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The effect of quota portfolio composition on optimal harvest strategy and profitability in a multi-species fishery

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The benefits of individual vessel quota (IVQ) management in terms of improved harvest strategy and profitability are well recognized, but there is less focus on how different components of a quota portfolio can influence decisions underlying the effort allocation and profit-maximizing behaviour of fishers. Variations in the components of the quota portfolio may create economic incentives that alter the optimal harvest strategy and profitability. Thus, we study the potential impact of different components of quota portfolio on the intra-annual harvest strategy and profitability in two segments of the Norwegian bottom trawl fleet. By developing a vessel-based spatio-temporal bioeconomic framework, we demonstrate and compare adopted harvest strategies and accrued profits for small and large trawl vessels under three scenarios regarding restrictive quotas in codfish fishery. Our analysis confirms that alternations in the components of the quota portfolio influence the spatio-temporal dynamics of the fishing effort for small and large trawl vessels in different ways, probably due to the differences in vessel-specific characteristics. We also demonstrate that the differences in profit between small and large vessels in part depend on the overall size of the quota portfolio. The economies of scale in the trawl industry are being eroded as the shares of higher-priced species in the quota portfolio decreases. The benefits of economies of scale cannot be reaped as trawlers respond to the reduction in profit by redirecting effort from offshore areas of the Arctic to nearshore waters or staying ashore. Likewise, having small quotas of high-priced species reduces the effectiveness of the IVQ system in meeting management objectives, and could in some cases undermine sustainability outcomes. Our results also demonstrate that both the intensity with which fishers react to the fluctuations in market price levels and fishers' perceptions of location attractiveness are influenced by the components of the quota portfolio.

Keywords: bottom trawling, harvest strategy, individual vessel quota, profit, vessel characteristics.

Introduction

Individual vessel quotas (IVQs) as predetermined shares of the yearly total allowable catch (TAC) have been introduced to improve the harvest strategy and enhance the profitability of fishing firms (Andersen et al., 2010; Flaaten et al., 2017; Bertheussen and Vassdal, 2021). IVQs reduce congregation of effort and short-pulse catches (Homans and Wilen, 2005; Birkenbach et al., 2017, 2020). This eliminates supply gluts and promotes ex-vessel prices due to improved quality and stable landings throughout the fishing year (Dupont et al., 2005; Homans and Wilen, 2005; NOAA, 2011; Tveteras et al., 2011; Scheld et al., 2012; Ashrafi et al., 2020; Pincinato et al., 2022). Therefore, under the IVQ scheme, fishers carefully consider effort allocation decisions with regard to target species, harvest timing, fishing location, and landing sites, taking account of market prices, harvest costs, and biological availability, to attain maximum return from their quota holdings (Grafton et al., 2006; Asche et al., 2007, 2015; Branch and Hilborn, 2008).

To date, most of the related bioeconomic studies have demonstrated the effect of IVQs in terms of improving the harvest strategy and profitability of fishing firms in different fisheries (Larkin and Sylvia, 1999; Dupont et al., 2005; Bastardie et al., 2010; Batsleer et al., 2015; Birkenbach et al., 2020; Ashrafi and Abe, 2021). However, under a multi-species quota-managed fishery, the optimal harvest pattern and profit depend not just on effort allocation attributes but also on the composition of the quota portfolio (QP). A QP is a set of quotas for commercial fish species—these can vary among vessels in both the total quantity and species composition. Hence, an equally important and related area of inquiry within an IVQ scheme concerns examining how an optimal harvest strategy and profit would be influenced under different scenarios regarding components of a QP. There is less concrete information in this regard in the bioeconomic literature. Therefore, we make an attempt to investigate the spatial and temporal variability of fishing efforts as well as vessel profitability as a result of variation in the QP components in a multi-species fishery.

Quotas are divisible assets and fishers can buy and sell quotas (Arnason, 1993; Hannesson, 2014) according to vessel catch and cargo capacity to maximize return per unit of quota. Each fish species in the QP has its own economic rate of return, which is influenced by the seasonally varying distribution of fish stocks over different fishing locations, stock effect, ecological dependence, managerial regulations, ex-vessel prices, discounting, and fishing costs (Hannesson, 2007; Fell, 2009; Hannesson et al., 2010; Smith, 2012; Kvamsdal, 2016; Birkenbach et al., 2020; Kvamsdal et al., 2020a). Hence, it is reasonable to expect change in the optimal harvest schedule and profitability as the components of QP change.

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Under an IVQ scheme, fishing operations would continue until the quota for all species is fulfilled in a given year. On the surface, one would think that it is economically rational to hold a large quota of commercially high-value fish species in the QP to attain higher levels of profit. Yet upon closer consideration, this circumstance does not straightforwardly reflect higher profit, as the economic gain from holding a larger QP against the cost of effort allocation needs to be assessed.

For example, if the biomass is available in areas that are far from port for most of the fishing year, the cost per unit of harvest increases as the fishing activities take place farther afield. Likewise, consider a scenario where a high-value fish species is subject to high price seasonality. Holding a large quota could force fishers to fish the quota at times when the market price is low to make sure that the yearly allotted quotas are fished before the fishing year ends. (Fishing quotas are valid for a given year.)

Correspondingly, consider a situation where the QP consists of a small quota for low-priced fish and a large quota for high-priced fish. Under this circumstance, there might be a strong economic incentive to jointly harvest the low-value fish together with the high-value fish to curtail travel costs. Adopting this harvest strategy, however, requires spatial and temporal overlap of these fish stocks. If there is indeed co-occurrence of these species, the illegitimacy of over-quota harvesting together with landing obligations could compound the adoption of this strategy. According to the landing obligations, all the caught fish, including target species and incidental catch, should be landed and counted against their corresponding quotas (Gullestad et al., 2015). Thus, if a fisher exhausts the quota for low-value fish species, there is no guarantee that there would be no incidental catch of this species in the catch of other available species in the remaining periods of the fishing year. Therefore, even though the joint catch of co-occurring species is a cost-reducing strategy, it increases the risk of overfished quota for low-priced fish, which may subvert the optimal solution (Bertheussen et al., 2020). (Overharvesting is an offence and over-quota catches are recorded and penalized; Quotas are confiscated if fishers contravene regulations.)

In addition to the QP composition that shapes the harvest strategy, firm-specific characteristics should also be considered when aspiring to understand a firm's strategy and profitability (Barney, 1991; Rijnsdorp et al., 2000). In reality, different fishing vessels holding the same QP might represent distinct effort distributions due to the differences in vessel characteristics such as gross registered tonnage (GRT), vessel length, and engine power. Technical features impact harvest decisions, which ultimately influence the cost per unit of effort and profitability (Rijnsdorp et al., 2000; Haynie and Layton, 2010). In light of this, we consider two groups of bottom trawl vessels with a GRT of <1500 and >1500 tonnes (which we shall henceforth call "small" and "large" vessels) from Norway to take the heterogeneity of vessels into account. (There are hardly any small trawlers in Norway. We use this terminology for the sake of differentiation in GRT.) GRT is an indicator of the overall mobility of vessels, which is an influential factor in choosing a fishing location (Standal, 2005), itself a driver with a noticeable impact on location choice, catch composition, and profit (Holland and Sutinen, 2000; Ran et al., 2011).

Using an optimization model, our first objective is to assess and compare the optimal harvest strategy and profitability of these two vessel groups under a suite of different scenarios regarding the QP in a multi-species fishery. Our second objective is to examine how the efficiency of an IVQ system is influenced in response to the changes in the components of the QP.

Our study has several policy implications. First, assessing and quantifying the potential profits from different QPs conveys appropriate signals about the market value of different fish quotas (Copes, 1986; Grafton, 1996; Newell et al., 2005; Lazkano and Nøstbakken, 2016). Moreover, the production possibilities in fisheries depend on the QP, which cannot easily change in the short run as purchasing quotas is costly and it would be considered a long-term investment (Standal and Aarset, 2008; Flaaten et al., 2017). Thus, investigating what combination of fish species in the QP is suitable for different types of fishing vessels helps quota holders to hold a QP that aligns best with the vessel's catch and cargo capacity. In addition, understanding fishers' adaptive behaviour in terms of redistributing fishing efforts in the face of different scenarios regarding restrictive quotas improves fishery managers' ability to predict behaviour under changing policy conditions (Hilborn, 2007; Fulton et al., 2011; Van Putten et al., 2012).

To answer our research questions, first, a brief description of the Norwegian bottom trawl fishery and IVQ system is presented. We then describe a research design and provide an illustration of the optimization model together with the input parameters used in the analysis. Following the presentation of relevant results, immediate insights are considered.

Overview of the Norwegian bottom trawl fishery

From the 1930s, licensed trawlers started to fish in Norwegian waters (Holm, 2001). Currently, bottom trawling is a common technique used to harvest commercially important codfish, which consists of Northeast Arctic (NEA) cod (*Gadus morhua*), saithe (*Pollachius virens*), and haddock (*Melanogrammus aeglefinus*; Asche et al., 2014). Since the 1980s, in Norway codfish fishery has been managed through the yearly TAC and IVQs (Standal, 2005). A codfish QP consists of a quota package that gives a trawl vessel the right to catch a certain volume of cod, saithe, and haddock. These three commercially important species constituted >73% of the total catch of the bottom trawl fleet in 2021. The most and the least economically valuable fish species in the QP are cod and saithe, respectively. The quota management scheme manages each species individually, meaning that each fish species receives a separate quota on an annual basis.

