

Recent recovery and future prospects of the northeast Atlantic halibut stock

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Abstract

Atlantic halibut (*Hippoglossus hippoglossus*) has been commercially exploited in the northeast Atlantic Ocean for at least two centuries, but today the Norwegian fishery is the only remaining targeted commercial halibut fishery. The regulation of the Atlantic halibut fishery in Norway is divided between two management units along the Norwegian coast, north and south of 62°N. Here we tell the story of the largest and most economically significant Norwegian halibut population north of 62°N. The status of the stock was for the first time assessed, using an index of relative abundance derived with a model-based approach from survey data for a non-target species using reconstructed historic landings to inform a Stochastic Surplus Production model in Continuous Time (SPiCT). Our analyses reveal a stock that has recovered from depletion and now again sustains a significant fishery. However, recent landings have reached a level that raises concerns about the sustainability of the fishery. We provide suggestions on how this long-lived species may be assessed and managed to avoid stock collapse. Our approach of using non-targeted survey data to enable an analytical stock assessment with SPiCT may translate to other recovering Atlantic halibut stocks as well as other data-limited to data-moderate long-lived stocks.

Keywords: fisheries management; *Hippoglossus hippoglossus*; long-lived species; stock recovery; overfishing; population decline; stock assessment; surplus production model; SPiCT

Introduction

Atlantic halibut (*Hippoglossus hippoglossus*) has been commercially exploited in the northeast Atlantic Ocean for at least two centuries (Munroe et al. 2015). Historically, two stocks of a similar size were found in Norwegian and Icelandic waters. However, the Atlantic halibut fishery in Norwegian waters is the only remaining commercial Atlantic halibut fishery in the northeast Atlantic. In Icelandic waters, the landings have declined by 85% over the past 35 years and the stock is expected to remain at low levels the coming years, despite a ban on targeted fishing since 2012 (Cadrin et al. 2022).

Atlantic halibut has a long history of exploitation in Norway (Haug 1984). The fishery in Norwegian waters was conducted with longlines in coastal waters and at fishing banks until 1936, when Atlantic halibut gillnets were introduced (Haug 1984). The gillnets were highly effective when placed in deep water at spawning grounds and led to significantly increased landings in 1936 and 1937, followed by low availability of Atlantic halibut. During World War II, fishing effort for Atlantic halibut decreased, probably facilitating stock recovery (Haug 1984). Intensive fisheries for Atlantic halibut resumed after World War II with high catches until 1950. A steady decline in landings at all fishing grounds followed thereafter, with the lowest amount ever recorded in 1995. Landings increased towards and after the millennium North of 62°N, particularly in the three northernmost counties in Norway (Norwegian Directorate of Fisheries 2022). The increase was driven by an increase in gears and boats, and the utilization of new and effective technology like long lines on

drums (Norwegian Directorate of Fisheries 2022). Landings south of 62°N have remained low at less than 3% of total landings in recent years. Atlantic halibut is also a popular target species for tourist and recreational fishing in Norway. Total catches in the recreational fishery are unknown but assumed to be minor compared to commercial catches, likely representing less than 10% of total catches (Ferber et al. 2023, Zimmermann et al. 2024).

The biology and the fishery of the northeast Atlantic halibut was well described in the 1980s. However, the stock has received little attention since and has often been ignored in ecosystem reviews (e.g. Kjesbu et al. 2022, Pedersen et al. 2021), with few exceptions (Pedersen et al. 2018, Planque et al. 2014). The limited new information about the biology of this long-lived species, along with the absence of stock assessments, poses an additional challenge for its management.

The regulation of the Atlantic halibut fishery has changed over time and was different in two management areas along the Norwegian coast, north and south of 62°N latitude (Haug 1984, 1990, Høines et al. 2009, Norwegian Directorate of Fisheries 2022). It is unclear whether the management units adequately match genetic stock structure, as current knowledge on population genetics in the NE Atlantic is limited and mismatches are common for many fish stocks (Reiss et al. 2009). The fishery has been regulated by gear-, bycatch, and no-catch period regulations. In addition, the minimum landing size (MLS) has gradually increased (50 cm in 1937, 60 cm in 1979, 80 cm in 2010, 84 cm in 2023; Haug 1984, Høines et al. 2009). It is also mandatory to release all Atlantic

halibut of more than 2 metres because of environmental toxins (Høstingsforskriften 2022, §51; Nilsen *et al.* 2016).

In this paper, we aim to tell the recent story of the Norwegian Atlantic halibut stock north of 62°N. The status of the stock is for the first time assessed by utilizing the available data, reconstructed historic landings, and modelled survey indices to provide stock estimates (e.g. exploitable biomass and fishing mortality) based on the Stochastic Surplus Production model in Continuous Time (SPiCT; Pedersen & Berg 2017). Because fisheries-independent data was from surveys not designed to monitor halibut, a survey index was estimated with a generalized additive mixed model (GAMM) to account for data limitations and the heterogeneous distribution of the species along the coast. In ICES, SPiCT is the recommended assessment model (ICES 2024) for assessing category 2 stocks (data-moderate stocks suitable for assessment with surplus production models; ICES 2022c). Surplus production models, also called biomass dynamics models, track changes in exploitable biomass over time by integrating population dynamics such as recruitment, growth, natural mortality, and fishing mortality into total biomass, reducing the need for detailed information on stock structure and life history. The model is described in the methods section. We provide suggestions on how this long-lived species may be assessed and managed to ensure a sustainable fishery in the future. This work was the basis for the Atlantic halibut advice provided by IMR in September 2024 (Zimmermann *et al.* 2024). Our approach may translate to recovering Atlantic halibut stocks, as well as other data-limited to data-moderate, long-lived stocks. The data and the code are available (<https://hdl.handle.net/11250/3188315>) to ensure transparency and to allow their utilization in education and training.

Biology and distribution

Atlantic halibut is the largest groundfish in the North Atlantic (Bowering 1986). This demersal species thrives at a few metres' depth to below 1000 m (Haug 1990). The species' main distribution area is the Norwegian coast, and the shelf areas surrounding Iceland, the Faroe Islands, and southern Greenland. The knowledge about local and regional population structures is limited, despite several tagging and genetic studies (Haug 1990). Spawning in fjords indicates separated populations along the coast (Seitz *et al.* 2014).

