UiT The Arctic University of Norway

Faculty of Biosciences, Fisheries and Economics - Norwegian College of Fishery Science

Stock Assessment of Norwegian Atlantic Halibut North of 62°N Latitude Using a Data-Limited Approach

Edvin Laberg Lindgård

Master’s thesis in Fisheries and Aquaculture Science (60 ETC), FSK-3960, May 2023


Photo: Private

Stock Assessment of Norwegian Atlantic Halibut North of 62°N Latitude Using a Data-Limited Approach

Edvin Laberg Lindgård

Masteroppgave i Fiskeri- og havbruksvitenskap (60 stp.)

Mai 2023

Norges Fiskerihøgskole

Fakultet for biovitenskap, fiskeri og økonomi

UiT – Norges Arktiske Universitet

Acknowledgements

I want to express my sincere gratitude towards my supervisors, Michaela Aschan and Erik Berg, for their insightful and invaluable guidance throughout my thesis project. Special thanks to Michaela for patient guiding in the initial phases of the project, for funding my attendance at the ICES WGDEEP meeting in Lisbon, Portugal and arranging participation on a fishing vessel. Special thanks to Erik for thorough guidance while working with the datasets and models, and for insight into the halibut stock.

Thanks to UiT – The Arctic University of Norway, the Faculty of Biosciences, Fisheries and Economics and the Norwegian College of Fishery Science for providing a rewarding and interesting education. Also, thanks to the latter two for funding my attendance at the ICES WGDEEP meeting.

I want to thank the Institute of Marine Research in Tromsø and the research group "Deepwater and cartilaginous fish" for data access and facilitation for my thesis. Thanks to Tone Vollen and Mikko Vihtakari for helping me with data and R. I would also like to thank Carsten Hvingel for sharing his knowledge about production models and Tore Haug for sharing his knowledge of the Atlantic halibut and works related to the species and stock.

Thanks to the fisherman Ronald Andersen for providing insight and allowing me onboard his fishing vessel M/S "Saltbåen" during halibut gillnet fishing in December 2022.

I would also like to express my gratitude to those who reviewed and provided feedback on my thesis, including my Mom, Dad, and partner.

Finally, I want to thank my fellow students and friends, family and my partner with whom I have enjoyed this inspiring journey.

Tromsø, 1st of May 2023

Edvin Laberg Lindgård

Summary (English)

Landings of Atlantic halibut (*Hippoglossus hippoglossus*) have increased significantly in later years. More fishing boats are joining the open-access fishery, with an ever-increasing number of fishing gear. The Atlantic halibut is also a popular tourist and recreational fishery target species. Atlantic halibut is a large, late-maturing flatfish with life history traits that make the stock sensitive to overfishing. The stock has a long history of exploitation, and historical fisheries show that increased landings over time have been followed by significant reductions in landings. The current regulations of the Norwegian Atlantic halibut fishery north of 62°N consist of input regulations (minimum catch size, no-catch periods, and fishing gear restrictions). Management authorities suggest new management actions to ensure a sustainable fishery of the Atlantic halibut stock in a long-term perspective.

The aim of this study was to perform a stock assessment of the Norwegian Atlantic halibut stock north of 62°N using a data-limited approach. The purpose was to use the Stochastic Surplus Production Model in Continuous Time (SPiCT) and empirical approaches (with Data-Limited Methods Toolkit (DLMtool)) on the limited data to assess the stock status and propose a management advice. The potential effects of tourist- and recreational fisheries were also examined through alternative landings (+20% and +40%) scenarios. Landings in Norway north of 62°N and Norwegian coastal scientific survey data were used. Four survey indices were developed from the scientific survey, of which one was used in the full assessment.

The SPiCT assessment fulfilled the technical criteria, and the halibut stock was given ICES (International Council for the Exploration of the Sea) category 2 MSY (maximum sustainable yield) advice. The DLMtool gave similar results and provided estimates of a new minimum catch size. The assessment showed that the stock is close to optimal levels and utilized around MSY. The stock is probably declining due to overfishing in recent years. The management advice for the Norwegian halibut stock north of 62°N is to reduce fishing by implementing a TAC at 2000-2424 tons. An increased minimum catch size of around 90-106 cm should be implemented (together with or independently of other measures) to fit the species' life-history traits better. Tourist- and recreational fisheries might have a negative effect on the halibut stock, especially locally. The findings in this thesis can contribute to better management of the Norwegian halibut stock north of 62°N.

Sammendrag (Norsk)

Landingene av atlantisk kveite (*Hippoglossus hippoglossus*) har økt signifikant de siste årene. Flere båter har blitt med i det åpne fiskeriet, og et stadig større antall fiskeredskaper er i bruk. Atlantisk kveite er også en populær målart for turist- og fritidsfiskerier. Arten atlantisk kveite er en stor flatfisk som blir sent kjønnsmoden, og som har livshistorietrekk som gjør at den er sensitiv for overfiske. Kveitefiske har en lang historie, og statistikk viser at økte landinger over tid følges av store reduksjoner i landinger. Dagens forvaltning av norsk atlantisk kveite nord for 62°N består av innsatsreguleringer (minstemål, fredningsperioder og restriksjoner av fiskeredskap). Nye forvaltningstiltak er blitt foreslått av fiskerimyndighetene for å sikre et bærekraftig fiske av kveitebestanden i et langtidsperspektiv.

Formålet med denne studien var å gjennomføre en bestandsvurdering av den norske atlantiske kveitebestanden nord for 62°N ved bruk av en databegrenset tilnærming. Målet var å teste og tilpasse en anerkjent stokastisk produksjonsmodell (Stochastic Surplus Production Model in Continuous Time - SPiCT) samt en empirisk tilnærming (med Data-Limited Methods Toolkit - DLMtool) for å vurdere bestandsstatus og foreslå et forvaltningsråd. De mulige effektene av turist- og fritidsfiske ble også undersøkt gjennom alternative scenarioer for landinger (+20% and +40%). Landingene for at atlantisk kveite i Norge nord for 62°N og data fra kysttoktet ble brukt. Fire indekser ble utviklet fra toktdataene, hvorav en ble brukt i hele bestandsvurderingen.

Bestandsvurderingen med SPiCT oppfylte de tekniske kriteriene, og kveitebestanden ble gitt MSY-råd (maksimal bærekraftig fangst) etter det internasjonale havforskningsrådets (ICES) bestandskategori 2. DLMtool ga tilsvarende resultater og forslag til nytt økt minstemål. Bestandsvurderingen viste at bestanden er i tilnærmet optimal tilstand og utnyttet rundt MSY. Bestanden minsker trolig på grunn av overfiske de siste årene. Forvaltningsrådet for den norske atlantiske kveitebestanden nord for 62°N er å redusere fiske ved å innføre en kvote på mellom 2000-2424 tonn i fiskeriet. I tillegg foreslås det å øke minstemålet til mellom 90-106 cm (i tillegg til, eller uavhengig av andre forvaltningstiltak) som er bedre tilpasset arten. Turist- og fritidsfiske kan ha en negativ effekt på kveitebestanden, særlig lokalt. Funnene i denne oppgaven kan bidra til en bedre forvaltning av dem norske atlantiske kveitebestanden nord for 62°N.

Glossary

B_{MSY} – biomass level that provides maximum sustainable yield

B_t – biomass level at a given time

C&R – Catch and release

Carrying capacity (K) – maximum size of a population that resources in a habitat can support

CI – confidence interval

CPUE – Catch per unit effort

DLMtool – Data-Limited Methods Toolkit

F – fishing mortality

Fiskeridirektoratet – Directorate of Fisheries

F_{MSY} – fishing mortality that provides maximum sustainable yield

F_t – fishing mortality at a given time

HS – maximum legal length

ICES - International Council for the Exploration of the Sea

IMR – Institute of Marine Research (Havforskningsinstituttet)

IUU fishing – illegal, unreported and unregulated fishing

L50 - length at 50% maturity

L5R – length at 5% retention

LFR – length at full retention

L_{inf} - von Bertalanffy's maximum theoretical length

M – natural mortality

MP – management procedure

MSE – management strategy evaluation

MSY – maximum sustainable yield

Nærings- og fiskeridepartementet – Ministry of Trade and Fisheries

Retention length – the length of the fish that are caught and kept by the fishing fleet

SPiCT – Stochastic Surplus Production Model in Continuous Time

t_0 – von Bertalanffy's theoretical age at which the organism would have had zero size

TAC – total allowable catch

UN – United Nations

Table of Contents

1 Introduction

1.1 Own motivation

The background for choosing this thesis topic was my fascination for the unknown related to the marine ecosystem. Atlantic halibut has always been a coveted and mysterious species, with great size and strength. In many ways, the halibut objectifies the secrets of the sea. The need for more knowledge and better management of the halibut stock triggered me. Performing a stock assessment allowed me to acquire quantitative skills that will be useful in my future career.

1.2 Halibut biology

Atlantic halibut (*Hippoglossus hippoglossus,* L.) (Figure 1) is a ray-finned fish (Actinopteri) in the order Pleuronectiformes (flatfish) and Pleuronectidae family (right-eyed flounders) (Haug, 1990). Andriyashev (1964) described the Atlantic halibut (from now on mostly referred to as halibut) as a fish with an elongated body covered mostly by cycloid scales. Its lateral line has a steep bend above the pectoral fin. The pectoral fin is better developed on the eye side than the blind side, where the caudal fin appears weakly emarginate. Both eyes are on the right side of the head, the eye side is pigmented dark brown, and the blind side white. The halibuts' jaws are large and symmetrical, with large teeth pointing posteriorly. The upper jaw has two rows of teeth, while the lower jaw has one row. Further, the intrapharyngeal teeth are sharp and in two rows, while the vomer is toothless. The anal spine is present; however, it is overgrown by the skin on adult specimens. Halibut have between 49 and 53 vertebrae.

Figure 1 – Scientific illustration of Atlantic halibut. "Atlantic halibut Hippoglossus hippoglossus *(Linnaeus, 1758)" CC BY-SA 4.0 by (Fekjan, n.d.).*

The halibut is the largest groundfish in the Atlantic Ocean and one of the by weight highest-valued groundfish species in the North Atlantic (Armsworthy & Campana, 2010; Bowering, 1986). Halibut is a demersal species which lives on or near the bottom (Haug, 1990). It is found at all depths, from a few meters to 1000 meters. Like many other deep-water species, the halibut matures late (Haug, 1990; Høines et al., 2009). It has a low natural mortality and can grow large and old if fishing pressure is low (Høines et al., 2009).

The Atlantic halibut (*Hippoglossus hippoglossus*) is similar to the Pacific halibut (*Hippoglossus stenolepis*), and historically there has been a debate about whether this constitutes one or two species (Haug, 1990). Grant et al. (1984) used genetic markers to investigate the genetic differences between the stocks. The results showed such severe genetic differences that the two stocks had to be considered two distinct species. Halibut most likely came to the Atlantic through the Bering Strait. After this, the Atlantic and Pacific halibut have been physically and reproductively isolated from each other for 1.7-4.5 million years.

The halibut is distributed in the northern part of the Atlantic Ocean (Figure 2) and in parts of the Arctic Ocean (Andriyashev, 1964). The species' main distribution area is along the Norwegian coast, around Iceland, the Faroe Islands, and off the southern coast of Greenland. The species also inhabit the Barents Sea and areas around Bear Island and Svalbard in the north. The southernmost distribution is the western parts of the North Sea and the Baltic Sea. Halibut is also found along the east coast of North America (Bowering, 1986).

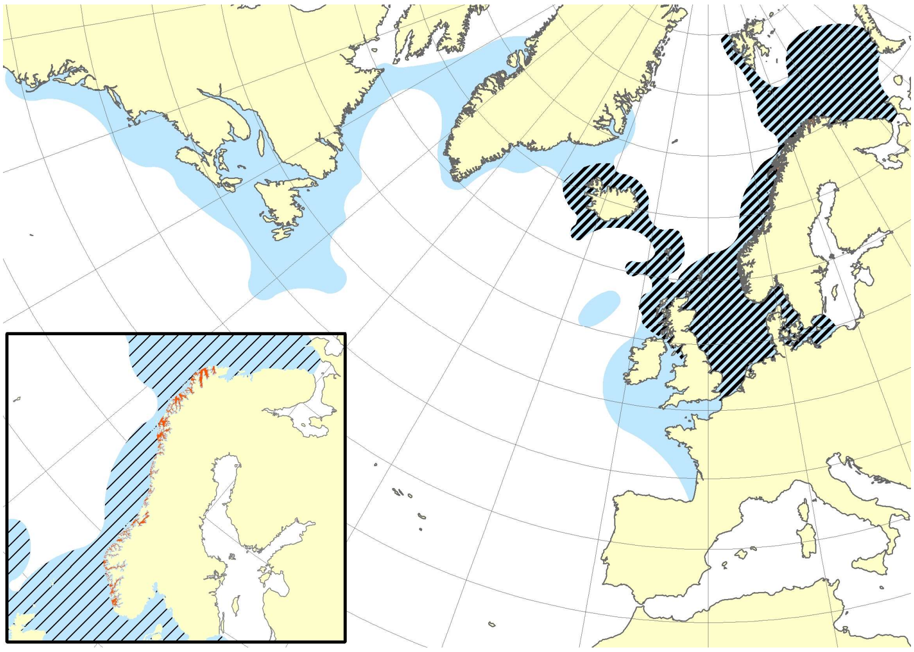

Figure 2 – The distribution area (blue), the spawning area in Norway (orange) and the distribution of halibut that spawn along the Norwegian coastline (black stripes) for the Atlantic halibut (Havforskningsinstituttet, 2020). Cropped version of the original illustration.

The knowledge about the halibut’s early life stages in the wild is limited. Halibut eggs and early larval stages are bathypelagic and found at around 100-300 meters depth (Haug et al., 1986; Haug & Sundby, 1987b). The embryo hatch after 18 days at 5°C (Lønning et al., 1982) and eventually undergoes one of nature’s most radical changes during metamorphosis, as the body and head rotate 90° (Haug, 1990). A minimal number of halibut larvae has been found in the wild (Bergstad & Gordon, 1993; Haug & Sundby, 1987a, 1987b; Shackell et al., 2021), and most of them are found near the surface, at around 5-50 meters depth (Haug, 1990). Most individuals settle at the bottom at about 34-40 mm long and 90 days post-hatching. The eggs and larvae are expected to be dispersed by the currents in the spawning area, but details are unknown (Shackell et al., 2021).

Young immature halibut are stationary in fjords and coastal areas with depths of 20-60 meters for the first 3-6 years after settling on a sandy bottom (Godø & Haug, 1988a; Haug & Sundby, 1987a). They then leave the nursing areas and undergo feeding migrations. The feeding areas may be deep and shallow, inshore and offshore. Most halibut perform short migrations within the same region (Godø & Haug, 1988a). A smaller number of individuals are found to perform long migrations, sometimes crossing deep water areas in the North Atlantic (Bowering, 1986; Godø & Haug, 1988a, 1988b). Studies have confirmed migrations from northern Norway to Iceland, Greenland and the White Sea, from the Faroes to Iceland and the North Sea (Godø & Haug, 1988a, 1988b; Haug & Sundby, 1987a), and from Iceland to the Faroes, Greenland, and Newfoundland (Vedel-Tåning, 1938, 1947, as cited in Haug, 1990). Similar migration patterns are also found on the east coast of North America (McCracken, 1958). Because of the migration, the mixing of geographically separate stocks is likely to occur on a significant scale (Bowering, 1986; Godø & Haug, 1988a). This coincides with the latest genetic study, a master thesis by Rasmussen (2020), showing no genetic differences or geographical clusters for halibut along the Norwegian coast and North America. Similar studies from the 1980s and 90s found genetic variations between halibut from different locations (Fevolden & Haug, 1988; Foss et al., 1998; Haug & Fevolden, 1986; Mork & Haug, 1983). The knowledge about local and regional population structure is limited.

The halibut changes diet with size (Iversen, 1936; Kohler, 1967; McIntyre, 1953, as cited in Haug, 1990; Rae, 1958, as cited in Haug, 1990; Scott, 1910, as cited in Haug, 1990). The smallest halibut sampled in the above studies (<30 cm) had a diet composed of crustaceans, while medium-sized halibut (31-60 cm) had a mixed diet with crustaceans and fish. The proportion of fish in the diet increased with size, and adult halibut were mainly piscivorous (Iversen, 1936; Kohler, 1967; McIntyre, 1953, as cited in Haug, 1990; Rae, 1958 as cited in Haug, 1990; Scott, 1910 as cited in Haug, 1990; T. Pedersen et al., 2021, Suppl. S2). As the halibut target prey items with increasing size as they grow, McIntyre (1953, as cited in Haug, 1990) suggested that searching for larger prey may cause feeding migration and movement from coastal waters.

When halibut mature, they undergo spawning migrations to suitable spawning grounds where mostly mature individuals occur (Devold, 1938; Haug & Tjemsland, 1986; Jákupsstovu & Haug, 1988). The spawning grounds are found at various locations along the coast, including fjords and the edge of coastal banks with a soft bottom consisting of mud or clay (Devold, 1938). The spawning happens at depths of 300-700 meters, in temperatures around 5-7 °C from December to March, with a peak in January and February (Kjørsvik et al., 1987). A female halibut can produce between 0.5-7 million eggs with a diameter of around 3 mm, depending on the body size (Haug & Gulliksen, 1988b). The eggs are spawned in batches throughout the spawning season. After the spawning season, halibut disperse and migrate to feeding grounds (Kjørsvik et al., 1987). Devold (1938) suggested that halibut return to the same spawning grounds for several consecutive years, which later have been supported by tagging experiments (Godø & Haug, 1988a).

Age and length at sexual maturation vary with gender (Haug, 1990). Literature from the 1980s estimates the maturation at around 80 cm and seven years for males and around 110 cm and eight years for females (Haug & Tjemsland, 1986; Høines et al., 2009). This data corresponds with data from the east coast of the USA (Sigourney et al., 2006). The age at maturation has decreased significantly from the 1950s to the 1980s (Godø & Haug, 1999; Haug, 1990; Haug & Tjemsland, 1986; Høines et al., 2009). Similar changes may have occurred from the 1980s to today, and updated knowledge is needed (Høines et al., 2009). The higher growth rate and lower age at maturity may be explained by several factors, including a decline in halibut density, environmental changes, and higher food availability (Godø & Haug, 1999; Haug & Tjemsland, 1986). The gear's selection for larger individuals in the fishery can also be an explaining factor. Early maturing individuals have a greater chance of spawning before being caught by fishing gear, passing on their characteristics and gradually changing the phenotype (Heino et al., 2015).

Halibut in the Northeast Atlantic are larger and grow faster in the northern part than in the south (Karlson et al., 2013). Individuals from higher latitudes have significantly higher length-at-age and weight-at-age. Norwegian halibut are found to have higher food conversion than individuals from other areas, while Icelandic halibut have greater weight at length (Jonassen et al., 2000). Jonassen et al. (2000) suggest that greater growth capacity at higher latitudes compensates for a shorter growing season rather than only temperature adaptation. This indicates interpopulation differences in energy utilization and body shape. Low rates of genetic mixing may be insufficient to cause genetic population structure but sufficient to cause differences in life history traits (Seitz et al., 2017). Such patterns are found for Pacific halibut. Differences may be caused by habitat, temperature, and food availability.

Females and males have no visual morphological differences (Haug & Fevolden, 1986). Both genders have a uniform growth in length and weight until they reach 4-6 years of age (Karlson et al., 2013). After that, females grow much faster than males. Male size-at-age flattens out at age 10-12, while female growth accelerates around the same age. Female halibut can grow to over 3 meters, males to 1,75 m, and both can become 50 years old (Armsworthy & Campana, 2010; Devold, 1938; Jákupsstovu & Haug, 1988). Males rarely grow bigger than 50 kg, while females grow significantly larger. The largest female individual recorded was 333 kg (Ehrenbaum, 1936, as cited in Mathisen & Olsen, 1968b).

1.3 History of the halibut fishery in Norway

The halibut has been a sought-after fish species for centuries, as it has been highly valued as food and well paid (Haug, 1984). According to the author, halibut fisheries used longlines in coastal waters and at fishing banks. Landings were high at the beginning of the 20th century, with a record year in 1907 (Figure 3). After this, landings decreased towards World War 1 (1914-1918), when landings were at their lowest. The counties Nordland and Møre were the most important areas for halibut fisheries before World War 1. Nordland, Troms and Finnmark became the most important counties for halibut fisheries after World War 1. Landings continued to increase until a new top year in 1932, with 6882 tons round weight of halibut. The following years, from 1933 to 1935, displayed dramatic reductions in landings. After this, drastic changes occurred in the halibut fisheries. More information about historical landings is found in appendix A.

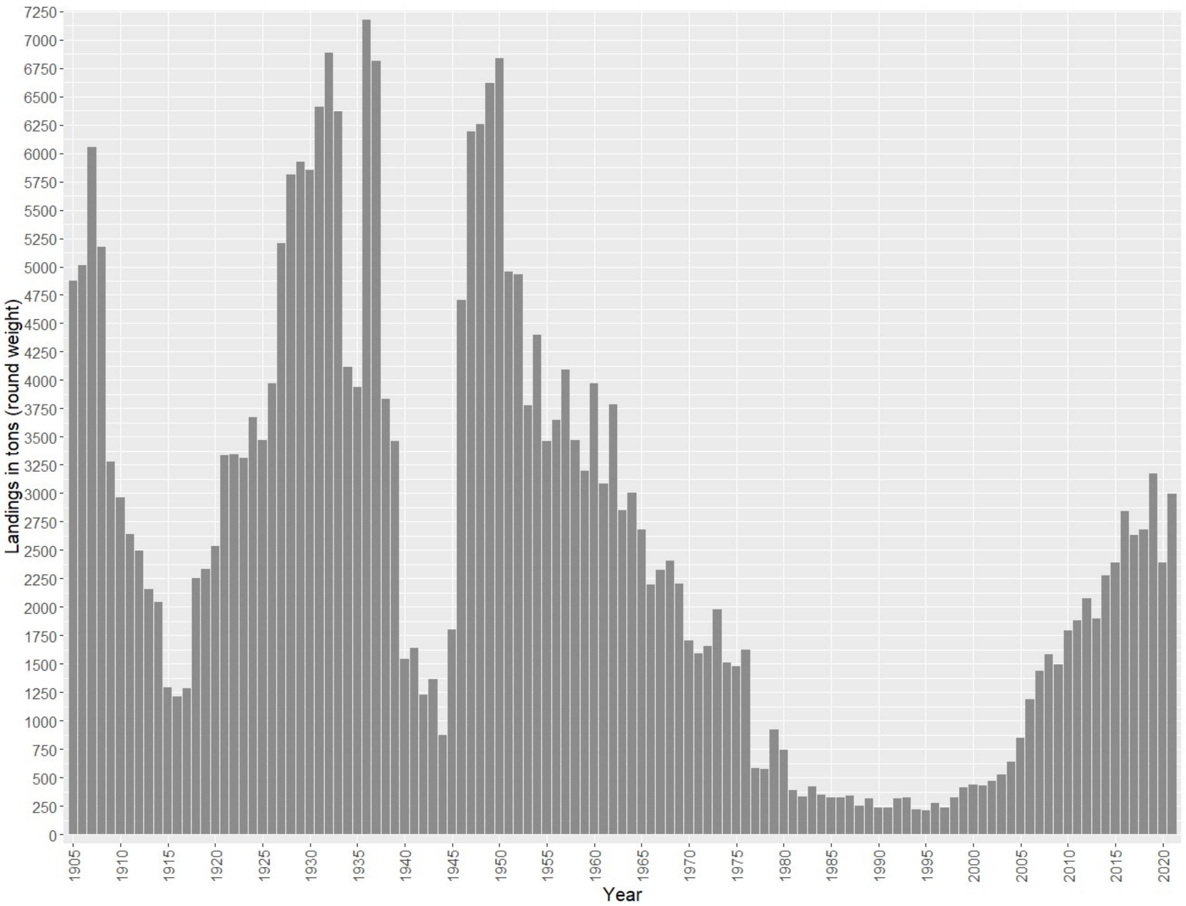

Figure 3 – Landings of halibut (round weight in tons) from 1905-2021 from Norwegian areas. Landings include catches from unreported areas, as they have a similar distribution between fishing gear. Landings from 1905-1977 are retrieved from Norwegian Fisheries Statistics (see Appendix, chapter A), while landings from 1978-2021 are retrieved from the Directorate of Fisheries database.

Longline fisheries traditionally stopped in early winter, as the halibut stops feeding during spawning and could not be caught efficiently. This pattern changed in 1936 when a new gillnet was developed for halibut fisheries (Devold, 1938, 1939; Haug, 1984). The authors write that gillnets were highly effective and were placed in deep water areas at halibut spawning grounds. The introduction of gillnets in the fisheries significantly increased effort and landings in 1936. Landings were also high in 1937, primarily due to large catches in the first few months of the year and an even higher fishing effort compared to 1936. The landings fell throughout 1937, with some previously important areas experiencing almost no catch. The introduction of gillnets and the subsequent reduction in landings led to a halibut research program in 1936. The program suggested the implementation of regulatory measures in the halibut fisheries. Gillnet fisheries became prohibited during the spawning period (15. December – 28. February) and at the weekends. A minimum catch size of 50 cm was introduced in addition to mesh size regulations for the halibut gillnet.

World War 2 (1940-1945) reduced the fishing effort for halibut (Haug, 1984). This reduction was positive for the stock's ability to recover, as catches in the previous years seemed to have been higher than long-term sustainable yield. New intensive fisheries for halibut began after World War 2 and gave high catches until 1950, with landings up to 6833 tons round weight. After this, the landings steadily declined until 1980, when they flattened out. A new research program was introduced in 1956 (Mathisen & Olsen, 1968; S. Olsen, 1969; S. Olsen & Tjemsland, 1963), which led to new regulatory measures with a reduction of the no-catch period for gillnets around the spawning period due to positive signs for the stocks in certain areas. A new mesh size for the gillnet was also implemented. In 1979, these were replaced by an increased no-catch period, a change in minimum catch size to 60 cm, and a ban on monofilament halibut gillnets (Haug, 1984). The minimum catch size increased to 80 cm in 2010 following a review of the fisheries done by the Institute of Marine Research (IMR) (Fiskeridirektoratet, 2022; Høines et al., 2009)

Landings dropped below 1000 tons, to 583 tons, in 1977 for the first time since World War 2. The decline continued until 1995, when the lowest landings recorded occurred with 211 tons. Landings increased by an average of 13,4% annually from 1995 to 2016 (Fiskeridirektoratet, 2022). This increase was probably the result of increased stock size and fishing effort. The introduction of sorting grids in shrimp trawls in 1990 (Isaksen et al., 1992) also significantly reduced bycatch and hence fishing mortality of young halibut (Høines et al., 2009). This bycatch reduction is probably one of the reasons why the stock has recovered. Investigations of catch composition from shrimp trawls show that caught fish reported as halibut mostly were American plaice (*Hippoglossoides platessoides*) and other flatfishes. The findings make the shrimp trawls effect on the halibut stock questionable (Erik Berg, personal communication, 29.03.2023). In the later years, the landings stabilized, except for lower landings in 2020, mainly because of considerable challenges related to the Covid-19 pandemic (Fiskeridirektoratet, 2022). In recent years, higher efficiency and more intensive fisheries on halibut have been reported. The increase includes more gear (hooks and gillnets), more boats from around the country, and new technology like long lines on drums.

The catch pattern of halibut has changed over time. While the main areas for halibut fisheries have been the northern counties, substantial landings have previously been reported further south in Trøndelag, Møre og Romsdal, Vestlandet and Skagerak (Haug, 1984). The decline in landings towards 1995 happened at all fishing grounds. However, the increase from 1995 was only found north of 62°N, particularly in the three northernmost counties (Fiskeridirektoratet, 2022). The reason is probably a lack of increase in the halibut population in the south.

1.4 Current regulations of the halibut fisheries

Fish species distributed along the Norwegian coast are often divided into two management units, north and south of 62°N latitude (Stad). This division applies to coastal cod (*Gadus morhua*), saithe (*Pollachius virens*) and haddock (*Melanogrammus aeglefinus*), to mention some. In addition, there are often different regulations for fishing north and south of 62°N latitude (Høstingsforskriften, 2022). The management units often mismatch the genetic population structure of the fish stocks (Reiss et al., 2009). Regulations in halibut fisheries are also divided at 62°N latitude (Fiskeridirektoratet, 2022; Høstingsforskriften, 2022). Almost 90% of the stock biomass is in the north (Erik Berg, personal communication, 18. October 2022), and the recent stock development differs from the south. Available knowledge about population structure does not suggest a more reasonable way to define and manage the halibut stock(s). Based on this, the thesis will focus on the halibut stock north of 62°N latitude.

Fisheries for halibut north of 62°N are subject to several regulatory measures. The minimum catch size for halibut is 80 cm (Høstingsforskriften, 2022, §47). It is also mandatory to release halibut with a length of more than 2 metres and 100 kg back into the sea regardless of its state (Høstingsforskriften, 2022, §51, letter F). Fishing for halibut with all fishing gear except hooks is prohibited between December 20. – March 31. (Høstingsforskriften, 2022, §39). Gillnet fisheries targeting other species in this period allow 1% halibut bycatch calculated in round weight for the entire period (Høstingsforskriften, 2022, §44). When fishing with gillnets for halibut, the minimum mesh size is 470 mm (Høstingsforskriften, 2022, §19). In addition, it is forbidden to use monofilament gillnets in this fishery (Høstingsforskriften, 2022, §21). All fishing gear targeting halibut is to be handled and processed at least every third day (Høstingsforskriften, 2022, §18).