The vessel quota (base quota) was initially linked to vessel size. For several decades, these initial allocations have been a fixed share of the vessel group quota allocation. In the early 1990s, the individual transferable quota system was introduced. This management regime enables vessels to buy additional quota (Norwegian: strukturkvoter). This gives fishers relatively large freedom in constructing their own QP according to the vessel's catch capacity to maximize the expected profit from a given QP. To prevent a heavy concentration of quota ownerships on a few vessels, there is a quota ceiling for each trawl vessel currently defined as four quota factors (i.e. a limit of four times the base quota for all species on one vessel; Standal and Aarset, 2008). The limit of four is a political decision. Under the current management, all vessels with a cod trawl licence are assigned haddock and saithe quotas as well.

The annual allocation of TAC for cod and haddock is agreed together with Russia based on scientific advice from international scientific organizations on how much should be harvested to avert overfishing (Standal and Aarset, 2008; Bertheussen and Vassdal, 2021), as well as on the existing harvest control rule (Kvamsdal et al., 2016). The NEA saithe is managed only by Norway, while North Sea saithe is managed jointly by Norway and the United Kingdom. Once the national TACs are set, they are further portioned off into smaller quotas between coastal vessels and bottom trawl vessels. Based on the "Trawl ladder" tool, 20–35% of the TAC for codfish belongs to the bottom-trawl fleet and the rest is caught by the coastal fleet (Standal and Aarset, 2008; Asche et al., 2014).

Along with the IVQs, the Norwegian fishery adopted landing retention requirements for cod and haddock fisheries in 1987 to reduce discards (Fiskeridepartementet, 1987). Landing obligations require fishers to retain and land all their caught fish, including bycatch species (Nærings og fiskeridepartementet, 2008). The landed catch, including bycatch species, is deducted from individual quotas of each species. To discourage fishers from throwing back the undesirable caught fish into the sea, fishers are allowed to sell the incidental catches (Nærings og fiskeridepartementet, 2013). Today, the discard policy and landing obligations apply to most of the commercially important species in Norway (Gullestad et al., 2014).

Bottom trawling is conducted by double- and single-trawl vessels. The vessels' GRT range from 500 to 4400 tonnes. The bottom trawl vessels are highly mechanized with on-board processing facilities and freezing capacity. Once the trawl nets are hauled on board from the stern, the catch is electronically stunned and conveyed to the on-board factory. The processing of fish usually includes evisceration (gutting), deheading, and packaging in a highly mechanized process. The bottom trawl vessels land primarily frozen codfish. The processing at sea eliminates trips back to port for trawl vessels while maintaining product quality (i.e. minimizing post-harvest losses). Therefore, fishing trip lengths are extended.

The Norwegian fisheries management has imposed a permanent ban on bottom trawl fishing <12 nautical miles (nm) off the coast to protect coastal fishers and to conserve habitats of marine organisms. In addition, trawl vessels cannot be licensed to use other gears.

Material and method

Study area

The map presented in Figure 1 shows that bottom trawling is conducted over a vast area, extending from the offshore areas of the Arctic regions to the northern parts of the North Sea. The large spatial scale of the trawling area is probably due to the stock distribution and migratory behaviour of the codfish. Cod, saithe, and haddock migrate between different habitats over the course of a year to feed and spawn (Olsen et al., 2010).

Region 1 covers the areas farther north, including the Arctic regions of Spitsbergen, Bear Island (Norwegian: Bjørnøya), and Svalbard. Region 2 straddles the boundary between the Arctic regions and the eastern Barents Sea. Region 3 includes the northernmost coast of Norway, where the Norwegian coastline starts to swing eastward. Region 4 is comprised of the north and central regions of the west coast. Region 5 corresponds to the southernmost fishing region in our study. This area lies between southern Norway and the north-west of Scotland.

The main landing sites are the ports of Tromsø and Ålesund. These ports are situated on the border of regions 3 and 4, and region 5, respectively. Trawlers primarily land cod and haddock in Tromsø, while saithe is generally landed in Ålesund.

NEA cod and haddock move seasonally between shallow waters along the west coast of Norway and the deep waters of the Arctic regions (Heino et al., 2012). Mature fish swim from deeper offshore areas of the Arctic (regions 1 and 2) and congregate along nearshore areas to spawn (i.e. central and northern coasts; regions 3 and 4) in winter, and then return to feeding areas of the Arctic (Heino et al., 2012). Mature cod start appearing along the north-west coast around January and spawning peaks during the period of March–April (Hannesson et al., 2010; Olsen et al., 2010). Haddock spawning mainly takes place in late April and early May (Bergstad et al., 1987). Saithe are widely distributed along the southern and central Norwegian coasts and in fjordic waters (regions 3, 4, and 5; Olsen et al., 2010). However, older age classes of NEA saithe can be found in deeper waters further offshore (Jakobsen, 1985; Olsen et al., 2010). Sometimes, younger saithe are also available in the northern parts of the west coast as currents carry the eggs and larvae northward and move them far away from the spawning ground (Jakobsen, 1985; Olsen et al., 2010). Saithe spawn in winter as well, peaking in February (Pethon, 2005).

Model specification

The theoretical point of departure of this study is built upon the general premise in bioeconomic literature that the objective of fishers is to maximize short-term profit with respect to constraints such as quotas (Clark, 1974; Salas et al., 2004). A trawl fisher is the unit of analysis in our model. The QP includes cod, saithe, and haddock. These fisheries are open throughout the year. Based on the current regulations, fishers can harvest at any time they wish. We have five regions (see Figure 1) in which profit-maximizing trawlers can fish the quotas. The representative fisher harvests until the annual QP is exhausted.

The trawler fisher seeks to optimize the allocation of effort over periods, target species, and areas, given annual quotas, period-specific prices, period- and area-specific catch per unit effort (CPUE) rates for target and bycatch species, and fuel costs to maximize annual profit. (According to the regulations, fishers are allowed to sell bycatch species to generate revenue. Hence, in this study, bycatch species (cod, saithe, and haddock) are also included in the analysis. The bycatch is counted against their quotas. Bycatch of species other than cod, saithe, and haddock is not considered in our model. However, fishers are obliged to deliver all bycatch species. The reason for excluding other species is because they are usually of little value and thus we can safely leave them out.) Further, fuel costs differ for steaming and trawling, as do steam times to the different areas from port. The trawlers typically freeze the catch on board and stay at sea for days, sometimes weeks (Sogn-Grundvåg et al., 2020). We thus use two weeks as our time unit, hereafter referred to as a "period".

The problem is a discrete, finite time optimization problem, maximizing the net present value of the annual QP. A number of studies have developed and applied optimization techniques to determine the optimal harvest strategies. This

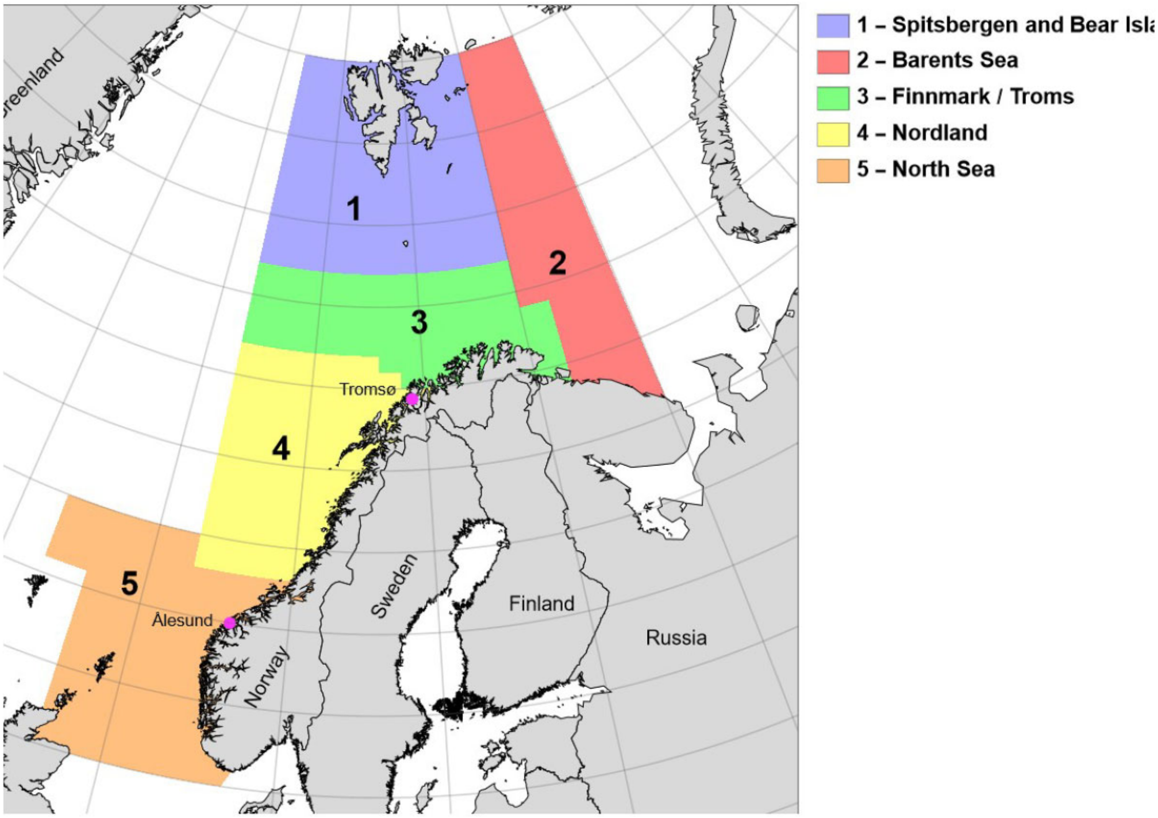

Figure 1. Five heavily trawled areas for cod, saithe, and haddock fisheries. The purple points indicate the locations of Tromsø and Ålesund landing ports.

is a branch of the bioeconomic literature that goes back to Scott (1955) and Clark and Munro (1975). Some recent publications are Alizadeh Ashrafi et al. (2022), Birkenbach et al. (2020), and Kvamsdal et al. (2020b). Another recent contribution may worth noting is Sandal et al. (2021), who developed an alternative approach to solving a relevant class of optimization problems that include finite time problems. Brown (2000) and Squires (2009) provide reviews of this literature.