Knowledge about the Atlantic halibut's early life stages in the wild is limited. The eggs are bathypelagic and found at 100–300 m depth and only few Atlantic halibut larvae have been found in the wild (Bergstad & Gordon 1993, Haug 1990, Haug & Sundby 1987a, 1987b). Atlantic halibut larvae undergo a substantial metamorphosis process before they settle at the bottom around 90 days post hatching (Haug 1990). The eggs and the larvae are dispersed by currents in the area (Haug *et al.* 1984). Immature individuals are stationary in fjords and coastal areas at depths of 20–60 m for the first 3–6 years (Haug 1990). Most halibut perform short migrations within the same region (Godø & Haug 1988). However, a small proportion performs long migrations, sometimes crossing deep water areas in the North Atlantic (Bowering 1986, Haug 1990). These long migrations are likely to cause mixing of geographically separate stocks.

The Atlantic halibut undergoes spawning migrations (Devold 1938, Haug 1990). The spawning grounds are found in

fjords, deep trenches at the coastal banks, and at the edge of coastal banks with mud or clay bottom (Devold 1938). Spawning happens at depths of 300–700 m, at 5°C–7°C from December to March, with a peak in January–February (Kjørsvik *et al.* 1987). Females are batch spawners and produce 0.5–7 million eggs (3-mm diameter) depending on body size (Haug & Gulliksen 1988). After spawning, Atlantic halibut disperse and migrate to feeding grounds (Kjørsvik *et al.* 1987). Devold (1938) suggested that Atlantic halibut return to the same spawning grounds, which later was supported by tagging experiments (Godø & Haug 1988). There is also increasing evidence of return migrations to non-spawning areas in the NW Atlantic (Ransier *et al.* 2024).

The growth rates of females and males are similar until they reach age 4–6. Thereafter, females grow faster than males (Haug 1990). The age and length at sexual maturation vary with sex, as male Atlantic halibut mature around 80 cm and 7 years, while females mature around 110 cm and eight years (Haug 1990, Høines *et al.* 2009, Sigourney *et al.* 2006). There is also spatial variation in length of maturation (Shackell *et al.* 2019). The late maturation makes Atlantic halibut vulnerable to recruitment overfishing. Male size-at-age flattens out at age 10–12 and a few years later for females. Female Atlantic halibut can reach over 3 m, and males can reach over 1.75 m, and both can become 50 years old (Armsworthy & Campana 2010, Devold 1938). Males rarely exceed 50 kg, while females grow significantly larger.

Material and methods

Fisheries statistics

Landings from 1905 to 1977 were reconstructed using annual Norwegian fisheries statistics reports, and landings were standardized to round weight (retrieved from Statistics Norway, www.ssb.no. See Lindgård (2023) for detailed description).

Official landings of Atlantic halibut from 1977 to 2023 were retrieved from the Norwegian Directorate of Fisheries. Landings were categorized based on whether they were caught in Norwegian areas or abroad. The Norwegian areas were divided between north and south of 62°N, in accordance with the management units established by the Norwegian Directorate of Fisheries. Some landings in the period 1977–1991 lacked catch area information and were thus allocated to the landings in Norwegian waters, based on similarities in fishing gear composition. These allocations were further distributed to north and south of 62°N based on the management units' respective share of the annual Norwegian landings. No individual length data by gear, and thereby no selectivity data from the commercial fishery is available.

This assessment does not include landings by tourist and recreational fishing, except sold and thus reported recreational landings.

Survey

The Norwegian coastal survey Q4 (ICES survey code: A6335/BTr Q4) constitutes the best available fisheries-independent time series for Atlantic halibut stock north of 62°N, as it has the best coverage of the halibut distribution area. The dataset was retrieved from The Norwegian Marine Data Centre. The annual survey conducted in October–November covered coastal areas, fjords and ocean banks from 62°N and north along the Norwegian coast to the Russian

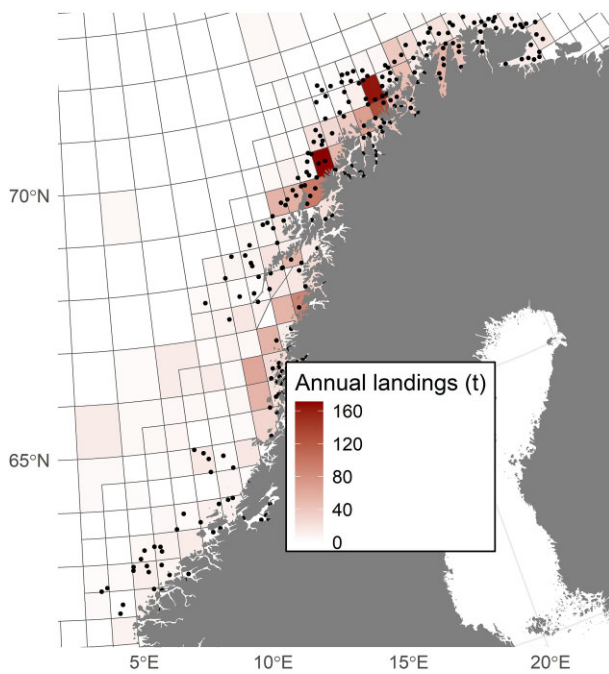


Figure 1. Coastal survey stations in 2022 (black dots) and mean annual landings (colour saturation in squares) of Atlantic halibut in 2012–2022 per statistical grid cell. Large grid cells are 60 nautical miles, small cells 30 nautical miles in the latitude direction. Landings include only reported landings (Norwegian landings slips register, Norwegian Directorate of Fisheries).

border (Fig. 1). The survey started as two sub-surveys from 1995 to 2002, where one had a fixed station grid, and the other only partly fixed stations. These were merged to one survey in 2003. The three surveys were treated as one time series, as they covered the same area and had similar station grid and sampling gear.

The dataset was filtered for fixed stations where the Campeleen 1800 shrimp trawl performed correctly. A standard door spread of 47 m was assumed for the time series. For stations lacking sampling distance, the parameter was set by multiplying sampling durations with a standard trawling speed of three knots.