1.5 Tourist- and recreational fisheries

Halibut is a popular target species for recreational and tourist fisheries (Fiskeridirektoratet, 2022). Marine recreational fisheries are defined as fishing from shore and boats by residents in Norway (Ferter et al., 2022). Recreational fishing does not require a fishing license or catch reporting. However, residents are allowed to sell catches to licensed buyers for approximately 50 000 NOK annually. Such sold and reported catches are registered in the official landings. These fisheries are often highly specialized, with gear like rods with halibut jigs, longlines, and gillnets. Tourist fishing is subject to more restrictions, as they only are allowed to fish with handheld gear and are prohibited from selling their landings (Fiskeridirektoratet, 2018; Nærings- og fiskeridepartementet, 2022). A large share of tourist fishing happens through fishing businesses, as it allows tourists to export 18 kg filets of their self-caught fish up to twice a year. Tourist fishing businesses must register in a national database if earning more than 50 000 NOK from guiding or rental. Registered businesses are mandated to register the catch of halibut and other selected species, including released fish, per trip and boat (Ferter et al., 2022; Fiskeridirektoratet, 2022). Therefore, catch from recreational fishing and tourist fishing is only partly reported in the same way as commercial landings, making it hard to quantify their annual yield.

1.6 Stock assessment and management

According to the United Nations, fisheries management should be based on the principle of precautionary approach (UN, 1995). A precautionary approach is a principle where the fish population must be maintained within safe biological limits. The principle is achieved by developing stock-specific or using predefined reference points. Within these limits, the objective of maximum sustainable yield (MSY) can be obtained, meaning that one achieves the highest possible yield in a long-term perspective (ICES, 2022d; UN, 1995). For the International Council for the Exploration of the Sea (ICES), MSY means maximizing the average long-term yield from a fish stock while maintaining its productivity (ICES, 2022d).

Fishing mortality is the only factor that can be directly controlled through fisheries management (ICES, 2022d). The stock size and condition undergo fluctuations related to natural variations. This may be due to variability in factors like recruitment, natural mortality including predation, stock size and food availability, to mention some. These factors cannot be directly affected by management but sometimes indirectly. Predators can, for example, have an increase or decrease in fishing pressure due to the management of the specific stock, resulting in higher or lower predation pressure for the stocks on which they predate. The fishing mortality F is the instantaneous rate of the proportion of fish in an age- or size group caught in one year. Fishing mortality F is often regulated using total allowable catch (TAC) based on the background of MSY and precautionary approach principles.

Fisheries may also be regulated by defining a minimum legal catch size. A minimum catch size regulation has two primary purposes (Froese et al., 2016). One purpose is to ensure enough fish mature and reproduce before recruiting into the fishable stock. The second purpose is to realize the fish's growth potential, so that catches can be maximized while reducing the impact of fishing on the stock. Minimum catch size may be particularly effective for slow-growing, long-lived, and late-maturing species (Ailloud et al., 2018).

The management practice in Norway varies between the different fish stocks. Most fish stocks harvested by direct fishing in Norway are assessed and managed (Sandberg et al., 1998). Managed stocks are given a TAC and other relevant regulations. Many of the stocks are shared between Norway and other coastal nations, as the fish have their distribution range across country borders. ICES develops advice for fishing opportunities for stocks shared between nations and for many national stocks. The advice for shared stocks is used in negotiations between concerned states, while advice for national stocks can be used directly in fisheries management. The advice for fishing opportunities for some national stocks in Norway is given directly from IMR to the managers.

ICES has developed a framework for stock categories based on the available data and knowledge for the stock assessment (ICES, 2022d). Based on the available knowledge, the stocks are divided into six categories (Table 1). Each category has its procedure for assessment and advice. Categories 3-6 are regarded as data-limited, meaning there is insufficient information for a traditional analytical assessment.

Table 1 – ICES stock categories based on the amount of available data and knowledge, slightly adjusted (ICES, 2022d, p. 1).

Stock category	**Description**
Category 1	Stocks with quantitative assessments; includes stocks with complete analytical assessments and forecasts that are either age-/length-structured or based on production models.
Category 2	Stocks with analytical assessments and forecasts that are only treated qualitatively, as well as stocks with surplus production models, e.g. SPiCT and JABBA, without a management strategy evaluation, includes stocks with quantitative assessments and forecasts which, for a variety of reasons, are considered indicative of trends in fishing mortality, recruitment, and biomass.
Category 3	Stocks for which survey-based assessments or exploratory assessments indicate trends; includes stocks for which survey, trends-based assessment, or other indices and life history information are available that provide reliable indications of trends in stock metrics such as total mortality, recruitment, and biomass.
Category 4	Nephrops stocks where information on possible abundance can be inferred and stocks for which survey-based assessments or exploratory assessments indicate trends; includes stocks for which survey, trends-based assessment, or other indices and life history information are available that provide reliable indications of trends in stock metrics such as total mortality, recruitment, and biomass.
Category 5	Stocks for which only data on landings or a short time series of catches are available.
Category 6	Stocks for which there are negligible landings and stocks caught in minor amounts as bycatch; includes stocks where landings are negligible compared to discards and stocks that are primarily caught as bycatch species in other targeted fisheries.

The halibut stock may be regarded as a category 3 stock, as there is an available survey and catch time series, in addition to life history information, that can be used to provide a reliable indication of trends in the stock. According to the ICES guidelines, a category 3 stock should be assessed with the Stochastic Surplus Production model in Continuous-Time (SPiCT) or similar (ICES, 2022c, 2022d). If ICES accepts the results from SPiCT, the stock will be upgraded to category 2 and advice provided according to the Category 2 MSY approach (Figure 4). An MSY advice is based on a hockey stick rule (ICES MSY 35th hockey-stick advice rule). Fishing mortality should be around MSY when current biomass B_t is more than half of the biomass providing MSY (B_{MSY}). Fishing mortality is reduced linearly towards zero when B_t/B_{MSY} is between 0.5 and 0.35. However, if SPiCT results are not adequate, empirical approaches are to be used. Empirical approaches with models based on length frequency, catch and biomass indices and life history traits should be explored.

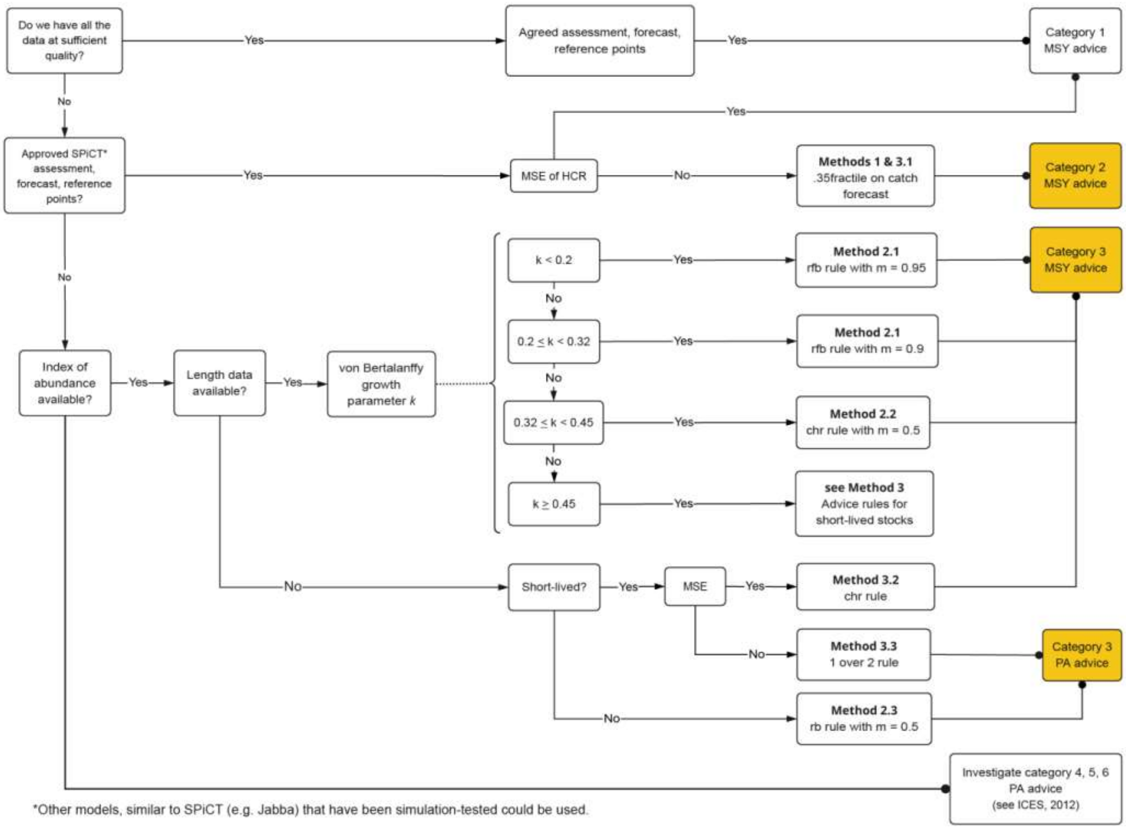

Figure 4 – Flow diagram showing the path of ICES advice based on the available data and assessment results. Diagram retrieved from (ICES, 2022c, p. 3).

1.7 Fisheries authorities suggest regulatory measures

A hearing was published in June 2022 proposing more extensive regulations of the halibut fisheries in Norway north of 62°N (Fiskeridirektoratet, 2022). The Norwegian regulatory authorities aim to prevent a negative development of the halibut stock by introducing new fishing gear restrictions. Total allowable catch (TAC) is mentioned as a possible regulatory measure for the fisheries, in addition to restrictions on the number of fishing gear, fishing time, and increased minimum catch size. However, a TAC cannot be introduced because a stock assessment and future prognosis for the halibut stock have not been developed and submitted to the authorities.

1.8 General objectives and specific objectives

The general objective of this thesis is to perform a stock assessment for the Norwegian halibut stock north of 62°N using data-limited models and the best available data. This general objective is addressed through the following specific objectives (SO):

SO1) Test and adapt SPiCT according to the ICES procedure.
SO2) Test empirical approaches according to the ICES procedure.
SO3) Investigate the effect of tourist- and recreational fisheries on the halibut stock by comparing scenarios in SPiCT with 20% and 40% higher historical landings.
SO4) Evaluate the stock status based on available information and stock assessment.
SO5) Suggest management advice for the halibut stock in Norway north of 62°N.

2 Material and methods

Throughout the data processing, several R packages were used. A list of all the packages, their usage and references are provided below (Table 2). In this chapter, the numerical material is first presented, followed by the various analyses performed.

Table 2 – R-packages used in data processing for this thesis. It contains the package's name, the description and usage of the different packages and their references.

R-package	**Description / Usage**	**Reference**
DLMtool	Package with multiple models for data-limited stock assessment.	(Carruthers & Hordyk, 2018)
ggFishPlots	Calculate and visualize life history parameters.	(Vihtakari, 2022a)
ggOceanMaps	Plotting data on oceanographic maps.	(Vihtakari, 2022b)
ggPlot2	Creating graphs and plots.	(Wickham, 2016)
gridExtra	Arrange multiple grid-based plots together.	(Auguie & Antonov, 2017)
lubridate	Work with times and dates.	(Grolemund & Wickham, 2011)
RColorBrewer	Colour palettes for plots.	(Neuwirth, 2022)
RstoxData	Read and manipulate IMR scientific trawl survey data.	(Umar et al., 2021)
SPiCT	Model for surplus production model stock assessment.	(M. W. Pedersen & Berg, 2017)
tidyverse	Collection of data packages used for data processing.	(Wickham et al., 2019)
writexl	Export data frames in «.xlsx»-format for use in Microsoft Excel.	(Ooms, 2022)

2.1 Scientific surveys

The IMR survey series «Kysttokt Varanger-Stad» (from now on survey) covered the halibut distribution area from 62°N latitude and north along the Norwegian coast to the Russian border. The survey took place in October and November and covered coastal areas, fjords and open ocean banks. No scientific survey had a good covering of the southern part of the stock (south of 62°N latitude). It constituted the best fisheries-independent time series for the species, although the survey was not developed for halibut specifically and did not cover the total area of distribution. The survey started in 1985 and is still operational, with survey data from 2021 being the last year available for this thesis. The survey was made up of three sub-survey series. The IMR survey for saithe (*Pollachius virens*) without a fixed station grid from 1995-2002 (Figure 5), and the Nofima/Fiskeriforskning coastal survey from 1995-2002 with a fixed station grid. In 2003, the two previous mentioned surveys were merged into a new survey as it is today. Today's survey was based on the fixed station grid from the Nofima/Fiskeriforskning coastal survey, with some additional stations to cover the saithe. The number of stations has gradually changed throughout the time series, and new stations were added in the period 2017-2021 to cover redfish (Mehl et al., 2018).

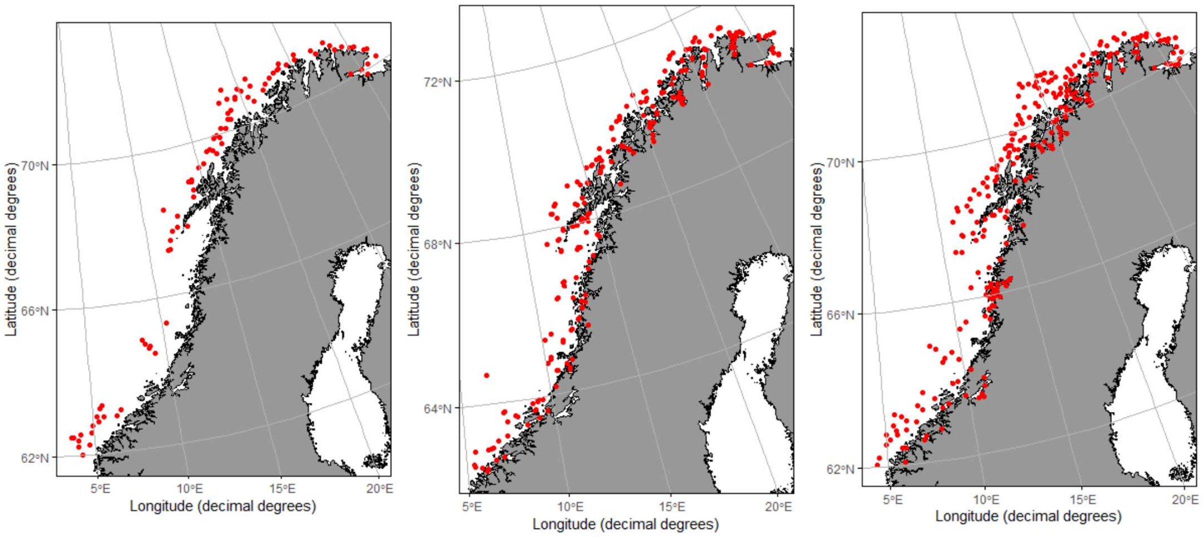

Figure 5 – Station grid for the saithe survey in 1997 (to the left), Fiskeriforskning/Nofima coastal survey in 1997 (in the middle) and today's coastal survey in 2021 (to the right). Red dots indicate the positions of the trawl stations. Maps generated using the R-package ggOceanMaps by Vihtakari (2022b).

The IMR saithe and today's survey were retrieved from the IMR database using a web browser. This process was done manually, downloading separate files for each vessel every year of the survey. Data from the IMR saithe survey from 1985 to 1994 were excluded because of no corresponding Fiskeriforskning/Nofima coastal survey cruise in that period. The Fiskeriforskning/Nofima coastal survey cruise dataset from 1995 to 2002 was received from Tone Vollen (Senior engineer, IMR) as it was not available on the IMR database. Station data, catch data and individual data were joined using year and station serial numbers as a unique identification. The three datasets were merged and treated as one, as data from the Fiskeriforskning/Nofima coastal survey and saithe survey covered the same area with a similar station grid, fishing gear and properties as the survey from 2003 until today.

The combined survey dataset was filtered to remove unwanted data before generating survey indices. Filtering was done using the IMR handbook for sampling (Mjanger et al., 2022). Stations without latitude and longitude were removed. Fishing gear other than the Campelen 1800 shrimp trawl variations were also removed. Then filtered for gear conditions "1" and "2" to include stations with gear in perfect order and gear with minor damage without significantly affecting selection and catch. Also filtered for sample quality "1" to include only stations where gear was set out in preselected position, and Scanmar trawl sensors show that everything was correct during trawling. A standard door spread was assumed for the time series, as investigated by Engås & Ona (1991). Stations lacking information about sampling distance (trawling distance) were manipulated: Two stations in 2015 lacked distance and sampling duration. Another station in the dataset had a negative sampling distance and duration. For these, station distance was set to a standard of 1 nautical mile (nm). One station in 2018 was missing distance information, and distance was defined by multiplying duration with the standard trawling speed of 3 knots.

2.2 Survey indices

The survey indices were fisheries-independent catch per unit effort (CPUE). Four survey indices were calculated from the dataset. The first survey index (CPUE1) based on individuals was calculated by dividing the total number of halibut caught each year by the total annual sampling distance (Table 3). Not all stations had standard sampling distance of 1 nautical mile, and the actual sampling distance was thus used. The second survey index (CPUE2) was based on individuals larger than the minimum catch size. The minimum catch size was 60 cm from 1995-2009 and 80 cm from 2010-. As the increase in minimum catch size represents a significant change in which size classes are included, the index was split in two between 2009 and 2010.

The third (CPUE3) and fourth (CPUE4) survey indices were calculated based on the weight of the halibut. Some halibut lacked individual samples, while unnaturally large variations in length-weight-relationship were identified for others. It was therefore decided to use the theoretical length-weight-relationship to calculate weights for the halibut. To find the length-weight relationship, a dataset filtered for halibut larger than minimum catch size, containing 371 individuals that had been length measured and weighted, was used. The length-weight-relationship was found using Equation 1.

$$W = a * L^b$$

Equation 1 – Length-weight-relationship for fish. Where W is the total body length in kg, L is the total length in cm, while a and b are coefficients for the relationship between W and L (Mehanna & Farouk, 2021).

The values for a and b were calculated using the least-square linear regression with Problem Solver in Microsoft Excel (from now on Excel). The dataset was not divided by sex, as sex information was missing for most individuals. Individuals with contradictory weight and length measurements had their weight multiplied by ten as their length indicated typing error. The estimated weight was calculated using Equation 1 for the 1070 halibut with length measurements. The third survey index (CPUE3) was calculated by dividing the total estimated halibut weight each year by the total sampling distance each year (Table 3). The fourth survey index (CPUE4) was based on the estimated halibut weight larger than the minimum catch size with the same restrictions as the second survey index.

Table 3 – The four survey indices from the coastal scientific survey cruise for Atlantic halibut with descriptions.

Survey indices	Description
CPUE1	Number of individuals/distance trawled per year.
CPUE2	Number of individuals larger than minimum catch size/distance trawled per year.
CPUE3	Weight of individuals/distance trawled per year.
CPUE4	Weight of individuals larger than minimum catch size/distance trawled per year.

2.3 Fisheries statistics

Official halibut landings collected by the Directorate of Fisheries from 1977-2021 were obtained from an IMR server, downloading one Excel file (.xls/.xlsx) for each year. The files were uploaded into RStudio and converted with the same column names and classes into a standardised format. All files were then merged and sorted into catch from unreported areas, Norwegian areas (where the Norwegian halibut stock is expected to be) and catch from abroad (assumed other halibut stocks).

The Norwegian areas were then divided into north of 62°N and south of 62°N (Figure 6). The statistical areas 09, 41, 42, 30 and 34 were not included in Norwegian areas as the areas are shared with other coastal nations. Landings statistics for the specified areas were expected to be incomplete and may contain halibut from other stocks. The statistical areas 03, 10, 13, 15 and 24 are only partly covered by the Norwegian Exclusive Economic Zone and Svalbard's Fisheries Protection Zone. These were included as they cover the same halibut stock. See appendix B for a more detailed map of the Norwegian Exclusive Economic Zone, Svalbard's Fisheries Protection Zone, and main statistical areas.

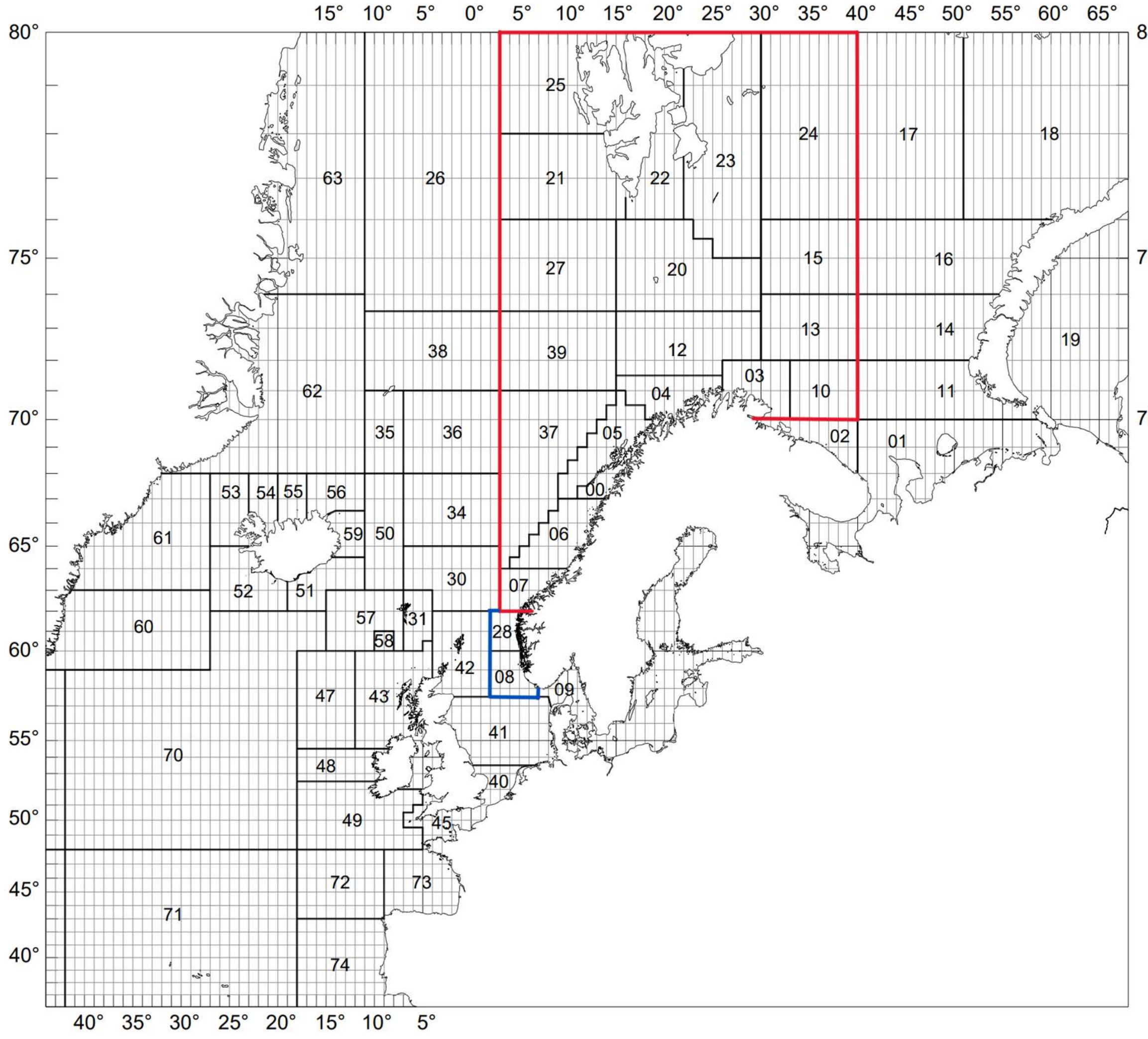

Figure 6 – Main areas in Norwegian fisheries statistics. Landings within the red and blue lines are assumed to be from the Norwegian halibut stock. The red lines indicate areas north of 62°N, while the blue line indicates areas south of 62°N. The original map was retrieved from (Mjanger et al., 2022, p. 117) and edited with coloured lines.

Official landing statistics contained information about the catch area and fishing gear. The period 1977-1991 had some landings with unreported catch areas. To investigate the catches origin, an overview of the gear used in Norwegian, non-Norwegian, and unreported areas was made. Fishing gears were grouped into the three most used; longlines, gillnets and trawls, in addition to other gears.

The landings from areas north of 62°N and south of 62°N were compared to determine the share of the total Norwegian catch. Based on the gear distribution and share of landings for areas north of 62°N and south of 62°N, the landings from unreported areas were allocated to Norwegian landings.

2.4 Surplus production models

Surplus production models have been used in assessing data-limited stocks for a long time (M. W. Pedersen & Berg, 2017). These models are often used when information about age- and size-composition is limited. The surplus production models use time series of catches and biomass indices (CPUE from commercial fleet or scientific surveys) for stock assessment (Polacheck et al., 1993; Punt, 2003). A surplus production model aims to find the relationship between the stock size and the biomass production, which is a dome-shaped curve (Pella & Tomlinson, 1969). The biomass which gives the highest biomass production can be determined by using the production curve. Some models, like the Schaefer model, are based on logistic parameters, resulting in a stock production curve where the MSY is at exactly half of the maximum stock size, known as the carrying capacity *k* (Schaefer, 1954). This assumption may not be valid for all fish stocks, as MSY may occur at less than or more than half of the carrying capacity. Therefore, other surplus production models allow positive and negative skewness to the stock production curve (Pella & Tomlinson, 1969).

Since surplus production models use limited data, they cannot produce the true variation in population dynamics found in a wild fish stock, like variation in recruitment, catchability, size structure, and environmental conditions (Pella & Tomlinson, 1969). To compensate for this, models include a term for random error. Random errors are incorporated into equations related to variability in biomass dynamics (process errors) and sampling errors in index data (observation errors). Models that incorporate random errors are called stochastic.

2.5 Stochastic Surplus Production model in Continuous Time (SPiCT)

SPiCT is a state space surplus production model Pedersen & Berg (2017) developed. The model is a re-parameterized version of the Pella-Tomlinson surplus production model (ICES, 2022c). SPiCT models the stock dynamics and fisheries dynamics and can, by doing this, reflect the errors and uncertainty of parameters in the management results (M. W. Pedersen & Berg, 2017). The model can estimate fishing mortality and biomass for any time by using data sampled at irregular and arbitrary intervals.

Supplementary information can be added to the SPiCT model to stabilize model fit and reduce the uncertainty of the estimates (M. W. Pedersen & Berg, 2017). This is done by using informative priors, probability distributions that limit the range of a target parameter in the model. Priors should only be used if the data foundation is strong and come from sources like meta-analyses and fisheries-independent data. If the priors and the information in the dataset contradict, priors lead to lower stability and higher uncertainty. However, for data-limited stocks or stocks with data lacking historical catches and that have limited contrasts in the abundance index, it is recommended to fix or reduce the variance of the shape parameter *n* (ICES, 2021). Assuming a symmetric Schaefer production curve by fixing $n = 2$ promotes the stability of the model (ICES, 2022b).

SPiCT was downloaded and run in RStudio according to the official handbook of Mildenberger et al. (2022) and the digital learning session I attended by ICES (Berg et al., 2022). The input data for the model were the CPUE indices (1995-2021) and fisheries statistics from 1977-2021 from Norwegian areas north of 62°N, including the allocated catch from unreported areas. These are found in appendix B. Stock assessments were performed with SPiCT, one with each of the four CPUE indices. The indices with change in minimum catch size were split in two at the time of the increase. The prior *n* was fixed at a symmetric Schaefer production curve. This prior promoted stability for the stock assessment. SPiCT was run with the ICES MSY 35th hockey-stick advice rule for fishing mortality and biomass prediction. The management rule was also used to suggest a TAC.

For a SPiCT assessment to be accepted and used in an official ICES advice, it needs to fulfil seven criteria (Table 4) (ICES, 2022c; Mildenberger, Kokkalis, et al., 2022). Tests were executed to check if the assessment fulfilled the criteria.

Table 4 – The seven criteria for accepting and using a SPiCT assessment according to ICES and SPiCT guidelines, slightly adjusted (ICES, 2022c; Mildenberger, Kokkalis, et al., 2022).

Criteria for accepting a SPiCT assessment according to ICES	
1.	The assessment has converged.
2.	All the variance parameters of the model parameters are finite.
3.	No serious violation of the model assumptions for one-step-ahead residuals (bias, auto-correlation, normality). P-values from the statistical tests built into SPiCT should be insignificant ($p > 0.05$). Minor deviations from the assumptions do not necessarily invalidate model results but should be examined.
4.	Retrospective analysis results in consistent patterns. No tendency of consistent over- or underestimation of the relative biomass (B/B_{MSY}) and relative fishing mortality (F/F_{MSY}) in successive assessments, and the values should be within credible intervals.
5.	The production curve is realistic. The shape of the production curve should not be too skewed. B_{MSY}/F should be between 0.1-0.9. Too low values of B_{MSY}/F can cause an infinite population growth rate.
6.	The main variance parameters in the model (biomass and fishing mortality processes and catch and index observations) should not be unrealistically high. The confidence intervals for relative biomass (B/B_{MSY}) and relative fishing mortality (F/F_{MSY}) should not span more than one order of magnitude. High assessment uncertainty can indicate a lack of input data contrast or violation of the ecological model assumptions.
7.	The initial values do not influence estimates of the parameters, meaning that the estimates should be the same for all initial values.

2.6 Scenarios with tourist- and recreational fisheries

Landings from tourist- and recreational fisheries were not registered in official landings statistics, so their magnitude was thus not known. To account for the unregistered fisheries, it was assumed that unregistered catches varied with the official landings and availability of halibut. This assumption meant that fishing effort in tourist- and recreational fisheries have been proportional to the fishing effort in the commercial halibut fisheries. Three scenarios were run using SPiCT with the chosen survey index and settings as described in previous sub-chapters. Scenario 1 was based on official landings, scenario 2 had 20% increased landings, and scenario 3 with 40% increased landings.

2.7 Empirical approach

The empirical approaches are used when there is not enough data for a stock to perform a traditional stock assessment or a stock assessment with a surplus production model (Carruthers et al., 2016; Fischer et al., 2020; ICES, 2022c, 2022d). Empirical approaches may be model-free estimations, length-based or life history-based methods, and generic algorithms. They often use empirical trends as indicators for defining management actions like the trend in landings, biomass indices or length-composition from the fisheries (Hillary et al., 2016). Unlike stock assessments, management procedures like total allowable catch are set without target reference points (Fischer et al., 2020). The goal of empirical approaches is to provide advice on fishing opportunities of a data-limited stock. To do this based on limited and varying amount of data, the approaches often include a significant precautionary approach to prevent stock depletion.

