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## Original Article

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

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Bottom trawlers are engaged in multi-species fisheries and fish for profit. In quota-regulated fisheries, intra- and inter-temporal substitutions of fishing effort is regarded as a key mechanisms that influences the profitability of the fishing portfolio. The feeding and spawning migration patterns of the available fish species in the fishing portfolio alter the bio-economic conditions of the different fishing areas. In addition, the spatial heterogeneity among different fishing areas in terms of the fuel costs and travel distance, accessibility to other fishing fleets, and sea ice extent affects the relative attractiveness of the fishing areas and further complicates the decisions underlying the effort allocation, such as when and where to fish what and how much to fish to maximize the profit. In this regard, the aim of this article is to identify the key drivers of intra- and inter-temporal effort allocation in a multi-species trawl fishery consisting of 61 Norwegian trawl vessels targeting cod, saithe, and haddock, the aim being to maximize the fishing profit within the quota constraints. We adopted a two-step Heckman estimator that incorporates the relative attractiveness of three heavily trawled areas, the southern and northern parts of the west coast of Norway and the high sea areas of the Arctic. The relative attractiveness is specified by the fish availability, measured using the catch per unit of effort, prices of the target species, fuel cost, intensity of the coastal fleet's participation in winter fishery, and seasonal sea ice extent in the Barents Sea during the period 2011–2016. Our results show that region-specific attributes and spatial margins have a profound impact on the intra-temporal and inter-temporal allocation of fishing effort to maximize the seasonal profit. Furthermore, we found evidence of economically rational behaviour of the Norwegian trawlers in constantly reallocating their fishing effort in response to the changes in the relative attractiveness of the selected fishing areas over the course of a fishing year.

**Keywords:** bottom trawl, effort allocation, Heckman estimator, inter-temporal, intra-temporal, multi-species fisheries, profit maximization

## Introduction

Bottom trawlers are profit oriented and seek to maximize their profit by constantly redistributing their fishing effort across multiple species over time and across space (Alizadeh Ashrafi *et al.*, 2020, 2021; Birkenbach *et al.*, 2020). The Norwegian bottom trawl fleet is quota regulated and targets commercially valuable species, including North-East Arctic (NEA) cod (*Gadus morhua*) as the main target together with saithe (*Pollachius virens*) and haddock (*Melanogrammus aeglefinus*) (Birkenbach *et al.*, 2020). Particular interest lies in identifying the effort allocation of the codfish trawl fleet, which leads to a profit-maximizing harvest strategy. One reason is that these three species make up approximately 77% and 78% of total value and landings of the trawl fleet, respectively (Norwegian Directorate of Fisheries, 2019). The spatial and temporal freedom of the trawl vessels as well as their capability to cope with the less desirable climatic conditions (Flaaten and Heen, 2004; Standal and Hersoug, 2015) could secure a steady supply of codfish throughout the year and further reinforce the Norwegian fisheries (Alizadeh Ashrafi *et al.*, 2020). Despite its importance, the effort allocation in codfish fishery has received little attention (Alizadeh Ashrafi *et al.*, 2020, 2021; Birkenbach *et al.*, 2020; Eide *et al.*, 2003). In this regard, the aim of this paper is to identify the influential drivers of the effort allocation over time and across space in codfish trawl fishery to maximize the annual profit.

Complexity in optimally allocating fishing effort (i.e. when and where to fish what and how much to harvest) in codfish fishery arises from the fact that these fish species are migratory and undertake long-distance migrations to spawn; from south in the North Sea (saithe) and the Arctic areas of the Barents Sea (cod and haddock) to the fishing grounds along the north-west coast of Norway during wintertime (Garrod, 1967; Godø and Michalsen, 2000; Olsen *et al.*, 2010). The spawning aggregations of cod, saithe, and haddock along the north-west coast of Norway peak in March–April, February, and March–June, respectively (Bergstad *et al.*, 1987; Pethon, 2005; Olsen *et al.*, 2010). This phenomenon causes a close interplay between spatiality (i.e. location choice) and temporality (i.e. harvesting time). Moreover, the constant movements of fish stocks across different locations over the course of a year produce locational heterogeneity in terms of relative population abundance measured by catch per unit of effort (CPUE) (Hilborn and Walters, 1992; Maunder *et al.*, 2006) and economic considerations such as the relative prices of fish species and the cost of fishing operations (Sandberg, 2006; Hannesson, 2007; Asche *et al.*, 2015). This, in turn, affects the relative attractiveness of the different fishing locations and effort allocation decisions (Holland and Sutinen, 1999, 2000).