Survey indices

A biomass index was estimated from catch per unit effort (CPUE, weight-per-distance-towed) data using a GAMM. Because the coastal survey was not designed to target Atlantic halibut and due to the patchy distribution of the species linked to complex bathymetry and ecosystem structure along the coast, GAMM provide a more flexible and suitable approach to standardize survey data than design-based approaches.

The GAMM to estimate the biomass index was implemented using the `sdmTMB` package (Anderson et al. 2024). CPUE per size group (over/under MLS) was modelled with a Tweedie distribution that included year as categorical intercept, bottom depth as continuous fixed effects with a thin-plate penalized smooth splined (restricted to five knots), and spatiotemporal Gaussian random effects ω with first order autoregressive (AR1) structure across

years:

$$CPUE_{s,a,l} = Year_{a,l} + s(Depth_s) + \omega_{s,a} + offset(distance),$$

with l as size group, station s , and year a .

Correlation structures of the Gaussian random fields were modelled as stationary Matérn in space. The latent haul was AR1 correlated in length and included to account for unexplained variation within each haul. The spatial meshes for the Gaussian random fields were built using the triangulation method provided by R-INLA (Bakka et al. 2018), with a minimum allowed distance between points of 40 km and a 100-km maximum edge distance, and the coastline as barrier to prevent correlation across fjords over land. Distances were determined based on data exploration and model selection. Estimated CPUE was predicted in time and space across equally spaced interpolation grids with grid cells of 10 km². Bottom depth was included for the midpoint of each grid cell using GEBCO bathymetric data (www.gebco.net). Biomass and abundance estimates, and their respective uncertainty, represent integrations of the estimated quantities across the entire grid for each year.

The survey index used for SPiCT modelling should be based on the part of the stock targeted by fisheries (Pedersen & Berg 2017). The index therefore only included individuals above the MLS to reflect the change in the fishable biomass. In the absence of size or age data from the commercial fishery, we were not able to estimate the fishing selectivity explicitly, and we considered the exclusion of individuals below MLS from the index estimation as acceptable approximation following Kokkalis et al. (2024).

Assessment model

Surplus production models are used for stock assessment when information about age- and size-composition is limited or lacking (Pedersen & Berg 2017). The surplus production models use time series of catches and biomass indices to calculate the relationship between the stock size and the biomass production, known as the production function (Pella & Tomlinson 1969).

SPiCT is a state space surplus production model developed by Pedersen & Berg (2017). SPiCT models the stock dynamics and fisheries dynamics and can reflect the errors and uncertainty of parameters in the results. SPiCT estimates the exploitable biomass and fishing mortality and reflects the uncertainty of estimated model parameters and management quantities.

SPiCT was run in R following the recommended procedure and initial parameter settings of Mildenerger et al. (2022). The input data were the fisheries statistics from 1977 to 2023 from Norwegian areas north of 62°N and the survey index based on the Norwegian coastal survey Q4 (A6335/BTr-Q4.)

For stocks lacking historical catch data or having 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 function by fixing the parameter $n = 2$ promotes the stability of the model (ICES 2022b).

For a SPiCT assessment to be accepted and used in an official ICES advice, it needs to fulfil several criteria (ICES 2022a, Mildenerger et al. 2022). Tests were therefore executed to check if the assessment fulfilled the criteria (see

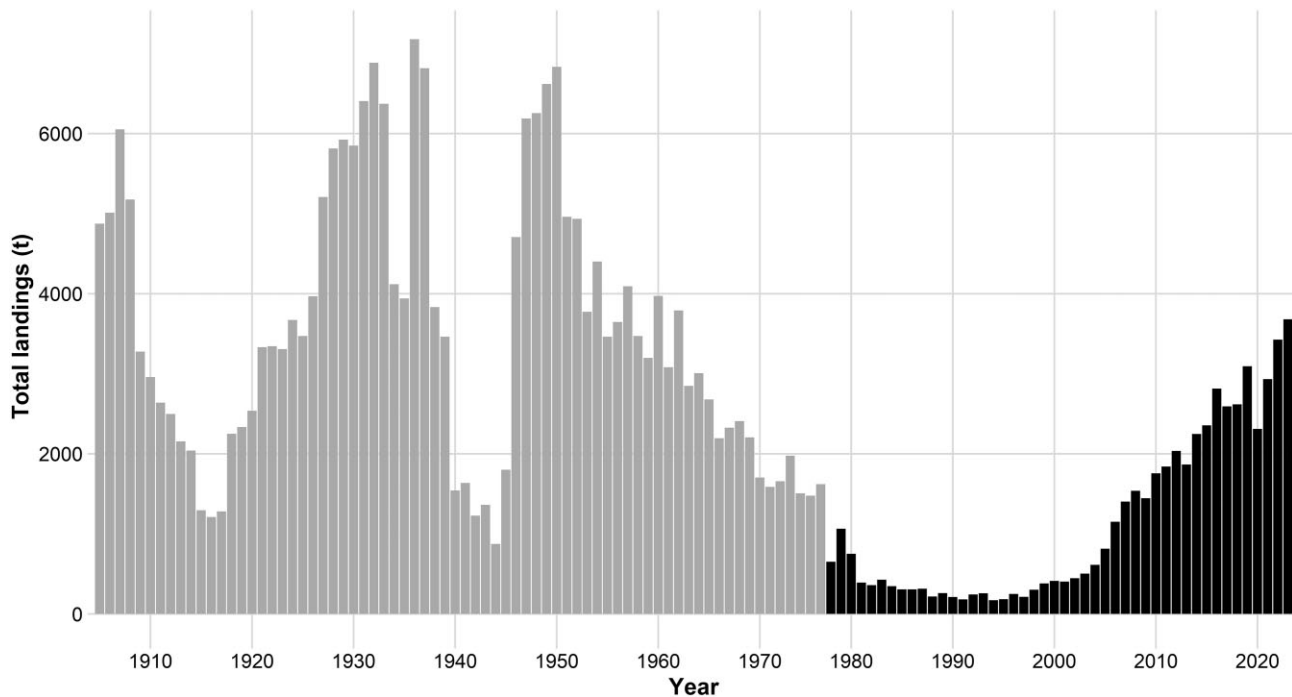


Figure 2. Atlantic halibut landings in Norway in tonnes of round weight from 1905 to 2023. Landings from 1905 to 1976 (light bars) are retrieved from Norwegian Fisheries Statistics and include landings from Norwegian waters (see Lindgård 2023), while landings from 1977 to 2023 (dark bars) are retrieved from the Norwegian Directorate of Fisheries database, and includes only landings north of 62°N, and this period is used in the assessment.

