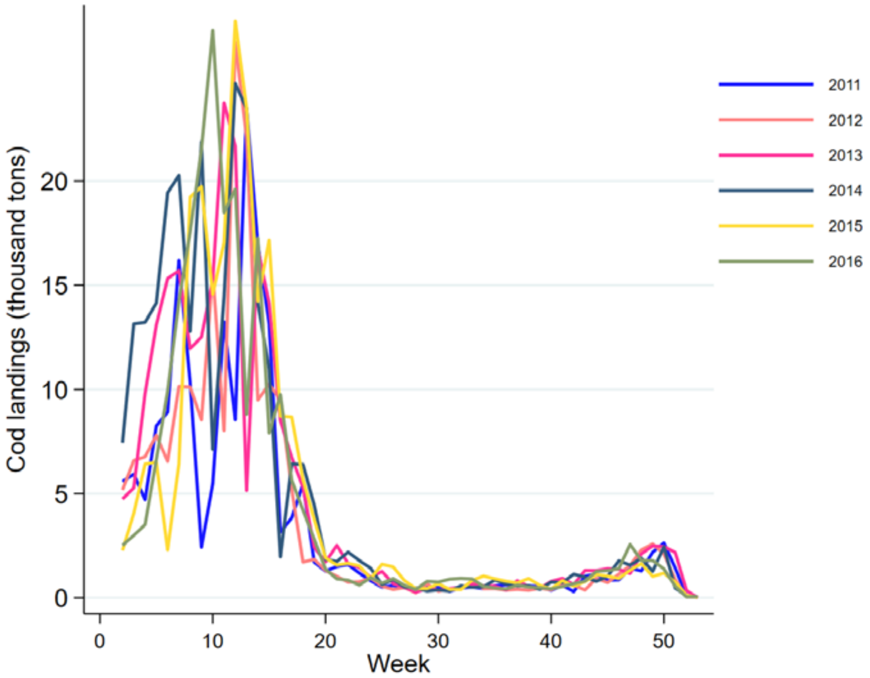

Figure 5. Total weekly landings of cod, measured in thousand tons, caught by the coastal vessels during 2011-2016. Source: The Norwegian Directorate of Fisheries.

As it is evident, cod landings are concentrated at the beginning of the fishing year during spawning migration. The limited geographical mobility of the coastal boats relative to the trawl vessels mandates them to fish close to the shore and rigidly follow seasonality of codfish.

In Figure 6, we depict the average monthly prices of the three species over 2011-2016. The prices for the frozen products of codfish are measured in Norwegian currency per kilo (Norwegian Kroner (NOK)). Since trawlers are equipped with processing and freezing facilities onboard, the prices are ascribed to the frozen fish products.

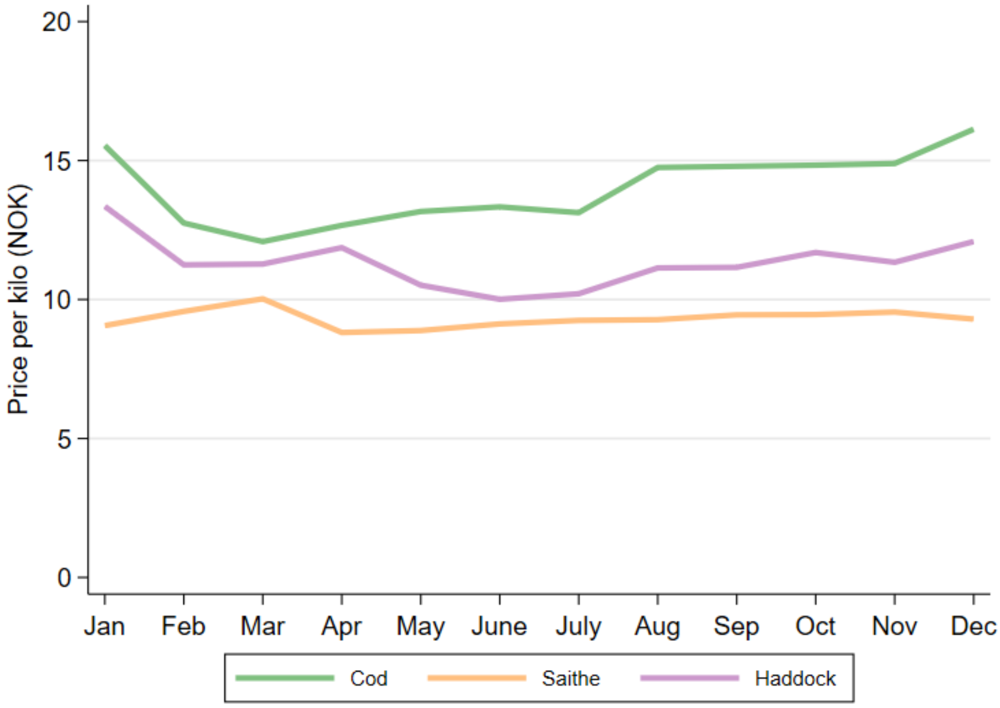

Figure 6. Monthly average prices for the landed frozen products of cod, saithe, and haddock, caught by trawl fleet during 2011-2016. The prices are in Norwegian krone. Source: Norwegian Fishermen's Sale organization.

As it is clear from Figure 6, cod and saithe are the most and least commercially valuable species in the codfish portfolio. At the beginning of the year, prices of cod and haddock follow a declining pattern. This is the time when these fish stocks aggregate in region B to spawn.

In contrast to the price patterns of cod and haddock, saithe fetches the highest price in March (around 10 NOK per kilo). One justification is that during this time, fishers, in particular coastal boats are intensively engaged in cod and haddock fisheries and the landing of saithe is probably lower. This might lead to the higher price of saithe. Generally, saithe price does not exhibit considerable fluctuations relative to the prices of cod and haddock. This could probably because the CPUE of saithe does not vary considerably over the course of a year (See Figure 2). Another relevant explanation could be that the global demand for fresh saithe is very limited and saithe is conserved in different forms than cod (Birkenbach et al., 2020; Hersoug, 2005). Moreover, due to the limited demand the processing capacity of the trawl industry is not influenced by the fluctuations in the landings of saithe (Birkenbach et al., 2020; Hersoug, 2005).

## 2.2 Construction and utilization of data

The data used in this study is obtained from multiple sources, covering 2011-2016. The statistical analysis for the intra and inter-temporal analysis are based on the weekly and monthly time resolutions, respectively. The reason to use monthly data for the inter-temporal effort allocation analysis is the lack of accessibility to the weekly fuel price data (i.e., using weekly data in inter-temporal analysis leads to collinearity as fuel price does not vary on weekly basis). Hence, in total we have 312 (i.e., every year consists of 52 weeks) and 72 observations for the intra and inter-temporal analysis.