Our optimization problem can be written as follows:

$$V\ (q) = \max_{\{e_t, a_t\}} \sum\nolimits_{t=1}^{T} \beta^t \times \Pi_t\left(q_t, e_t, a_t\right). \qquad (1)$$

The value function $V(q)$ depends on the initial quota allocation vector $q\ = q_1$ defining annual quotas for each species. In each period, net returns (profits) $\Pi(q_t, e_t, a_t)$ depend on the vector of remaining quota q_t, the effort vector e_t, and the area indicator a_t. The role of the remaining quota q_t in the return function $\Pi(\cdot)$ is as a limit on harvesting and will for most periods be non-binding. There is an upper limit to the amount of effort one is able to employ in each period, and a unit of effort must be targeted towards one species. Effort has known catch and bycatch rates. β is the discount factor.

The problem is deterministic, meaning that prices, costs, catch, and bycatch rates are known for all periods and areas. This setup implies that the representative fisher knows the distribution of the target species in different fishing grounds at a certain time, the cost of switching to different fishing grounds or between target species, and the fluctuations in the ex-vessel prices of the fish species in the QP. Notably, prices do not vary over areas, but costs vary with area and target species.

That the model is deterministic is an obvious limitation of our study, as fisheries in general are subject to significant uncertainties. However, the deterministic model is the first order approximation to the real problem. As we will explain below, our solutions are on feedback form that are adaptive to unexpected perturbations (Sandal and Steinshamn, 1997). Likely the most uncertain part of our model, is the CPUE-rates that will vary with environmental conditions and stock availability. In a similar model, Alizadeh Ashrafi et al. (2022) found the deterministic solution to be fairly robust to variations in the CPUE-rates.

In each period, the representative fisher faces a trade-off between the return from harvest in the present period, which will reduce the remaining quota for future periods, and the (net present) value of future harvests. That is, in period t, the decision problem can be written as follows.

$$V_t\ (q_t) = \max_{\{e_t, a_t\}} \left(\Pi_t\left(q_t, e_t, a_t\right) + \beta \times V_{t+1}\left(q_{t+1}\right)\right). \qquad (2)$$

We have $V(q)\ = V_1\ (q_1)$ and $q_{t+1} = q_t\ - h_t$, that is, the remaining quota in the next period is quota available in the given period minus harvest h_t. The equation for q_{t+1} specifies the transition function in state space. Harvest is $h_t = cpue_{t,a_t} \times e_t$. The matrix $cpue_{t,a_t}$ defines catch and bycatch rates per unit effort for period t and area a_t. The final period problem is different (essentially, $V_{T+1} =\ 0$, or rather, period $T+1$ does not exist)

$$V_T\ (q_T) = \max_{\{e_T, a_T\}} \Pi_T\left(q_T, e_T, a_T\right). \qquad (3)$$

The problem is solved by backward induction. That is, we first solve Equation (3) for V_T over a grid of possible q_T. The solution vectors e_T^* and a_T^* are defined for all possible levels of remaining quota in the final period, that is, they are given on feedback form. $V_{t+1}(q_{t+1})$ is now known and well defined for $t = T - 1$. We can thus solve Equation (2) for V_{T-1} over all possible q_{T-1}, and by iteration solve Equation (2) for all V_t (see Bertsekas, 2005).

The numerical approach relies on brute force, solving the optimization problem for each period over a state space grid. The state space is defined as all possible combinations of quota holdings. We solve the optimization problem in each grid node and use linear interpolation to represent the solution in off-grid locations. In particular, we use interpolation to represent $V_{t+1}\ (q_{t+1})$ in Equation (2). We also define a grid of possible effort allocations, and in each grid node in state space, we consider the objective of the maximum operator over the effort grid and for all areas. Another assumption in the model is that all effort in a given period is allocated to the same area. That is, we assume that the representative fisher only changes area between periods. This assumption is justified by high steaming costs. A similar assumption is used in an empirical effort allocation study (Alizadeh Ashrafi and Abe, 2021). However, our model allows the fisher to switch between target species in any given time period in a specific location. This assumption is due to spatial overlap in the codfish fishery. There is an upper limit e_{max} to the amount of effort available in each period such that $\sum_i e_t(i) \leq e_{max}$, where the index i runs over the elements in the vector e_t.

Three catch quota combinations are examined in the model (i.e. large-, medium-, and small-catch QPs). The state space grid used in the example below runs from 0 to 6000 (tonnes) along the first dimension (cod), from 0 to 4000 (tonnes) along the second dimension (saithe), and from 0 to 2200 (tonnes) along the third dimension (haddock). There are 25 grid nodes in each of the three grid directions, and the total number of grid nodes is $N_Q = 25^3 = 15625$. The effort grid runs from 0 to 90 (hours) and has up to 10 nodes in each of the three grid directions with $N_E = 220$ nodes in total. With five potential fishing areas, there are $5 \times 220 = 1100$ options to consider in each state space grid node for each time period. Since we assume that the fishing behaviour of the representative trawler is based on economic rationality and the adopted harvest strategy is driven by the profitability of fishing, the representative fisher can choose to stay in port if the costs of fishing exceed the catch profit, or if the opportunity cost of using quota in the present period is higher than returns. The model is defined with 26 (two-week) periods, and the total number of period–area–effort–quota combinations that are considered is thus some 446 million.

The fishing profit function is revenue minus cost. [Risk is also an import factor in shaping harvest strategy. However, we exclude risk considerations as a recent study has shown that risk is not a big concern for trawl fishers. For more detailed information please see: Ashrafi et al. (2021).] We define profit function as follows:

$$\Pi_{\mathrm{t}}\ (q_t, e_t, a_t) = R_t\ \left(h_t, q_t, a_t\right) - C_t\left(e_t, h_t, a_t\right). \tag{4}$$

We decompose cost function and rewrite Equation (4).

$$\Pi_{\mathrm{t}}\ (q_t, e_t, a_t) = R_t\ \left(h_t, q_t, a_t\right) - c^F\left(e_t\right) - c^P\left(e_t\right) - c^{MO}\left(h_t\right) - c^A\left(a_t\right). \tag{5}$$

The first term in the profit function is the revenue term and is given by $R_t\ (h_t, q_t, a_t) = rp_t \times \min(h_t, q_t)$. The parameter $r = 66\%$ is the revenue ratio that scales down realized revenues because of revenue-dependent fees and crew wages. The price vector p_t varies over periods. The expression $\min(h_t, q_t)$ applies the quota limitation such that only the harvest h_t that is within the remaining quota is taken into account. Thus, effort levels that result in a harvest larger than the remaining quota will not generate revenue for the excessive harvest, but will generate costs connected to both effort and processing and so on, such that fishers have no incentive to harvest beyond their quota.

The second term in the profit function is fuel costs $c^F(e_t)$ related to effort and processing, and given as follows: $c^F\ (e_t) = p_F\ (F^E e_t + F^P \sum_i h_t)$. The fuel price is given by p_F and is constant throughout the year. The fuel price does of course vary, but we assume fishers have no particular skill in predicting the fuel price and use an expected fuel price in their decision-making. Another reason for implementing a fixed fuel price is that in our study period, the fuel prices were mostly stable. The vector F^E is fuel use factors for the different target species, given as litres per hour. (F^E is a row vector and e_t is a column vector such that $F^E\ e_t = \sum_i F^E(i)e_t(i)$.) Fuel usage for processing is given by F^P as litres per tonnes and is multiplied by total harvest, summed over all species i.

The third and fourth terms in the profit function are provisions and maintenance and other costs. Provisions are estimated as cost per day (c^D), and costs are given as cost per day divided by the average amount of effort per day (e_D) for the fleet and multiplied by total effort: $c^P\ (e_t) = {}^{c^D}\!/_{e_D} \times \sum_i e_t$. Maintenance and other costs are lumped together in the maintenance cost function and given as cost per tonne of catch: $c^{MO}\ (h_t) = (c^M + c^O)\ \times \sum_i h_t$.

The fifth and final term in the profit function is area-specific fixed costs that reflect costs related to steaming to and from the different fishing areas. The function is given as follows: $c^A\ (a_t) = \sum_j 1_j(a_t) \times p^F F^S a^j$. $1_j(x)$ is the indicator function that equals one if $x = j$, p^F is the fuel price as earlier, F^S is fuel usage when steaming, and a^j is the estimated number of hours of steaming related to area j. The function sums over all areas j, but the indicator function makes sure that only steaming costs for the relevant area (a_t) are taken into account.