Nearshore areas are economically advantageous in terms of lower fuel consumption and less required travel time. Increased CPUE as a result of codfish aggregation along the north-west coast of Norway during wintertime and reduced cost per unit of production increase the attractiveness of this area. Of the total allowable catch (TAC) of codfish quotas, 65–80% belong to the coastal fleet using conventional gears such as gill nets and longlines (Asche *et al.*, 2014; Standal and Hersoug, 2015). Since coastal boats cannot venture into off-shore fishing due to their limitations in technical specifications (i.e. engine power and size) (Flaaten and Heen, 2004; Standal and Hersoug, 2015), they utilize a big part of their quotas at this time (Hermansen and Dreyer, 2010). The congestion of coastal boats during spawning aggregation along the north-west coast produces production externalities (Boyce, 1992), which would then negatively influence the effort allocation decisions of the trawlers (Alizadeh Ashrafi *et al.*, 2020; Birkenbach *et al.*, 2020). More precisely, the first hand price of cod is endogenous to the large landings (Arnason *et al.*, 2004; Asche *et al.*, 2002a, 2002b; Birkenbach *et al.*, 2020), hence a large supply of cod by coastal fishers reduces its price (Alizadeh Ashrafi *et al.*, 2020; Hermansen and Dreyer, 2010). The prices of saithe and haddock are less responsive to the landing volumes (Birkenbach *et al.*, 2020).

After spawning in the winter months, cod and haddock migrate dispersedly (i.e. lower CPUE) to the sub-Arctic areas of the Barents Sea and Svalbard to feed (Bergstad *et al.*, 1987; Trout, 1957). Fishing in the sub-Arctic regions requires more traveling time and more hauling duration due to the decreased CPUE. Additionally, the fishing grounds of the sub-Arctic areas are characterized by less desirable climatic conditions (e.g. ice-covered waters and wind chills). The Barents Sea has the most ice coverage in March–April (Årthun *et al.*, 2012; Kvingedal, 2005). Fishers might avoid fishing in ice-covered waters due to the increased fuel consumption as well as the greater risk of facing hazardous situations (Misund *et al.*, 2016; Pfeiffer and Haynie, 2012). (The effect of ice coverage on the fishing patterns of the Norwegian trawlers is a controversial topic. However, the satellite observations from https://www.barentswatch.no/fiskinfo/ show that trawlers retreat upon the signs of approaching sea ice. Hence, we have decided to include the sea ice index in our analysis.) However, at this time, the prices of cod are higher due to the smaller landings as the coastal fleet has already filled its quotas during the winter months (Alizadeh Ashrafi *et al.*, 2020; Hermansen and Dreyer, 2010). As the relative attractiveness of a particular area changes over the course of a year, the fishing effort might be displaced to other areas or time periods.

Since the advantageous (e.g. high price and proximity to shore) and disadvantageous (e.g. low CPUE and sea ice extent) locational attributes are present at the same time, the optimal allocation of fishing effort to maximize profit is complex. This article employs Heckman's (1976) two-step estimator to scrutinize the drivers of intra-temporal and inter-temporal effort allocation with respect to the changes in the attractiveness of different fishing areas for the Norwegian trawl fleet to maximize the annual profit, while considering quota constraints. The model emphasizes locational heterogeneity and incorporates the fish abundance measured by the CPUE, market prices of the fish species, fuel cost, and availability of coastal fishers in three heavily trawled regions, the northern and southern parts of the west coast of Norway and the high sea areas of the Barents Sea. What we mean by intra-temporal effort allocation is the way in which fishers reallocate their fishing effort across the three selected areas within the same time period respect to the changes in the relative attractiveness of the selected areas. Inter-temporality refers to the reallocation of fishing effort over time within the same location.

A recent work by Birkenbach *et al.* (2020) investigated the seasonal allocation of the quota in the Norwegian trawl fleet as an example of a multi-species quota management fishery to maximize profit. The effort allocation under dynamic planning of seasonal profit maximization cannot be analysed thoroughly without the spatial consideration as the constant movement of the fish influences the spatial margins (Holland and Sutinen, 1999, 2000).

Investigation of how trawlers displace effort with respect to the changes in the bio-economic, environmental, and regulatory conditions is beneficial for the fishers and fisheries managers. Fishers can improve the existing harvest pattern to enhance the economic yield by redistribution of fishing effort in an optimal manner. Moreover, bottom trawling across seabed damages the sea bottom. This fishing method captures non-target species as well as the fish that its size is below the minimum landing sizes. By investigation of the trawlers' fishing behaviour, managers could identify heavily fished areas and evaluate the likelihood of bycatch within a fishing season to recommend conservation policies (e.g. area or season closure and modifying fishing gear) to achieve a sustainable exploitation of fishery resources (Russo *et al.*, 2015, 2019). This also deepens managers' knowledge about spatial interactions and population dynamics as well as the bio-economic importance of each location for the fishers (Russo *et al.*, 2019; Smith *et al.*, 2009). This knowledge provides important insights that policymakers may take into consideration when designing and/or refining management plans.