A haul-level data set of fifty-one codfish trawlers is provided by the Norwegian Directorate of Fisheries (Norwegian: Fiskeridirektoratet). The main targets of these trawlers are cod, saithe, and haddock. Every observation in the data set is associated with geographical coordinates (spatial dimension) and harvest time (temporal dimension). The catch and effort data is used to estimate standardized CPUE for individual vessels (See Equation 17 in section 3.3.1). In addition, this data set comprises the information about the technical features of the vessels such as engine power and tonnage.

Weekly fish prices for the frozen products of cod, saithe, and haddock are obtained from the Norwegian Fishermen's Sales organization (Norges Råfisklag). Codfish trawlers are equipped with freezing and storage capacities, and the harvested fish is processed and refrigerated onboard. In order to tackle the potential problem of endogeneity of cod price (Section 3.3.2), we utilize weekly exchange rate of NOK/EURO as instrumental variable. The weekly exchange rates are derived from Statistics Norway Bureau (SSB).

For calculation of fuel cost, we acquire annual fuel data for the trawl fleet from Guarantee Fund for Fishermen (Garantikassen for fiskere). Table 1 shows the average cost of fuel for the trawl fleet per liter. Value added tax (VAT) is subtracted from the prices.

Table 1- Average annual fuel price for the trawl fleet- Source: Guarantee Fund for Fishermen (Garantikassen for fiskere). Value added tax (VAT) is deducted from the prices.

| Year | Price per liter (NOK) |
|---|---|
| 2011 | 4.21 |
| 2012 | 4.46 |
| 2013 | 4.54 |
| 2014 | 4.47 |
| 2015 | 3.45 |
| 2016 | 2.98 |

In order to account for the variation in the fuel expenditure, we also obtain monthly data of gasoline price from Statistics Norway Bureau (SSB) for 2011-2016. We calculate the percent change of monthly gasoline price respect to the average price of 2011, which is equal to 13.95. Then we multiply the percentage changes by the annual fuel prices, presented in Table 1.

Moreover, in order to address the possible effect of the coastal fleet's behavior on trawlers' adopted harvest strategy, weekly landings of cod, measured in tons is obtained from the Norwegian Directorate of Fisheries. Since cod is the most important fish species for the coastal and trawl fleet during winter fishery, we only consider the possible effect of cod landings of coastal fishers on trawlers' harvest behavior.

# 3 Method

## 3.1 Theoretical framework

Our proposed model considers an owner of a trawl vessel, holding a quota portfolio of cod, saithe, and haddock as a perfect foresight decision-maker, whose aim is to maximize the annual profit. To do so, fisher constantly re/allocates fishing effort across space and over time, respect to the quota constraints. The expected profit rates of different fishing locations depend on fish availability (measured by CPUE), market prices, fuel expenditure, and aggregation of the coastal boats. Considering this argument, we articulate that the relative attractiveness of fishing locations determines the choice(s) of target species.

To formulate our problem, we specify model's sets as follows. Set $A$ shows the available fishing regions, each region is represented as $a$. $T$ is the set of time period, where each period is indexed as $t$. We index each species (here, cod, saithe and haddock) as $j$ in the entire set of species $J$. For the sake of simplicity, we disregard any in-season stock dynamics such as recruitments and growth dynamics of the fish stocks.

The decision variable is the fishing effort $e_{at}$ to target species $j$, which maximizes the profitability of the fishing portfolio. We should bear in mind that fishing effort includes only the subscripts of location and time as we already delineated that location choice over the course of a year specifies the choice of target species.

Profit is represented as a discounted sum of the difference between periodical revenue and cost. The revenue is obtained by fish price $p_{jt}$ multiplied by harvest function $H_j(e_{at}, X_{ajt})$, where $X_{ajt}$ shows the availability of each species at specific location and time. The cost is a function of fishing effort $e_{at}$ and location-specific costs $c_{at}$. Here, $c_{at}$ comprises the cost related to fuel consumption to travel to location a and the cost caused by congregation of coastal fishers along the north-west coast of Norway, particularly during winter fishery. The objective function that maximizes profitability of the fishing portfolio over a one-year period, is presented in Equation (1).

$$\max_{e_{at}} \sum_{t=1}^{T} \rho^{t} \sum_{a=1}^{A} \left\{ \sum_{j=1}^{J} p_{jt} H_j(e_{at}, X_{ajt}) - c_{at} e_{at} \right\} \tag{1}$$

where $\rho$ is a discount factor. In the following equations, different constraints of the maximization model are presented.

$$\sum_{t=1}^{T}\sum_{a=1}^{3} H_j\big(e_{at}, X_{ajt}\big) \leq \bar{Q}_j, \qquad \forall j \in \{1, 2, 3\} \tag{2}$$

$$\sum_{a=1}^{A} e_{at} \leq \bar{e} \qquad\qquad when\ 0 < t < T \tag{3}$$

$$e_{at} \geq 0 \qquad\qquad when\ 0 < a < A\ and\ 0 < t < T \tag{4}$$

$\bar{Q}_j$ indicates the annual allocated quota for species $j$. Under a quota-managed fisheries, fishers cannot fish more than the allocated quota, and overfished quotas could be confiscated, or penalized (Hersoug, 2005). Equation (3) refers to the upper limit for the total effort that could be allocated per period. This is specified to show that the fishing operation is constrained by the fishing duration and vessel's capacity. Equation (4) guaranties the non-negativity of the decision variable $e_{at}$. The profit maximization problem is solved using Lagrangian method. The Lagrangian is set up as follows:

$$L = \sum_{t=1}^{T} \rho^t \sum_{a=1}^{A} \Bigg(\Bigg\{ \sum_{j=1}^{J} p_{jt} H_j\big(e_{at}, X_{ajt}\big) - c_{at} e_{at} \Bigg\} + \sum_{j=1}^{J} \lambda_j \left( \bar{H}_j - \sum_{t=1}^{T}\sum_{a=1}^{A} H_j\big(e_{at}, X_{ajt}\big) \right) + \sum_{t=1}^{T} \bar{\kappa}_t \left( \bar{e} - \sum_{a=1}^{A} e_{at} \right) + \sum_{t=1}^{T}\sum_{a=1}^{A} \underline{\kappa}_{at} e_{at} \tag{5}$$

First order conditions (F.O.C) with respect to $e_{at}$is:

$$\rho^t \left( \sum_{j=1}^{J} p_{jt} \frac{\partial H_j\big(e_{at}, X_{ajt}\big)}{\partial e_{at}} - c_{at} \right) - \sum_{j=1}^{J} \lambda_j \frac{\partial H_j\big(e_{at}, X_{ajt}\big)}{\partial e_{at}} = \bar{\kappa}_t - \underline{\kappa}_{at} \tag{6}$$

$\lambda_j$, $\bar{\kappa}_t$ and $\underline{\kappa}_{at}$ are Lagrange multipliers. The Lagrangian multiplier $\lambda_j$ represents the shadow value of quota. Equation (5) indicates that if discounted (the present value of) periodical marginal profit exceeds the shadow value of quota, fisher would choose to allocate fishing effort. Equation (6) shows the Kuhn-Tucker conditions. If the periodical profit is below the shadow value, the allocated effort in area $a$ at time $t$ becomes zero.