Supplementary S1). Limitations and sources of error are discussed in Supplementary S2.

Results

Fisheries statistics

The reconstructed landing data used in the assessment includes the last part of the decline seen in the historical graph (Fig. 2). Landings then stabilized at a historically low level for around 20 years. An upwards trend began around the turn of the millennium, bringing landings to late-1950 levels in 2023.

Stock development over time

The index of stock development over time based on fisheries-independent data from the survey confirm a substantial increase from mid-1990s to early 2000 but indicate that the stock biomass stabilized in the period from 2001 to 2010 (Fig. 3). While the initial phase is in line with the strong increase in landings between 1995 and 2001, the levelling-off in the stock index contrasts the changes in landings that may have more than quadrupled since 2001 and nearly doubled from 2010 to 2020 (Fig. 2). The trends in stock biomass for the entire stock and the part of the stock above MLS are closely correlated, suggesting that the stock biomass is dominated by individuals above the MLS (Fig. 3). This pattern has remained consistent over time despite the change in MLS in 2010.

Stock composition

Compared to the commercial landings, the survey data has a broader size selectivity, with a large share of the fish below the MLS (Fig. 4). The discrepancy in size selectivity increased from 2010 onwards when the MLS changed from 60 to 80 cm. However, because weight increases over-proportionally with

size, the different selectivity translated to insignificant differences in biomass (Fig. 3).

Stochastic Surplus Production model in Continuous Time

SPiCT estimated the Atlantic halibut stock to be very small from the start of the assessment period (1977) until the turn of the millennium (Fig. 5). The stock size increased first gradually, then linearly, before it flattened out above the biomass reference point for maximum sustainable yield (B_{MSY}). The estimated stock size uncertainty was low until the introduction of survey observations and increased with increased year-to-year variation in the survey index. Parameter and stock estimates are detailed in Tables S1 and S2, respectively.

The SPiCT estimated fishing mortality (Fig. 5) for the Atlantic halibut stock had the opposite trend of the biomass. The fishing mortality was well above the fishing mortality reference point for maximum sustainable yield (F_{MSY}) in the first approximately 20 years of the assessment period. The trend was downwards facing from the peak around 1980, to the lowest estimated fishing mortality around 2004.

The model estimated catch mostly followed the pattern of the landings in the fisheries statistics (Fig. 2) and was below the production until 1990. Since 1990, the net production was above zero and increasing (Fig. 6), and it peaked in 2005. After 2021, the estimated catch has been larger than production and hence negative net production. During the initial period of the time series, very low biomass resulted in low and stagnant production. SPiCT estimated the biomass and production to move up along the curve from 1999, with both stock size and net biomass production increasing until around 2010. Thereafter, production remained relatively stable while the biomass increased in relation to the carrying capacity K . Uncertainty in catches and production increased towards the end of the time

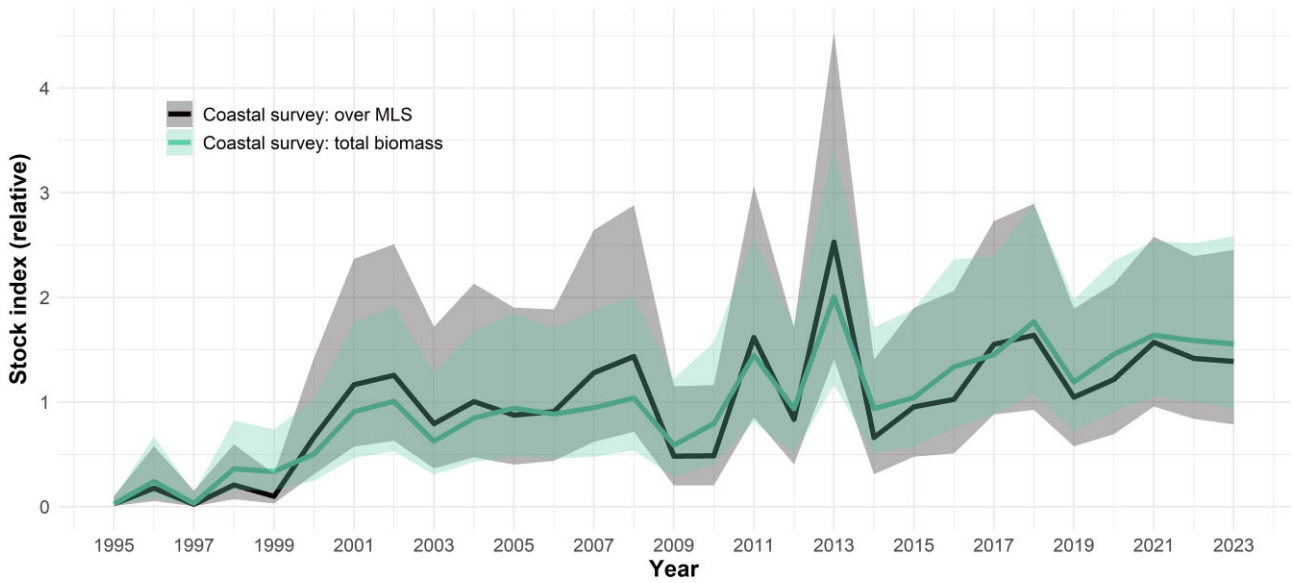


Figure 3. Standardized stock indices from the coastal survey for the entire Atlantic halibut stock (light colored line) and the part of the stock above MLS (dark colored line). Solid lines show mean estimates from spatio-temporal GAMMs scaled to the mean of the time series and shaded areas the 95% confidence intervals. MLS was 60 cm before 2010 and 80 cm since 2010.