## Data description

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

Figure 1 shows the predominant areas of the trawl fishery, where cod, saithe, and haddock fishery is conducted. The number of trawl vessels is 61. The area consists of the Norwegian west coast, from the

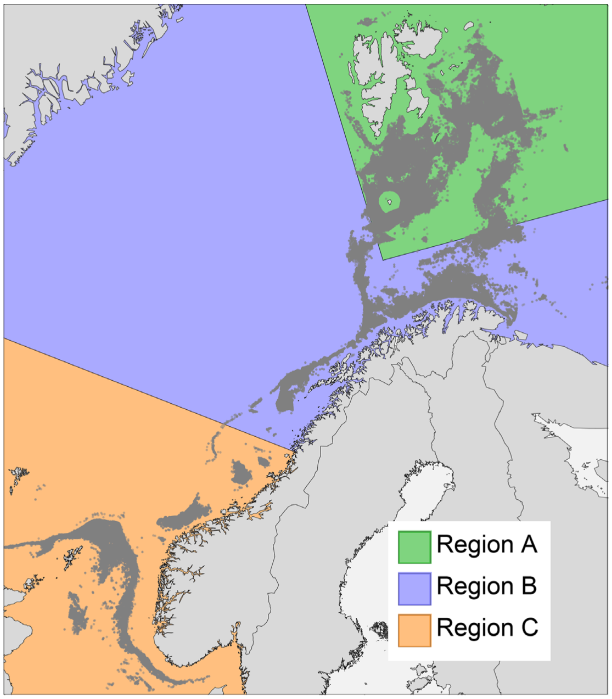

**Figure 1.** The map shows three arbitrary regions where cod, saithe, and haddock fishery is conducted. Cod and haddock fishery prevails in regions A and B, while saithe fishery is dominant in region C. The map also shows the location of trawling based on individual hauls in the selected areas over the period 2011–2016. Trawl vessels dominate the fishing along the west coast of Norway and in the sub-Arctic areas. A total of 86418, 67071, and 38928 haul-based observations by 61 trawl vessels were recorded for cod, saithe, and haddock fisheries, respectively. Source: The Norwegian Directorate of Fisheries.

south of the North Sea to the shallow shelf along the northern parts of the west coast, extending towards the deep-sea areas of the Arctic (including Svalbard and Bear Island). We divide the fishing area into three arbitrary sub-regions, A, B, and C, based on the relative availability of fish species according to their feeding and spawning migration patterns over the course of a year.

Region A consists of the high sea areas of the Barents Sea, where predominantly cod fishery and to a lesser extent haddock fishery are conducted. After spawning in the winter months, cod and haddock swim to the sub-Arctic areas to feed. Region B corresponds to the west coast of northern Norway, where three fisheries overlap, mostly during winter. Every winter, mature NEA cod and haddock perform an extensive migration from the Arctic sub-areas, where they feed, to the shallow waters of the north-west coast of Norway to spawn, with peak activities in March–April and March–June, respectively (Korsbrekke, 1999; Olsen *et al.*, 2010; Rose, 1993). Similar to NEA cod and haddock, saithe spawns in winter during February to April, with its peak in February, along the coastal banks of the west of Norway (Olsen *et al.*, 2010; Pethon, 2005). The congestion of NEA cod, saithe, and haddock spawning along the west coast of northern Norway leads to intensive trawling in this area. Region C consists of the southern part of the west coast of Norway, where saithe fishery is dominant. The spawning of saithe occurs over a wider area than that of NEA cod and haddock, towards the southern parts of Norway in the North Sea. The feeding migration of saithe takes place across a narrower area towards the northern parts (Jakobsen and Olsen, 1987; Olsen *et al.*, 2010).

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

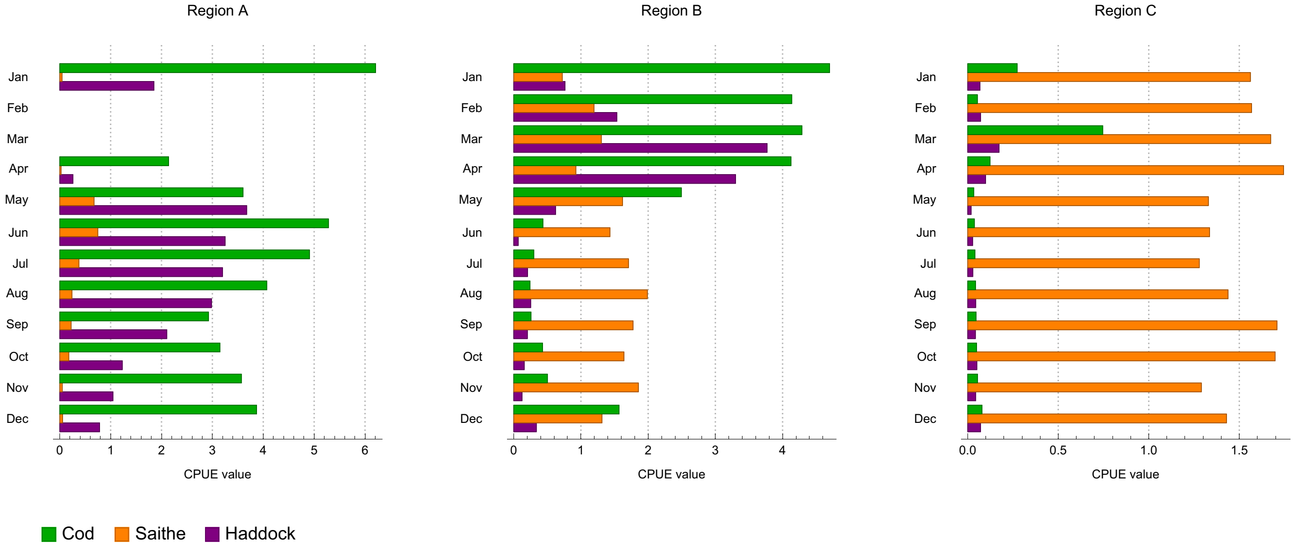

**Figure 2.** Temporal variation in the CPUE, measured in tons per hour of trawling in the cod, saithe, and haddock fisheries in the selected regions on a monthly basis. A haul-level catch and effort data of 61 trawlers over the period 2011–2016 is used to calculate CPUE. Source: The Norwegian Directorate of Fisheries.