### 3.1.1 Intra-temporal and inter-temporal substitutions of the effort

An important aspect of effort allocation is to see how substitutions in the spatial and temporal senses are connected. The intuition is that as the relative attractiveness of a particular area changes over the course of a year, the fishing effort might be displaced to other areas or time periods. Here, an important question arises and that is: how trawlers would substitute fishing effort across different locations within the same period (intra-temporal), and over time within the given location (inter-temporal).

We derive the equations for the intra-temporal and inter-temporal effort substitution based on Equation (5), where trawlers choose location $a$ at time $t$ to target species $j$ to maximize profitability of the quota portfolio. To do so, we first define the net value of fish species as $y_{jt} \equiv \rho^t p_{jt} - \lambda_j$. In intra-temporal analysis, we have $A$ equations in a given period $t$.

$$\sum_{j=1}^{J} y_{jt} \frac{\partial H_j\left(e_{at}, X_{ajt}\right)}{\partial e_{at}} - \rho^t c_{at} = 0 \ , \qquad a = \{1,2,3\} \tag{7}$$

If the number of areas $A$ is equal to or greater than the number of targeted species $J$, the system of equations for $y_{jt}$ is solvable because there are $A$ equations and $J$ unknowns. In our case study, there are three target species and three defined areas. Hence, the system of equations is exactly identified. The solution for $y_{jt}$ will be a function of $e_{at}, \left\{X_{ajt}\right\}_{j \in J}, c_{at}, \rho^t$, for all $a \in A$ given $t$. Once we obtain $y_{jt}$, we substitute $y_{jt}$ into Equations (7) to yield $e_{at}$ for all $a$ in terms of contemporaneous variables.

$$e_{at} = e_{intra-temporal}\left(\{c_{at}\}_{a=1}^{3}, \left\{\{X_{ajt}\}_{j=1}^{J}\right\}_{a=1}^{3}, \rho^{t}\right) \tag{8}$$

From equation (8), we see that the fishing effort turns out to be function of area-specific costs, resource abundance, and discount factor.

The equation below shows the inter-temporal effort substitution.

$$\sum_{j=1}^{J} y_{jt} \frac{\partial H_j(e_{at}, X_{ajt})}{\partial e_{at}} - \rho^{t} c_{at} = 0 \ , \ \ t = \{1,2, \dots, 12\} \tag{9}$$

If the number of $T$ is equal to or greater than $J$, the equation can be solved. In our case, we choose own period $\tau$ and two-period lagged variables, so that the system of equation is exactly identified. We obtain $e_{a\tau}$ for the multiple time periods given an area $a$ in Equation (10).

$$e_{a\tau} = e_{inter-temporal}\left(\{c_{at}\}_{t=\tau-2}^{\tau}, \{X_{ajt}\}_{t=\tau-2}^{\tau}, \{p_{jt}\}_{t=\tau-2}^{\tau}, \{\rho^{t}\}_{t=\tau-2}^{\tau}\right) \tag{10}$$

The fishing effort is expressed as a function of area-specific costs, resource abundance, and price of target species in the contemporaneous and the past two periods, and as well as the discount factor.

### 3.2 Empirical model

In this section, we estimate the inter-temporal and intra-temporal effort substitutions in response to the variations in attractiveness of different fishing locations.

As stated earlier, the decisions underlying fishing effort of individual trawlers are influenced by combination of factors. A possible adaptive response of trawlers when the fishing condition is unfavorable (i.e., expected profit becomes negative) at specific location and time, is to switch to other available alternatives. Simply, this means that we have missingness in the fishing effort allocation data (i.e., dependent variable). Statistically, including substantial zero observations would bias the estimation results because the distribution of the effort observations is truncated or bunching at zero.

The Heckman's (1976) selection model provides a potentially useful tool under this circumstance, as it enables us to both test and correct for the potential bias created by the missingness in the fishing effort data. Another benefit of employing Heckman’s two-step estimation approach is that it enables us not only to estimate the decision to fish or not (i.e., using Probit model (first step)), but it also acquires the continuous effort allocation conditional on the participation decision (second step).

Our dependent variable is the allocated fishing effort in area $a$ and time $t$ by trawler $i$. The explanatory variables, which define the relative attractiveness of locations are fish availability measured by CPUE (tons per hour of trawling), price of fish per kilo (Norwegian Kroner (NOK)), fuel price per liter to travel to the available locations (Norwegian Kroner (NOK)) and intensity of coastal fleet’s participation during the winter cod fishery (i.e., approximated by total landings of cod in tons by coastal boats).

### 3.2.1 Estimation of intra-temporal effort allocation

We start with the estimation of intra-temporal effort allocation for the fifty-one codfish trawl vessels. The estimation equation for the intra-temporal substitution is based on the theoretical results, expressed in Equation (8).

Equation (11) and (12), show the estimation procedure for the Probit model, where trawler $i$ decides whether to allocate fishing effort in area $a$ and time $t$, in respect to the attractiveness of the selected area. The latent variable for fishing effort $e_{iat}^{*r}$ in the Probit model is specified in Equation (12). $D_{iat}^{r}$ is a binary variable which is equal to 1 if trawler allocates fishing effort at location $a$ and time $t$ and 0 otherwise. Superscript 1 in Equation (11) refers to the first step of the estimation procedure. Superscript $r$ refers to the intra-temporality equations.

$$e_{iat}^{*\,r} = \phi_i^{r\,1} + \theta_t^{r1} + \omega_a^{r1} + \sum_j \beta_{1j}^{r1} CPUE_{ajt} + \sum_a \beta_{2j}^{r1} fp_t + \sum_a \beta_{3a}^{r1} cc_t + \varepsilon_{iat}^{r1} \qquad (11)$$

$$D_{iat}^{r} = \begin{cases} 1 & if\ e_{iat}^{*r} > 0 \\ 0 & otherwise \end{cases} \qquad (12)$$

$\phi_i^{r1}$ refers to individual vessel fixed effect which is either engine power or gross tonnage. $\theta_t^{r1}$, and $\omega_a^{r1}$ are period and area fixed effects, respectively. $CPUE_{ajt}$ is the standardized catch per unit of effort (i.e., The standardization procedure is explained in section 3.3.1). $fp_t$ refers to the fuel price, which approximates the cost of traveling to the considered location. $cc_{at}$ refers to the total landings of cod by the coastal fishers, which is a proxy for the possible congestion effect of the coastal boats on trawlers' harvest strategy. $\varepsilon_{iat}^{z1}$ refers to the residuals.