The final step to specify is the (annual) discount rate δ. We base our parameter value on an estimate for Norwegian fishers, provided by Diekert et al. (2016). The discount factor β depends on the number of periods and is given as follows: $\beta = 1/(1+\delta)^{1/T}$. Table 1A in the Supplementary Appendix reports parameter values and grid settings for the model. Within any particular scenario regarding QP, we run our model for small and large trawl vessels. This enables us to compare the adopted harvest strategy and accrued profitability of small and large trawl vessels for a given QP.

Data

To characterize the harvest patterns and corresponding profits subject to the variations in the components of the QP for large and small trawl vessels, we have combined several datasets, covering the period 2011–2019. Our dataset includes information on 32 codfish bottom trawl vessels. (Some of the codfish bottom trawl vessels target shrimp in good years. However, we exclude these boats from our analysis.) Out of 32 vessels, the GRT of 13 trawl vessels is <1500 tonnes (i.e. small vessels) and that of 19 is >1500 tonnes (i.e. large vessels). Parameters representing GRT for small and large vessels are given in the Supplementary Appendix. This information underpins the heterogeneity between small and large trawl vessels and creates a reasonable justification for dividing the fleet into two segments.

According to the fisheries regulations in Norway, all fishing vessels >15 m in length are required to use an electronic reporting system (ERS). Each vessel has a specific identification code. For each trawl haul at a given time, the transceiver units send latitude and longitude position reports that include vessel identification, time, and date. They also record the geographic locations of the net sets and lifts in latitude and longitude format. This enables us to track the positions of vessels in five selected regions (see the Subsection "Study area") to analyse the spatial and temporal distribution of fishing effort.

In addition, haul-based data from fishers' logbooks contain detailed information about the volume (in tonnes) and composition of the catch per haul (i.e. records of not only the main catch but also other quota regulated species as well as landings of non-quota species; the dataset uses standard three-letter species codes to record any species that are caught by a trawl net). However, for the purpose of this study, we only consider cod, saithe, and haddock in the main and incidental catches due to their high commercial value. Catch is measured in metric tonnes. All catches of cod, saithe, and haddock are counted against the fishers' QP.

Moreover, effort per haul, measured in number of trawling hours, is recorded. In total, 74267, 97049, and 80137 hauls for cod, saithe, and haddock fisheries, respectively, are recorded for the small trawlers, whereas the number of hauls for large trawl vessels reached 160115 for cod, 134916 for saithe, and 10351 for haddock. We define cod, saithe, and haddock fishing based on the catch composition. For instance, if cod weight prevails in the catch composition, we define that haul as cod fishing.

Using catch and effort data, CPUE (catch in tonnes/effort in hours of trawling) is quantified for each time period, each area, and vessel group to ascertain the availability of fish (Campbell, 2004; Zhang and Smith, 2011). The unit of CPUE is fish caught in tonnes per hour of trawling. The logbook also contains information about vessel tonnage, engine power, vessel length, and harvesting time. The logbook data are collated by the Norwegian Directorate of Fisheries (Norwegian: Fiskeridirektoratet).

In order to calculate profit, we further supplement our dataset with economic information such as ex-vessel prices and trawling cost. The Norwegian Fishermen's Sales Organization (Norwegian: Norges Råfisklag) provides weekly ex-vessel prices for the frozen codfish products. The prices are in Norwegian currency (NOK). Using price data and catch records from logbooks, we can obtain the generated revenue for each fishery in each time period in a given region. Due to the landing retention and obligation rules (see the Section "Overview of the Norwegian bottom trawl fishery"), contributions to the revenue of bycatch species are also taken into account in our model. (In this study, the bycatch species in the cod fishery are saithe and haddock, while in the saithe fishery they are cod and haddock and in the haddock fishery they are cod and saithe.)

The two major cost elements of trawl fishery are related to labour and fuel expenses. The fuel cost can constitute up to 50% of the total fishing costs for trawl vessels (Schau et al., 2009; Cheilari et al., 2013; Asche and Roll, 2019). Based on the remuneration system in the trawl fishery, the crew are remunerated ∼30% of the value of the total catch (this encourages the crew to elicit the best efforts to increase the total value of the harvest; Fiskarlag, 2022).

Fuel cost (total fuel consumption × price per litre of fuel) comprises two components: fuel cost during steaming and towing. Unfortunately, information about fuel consumption per fishing trip or per haul is unavailable. Hence, we need to quantify the fuel cost to implement it in our model. In our meeting with trawling companies in Tromsø, Norway, we were advised that bottom trawl vessels on average consume 400 l/h when idling. (When bottom trawl vessels are sitting still in port, they use quite a lot of fuel to provide electrical power for the lights, kitchen, and other equipment.) Steaming adds an extra 100 l/h to the baseline consumption (i.e. 500 l/h). Since towing heavy trawl gear across the ocean floor to target demersal species is energy-consuming, trawling adds 200 l/h (i.e. 600 l/h).

To quantify steaming cost, we first obtain the distance travelled from Tromsø and Ålesund ports to the centroid of five selected regions in kilometres (km). Having latitude and longitude information from the ERS dataset enables us to calculate the distance between different locations. The steaming speed of an average bottom trawler is 10 knots (nautical miles per hour), which is equal to 18.55 km/h. Using this information, we can calculate how long it takes to travel from Tromsø and Ålesund ports to the centroid of five selected regions. Once we find this travel time, we multiply the hours travelled by 500 l/h to find the amount of fuel consumed during steaming. Finally, to obtain the fuel cost associated with steaming, we multiply the consumed fuel by 4.9 NOK, the latter being the average price per litre during the period 2011–2019. The information about the fuel price is obtained from the Guarantee Fund for Fishers (Norwegian: Garantikassen for fiskere). In order to find the fuel cost of trawling (i.e. when the gear is being towed), we first obtain fuel consumption by multiplying trawling hours (i.e. fishing effort) by 600 l/h. We then multiply the calculated numbers by 4.9 NOK.

To work out the effect of different QPs on optimal effort allocation and profit sizes, we requested the QP of these 32 vessels from the Norwegian Directorate of Fisheries. By looking at the quota data, we have realized that largely speaking, codfish bottom trawl vessels hold three different types of QPs, namely (1) large quotas for cod, saithe, and haddock (large QP); (2) medium-sized quotas for cod, saithe, and haddock (medium QP); and (3) small quotas for cod, saithe, and haddock (small QP). Besides the economic importance of these three species that motivates fishers to hold combinations of cod, saithe, and haddock in their QP, under the current management regime, all trawl vessels with a cod licence are also assigned haddock and saithe quotas.

We run our optimization model subject to these three QP constraints. The quota volume is measured in tonnes. The information about quotas in the three different scenarios is presented in the Supplementary Appendix.

Simulation results

In this section, the outcomes of three different scenarios in terms of intra-annual harvest patterns and accrued profits for small and large bottom trawl vessels across five different fishing locations are presented. Three different scenarios are built based on the variations in quota holdings across the trawl fleet. The optimal harvest patterns and profit graphs for

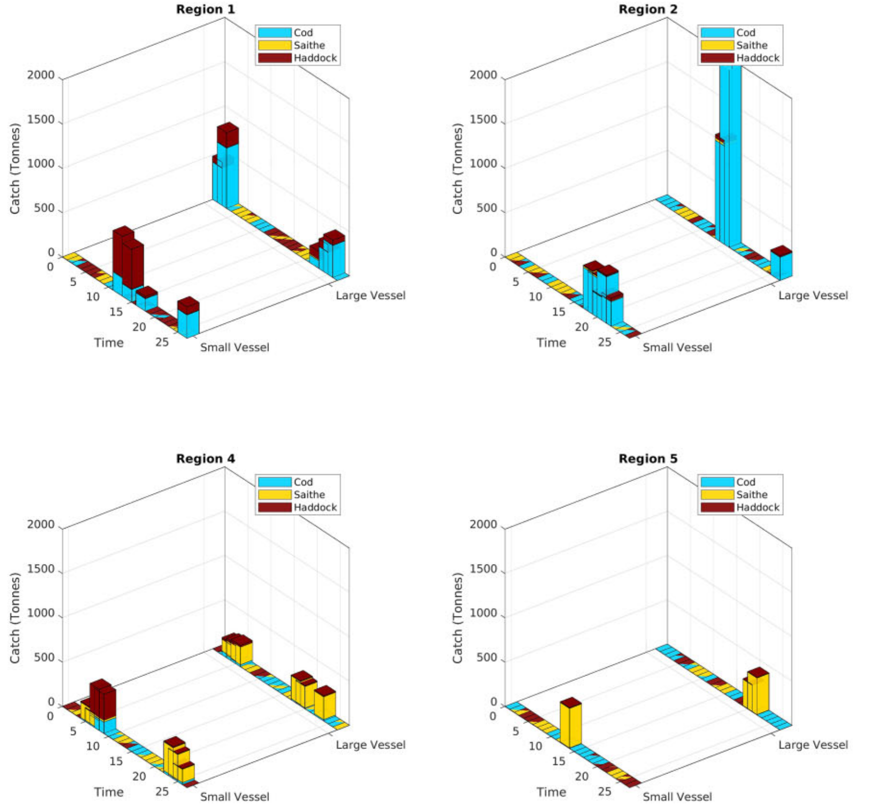

Figure 2. Optimal harvest patterns of the small and lage bottom trawls over the course of a fishing year in five selected regions in the first scenario. The QP in the first scenario consists of a large amount of cod, saithe, and haddock.

small and large vessels are presented. The catch is measured in tonnes while profit is measured in million NOK.