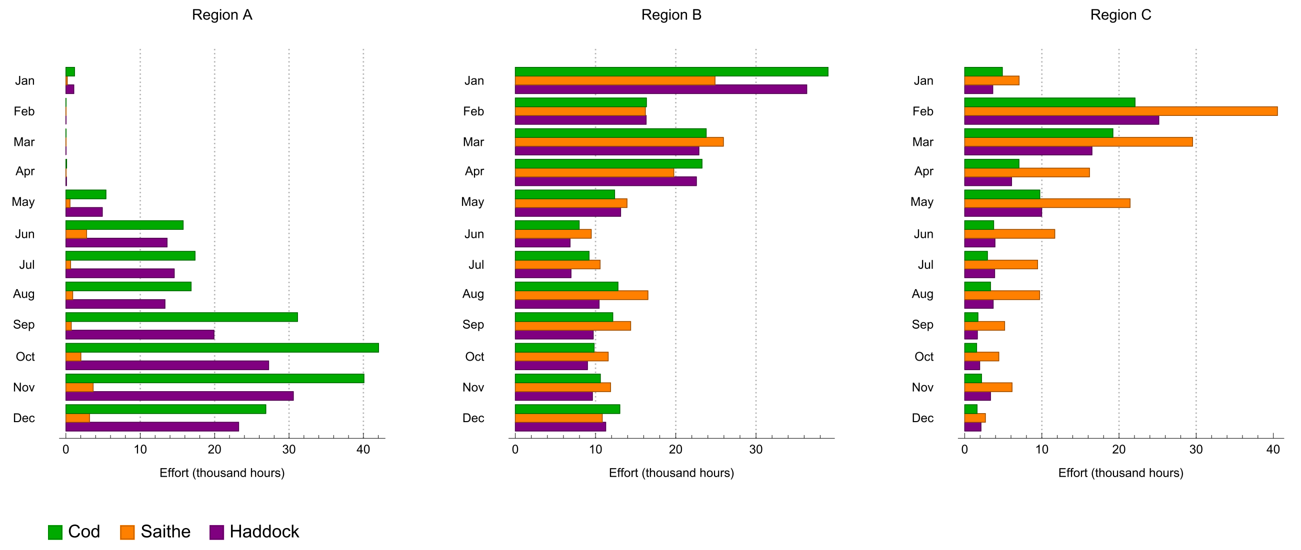

**Figure 3.** Fishing effort allocation of the Norwegian trawlers in the cod, saithe, and haddock fisheries, measured in thousands of trawling hours, in the three selected regions on a monthly basis over the period 2011–2016. Source: The Norwegian Directorate of Fisheries.

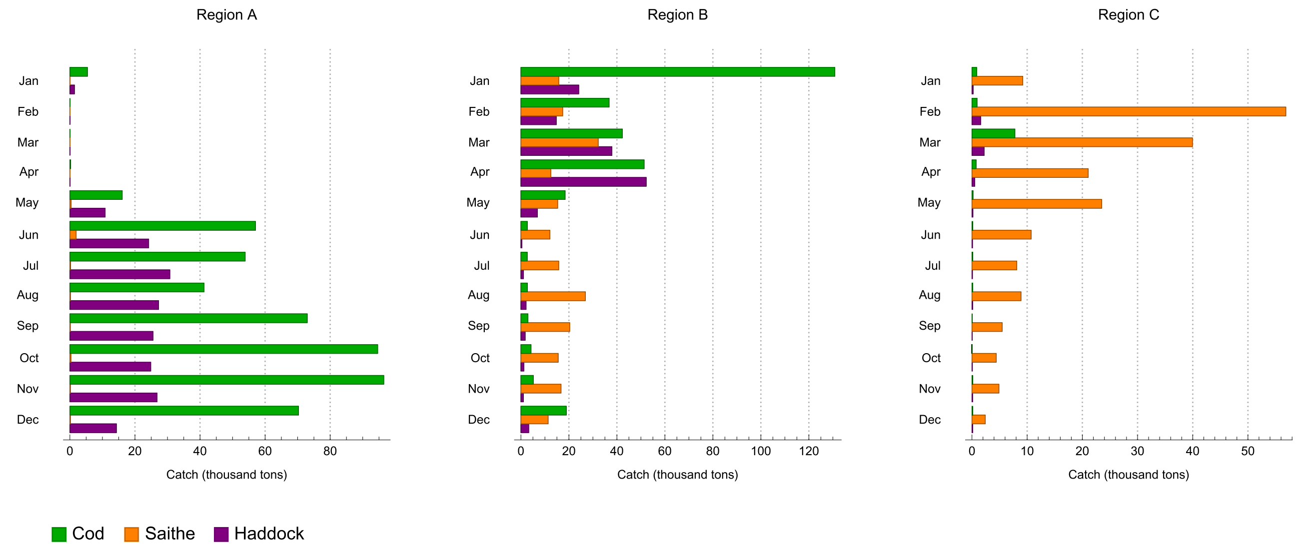

**Figure 4.** Distribution of the total catch in the cod, saithe, and haddock fisheries, measured in thousands of tons, in the three regions on a monthly basis over the period 2011–2016. Source: The Norwegian Directorate of Fisheries.