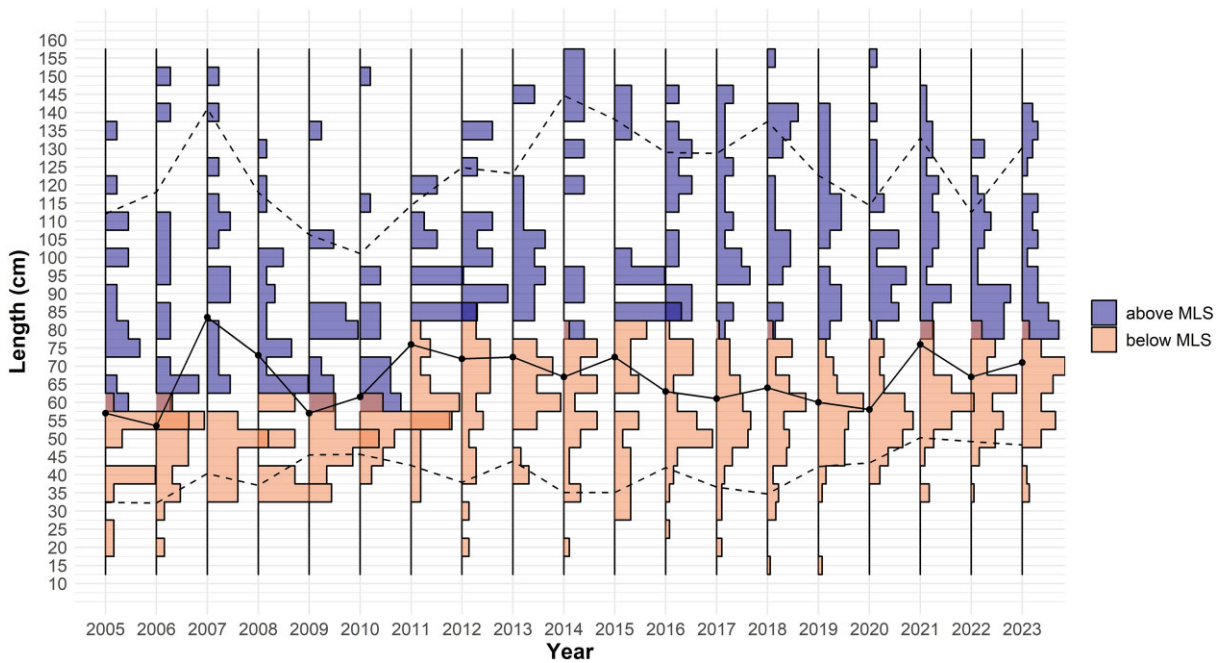


Figure 4. Length frequency distributions of Atlantic halibut per year observed on the coastal survey in 2005–2023. Shown are number of registered individuals per 5 cm length group (bar label at mid-point of each bin) and median (solid line and dots) and 5% and 95% percentiles (dashed lines). Bar colours indicate the MLS (changed in 2010 from 60 to 80 cm).

series, together with the increasing difference in year-to-year survey observations.

Discussion

Status of the stock

Our results show that Atlantic halibut has recovered from depletion and again sustains a significant fishery in northern Norway. Although recent landings are below historic peaks in the 1930s and 1950s, the historic landings before 1977 in-

clude landings from a wider geographic area. Our analysis of the Atlantic halibut stock indicates that recent landings in the northern part have reached a level that likely exceeds sustainable reference points for the stock (Fig. 7).

The trends in stock development were found to be robust to a range of assumptions despite data limitations. Main limitations are the relatively low sample size of halibut in the survey time series and the mismatch between the trawl selectivity in the survey and the gear selectivity of the mostly gillnet- and longline-based commercial fleets. Challenges, strengths, and

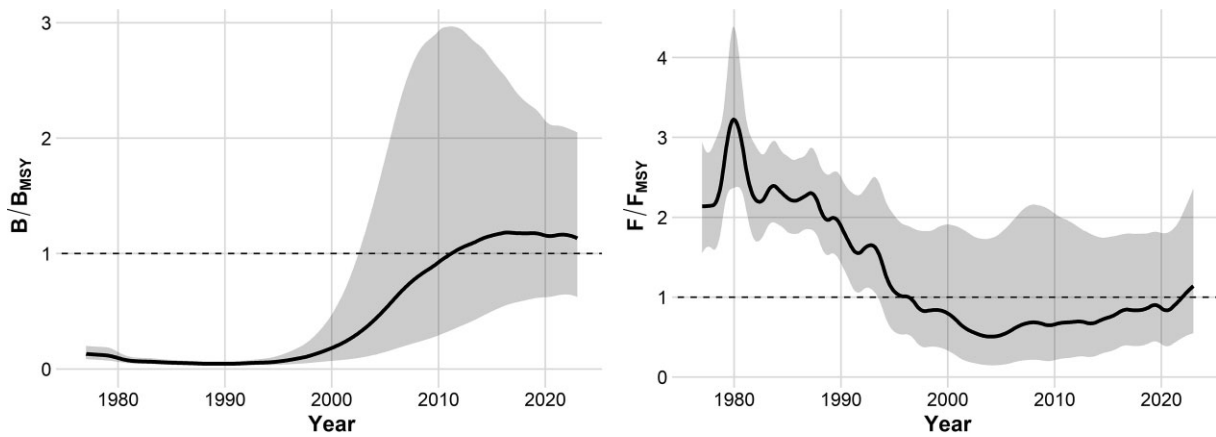


Figure 5. Relative biomass (left) and fishing mortality (right) trends over time for the Norwegian Atlantic halibut stock north of 62°N. Mean estimates are shown by the solid line, and shaded areas indicate the 95% confidence intervals (CI). B equals B_{MSY} and F equals F_{MSY} shown as dashed lines.