ICES (2022c) describes three empirical rules for ICES category 3 stocks. These have been generically developed and tested using management strategy evaluation to follow ICES precautionary approach. These empirical rules are included in the Data-Limited Methods Toolkit (DLMtool). To test a broader range of empirical approaches based on different types of input data, it was decided to use DLMtool to test the empirical approaches in this thesis.

2.8 The Data-Limited Methods Toolkit (DLMtool)

The Data-Limited Methods Toolkit (DLMtool) is an R package developed for the management of data-limited fish stocks (Carruthers & Hordyk, 2018). The package uses the management strategy evaluation (MSE) approach, combining data, models and methods for data analysis and management actions (Punt et al., 2016). The goal is to identify the best management strategy or evaluate the performance of different strategies by comparing them. The DLMtool contains over 80 models, algorithms and management procedures (Carruthers & Hordyk, 2018). It could also used with actual historical data, where management procedures are automatically chosen and run based on the input data. The relatively simple structure of the models and harvest rules (MPs) is easily understandable to understand for management and stakeholders (Carruthers et al., 2016; Geromont & Butterworth, 2015).

The package DLMtool was downloaded and run in RStudio to test empirical approaches in accordance with the official user guide (Blue Matter Science, 2020; Carruthers & Hordyk, 2020). An Excel worksheet was created in the working directory and then populated with the available data for the halibut stock (Table 5). The survey index was used as a continuous time series and not split in two as done for SPiCT. The data objects not mentioned in the table were missing information and subsequently set to NA in the program. The populated Excel sheet was afterwards imported into RStudio.

Table 5 – Input data for Norwegian Atlantic halibut stock north of 62°N latitude for DLMtool. Data fields not mentioned in the table were missing information and were set to NA.

Data	**Input**	**Description / Source**
Units	Tons	Unit for landings statistics.
Natural mortality M	0.175	Lower end of den Heyer et al. (2013) estimates as females dominate stock biomass.
Von Bertalanffy Linf	205.1	For female halibut with most observations in Armsworthy & Campana (2010).
Von Bertalanffy K	0.10	For female halibut with most observations in Armsworthy & Campana (2010).
Von Bertalanffy t0	0.49	For female halibut with most observations in Armsworthy & Campana (2010).
Length-weight parameter a	0.00538	Results from length-weight-relationship equation 1.
Length-weight parameter b	3.18	Results from length-weight-relationship equation 1.
Length at 50% maturity (L50)	95	(Haug & Tjemsland, 1986; Høines et al., 2009).
Length at 95% maturity	120	(Haug & Tjemsland, 1986; Høines et al., 2009).
Length at first capture	80	Minimum catch size (Høstingsforskriften, 2022, §47).
Length at full selection	100	Gillnets have full selection towards larger individuals (100-110 cm), while longlines have a selection around minimum catch size (Erik Berg, personal communication, 26. January 2023).
Current stock depletion	0.5	SPiCT results with fixed Schaefer (1954) production curve.
BMSY/B0	0.5	Schaefer (1954) production curve assumption.
Catch Reference	2588	MSY from SPiCT with CPUE4.
Biomass Reference	9652	Biomass in 2021 from SPiCT with CPUE4.
Average catch over time t	1039.50853	Average landings from 1977-2021.
Depletion over time t	6.25	Landings in 2021 / Landings in 1977.
Year	1977-2021	Years in landings statistics.
Duration t	44	Number of years in landings statistics.
LHYear	2021	Last year with landings in statistics.
Catch	Landings statistics	From the period 1977-2021, see appendix B.
Abundance index	Survey index CPUE4	From the period 1995-2021, see appendix B.
Maximum age	50	(Armsworthy & Campana, 2010).

Management procedures (MPs) that could be run based on the data input were identified. Of the MPs that could be run, feasible MPs were selected for further use. MPs chosen were based on total allowable catch (TAC) and size selectivity (SL). Insufficient information about effort and spatial distribution excluded total allowable effort MPs and spatial MPs. Several MPs were slight variations of the same equation, like CC1, CC2, CC3, CC4, CC5 where the degree of precaution varied as historical catch were multiplied by 1, 0.9, 0.8, 0.7 and 0.6. When two MPs of the same kind existed, the most conservative MP was chosen. In the cases with three or more MPs of the same kind, a MP in the middle (not least or most conservative) was chosen. After the first run, two MPs (DD and NFref) were removed as they required survey indices in absolute biomass format.

Life history parameters were first calculated using the survey dataset and the R-package ggFishplot (Vihtakari, 2022a). However, because the dataset contained a few very large individuals, the von Bertalanffy parameter L_{inf} became implausible (L_{inf} = 511.2 cm, K = 0.02 and t0 = -1.42). Life history parameters were retrieved from Armsworthy & Campana (2010), based on female halibut with the highest number of individuals was (Table 5). Mixed sex estimation did not work well as males and females have different growth patterns.

3 Results

3.1 Scientific survey

The number of stations and sampling distance varied throughout the survey time series (Figure 7). The filtered survey dataset contained a total of 3982 stations and a total sampling distance of 4938 nautical miles in the period from 1995-2021. The number of stations and sampling distance were low for the first two years before increasing until 2000. Then followed a reduction, interrupted by a peak in 2002. The number of stations and the sampling distance increased from 2017 and was the highest in 2021, with 241 stations and 297 nautical miles.

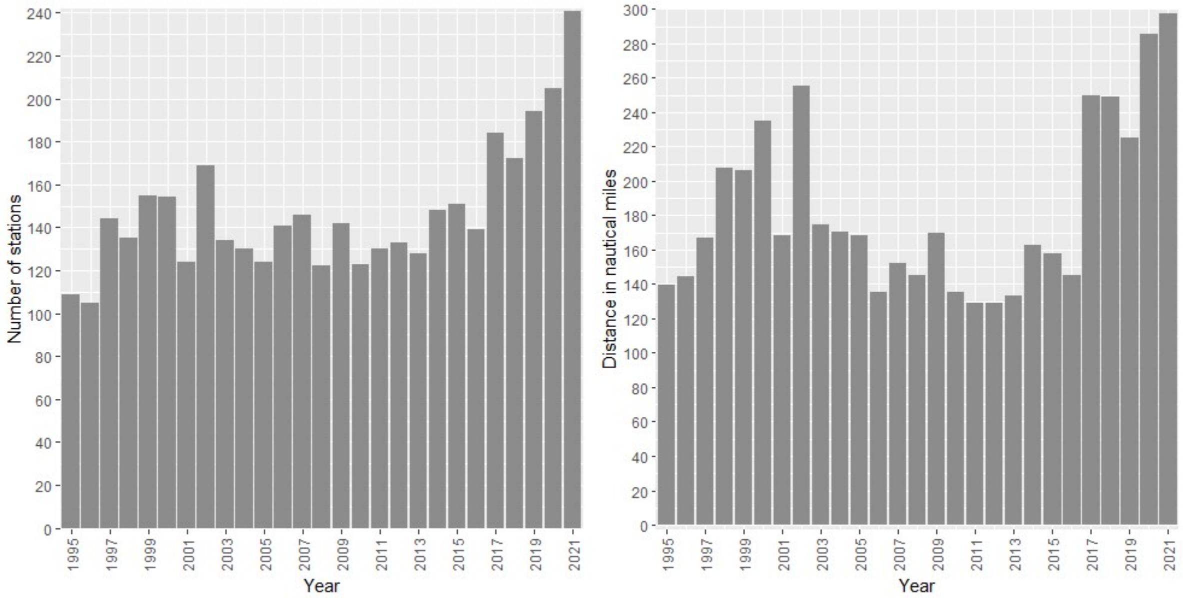

Figure 7 – The number of stations (left side) and sampling distance (right side) each year for the scientific coastal survey from 1995-2021.

The station depth distribution throughout the survey time series were relatively stable (Figure 8). The difference between the shallowest and deepest stations was substantial every year, yet the depth distribution was similar between the years. The shallowest stations had a depth of around 40 meters, while the deepest had between 550 and 600 meters deep. The median depth for most survey years was a bit below 200 meters.

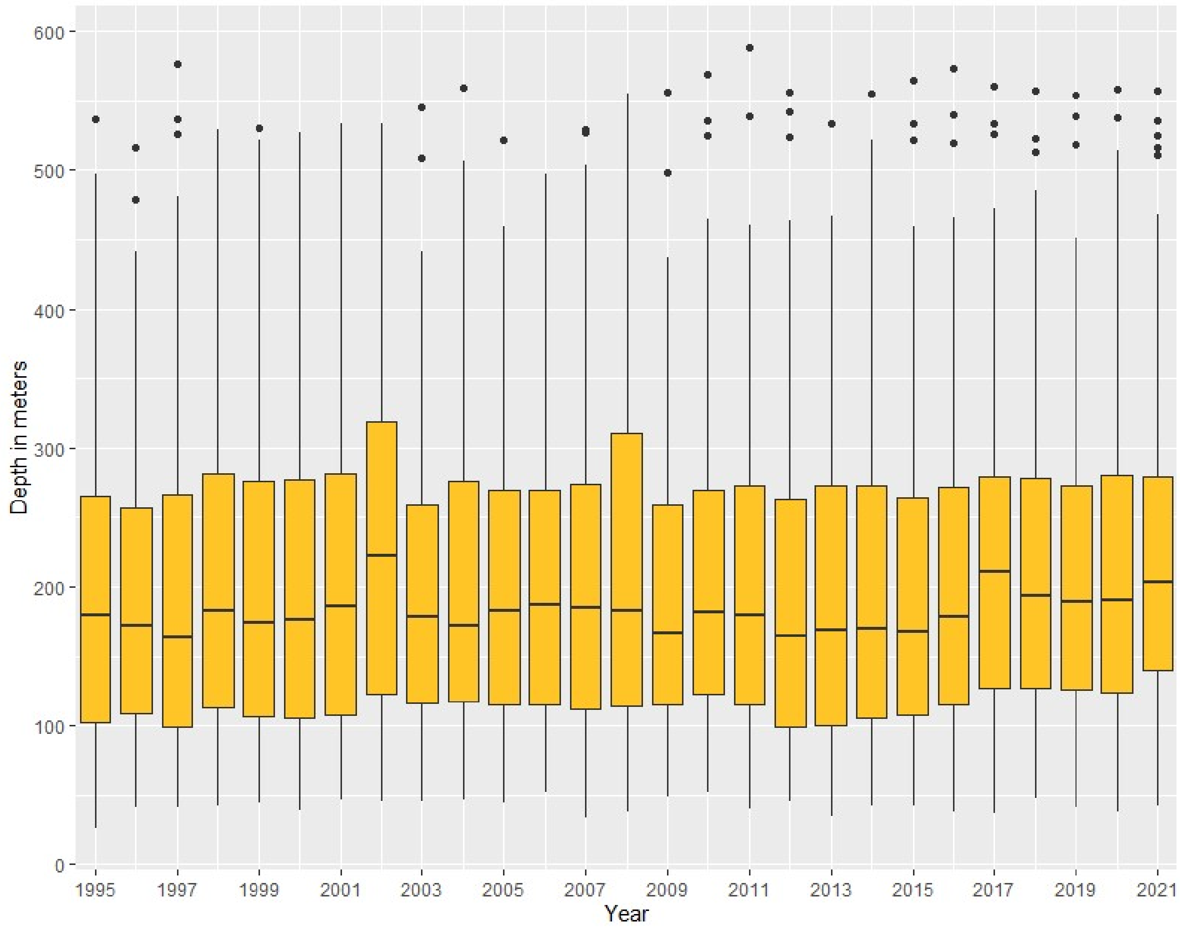

Figure 8 – Box plot showing depth distribution for stations each year in the filtered scientific coastal survey dataset. The box represents the middle 50% of the data (the interquartile range (IQR)). 25% of the data is above and below the median line. The whiskers show the range of the data, excluding outliers. Outliers are data points that are more than 1.5 times the IQR away from either end of the box.

The dataset contained 1136 halibut, of which 1070 were length measured (Figure 9). A total of 383 individuals were larger than the minimum catch size, 165 halibut in 1995-2009 and 218 halibut in 2010-2021. The minimum catch size was 60 cm from 1995-2009 and increased to 80 cm in 2010. Some individuals lacked length measurements, and the most significant deviation was found in 2000, where only 15 out of 44 were length measured.

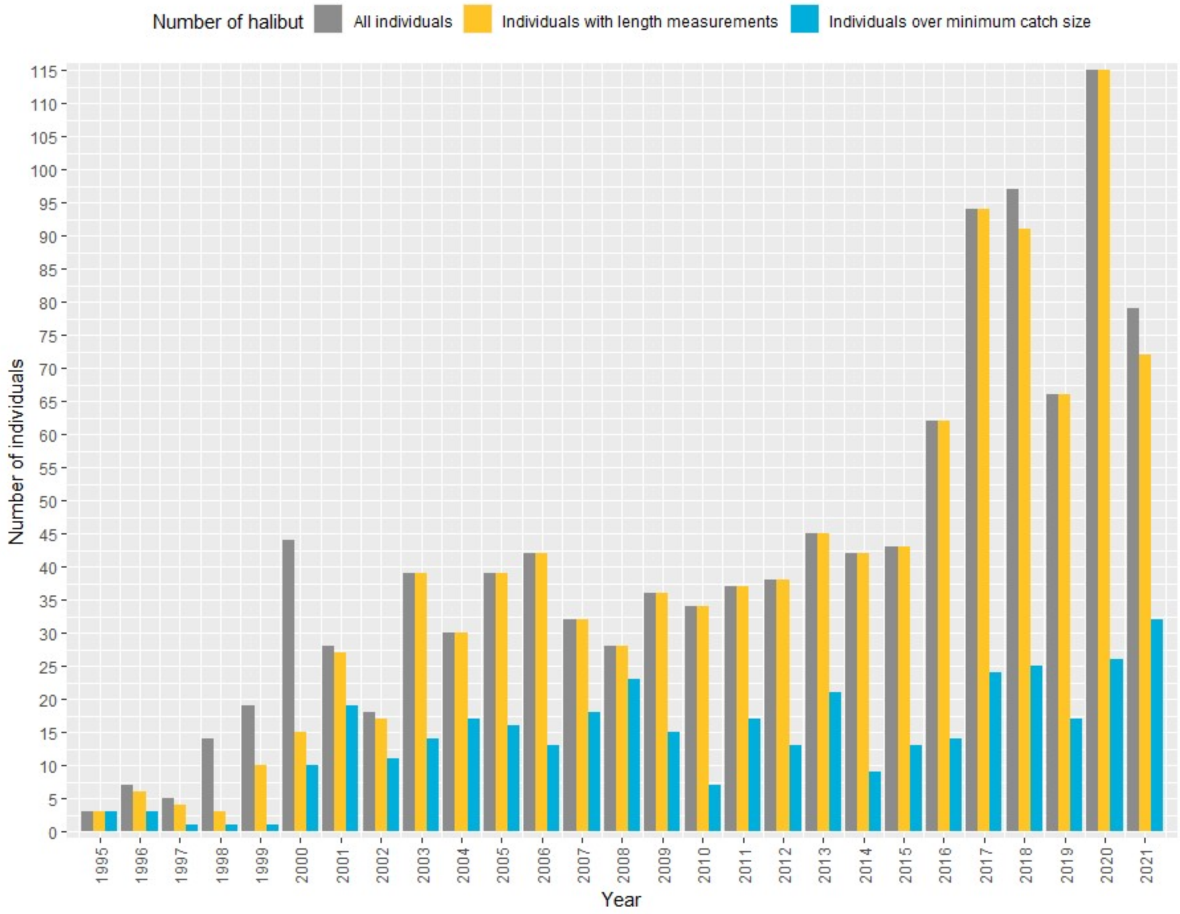

Figure 9 – Number of Atlantic halibut caught each year in the coastal survey. The grey bar represents all individuals in the dataset, the yellow bar represents all individuals with length measurements, and the blue bar represents all Atlantic halibut larger than the minimum catch size in the dataset. The minimum catch size was 60 cm in 1995-2009 and 80 cm in 2010-2021.

Halibut length distribution showed that most halibut caught in the survey are small (Figure 10). The length distribution varied between the years; some years had a larger spread than the rest. The median length was above the minimum catch size of 60 cm for most of the years until 2009. When the minimum catch size increased to 80 cm in 2010, the median length was below the fishery's length regulation.

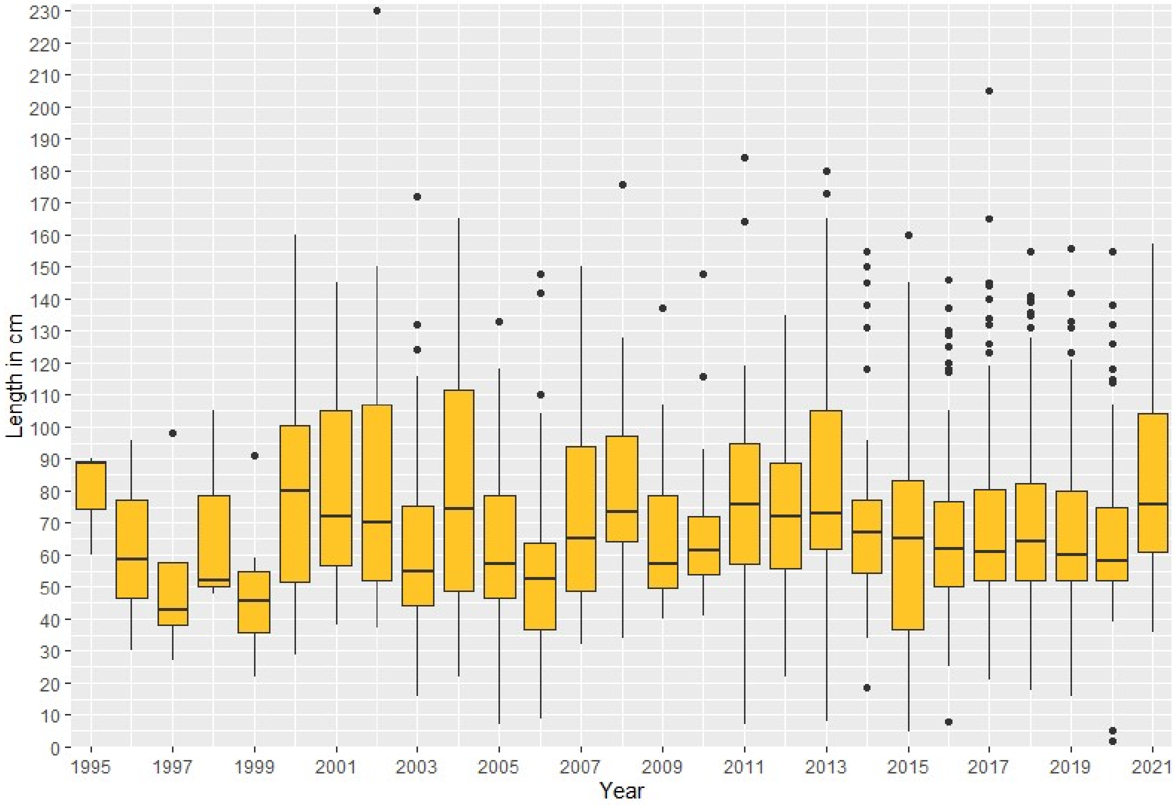

Figure 10 – Box plot showing length distribution for the length measured Atlantic halibut by year in the merged and filtered Norwegian coastal survey dataset. The box represents the middle 50% of the data (the interquartile range (IQR)). 25% of the data is above and below the median line. The whiskers show the range of the data, excluding outliers. Outliers are data points that are more than 1.5 times the IQR away from either end of the box.

The weight distribution plot also displayed that most halibut caught during the survey was small (Figure 11). There were relatively few heavy halibuts (seen as outliers), and two individuals stood out, weighing over 100 kilos each. The number of extreme observations increased towards the end of the time series.

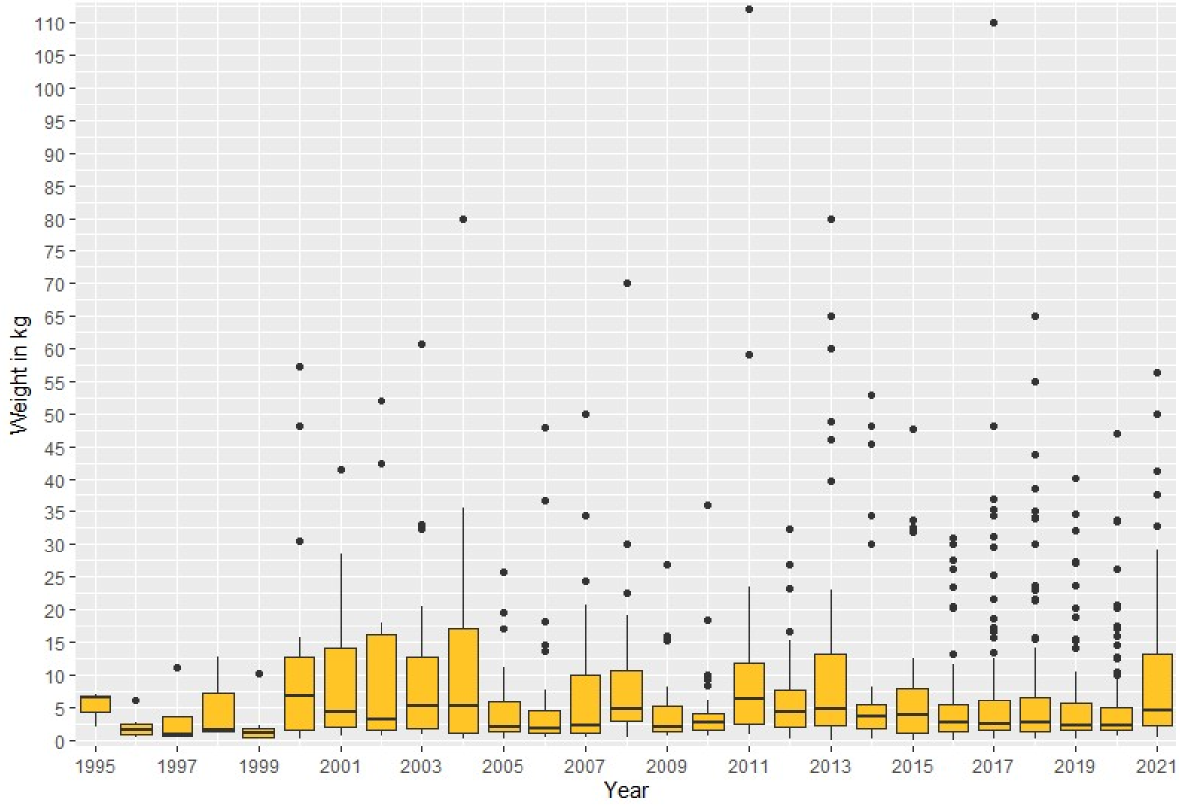

Figure 11 - Box plot showing weight distribution for the weight measured Atlantic halibut in the merged and filtered Norwegian coastal survey dataset. The box represents the middle 50% of the data (the interquartile range (IQR)). 25% of the data is above and below the median line. The whiskers show the range of the data, excluding outliers. Outliers are data points that are more than 1.5 times the IQR away from either end of the box.

3.2 Survey indices

The difference between CPUE1 and CPUE2 was evident (Figure 12). CPUE1 contained all the individuals in the survey and had a generally increasing trend until 2016 with large variations between years. The index peaked in 2016, with a somewhat indistinct downward trend afterwards. The number of halibut caught per nautical mile was noticeably reduced when removing individuals below minimum catch size. CPUE2 showed a flat trend for the first five years, followed by two years of increased values. After that, the index varied around 0.1 halibut caught per nautical mile. The last two years showed a small positive trend.

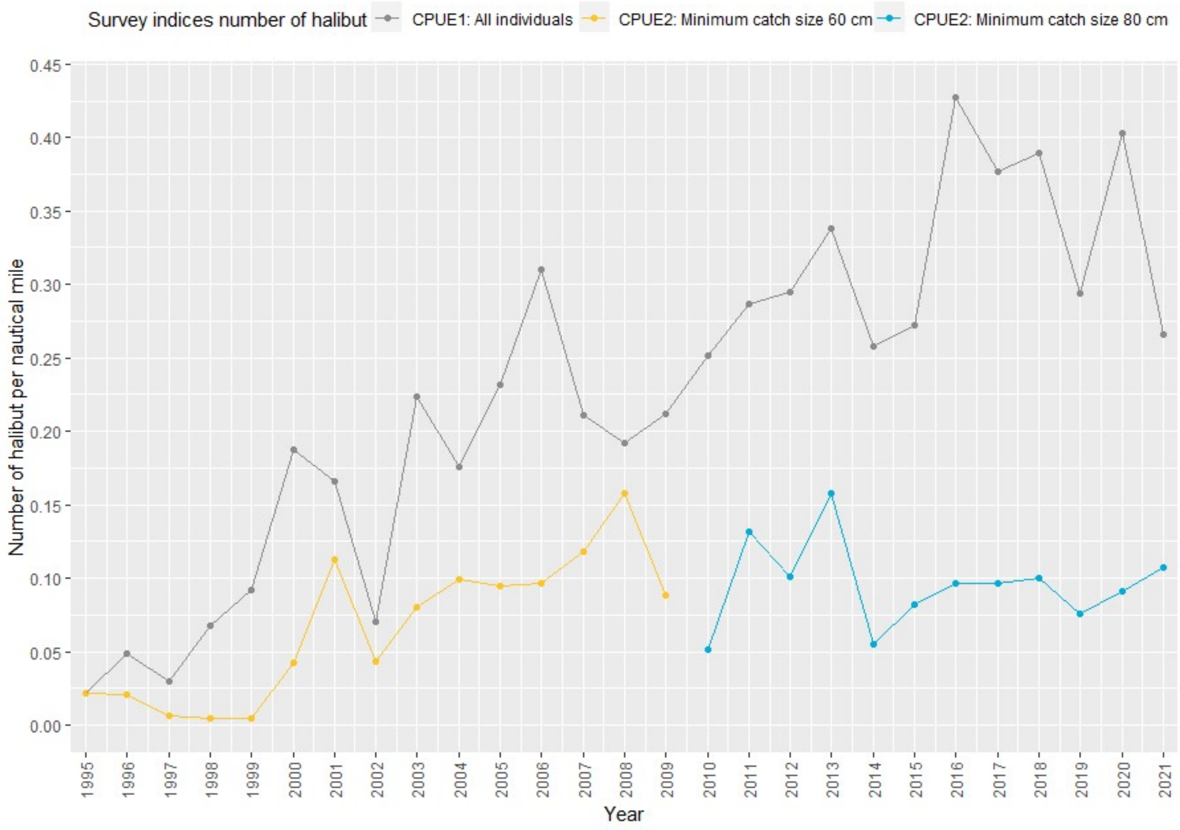

Figure 12 – Survey indices of Atlantic halibut from the Norwegian coastal survey (number of halibut per nautical mile trawling). The grey line represents CPUE1 which includes all the individuals in the dataset. The yellow and blue lines represent CPUE2, including individuals over minimum catch size, 60 cm in 1995-2009 and 80 cm in 2010. CPUE2 was split between 2009 and 2010 when the minimum catch size increased.

After calculating the constants for the length-weight-relationship equation 1, one got the final equation presented below, where W=weight in kg and L=length in cm. The equation was used to calculate the estimated weight for the halibut with length measurements, which was included in the survey indices based on halibut weight.

$$W = (\sim 5.38 * 10^{-6}) * L^{\sim 3.18}$$

CPUE3 and CPUE4 were based on halibut weight in kg per nautical mile of trawling and had similar development (Figure 13). The trend was low and flat for both indices in the first five years before an increase was seen in 2000. Then followed a relatively stable period with variations between ~1 and ~1,75 kg per nautical mile until 2008. The indices were then halved in 2009 compared to the previous year. The indices' value doubled in 2011, reduced in 2012, and peaked in 2013. The last five years showed a new top in 2017. CPUE3 has shown a positive development for the last two years, while CPUE4 showed an increase in 2021. The two indices had quite similar values in the first half of the time series, while the differences were more noticeable in the second half.

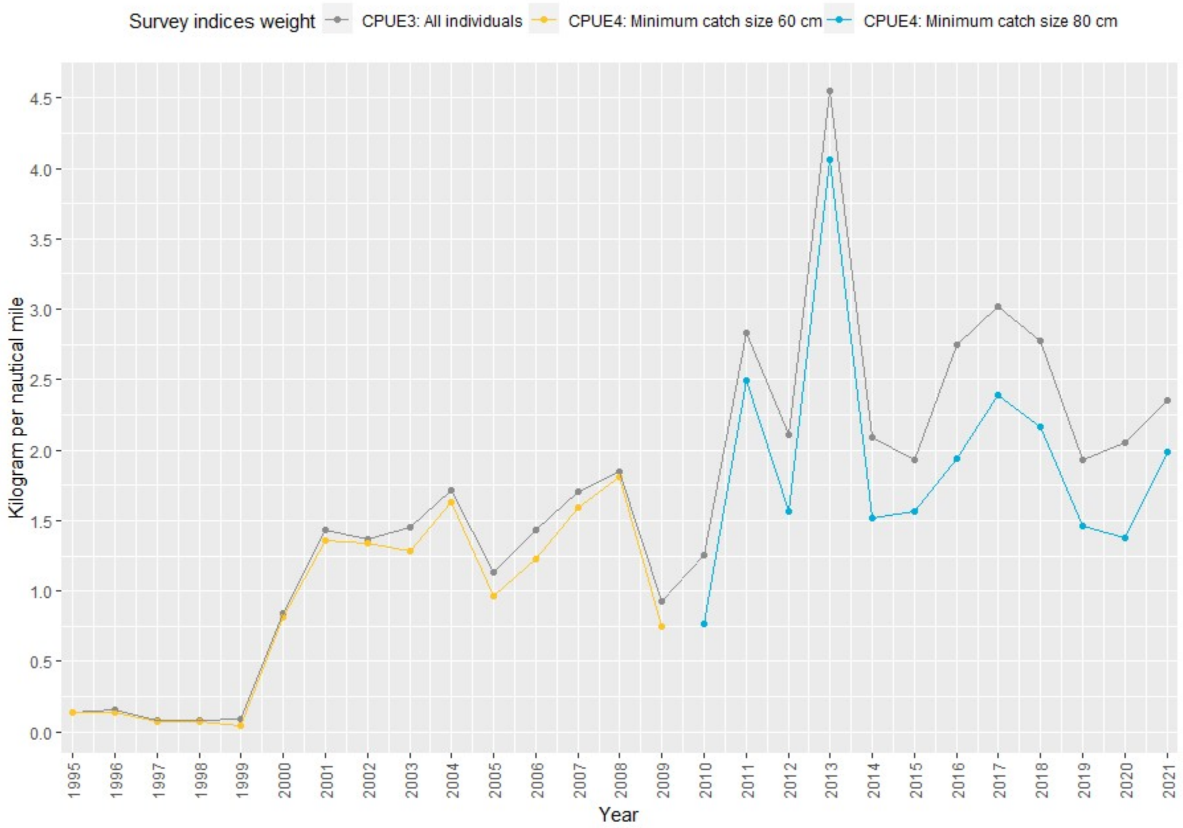

Figure 13 - Survey indices of Atlantic halibut from the Norwegian coastal survey (kg per nautical mile trawling). The grey line represents CPUE3 which includes all the weighed individuals in the dataset. The yellow and blue lines represent CPUE4, including individuals over minimum catch size, which was 60 cm from 1995-2009 and 80 cm from 2010. CPUE4 was split between 2009 and 2010 when the minimum catch size increased.