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

Figure 3 shows the average monthly variation in the allocation of fishing effort in the cod, saithe, and haddock fisheries over the period 2011–2016. The fisheries are defined based on the main target species for each haul. The fishing effort is measured in thousands of trawling hours.

The highest concentration of effort in region A in the cod and haddock fisheries takes place towards the end of the year. This is the time when cod and haddock are in the Arctic waters to feed (Bergstad *et al.*, 1987; Trout, 1957). The patterns of fishing effort allocation in the cod and haddock fisheries in region B follow a declining trend over the course of a year. A sharp drop is obvious at the beginning of the fishing year in these two fisheries in region B. Concurrent with the drop in fishing effort in the cod and haddock fisheries, the effort allocation in the saithe fishery increases in region C in February. The effort allocation in the saithe fishery in region C follows a decreasing pattern towards the end of the year.

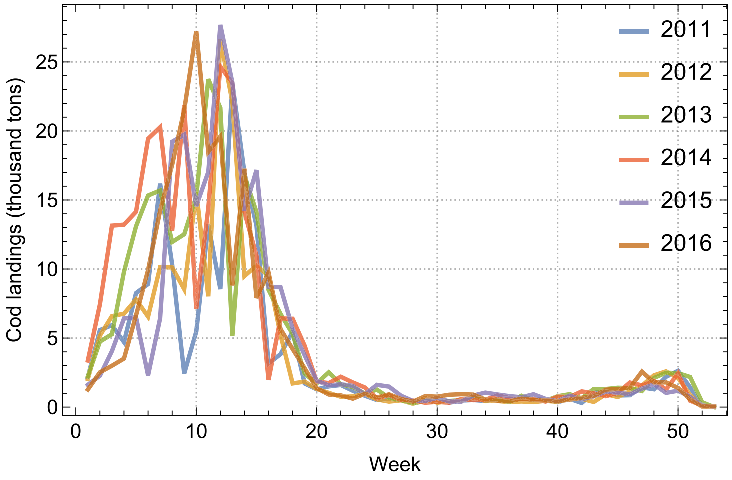

**Figure 5.** The total weekly landings of cod, measured in thousands of tons, caught by the Norwegian coastal vessels during the period 2011–2016. Source: The Norwegian Directorate of Fisheries.

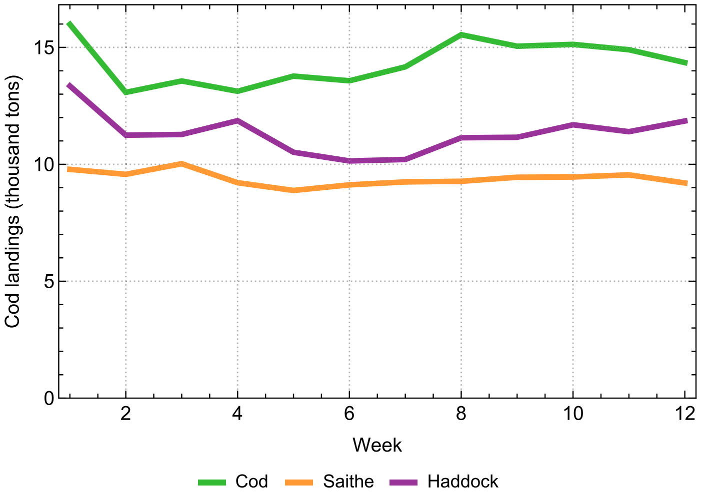

**Figure 6.** Monthly average prices for the landed frozen products of cod, saithe, and haddock caught by the trawl fleet during the period 2011–2016. The prices are in NOK. Source: Norwegian Fishermen's Sale Organization.

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

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

To investigate the possible impact of the availability of coastal fishers during the winter in region B on trawlers' harvest strategy, in Figure 5, we depict the average of the total weekly cod catch of coastal vessels measured in thousands of tons during the period 2011–2016. Since cod fishery is the most important element of winter fishery (i.e. Lofoten fishery), in Figure 5 we only show the total catch of cod.