Harvest strategies

Figures 2, 3, and 4 show the optimal harvest patterns from the first, second, and third scenarios for the small and large vessels.

Scenario 1: Scenario 1 corresponds to the situation where the profit-maximizing fisher holds a QP with a large amount of cod, saithe, and haddock. As can be seen from Figure 2, the small trawl starts the fishing year by targeting cod in region 3 (along the north-west coast of Norway), while the large trawl vessel targets cod in region 1 (Arctic region).

Two possible reasons could justify the difference in the choice of location. The large vessel avoids region 3 probably because of the possible effort congregation during the spawning period in winter as cod is harvested together by coastal boats. The small vessel prefers region 3, probably because the harsh climate conditions in the Arctic regions in January preclude the small trawler from fishing cod quota in region 1 as fishing in extreme wind and waves is perceived as more risky for smaller vessels.

Another striking difference between the harvest strategies of the small and large vessels is that at the end of January, the large vessel moves to regions 3 and 4 to target saithe and haddock. The large vessel appears to avoid utilizing cod quota at this time and the caught cod seems to be bycatch in saithe and haddock fisheries. There is one possible economic mechanism behind such a rapid switch from cod fishery in region 1 and changing the harvest location to region 3 to target saithe and haddock.

Increased fish availability due to the spawning migration at predictable sites and times may confer price reductions due to concentrated landings in a short season (Casey et al., 1995; Hermansen and Dreyer, 2010). In other words, the high fish density in region 3 due to aggregative spawning motivates fishers, particularly the coastal fleet, to catch cod due to its high commercial value. This may, in turn, lead to reduced prices and might encourage the large vessel to switch to saithe and haddock fisheries (i.e. commercially less valuable species) and stop using cod quota in the spawning season. Thus, it is a rational strategy for the large vessel to reserve cod quota for the periods when the market price is high.

In contrast, the small vessel stays in region 3 until the end of February and displaces effort to region 4 and again to region 3 to utilize cod, saithe, and haddock quotas. It seems that the caught cod in this period is the main target. Unlike the large vessel, the small vessel intentionally targets cod despite the fact that the cod price is low. This suggests that the large vessel is more responsive to the price reduction in cod than the small vessel.

There is a tendency for both small and large vessels to catch the remaining cod quota outside the spawning season in regions 1 and 2, mostly towards the end of the year. At this time, NEA cod is available in regions 1 and 2 to feed. The rationale behind this harvest strategy is that the price of cod is higher outside the spawning season because of the limited supply of cod as the coastal fleet has already fished its codfish quota (Hermansen and Dreyer, 2010). The small and large vessels reserve about 40% and 80% of the cod quota, respectively, to utilize in this region. One possible explanation for the small vessel keeping less of the cod quota may be related to

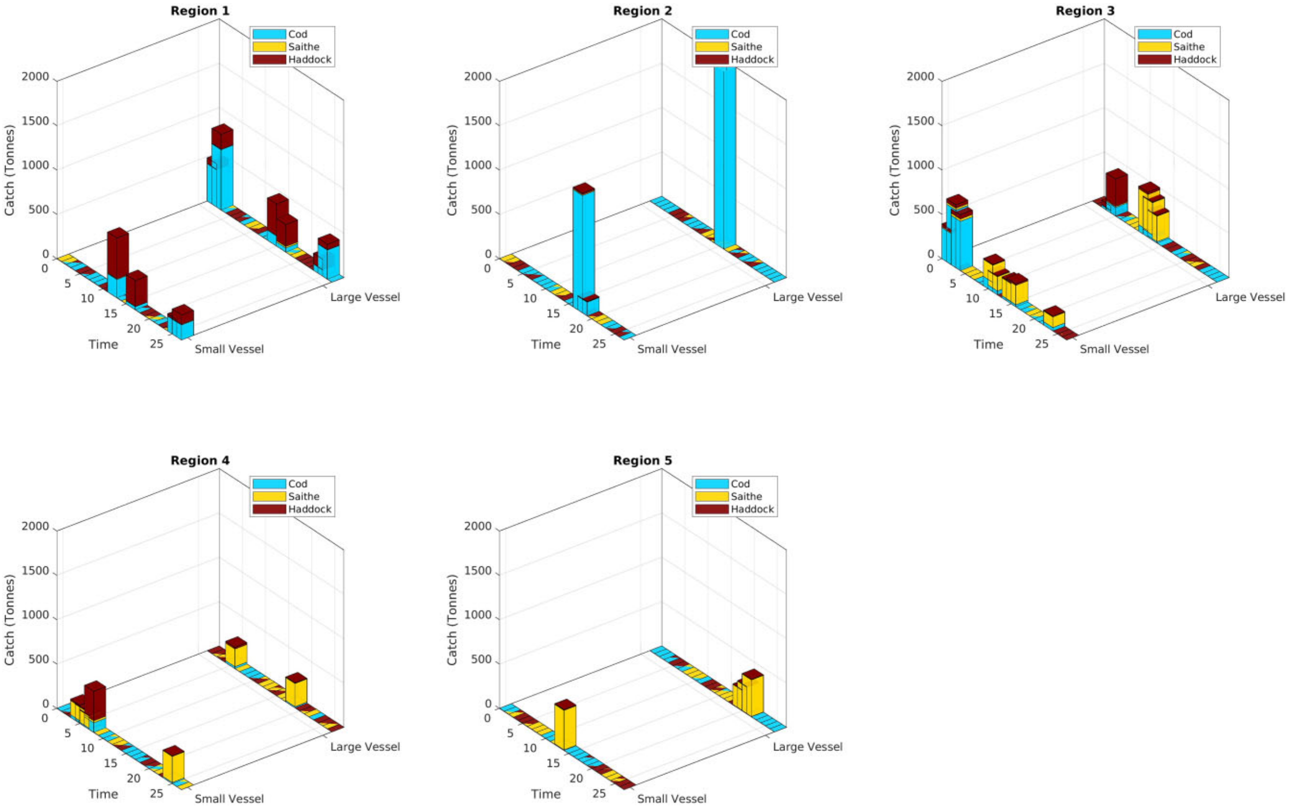

Figure 3. Optimal harvest patterns of the small and lage bottom trawls over the course of a fishing year in five selected regions in the second scenario. The QP in the second scenario consists of a meduim size quotas for of cod, saithe, and haddock.

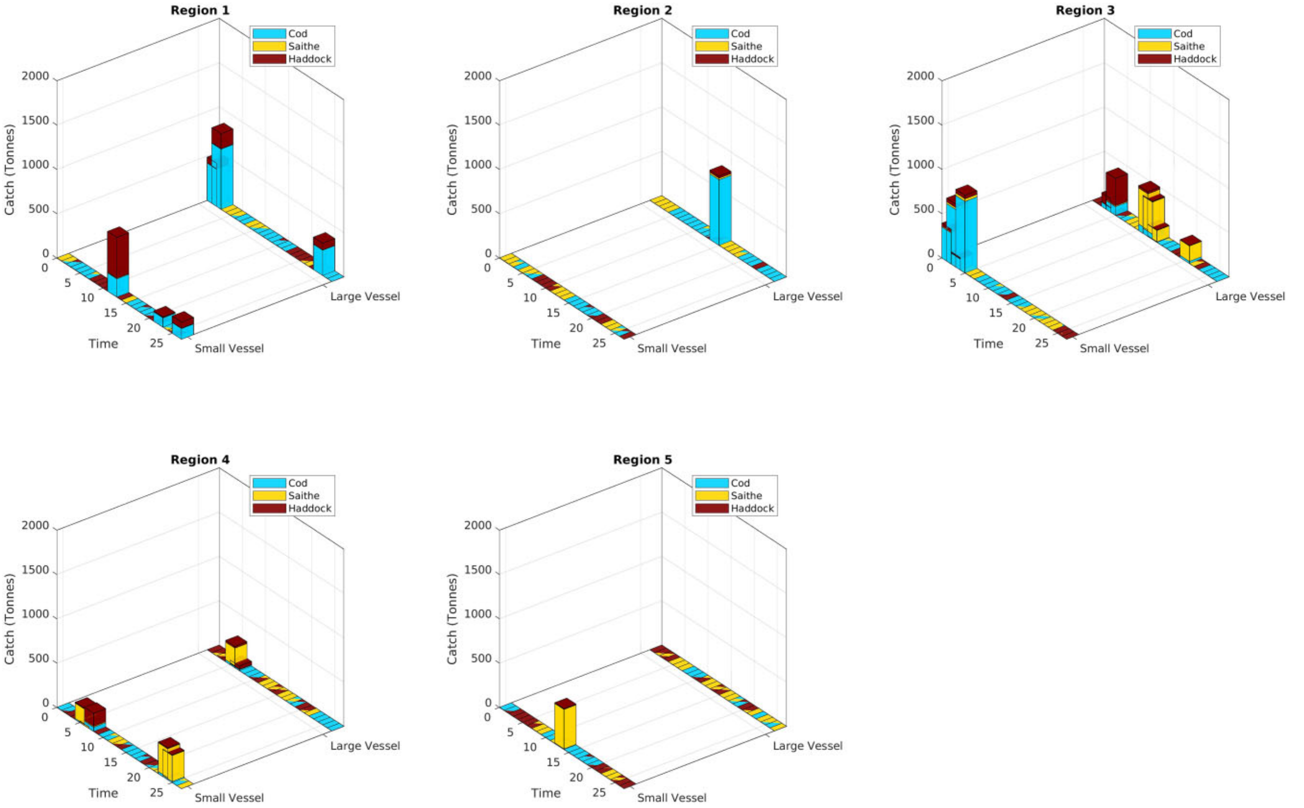

Figure 4. Optimal harvest patterns of the small and lage bottom trawls over the course of a fishing year in five selected regions in the third scenario. The QP in the third scenario consists of a small amount of cod, saithe, and haddock.

vessel-specific characteristics such as the smaller catch capacity. This means that the small vessel keeping a larger share of the cod quota to be utilized in this area and at this time increases the likelihood of being unable to exhaust the quota by the end of the year. Another important point from Figure 2 is that with a large QP, both small and large vessels spread catch over the fishing season.