In the second step, the continuous effort, in logarithmic form, conditional on the participation decision (first step) is estimated. Superscript 2 in Equation (13) refers to the second step of the estimation procedure.

$$\ln e_{iat} = \phi_i^{r2} + \theta_t^{r2} + \omega_a^{r2} + \sum_j \beta_{1j}^{r2}(V_i) CPUE_{ajt} + \sum_a \beta_{2j}^{r2} fp_t + \sum_a \beta_{3a}^{r2} cc_t + \varepsilon_{iat}^{r2} \qquad (13)$$

Here, we add varying coefficients $V_i$ on *CPUE*, which refers to the vessel's technical attributes (e.g., engine power or gross tonnage). We take the vessel characteristics into account as fishers might allocate fishing effort differently even when they target the same species at the same location and time due to the distinct features of the vessel. The specification of varying coefficient is linear: $\beta_{1j}^{r2}(V_i) = \eta_{1j}^{r2} + \eta_{2j}^{r2} V_i$. $\varepsilon_{iat}^{r2}$ refers to the residuals.

### 3.2.2 Estimation of inter-temporal effort allocation

The estimating equation for the inter-temporal substitution is based on the theoretical result expressed in Equation (10). However, we need to refine Equation (10) to specify the corresponding empirical model. Perfect foresight assumption means that the trawler’s choices are made at the start of the planning horizon (period zero), but indeed trawlers decide about effort allocation at time $t$. Hence, the discounted factor is not included in the empirical model. Moreover, Equation (10) includes the historical CPUEs. In the empirical model, we include past catches instead of CPUEs. Additionally, since inter-temporal effort allows for time variation, we also include the prices of fish species in our model. Superscript $z$ refers to the inter-temporality.

$$e_{iat}^{*z} = \phi_i^{z1} + \theta_t^{z1} + \omega_a^{z1} + \sum_{\tau=t-2}^{t} \left[ \sum_j \beta_{1j\tau}^{z1}(Price_{jt}) CPUE_{aj\tau} + \sum_a \beta_{2j}^{z1}\, fp_t + \sum_a \beta_{3\tau}^{z1} cc_{a\tau} \right] + \varepsilon_{iat}^{z1} \tag{14}$$

$$D_{iat}^{z} = \begin{cases} 1 & if\ e_{iat}^{*z} > 0 \\ 0 & otherwise \end{cases} \tag{15}$$

The key differences from the first step equation of the intra-temporal substitution (See Equation (11)) are the inclusion of current period and two previous periods $(\tau = t-1, t-2)$ as well as the prices of target species. $Price_{jt}$ refers to the price of target species $j$ at time $t$. The varying coefficient is linear: $\beta_{1j\tau}^{z1}(Price_{j\tau}) = \eta_1^{z1} + \eta_2^{z1} Price_{j\tau}$. $\varepsilon_{iat}^{z1}$ refers to the residuals. The second step estimation equation for the inter-temporal substitution is specified in Equation (16).

$$\ln e_{iat} = \phi_i^{z2} + \theta_t^{z2} + \omega_a^{z2} + \sum_{\tau=t-2}^{t}\left[\sum_j \beta_{1j\tau}^{z2}(V_i, Price_{jt})CPUE_{aj\tau} + \sum_a \beta_{2j}^{z1}\, fp_\tau + \sum_a \beta_{3\tau}^{z2} cc_{a\tau}\right] + \varepsilon_{iat}^{z2} \quad (16)$$

The varying parameter on CPUE is specified as $\beta_{1j\tau}^{z2}(V_i, Price_{jt}) = \eta_1^{z2} + \eta_2^{z2}V_i + \eta_3^{z2}Price_{jt}$. $\varepsilon_{iat}^{z2}$ refers to the residuals.

## 3.3 Correction of some potential econometric issues

In order to properly specify our model, prior to the estimation of intra and inter-temporal effort substitutions, we discuss and correct the potential problems in using CPUE and cod price as explanatory variables.

### 3.3.1 Standardization of CPUE

Within fisheries research CPUE is a commonly employed index to assess the average stock size (Hilborn & Walters, 1992; Maunder et al., 2006). To calculate the values of CPUE, total catch of each haul is divided by the corresponding fishing effort. In this article, we are dealing with the effort allocation decisions of fifty-one individual trawl vessels over 2011-2016. Even if trawlers coexist at the same time and location, and being exposed to the same level of fish abundance, the effort allocation decisions and, subsequently catch sizes might be different. In order to take this heterogeneity into account, we construct a vessel-specific index for the CPUE for each trawler to implement it in the estimation equations.

To this aim, in Equation (17) we regress individual catch sizes of species $j$ in logarithmic form at location $a$ and time $t$, caught by trawler $i$ against fishing effort in logarithmic form and a series of dummy variables to capture the fixed effects.

$$lnc_{ijat} = \alpha_1 DW_t . DL_a + \alpha_2 DY_t + \alpha_3 DV_i + \ln e_{ijat} \quad (17)$$

$c_{ijat}$ is a quantity of catch in metric tons of species $j$ ,caught by vessel $i$ in area $a$ in period $t$. D$W_t$ refers to dummy variable for week effect in intra-temporality analysis and month effect in inter-temporality analysis. $DL_a$, $DY_t$ and $DV_i$ refer to dummy variables to capture area, year and individual specific effects, respectively. We include the interaction variable between week/month and location as CPUE can be different across different locations given the same week/ month. The variable $e_{ijat}$ is measured in trawling hours. Once, we estimate catch size, $CPUE_{ijat}$ is calculated by divining catch by corresponding effort. The unit of estimated CPUE is tons of fish, caught per hour of trawling.

### 3.3.2 Endogeneity problem of the cod price

Another estimation issue is related to the potential problem of price endogeneity of the cod fishery. Birkenbach et al. (2020), Asche, Gordon, et al. (2002) and Arnason et al. (2004) discuss that the Norwegian trawlers confront a downward-sloping demand for cod. This is probably because the cod market is segmented. Therefore, a large supply of cod, in particular during winter fishery may reduce the price, while we estimate the response of trawlers to the exogenous variation of cod demand.

As a large portion of Norwegian cod catch is exported to foreign countries, particularly those in European Union (EU) (Asche, Flaaten, et al., 2002; Asche, Gordon, et al., 2002), the exchange rate NOK/EURO is expected to affect the international buyers' evaluation of fish market, but it is not affected by weekly cod landings (i.e., definition of instrumental variable). Therefore, we first estimate the cod prices by instrumenting the exchange rate of NOK/EURO. Thereafter, we implement the estimated cod prices in the estimation equations.