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

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

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

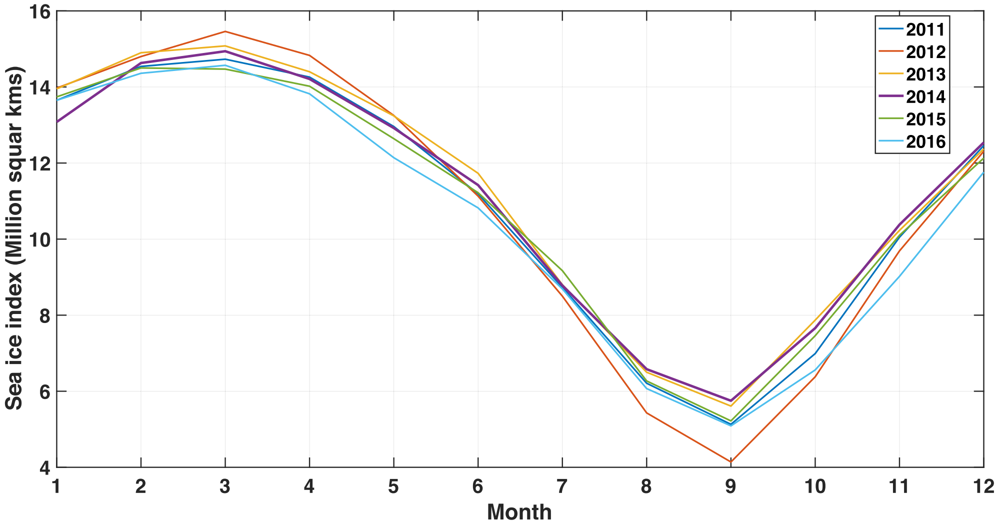

**Figure 7.** Monthly ice coverage index of the Barents Sea, measured in millions of square kilometres, during the period 2011–2016. Source: The European Organization for the Exploitation of Meteorological Satellites.

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

In Figure 7, we depict the monthly ice coverage index of the Barents Sea, measured in millions of square kilometres. As is evident from Figure 7, the ice is thicker earlier in the fishing year. This could increase the risk associated with cod and haddock fishing in region A. This is, indeed, in accordance with the pattern of the allocation of fishing effort in Figure 3, in which no cod and haddock fishing takes place in region A in February and March as trawlers cannot physically enter the areas of the Arctic where the ice is considerably thick. From around May, the ice starts to retreat. Compared with Figure 3, this is the time when trawlers start to reallocate their fishing effort to region B. However, we do not contend that the sea ice and possibly less desired climatic conditions of the Arctic area are the *only* prevailing reason for abandoning the cod and haddock fisheries in region A. Another possible reason could be the high CPUE of cod and haddock in region B.

## Construction and utilization of data

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

A haul-level data set of 61 codfish trawlers obtained from fishers' logbooks. These data are compiled by the Norwegian Directorate of Fisheries (Norwegian: Fiskeridirektoratet). The main targets of these trawlers are cod, saithe, and haddock. A total of 86418, 67071, and 38928 haul-based observations were recorded for cod, saithe, and haddock fisheries, respectively. Every observation in the data set is associated with geographical coordinates (spatial dimension) and harvest time (temporal dimension). The catch and effort data are used to estimate the CPUE for individual vessels [see Equation (17) in Section 3.3.1].

The weekly fish prices for the frozen products of cod, saithe, and haddock are obtained from the Norwegian Fishermen's Sales Organization (Norwegian: Norges Råfisklag). Codfish trawlers are equipped with freezing and storage capacities, and the harvested fish is processed and refrigerated onboard. To tackle the problem of endogeneity of the cod price (see Section 3.3.2), we utilize the monthly global wholesale market prices for the Atlantic cod as an instrumental variable. The Atlantic cod was caught in the Barents Sea by Russian and Norwegian fleets during the period 2011–2016. The data are obtained from (https://www.undercurrentnews.com/data/prices/#/russiaCod&start=0&end=5). The original prices were in the United States dollar (USD). We have used average monthly exchange rate to convert USD to the Norwegian currency. The exchange rates are derived from the Statistics Norway Bureau (SSB) (Norwegian: Statistisk sentralbyrå).

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

To account for the variation in the fuel expenditure, we also obtain monthly data on the gasoline price from SSB for 2011–2016. We calculate the percentage change in the monthly gasoline price with respect to the average price in 2011, which is equal to 13.95.

**Table 1.** The average annual fuel price for the trawl fleet.

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

Source: The Guarantee Fund for Fishermen (Garantikassen for fiskere). VAT is deducted from the prices.

Then we multiply the percentage change by the annual fuel price, as presented in Table 1.

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

Because information on the ice coverage index is unavailable on a weekly basis, we employ the monthly sea ice concentration in the Barents Sea, measured in millions of square kilometres, in the econometric analysis. The data are obtained from the European Organization for the Exploitation of Meteorological Satellites.

## Methods

### Theoretical framework

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

To formulate our problem, we specify model sets as follows. Set $A$ shows the available fishing regions, each region being represented as $a$. A fishing season lasts from 0 to $T$, for which each period is indexed as $t$. We index each species (here, cod, saithe, and haddock) as $j$ in the entire set of species, $J$. For the sake of simplicity, we disregard any in-season stock dynamics, such as recruitment and growth dynamics of the fish stocks.