3.3 Fisheries statistics

Official Norwegian landings of halibut were divided into three categories based on their catch areas (Figure 14). Most halibut were caught north of 62°N, while a small share was caught south of 62°N. In addition, some landings were caught in unreported areas from 1977-1991. Catches from unreported areas may originate from Norwegian waters or abroad.

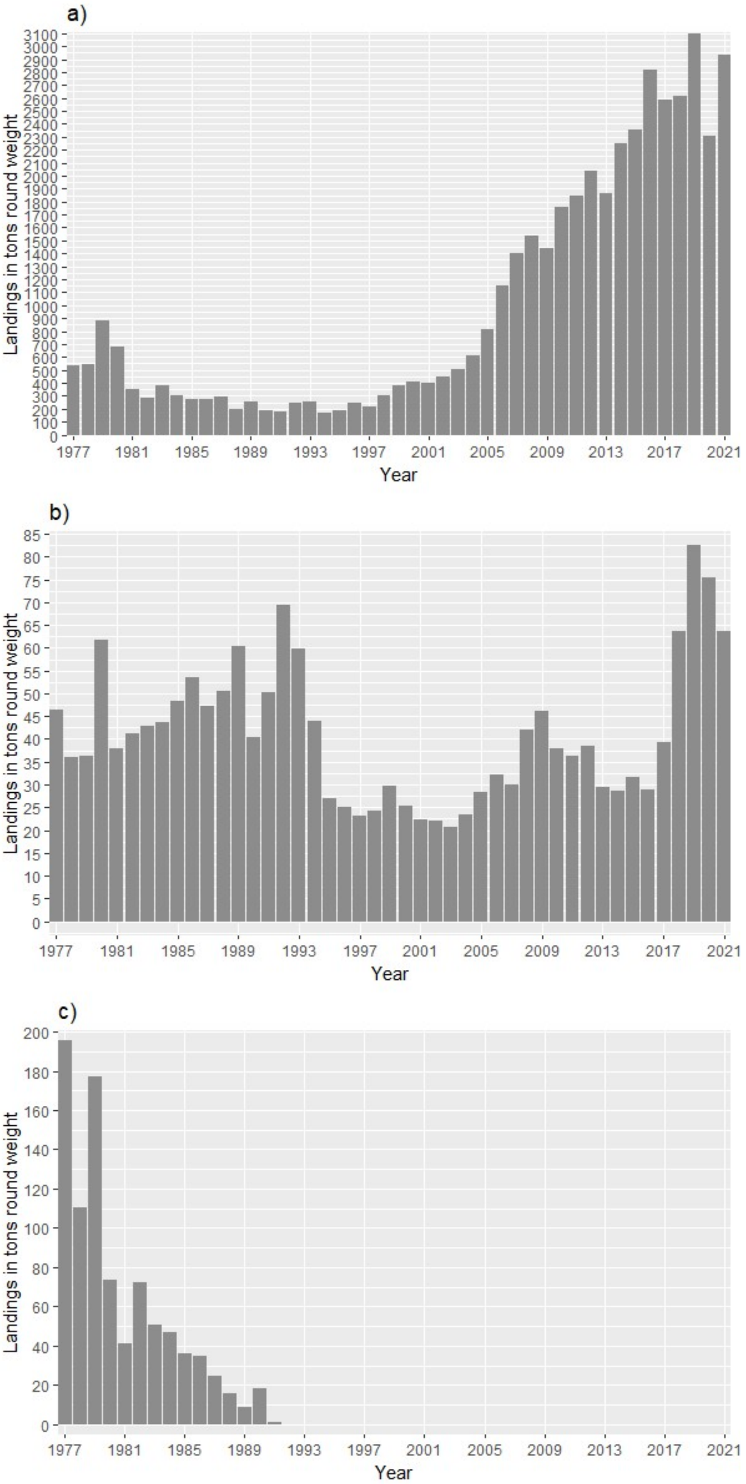

Figure 14 - Landing statistics for Atlantic halibut. a) Landings from Norwegian areas north of 62°N, b) and south of 62°N, and c) landings from unreported areas. Pay attention to different scales on the Y-axis.

The gear distribution in the non-Norwegian, Norwegian, and unreported areas vary (Figure 15). Non-Norwegian areas stand out the most, with a predominance of longlines for all the years. The similarity in gear distribution for Norwegian areas and unreported areas indicate that landings from unreported areas were misreported landings from Norwegian waters. Landings from unreported areas were allocated to landings from Norwegian areas.

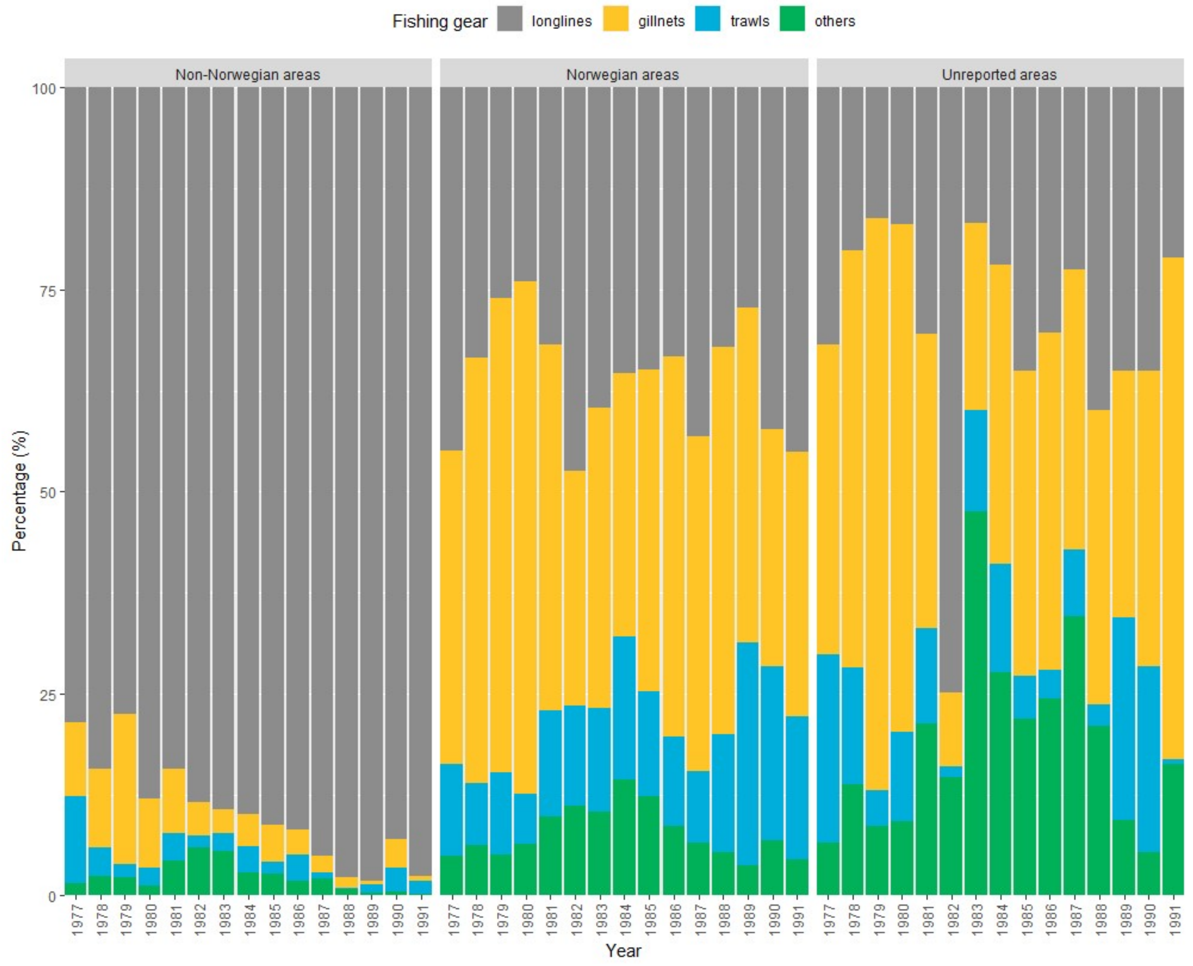

Figure 15 – The gear distribution for Atlantic halibut landings caught abroad, in Norway and in unreported areas in percentage for each year with unreported catch from 1977-1991.

Landings from areas north of 62°N constituted between 77,84% and 98,98% through the time series (Figure 16). The landings from unreported areas were distributed between Norwegian areas north of 62°N and south of 62°N based on their share of the total catch from Norwegian areas.

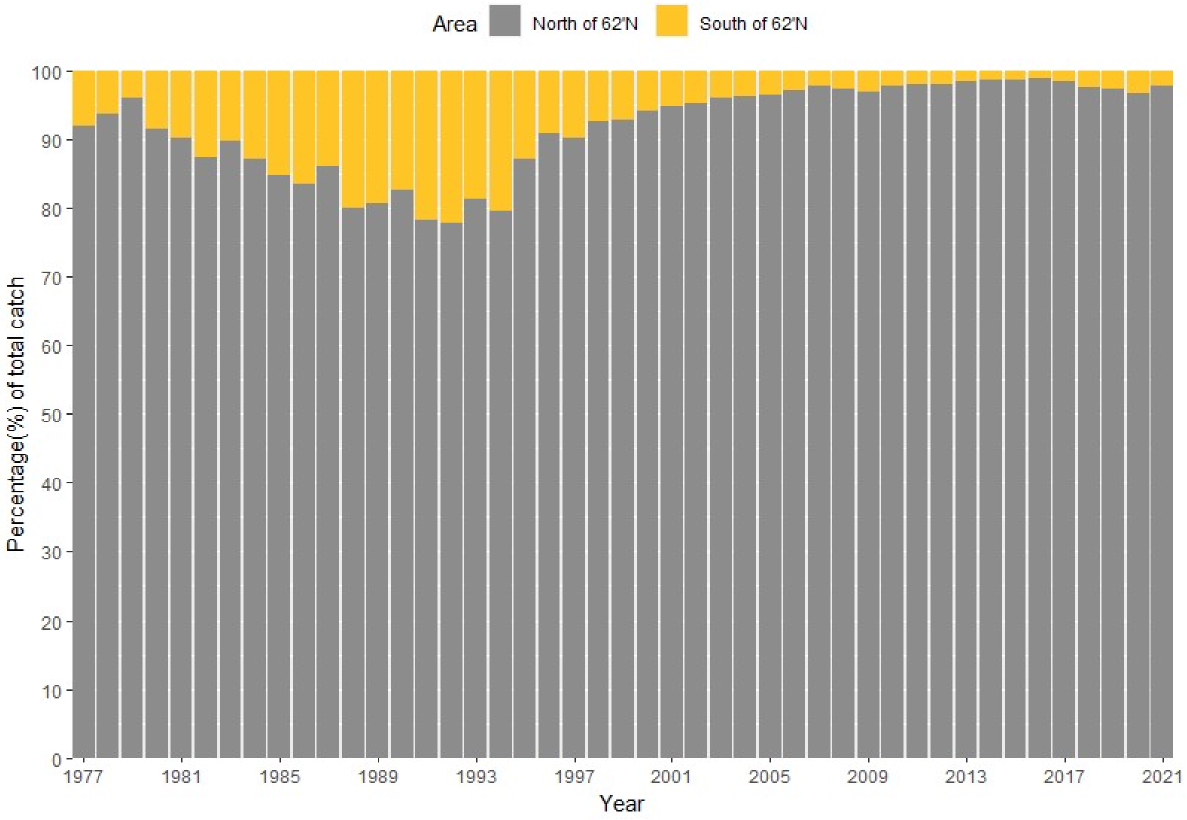

Figure 16 – Distribution of Atlantic halibut landings between Norwegian areas north of 62°N and south of 62°N displayed in percentage of the total catch for each year from 1997-2021. The grey bars represent the areas north of 62°N, while the yellow bars represent areas south of 62°N.

The final plot for Norwegian halibut landings north of 62°N, including allocated landings from unreported areas, was used as input in the models (Figure 17). Landings for the first years had become somewhat higher after allocating landings from unreported areas. The last years of the 1970s showed relatively stable landings before landings were reduced to half in 1981. At this point, the stock was regarded as depleted. This was seen through the landing statistics until 1998/1999 when a positive trend emerged. From that point onward, the landings grew to over 3000 tons, and the positive trend may be diminishing.

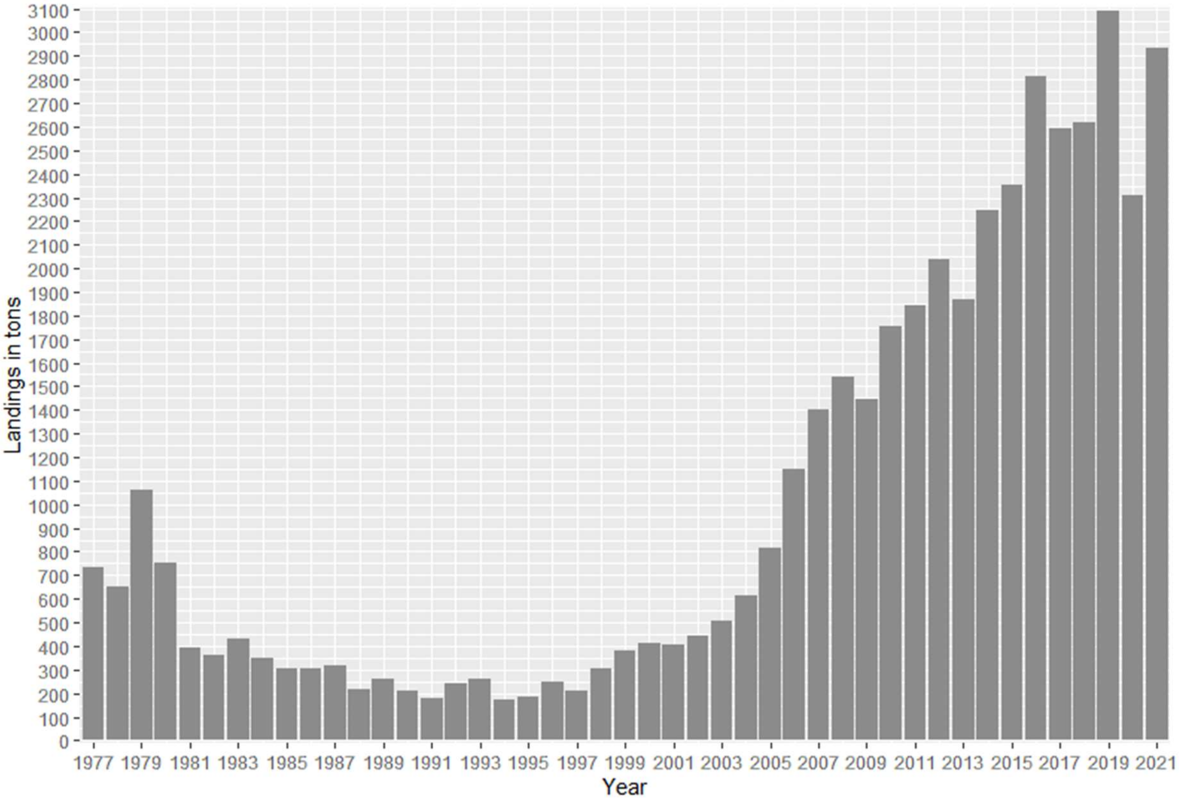

Figure 17 – Official landings of Atlantic halibut from Norwegian areas north of 62°N. This includes landings from unreported areas distributed according to the percentage distribution of total Norwegian landings between North of 62°N and South of 62°N.

3.4 SPiCT

The SPiCT ran with the four survey indices resulted in variations of the reference point estimates B_{MSY}, F_{MSY}, and MSY, with their corresponding confidence interval (CI) range (Table 6). The B_{MSY} (biomass that can maintain MSY in the long term) estimated ranged from 9443 tons to 15790 tons. The lowest B_{MSY} value within 95% CI was 4550 tons, while the highest was 26784 tons. The uncertainty range spanned from 13701 tons (CPUE3) to 17475 tons (CPUE1). The reference point F_{MSY} (fishing mortality giving MSY in the long term) was estimated between 0.15 and 0.27 for the indices, with F 0.11 as the lowest value within 95% CI and F 0.52 as the highest. The 95% CI range spanned from F 0.10 (CPUE1) and F 0.38 (CPUE2 and 4). The estimates for MSY were similar for all four indices, with the lowest estimate at 2394 tons and the highest estimate at 2588 tons, a variation of 194 tons. The confidence interval differed from 1176 tons (CPUE2) to 1403 tons (CPUE3). The carrying capacity K for the stock varied with 12 698 tons, and the confidence interval ranges from 27 536 (CPUE3) to 34 984 (CPUE1).

Table 6 – The estimated stochastic reference points B_{MSY}, F_{MSY} and MSY and model parameter K for 2021 with confidence interval (CI) 95% range in parenthesis for SPiCT runs with the four survey indices (CPUE) for the Atlantic halibut north of 62°N latitude. The last row contains criteria fulfilment for acceptance of the SPiCT assessment. Descriptions of the criteria are found in Table 4.

Reference points (Min/max within CI 0.95)	**CPUE1 (N/nm trawling): all**	**CPUE2 (N/nm trawling): over minimum catch size**	**CPUE3 (kg/nm trawling): all**	**CPUE4 (kg/nm trawling): over minimum catch size**
B_{MSY}	15790 (9309 - 26784)	9443 (4580 - 19472)	11061 (6160 - 19861)	9652 (4550 - 20472)
F_{MSY}	0.15 (0.11 - 0.21)	0.27 (0.14 – 0.52)	0.23 (0.15 – 0.34)	0.27 (0.14 - 0.52)
MSY	2394 (1817 - 3153)	2565 (2043 - 3219)	2490 (1885 - 3288)	2588 (2018 - 3318)
K	31676 (18693 - 53677)	18978 (9201 - 39147)	22204 (12358 - 39894)	19406 (9141 - 41201)
Criteria fulfilment	All (1-7)	All (1-7)	1,2,4,5,6,7	1,2,4,5,6,7

Index CPUE2 and CPUE4 had similar values for all reference points, while CPUE1 and CPUE3 differed from the others (Table 6). There was no difference in F_{MSY}, a few tons difference in MSY and a 209 tons difference in B_{MSY} between CPUE2 and CPUE4. Survey index CPUE1 was the most different from the others, while CPUE3 had values situated between CPUE1 and CPUE2 and CPUE4. Two of the four assessments fulfilled the criteria for accepting the SPiCT results. The CPUE1 and CPUE2 fulfilled all criteria, while CPUE3 and CPUE4 met 6 out of 7 criteria. The two latter did not meet criteria 3 for the survey index's Shapiro p-value test (normality test). Detailed results are found in appendix D.

The survey index used for SPiCT modelling should be based on the same measure of quantity as the fisheries statistics (M. W. Pedersen & Berg, 2017). In addition, it should be based only on the part of the stock targeted by fisheries. Because of this, it was correct to use CPUE4 based on biomass (weight) for individuals over minimum catch size. Therefore, the rest of the chapter shows results for the SPiCT assessment with index CPUE4.

SPiCT estimated a positive trend for halibut biomass development throughout the time series (Figure 18). The halibut stock was low in 1977, with a slight negative trend in the first few years. The biomass development was flat afterwards, until around 1995 when a slight increase appeared. The stock grew gradually faster, reaching a near-linear biomass growth from around 2005 until 2017. The stock size was above B_{MSY} from 2016-2019 before it dropped marginally to 98% of B_{MSY}. Uncertainty in the model predictions increased from the first year with survey data before it flattened out around 2015. The biomass was estimated to be 9496 tons at the end of 2021. The uncertainty for the absolute biomass was approximately 2/3 higher than the uncertainty for the relative values. The development for 2022 was based on simulations with the ICES MSY 35th hockey-stick advice rule and did not represent actual development for 2022 (this applies to all SPiCT plots). With the management strategy, biomass was expected to reach reference point B_{MSY} in 2022/2023.

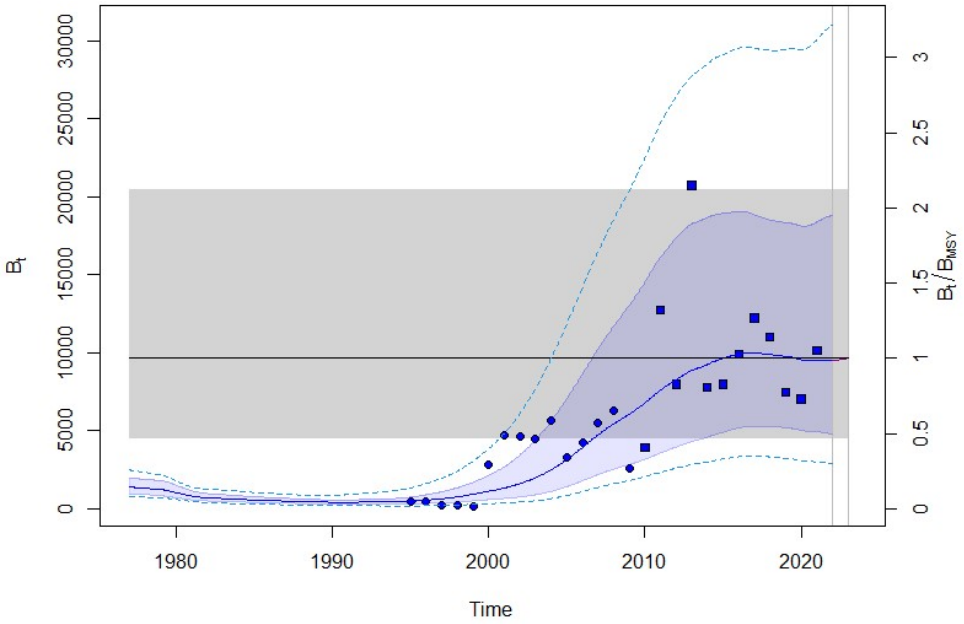

Figure 18 – Estimated biomass development for the Norwegian Atlantic halibut stock north of 62°N. Absolute biomass (B_t) and relative biomass (B_t/B_{MSY}) estimates are shown by the blue line. The dashed blue line shows absolute quantities within a 95% confidence interval (CI). The shaded blue region shows relative quantities within 95% CI. Estimated B_{MSY} marked by the black line, with grey shaded area marking 95% CI. Round blue dots show converted data from the survey 1995-2009, and squared blue dots show converted data from the survey 2010-2021. The grey vertical line in 2021 marks the end of the input data range, and beyond the line are predictions.

The results from the SPiCT modelling displayed a large variation in fishing mortality throughout the time series (Figure 19). The initial fishing mortality was approximately double the estimated F_{MSY} and rose even higher in 1980. From that point onwards, it gradually reduces until around 2004. From around 2002-2018, the fishing mortality was below the estimated F_{MSY}. Fishing mortality has been slightly above F_{MSY} for the last three years. The fishing mortality was estimated to be 0.29 at the end of 2021. The chosen ICES management strategy reduced F below F_{MSY} in the forecast period 2022. Uncertainty for absolute fishing mortality was estimated to be considerably more significant than the uncertainty for relative fishing mortality.

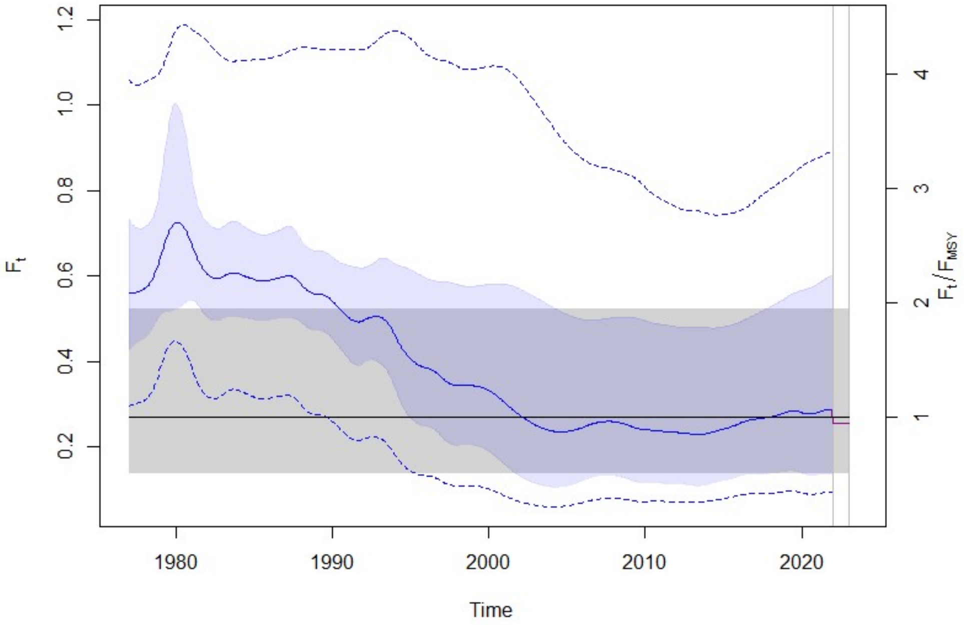

Figure 19 – Estimated fishing mortality estimates for the Atlantic halibut stock north of 62°N. The blue line shows absolute fishing mortality (F_t) and relative biomass (F_t/FMSY). Dashed blue lines show absolute quantities within 95% confidence interval (CI). The shaded blue region show relative quantities within the 95% CI. Estimated F_{MSY} is marked by the black line, with grey shaded area marking the 95% CI. The grey vertical line in 2021 marks the end of the input data range, and beyond the line are predictions.

The estimated landings from SPiCT were smoother than official landings (Figure 20). The uncertainty of the estimates was around the values of official landings and increased for the last five years as landings displayed greater variation. Reference point MSY at 2588 tons was surpassed in 2016. The lowest value within 95% CI was reached in 2012, while landings still have not exceeded the upper limit of the CI. Landings were reduced to 2424 tons in the forecast period 2022 based on simulations with the ICES MSY 35th hockey-stick advice rule.

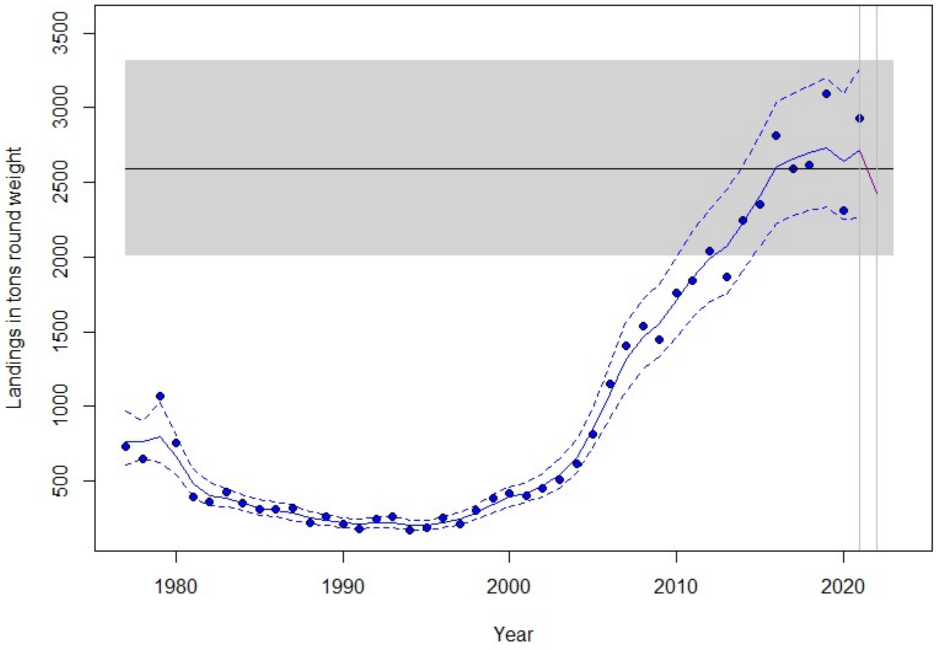

Figure 20 – Plot showing observed landings (blue dots) and estimated landings (blue line) for the Norwegian Atlantic halibut stock north of 62°N. The dashed blue line indicates uncertainty for the estimated landings within 95% CI. The black horizontal line indicates estimated MSY, with the grey region indicating uncertainty 95% CI. The grey vertical line in 2021 marks the end of the input data range, and beyond the line are predictions.

The Kobe plot showed that the halibut stock has been in the red state for large parts of the time series (Figure 21). The combination of low stock biomass and fishing mortality substantially over F_{MSY} resulted in a stock decline in the upper left red corner. The state changed when fishing mortality dropped below F_{MSY} halfway into the time series. The development towards the right side indicated that the stock size increased until it entered the green area. In 2020, fishing mortality increased above F_{MSY}, reducing the stock size. The stock briefly entered the second yellow field before it moved back into the red area in 2021. Stock development for 2022 was expected to move from the red area to the lower left yellow field, based on simulations with the ICES MSY 35th hockey-stick advice rule.