## 4 Results

We estimate Equations (11), (13), (14), and (16) using the comprehensive panel dataset discussed in section 2.2. Table 2 and 3 show the estimation results for the intra-temporal effort allocation, while Table 4 and 5 refer to the inter-temporal analysis, using Heckman's two-step estimator. The results represented in Table 2 and 4 report the estimations based on the first step —participation decisions— (Probit regression). They also provide the magnitude of effort displacement by marginal effects. Marginal effects show how fishing effort changes for a one unit change in the explanatory variables.

The estimation results based on the second step, —trawling hour— conditional on participation decisions are presented in table 3 and 5. The first step estimates are used to calculate the inverse of Mill's ratio, which is used to estimate the second step. In the second step, two vessel specifications are used: engine size and gross tonnage.

### 4.1 Results of intra-temporal effort allocation

The results in Table 2 and 3 show how trawlers switch between region A, B and C in response to the changes in the relative attractiveness of these regions within the same time period to maximize profit.

Table 2. Estimation results of the first step from Equation (11)- Marginal effects show the magnitude of effort displacement- intra-temporal analysis

| **Explanatory variables** | **Probit estimations** | **Marginal effects** |
|---|---|---|
| Fuel price, region A | -0.035 | 0.014 |
| Fuel price, region B | -0.113*** | -0.044*** |
| Fuel price, region C | 0.347*** | 0.135*** |
| Coastal landing, region A | -0.017*** | -0.042*** |
| Coastal landing, region B | -0.039*** | -0.015*** |
| Coastal landing, region C | 0.146*** | 0.057*** |
| Cod: CPUE | 0.006*** | 0.002*** |
| Saithe: CPUE | -0.004 | -0.001 |
| Haddock: CPUE | -0.131*** | -0.051*** |
| * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$ | | |

Table 3. Estimation results of the second step from Equation (13)- intra-temporal analysis

| **Explanatory variables** | **Engine power** | **Tonnage** |
|---|---|---|
| Fuel price, region A | -0.063* | 0.063 |
| Fuel price, region B | -0.098*** | -0.98*** |
| Fuel price, region C | 0.229*** | 0.228*** |
| Coastal landing, region A | -0.002 | -0.002 |
| Coastal landing, region B | -0.015 | -0.015 |
| Coastal landing, region C | 0.03 | 0.03 |
| Cod: CPUE | 0.008 | 0.001 |
| Saithe: CPUE | 0.002 | -0.002 |
| Haddock: CPUE | -0.09 | -0.094 |
| Cod: Engine × CPUE | -0.002* | - |
| Saithe: Engine × CPUE | -0.003* | - |
| Haddock: Engine × CPUE | -0.000 | - |
| Cod: Tonnage × CPUE | - | -0.001 |
| Saithe: Tonnage × CPUE | - | -0.004* |
| Haddock: Tonnage × CPUE | - | 0.002 |
| Inverse of Mills ratio | 0.12 | 0.124 |
| * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$<br>$R^2 = 0.173$<br>Note: The dependent variable is trawling hour per week in a specific location. | | |

The negative and significant coefficient of the fuel price in region B, and positive and significant coefficients of the fuel price in region C in the first and second steps indicate that higher fuel prices increase the likelihood that trawlers shift from region B to region C to fish saithe. This harvest behavior is justifiable. When travel cost increases, fishing regions nearshore are more preferable (regions B and C). However, the negative coefficient of region B shows that the trawlers would spend less trawling time in this region. Region B is not favorable probably because of the adverse effect of the presence of coastal fleet in this region. Unsurprisingly, the negative and significant coefficient of region A in the second step (when the chosen vessel characteristic is engine power) shows that the participant trawlers would avoid region A when the fuel price is high as this region is farther and costs of fishing increase with distance. This provides insight about effort substitution among different regions to maximize profit.

With regard to the effect of coastal fleet on adopted harvest strategy of the trawlers, the negative signs in region A and B, and positive sign in region C indicate that the intensity of participation of coastal boats during the winter months shifts the effort allocation of the trawlers to region C (first step). Observing this choice is unsurprising as it is rational to avoid region B to fish cod and haddock, probably because of the low prices during Lofoten fishery (See Figure 6). Region A will be avoided as well probably due to the less desirable climatic conditions of the sub-Arctic areas during wintertime. However, once trawlers decide where to fish, the magnitude of allocated effort is not affected by the intensity of coastal fishers' participations. This means that the decisions underlying fishing effort is made while being aware of the possible negative impacts of the congestion of the coastal boats. Probably, the participant fishers have evaluated the situation and come to the conclusion that they are able to overcome or at least offset the possible negative impacts of the congregation of the coastal boats on the profit of the fishing portfolio.

The probability of allocation of fishing effort is increased/ decreased with higher/ lower values of CPUE for cod and haddock fishery. In the second step, the effect of CPUE is captured through two variables, one is CPUE itself, and the other one is the interaction between CPUE and vessel technical specifications. The coefficients of the interaction variables have small and negative values. This implies that the overall effect of CPUE is positive on the allocated effort, if the vessel is less powerful or smaller in size. This means that fishers with less powerful boats need to rigidly follow the seasonality of fish.

The inverse of Mills ratio is statistically not different from zero. This means that the model does not suffer from sample selection problem. The explanatory power of Heckman's two-step estimator is 18%.

## 4.2 Results of inter-temporal effort allocation

The results in Tables 4 and 5 show how trawlers allocate fishing effort over time in a given region.

Table 4. Estimation results of the first step from Equation (14)- Marginal effects show the magnitude of effort displacement inter-temporal analysis

| Explanatory variables | Probit estimations | Marginal effects |
|---|---|---|
| Fuel price | -0.022 | -0.008 |
| Fuel price$_{t-1}$ | -0.03 | -0.011 |
| Fuel price$_{t-2}$ | -0.055 | -0.02 |
| Coastal landing | -0.011*** | -0.004*** |
| Coastal landing$_{t-1}$ | 0.012*** | 0.004*** |
| Coastal landing$_{t-2}$ | -0.007*** | -0.003*** |
| Cod: CPUE | -3.413*** | -1.297*** |
| Saithe: CPUE | -1.096*** | -0.394*** |
| Haddock: CPUE | -5.408*** | -1.944*** |
| Cod: Price × CPUE | 0.187*** | 0.067*** |
| Saithe: Price × CPUE | 0.082*** | 0.029*** |
| Haddock: Price × CPUE | 0.334*** | 0.12*** |
| Cod: Price × Catch$_{t-1}$ | 0.075*** | 0.027*** |

| | | |
|---|---|---|
| Saithe: Price × Catch$_{t-1}$ | 0.334*** | 0.12*** |
| Haddock: Price × Catch$_{t-1}$ | 0.049*** | 0.018*** |
| Cod: Price × Catch$_{t-2}$ | 0.004 | 0.001 |
| Saithe: Price × Catch$_{t-2}$ | -0.005 | -0.002 |
| Haddock: Price × Catch$_{t-2}$ | 0.022 | 0.008 |
| * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$ | | |