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

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

$$\max_{e_{at}} \sum_{t=0}^{T} \rho^t \sum_{a\in A} \left\{ \sum_{j\in J} p_{jt} H_j\left(e_{at}, X_{ajt}\right) - c_{at} e_{at} \right\}, \tag{1}$$

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

$$\sum_{t=0}^{T} \sum_{a\in A} H_j\left(e_{at}, X_{ajt}\right) \le \bar{Q}_j,\ \ \forall j\ \in \{1,\ 2,\ 3\}. \tag{2}$$

$$\sum_{a\in A} e_{at} \le \bar{e} \ \textit{when}\ 0 \le t \le T. \tag{3}$$

$$e_{at} \ge 0 \ \textit{when}\ a \in A \ \textit{and}\ 0 \le t \le\ T. \tag{4}$$

$\bar{Q}_j$ indicates the annual allocated individual quota for species $j$. In Norwegian quota-managed fisheries, quotas are issued annually based on the stock assessment (Hersoug, 2005). Fishers cannot catch more than the allocated quota, meaning that the overfished quotas could be confiscated or penalized (Hersoug, 2005; Johnsen and Eliasen, 2011). Equation (3) refers to the upper limit for the total effort that can be allocated per period. This is specified to show that the fishing operation is constrained by the duration of fishing and the vessel's capacity. Equation (4) guarantees the non-negativity of the decision variable $e_{at}$. The profit maximization problem is solved using the Kuhn–Tucker Lagrangian method as follows:

$$L = \sum_{t=0}^{T} \rho^t \sum_{a\in A} \left\{ \sum_{j\in J} p_{jt} H_j\left(e_{at}, X_{ajt}\right) - c_{at} e_{at} \right\} + \sum_{j\in J} \lambda_j \left( \bar{Q}_j - \sum_{t=0}^{T} \sum_{a\in A} H_j\left(e_{at}, X_{ajt}\right) \right) + \sum_{t=0}^{T} \bar{\kappa}_t \left( \bar{e} - \sum_{a\in A} e_{at} \right). \tag{5}$$

The first-order conditions are:

$$\frac{\partial L}{\partial e_{at}} = \rho^t \left( \sum_{j\in J} p_{jt} \frac{\partial H_j\left(e_{at}, X_{ajt}\right)}{\partial e_{at}} - c_{at} \right) - \sum_{j\in J} \lambda_j \frac{\partial H_j\left(e_{at}, X_{ajt}\right)}{\partial e_{at}} - \bar{\kappa}_t \le 0 \tag{6.1}$$

$$e_{at} \frac{\partial L}{\partial e_{at}} = 0. \tag{6.2}$$

$$\frac{\partial L}{\partial \lambda_j} = \bar{Q}_j - \sum_{t=0}^{T} \sum_{a\in A} H_j\left(e_{at}, X_{ajt}\right) \ge 0\ \forall j \in \{1, 2, 3\}. \tag{6.3}$$

$$\lambda_j \left( \bar{Q}_j - \sum_{t=0}^{T} \sum_{a\in A} H_j\left(e_{at}, X_{ajt}\right) \right) = 0\ \forall j \in \{1, 2, 3\}. \tag{6.4}$$

$$\bar{e} - \sum_{a\in A} e_{at} \le 0. \tag{6.5}$$

$$\bar{\kappa}_t \left( \bar{e} - \sum_{a\in A} e_{at} \right) = 0. \tag{6.6}$$

$\lambda_j$ and $\bar{\kappa}_t$ are Lagrange multipliers. The Lagrangian multiplier $\lambda_j$ represents the shadow value of the quota of species $j$. Equations (6.1) and (6.3) indicate that, if the discounted (the present value of the) periodical marginal profit exceeds the shadow value of the quota, the fisher would choose to allocate fishing effort. If the periodical profit is below the shadow value, the allocated effort in area $a$ at time $t$ becomes zero. Equations (6.3) and (6.4) shows the Kuhn–Tucker conditions for the Lagrange multipliers of quota constraint. While this condition indicates the possibility that the quota is not fully utilized over a season, we focus on the case in which the quota is fully consumed as the fishery of our interest practically exhausts the quotas for all three main species. Our justification for full utilization of the quota portfolio is that the Norwegian quota management follows the rule of "use-it-or-lose-it," thus the un-used part of the quota is not granted in the subsequent year (Hersoug, 2005). This implies that under-utilization of the quota portfolio is associated with a huge economic loss as quotas are very costly to purchase. This circumstance mandates a profit-maximizing trawler to fully fish the quota portfolio within a fishing year.

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

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

Based upon the theory that we have discussed in the previous section, the econometric model is specified as follows. Our theoretical framework tells how the factors affect the decisions of the optimal trawler. The Kuhn–Tucker condition in Equation (6.2) shows two possible cases: the effort in area $a$ at time period $t$ is zero or positive. In the case of $e_{at} = 0$, the left-hand side of Equation (6.1) becomes negative. This implies no participation in area $a$ at time $t$. There are three factors that makes the term negative. First, the area is not attractive if the area specific cost $c_{at}$ is large. Second, the species $j$ which is caught in area $a$ has less commercial value, which leads to a negative $p_{jt} - \lambda_j$. Third, the area may not be relatively attractive even although the net benefit is positive. This relativeness in selection is captured by $\bar{\kappa}_t$. These three factors affect the participation decision in a specific area.

In the case of $e_{at} > 0$ for all area $a$, we derive the equations for the intra-temporal and inter-temporal effort substitution based on Equations (6.1)-(6.4), in which trawlers choose location $a$ at time $t$ to target species $j$ to maximize the profitability. Accordingly, we first define the net value of fish species as $y_{jt} \equiv \rho^t p_{jt} - \lambda_j$. In the intra-temporal analysis, we have $|A|$ equations in a given period $t$.