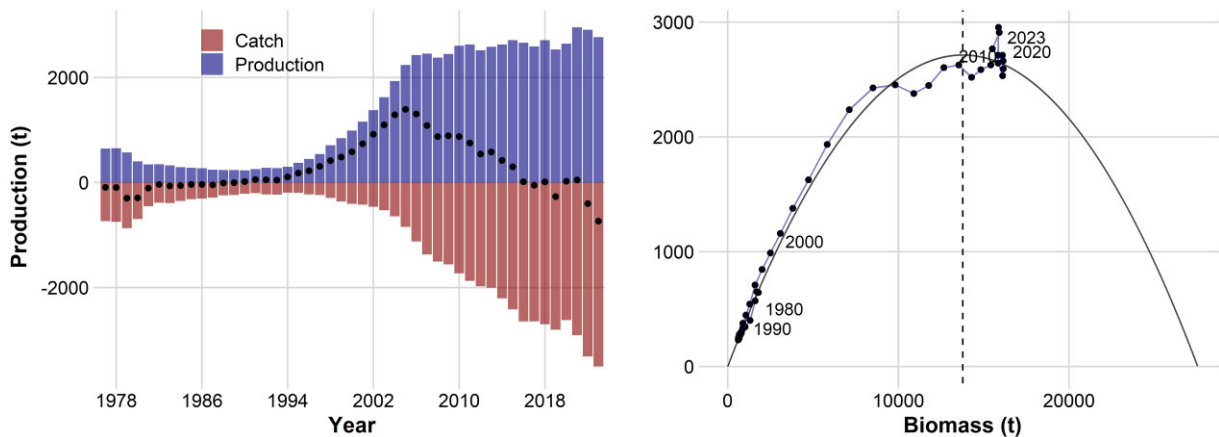


Figure 6. Production and catch of the Norwegian Atlantic halibut stock north of 62°N. The net production (left, black dots) is the difference between estimated production (bars above 0) and observed catches (bars below 0). The estimated production function (right, black line) with the annual production estimates (black dots and blue line) in relation to estimated exploitable biomass. The vertical dashed line indicates B_{MSY}.

weaknesses of the trawl survey index are further discussed in [Supplementary Material S2](#). Our analysis of the Atlantic halibut stock indicates that these limitations do not affect the underlying trend and perception of stock status significantly, but they contribute to the high uncertainty of stock estimates.

The estimated biomass trend from the SPiCT assessment model recovered from a depleted state in the first part of the time series (1977–2000) ([Fig. 7](#)). The stock is, at present, estimated to be overfished and the stock biomass just above B_{MSY} ([Fig. 7](#)). The long-lived Atlantic halibut is sensitive to overfishing, and historical landings ([Fig. 1](#)) show that increased landings over time were followed by reduced yield. According to Bell & Pruter (1958, as cited in [Haug 1990](#)), the above-mentioned pattern was found to be so consistent for Atlantic halibut fisheries that the future of the fishery may be predicted from its history. The same patterns were found for the stocks in the northwest Atlantic ([Cox et al. 2016](#), [Johnson et al. 2024](#), [Shackell et al. 2021](#), [Trzcinski & Bowen 2016](#)). The stock is believed to be in relatively good condition only in the northern part of the Norwegian distribution area. When comparing historical landings with the recent years' continuously increasing landings, we would therefore expect a decline of the stock

biomass unless the positive trend in the northern part of the distribution area is extended to the southern part.

The fishing effort in the halibut fishery is believed to have significantly increased in recent years, primarily as a result of the adaptation of drum longlines (Norwegian Directorate of Fisheries [2022](#)), which increase the fishing effort for each vessel. In addition, the fleet has expanded, with more vessels entering the fishery. While total landings have remained relatively stable, the intensified effort suggests a likely decline in CPUE. Stable or decreasing CPUE combined with increasing effort is a sign of a stock below 0.5 of the carrying capacity k ([Martell & Froese 2012](#)), and indicates an overfished stock, where fishing mortality should be reduced. The stock was estimated to be on the left side of the production function throughout most of the time series ([Fig. 6](#)). The lack of contrast in the time series made estimating MSY difficult. Only an unfished stock around carrying capacity can be investigated to determine a precise carrying capacity ([Bouch et al. 2021](#)). Therefore, our estimate of the carrying capacity and the B_{MSY} may deviate from the true values (S2).

In the newly published assessment report ([Zimmermann et al. 2024](#)), additional stock indices were evaluated, e.g. data

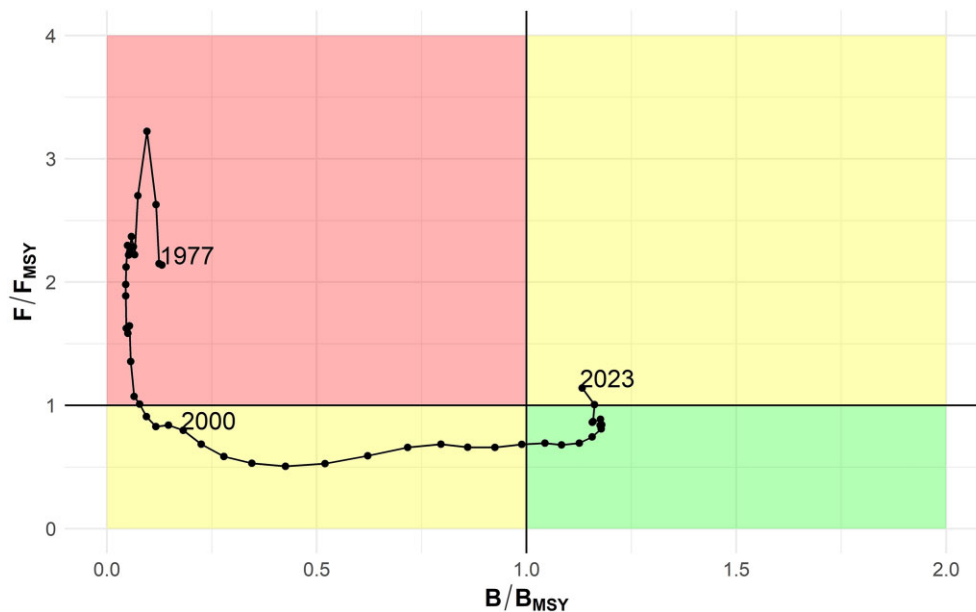


Figure 7. Kobe plot of the Norwegian Atlantic halibut stock (north of 62°N, 1977–2023) showing relative biomass and fishing mortality. Quadrants are divided by B_{MSY} and F_{MSY} : Upper left (low biomass, high fishing mortality), lower left (low biomass, low fishing mortality), upper right (high biomass, high fishing mortality), and lower right (high biomass, low fishing mortality).