Table 5. Estimation results of the second step from Equation (16)- inter-temporal analysis

| **Explanatory variables** | **Engine power** | **Tonnage** |
|---|---|---|
| Fuel price | 0.6** | 0.619*** |
| Fuel price$_{t-1}$ | -0.636** | -0.655*** |
| Fuel price$_{t-2}$ | -0.016 | -0.017 |
| Coastal landing | -0.014*** | -0.014*** |
| Coastal landing$_{t-1}$ | 0.006 | 0.006 |
| Coastal landing$_{t-2}$ | 0.006** | 0.006** |
| Cod: CPUE | -0.185 | -0.236 |
| Saithe: CPUE | 0.127 | 0.101 |
| Haddock: CPUE | 2.911 | 2.881 |
| Cod: Price × CPUE | 0.005 | 0.011 |
| Saithe: Price × CPUE | -0.009 | -0.008 |
| Haddock: Price × CPUE | -0.175 | -0.178 |
| Cod: Price × Catch$_{t-1}$ | -0.007 | 0.008 |
| Saithe: Price × Catch$_{t-1}$ | 0.019 | 0.021 |
| Haddock: Price × Catch$_{t-1}$ | -0.019 | -0.018 |
| Cod: Price × Catch$_{t-2}$ | 0.001 | 0.001 |
| Saithe: Price × Catch$_{t-2}$ | 0.033** | 0.034** |
| Haddock: Price × Catch$_{t-2}$ | 0.005 | 0.005 |
| Cod: Engine × CPUE | 0.004* | - |

| | | |
|---|---|---|
| Saithe: Engine × CPUE | -0.003 | - |
| Haddock: Engine × CPUE | -0.033 | - |
| Cod: Tonnage × CPUE | - | 0.003 |
| Saithe: Tonnage × CPUE | - | -0.003 |
| Haddock: Tonnage × CPUE | - | -0.033 |
| Inverse of Mills ratio | -0.869*** | -0.846*** |
| * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$<br>$R^2 = 0.271$<br>Note: The dependent variable is trawling hours per month in a specific location. | | |

An increase in the fuel price in the given month and in the past two months does not affect the decision to allocate fishing effort in the current month in the given location. This is probably because of the impact of quota regulations. The introduction of quota mandates fishers to exhaust their quotas within the fishing year regardless of fuel price. For the trawlers who have already decided to allocate fishing effort at a specific location, the rise in fuel price at time $t-1$ negatively affects the amount of effort allocation at time $t$ in the chosen location. However, the higher fuel price at time $t$ is associated with increased effort at time $t$. This offers some insights into the possible effect of the quota constraints. As time elapses towards the end of the year, the concern over underutilization of quota is enhanced. Hence, fishers increase the effort despite the higher fuel prices. The effort displacement over time with respect to fuel cost provides an insight that fishers try to balance out the fuel expenditure over the course of a year.

The increased activity of coastal fleet in the current month and two months before in region B decreases the probability of fishing effort allocation in the current month in this region. For the trawlers who already decided to fish in region B, the activity of coastal fleet in the current month negatively affects the amount of the allocated fishing effort in the same period.

The activity of coastal boats with two months lag positively affects the magnitude of fishing effort allocation in the current month in region B.

CPUE affects the probability of effort allocation decision through itself and the interaction term between CPUE and price. The overall effect of CPUE of cod, saithe and haddock on effort allocation decision are equal to: $-3.413 + 0.187 \times Price$, $-1.096 + 0.082 \times Price$ and $-5.408 + 0.334 \times Price$, respectively. This means that the CPUE has positive effect on the probability of effort allocation if and only if the prices are high enough to encourage trawlers to fish their quotas. Otherwise, trawlers would not waste the quota when the prices are low. Once trawlers decide to fish, the value of CPUE in the current period and two previous periods do not affect the magnitude of effort allocation.

The interaction variable between catch and price shows revenue. The increase in generated revenue in cod, saithe, and haddock fisheries during the last period positively affects the possibility of utilizing the quotas in the current period in the same area. The positive and significant coefficient of the interaction variable of catch and price of saithe at time $t-2$ indicates that the large catches of saithe in the past increase the allocated effort in the same area. This results show that fishers update their expectation about CPUE and consider it as chance to consume the quotas.

The statistically significant inverse of Mills ratio means that the model suffers from sample selection problem. The predictive power of the model is 28%.

## 5 Discussion

The intra and inter-temporal estimation results are obtained from a two-step Heckman selection model. In the first step Probit model is estimated to examine whether fishers would allocate effort based on the attractiveness of the selected regions. The second step estimates the continuous effort allocation conditional on the participation decision.

Our results are informative about trawlers' response to the changes in the relative attractiveness of the selected regions under quota regulations. Changes in CPUE and relative prices of fish as well as location-specific costs such as fuel price to travel to the fishing grounds and the intensity of coastal fishers' participations defines the relative attractiveness of the fishing areas. Since our results reveal that region-specific costs have substantial effect on decisions underlying effort allocation, we narrow our focus in discussion part on this matter.

With regard to the fuel price, intra and inter-temporal substitutions in the allocation of fishing effort were detected. With the increased fuel prices, trawlers are discouraged to fish in region B, as region B already incurs cost on trawl fishers due to the congestion of coastal fishers. Hence, trawlers choose region C to fish. Similarly, the magnitude of effort displacement is increased/ decreased in region C/ B with the higher fuel prices. Moreover, the participant fishers avoid region A because of two possible reasons. First is that region A is located farther and costs of fishing increase with distance. Second, since the fishing grounds of sub-Arctic areas are characterized by less desirable climatic conditions, fishers might avoid fishing in the high sea areas due to the increased risk of ending up in hazardous situations.

From inter-temporal point of view, increased fuel price in the previous month negatively affects the amount of allocated effort in the current month in the same region. The reason could be that trawler might postpone to fish in a specific area in the hope of getting lower fuel prices in the remaining months. During the waiting time, trawlers might allocate fishing effort in the regions closer to the shore to balance out the total transportation cost over the year. The hike in fuel price in the current month increases the amount of effort in the same month in the chosen region. This could be ascribed to the cost of waiting for too long to get a lower price for the fuel. Since, trawlers need to exhaust the quota portfolio within the fishing year, waiting too long to get a lower fuel price can result in underutilization of quota and an economic loss.

The negative effect of the congestion of coastal fleet on trawlers' decision-making underlying effort allocation is irrefutable. Based on our results, the intensified fishing activities of coastal fishers, reduces the probability of trawlers' participation in region B.