Scenario 2: The second scenario involves holding a medium-sized QP of codfish. Fishing outcomes are shown in Figure 3. Similar to scenario 1, the small vessel starts with cod fishery in region 3, while the large vessel targets cod in region 1. Another similarity is the swift action of the large vessel in reallocating fishing effort from cod fishery in region 1 to regions 4 and 3 to utilize saithe and haddock quotas.

What is noticeable from the harvest patterns shown in Figure 3 is that the small and large trawl vessels are not operating at full capacity and there are some periods when the vessels lie idle in ports. Holding a smaller QP in comparison to scenario 1 is admittedly associated with lower expected profit. Thus, a profit-maximizing fisher will find it rational to stay ashore and not supply continuously throughout the year to curtail operating costs. There are more idle periods for the large vessel (i.e. 9 periods) than the small one (i.e. 6 periods), which could mean that larger vessels are more sensitive to the reduction in the expected profit than small trawlers. It could also underpin that large vessels have larger capacity and need less time to fill up their quotas. This could be explained by the fact that larger vessels incur higher operating costs.

An interesting fact is that the large vessel stays mostly idle in port during March until the end of April. This is the time when the cod price is low. Observing this behaviour is a strong indicator that large trawlers are more price-sensitive than small vessels. Ceasing fishing operations when the cod price is low is indeed a rational decision to remain profitable. The idle period for the small vessel is mostly at the end of the year (October–December). This period is chosen probably because the small vessel has already fished a large part of the quota during the spawning season early in the fishing year. Moreover, waiting too long to fish cod towards the end of the year prompts fears of ending up with unfished quotas. Another possible reason could be related to the discounting preference. Maybe small trawlers prefer early rewards from landing fish by utilizing quotas at the beginning of the year rather than late rewards from fishing at the end of the year.

As in scenario 1, the larger portion of the cod quota for the large vessel is fished in the offshore area of the Arctic, whereas the small vessel utilizes most of the cod quota in region 3. Another similarity with scenario 1 is that a part of the cod quota is reserved to be utilized at the end of the year in regions 1 and 2 when the cod price is higher.

Scenario 3: In scenario 3, the QP holder has small IVQs for cod, saithe, and haddock fisheries. See results in Figure 4. The lower expected profit of the portfolio lengthens the idle periods for both small (i.e. 13 periods) and large (i.e. 14 periods) vessels. In fact, they remain ashore for almost half the year.

Under this scenario, location choices have been markedly altered. With a small codfish quota, small vessels do not allocate fishing effort in region 2 to target cod and/or haddock. Large vessels avoid region 5 to catch saithe and fish saithe quota in regions 3 and 4. These decisions are probably shaped by the higher cost of travelling to regions 2 and 5 due to longer travel distances from the ports to the fishing grounds in these regions. Saithe as the least commercially valuable species is abundant in region 5. Thus, the large vessel might not find it profitable to sail to region 5. The large vessel utilizes saithe quota in regions 3 and 4.

Another distinguishing feature is that, unlike the previous scenarios where the large vessel tended to avoid utilizing cod quota at the beginning of the year, in this scenario the large vessel switches from region 1 to region 3 to utilize cod and haddock quotas. There are two possible explanations for this. With a small cod quota, the large vessel prefers an immediate reward from landing cod at a low price at the beginning of the year over waiting until the end of the year to profit from high prices. Another economic rationale might be that with a small cod quota, the pay-off of the improved cod price after the spawning season is not particularly high, so there is no benefit to delaying the cod harvest.

Profits

Figures 5, 6, and 7 show and compare profits from the three scenarios for the small and large vessels. The figures also show the economic contribution (i.e. location attractiveness) of each region to the total profit.

Scenario 1: Figure 5 displays the profit generated for the small and large trawl vessels with respect to the quota constraints in the first scenario. One point worth noting here is that, notwithstanding the differences in allocation of fishing effort, the difference in profitability between the small (59 million NOK) and large (65 million NOK) trawl vessels is only ∼10%. From Figure 5, we realize the economic significance of region 3 for the small vessel, while the large vessel gets most of the profit from regions 1 and 2. The majority of the generated profits comes from cod fishery in regions 1, 2, and 3. The small vessel in total catches 50% of the cod quota in region 3, while the large vessel utilizes 90% of the cod quota in the offshore areas of the Arctic (i.e. regions 1 and 2).

Scenario 2: As in the first scenario, despite the difference in the allocation of fishing effort between small and large trawl vessels, the profit differences are not huge. The generated profits for small and large vessels are approximately 42 and 60 million NOK, respectively. As illustrated in Figure 6, the economic significance of region 3 is pronounced for the small vessel, whereas 80% of the obtained profit for the larger vessel comes from regions 1 and 2.

Scenario 3: Results are shown in Figure 7. The accrued profit is ∼26 million NOK for the small and large trawl vessels. Supposedly, with a smaller codfish quota, the profit differences between small and large vessels get smaller. Similarly to the previous scenarios, the north-west coast of Norway (region 3) contributes the most to the generated profits for the small vessel. What is remarkably different in this scenario in comparison to the two previous scenarios is that both small and large vessels increase the utilization of cod quota in region 3. In scenarios 1 and 2, with a sufficient amount of high-value species, during the spawning season small and large vessels utilize ∼50% and <1% of the cod quota in region 3, respectively, whereas our results from scenario 3 show that when the shares of high-value species get smaller and fishers expect lower profitability, the attractiveness of the location of region 3 increases for both vessel groups. The small vessel utilizes 80% of the quota in region 3 and the large vessel fishes 11% of the cod quota in this region. The fishers' spatial adjustment under this scenario is an indicator that the potential benefits of fishing in region 3 during the spawning season (i.e. lower

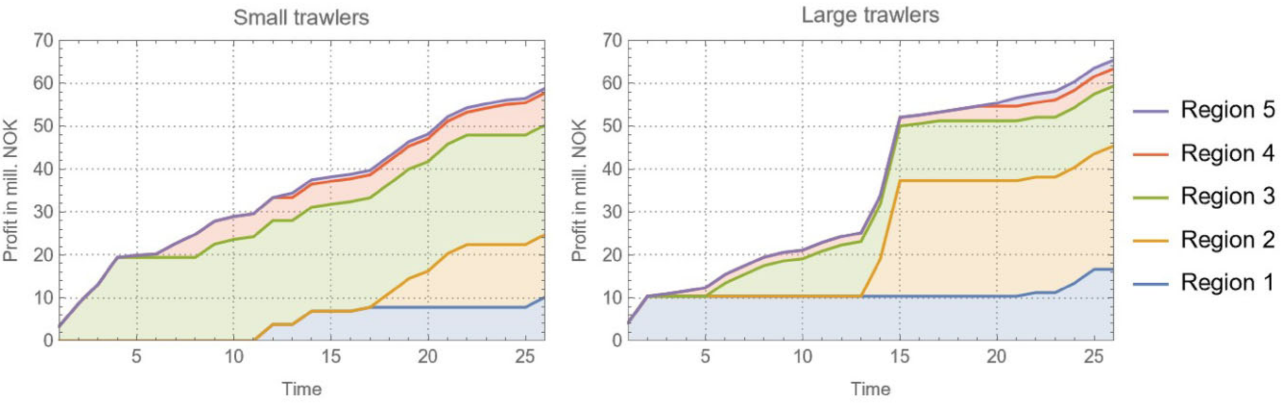

Figure 5. Comparison of the generated profits from holding a QP that consists of a large amount of cod, saithe, and haddock. The generated profit is broken down by regions to show the economic contribution of each region to the total profit.

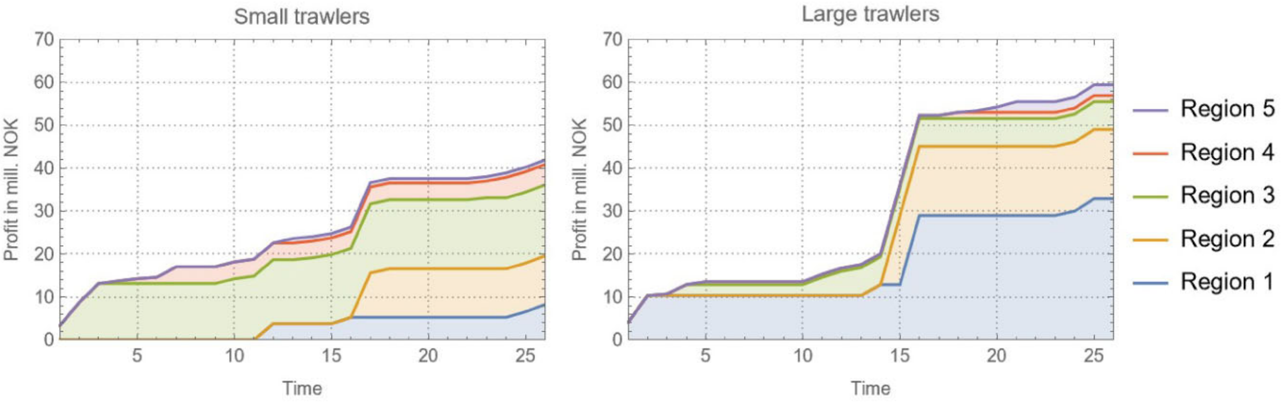

Figure 6. Comparison of the profits generated from holding a QP that consists of medium-sized quotas for cod, saithe, and haddock. The generated profit is broken down by regions to show the economic contribution of each region to the total profit.