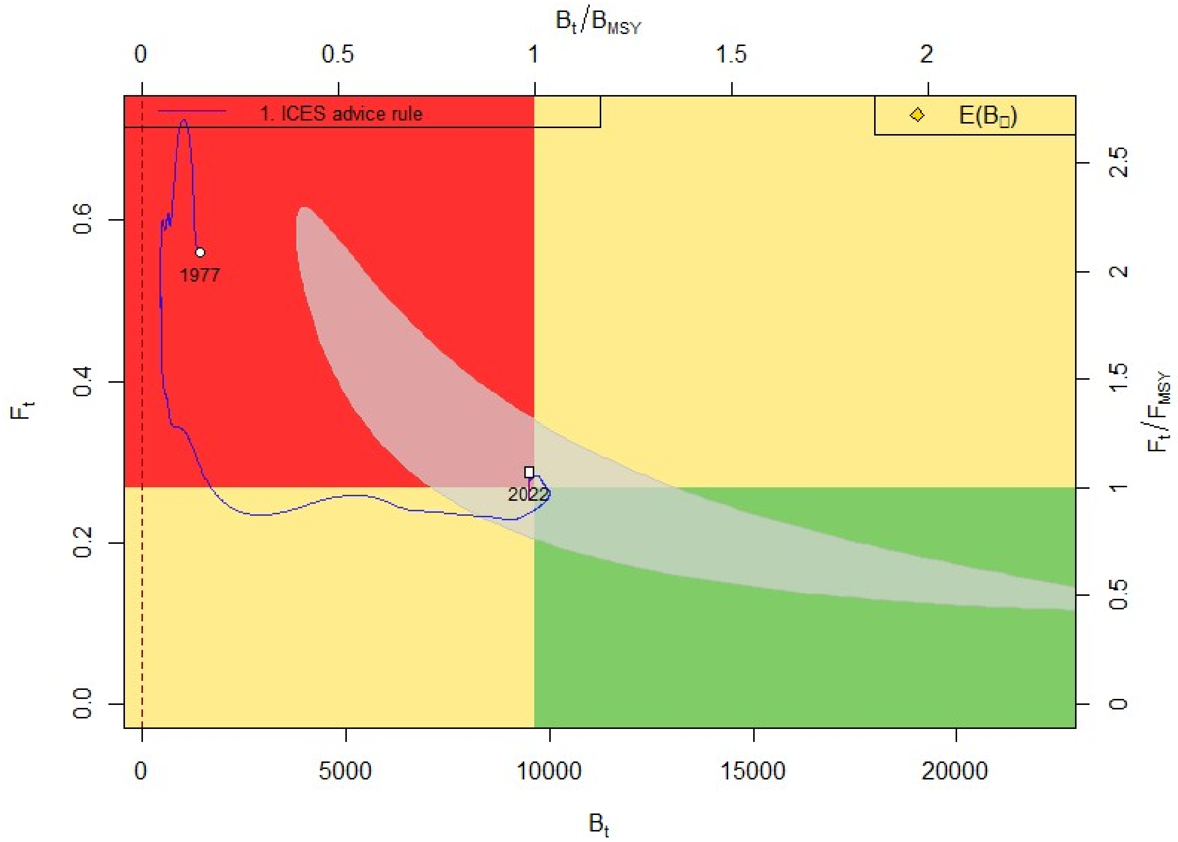

Figure 21 – Kobe plot showing the development of the Norwegian Atlantic halibut stock north of 62°N from 1977-2021 with biomass and fishing mortality in absolute and relative values. The plot is divided into four by B_{MSY} and F_{MSY}. The red area indicates biomass under B_{MSY} and fishing mortality over F_{MSY}, meaning biomass is too low, and fishing mortality is too high. The yellow area in the bottom left corner indicates low biomass and acceptable fishing mortality. The yellow area in the upper right corner indicates acceptable biomass and too high fishing mortality. The green area indicates biomass is above B_{MSY} and fishing mortality is below F_{MSY}. The shaded grey area indicates the 95% confidence region of the pair F_{MSY} and B_{MSY}. The black dotted vertical line indicates the biomass level at which the stock is depleted.

The stock had low initial biomass on the left-hand side of the production curve in 1977 (Figure 22). The development was negative for some years, with the lowest estimated values in the 1980s and almost all of the 1990s. The negative trend showed a low stock size and net biomass production. The observations began to move up along the curve from 1999, with a relatively large distance between each observation. Both stock size and net biomass production were increasing. The production flattened from around 2010. The stock was located slightly on the right side of the production curve maximum in 2016-2019 before moving back to the left side. All the observations were found on or close to the line of the production curve.

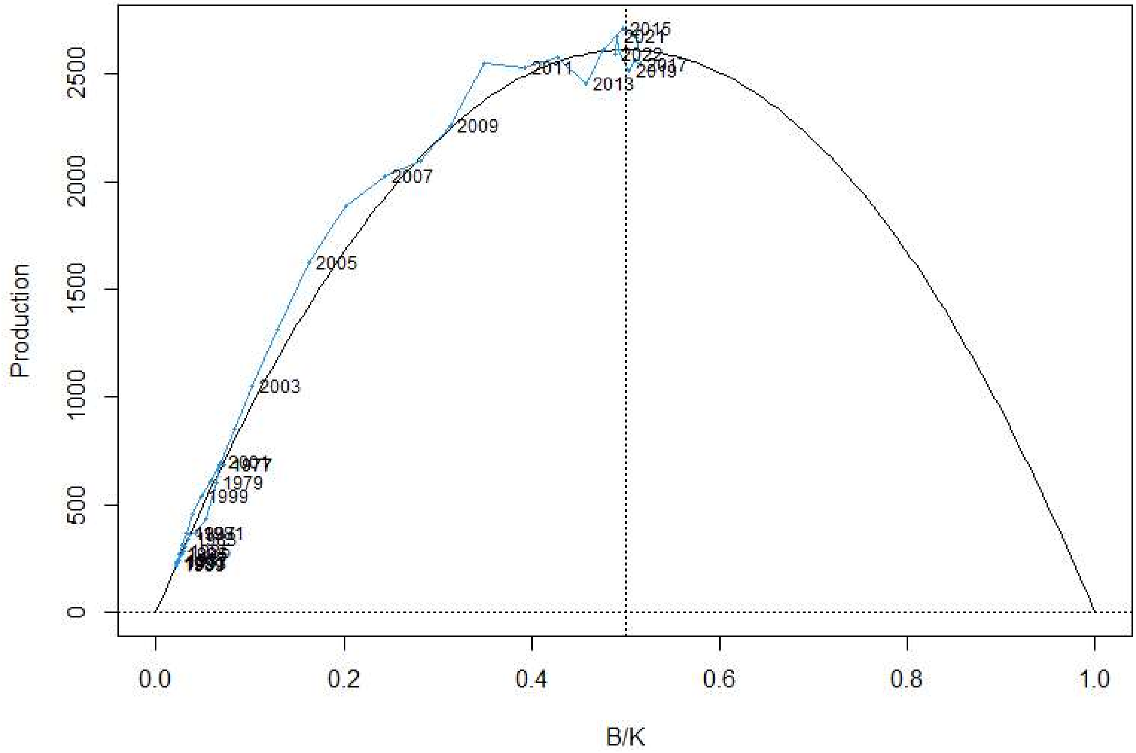

Figure 22 – Production curve for the Norwegian Atlantic halibut stock north of 62°N showing the dome-shaped relationship between net biomass production and the stock size B/K, where B is the stock size in biomass, and K is the carrying capacity for the stock. The blue line indicates the model-estimated halibut landings north of 62°N. Every second year is marked with text and small blue dots. The vertical dotted line indicates B_{MSY}, at the peak of the production curve.

The SPiCT with ICES MSY 35th hockey-stick advice rule suggested a TAC of 2424 tons for 2022 (Figure 23). This TAC suggestion included reducing the relative fishing mortality F/F_{MSY} to 0.94, while the relative biomass B/B_{MSY} was estimated to be at 1.

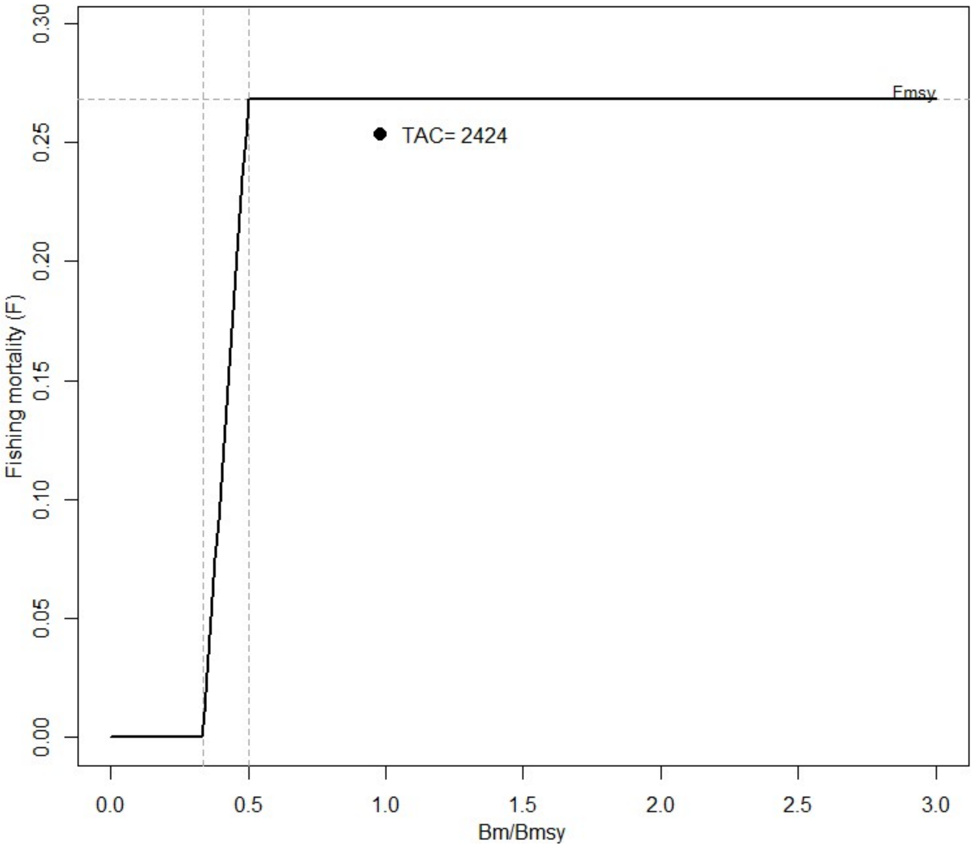

Figure 23 – ICES MSY 35th hockey-stick harvest control rule for the Norwegian Atlantic halibut fishery north of 62°N. Fishing mortality is reduced from F_{MSY} when the B/B_{MSY} ratio is between 0.5 and 0.35. Fishing mortality is terminated if B_t/B_{MSY} is reduced below 0.35.

3.5 Scenarios with tourist- and recreational fisheries

The SPiCT estimates increased proportionally with increased landings (Table 7). Values for biomass estimates and MSY increased by 20% in scenario 2 and 40% in scenario 3 compared to the original numbers. The same was for the confidence interval for estimated B_{MSY} and MSY, where the range increases by 20% and 40%, respectively. There was no change in F_{MSY} values for either scenario.

Table 7 – Scenarios with tourist and recreational fisheries for Atlantic halibut in Norway north of 62°N latitude run in SPiCT by increasing landings by 20% (scenario 2) and 40% (scenario 3). Estimated biomass B_t and fishing mortality F_t for the end of 2021. MSY, B_{MSY} and F_{MSY} estimated by SPiCT Including uncertainty within a confidence interval (CI) of 95%. Landings for 2021 included (not estimates). All scenarios based on CPUE4 composed of weight for individuals above the minimum catch size (60 cm in 1995-2009, 80 cm from 2010).

Reference points (Min/max CI 0.95)	**Scenario 1: Official landings (CPUE4)**	**Scenario 2: 20% higher landings (CPUE4)**	**Scenario 3: 40% higher landings (CPUE4)**
B_{2021}	9496	11395	13295
B_{MSY}	9652 (4550-20472)	11582 (5460 - 24566)	13512 (6370 - 28661)
F_{2021}	0.29	0.29	0.29
F_{MSY}	0.27 (0.14 - 0.52)	0.27 (0.14 – 0.52)	0.27 (0.14 – 0.52)
Landings 2021	2934	3520	4107
MSY	2588 (2018 – 3318)	3105 (2422 - 3982)	3623 (2826 – 4645)

3.6 DLMtool

The DLMtool estimated the range of TAC and median TAC differently for each MP (Figure 24). The median TAC estimates ranged from 1002 to 2971 tons. MCD and AvC had the two lowest estimates, with approximately the same results, while ICI estimated the highest median TAC. A short description of the MPs and information about input data and results (including standard deviation (SD) range) are found in Table 8.

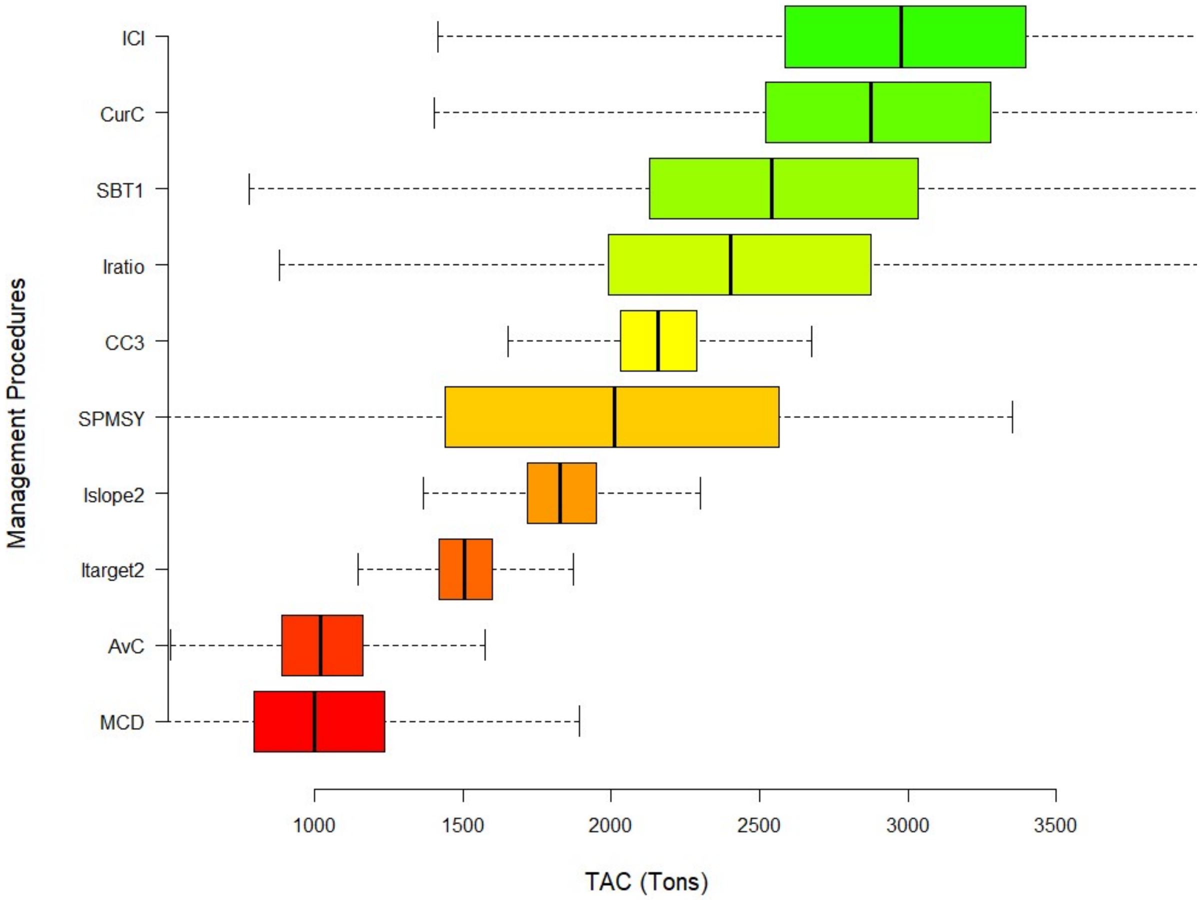

Figure 24 - Management procedures (MPs) and their estimates of total allowable catch (TAC) for Atlantic halibut in Norway north of 62°N latitude presented in a box plot. The results are based on 10000 simulations for each MP. The box represents the middle 50% of the data (the interquartile range (IQR)). 25% of the data is above and below the median line. The whiskers show the range of the data.

Table 8 – TAC MPs results (with standard deviation (SD) range) from DLMtool for Norwegian halibut north of 62°N latitude. The table also includes a short description and information about input data based on the documentation for DLMtool R-package found using the "Help"-function and in Github (Carruthers et al., 2022).

TAC MPs	**Description**	**Input data**	**Result in tons (SD)**
ICI	TAC is adjusted (1.05x up, 0.75x down or constant) by the survey index value compared to the upper and lower level of the standard error for the mean survey index time series.	Catch, index	2971 (617)
CurC	TAC is equal to last year's catch.	Catch	2878 (586)
SBT1	TAC is based on index levels relative to target BMSY/B0 and catch levels relative to MSY. Incremental adjustments are made based on the trend in CPUE.	Catch, index	2535 (709)
Iratio	TAC equals last year's catch multiplied by a factor alpha, composed of a numerator of the mean index in the most recent two years of the time series and the denominator being the mean index in the three years prior to those in the numerator.	Catch, index	2401 (683)
CC3	TAC is the average historical catch from recent 5 years, multiplied by 0.8.	Catch	2158 (194)
SPMSY	TAC is based on a Schaefer surplus production model. The MP uses catch, stock depletion, carrying capacity k and population growth r. The MP calculates the factors r and k by using life history parameters. This is possible as only a few k-r combinations can maintain the stock within the MSY range.	Catch, length at 50% maturity (L50), max age, stock depletion, von Bertalanffy K, von Bertalanffy L_{inf}, von Bertalanffy t0	2014 (703)
Islope2	TAC is incrementally adjusted to maintain a constant CPUE or relative abundance index. Reference TAC is 0.7 average catch.	Catch, index	1827 (175)
Itarget2	TAC is incrementally adjusted to reach a target CPUE / relative abundance index. Reference TAC is 0.7 average catch.	Catch, index	1503 (134)
AvC	TAC is set at the average historical catch.	Catch	1016 (209)
MCD	TAC is based on the average historical catch multiplied by an estimate of current stock depletion and the constant 2.	Catch, stock depletion	1002 (335)

The 100000 simulations for the ten TAC MPs showed TAC estimates between 0-5999 tons (Figure 25). Around a quarter of the simulations, the MPs estimated a TAC between 1500-1999 tons, closely followed by TAC between 2000-2499 tons. TAC interval 1000-1499 tons was the third most, with around 17% of the total, while TAC between 2500-2999 tons was the fourth, with around 15%. TACs between 500-999 tons and 3000-3499 tons made up ~10% of the simulations each. A smaller share of the simulations estimated a TAC below 500 tons and above 4000 tons.

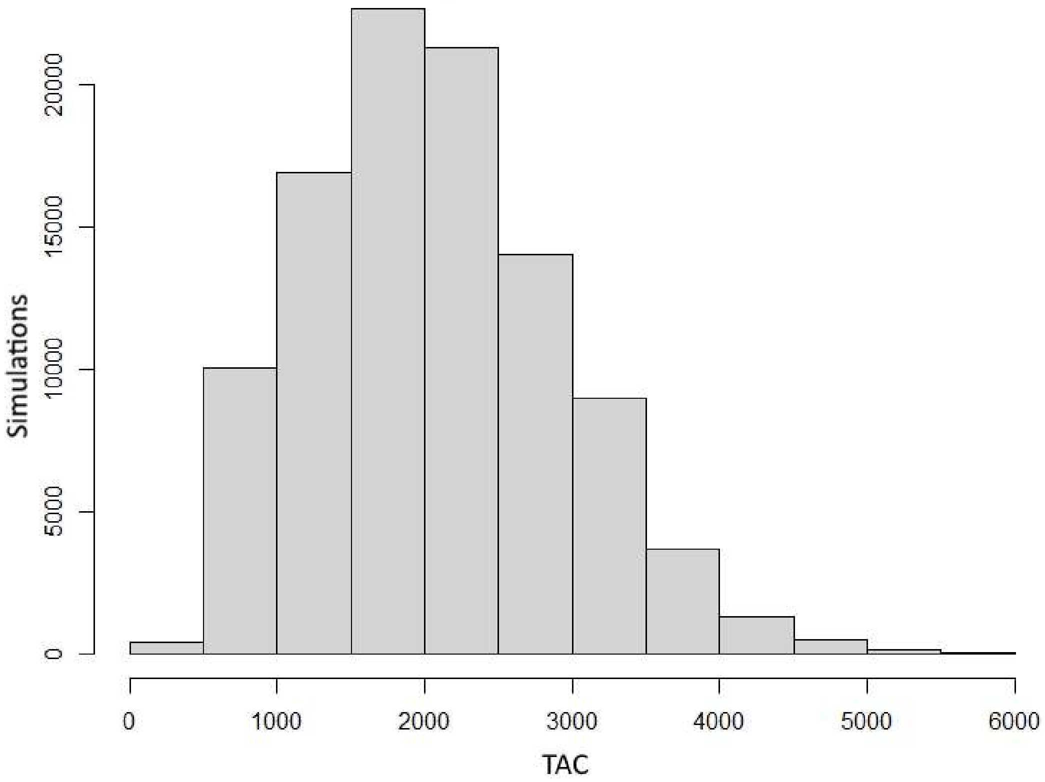

Figure 25 – Distribution of TAC estimates for the ten MPs applying the DLMtool for Norwegian Atlantic halibut north of 62° latitude. Results are based on 10000 simulations with the ten MPs.

Four MPs based on size selectivity (SL) were identified as feasible for the halibut dataset (Table 9). The goal of MP minlenLopt1 was to maximise the stock biomass, while the other three aimed to ensure that enough individuals mature and spawn before being captured by the fleet. The four models estimated length at 5% retention (LR5) to 90-99 cm and length at full retention (LFR) to 95-106 cm. The MPs matlenlim2 and slotlim estimated the same LR5 and LFR values. The length at 5% retention (LR5) may be considered an estimation of minimum catch size. All estimated LR5 were above the legal minimum catch size of 80 cm. The MP slotlim estimated the maximum legal length (HS) to be 180 cm.

Table 9 – Feasible size selectivity (SL) management plans (MPs) for the Norwegian Atlantic halibut north of 62°N, with description and results. Results contain estimated length at 5% retention (LR5), length at 100% retention (LFR) and upper slot limit (HS). Description and input data are based on documentation for DLMtool R-package found by using the "Help"-function and in Github (Carruthers et al., 2022).

SL MPs	**Description**	**Input**	**Results**
matlenlim	Retention length in fishery set equivalent to the maturity curve.	Length at 50% maturity (L50)	LR5 90 LFR 95
matlenlim2	Retention length in fishery set 10% higher than the length-at-maturity.	L50	LR5 99 LFR 105
minlenLopt1	Minimum retention length set to a fraction of the length, which maximises the biomass. The goal is to restrict the catch of small fish and affect the length composition towards the optimal length for stock biomass and production.	Natural mortality M, von Bertalanffy K, von Bertalanffy L_{inf}, weight-length relationship parameter b	LR5 95 LFR 106
slotlim	Retention length is set using a minimum and maximum legal length. The maximum length is the 75th percentile between the estimated minimum legal length and the estimated asymptotic length L_{inf}.	L50, von Bertalanffy L_{inf}	LR5 99 LFR 105 HS 180

4 Discussion

The outcome of this thesis provides insight into the Norwegian halibut stock north of 62°N. The results should be interpreted cautiously, as they are based on a data-limited approach. This discussion starts with reflecting on the input data used in the stock assessment, followed by discussions about the SPiCT results (SO1) and DLMtool results (SO2). Then the effects of tourist- and recreational fisheries are evaluated (SO3). The stock status (SO4) is assessed as a natural part of the three preceding sub-chapters. After reflecting upon potential limitations, sources of error, and other considerations, a management advice for the stock is suggested (SO5). The chapter ends by evaluating future perspectives for this work.

4.1 Input data

The survey was not designed to monitor the development of the halibut population. Because of this, Høines et al. (2009) pointed out that great caution should be exercised in interpreting the survey data. Length and weight plots (Figure 10 and Figure 11) showed that a large proportion of halibut caught in the survey was below the minimum catch size. Results showed an increase in large halibut at the last part of the time series, implying more large individuals. If true, that was a good sign for the stock's ability to maintain sustainable production.

Information about the stock development may be retrieved from the indices. Even though the indices CPUE1 and CPUE2 were considered unsuitable for the assessment, they provided valuable information about stock development. CPUE1 had an increase in the number of halibut until 2016 (Figure 12). This probably indicated increased recruitment of small halibut. The increased recruitment was expected to be from small halibut, as the CPUE2 (individuals over minimum catch size) showed a flat development from around 2010. The rise seen in the two weight-based indices CPUE3 and CPUE4 (Figure 13) was partly expected to be based on halibut previously recruited in the time series that had survived and grown large. It was clear by comparing CPUE3 and CPUE4 that most biomass came from large halibut. At the same time, there was a more significant difference between the two indices at the end of the time series, reflecting the increased number of small halibut. In other words, it may seem that the recruitment varied, with some stronger years. When the stronger year classes grew, some survived to increase the spawning biomass and recruitment.

The survey indices increase was more rapid than in the reported landings. The difference could be explained by the fact that few fishermen were fishing directly for halibut after a long period with a depleted stock. Most landings in this period could be bycatch from other fisheries. Bycatch from other fisheries was expected to come from other areas and periods than where direct fishing for halibut would have taken place. The situation meant that the bycatch did not reflect the stock increase. Gear used in other fisheries had a deviating selection of halibut compared to fishing gear designed for halibut as target species. When the halibut stock began increasing, the fishing may have occurred with another effort than seen in the surveys. Then it probably took time before enough fishermen started fishing directly for halibut on a scale, leading to significantly increased landings.

The survey indices increased or maintained a relatively stable development despite the growth of landings. This development could be explained by the increase in the minimum catch size in the middle of the time series. Had the minimum catch size of 60 cm remained unchanged for the entire time series, one could expect a more significant increase than in the index (CPUE4). The stock may thus have been in a better condition than reflected in the index in the years after the minimum catch size increased. On the contrary, the stock and the index could have experienced a more significant reduction during the later period if individuals between 60 and 80 cm were caught with high fishing effort. This change may not have been that important since the indices reflected the fishable part of the stock throughout the time series.

The landings statistics indicated a significant development for the halibut stock north of 62°N from 1977-2021. Around 90% of the total halibut landings in the assessed period came from areas north of 62°N (Figure 16). However, historically the stock had sustained relatively large fisheries along larger parts of the Norwegian coast (Haug, 1984). The current halibut stock has grown considerably since the depletion but cannot be expected to produce the same yield as seen historically. This applies unless a similar trend in the stock is seen further south or the carrying capacity in the northernmost area has increased over time.

4.2 SPiCT estimates

Using four different indices demonstrated how different input data could affect SPiCT estimates. The effects of indices' values and trends were seen in the biomass estimates B_{MSY} and K (Table 6). SPiCT estimated higher reference points for indices including all size classes in the stock (CPUE1 and CPUE3) compared to indices covering the fishable part of the stock (CPUE2 and CPUE4). Likewise, CPUE1 and CPUE2, which had the most significant trend differences, deviated most from each other in biomass estimates. The deviation demonstrated the importance of using the most suited index for stock assessment. At the same time, MSY was estimated to be relatively similar when using the four survey indices. Thus, MSY was less affected by indices and more by landings. The variation seen for F_{MSY} can be explained by the different relations between estimated MSY and biomass size, as fishing mortality describes how large a fraction of the stock was fished. Comparing SPiCT results with different indices showed the importance of correct input data in the assessment.

The CPUE3 and CPUE4 only partly fulfilled criteria 3, as results for the Shapiro-Wilk normality test for the index were significant (Table 6 and appendix D). Deviation from criteria 3 did not necessarily mean that the model results were invalid, but rather that the results should be examined further (Table 4). Non-normal residuals may be caused by extreme outlying observations (M. W. Pedersen & Berg, 2017). Outliers were especially the case in 2013, which deviated significantly from the trend. The same extreme observations were not found in CPUE1 and CPUE2, which fulfilled the criteria. The cause for the criteria 3 violation was thus considered to be known. The fact that the dataset contained a few large individuals with a significant impact on the index value led to great variation between years. The lack of non-normal distribution was not expected to be decisive for the results of this stock assessment. Acceptance of similar issues for other data-limited species (ICES, 2022a) strengthened this argument. Based on that, CPUE4 was considered the appropriate index for the SPiCT assessment.

The biomass trend was very stable compared to the survey observations (Figure 18). Stability indicated that SPiCT did not attach great importance to individual observations but rather trends in indices and landings. In addition, the relative values from SPiCT had a considerably lower uncertainty range than the absolute quantities. According to the SPiCT creators M. W. Pedersen & Berg (2017), relative values are also less affected by biases in the data. The model was thus better able to assess the condition of the stock rather than to calculate the exact current levels and reference points. As a result, the relative values should be the primary basis for evaluating the stock condition and when developing management decisions, as also concluded by M. W. Pedersen & Berg (2017).

The biomass development revealed a recovering halibut stock (Figure 18). The stock was practically depleted in the first part of the time series. There was no information from the survey before 1995, so biomass development before that should be given limited attention. The increased uncertainty seen with the survey's introduction was believed to be caused by inconsistent values and trends for survey and landings, as stated as a common issue by the

SPiCT creators (M. W. Pedersen & Berg, 2017). High uncertainty for biomass estimates should be noted. The positive trend brought the biomass to desired levels above B_{MSY} from 2016-2019. The subsequent biomass decrease slightly below B_{MSY} was probably caused by the fact that the recruitment no longer compensates for the increased fishing pressure.

The production curve is the core of the surplus production model SPiCT. The estimations showed clearly how the stock recovered. The small initial biomass maintained a small production, and the fishing at the start of the period was higher than this production, causing biomass decline. The decline reduced production further, worsening the state of the stock. When fishing was reduced below the production level, it had a great positive effect on the stock. Facilitation for biomass recovery drastically increased yield and the stocks' ability to recover. The stock has stabilized around the top of the production curve in recent years, which indicated optimal biomass size and production for long-term utilization.