In the winter months, the spawning aggregation of cod, saithe, and haddock along the west coast of Norway lowers the cost per unit of effort (Hannesson, 2007; Sandberg, 2006). The lower cost per unit of effort together with the limited geographical mobility of the coastal fleet encourages coastal fishers to fish a big portion of their quotas at this time. Up to 80% of codfish quota belongs to the coastal fishers (Asche et al., 2014; Birkenbach et al., 2020). As a result of a large supply of cod, price of cod drops (Alizadeh Ashrafi et al., 2020; Hermansen & Dreyer, 2010) (See also Figure 6). With reduced prices, it is economically irrational for the trawlers to fish the cod quota in region B. Hence, trawlers avoid region B.

Moreover, as our intra-temporal results show, during winter fishery trawlers would not participate in region A either, probably because of the harsh climatic condition of the Arctic areas during the winter months and/or the availability of less dense fish stocks as cod and haddock migrate to the north-west coast to spawn (i.e., high cost per unit of effort). Hence, trawlers are left with the only option and that is to fish saithe quota in region C. This result is consistent with the catch patterns in Figure 4. In region B, the largest landing of cod takes place in January, followed by a considerable and sudden decline towards the end of the year. Right after this drop, the catch of saithe in area C has increased. This might indicate that trawlers redirect fishing effort from cod fishery in region B to saithe fishery in region C.

The adaptation of this strategy is confirmed by Birkenbach et al. (2020) to maximize profit. However, they provide a different reason for shifting from cod and haddock fisheries to saithe fishery. Birkenbach et al. (2020) concluded that in order to maximize profit trawlers need to consume the fishing quota of lower value species (in their case saithe) during a short period at the beginning of the fishing year. In contrast, the supply of higher valued species (in their case cod) should be spread over the season. Our intra-temporal result provides a more rational explanation for observing this harvest strategy. Region C is preferred to fish saithe quota as, region B cannot be an option for the trawlers (See Figure 4 where there is no fishing in February and March in region B). Region A is not an option either due to the lower price of cod and haddock (See Figure 6). After spawning, when cod and haddock swim back to the Arctic to feed, the prices start to rise (See Figure 6) due to the lower landings, as coastal fleet has already fished their quotas during winter fishery (Asche et al., 2015; Hermansen & Dreyer, 2010). At this time trawlers utilize the remaining cod and haddock quotas (See Figure 4). This result is in line with the result of study by Alizadeh Ashrafi et al. (2020) where they found that the magnitude of reduction in cod price during the winter fishery outweighs the reduction in cost of fishing, hence trawlers reserve the cod quota for the time when the cod price starts to rise towards the end of the year.

With regard to the inter-temporal effort allocation, the intense fishing of coastal fishers in a given month, reduces both the probability to allocate effort and the amount of allocated effort in that month in region B. However, the intensified fishing activities of coastal fishers in the previous two months is associated with increased fishing effort of trawlers in the current month in region B. This could mean that congestion of coastal fleet and the price reduction in cod and haddock during winter fishery is a transient phenomenon, and as time elapses towards the end of the year the price of cod and haddock will rise (See Figure 6).

Considering the above arguments, we see that trawlers are able to respond to the changes in location-specific cost in a rational manner. This finding is in agreement with the outcome of the study by Alizadeh Ashrafi et al. (2020), where rational decision making underlying effort allocation in the cod trawl fishery is underpinned.

## 6 Conclusion

The Norwegian bottom trawlers are generally engaged in multi-species fisheries, fishing for profits. The harvest strategy and effort allocation decisions aiming to maximize annual profits may be understood as game strategies, as the fishers need to consider multiple and interrelated factors; such as biological, environmental, economic, and managerial considerations, and constantly reallocate the fishing effort.

The main target species of the investigated trawler fleet are cod, saithe, and haddock. These species migrate across feeding and spawning habitats. Hence, trawling takes place in a vast geographical area, from the sub-Arctic areas of the Barents Sea to the southern parts of the North Sea. The fishing locations are heterogeneous in terms of fish availability, market prices for fish, fuel expenditure and travel time, and accessibility to other fishing fleets. These factors fluctuate over the course of a year, followed by varying relative attractiveness of available fishing locations and harvest strategies.

Despite the fact that these fisheries have long been studied, knowledge of fishing effort allocation is underdeveloped. In this regard, the present article aims to extend the insight on spatio-temporal allocation of fishing effort in the trawl fishery, and its profit maximizing harvest strategy. To do so, we have adopted a two-step Heckman’s estimator and modeled the fishing effort allocation across the three species and three regions over the course of a year. We have defined location heterogeneity in terms of fish availability, fish prices, fuel cost to traverse, and coexistence of coastal fleet.

Our major finding is that the region-specific attributes such as proximity to shore and less steaming time as well as the presence of coastal boats and the intensity of their fishing activities during winter fishery have substantial effect on the adopted harvest strategy of the trawlers’ profit maximization.

Another finding is that the decisions underlying spatio-temporal effort allocation of trawlers are not made in a random or haphazard manner. Indeed, trawlers are capable of identifying the changes in the biological, environmental, and economic conditions in these regions, and respond to these changes in an economically rational way. The technical advances of the trawl vessel (e.g., powerful engine and large size) offer them temporal and spatial flexibility, and this could explain the ability of fishers to make rational choices regarding effort reallocation.

The identification of the trawlers' harvest strategy and the potential factors whose effects may explain the choices regarding effort allocation contribute to a better understanding of the fishers' potential responses to biological, environmental, economic, and regulatory changes.

## References

Abernethy, K. E., Allison, E. H., Molloy, P. P., & Côté, I. M. (2007). Why do fishers fish where they fish? Using the ideal free distribution to understand the behaviour of artisanal reef fishers. *Canadian Journal of Fisheries and Aquatic Sciences, 64*(11), 1595-1604.

Alizadeh Ashrafi, T., Eide, A., & Hermansen, Ø. (2020). Spatial and temporal distributions in the Norwegian cod fishery. *Natural Resource Modeling,* e12276.

Arnason, R., Sandal, L. K., Steinshamn, S. I., & Vestergaard, N. (2004). Optimal feedback controls: comparative evaluation of the cod fisheries in Denmark, Iceland, and Norway. *American Journal of Agricultural Economics, 86*(2), 531-542.

Asche, F. (2009). Adjustment cost and supply response in a fishery: A dynamic revenue function. *Land Economics, 85*(1), 201-215.

Asche, F., Bjørndal, M. T., & Bjørndal, T. (2014). Development in fleet fishing capacity in rights based fisheries. *Marine Policy, 44*, 166-171.

Asche, F., Bjørndal, T., & Gordon, D. V. (2009). Resource rent in individual quota fisheries. *Land Economics, 85*(2), 279-291.

Asche, F., Chen, Y., & Smith, M. D. (2015). Economic incentives to target species and fish size: prices and fine-scale product attributes in Norwegian fisheries. *Ices Journal of marine science, 72*(3), 733-740.