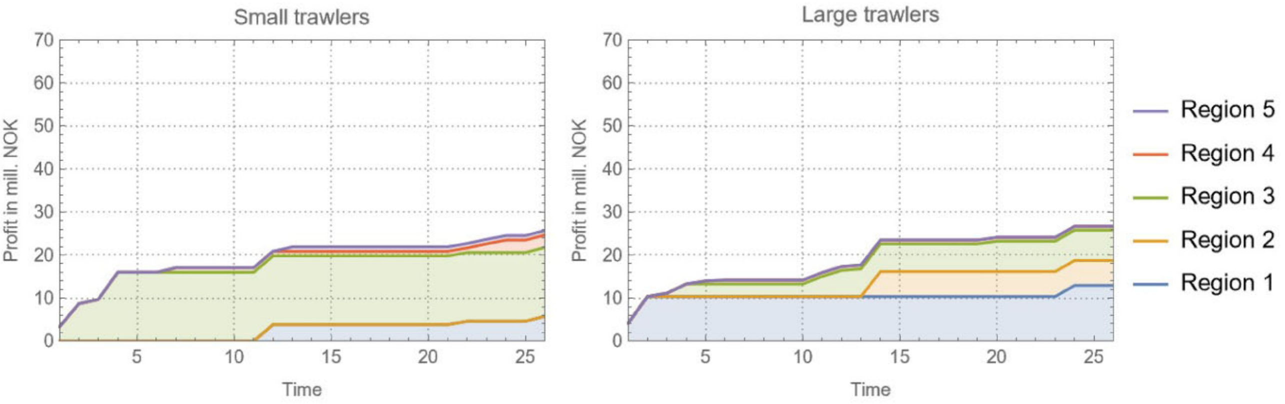

Figure 7. Comparison of the generated profits from holding a QP that consists of a small amount of cod, saithe, and haddock. The generated profit is broken down by regions to show the economic contribution of each region to the total profit.

steaming cost and lower cost per unit of effort) will outweigh the potential gain from the increased price of cod and haddock during the feeding period in the offshore areas of the Arctic.

As can be seen in Figure 7, even though the attractiveness of region 3 has increased for the large vessel, the offshore areas of the Arctic generate the biggest share of profits.

Discussion

The simulation model of the optimal harvest strategy (as outlined in Subsection "Model specification") was used to illustrate the distribution of fishing effort across five selected areas over the course of a fishing year for small and large bottom trawl vessels using three different scenarios regarding the components of the QP in codfish fishery. The total generated profits attributed to each harvest strategy for these two groups of trawl vessels are also obtained. Our model captures the economic contributions of the different regions in relation to the components of the QP for small and large vessels.

Here, we first briefly summarize the key messages from our analysis. Our results show that the components of the QP shape the adopted harvest strategies, that is, the timing of quota utilization, the choice of harvest location and target species, and decisions about venturing into the sea or staying ashore. Moreover, our study reveals that although small and large vessels hold the same QP, their profit-maximizing harvest strategies are different. Our speculation is that this is probably due to the vessel-specific characteristics that manifest themselves in different spatio-temporal effort allocations between small and large vessels. Our analysis also suggests that the intensity with which fishers react to the fluctuations in the market price levels depends on the configuration of the QP, and large vessels are more responsive to price fluctuations in high-priced species (cod). We have demonstrated that during the spawning season, the large vessel with a large QP would withdraw from cod fishery in response to the reduction in cod price due to the glut of cod in the market. However, the large trawl vessel becomes less sensitive, or maybe even insensitive, to the reduction in cod price when the QP is small.

We have also shown that the profitability changes following the change in harvest strategy. The profit differences between small and large vessels become smaller as the size of the codfish QP shrinks. This is probably because with a small-size QP and low expected profit, large vessels cannot benefit from the lower per-unit costs (including fixed and variable costs; i.e. economies of scale).

In addition, location attractiveness depends on the QP. As the cod quota shrinks in the QP, the attractiveness of the Arctic regions (regions 1 and 2) diminishes. Instead, the west coast of northern Norway (region 3) becomes more attractive to both small and large trawlers.

In what follows, we discuss socio-economic consequences of these three scenarios regarding the restrictive QPs in the codfish fishery.

Economic efficiency and economies of scale

The Norwegian fishery was initially open access (Årland and Bjørndal, 2002). The current form of Norwegian fisheries management has evolved over the years, often in response to crises (Årland and Bjørndal, 2002). In the late 1980s, the Norwegian cod stock declined sharply. In response to this situation, the TAC was reduced and an IVQ was introduced in 1990.

After the introduction of the IVQ system, the trawl fleet experienced an increasing trend in vessel size (Standal and Aarset, 2008). The tendency to build larger trawl vessels was driven, to a large extent, by the presence of economies of scale to reduce unit costs, ultimately improving the efficiency and profitability of the fishing industry (Hannesson, 2017). Economies of scale in large bottom trawl vessels are achieved by flexibility in spatial movements, modern capture technology, large hold size, greater cargo handling, on-board freezing facilities, and unloading equipment. Moreover, large trawl vessels are designed for long-distance cruising; therefore, they stay out at sea for longer periods without going back to port to land fish. This reduces unit transport costs and secures economies of scale (Standal and Sønvisen, 2015; Bertheussen et al., 2020). With regard to the efficiency of trawl vessels, Brinkhof et al. (2018) mentioned that trawl vessels can have large catches of up to 30 metric tons during short towing periods (10–20 min).

Our simulation results, however, show that the potential economies of scale can only be reaped when the QP is sufficiently large, in particular cod and haddock quotas (high-value species in our portfolio and the main source of revenue; scenario 1). This means that both small and large trawl vessels work at full capacity (i.e. 26 periods) and utilize their cod and haddock quota in distant waters of the Arctic (regions 1 and 2).

In scenario 3, where the vessels are assigned small cod and haddock quotas, the small and large trawlers redistribute the fishing effort from distant waters to nearshore waters as a result of lower expected profitability. One of the behavioural responses of fishers in adjusting the allocation of their fishing effort is to move towards areas that are closer to ports rather than choosing distant grounds with potentially larger catches and higher values and lower effort aggregation. This spatial adjustment in effort allocation in response to the decrease in profit is in line with findings from the existing literature (Sampson, 1991; Abernethy et al., 2010; Alizadeh Ashrafi and Abe, 2021).

The reduction in the expected QP profit and the higher costs of steaming time to reach the Arctic waters (regions 1 and 2; a two-way voyage from Tromsø port takes >100 h) potentially undermine or offset the efficiency and scale in the trawl industry, particularly for larger trawl vessels. Reducing considerable distance-related costs by reallocating effort to fishing areas closer to ports (region 3) could indicate underutilization of on-board freezing and refrigeration capacity as vessels operating close to the shore can frequently visit ports to land their catch.

Moreover, in scenarios 2 and 3, we see that as the share of cod and haddock quotas gets smaller in the QP, the number of periods with no fishing activities increases. This can be because they do not have enough quota to keep fishing. Another explanation is that the main contributing factor with respect to the running cost of a trawl vessel is fuel consumption (Asche and Roll, 2019). Hence, it is understandable that trawlers stay in port rather than setting sail when the expected profit from the QP is low. Furthermore, as our analysis shows, the larger trawlers are, as expected, the more vulnerable they are to a reduction in profit relative to their smaller counterparts. The large vessel has more idle periods than the small vessel. This can be justified by the fact that large bottom trawl vessels are the most fuel-consuming fishing vessel (Bastardie et al., 2010), as towing bigger gear and dragging heavier nets across the seabed is more costly for larger trawlers. The outcome of our model in terms of idle periods is indeed a reasonable representation of reality. In the real world, some trawlers are idle during certain times of the year when the profitability is low. Another alternative to being idle is to participate in other fisheries, such as, in particular, Greenland halibut and shrimp fisheries.

Furthermore, as the cod and haddock quotas become smaller in scenarios 2 and 3, the profit differentials between large and small ships decrease. The fact that large trawl vessels with larger capacity and greater productivity in cargo handling generate almost the same amount of profit as small vessels indicates that the diminishing economies of scale are more pronounced in large vessels. In other words, larger vessels cannot benefit from economies of scale when they hold small codfish quota. This is probably due to the disproportionate increase in cost and revenue of the large vessel with low quotas for high-value species. In reality, some large vessels hold small QP of the codfish partly due to the opportunity to participate in the shrimp fishery, where they are not quota restricted.

Avoiding offshore areas of the Arctic to fish cod and haddock quotas as well as idling the vessel to cut back on fishing costs may negate the presence of economies of scale in the trawl industry. Our findings are supported by the study of Hannesson (2017), which states that all else being equal, a larger quota leads to better exploitation of economies of scale.