Observations were only found on the left side of the production curve, which made it hard for the model to estimate MSY levels. The reason is that a recovering stock's carrying capacity is hard to determine. Only an unfished stock (at carrying capacity) can be investigated to determine a precise carrying capacity (Bouch et al., 2021). Therefore, the carrying capacity for the halibut stock could deviate from the estimate, thus displacing B_{MSY} and the production potential. Because the production curve was dependent on the stock size and carrying capacity, MSY could be found at a higher level (Schaefer, 1954). The model estimates were used, as there was no evidence of higher biomass reference points.

The estimated F_{MSY} of 0.27 and F_{2021} at 0.29 seemed too high for a long-lived species such as halibut. This level was higher than most natural mortality M (0.18-0.27) found for halibut off the east coast of North America (den Heyer et al., 2013). These values were again high compared to M 0.1 used for halibut stock assessment in Canada (Trzcinski et al., 2011, as cited in den Heyer et al., 2013). Using an index covering the fishable size classes (CPUE4) caused high SPiCT estimates, as landings comprised a larger proportion of the biomass estimate. The fishing mortality for the total halibut stock was thus lower. A rule of thumb is that F_{MSY} equals natural mortality (Zhou et al., 2012). Consequently, the F_{MSY} of 0.15 estimated with CPUE1 was believed to be plausible for the halibut stock when including all size classes. The absolute fishing mortality estimates were uncertain (Figure 19) and, therefore, not emphasized in further assessment.

The fishing mortality underwent a downward trend stabilizing around F_{MSY} (Figure 19). Even a small harvest made up a significant proportion of the stock at the start of the time series, causing major overfishing. The lack of survey data before 1995 made fishing mortality estimates more uncertain than they appeared. Fishing mortality was slightly above the reference point F_{MSY} at the end of the assessment. From a precautionary approach perspective, F_{MSY} is considered a limit rather than a management goal (Horbowy & Luzeńczyk, 2012). Subsequently, the fishing mortality was too high and must be reduced to ensure a sustainable stock close to MSY.

Landings above MSY are a sign of overfishing (Martell & Froese, 2012). Given the uncertainty in the MSY estimate, it may be that MSY was reached already in 2012 (Figure 20). If that was the case, landings after 2012 were above MSY and subsequently contributed to the overfishing of the stock. On the other hand, the MSY uncertainty may indicate that the optimal yield is yet to be reached in the fishery. At the same time, we know that the fishing effort has increased substantially in the last few years (Fiskeridirektoratet, 2022). More boats have joined the fishery, and new technology like drum longlines have been introduced, drastically enhancing the fleet's fishing capacity (technological creep (Marchal et al., 2007)). The catch per unit effort (CPUE) in the fishery was expected to be decreasing. The survey index CPUE4 indicated a negative trend for four of the five last years. Stable or decreasing CPUE is a sign of a stock below 0.5 of the carrying capacity *k* (Martell & Froese, 2012). This was another indication that the stock could be overfished, and fishing mortality should be reduced and kept low until a clear increase or stabilization in the index is seen.

Empirical evidence showed that halibut is sensitive to overfishing. Historical landing statistics (Figure 3) show that increased landings over time were followed by reduced yield. The same patterns were found for the species on the east coast of North America (Shackell et al., 2021; Trzcinski & Bowen, 2016). According to Bell & Pruter (1958, as cited in Haug, 1990), this pattern (increased fishing effort and yield reduction) was so consistent for halibut fisheries that future fishery may be predicted from its history. The development seen for the halibut fishery is common for open-access fisheries. Fishermen increase their effort to maximize their profit but deplete the stock and become losers themselves (Berck, 1979; Berkes, 1985). This case is known as the “Tragedy of the Commons” (Hardin, 1968). To avoid this classical scenario, one must manage the fishery to reduce the effort (Berkes, 1985; Hardin, 1968).

It was stated in the introduction that the halibut stock may be considered a data-limited ICES category 3 stock. However, as the halibut stock has been evaluated and fulfilled the technical criteria for accepting the SPiCT assessment in this thesis, the stock should be upgraded. The halibut stock should be considered category 2 stock, and the advice provided should be based on the ICES MSY approach for category 2 (ICES, 2022c, 2022d). The halibut stock could later be upgraded to category 1 if a stock-specific MSE is performed to provide the best harvest control rules. A final acceptance of the SPiCT assessment requires peer reviewing. Nevertheless, it was assumed that the SPiCT criteria were met in this thesis.

ICES MSY 35th percentile hockey-stick rule was recommended for halibut management as the stock fulfilled the requirements for the ICES category 2 MSY approach (ICES, 2022c). The harvest rule required reduced fishing mortality and yield for the coming period (2022). The reduction allows the stock to rebuild to B_{MSY} so that landings can be increased to MSY again. Alternatively, continuous overfishing may bring the biomass so low that the ICES hockey-stick rule calls for a drastic reduction in fishing mortality. Given that the SPiCT assessment provides the correct stock status, a slight reduction in TAC compared to MSY is also rational in a precautionary approach.

The proposed management actions will bring the stock to B_{MSY}. Pacific halibut in the US and Canada has been managed efficiently for 90 years (Gates, 2005). At the same time, it is important to be aware that management actions may not have the intended impact on the stock. Management actions with a positive effect in one place may not necessarily work elsewhere. It should be expected that results from management actions may take several years to observe (Trzcinski & Bowen, 2016).

Fluctuations are expected in a natural population influenced by numerous unknown factors, especially for a surplus production model not considering individual processes like recruitment and individual growth (Pella & Tomlinson, 1969). The relative biomass level indicated a stock in good condition that can probably be returned to the reference point level with minor management adjustments. However, it did not rule out that slightly unfavourable values could indicate a diminishing stock. Even though the stock was expected to be above a size which requires drastic measures, it would be wise to incorporate more precaution in the advice, given the uncertainty associated with the estimates.

SPiCT may be optimistic compared to other assessment methods. A study by (Bouch et al., 2021) found that SPiCT tends to overestimate relative biomass and underestimate relative fishing, resulting in an overly optimistic assessment. This contrasted with the findings of Mildenberger, Berg, et al. (2022) and M. W. Pedersen & Berg (2017), which did not indicate such biases in SPiCT. Whether SPiCT tends to overestimate may therefore be difficult to decide. It is, however, found that SPiCT gives higher advice than most empirical rules (ICES, 2023). Changing from trend-based to assessment-based advice may result in differences, as trend-based advice often includes highly precautionary rules. Hence, it may be several reasons that SPiCT assessments result in higher advice than other methods. Nevertheless, if the SPiCT assessment is accepted, advice should follow from it (ICES, 2023). Higher estimates do not necessarily mean that SPiCT overestimated the fishing opportunities.

4.3 DLMtool estimates

If the SPiCT assessment is not accepted later, the DLMtool analyses provided category 3 advice based on an empirical approach. The DLMtool found 14 feasible MPs for the halibut, of which 10 MPs provided TAC and 4 MPs provided size selectivity suggestions. The program proved to be a simple and time-effective way of producing MPs and comparing their results. They thus constituted a less demanding alternative to more complex stock assessments like SPiCT. The results and credibility of the 14 MPs will now be discussed to determine their relevance for the halibut stock assessment.

Four TAC MPs can be ruled out for use in the management advice based on their simplicity and input data. The simplest MPs were based on historical landings (Table 8), and the lacked important parameters like abundance index, life history traits and MSY consideration (Geromont & Butterworth, 2015). The development of landings alone did not necessarily say anything about the status and development of the stock. Even though the MCD included current stock depletion in addition to the average catch, it was also considered too simple compared to the other available MPs. The MPs AvC, MCD, CC3 and CurC were thus considered irrelevant.

The MPs Islope2 and Itarget2 may not be optimal for use in halibut management. Relatively simple MPs are often trade-offs between lower yield and higher biological risk (Carruthers et al., 2016). The authors found that Islope2 and Itarget2 had a high degree of precautionary approach, resulting in a high probability of maintaining sustainable biomass but a low chance of providing catches at the MSY level. Even though the MPs Islope2 and Itarget2 were expected to keep the halibut stock out of depletion risk, they were ruled out as they probably led to sub-optimal utilization of the halibut stock.

The four TAC MPs SPMSY, Iratio, SBT1 and ICI remained relevant to use on the halibut stock. These were more advanced than those ruled out, and they all include some of the important parameters like abundance index, life history traits, production models and MSY considerations. SPMSY provided the lowest TAC. The low estimate could be explained by the fact that SPMSY generally estimated a higher biomass threshold and lower fishing mortality threshold than other models (Martell & Froese, 2012). Because the estimates were based on conservative calculations, the same reasoning for Islope2 and Itarget2 may apply to SPMSY. However, the model was more robust and was thus considered relevant. Iratio and SBT1 provided estimates close to SPiCT, which seemed reasonable, given that the SPiCT assessment was correct. ICI estimated the highest TAC of all the MPs, with an estimate above 2021 catch level. The ICI estimate could be regarded as high, especially given the uncertainty and development in the SPiCT assessment. The four relevant MPs provided a TAC estimate between 2014-2971 tons, relatively similar to SPiCT's MSY uncertainty range. The TAC simulation peak in the histogram (similar to Figure 25) was around 2500 tons for the four MPs. The DLMtool could thus be said to have provided similar but somewhat higher estimates than the more complex SPiCT assessment.

MPs have varying performance depending on the stock's characteristics and status (Carruthers et al., 2016). Evaluating the MPs' performance through MSE in the DLMtool is a commonly used method (Carruthers et al., 2014, 2016; Carruthers & Hordyk, 2020; Geromont & Butterworth, 2015; Harford & Carruthers, 2017; Jardim et al., 2015; Martell & Froese, 2012; Punt et al., 2016). This could provide informative results if adapted to the halibut stock and fishing fleet. Without specific performance testing, it is hard to develop appropriate management. However, general MSE has revealed the characteristics of some of the MPs, which indicate how they might perform for the halibut stock. Iratio was efficient at stabilizing landings and biomass at a recent level but may not be suitable for a stock in recovery (Jardim et al., 2015). It may therefore suit the halibut stocks' current situation. SBT1 often needed tuning to the specific stock to perform well (according to the help section for DLMtool, T. Carruthers et al., 2022) but then had high chances of achieving MSY (Jardim et al., 2015). Even though the SBT1 were not tuned to the stock in question, they produced plausible results. The ICI was found to give high and consistently sustainable results by reducing TAC more with a downward index trend than increased with a positive trend

(Jardim et al., 2015). This explained the high estimates for the halibut, which may be sustainable given the design of the MP. Even though the results were not examined, using the models together as this could contribute to supporting results from other methods like SPiCT.

All four MPs (matlenlim, matlenlim2, minLenLopt1, slotlim) estimated length restrictions larger than the legal minimum catch size of 80 cm (Table 9). LR5 (length at 5% retention) indicated the length at first catch for the fleet and could be considered the same as the minimum catch size. Therefore, it was conceivable that the minimum catch size should be higher to better suit the halibut stock's life history traits. For species with strong sexual dimorphism, a minimum size limit should be considered for the larger and later maturing sex (Froese et al., 2016). The stock would be better protected against overfishing, as most individuals have spawned and contributed to the future biomass before being caught. If not, fewer individuals of female halibut can mature and reproduce. The minimum catch size in US Fisheries is 104 cm (41 inches) (NOAA, 2022a, 2022b). Increasing the minimum catch size may be reasonable based on the arguments above. The estimated LR5 of 90-99 cm seemed sensible, but considering female length-at-maturity may speak for a higher minimum catch size around LFR of 106 cm.

Higher landings and biomass can be obtained by increasing the minimum catch size (Beverton & Holt, 1957, as cited in Froese et al., 2016). The highest biomass for a year class in the stock is determined by the species' growth characteristics and mortality (Cardinale & Hjelm, 2012; Hordyk et al., 2015). Reducing fishing mortality for small individuals by increasing the minimum catch size close to a length where a year class has its maximum biomass will theoretically achieve the highest possible biomass and production in a long-term perspective. It allows the fish to achieve more of its growth potential before being caught. An important factor to consider is that gillnet constitutes around half of the halibut landings (Fiskeridirektoratet, 2022) and has full selection above 100 cm (Erik Berg, personal communication, 26. January 2023). Therefore, large proportions of the landings are already in the upper tier of the proposed minimum catch size. Consequently, it is not given that the effect of increased minimum catch size would have a large impact on the halibut stock.

The MP slotlim also estimated a maximum catch size of 180 cm (Table 9). This estimate was lower than the existing maximum size limit of 2 meters set because of environmental toxins in large halibut (Høstingsforskriften, 2022, §51, letter F). A biological argument for setting a maximum catch size is that large female individuals are important for the spawning success of the stock, as larger female halibut have better egg quality than their younger counterparts (Haug & Gulliksen, 1988a). It should be noted that the maximum catch size length of 180 cm is based on a maximum theoretical length of 205 cm, while halibut over 3 meters are registered. The proposed maximum catch size was considered less relevant as exciting regulation had a comparable size restriction.

An increased minimum catch size will reduce TAC in a short-term perspective (Ailloud et al., 2018). The negative short-term effect can be reduced by stepwise implementing a higher minimum catch size. If so, fishing gear may need to be adapted to the new limitations, and it is important to consider the financial downside of several changes to fishing gear. The long-term effect of a well-reasoned increase in minimum catch size is expected to be positive (Ailloud et al., 2018; Froese et al., 2016). Implementing TAC and increasing minimum catch size in the US is believed to have contributed to recovering their Atlantic halibut stocks (Shackell et al., 2021; Trzcinski & Bowen, 2016).

Input control may perform better than output control regulations (for instance, TAC) for data-limited stocks (Walters & Martell, 2004, as cited in T. R. Carruthers et al., 2016). Adapting minimum catch size to halibut's life history traits may be as important as establishing a TAC. This claim was supported by the fact that halibut caught with rod and hook or longlines had high survivability when catch and release (C&R) were executed correctly (Ferter et al., 2017; Neilson et al., 1989), making it a powerful regulation. C&R may be especially relevant to tourist fishing, as the export quota for tourists limits the amount of fish they can bring home (Fiskeridirektoratet, 2022). At the same time, the halibut stock is sensitive to the level of fishing mortality, which minimum catch size is less effective at regulating (Neilson & Bowering, 1989; Trzcinski & Bowen, 2016). Therefore, input regulations alone may not be enough to ensure a sustainable stock size and MSY.

4.4 Effect of tourist- and recreational fisheries

Tourist- and recreational fisheries were added on top of the modelled results. It can be assumed that the stock biomass was higher than the modelling with official landings showed. The unknown factor was at which level this unreported fishing has been historically and how it has developed. Recreational and tourist fisheries have the potential to have a significant negative effect on a fish stock, especially locally (Cooke & Cowx, 2006). The catch pattern and fishing pressure may differ between tourist- and recreational fisheries and commercial fisheries. The scenarios were thus not considered fully representative. By increasing the landings by 20% and 40%, it became apparent that the stock had sustained larger landings than official numbers show.

Given the knowledge available for this thesis, the levels of tourist- and recreational fisheries were impossible to estimate. Nevertheless, it was assumed to be significant as halibut was a popular target species. These non-commercial fisheries were unlikely to reach 40% of commercial landings, which was considered an extreme scenario. More realistic was the estimate of 20% of commercial landings. Høines et al. (2009) outlined three possible situations for the historical development of tourist- and recreational fishing. The first situation was historically stable catches. This situation was not considered very plausible, as catchability and landings were expected to vary with the stock size. The second situation was catches and effort that varied correspondingly to the official landings. This situation was considered more realistic and was used for simulations. The third situation was something in between fixed landings and corresponding effort. This may be the most probable situation, but it was hard to simulate without knowing how the tourist- and recreational fisheries may have deviated from the commercial trend. Nevertheless, deviations from the commercial trend were expected, which affected the stock development in unknown directions.

4.5 Limitations and sources of error

The survey consisted of three sub-surveys, which complicated comparisons within the time series. Variations in the number of stations and the distance surveyed may have reduced comparability between years. The effect was considered minor, as the indices were standardized to abundance and biomass per nautical mile. The increased number of stations at the end of the time series was likely beneficial, as it covered more depths and locations.

The survey had a fixed station grid, and the stations were not stratified. The reason was that the survey area included fjords and coastal areas with limited stations suitable for trawling. The lack of depth stratification and randomization of locations may introduce biases into the dataset. The stations seem to be distributed relatively evenly at all depths (Figure 8). Median station depth was also very similar throughout the time series, indicating comparability between the years. One can do little about the station grid due to the characteristics of the survey area. The IMR has divided the survey into three sub-areas and 23 smaller geographical strata (north of 67°N, 65°-67°N and 62°-65°N) when working with coastal cod (Aglen et al., 2021). The lack of depth stratification is believed to cause limited biases as the halibut are found at all depths (Erik Berg, personal communication, 18. October 2022). The lack of randomization and stratification was thus expected to have a limited effect on the results.

The sampling gear could affect the catch composition in the survey, as it may have different selectivity for the different size groups (Maunder & Piner, 2015). The timing of the survey, combined with the fact that individuals in different life stages are often expected to be found in separate areas and at different depths at different times (time of day, season), were also expected to influence the catchability. This is a common challenge when assessing data-limited stocks, as they are often not the survey's target species (ICES, 2023).

The length- and weight measurements from the survey probably contained sampling errors. A small proportion of the halibut was length measured in 1998-2000, which led to artificially low values for the indices (CPUE2, CPUE3 and CPUE4) in these years. This could have affected the stock assessment as the period was the start of the recovery. The dataset also contained irregularities in the length-weight relationship, probably caused by the fact that the scales onboard the IMR research vessels were limited to 35 kg (Erik Berg, personal communication, 12. January 2023). This may have affected the weighing of large halibut unless they were cut into smaller pieces and weighed in several rounds. However, the estimated length-weight relationship parameters found were considered reliable as they were similar to those previously found by Wigley et al. (2003) and Froese et al. (2014). The latter was listed at FishBase.org (Froese & Pauly, 2022). While measurements from the survey may constitute a source of error, the effect on the results was considered limited.

The distribution of landings from unreported areas may have constituted a source of error. Allocation of all landings from unreported areas to landings from Norwegian areas based on comparing gear distribution may be an overly simplistic solution. At the same time, it is assumed that fishing in foreign waters has been registered. Firstly, registering catches from abroad is mandatory; secondly, it benefits the fishermen. Quota-regulated fish caught abroad may not be counted towards quotas given in Norwegian waters. Norwegian fishermen have access to halibut quotas in Greenland waters and bycatch quotas (including halibut) in Icelandic, Faroe, and EU waters (Meld. St. 26 (2020 –2021)). Halibut regulated by quota and caught as bycatch in other quota-covered fisheries abroad were thus expected to be registered. The margin of error of a few tonnes for the landings was unlikely to affect the results.

It cannot be ruled out that illegal, unregulated, and unreported (IUU) fishing has occurred in the halibut fishery. The fact that the Directorate of Fisheries suspects cheating with the reporting of halibut caught as bycatch and changing of reported gear type in the spawning period (Fiskeridirektoratet, 2022) indicated some IUU fishing activity. Thus, it is realistic to believe that some landings were not registered and were sold illegally according to Norwegian law (Fiskesalgslagsloven, 2013). These landings that may be missing from the official statistics were not expected to be large, and their effect was accounted for through the scenarios of increased landings with recreational and tourist fishing.

Including uncertainty for landings in SPiCT allows for observation noise (M. W. Pedersen et al., 2022). In theory, the uncertainty may compensate for unreported landings or minor deviations in the official landing statistics. On the contrary, SPiCT smoothened the landings, with the actual landings as minimum and maximum values within the uncertainty (Figure 20). This smoothing means that SPiCT reduced the highest landings in recent years significantly. Smoothing of landings may affect the stock assessments, leading to lower MSY estimates. SPiCT's lower estimated landings should be investigated by comparing SPiCT to other similar assessment methods.

The SPiCT assessment was performed with a fixed Schaefer production curve. The prior was set despite many stocks having a skewness in their production curve, with MSY occurring at other fractions than half of the carrying capacity (Pella & Tomlinson, 1969). The assumption may affect estimates of the reference points F_{MSY}, B_{MSY}, MSY and K as they depend on the production curve shape. According to ICES (2021, 2022b, 2022a) procedures, the shape parameter was fixed at a Schaefer production curve to promote stability. The reason was that input data contain little information about whether the production curve should be skewed in one way or another and to what degree. While debatable, this assumption was considered the best option for the halibut stock assessment. In data-limited situations, a fixed Schaefer production curve had the best performance.

The results for the scenario simulations showed weaknesses. When landings were increased by 20% and 40%, it resulted in 20% and 40% higher estimates. The uncertainty also increased by 20% and 40%, respectively. The equal increase in landings and estimates illustrated that the simulation design combined with the SPiCT assessments had limitations. Despite the weaknesses in these simulations, they showed that the potential properties of the stock could change if more information about unreported landings is obtained.

The limitations of the assessment conducted and potential sources of error may affect the stock assessment. More detailed input data and model adjustments may contribute to better estimates, but the effects are thought to be minor. It cannot be ruled out that other sources of error not identified could also affect the results. However, none of the sources of error were expected to affect the assessment significantly because the data-limited approach was expected to handle the uncertainty in the data. The precautionary approach also included an additional safety margin for the stock, reducing the potential negative effect to a minimum.

4.6 Other considerations

Management should optimally be adapted to the biological units to avoid local overfishing and reduced productivity (Reiss et al., 2009). Questions may be raised regarding whether halibut north of 62°N latitude should be considered a separate management unit. Norwegian management regime often divides fish species into two management units: north and south of 62° latitude. For halibut, this included different gear restrictions and conservation periods. A limited amount of exchange was believed to happen between geographical areas. Expanding this system to include quotas may be sensible, as most halibut are stationary.

Another important factor was that the coastal survey did not cover the area south of 62°N. Indices were probably not representative of the development in the south, which was found to be different compared to the north. On the other hand, the lack of genetic variation may speak against different management units. These genetic studies were, however, limited. It was not unthinkable that the halibut have a genetic gradient along the Norwegian coast. Such genetic gradients were found for coastal cod, which have a similar distribution along the coast (Dahle et al., 2018). Life history differences existed between different populations in the Atlantic and previously between locations in Norway. It may therefore be that there were several relatively reproductive-isolated biological units of halibut along the coast. Given today's knowledge about the halibut and the different development for the stock south of 62°N, dividing the halibut into management units north and south of 62°N was most sensible.

Substantial changes in ecosystems are expected due to climate change (Collie et al., 2016), which leads to uncertainty around the future development of the halibut stock. Due to rising ocean temperatures, marine species are expected to expand northwards as new areas come within their thermal tolerance (Sunday et al., 2012). For the halibut, a northward shift in abundance has been detected from 1995 to 2017, according to Skants (2019). The author also found indications of a shift from coastal areas to open bank areas where the water was colder.

It was thus suggested that halibut moved to colder habitats. That pattern was found for many North Sea cold-water species (Dulvy et al., 2008). Thus, the halibut stock may be changing distribution because of increased sea temperature. The boreal ecosystems where most of the halibut are found today, and the arctic ecosystems where halibut may be expected to be more present in the future, will experience significant changes in ecosystems and food webs (Aschan et al., 2013; Fossheim et al., 2015; Kortsch et al., 2015). Consequently, it is essential to establish a management regime to monitor and protect the stock from human overexploitation in an uncertain future.

Most fisheries reference points are set using single-species models, yet ecosystem-based approaches have been the goal for fisheries management for a long time (Collie et al., 2016; Holsman et al., 2016; Ramírez-Monsalve et al., 2016; Säterberg et al., 2019). Single-species models treat the stock as an isolated unit, not considering the rest of the ecosystem. Management may therefore become unbalanced with the surroundings. An ecosystem-based fisheries management (EBFM) can include biotic and abiotic elements into a model and manage fisheries in a multi-species context, thus highlighting and possibly preventing human overexploitation of the entire ecosystem. The challenges with EBFM are its complexity and often high level of uncertainty. Modelling ecosystem interactions requires a lot of knowledge and data. A multispecies approach may produce different results than single-species models (Gislason, 1999; Säterberg et al., 2019). Predator species can be reduced to very low levels to maximize the total production though increasing their prey items. As a result, a top predator like halibut may be reduced to undesirable levels where the stock cannot sustain a fishery of a certain scale. At the same time, the criticism against single-species models is somewhat exaggerated. The models include species and ecosystem interaction through parameters like growth, natural mortality and carrying capacity (Froese et al., 2016). Single-species models are found to perform well and were therefore considered reasonable for this assessment.

4.7 Management advice

SPiCT assessment with ICES MSY 35th hockey-stick advice rule according to the ICES stock category 2 advice suggested a TAC of 2424 tons. The advice was based on a halibut stock assessed to be slightly below biomass and above fishing mortality reference points. There was consensus between the SPiCT assessment and the TAC estimates found by the MPs considered most relevant in DLMtool. The simulation from the relevant models in DLMtool showed a peak in TAC estimates of around 2500 tons. Should the SPiCT assessment later not be accepted, an empirical approach still justifies the TAC level. Therefore, the TAC for the Norwegian halibut stock north of 62°N latitude should be set between 2000-2424 tons based on precautionary approach considerations. This management advice will bring the stock back to sustainable levels so that it could provide MSY in a long-term perspective.

In addition to the suggested TAC, the minimum catch size should be increased to better fit the life history traits of the halibut stock. Increasing the minimum catch size within the 90-106 cm range would be more appropriate, based on the findings in this thesis. Change in minimum catch size could be done together with and independently of other management actions like TAC. The estimates by SPiCT and the TAC MPs should be re-evaluated if they are used with an increase in minimum catch size.

4.8 Further steps and perspectives

The survey indices can be improved with stratification and standardization models. Stratification for depths and creating one index per strata would reduce the standard deviation around the mean value. In addition, removing new stations added during the time series would increase comparability between the years. Standardization models can, among other things, correct for catchability at different depths and areas by creating standardized indices (Thorson & Ward, 2013). A common way to standardize survey indices is by using generalized linear models. These measures could increase the precision of the survey indices and contribute to more precise stock assessments.

Several potential improvements to the SPiCT assessment models are yet to be made. Including other IMR survey cruises that cover other parts of the halibut distribution is possible. If different indices are used, standardization is required (ICES, 2023). The survey timing could be shifted to the survey date (October), but initial tests displayed insignificant differences compared to standard survey timing (1st of January). The effect of landings divided into months should be investigated in future analyses. Landings from before 1977 may be included in future works. Including historical landings may be valuable as historical high landings can give information about carrying capacity (Bouch et al., 2021; ICES, 2023). Initial tests with historical landings could not obtain model convergence. Including new and more detailed data could potentially enhance the stock assessment.

Data from the coastal reference fleet can be utilized in the future. The reference fleet consists of selected vessels that are close to representative for the coastal fishing fleet (Haltebrekke et al., 2021). The reference fleet provides detailed data on landings composition compared to official landings statistics. In addition to their regular fishing activity, they register the number of individuals per species and provide individual data like the size- and age composition. Information about fishing effort and landings can be used in a fishery-dependent CPUE. The length-frequency data can provide valuable information about the fishing pressure of different size groups of the stock (Baldé et al., 2019). However, this thesis did not include data from the reference fleet, as the time was limited.

It is possible to further increase SPiCT model stability by defining a prior for the intrinsic growth rate *r* (ICES, 2021). Priors can be generated using the R-package SPMpriors (Thorson, 2020). Defining other priors may reduce estimate uncertainty in the assessment (Bouch et al., 2021; M. W. Pedersen & Berg, 2017). However, SPiCT could be used in management advice with default parameter settings when limited information does not allow for precise prior adjustment (ICES, 2023). The SPiCT assessment was run with relatively standard parameter settings, and further adjustments were beyond the range of this thesis.

In later years, there has been a rapid growth in data-limited assessment methods (Bouch et al., 2021; Cousido-Rocha et al., 2022; Polacheck et al., 1993). There are also constant updates for SPiCT (M. W. Pedersen et al., 2022). With future developments in the data-limited approach, further improvements in halibut stock assessments are expected.

It is also essential to improve the knowledge base for the tourist- and recreational fisheries so that their actual effect and trend can be revealed. So far, only single-year estimates have been published (Ferter et al., 2022; Fiskeridirektoratet, 2022). From a short-term perspective, tourist fisheries may be the easiest to quantify, as a database with mandatory registrations was established in 2018. There are also plans to establish a time series for recreational fisheries (Ferter et al., 2022). The effect of these fisheries should be quantified so that they could be included in future management (Cooke & Cowx, 2006; Ferter et al., 2022).

The assessment includes landings and survey data up to and including 2021. Stock status and management advice are therefore applicable for 2022. In addition, advice from SPiCT should only be used in short-term forecasting (M. W. Pedersen & Berg, 2017). Towards the end of the master project, the statistics for 2022 were made available and have been quality assured. The landings for 2022 for halibut north of 62°N is around 3250 tons (Erik Berg, Personal communication, 17.03.2023). The survey index value for 2022 corresponding to CPUE4 (weight for halibut above minimum catch size) show a reduction compared to 2021. Although one should be careful reading too much into single-year observations, increased landings and the reduced index could strengthen the impression of an overfished, possibly diminishing stock. The stock should be re-assessed to investigate the effect of the new data.

The proposals for new regulations for the halibut fishery north of 62°N (Fiskeridirektoratet, 2022) that was on hearing at the start of this master project seem to be coming into effect soon (J. E. Olsen, 2023). The minimum catch size will be increased to 84 cm, and halibut will be protected from fishing with all gear between December 20. – March 31. There will also be restrictions on the number of gillnets and hooks on longlines used at any time. A new reporting regime and a lower bycatch allowance will be implemented. These new management actions are positive for the halibut stock, but many actors strongly want the fishery to be regulated by quotas (Erik Berg, Personal communication, 25.04.2023). This thesis has laid the foundation for implementing a quota in the halibut fishery by providing advice on such a management action.

5 Conclusion

A stock assessment of the Norwegian halibut stock north of 62°N has been performed successfully using data-limited models and the best available data. The specific objectives were fulfilled in the following way:

SO1) The SPiCT model was successfully tested and adapted to the halibut stock north of 62°N according to ICES procedure. The SPiCT results fulfilled the technical criteria, and the halibut was considered a category 2 stock and given category 2 MSY advice.