from reference fleet, electronic recording and reporting system logbook data, tourist and recreational fishery. When these data were included, the uncertainty of the assessment reduced slightly, but did not change the overall perception of the stock trajectory. As the input data show a unidirectional increase in catches, while the biomass index is stable or increasing, the model struggles to estimate model parameters. To amalgamate partially conflicting information from input time series is a common challenge for surplus production models such as SPiCT (Bouch et al. 2021). One reason is that the data and modelling framework used here does not allow us to account for recruitment explicitly, even though increases in stock biomass as observed here are often the result of strong year classes. Surplus production models assume that all individuals, regardless of age and size, contribute equally, simplifying population dynamics to changes in total biomass as a function of productivity. Therefore, for long-lived species shifts in fluctuations due to year class variations, changes in stock productivity and lags, may not be fully accounted for. Despite these limitations, the assessment model was implemented following recommended best practices (Kokkalis et al. 2024), and showed an acceptable performance even with a default configuration, mainly because of the available long time series with substantial contrast.

Edgar et al. (2024) indicate that recovering stocks' biomass and fishing pressure often are respectively overestimated and underestimated in the assessment year. Although retrospective analysis alone is not suitable to determine bias in stock assessment but rather indicate model misspecification (Cadrin 2025), a precautionary approach suggests taking extra caution when assessing, advising, and regulating recovering stocks to avoid overexploitation.

Tourist and recreational fishing

Atlantic halibut is a popular target for tourist and recreational fishing in Norway. Recreational fishing is especially relevant as

Norway is probably the country in Europe with highest participation in recreational fishing (Hyder et al. 2018). There are few limitations to recreational fishing beyond gear restrictions, and catch reporting is not obligatory for Norwegian residents participating in recreational fishing. Tourists seeking to transport their catch abroad must utilize tourist fishing businesses, which are obliged to register Atlantic halibut catches (Ferber et al. 2023).

Tourist and recreational fishing can have significant negative effect on a fish stock, especially locally (Cooke & Cowx 2006). The landings from tourist- and recreational fisheries should be fully quantified and included in stock assessments and further management (Ferber et al. 2023). The fishing pattern associated with tourist and recreational fishing are expected to deviate from commercial fishing (Ferber et al. 2023, Høines et al. 2009, Norwegian Directorate of Fisheries 2022). In general, fishing pressure from the recreational and tourist fishery is assumed to be higher in the southern part of Norway compared to the northern part. Recreational and tourist fishery in the most populated areas in the southern part may stand for almost all fishing mortality for some species in coastal areas, while approximately 10% in the northern area (Zimmermann et al. 2024). This may be one of the reasons why the Atlantic halibut stock in the southern part of Norway has not recovered as it has in the north.

Climate and fisheries impact

Marine ecosystems alter due to climate change, and up to 85% of species have shifted their distribution (Dulvy et al. 2008, Melbourne-Thomas et al. 2022). Boreal marine ecosystems, where most of the Norwegian Atlantic halibut are found today, and Arctic ecosystems where the Atlantic halibut is expected to be more present in the future, are undergoing significant alterations in the open sea and along the coast (Fossheim et al. 2015, Gordó-Vilaseca et al. 2023, Siwertsson et al. 2024). The distribution range of Atlantic halibut is likely to change

and increase in the north, as new areas may come within thermal reach for the species, while warmer areas in the south become less suitable. The thermal envelope for Atlantic halibut is estimated to be from 3.4°C to 7.9°C, and a shift of almost 8 km/yr, was observed in the Norwegian Sea in the period 2005–2020 (Gordó-Vilaseca *et al.* 2023).

The suitable thermal habitat and abundance of the Atlantic halibut are expected to increase also in Canadian waters (Czich *et al.* 2023). The Canadian Atlantic halibut stock recovery is partially explained by increased suitable thermal habitat caused by increased bottom temperatures in the recovery period. Rising water temperatures along the Norwegian coast may be a plausible explanation for the observed increased abundance of Atlantic halibut in the northern part of Norway, especially after 2000 when abrupt temperature increase was observed (Siwertsson *et al.* 2024). However, disentangling the different environmental drivers and impacts from fishing or other anthropogenic sources remains difficult (Cury *et al.* 2014), especially in the absence of high-quality data on year-class variation, as in the case of Atlantic halibut.

Fishing is usually a stronger driver of stock biomass than climate change in the north Atlantic (Beaugrand *et al.* 2022). Thirty years of low landings indicate that a whole generation of fishermen never, or to a small extent, targeted Atlantic halibut after the fishery collapsed in the 1980s. Low fishing pressure is therefore also an important explanatory variable for the recovery of the Atlantic halibut stock. This is also seen in the historical landings data, especially in the period before and after WORLD WAR II (Fig. 2), as well as for the halibut recovery in the largest Canadian Atlantic halibut stock (Trzcinski & Bowen 2016). As the fishing pressure has increased and reached F_{MSY} -proxy in the last 5 years (Figs 2 and 7), caution should be taken when managing the stock.

Future management perspectives

From a precautionary approach perspective, F_{MSY} is considered a limit rather than a management goal (Horbowy & Luzeńczyk 2012). Considering the relatively high assessment uncertainty, the harvest rate should, therefore, according to ICES (2024), be reduced to ensure a stock biomass capable of sustaining catches close to or above the MSY .

Higher landings and biomass can be obtained by optimizing the MLS (Beverton & Holt 1993). For species with strong sexual dimorphism, MLS should be considered for the larger and later maturing sex (Froese *et al.* 2016). The stock would be less exposed for overfishing, as most individuals have spawned before being caught. The MLS for the Atlantic halibut in Norway is 84 cm, corresponding to male length-at-maturation (Haug 1990). The MLS in US Fisheries is 104 cm (NOAA, <https://www.noaa.gov/>), corresponding to the female length-at-maturation for Atlantic halibut (Haug 1990). We assume that an increase in MLS for Atlantic halibut in Norwegian waters therefore would increase the reproduction potential of the stock. However, a closed loop simulation was used to explore the impact of higher MLS for one of the Canadian stocks and was not found to improve the sustainability of higher harvest levels (Johnson *et al.* 2024).