Asche, F., Flaaten, O., Isaksen, J. R., & Vassdal, T. (2002). Derived demand and relationships between prices at different levels in the value chain: a note. *Journal of Agricultural Economics, 53*(1), 101-107.

Asche, F., Gordon, D. V., & Hannesson, R. (2002). Searching for price parity in the European whitefish market. *Applied Economics, 34*(8), 1017-1024.

Béné, C., & Tewfik, A. (2001). Fishing effort allocation and fishermen's decision making process in a multi-species small-scale fishery: Analysis of the conch and lobster fishery in Turks and Caicos Islands. *Human Ecology, 29*(2), 157-186.

Bergstad, O., Jørgensen, T., & Dragesund, O. (1987). Life history and ecology of the gadoid resources of the Barents Sea. *Fisheries Research, 5*(2-3), 119-161.

Birkenbach, A. M., Cojocaru, A. L., Asche, F., Guttormsen, A. G., & Smith, M. D. (2020). Seasonal Harvest Patterns in Multispecies Fisheries. *Environmental and Resource Economics, 75*(3), 631-655.

Branch, T. A., & Hilborn, R. (2008). Matching catches to quotas in a multispecies trawl fishery: targeting and avoidance behavior under individual transferable quotas. *Canadian Journal of Fisheries and Aquatic Sciences, 65*(7), 1435-1446.

Charles, A. T. (1995). Fishery science: the study of fishery systems. *Aquatic Living Resources, 8*(3), 233-239.

Cojocaru, A. L., Asche, F., Pincinato, R. B. M., & Straume, H.-M. (2019). Where are the fish landed? An analysis of landing plants in Norway. *Land Economics, 95*(2), 246-257.

Copes, P. (1986). A critical review of the individual quota as a device in fisheries management. *Land Economics, 62*(3), 278-291.

Eide, A., Skjold, F., Olsen, F., & Flaaten, O. (2003). Harvest functions: the Norwegian bottom trawl cod fisheries. *Marine Resource Economics, 18*(1), 81-93.

Flaaten, O., & Heen, K. (2004). Fishing vessel profitability and local economic link obligations—the case of Norwegian trawlers. *Marine Policy, 28*(6), 451-457.

Garrod, D. (1967). Population dynamics of the Arcto-Norwegian cod. *Journal of the Fisheries Board of Canada, 24*(1), 145-190.

Guttormsen, A. G., & Roll, K. H. (2011). Technical efficiency in a heterogeneous fishery: the case of Norwegian groundfish fisheries. *Marine Resource Economics, 26*(4), 293-307.

Hannesson, R. (2007). A note on the" stock effect". *Marine Resource Economics, 22*(1), 69-75.

Hannesson, R., Salvanes, K. G., & Squires, D. (2010). Technological change and the tragedy of the commons: the Lofoten fishery over 130 years. *Land Economics, 86*(4), 746-765.

Heckman, J. J. (1976). The common structure of statistical models of truncation, sample selection and limited dependent variables and a simple estimator for such models. In *Annals of economic and social measurement, volume 5, number 4* (pp. 475-492): NBER.

Hermansen, Ø., & Dreyer, B. (2010). Challenging spatial and seasonal distribution of fish landings—The experiences from rural community quotas in Norway. *Marine Policy, 34*(3), 567-574.

Hersoug, B. (2005). *Closing the commons: Norwegian fisheries from open access to private property*. Utrecht: Eburon Academic Publishers.

Hersoug, B., & Leonardsen, D. (1979). *Bygger de landet? : distriktspolitikk og sosialdemokrati 1945-1975*. Oslo: Pax Forlag.

Hilborn, R. (1985). Fleet dynamics and individual variation: why some people catch more fish than others. *Canadian Journal of Fisheries and Aquatic Sciences, 42*(1), 2-13.

Hilborn, R. (2007). Managing fisheries is managing people: what has been learned? *Fish and Fisheries, 8*(4), 285-296.

Hilborn, R., & Walters, C. J. (1992). *Quantitative fisheries stock assessment: choice, dynamics and uncertainty*. New York: Chapman and Hall.

Holland, D. S., & Sutinen, J. G. (1999). An empirical model of fleet dynamics in New England trawl fisheries. *Canadian Journal of Fisheries and Aquatic Sciences, 56*(2), 253-264.

Holland, D. S., & Sutinen, J. G. (2000). Location choice in New England trawl fisheries: old habits die hard. *Land Economics*, 133-149.

Jakobsen, T., & Olsen, S. (1987). Variation in rates of migration of saithe from Norwegian waters to Iceland and Faroe Islands. *Fisheries Research, 5*(2-3), 217-222.

Korsbrekke, K. (1999). Variations in maturity of haddock in the Barents Sea in relation to year-class strength, age, size, sex and area. *Journal of Northwest Atlantic Fishery Science, 25*.

Maunder, M. N., Sibert, J. R., Fonteneau, A., Hampton, J., Kleiber, P., & Harley, S. J. (2006). Interpreting catch per unit effort data to assess the status of individual stocks and communities. *Ices Journal of marine science, 63*(8), 1373-1385.

Maurstad, A. (2000). To fish or not to fish: small-scale fishing and changing regulations of the cod fishery in northern Norway. *Human Organization,* 37-47.

Olsen, E., Aanes, S., Mehl, S., Holst, J. C., Aglen, A., & Gjøsæter, H. (2010). Cod, haddock, saithe, herring, and capelin in the Barents Sea and adjacent waters: a review of the biological value of the area. *Ices Journal of marine science, 67*(1), 87-101.

Opaluch, J. J., & Bockstael, N. E. (1984). Behavioral modeling and fisheries management. *Marine Resource Economics, 1*(1), 105-115.

Pethon, P. (2005). *Aschehougs store fiskebok: Norges fisker i farger* (B. O. Nyström Ed.). Oslo: Aschehoug & Co.

Rose, G. A. (1993). Cod spawning on a migration highway in the north-west Atlantic. *Nature, 366*(6454), 458.

Sandberg, P. (2006). Variable unit costs in an output-regulated industry: the fishery. *Applied Economics, 38*(9), 1007-1018.

Squires, D., Campbell, H., Cunningham, S., Dewees, C., Grafton, R. Q., Herrick Jr, S. F., . . . Shallard, B. (1998). Individual transferable quotas in multispecies fisheries. *Marine Policy, 22*(2), 135-159.

Standal, D., & Hersoug, B. (2015). Shaping technology, building society; the industrialization of the Norwegian cod fisheries. *Marine Policy, 51*, 66-74.

Trout, G. (1957). *The Bear Island Cod: Migrations and Movement*. Ministry of Agriculture and Food Fisheries Investigations Series **2, 21**

Wilen, J. E., Smith, M. D., Lockwood, D., & Botsford, L. W. (2002). Avoiding surprises: incorporating fisherman behavior into management models. *Bulletin of Marine Science, 70*(2), 553-575.