SO2) Empirical approaches were successfully tested according to ICES procedure using the DLMtool where 8 out of 14 models seemed relevant.

SO3) The effects of tourist- and recreational fisheries were that the stock had sustained higher landings and fishing effort than official numbers show. Tourist- and recreational fisheries might have a negative effect on the halibut stock locally.

SO4) According to the stock assessments presented here, the stock was around optimal levels and utilized around MSY. The stock was probably declining due to overfishing in recent years.

SO5) The management advice for the halibut stock in Norway north of 62°N is to reduce fishing by implementing a TAC at 2000-2424 tons. An increase in minimum catch size of around 90-106 cm should be implemented (together with or independently of other measures) to fit the species' life-history traits better.

6 References

Aglen, A., Fall, J., Gjøsaeter, H., & Staby, A. (2021). *Abundance indices for Norwegian coastal cod north of 62°N* (Rapport fra Havforskningen Nr. 2021-6). https://www.hi.no/hi/nettrapporter/rapport-fra-havforskningen-en-2021-6

Ailloud, L. E., Gedamke, T., & Hoenig, J. M. (2018). Short-Term Pain and Long-Term Gain: Using Phased-In Minimum Size Limits to Rebuild Stocks—the Pacific Bluefin Tuna Example. *Transactions of the American Fisheries Society*, *147*(6), 1015–1029. https://doi.org/10.1002/TAFS.10098

Andriyashev, A. P. (1964). *Fishes of the northern seas of the U.S.S.R*. Israel Program for Scientific Translations.

Armsworthy, S. L., & Campana, S. E. (2010). Age determination, bomb-radiocarbon validation and growth of Atlantic halibut (*Hippoglossus hippoglossus*) from the Northwest Atlantic. *Environmental Biology of Fishes*, *89*(3), 279–295. https://doi.org/10.1007/S10641-010-9696-8

Aschan, M., Fossheim, M., Greenacre, M., & Primicerio, R. (2013). Change in Fish Community Structure in the Barents Sea. *PLOS ONE*, *8*(4), e62748. https://doi.org/10.1371/JOURNAL.PONE.0062748

Auguie, B., & Antonov, A. (2017, September 9). *gridExtra: Miscellaneous Functions for 'Grid' Graphics [R package gridExtra version 2.3]*. Comprehensive R Archive Network (CRAN). https://CRAN.R-project.org/package=gridExtra

Baldé, B. S., Fall, M., Kantoussan, J., Sow, F. N., Diouf, M., & Brehmer, P. (2019). Fish-length based indicators for improved management of the sardinella fisheries in Senegal. *Regional Studies in Marine Science*, *31*(100801). https://doi.org/10.1016/J.RSMA.2019.100801

Berck, P. (1979). Open Access and Extinction. *Econometrica*, *47*(4), 877–882. https://doi.org/10.2307/1914136

Berg, C. W., Kokkalis, A., Mildenberger, T., & Pedersen, M. W. (2022). *Stochastic production model in continuous-time (SPiCT) - BWKMSYSPICT learning session, September 2022.*

Bergstad, O. A., & Gordon, J. D. M. (1993). First record of Atlantic halibut (*Hippoglossus hippoglossus* (L.)) larvae from the Skagerrak. *ICES Journal of Marine Science*, *50*, 231–232.

Berkes, F. (1985). Fishermen and 'The Tragedy of the Commons'. *Environmental Conservation*, *12*(3), 199–206. https://www.jstor.org/stable/44520413

Blue Matter Science. (2020). *openMSE*. https://openmse.com/

Bouch, P., Minto, C., & Reid, D. G. (2021). Comparative performance of data-poor CMSY and data-moderate SPiCT stock assessment methods when applied to data-rich, real-world stocks. *ICES Journal of Marine Science*, *78*(1), 264–276. https://doi.org/10.1093/ICESJMS/FSAA220

Bowering, W. R. (1986). *The Distribution, Age and Growth and Sexual Maturity of Atlantic Halibut (*Hippoglossus Hippoglossus*) in the Newfoundland and Labrador Area of the Northwest Atlantic* (Canadian Technical Report of Fisheries and Aquatic Sciences, 1432).

Cardinale, M., & Hjelm, J. (2012). Size matters: Short term loss and long term gain in a size-selective fishery. *Marine Policy*, *36*(4), 903–906. https://doi.org/10.1016/j.marpol.2012.01.001

Carruthers, T. R., & Hordyk, A. (2020). *Data-Limited Methods Toolkit (DLMtool 5.4.2) User Guide*. https://dlmtool.github.io/DLMtool/userguide/userguide.pdf

Carruthers, T. R., & Hordyk, A. R. (2018). The Data-Limited Methods Toolkit (DLMtool): An R package for informing management of data-limited populations. *Methods in Ecology and Evolution*, *9*(12), 2388–2395. https://doi.org/10.1111/2041-210X.13081

Carruthers, T. R., Hunynh, Q., Hordyk, A., Bryan, M., Geremont. H. F., Grandin, C., Harford, W., & Walters, C. (2022, June 20). *Data-Limited Methods Toolkit [R package DLMtool version 6.0.6]*. Comprehensive R Archive Network (CRAN). https://CRAN.R-project.org/package=DLMtool

Carruthers, T. R., Kell, L. T., Butterworth, D. D. S., Maunder, M. N., Geromont, H. F., Walters, C., McAllister, M. K., Hillary, R., Levontin, P., Kitakado, T., & Davies, C. R. (2016). Performance review of simple management procedures. *ICES Journal of Marine Science*, *73*(2), 464–482. https://doi.org/10.1093/ICESJMS/FSV212

Carruthers, T. R., Punt, A. E., Walters, C. J., MacCall, A., McAllister, M. K., Dick, E. J., & Cope, J. (2014). Evaluating methods for setting catch limits in data-limited fisheries. *Fisheries Research*, *153*, 48–68. https://doi.org/10.1016/J.FISHRES.2013.12.014

Collie, J. S., Botsford, L. W., Hastings, A., Kaplan, I. C., Largier, J. L., Livingston, P. A., Plagányi, É., Rose, K. A., Wells, B. K., & Werner, F. E. (2016). Ecosystem models for fisheries management: finding the sweet spot. *Fish and Fisheries*, *17*(1), 101–125. https://doi.org/10.1111/FAF.12093

Cooke, S. J., & Cowx, I. G. (2006). Contrasting recreational and commercial fishing: Searching for common issues to promote unified conservation of fisheries resources and aquatic environments. *Biological Conservation*, *128*(1), 93–108. https://doi.org/10.1016/j.biocon.2005.09.019

Cousido-Rocha, M., Pennino, M. G., Izquierdo, F., Paz, A., Lojo, D., Tifoura, A., Zanni, M. Y., & Cerviño, S. (2022). Surplus production models: a practical review of recent approaches. *Reviews in Fish Biology and Fisheries*, *32*(4), 1085–1102. https://doi.org/10.1007/S11160-022-09731-W/FIGURES/4

Dahle, G., Quintela, M., Johansen, T., Westgaard, J. I., Besnier, F., Aglen, A., Jørstad, K. E., & Glover, K. A. (2018). Analysis of coastal cod (*Gadus morhua* L.) sampled on spawning sites reveals a genetic gradient throughout Norway's coastline. *BMC Genetics*, *19*(1), 1–17. https://doi.org/10.1186/S12863-018-0625-8/FIGURES/6

den Heyer, C. E., Schwarz, C. J., & Trzcinski, M. K. (2013). Fishing and Natural Mortality Rates of Atlantic Halibut Estimated from Multiyear Tagging and Life History. *Transactions of the American Fisheries Society*, *142*(3), 690–702. https://doi.org/10.1080/00028487.2012.760482

Devold, F. (1938). The North Atlantic Halibut and Net fishing. *Fiskeridirektoratets Skrifter, Serie Havundersøkelser*, *5*(6).

Devold, F. (1939). Kveiteundersøkelsene 1938. *Fiskeridirektoratets Skrifter, Serie Havundersøkelser*, *6*(1), 85–95.

Dulvy, N. K., Rogers, S. I., Jennings, S., Stelzenmüller, V., Dye, S. R., & Skjoldal, H. R. (2008). Climate change and deepening of the North Sea fish assemblage: a biotic indicator of warming seas. *Journal of Applied Ecology*, *45*(4), 1029–1039. https://doi.org/10.1111/J.1365-2664.2008.01488.X

Engås, A., & Ona, E. (1991). *A method to reduce survey bottom trawl variability* (ICES CM 1991/B:39). https://www.ices.dk/sites/pub/CM%20Doccuments/1991/B/1991_B39.pdf

Fekjan, J. (n.d.). *Kveite* Hippoglossus hippoglossus *(Linnaeus, 1758)*. Retrieved 1 December 2022, from https://artsdatabanken.no/Files/37490/107_Kveite.png

Ferter, K., Otterå, H., Christman, M., Kleiven, A. R., Weltersbach, M. S., Gundersen, S., Djønne, C., Bjelland, O., Hartill, B., Lyle, J., Hyder, K., Borch, T., & Vølstad, J. H. (2022). Integrating complementary survey methods to estimate catches in Norway's complex marine recreational hook-and-line fishery. *ICES Journal of Marine Science*, *0*, 1–15. https://doi.org/10.1093/ICESJMS/FSAC216

Ferter, K., Rikardsen, A. H., Evensen, T. H., Svenning, M. A., & Tracey, S. R. (2017). Survival of Atlantic halibut (*Hippoglossus hippoglossus*) following catch-and-release angling. *Fisheries Research*, *186*(3), 634–641. https://doi.org/10.1016/J.FISHRES.2016.05.022

Fevolden, S. E., & Haug, T. (1988). Genetic Population Structure of Atlantic Halibut, *Hippoglossus hippoglossus*. *Canadian Journal of Fisheries and Aquatic Sciences*, *45*(1), 2–7. https://doi.org/10.1139/F88-001

Fischer, S. H., de Oliveira, J. A. A., & Kell, L. T. (2020). Linking the performance of a data-limited empirical catch rule to life-history traits. *ICES Journal of Marine Science*, *77*(5), 1914–1926. https://doi.org/10.1093/ICESJMS/FSAA054

Fiskeridirektoratet. (2018, February 28). *Sea angling in Norway – Regulations for foreign visitors*. https://www.fiskeridir.no/English/Fishing-in-Norway/Sea-angling-in-Norway

Fiskeridirektoratet. (2022, September 22). *Forslag til reguleringstiltak i fisket etter kveite*. https://www.fiskeridirektoratet.no/Yrkesfiske/Dokumenter/Hoeringer/forslag-til-reguleringstiltak-i-fisket-etter-kveite

Fiskeridirektoratet. (2023). *Yggdrasil - Fiskeridirektoratets kart for fiskeri*. https://portal.fiskeridir.no/

Fiskesalgslagsloven. (2013). *Lov om førstehandsomsetning av viltlevande marine ressursar* (LOV-2013-06-21-75). Lovdata. https://lovdata.no/dokument/NL/lov/2013-06-21-75

Foss, A., Imsland, A. K., & Naevdal, G. (1998). Population genetic studies of the Atlantic halibut in the North Atlantic Ocean. *Journal of Fish Biology*, *53*(4), 901–905. https://doi.org/10.1111/J.1095-8649.1998.TB01845.X

Fossheim, M., Primicerio, R., Johannesen, E., Ingvaldsen, R. B., Aschan, M. M., & Dolgov, A. V. (2015). Recent warming leads to a rapid borealization of fish communities in the Arctic. *Nature Climate Change 2015*, *5*(7), 673–677. https://doi.org/10.1038/nclimate2647

Froese, R., & Pauly, D. (2022). *Fishbase. World Wide Web electronic publication*. https://www.fishbase.se/

Froese, R., Thorson, J. T., & Reyes, R. B. (2014). A Bayesian approach for estimating length-weight relationships in fishes. *Journal of Applied Ichthyology*, *30*(1), 78–85. https://doi.org/10.1111/JAI.12299

Froese, R., Winker, H., Gascuel, D., Sumaila, U. R., & Pauly, D. (2016). Minimizing the impact of fishing. *Fish and Fisheries*, *17*(3), 785–802. https://doi.org/10.1111/FAF.12146

Gates, J. M. (2005). Management of the Pacific Halibut Fishery. In S. Cunningham & T. Bostock (Eds.), *Successful Fisheries Management: Issues, Case Studies and Perspectives* (pp. 45–73). University of Chicago Press.

Geromont, H. F., & Butterworth, D. S. (2015). Generic management procedures for data-poor fisheries: forecasting with few data. *ICES Journal of Marine Science*, *72*(1), 251–261. https://doi.org/10.1093/ICESJMS/FST232

Gislason, H. (1999). Single and multispecies reference points for Baltic fish stocks. *ICES Journal of Marine Science*, *56*(5), 571–583. https://doi.org/10.1006/JMSC.1999.0492

Godø, O. R., & Haug, T. (1988a). Tagging and recapture of Atlantic halibut (*Hippoglossus hippoglossus*) in Norwegian waters. *Journal Du Conseil - Conseil International Pour l'exploration de La Mer*, *44*, 169–179. https://doi.org/10.1093/icesjms/44.2.169

Godø, O. R., & Haug, T. (1988b). Tagging and Recapture of Atlantic Halibut (*Hippoglossus hippoglossus* L.) on the Continental Shelves off Eastern Canada & and off Western and Eastern Greenland. *Journal of Northwest Atlantic Fishery Science*, *8*, 25–31. https://doi.org/10.2960/J.v8.a3

Godø, O. R., & Haug, T. (1999). Growth Rate and Sexual Maturity in Cod (*Gadus morhua*) and Atlantic Halibut (*Hippoglossus hippoglossus*). *Journal of Northwest Atlantic Fishery Science*, *25*, 115–123. http://journal.nafo.int

Grant, W. S., Teel, D. J., Kobayashi, T., & Schmitt, C. (1984). Biochemical Population Genetics of Pacific Halibut (*Hippoglossus stenolepis*) and Comparison with Atlantic Halibut (*H. hippoglossus*). *Canadian Journal of Fisheries and Aquatic Sciences*, *41*(7), 1083–1088. https://doi.org/10.1139/F84-127

Grolemund, G., & Wickham, H. (2011). Dates and Times Made Easy with lubridate. *Journal of Statistical Software*, *40*(3), 1–25. https://doi.org/10.18637/JSS.V040.I03

Haltebrekke, H. H., Gundersen, S., Nedreaas, K., Vølstad, J. H., & Kolding, J. (2021). *The Coastal Reference Fleet 2007-2019* (Rapport fra havforskningen 2021-52). https://www.hi.no/hi/nettrapporter/rapport-fra-havforskningen-en-2021-52

Hardin, G. (1968). The Tragedy of the Commons. *Science*, *162*(3859), 1243–1248. https://www.jstor.org/stable/1724745

Harford, W. J., & Carruthers, T. R. (2017). Interim and long-term performance of static and adaptive management procedures. *Fisheries Research*, *190*, 84–94. https://doi.org/10.1016/J.FISHRES.2017.02.003

Haug, T. (1984). Utvikling og reguleringer i det norske kveitefisket. *Fiskets Gang*, *4*, 117–122.

Haug, T. (1990). Biology of the Atlantic Halibut, *Hippoglossus hippoglossus* (L., 1758). *Advances in Marine Biology*, *26*, 1–70.

Haug, T., & Fevolden, S. E. (1986). Morphology and biochemical genetics of Atlantic halibut, *Hippoglossus hippoglossus* (L.), from various spawning grounds. *Journal of Fish Biology*, *28*(3), 367–378. https://doi.org/10.1111/J.1095-8649.1986.TB05173.X

Haug, T., & Gulliksen, B. (1988a). Variation in liver and body condition during gonad development of Atlantic halibut, *Hippoglossus hippoglossus* (L.). *Fiskeridirektoratets Skrifter, Serie Havundersøkelser*, *18*, 351–363.

Haug, T., & Gulliksen, B. (1988b). Fecundity and oocyte sizes in ovaries of female atlantic halibut, *Hippoglossus Hippoglossus* (L.). *Sarsia*, *73*(4), 259–261. https://doi.org/10.1080/00364827.1988.10413411

Haug, T., Kjørsvik, E., & Solemdal, P. (1986). Influence of some physical and biological factors on the density and vertical distribution of Atlantic halibut *Hippoglossus hippoglossus* eggs. *Marine Ecology Progress Series*, *33*(3), 207–216. https://doi.org/10.3354/meps033207

Haug, T., & Sundby, S. (1987a). *A preliminary report on the natural occurrence and ecology of Atlantic halibut,* Hippoglossus hippoglossus*, postlarvae and young immature stage* (ICES CM 1987/F:38).

Haug, T., & Sundby, S. (1987b). *Kveitelarver og miljø. Undersøkelser på gytefeltene ved Sørøya* (Havforskningsinstituttets egg- og larveprogram (HELP) 1987 nr.2).

Haug, T., & Tjemsland, J. (1986). Changes in size- and age-distributions and age at sexual maturity in atlantic halibut, *Hippoglossus hippoglossus*, caught in North Norwegian waters. *Fisheries Research*, *4*(2), 145–155. https://doi.org/10.1016/0165-7836(86)90039-1

Havforskningsinstituttet. (2020, April 16). *Topic: Atlantic halibut.* https://www.hi.no/en/hi/temasider/species/halibut

Heino, M., Díaz Pauli, B., & Dieckmann, U. (2015). Fisheries-Induced Evolution. *Annual Review of Ecology, Evolution, and Systematics*, *46*, 461–480. https://doi.org/10.1146/ANNUREV-ECOLSYS-112414-054339

Hillary, R. M., Preece, A. L., Davies, C. R., Kurota, H., Sakai, O., Itoh, T., Parma, A. M., Butterworth, D. S., Ianelli, J., & Branch, T. A. (2016). A scientific alternative to moratoria for rebuilding depleted international tuna stocks. *Fish and Fisheries*, *17*(2), 469–482. https://doi.org/10.1111/FAF.12121

Høines, Å., Bjelland, O., Michalsen, K., Vølstad, J. H., Helle, K., Vollen, T., Nedreaas, K., & Albert, O. T. (2009). *Kveite i norske farvann: Status og utfordringer for forvaltning og forskning* (Rapport fra havforskningen 1-2009). https://www.hi.no/hi/nettrapporter/rapport-fra-havforskningen/2009/havrapp_2009-1_til_web

Holsman, K. K., Ianelli, J., Aydin, K., Punt, A. E., & Moffitt, E. A. (2016). A comparison of fisheries biological reference points estimated from temperature-specific multi-species and single-species climate-enhanced stock assessment models. *Deep Sea Research Part II: Topical Studies in Oceanography*, *134*, 360–378. https://doi.org/10.1016/J.DSR2.2015.08.001

Horbowy, J., & Luzeńczyk, A. (2012). The estimation and robustness of F MSY and alternative fishing mortality reference points associated with high long-term yield. *Canadian Journal of Fisheries and Aquatic Sciences*, *69*(9), 1468–1480. https://doi.org/10.1139/F2012-070

Hordyk, A., Ono, K., Sainsbury, K., Loneragan, N., & Prince, J. (2015). Some explorations of the life history ratios to describe length composition, spawning-per-recruit, and the spawning potential ratio. *ICES Journal of Marine Science*, *72*(1), 204–216. https://doi.org/10.1093/ICESJMS/FST235

Høstingsforskriften. (2022). *Forskrift om gjennomføring av fiske, fangst og høsting av viltlevende marine ressurser* (FOR-2021-12-23-3910). Lovdata. https://lovdata.no/forskrift/2021-12-23-3910

ICES. (2021). *Benchmark Workshop on the development of MSY advice for category 3 stocks using Surplus Production Model in Continuous Time; SPiCT (WKMSYSPiCT)* (ICES Scientific Report 3:20). https://doi.org/10.17895/ices.pub.7919

ICES. (2022a). *Benchmark Workshop for Selected Elasmobranch Stocks (WKELASMO)* (ICES Scientific Reports. 4:47). https://doi.org/10.17895/ices.pub.21025021

ICES. (2022b). *Benchmark Workshop on Pandalus Stocks (WKPRAWN)* (ICES Scientific Reports 4:20). https://doi.org/10.17895/ices.pub.19714204

ICES. (2022c). ICES technical guidance for harvest control rules and stock assessments for stocks in categories 2 and 3. In *Report of ICES Advisory Committee, 2022, Section 16.4.11*. ICES Technical Guidelines. https://doi.org/10.17895/ICES.ADVICE.19801564.V1

ICES. (2022d). Advice on fishing opportunities. In *Report of ICES Advisory Committee, 2022. ICES Advice 2022, Section 16.4.11*. https://doi.org/10.17895/ICES.ADVICE.19928060.V1

ICES. (2023). *Eleventh Workshop on the Development of Quantitative Assessment Methodologies based on LIFE-history traits, exploitation characteristics, and other relevant parameters for data-limited stocks (WKLIFE XI)* (ICES Scientific Reports 5:21). https://doi.org/10.17895/ices.pub.22140260

Isaksen, B., Valdemarsen, J. W., Larsen, R. B., & Karlsen, L. (1992). Reduction of fish by-catch in shrimp trawl using a rigid separator grid in the aft belly. *Fisheries Research*, *13*(3), 335–352. https://doi.org/10.1016/0165-7836(92)90086-9

Iversen, T. (1936). Sydøstgrønland, Jan Mayen. Fiskeriundersøkelser. *Fiskeridirektoratets Skrifter, Serie Havundersøkelser*, *5*(1).

Jákupsstovu, S. H., & Haug, T. (1988). Growth, Sexual Maturation, and Spawning Season of Atlantic Halibut, *Hippoglossus hippoglossus*, in Faroese Waters. *Fisheries Research*, *6*(3), 201–215. https://doi.org/10.1016/0165-7836(88)90014-8

Jardim, E., Azevedo, M., & Brites, N. M. (2015). Harvest control rules for data limited stocks using length-based reference points and survey biomass indices. *Fisheries Research*, *171*, 12–19. https://doi.org/10.1016/J.FISHRES.2014.11.013

Jonassen, T. M., Imsland, A. K., Fitzgerald, R., Bonga, S. W., Ham, E. v., Naevdal, G., Stefansson, M. O., & Stefansson, S. O. (2000). Geographic variation in growth and food conversion efficiency of juvenile Atlantic halibut related to latitude. *Journal of Fish Biology*, *56*(2), 279–294. https://doi.org/10.1111/J.1095-8649.2000.TB02106.X

Karlson, S., Michalsen, K., & Folkvord, A. (2013). Age determination of Atlantic halibut (*Hippoglossus hippoglossus L.*) along the coast of Norway: status and improvements. *ICES Journal of Marine Science*, *70*(1), 50–55. https://doi.org/10.1093/ICESJMS/FSS174

Kjørsvik, E., Haug, T., & Tjemsland, J. (1987). Spawning season of the Atlantic halibut (*Hippoglossus hippoglossus*) in northern Norway. *Journal Du Conseil - Conseil International Pour l'exploration de La Mer*, *43*(3), 285–293. https://doi.org/10.1093/icesjms/43.3.285

Kohler, C. (1967). Size at Maturity, Spawning Season, and Food of Atlantic Halibut. *Journal of the Fisheries Research Board of Canada*, *24*(1), 53–66.

Kortsch, S., Primicerio, R., Fossheim, M., Dolgov, A. V., & Aschan, M. (2015). Climate change alters the structure of arctic marine food webs due to poleward shifts of boreal generalists. *Proceedings of the Royal Society B: Biological Sciences*, *282*(1814). https://doi.org/10.1098/rspb.2015.1546

Lønning, S., Kjørsvik, E., Haug, T., & Gulliksen, B. (1982). The early development of the halibut, *Hippoglossus hippoglossus* (L.), compared with other marine teleosts. *Sarsia*, *67*, 85–91.

Marchal, P., Andersen, B., Caillart, B., Eigaard, O., Guyader, O., Hovgaard, H., Iriondo, A., Le Fur, F., Sacchi, J., & Santurtún, M. (2007). Impact of technological creep on fishing effort and fishing mortality, for a selection of European fleets. *ICES Journal of Marine Science*, *64*(1), 192–209. https://doi.org/10.1093/ICESJMS/FSL014

Martell, S., & Froese, R. (2012). A simple method for estimating MSY from catch and resilience. *Fish and Fisheries*, *14*(4), 504–514. https://doi.org/10.1111/j.1467-2979.2012.00485.x

Mathisen, O. A., & Olsen, S. (1968). Yield isopleths of the halibut, *Hippoglossus hippoglossus*, in northern Norway. *Fiskeridirektoratets Skrifter, Serie Havundersøkelser*, *14*(3), 129–159. http://hdl.handle.net/11250/114704

Maunder, M. N., & Piner, K. R. (2015). Contemporary fisheries stock assessment: many issues still remain. *ICES Journal of Marine Science*, *72*(1), 7–18. https://doi.org/10.1093/ICESJMS/FSU015

McCracken, F. D. (1958). On the Biology and Fishery of the Canadian Atlantic Halibut, *Hippoglossus hippoglossus* L. *Journal of the Fisheries Board of Canada*, *15*(6), 1269–1311. https://doi.org/10.1139/F58-070

Mehanna, S. F., & Farouk, A. E. (2021). Length-Weight Relationship of 60 Fish Species From the Eastern Mediterranean Sea, Egypt (GFCM-GSA 26). *Frontiers in Marine Science*, *8*. https://doi.org/10.3389/FMARS.2021.625422/BIBTEX

Mehl, S., Berg, E., Korsbrekke, K., Olsen, E., & Staby, A. (2018). *Acoustic abundance of saithe, coastal cod and haddock Finnmark – Møre Autumn 2017* (Toktrapport Nr. 2-2018).

Meld. St. 26 (2020 –2021). (2021). *Noregs fiskeriavtalar for 2021 og fisket etter avtalane i 2019 og 2020*. Nærings- og Fiskeridepartementet. https://www.regjeringen.no/no/dokumenter/meld.-st.-26-20202021/id2842982/

Mildenberger, T. K., Berg, C. W., Kokkalis, A., Hordyk, A. R., Wetzel, C., Jacobsen, N. S., Punt, A. E., & Nielsen, J. R. (2022). Implementing the precautionary approach into fisheries management: Biomass reference points and uncertainty buffers. *Fish and Fisheries*, *23*(1), 73–92. https://doi.org/10.1111/FAF.12599

Mildenberger, T. K., Kokkalis, A., & Berg, C. W. (2022). *Guidelines for the stochastic production model in continuous time (SPiCT)*. https://github.com/DTUAqua/spict/raw/master/spict/inst/doc/spict_guidelines.pdf

Mjanger, H., Svendsen, V., Fuglebakk, E., Gulbrandsen, M. L., Diaz, J., Johansen, G. O., Bruck, S. A., & Gundersen, S. (2022). *Håndbok for prøvetaking av fisk, krepsdyr og andre evertebrater*.

Mork, J., & Haug, T. (1983). Genetic variation in halibut *Hippoglossus hippoglossus* (L.) from Norwegian waters. *Herediras*, *98*(2), 167–174. https://doi.org/10.1111/j.1601-5223.1983.tb00591.x

Nærings- og fiskeridepartementet. (2022, June 27). *Turistfiske*. https://www.regjeringen.no/nn/tema/mat-fiske-og-landbruk/fiskeri-og-havbruk/1/fiskeri/turistfiske/id2601773/

Neilson, J. D., & Bowering, W. R. (1989). Minimum Size Regulations and the Implications for Yield and Value in the Canadian Atlantic Halibut (*Hippoglossus hippoglossus*) Fishery. *Canadian Journal of Fisheries and Aquatic Sciences*, *46*(11), 1899–1903. https://doi.org/10.1139/F89-239

Neilson, J. D., Waiwood, K. G., & Smith, S. J. (1989). Survival of Atlantic Halibut (*Hippoglossus hippoglossus*) Caught by Longline and Otter Trawl Gear. *Canadian Journal of Fisheries and Aquatic Sciences*, *46*(5), 887–897. https://doi.org/10.1139/F89-114

Neuwirth, E. (2022, April 3). *RColorBrewer: ColorBrewer Palettes*. Comprehensive R Archive Network (CRAN). https://CRAN.R-project.org/package=RColorBrewer

NOAA. (2022a, August 30). *Recreational Fishing Regulations by Species*. https://www.fisheries.noaa.gov/new-england-mid-atlantic/recreational-fishing/recreational-fishing-regulations-species#halibut

NOAA. (2022b, December 15). *Northeast Multispecies (Groundfish)*. https://www.fisheries.noaa.gov/species/northeast-multispecies-groundfish#commercial

Olsen, J. E. (2023, March 17). Alt klart for omfattende kveitereguleringer. *Fiskeribladet*. https://www.fiskeribladet.no/reguleringer/alt-klart-for-omfattende-kveitereguleringer/2-1-1420748

Olsen, S. (1969). The Halibut Gillnet Fishery in West Finnmark- Analysis of Landings Data from Øksfjord 1955-65. *Fiskeridirektoratets Skrifter, Serie Havundersøkelser*, *15*(3), 186–197.