Stability in fish supply and extended fishing season

Another reason for upsizing trawl vessels after the introduction of the IVQ was to dilute the seasonality in codfish fishery during periods of spawning aggregation (Standal and Aarset, 2008; Ashrafi et al., 2020). Historically, every winter, cod gather along the north-west coast of Norway (region 3) to spawn (Lofoten fishery; Olsen et al., 2010). Prior to the emergence of large ocean-going trawl vessels, only coastal vessels with a limited mobility could harvest and land periodically available cod along the coast. Hence, almost the entire industry's cod catch was landed during a compressed season in winter. Large ocean-going trawl vessels with spatial freedom and extensive on-board facilities for processing and freezing have smoothed out seasonality in fish landings and extended the fishing season.

However, our results from the first scenario show that the length of the season for high-value species (here, cod and haddock) is extended only when the QP consists of a sufficiently large amount of cod and haddock. With a large quota for high-value species, trawlers expand effort allocation over different areas at different times of the year to benefit from fluctuations in biomass levels as well as market prices.

Hannesson (2007) has shown that that there is a significant stock effect in the codfish fisheries, such that the effort allocation costs depend on the size and distribution of the biomass. Hence, it is rational for fishers to utilize their QP during spawning aggregation when the cost of effort allocation is lower. However, the findings from the first scenario show that at the beginning of the year, trawl vessels, particularly large vessels, avoid targeting cod in region 3. What makes trawlers reluctant to fish cod in this period is probably related to effort congestion externalities (Hermansen and Dreyer, 2010; Ashrafi et al., 2020)—an externality where the actions of a group of fishers imposes costs on other fishers (Boyce, 1992; Huang and Smith, 2014). As a result of effort congregation by the coastal fleet along the west coast and large fish landings during spawning periods, the market prices goes down (Hermansen and Dreyer, 2010). Hence, with a large quota for high-value species, it is an economically rational strategy to withdraw from cod and haddock fisheries in periods of persistently low prices in wintertime and wait for a "better" time: when cod and haddock swim back to the Arctic waters to feed and prices go up due to the limited supply of fish (Hermansen and Dreyer, 2010). Utilizing cod and haddock quotas out of the spawning season in the Arctic regions is associated with higher steaming costs, but apparently the increase in the price of cod during feeding periods surpasses the cost of effort allocation (Ashrafi et al., 2020). Hence, with a large QP, trawlers allocate effort over different times and locations—from nearshore waters to offshore areas of the Arctic. This harvest strategy also shows that with a sufficiently large amount of high-value species in the QP, large trawlers respond to the reduction in cod price during spawning season. This indicates that holding large cod and haddock quotas helps large trawlers to circumvent the negative consequences of effort congestion externalities (e.g. market flooding and reduced cod price) induced by stock aggregation. Several empirical papers render support for this finding (Ashrafi et al., 2020; Birkenbach et al., 2020; Ashrafi and Abe, 2021).

The results from scenario 3 contradict the widely held belief that the implementation of IVQs in general extends fishing seasons and reduces fishing effort congestion (Copes, 1986; Squires et al., 1998; Birkenbach et al., 2017). Under this scenario, QP utilization takes place in a compressed season.

Whether or not the IVQs inhibit congestion of effort and short pulse of landings is debatable. Casey et al. (1995), Homans and Wilen (1997), and Birkenbach et al. (2017) provide evidence of an extended fishing season, while Pincinato et al. (2022) have not come to a consensus that the implementation of an IVQ precludes landing seasonality. One important message here is that the implementation of an IVQ is not a silver-bullet solution to motivate fishers to extend the fishing season over the course of a fishing year. This depends on an array of different factors, such as existing regulations (e.g. geographical and gear constraints), market structure, biological features of fish stocks, effort externalities, spatial behaviour between spawning and non-spawning periods, stock externalities, and vessel types (Boyce, 1992; Grafton, 1996; Hannesson, 2007; Pincinato et al., 2022). Our analysis shows that the components of the QP play an important role in expanding or compressing the fishing season.

The results from scenario 3 also call into question the effectiveness of an IVQ in regard to price increases due to improved market timing (Grafton, 1996; Scheld et al., 2012). Under the IVQ system, fishers can plan their quota utilization based on market conditions, without having to account for the catches of other fishers. However, the results from scenario 3 show that with a small QP, trawl vessels redirect their effort to nearshore waters during the spawning season where coastal fishers operate. Coastal fishers and trawlers landing an enormous amount of fish in a compressed season can push prices further down.

Social consequences

One of the theoretical social benefits of IVQs is increasing the period of employment (Grafton, 1996), as under quota-managed fisheries, fish are expected to be landed over an extended period of time. Employment considerations, the well-being of coastal communities and maintaining traditional small-scale coastal fisheries are among the main objectives of the Norwegian fisheries regulations (Årland and Bjørndal, 2002). This is because well-functioning coastal and fishing-dependent communities contribute to the improvement of governance systems and the preservation of healthy fisheries (Jentoft, 2000). Thus, the Norwegian fisheries regulatory system has, to a certain degree, been developed to attain these goals. For example, according to the regulations, trawler companies need to land part of their caught fish in onshore processing plants along the coast to maintain employment (Hermansen and Dreyer, 2010).

As stated earlier, with a large amount of high-value species in the QP, the fishing season is extended and a steady supply of fish to the processing plants is maintained throughout the year. This either hinders or reduces employment discontinuity in coastal communities. However, in scenarios 2 and 3, with the reduction in the periods at sea in response to the lower expected profits, on-board crew recruitment and employment in onshore processing plants are likely to become patchy and discontinuous. This can put the economic and social conditions of the coastal communities in jeopardy. Areas with high discontinuous unemployment rates may become unattractive and local workers might need to leave to find more stable jobs elsewhere in the country.

Conclusion and policy highlights

The IVQ system has created incentives for fishers to adopt an economically rational harvest strategy aimed at improving profitability. The short-run decision-making behaviour of fishers with respect to quota constraints has been a topic of ongoing empirical and theoretical research (Larkin and Sylvia, 1999; Dupont et al., 2005; Bastardie et al., 2010; Batsleer et al., 2015; Birkenbach et al., 2020; Ashrafi and Abe, 2021). However, despite confirming that IVQs could lead to a profit-maximizing harvest strategy, a number of questions regarding how different components of the QP could possibly influence effort allocation decisions, profit size, and the efficiency of the IVQ scheme remain unanswered. For this purpose, this paper addresses this lack of analysis and seeks to explain how variations in the components of the codfish QP influence the adopted harvest strategy and the corresponding profitability for small and large bottom trawl vessels. We also investigate how different components of the QP impacts the efficiency of the IVQ system. For this purpose, we have used a spatio-temporal bioeconomic framework to assess and compare segment-specific harvest strategies and profitability under different scenarios regarding the codfish QP.

Our analysis shows that changing the components of the codfish QP influences the adopted harvest strategies and accrued profitability. Although small and large vessels hold the same QP, their profit-maximizing harvest strategies are different, probably due to the differences in technical features. Moreover, the simulation results show that both large and small trawlers respond rationally, in the economic sense, to the changes in the components of the QP. They are adaptive in their fishing behaviour and redirect fishing effort to alternative locations, times, and available species as the components of the QP change.

Furthermore, the results from the optimization model demonstrate that implementing an IVQ is not necessarily an appropriate or sufficient solution to the congregation of effort, short-pulse catches, and discontinuity of employment that are inherent in an open-access fishery. Our study shows that the theoretical advantages of IVQs, such as a longer fishing season and continuity of employment are attainable in a specific situation.

Our findings show that the IVQ system is effective only if the QP contains a sufficiently large amount of high-value species. Similarly, trawl vessels, especially large ones, can benefit more from economies of scale if they hold a large QP consisting of a large amount of high-value species.

The management implication here is that authorities should not set vessel quota limits too low to enable trawlers to benefit from potential advantages of IVQs and economies of scale. Moreover, trawlers need to be able to trade quotas and adjust the QP until it covers a catch level that maximizes its expected profits based on the vessel's technical features.

Even though, under the current regime, trading quotas are legal in Norway, the regulations are very strict. Quotas are only transferable within the same vessel group, fish stock, and geographical area. For instance, there is stringency to scrap a cod trawler in northern Norway and transferring its quotas to a trawl vessel operating in the southern counties. Furthermore, leasing quotas is not allowed in Norway.

Hence, one solution to better reap the economies of scale and to improve sustainable use of fish stocks and areas is to develop flexible management tools that simplify regulations. For example, some leniency in quota trading and flexibility in the regulations such as between-year quota transfers might be helpful, as might the ability to carry forward unused quota or borrow from the following year's allocation, allowing for more quota consolidation (currently there are only four quota factors) and leasing of quotas.

Even though the present paper provides a case study for the Norwegian bottom trawl fleet assigned a codfish quota, our model and results should be of general interest since IVQ management regimes exist in many multi-species fisheries around the world.

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Supplementary data

Supplementary material is available at the *ICESJMS* online version of the manuscript.

Author contributions

ØH, SK, and TAA conceived the research idea. ØH has collected the data. SK has suggested the methodology, analysed the data, and developed the model. TAA and SK wrote the manuscript. All three authors contributed critically to the drafts and gave final approval for publication.

Conflict of interest

The authors declare no conflict of interest.

Data availability

The datasets used in this article come from multiple sources. Most of the data are openly available at:

https://www.fiskeridir.no
https://www.garantikassen.no
https://www.fiskarlaget.no

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