As the large demersal fish stocks (notably, Atlantic cod and haddock) of the Northeast Atlantic are in decline, the smaller, less regulated demersal stocks experience increased fishing pressure as they become the target species. During the cod collapse in the early 1990s, several unregulated stocks were

overfished. Therefore, as the abovementioned cod species are now again in decline there is a concern about the future of the Atlantic halibut stock and other similar less-regulated demersal stocks. For these stocks, regulations must ensure that the fishing pressure is within safe biological limits.

Our results suggest that science-based management, including output restrictions such as a total allowable catch, should be implemented to ensure a sustainable Atlantic halibut fishery. A precautionary approach in the management of the stock is recommended considering the substantial uncertainty that is exacerbated by data limitations, high fishing pressure (commercial and recreational) and climate change. There is also a need to evaluate the effectiveness of different management measures and how they interact, both through monitoring and simulation analysis. Other regulations such as higher MLS may also help to ensure the resilience of the stock, but the presented assessment framework that ignores stock demographics does not allow for including such regulatory changes explicitly. Alternative assessment methods such as length-based indicators should therefore be explored and potentially integrated into the current assessment framework. Approaches such as the RFB rule (ICES 2024) provide examples of how relative abundance indicators can be combined with length-based indicators. Because length composition data from the Atlantic halibut stock is currently not considered sufficiently consistent there is a clear need for improved data collection.

Generalizability—application to other stocks

Biomass models implemented in SPiCT are used in e.g. shrimp, *Nephrops*, cod, and snow crab assessments in the NE Atlantic. Our study indicates that SPiCT or other surplus production models could be considered in the assessment of long-lived species with relatively stable recruitment due to large eggs or being ovoviviparous, and where data is insufficient for age- or length-based population dynamics. Fish stocks in the NE Atlantic where this model may be applied are e.g. tusk, ling and red fish species. For these usually relatively small stocks, recruitment indices, age and/or length distribution of landings, and stock size indices are often not available. Therefore, age- and length-based assessment models are not applicable. However, whether surplus production models are appropriate requires case-specific evaluation, including simulation testing. Management strategy evaluation frameworks may be useful both when evaluating the performance of stock assessment models and when developing stock-specific advice.

There are other Atlantic halibut stocks with fishing restrictions such as in southern Norway, Iceland, the Faroe Islands and Greenland. These are not yet assessed by using a quantitative assessment model. In the NW Atlantic, four management areas are identified, and the stocks are recovering (Shackell *et al.* 2021, Trzcinski & Bowen 2016). The largest of these stocks, the Scotian Shelf and Southern Grand Banks Halibut Atlantic halibut stock, has recently been assessed with a spatially integrated statistical catch-at-length model, although the spatial structure was not implemented (Johnson *et al.* 2024). Our experiences and findings with the stock assessment of the Atlantic halibut in northern Norway may be transferable to other stocks of halibut and other species, as they demonstrate that important conclusions on stock status to inform management can be efficiently produced despite limited data and capacity.

Conclusions

- The SPiCT model proves to be applicable to assess the long-lived Atlantic halibut stock in northern Norway as landings and fisheries independent data are available. The assessment could be further enhanced through simulation testing and model validation (Carvalho et al. 2021), improved knowledge of key parameters and prior configuration, more information on size and age composition, increased quality of commercial data as basis for a commercial CPUE index, and inclusion of data from recreational fishery.
- Our analyses reveal an Atlantic halibut stock that has recovered from depletion and now again sustains a significant fishery. Yet, recent landings have reached a level that raises concern about the sustainability of the fishery.
- As long as the stock is managed in a sustainable manner, by limiting landings, climate warming will probably support the sustainable development of the stock in the north.
- If landing and standardized biomass indices (fisheries-dependent or fisheries-independent) can be made available, the approach is applicable to other stocks (e.g. Atlantic halibut in southern Norway, Iceland, Greenland) as well as other species (e.g. ling and tusk).

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Author contributions

Edvin L. Lindgård (Conceptualization [equal], Data curation [equal], Formal analysis [equal], Funding acquisition [supporting], Investigation [equal], Methodology [lead], Project administration [lead], Validation [equal], Visualization [equal], Writing – original draft [lead], Writing – review & editing [lead]), Erik Berg (Conceptualization [equal], Formal analysis [supporting], Investigation [supporting], Methodology [supporting], Resources [equal], Supervision [equal], Validation [equal], Writing – original draft [equal], Writing – review & editing [equal]), Fabian Zimmermann (Data curation [equal], Formal analysis [equal], Funding acquisition [equal], Investigation [equal], Methodology [equal], Resources [equal], Validation [equal], Visualization [lead], Writing – review & editing [equal]), and Michaela Aschan (Conceptualization [equal], Formal analysis [supporting], Funding acquisition [lead], Methodology [supporting], Supervision [equal], Validation [supporting], Writing – original draft [supporting], Writing – review & editing [equal]).

Supplementary data

Supplementary data is available at *ICES Journal of Marine Science* online.

Conflict of interest: The authors have no conflicts of interest to declare. E.L.L. was writing his master thesis at UiT (August 2022–June 2023), and this paper was drafted in that period. E.L.L. is now working with Atlantic halibut regulations at the

Norwegian Directorate of Fisheries. There is no conflict of interest, but this information is provided for the sake of transparency.

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Data availability

Data and code underlying this paper are available in the Brage depository at IMR: <https://imr.brage.unit.no/imr-xmlui/handle/11250/3188315>. The available files contain (i) raw data from IMR's coastal ecosystem survey used to estimate the stock; (ii) the estimated stock index used as input for the stock assessment; (iii) total landings time series used as input for the stock assessment; and (iv) SPiCT script and model object. The datasets were derived from sources in the public domain: Statistics Norway (www.ssb.no), Norwegian Directorate of Fisheries (<https://www.fiskeridir.no/statistikk-tall-og-analyse/data-og-statistikk-om-yrkesfiske/apne-data-fangstdata-sedd-el-koblet-med-fartoydata>) and The Norwegian Marine Data Centre.

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