Olsen, S., & Tjemsland, J. (1963). A method of finding an empirical total selection curve for gill nets, describing all means of attachment. *Fiskeridirektoratets Skrifter, Serie Havundersøkelser*, *13*(6), 88–94. https://imr.brage.unit.no/imr-xmlui/handle/11250/114584

Ooms, J. (2022). *writexl: Export Data Frames to Excel 'xlsx' Format.* https://docs.ropensci.org/writexl/

Pedersen, M. W., & Berg, C. W. (2017). A stochastic surplus production model in continuous time. *Fish and Fisheries*, *18*(2), 226–243. https://doi.org/10.1111/FAF.12174

Pedersen, M. W., Kokkalis, A., Mildenberger, T. K., & Berg, C. W. (2022). *Handbook for the Stochastic Production model in Continuous Time (SPiCT).* https://github.com/DTUAqua/spict/commit/2b487efc0e1193b11cd9dbe77e87d7c2a9f4413e

Pedersen, T., Mikkelsen, N., Lindstrøm, U., Renaud, P. E., Nascimento, M. C., Blanchet, M. A., Ellingsen, I. H., Jørgensen, L. L., & Blanchet, H. (2021). Overexploitation, Recovery, and Warming of the Barents Sea Ecosystem During 1950–2013. *Frontiers in Marine Science*, *8*. https://doi.org/10.3389/fmars.2021.732637

Pella, J. J., & Tomlinson, P. K. (1969). A generalized stock production model. *Bulletin of the Inter-American Tropical Tuna Commission*, *13*(3), 421–454. http://hdl.handle.net/1834/21263

Polacheck, T., Hilborn, R., & Punt, A. E. (1993). Fitting surplus production models: Comparing methods and measuring uncertainty. *Canadian Journal of Fisheries and Aquatic Sciences*, *50*(12), 2597–2607. https://doi.org/10.1139/f93-284

Punt, A. E. (2003). Extending production models to include process error in the population dynamics. *Canadian Journal of Fisheries and Aquatic Sciences*, *60*, 1217–1228. https://doi.org/10.1139/F03-105

Punt, A. E., Butterworth, D. S., de Moor, C. L., de Oliveira, J. A. A., & Haddon, M. (2016). Management strategy evaluation: best practices. *Fish and Fisheries*, *17*(2), 303–334. https://doi.org/10.1111/FAF.12104

Ramírez-Monsalve, P., Raakjær, J., Nielsen, K. N., Santiago, J. L., Ballesteros, M., Laksá, U., & Degnbol, P. (2016). Ecosystem Approach to Fisheries Management (EAFM) in the EU – Current science–policy–society interfaces and emerging requirements. *Marine Policy*, *66*, 83–92. https://doi.org/10.1016/J.MARPOL.2015.12.030

Rasmussen, S. T. (2020). *Population structure of farmed and wild Atlantic halibut (*Hippoglossus hippoglossus*) and the potential for genetic assignment of farmed escapees* [Master Thesis]. Aarhus University.

Reiss, H., Hoarau, G., Dickey-Collas, M., & Wolff, W. J. (2009). Genetic population structure of marine fish: mismatch between biological and fisheries management units. *Fish and Fisheries*, *10*(4), 361–395. https://doi.org/10.1111/J.1467-2979.2008.00324.X

Sandberg, P., Bogstad, B., & Røttingen, I. (1998). Bioeconomic advice on TAC – the state of the art in the Norwegian fishery management. *Fisheries Research*, *37*(1–3), 259–274. https://doi.org/10.1016/S0165-7836(98)00142-8

Säterberg, T., Casini, M., & Gårdmark, A. (2019). Ecologically Sustainable Exploitation Rates—A multispecies approach for fisheries management. *Fish and Fisheries*, *20*(5), 952–961. https://doi.org/10.1111/FAF.12390

Schaefer, M. B. (1954). Some aspects of the dynamics of populations important to the management of the commercial Marine fisheries. *Bulletin of the Inter-American Tropical Tuna Commission*, *1*(2), 27–56. https://doi.org/10.1007/BF02464432

Seitz, A. C., Farrugia, T. J., Norcross, B. L., Loher, T., & Nielsen, J. L. (2017). Basin-scale reproductive segregation of Pacific halibut (*Hippoglossus stenolepis*). *Fisheries Management and Ecology*, *24*(4), 339–346. https://doi.org/10.1111/FME.12233

Shackell, N. L., Fisher, J. A. D., den Heyer, C. E., Hennen, D. R., Seitz, A. C., Le Bris, A., Robert, D., Kersula, M. E., Cadrin, S. X., McBride, R. S., McGuire, C. H., Kess, T., Ransier, K. T., Liu, C., Czich, A., & Frank, K. T. (2021). Spatial Ecology of Atlantic Halibut across the Northwest Atlantic: A Recovering Species in an Era of Climate Change. *Reviews in Fisheries Science & Aquaculture*, *30*(3), 281–305. https://doi.org/10.1080/23308249.2021.1948502

Sigourney, D. B., Ross, M. R., Brodziak, J., Burnett, J., Sigourney, D. B., Ross, M. R., Brodziak, J., & Burnett, J. (2006). Length at Age & Sexual Maturity and Distribution of Atlantic Halibut & *Hippoglossus hippoglossus* L. & off the Northeast USA. *Journal of Northwest Atlantic Fishery Science*, *36*, 81–90. https://doi.org/10.2960/J.v36.m574

Skants, K. D. (2019). *Species composition, distribution and ecology of the demersal fish community along the Norwegian coast north of Stad under varying environmental conditions* [Master Thesis]. University of Bergen. https://bora.uib.no/bora-xmlui/handle/1956/20011

Sunday, J. M., Bates, A. E., & Dulvy, N. K. (2012). Thermal tolerance and the global redistribution of animals. *Nature Climate Change 2012*, *2*(9), 686–690. https://doi.org/10.1038/nclimate1539

Thorson, J. T. (2020). Predicting recruitment density dependence and intrinsic growth rate for all fishes worldwide using a data-integrated life-history model. *Fish and Fisheries*, *21*(2), 237–251. https://doi.org/10.1111/FAF.12427

Thorson, J. T., & Ward, E. J. (2013). Accounting for space–time interactions in index standardization models. *Fisheries Research*, *147*, 426–433. https://doi.org/10.1016/J.FISHRES.2013.03.012

Trzcinski, M. K., & Bowen, W. D. (2016). The recovery of Atlantic halibut: A large, long-lived, and exploited marine predator. *ICES Journal of Marine Science*, *73*(4), 1104–1114. https://doi.org/10.1093/icesjms/fsv266

Umar, I., Vatnehol, S., Holmin, A. J., Fuglebakk, E., & Johnsen, E. (2021). *RstoxData: Tools to Read and Manipulate Fisheries Data*. https://CRAN.R-project.org/package=RstoxData

UN. (1995). *United Nations Conference On Straddling Fish Stocks and Higly migratory Fish Stocks (1993-1995)*. https://documents-dds-ny.un.org/doc/UNDOC/GEN/N95/274/67/PDF/N9527467.pdf?OpenElement

Vihtakari, M. (2022a). *ggFishPlots: Visualise and calculate life history parameters for fisheries science using 'ggplot2'. R package version 0.1.7.* https://github.com/DeepWaterIMR/ggFishPlots

Vihtakari, M. (2022b). *ggOceanMaps: Plot Data on Oceanographic Maps using 'ggplot2'. R package version 1.3.4*. https://mikkovihtakari.github.io/ggOceanMaps/

Wickham, H. (2016). *ggplot2: Elegant Graphics for Data Analysis*. Springer-Verlag New York. https://ggplot2.tidyverse.org/

Wickham, H., Averick, M., Bryan, J., Chang, W., D', L., Mcgowan, A., François, R., Grolemund, G., Hayes, A., Henry, L., Hester, J., Kuhn, M., Lin Pedersen, T., Miller, E., Bache, S. M., Müller, K., Ooms, J., Robinson, D., Seidel, D. P., … Yutani, H. (2019). Welcome to the Tidyverse. *Journal of Open Source Software*, *4*(43), 1686. https://doi.org/10.21105/JOSS.01686

Wigley, S. E., McBride, H. M., & McHugh, N. J. (2003). *Length-Weight Relationships for 74 Fish Species Collected during NEFSC Research Vessel Bottom Trawl Surveys, 1992-99* (NOAA Technical Memorandum NMFS-NE-171).

Zhou, S., Yin, S., Thorson, J. T., Smith, A. D. M., & Fuller, M. (2012). Linking fishing mortality reference points to life history traits: An empirical study. *Canadian Journal of Fisheries and Aquatic Sciences*, *69*(8), 1292–1301. https://doi.org/10.1139/f2012-060

Appendix

A. Norwegian fisheries statistics of halibut from 1905-1982

Norwegian fisheries statistics contained detailed information about halibut landings as far back as 1905. These statistics were found in yearly reports about Norwegian fisheries, and as part of this master's thesis, the reports from 1905-1982 have been reviewed. In such a long period, the statistics have changed several times. The statistics were therefore converted into the same format of round weight.

Landings from 1905 to 1977 were given in gutted weight, while landings from 1960-1982 were given in round weight. The conversion rate between gutted and round weight was found by comparing the years from 1960-1977. The conversion rate from gutted weight to round weight for 1972-1977 was ~1.35, while the conversion rate for the years 1960-1971 was ~1.21. To calculate round weight for 1905-1959, the conversion rate 1.21 was used.

Some of the landings in the Norwegian fisheries statistics came from distant waters. Distant waters included Norwegian areas far away from the coast and foreign waters. Norwegian waters included the Norwegian Sea, Bear Island and Spitzbergen, while foreign waters included Shetland, Iceland, The Faroes, the Hebrides, Rockall, Greenland, Labrador, and Newfoundland. The North Sea was also considered a non-Norwegian area, as it most probably contained catches outside the Norwegian halibut stock distribution area. Landings from distant waters which were non-Norwegian were removed from the dataset. 1957-1972 contained landings from several gear types, while 1956 contained only catches from longlines. Landings from distant waters in 1935 and 1936 contained fresh, frozen, and salted halibut but were treated as gutted weight.

Table 10 – Landings for Atlantic halibut in Norwegian waters from 1905-1982 retrieved from the reports on Norwegian Fisheries Statistics. Table 1/2

Year	Landings (round weight t) (distant waters removed)	Landings (gutted weight tons)	Convert rate	Landings (round weight tons)	Landings distant waters (round weight tons)	Link to the statistics reports
1982	508			508	0	https://www.ssb.no/a/histstat/nos/nos_b496.pdf
1981	593			593	0	https://www.ssb.no/a/histstat/nos/nos_b366.pdf
1980	1287			1287	0	https://www.ssb.no/a/histstat/nos/nos_b282.pdf
1979	1604			1604	0	https://www.ssb.no/a/histstat/nos/nos_b216.pdf
1978	1199			1199	0	https://www.ssb.no/a/histstat/nos/nos_b162.pdf
1977	1404	1040	1.35	1404	0	https://www.ssb.no/a/histstat/nos/nos_b087.pdf
1976	1621	1198	1.35	1621	0	https://www.ssb.no/a/histstat/nos/nos_xii_294.pdf
1975	1478	1093	1.35	1478	0	https://www.ssb.no/a/histstat/nos/nos_xii_294.pdf
1974	1506	1115	1.35	1506	0	https://www.ssb.no/a/histstat/nos/nos_xii_288.pdf
1973	1976	1463	1.35	1976	0	https://www.ssb.no/a/histstat/nos/nos_xii_288.pdf
1972	1656	1652	1.35	2232	436	https://www.ssb.no/a/histstat/nos/nos_xii_284.pdf
1971	1588	1981	1.21	2392	670	https://www.ssb.no/a/histstat/nos/nos_xii_282.pdf
1970	1704	2192	1.21	2644	788	https://www.ssb.no/a/histstat/nos/nos_xii_278.pdf
1969	2205	2324	1.20	2799	494	https://www.ssb.no/a/histstat/nos/nos_xii_273.pdf
1968	2409	2382	1.21	2878	392	https://www.ssb.no/a/histstat/nos/nos_xii_267.pdf
1967	2326	2501	1.21	3017	578	https://www.ssb.no/a/histstat/nos/nos_xii_262.pdf
1966	2195	2362	1.21	2854	548	https://www.ssb.no/a/histstat/nos/nos_xii_241.pdf
1965	2680	3248	1.21	3931	1038	https://www.ssb.no/a/histstat/nos/nos_xii_225.pdf
1964	3006	3562	1.21	4306	1090	https://www.ssb.no/a/histstat/nos/nos_xii_206.pdf
1963	2848	3794	1.21	4592	1444	https://www.ssb.no/a/histstat/nos/nos_xii_179.pdf
1962	3789	4687	1.21	5672	1562	https://www.ssb.no/a/histstat/nos/nos_xii_144.pdf
1961	3080	4292	1.20	5150	1726	https://www.ssb.no/a/histstat/nos/nos_xii_116.pdf
1960	3972	5663	1.24	7018	2464	https://www.ssb.no/a/histstat/nos/nos_xii_089.pdf
1959	3198	5229	1.21	6327	2596	https://www.ssb.no/a/histstat/nos/nos_xii_060.pdf
1958	3471	5622	1.21	6803	2760	https://www.ssb.no/a/histstat/nos/nos_xii_017.pdf
1957	4093	4793	1.21	5800	1927	https://www.ssb.no/a/histstat/nos/nos_xi_336.pdf
1956	3647	4278	1.21	5176	1267	https://www.ssb.no/a/histstat/nos/nos_xi_293.pdf
1955	3463	4410	1.21	5336	1551	https://www.ssb.no/a/histstat/nos/nos_xi_275.pdf
1954	4401	4785	1.21	5790	1148	https://www.ssb.no/a/histstat/nos/nos_xi_256.pdf
1953	3774	4068	1.21	4922	949	https://www.ssb.no/a/histstat/nos/nos_xi_237.pdf
1952	4936	5126	1.21	6202	1050	https://www.ssb.no/a/histstat/nos/nos_xi_205.pdf
1951	4960	5273	1.21	6380	1183	https://www.ssb.no/a/histstat/nos/nos_xi_149.pdf
1950	6833	6089	1.21	7368	461	https://www.ssb.no/a/histstat/nos/nos_xi_086.pdf
1949	6619	5705	1.21	6903	267	https://www.ssb.no/a/histstat/nos/nos_xi_081.pdf
1948	6254	5209	1.21	6303	69	https://www.ssb.no/a/histstat/nos/nos_xi_058.pdf
1947	6187	5172	1.21	6258	151	https://www.ssb.no/a/histstat/nos/nos_xi_032.pdf
1946	4706	3889	1.21	4706	0	https://www.ssb.no/a/histstat/nos/nos_xi_019.pdf
1945	1800	1488	1.21	1800	0	https://www.ssb.no/a/histstat/nos/nos_x_199.pdf
1944	875	723	1.21	875	0	https://www.ssb.no/a/histstat/nos/nos_x_150.pdf

Table 11 - Landings for Atlantic halibut in Norwegian waters from 1905-1982 retrieved from the reports on Norwegian Fisheries Statistics. Table 2/2

Year	Landings (round weight t) (distant waters removed)	Landings (gutted weight tons)	Convert rate	Landings (round weight tons)	Landings distant waters (round weight tons)	Link to the statistics reports
1943	1362	1126	1.21	1362	0	https://www.ssb.no/a/histstat/nos/nos_x_125.pdf
1942	1228	1015	1.21	1228	0	https://www.ssb.no/a/histstat/nos/nos_x_085.pdf
1941	1636	1352	1.21	1636	0	https://www.ssb.no/a/histstat/nos/nos_x_059.pdf
1940	1544	1276	1.21	1544	0	https://www.ssb.no/a/histstat/nos/nos_x_043.pdf
1939	3462	3244	1.21	3925	439	https://www.ssb.no/a/histstat/nos/nos_x_017.pdf
1938	3833	3454	1.21	4179	286	https://www.ssb.no/a/histstat/nos/nos_ix_195.pdf
1937	6816	5799	1.21	7017	260	https://www.ssb.no/a/histstat/nos/nos_ix_172.pdf
1936	7178	6272	1.21	7589	452	https://www.ssb.no/a/histstat/nos/nos_ix_139.pdf
1935	3941	3728	1.21	4511	548	https://www.ssb.no/a/histstat/nos/nos_ix_108.pdf
1934	4119	3859	1.21	4669	455	https://www.ssb.no/a/histstat/nos/nos_ix_088.pdf
1933	6371	5265	1.21	6371	0	https://www.ssb.no/a/histstat/nos/nos_ix_068.pdf
1932	6882	5688	1.21	6882	0	https://www.ssb.no/a/histstat/nos/nos_ix_039.pdf
1931	6405	5293	1.21	6405	0	https://www.ssb.no/a/histstat/nos/nos_ix_013.pdf
1930	5848	4833	1.21	5848	0	https://www.ssb.no/a/histstat/nos/nos_viii_199.pdf
1929	5923	4895	1.21	5923	0	https://www.ssb.no/a/histstat/nos/nos_viii_167.pdf
1928	5813	4804	1.21	5813	0	https://www.ssb.no/a/histstat/nos/nos_viii_135.pdf
1927	5208	4304	1.21	5208	0	https://www.ssb.no/a/histstat/nos/nos_viii_102.pdf
1926	3969	3280	1.21	3969	0	https://www.ssb.no/a/histstat/nos/nos_viii_072.pdf
1925	3470	2868	1.21	3470	0	https://www.ssb.no/a/histstat/nos/nos_viii_037.pdf
1924	3671	3034	1.21	3671	0	https://www.ssb.no/a/histstat/nos/nos_viii_008.pdf
1923	3307	2733	1.21	3307	0	https://www.ssb.no/a/histstat/nos/nos_vii_175.pdf
1922	3344	2764	1.21	3344	0	https://www.ssb.no/a/histstat/nos/nos_vii_167.pdf
1921	3330	2752	1.21	3330	0	https://www.ssb.no/a/histstat/nos/nos_vii_134.pdf
1920	2537	2097	1.21	2537	0	https://www.ssb.no/a/histstat/nos/nos_vii_114.pdf
1919	2335	1930	1.21	2335	0	https://www.ssb.no/a/histstat/nos/nos_vii_053.pdf
1918	2251	1860	1.21	2251	0	https://www.ssb.no/a/histstat/nos/nos_vii_024.pdf
1917	1280	1058	1.21	1280	0	https://www.ssb.no/a/histstat/nos/nos_vi_183.pdf
1916	1211	1001	1.21	1211	0	https://www.ssb.no/a/histstat/nos/nos_vi_182.pdf
1915	1295	1070	1.21	1295	0	https://www.ssb.no/a/histstat/nos/nos_vi_115.pdf
1914	2040	1686	1.21	2040	0	https://www.ssb.no/a/histstat/nos/nos_vi_074.pdf
1913	2155	1781	1.21	2155	0	https://www.ssb.no/a/histstat/nos/nos_vi_028.pdf
1912	2497	2064	1.21	2497	0	https://www.ssb.no/a/histstat/nos/nos_v_220.pdf
1911	2639	2181	1.21	2639	0	https://www.ssb.no/a/histstat/nos/nos_v_186.pdf
1910	2958	2445	1.21	2958	0	https://www.ssb.no/a/histstat/nos/nos_v_150.pdf
1909	3277	2708	1.21	3277	0	https://www.ssb.no/a/histstat/nos/nos_v_127.pdf
1908	5175	4277	1.21	5175	0	https://www.ssb.no/a/histstat/nos/nos_v_100.pdf
1907	6052	5002	1.21	6052	0	https://www.ssb.no/a/histstat/nos/nos_v_069.pdf
1906	5011	4141	1.21	5011	0	https://www.ssb.no/a/histstat/nos/nos_v_046.pdf
1905	4873	4027	1.21	4873	0	https://www.ssb.no/a/histstat/nos/nos_v_019.pdf

B. Main statistical areas and Exclusive Economic Zone

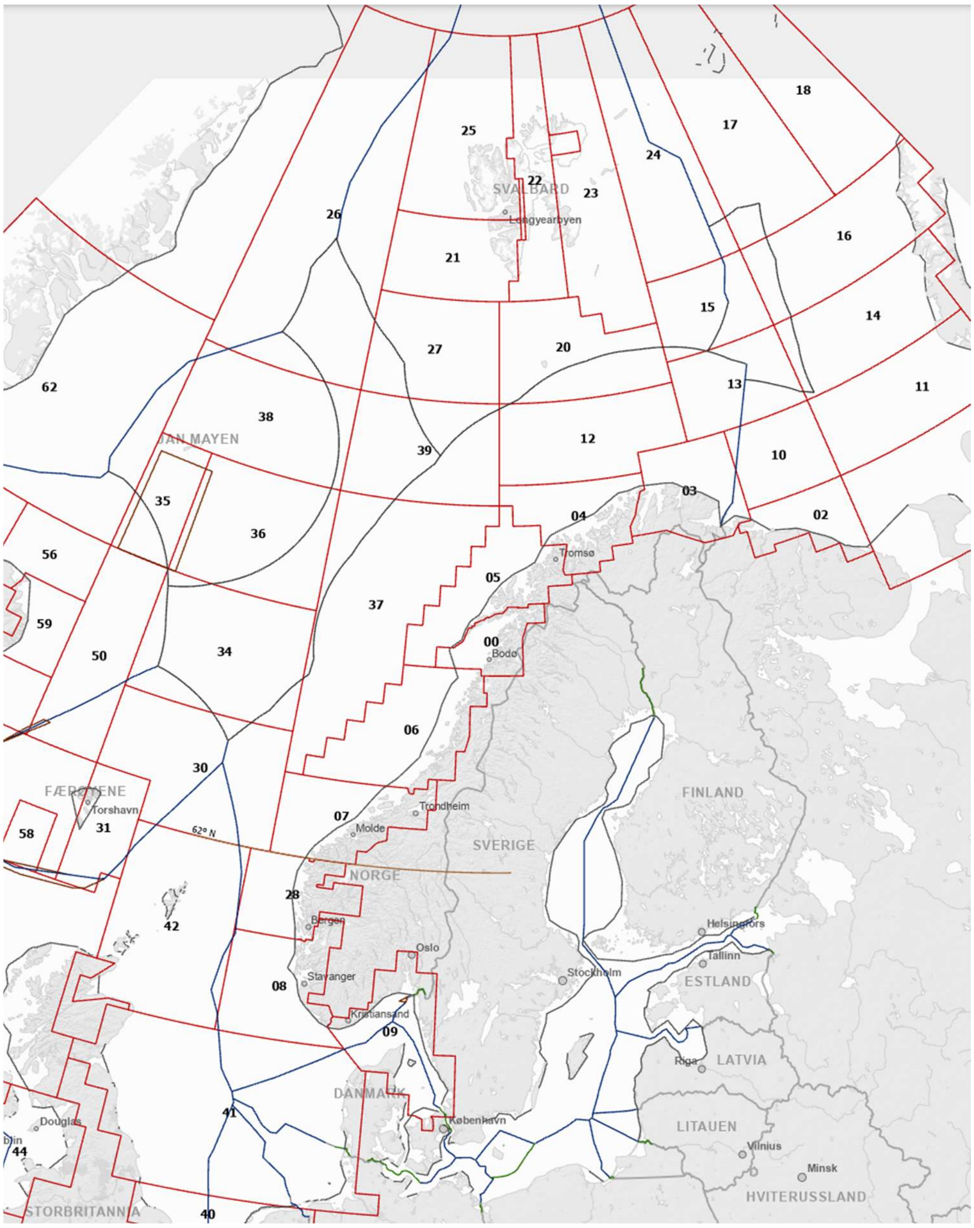

Figure 26 – Map showing Exclusive Economic Zone (blue lines) and main statistical areas (red lines and numbers) around the Norwegian coast and Svalbard. It was generated using the Directorate of Fisheries map service Yggdrasil (Fiskeridirektoratet, 2023).

C. Model input data

Table 12 – Model input for SPiCT and DLMtool. Landings for Atlantic halibut in Norwegian waters north of 62°N, including allocated landings from unreported areas. CPUE1-4 are survey indices from the Norwegian coastal survey cruise. CPUE1 is the number of halibut divided by distance in nm. CPUE2 is the number of halibut over the minimum catch size divided by distance. CPUE3 is the weight of halibut divided by distance in nm. CPUE4 is the weight of halibut over minimum catch size divided by distance. The minimum catch size was 60 cm until 2010, when it increased to 80 cm. Table 1/2

Year	Landings	CPUE1	CPUE2	CPUE3	CPUE4
1977	732.4692				
1978	651.3395				
1979	1064.3917				
1980	751.4028				
1981	392.5035				
1982	359.4527				
1983	428.5807				
1984	346.8661				
1985	307.105				
1986	307.5834				
1987	315.6354				
1988	218.622				
1989	260.4666				
1990	211.705				
1991	181.7995				
1992	243.512				
1993	259.4926				
1994	172.8209				
1995	184.4717	0.02144389	0.02144389	0.14259536	0.14259536
1996	250.5209	0.04844291	0.02076125	0.16162147	0.14130717
1997	213.2865	0.030012	0.0060024	0.0814563	0.0700893
1998	302.1548	0.06743738	0.00481696	0.08334534	0.07005759
1999	380.4551	0.09205426	0.00484496	0.0902395	0.04468806
2000	412.8147	0.18739353	0.04258944	0.83917388	0.81863958
2001	404.2731	0.16617211	0.11275964	1.42940839	1.35606396
2002	446.7072	0.07058824	0.04313725	1.36705177	1.33663108
2003	504.4354	0.2233677	0.08018328	1.45268994	1.2862201
2004	614.9749	0.17574692	0.09958992	1.7168282	1.62809154
2005	815.8274	0.23172906	0.09506833	1.13397126	0.96161209
2006	1151.8098	0.31042129	0.09608278	1.43294472	1.2268009
2007	1403.438	0.21052632	0.11842105	1.70374146	1.59617309
2008	1539.3084	0.19243986	0.1580756	1.84762551	1.80977606
2009	1445.0503	0.21226415	0.0884434	0.92564137	0.74489588

Table 13 - Model input for SPiCT and DLMtool. Landings for Atlantic halibut in Norwegian waters north of 62°N, including allocated landings from unreported areas. CPUE1-4 are survey indices from the Norwegian coastal survey cruise. CPUE1 is the number of halibut divided by distance in nm. CPUE2 is the number of halibut over the minimum catch size divided by distance. CPUE3 is the weight of halibut divided by distance in nm. CPUE4 is the weight of halibut over minimum catch size divided by distance. The minimum catch size was 60 cm until 2010, when it increased to 80 cm. Table 2/2

Year	Landings	CPUE1	CPUE2	CPUE3	CPUE4
2010	1756.2729	0.25110783	0.05169867	1.25080713	0.77037402
2011	1841.0607	0.28682171	0.13178295	2.83299622	2.49384166
2012	2036.0493	0.29503106	0.10093168	2.11338188	1.56126994
2013	1865.6345	0.33809166	0.15777611	4.54626337	4.0602591
2014	2246.9509	0.25767844	0.05521681	2.08871462	1.52207469
2015	2355.008	0.27199732	0.08223175	1.9275444	1.56371957
2016	2813.5689	0.42754381	0.09654215	2.75220096	1.9382424
2017	2591.7295	0.37651999	0.09613276	3.01889859	2.39451202
2018	2618.2881	0.38957466	0.10040584	2.77867099	2.16136943
2019	3093.0682	0.29346637	0.07558982	1.92764071	1.46303777
2020	2311.9176	0.40261172	0.09102526	2.05013577	1.37878202
2021	2933.5498	0.26570877	0.10762887	2.35721853	1.98346476

D. Criteria results for accepting SPiCT assessment

Table 14 – Criteria results for acceptance of SPiCT assessment of Norwegian halibut north of 62° latitude. Red text marks the tests that fail to meet the requirements. The criteria are found in Table 4.

Criteria	**CPUE1: all individuals**	**CPUE2: individuals larger than the minimum catch size**	**CPUE3: weight**	**CPUE4: weight individuals larger than minimum catch size**
1	0	0	0	0
2	True	True	True	True
3	Catch: Bias p-val: 0.9603 LBox p-val: 0.2248 Shapiro p-val: 0.137 Index: Bias p-val: 0.2884 LBox p-val: 0.5392 Shapiro p-val: 0.9627	Catch: Bias p-val: 0.8452 LBox p-val: 0.5656 Shapiro p-val: 0.1876 Index 1: Bias p-val: 0.1478 LBox p-val: 0.1507 Shapiro p-val: 0.2815 Index 2: Bias p-val: 0.9796 LBox p-val: 0.5563 Shapiro p-val: 0.677	Catch: Bias p-val: 0.9684 LBox p-val: 0.6269 Shapiro p-val: 0.1578 Index: Bias p-val: 0.2384 LBox p-val: 0.0341 Shapiro p-val: 0.0489	Catch: Bias p-val: 0.7997 LBox p-val: 0.5554 Shapiro p-val: 0.1969 Index 1: Bias p-val: 0.2061 LBox p-val: 0.1803 Shapiro p-val: 0.4246 Index 2: Bias p-val: 0.8926 LBox p-val: 0.4823 Shapiro p-val: 0.0273
4	Mohn's rho B/B_{MSY} = 0.048 Mohn's rho F/F_{MSY} = -0.032	Mohn's rho B/B_{MSY} = 0.005 Mohn's rho F/F_{MSY} = 0.017	Mohn's rho B/B_{MSY} = 0.034 Mohn's rho F/F_{MSY} = -0.039	Mohn's rho B/B_{MSY} = 0.024 Mohn's rho F/F_{MSY} = -0.042
5	0.4999999	0.5000003	0.4999999	0.5000002
6	B/B_{MSY} F/F_{MSY} Lower 0.37 0.53 Estimate 0.91 1.28 Upper 2.23 3.07 CI 1.86 2.54 Magnitude 1 1	B/B_{MSY} F/F_{MSY} Low. 0.51 0.54 Est. 0.98 1.08 Upp. 1.90 2.15 CI 1.39 1.60 Mag. 1 1	B/B_{MSY} F/F_{MSY} Low. 0.54 0.52 Est. 1.01 1.09 Upp. 1.89 2.26 CI 1.35 1.74 Mag. 1 1	B/B_{MSY} F/F_{MSY} Low. 0.50 0.51 Est. 0.98 1.07 Upp. 1.95 2.24 CI 1.45 1.73 Mag. 1 1
7	Distance: Trail 1 0.04 Trail 2 0.01 Trail 3 0.01 Trail 4 0.01 Trail 5 0.01 Trail 6 0.00 Trail 7 0.01 Trail 8 0.00 Trail 9 0.01 Trail 10 0.01	Distance: Trail 1 0.00 Trail 2 0.19 Trail 3 0.06 Trail 4 0.05 Trail 5 0.00 Trail 6 0.03 Trail 7 0.33 Trail 8 0.00 Trail 9 0.07 Trail 10 0.06	Distance: Trail 1 0.02 Trail 2 0.00 Trail 3 0.01 Trail 4 0.09 Trail 5 0.01 Trail 6 0.06 Trail 7 0.01 Trail 8 0.05 Trail 9 0.01 Trail 10 0.01	Distance: Trail 1 0.06 Trail 2 0.04 Trail 3 0.05 Trail 4 0.00 Trail 5 0.06 Trail 6 0.08 Trail 7 0.05 Trail 8 0.14 Trail 9 0.06 Trail 10 0.07