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

If the number of areas $|A|$ is equal to or greater than the number of targeted species $|J|$, the system of equations for $y_{jt}$ is solvable because there are $|A|$ equations and $|J|$ unknowns. Despite the possibility of having infinite solutions for this system of equations, this case is excluded because the area-specific variables sufficiently varies across areas. Moreover, fishers cannot limitlessly allocate effort as they are constrained by capacity and trawling duration as well as quotas. Similarly, no solution case is meaningless in our study as fishers have to allocate effort to use quotas to generate profit. Hence, we narrow our focus on the case of interior solutions. In our case study, there are three target species and three defined areas. Hence, the system of equations is exactly identified. The solution for $y_{jt}$ will be a function of $e_{at},\ \{X_{ajt}\}_{j\in J},\ c_{at},\ \rho^t$ for all $a \in A$ given $t$. Once we obtain $y_{jt}$, we substitute it into Equation (7) to yield $e_{at}$ for all $a$ in terms of contemporaneous variables.

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

From Equation (8), we see that the fishing effort turns out to be a function of the area-specific costs of the own and other areas for all species, resource abundance, and discount factors.

The equation below shows the inter-temporal effort substitution.

$$\sum_{j\in J} \left(\rho^t p_{jt} - \lambda_j\right) \frac{\partial H_j\left(e_{at}, X_{ajt}\right)}{\partial e_{at}} - \rho^t\ c_{at} = 0, \qquad t = \{1, 2, \ldots, 12\}. \tag{9}$$

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

$$e_{at} = e_{inter-temporal}\left(\{c_{a\tau}\}_{\tau=t-2}^{t}, \left\{\left\{X_{aj\tau}\right\}_{j=1}^{3}\right\}_{\tau=t-2}^{t}, \{p_{j\tau}\}_{\tau=t-2}^{t}, \{\rho^\tau\}_{\tau=t-2}^{t}\right). \tag{10}$$

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

## Empirical model

In this section, we estimate the inter-temporal and intra-temporal effort substitutions in response to the variations in attractiveness of different fishing locations and the corresponding profitability. This study uses Heckman's (1976) selection model for the empirical estimation of the intra- and inter-temporal allocation of fishing effort to maximize profit. Heckman's two-step estimation approach enables us not only to estimate the decision to allocate effort or not [i.e. using the probit model (the first step)] but also to acquire the continuous effort allocation (i.e. how long to trawl) conditional on the participation decision (the second step).

Another reason to use Heckman model in our study is because of the problem of non-random sample selection bias. This problem occurs when the sample is unrepresentative of the population we are interested in. More precisely, in our study, we investigate the factors affecting the effort allocation behaviour of fishers. Yet, we do not observe effort allocation of fishers who refuse to allocate effort because the perceived expected profit was relatively low given their level of effort. Under this circumstance, ordinary least squares estimation gives biased estimates (Wooldridge, 2009).

Heckman's (1976) solution to correct the potential selection problem is to predict the likelihood of participation in fishing at first stage using a probit model with a specific vector of predictors (i.e. in our case the explanatory variables that define the location attractiveness) and obtain the predicted inverse Mills ratio. The second stage equation is estimated using the predicted values of inverse Mills ratio as new regressors in the model together with the same vector of predictors to yield a consistent estimates. However, since the first and second stage equations contain the same vector of regressors, the predicted value in the first stage is highly correlated with the predictors in the second stage. In order to tackle this, we need to include one or more additional explanatory variables in the first stage that are absent in the second stage. The selection of additional explanatory variables should be in a way that they affect the probability of participation but not the length of trawling (Wooldridge, 2009).

Our dependent variable is the allocated fishing effort in area $a$ and time $t$ by trawler $i$. The explanatory variables, which define the relative attractiveness of locations, are the fish availability measured by the CPUE (tons per hour of trawling), price of fish per kilo (NOK), fuel price per litre to travel to the available locations (NOK), intensity of the coastal fleet's participation in winter cod fishery (i.e. approximated by the total landings of cod in thousand tons by coastal boats), and sea ice concentration. The additional independent variable to overcome the collinearity problem in the first stage is the switching cost from one location to the other available alternative. Here, switching cost refers the fishing location in the previous time period. This lagged dummy variable increases the likelihood of allocation of fishing effort in the same location as fishers could save steaming cost by staying at the same fishing site (first stage). However, the previous catch location is not associated with how long fishers would spend time to trawl in the new location (second stage).

## Estimation of the intra-temporal effort allocation

The estimating equation for the intra-temporal substitution is based on the theoretical result expressed in Equation (8). Equations (11) and (12) show the estimation procedure for the probit model, in which trawler $i$ decides whether to allocate fishing effort in area $a$ and time $t$ with respect to the attractiveness of the selected area. The latent variable for fishing effort $e^{*r}_{iat}$ in the probit model is specified in Equation (12). $D^{r}_{iat}$ is a binary variable that is equal to 1 if the trawler allocates fishing effort to location $a$ and time $t$ based on the perceived expected profit and 0 otherwise. The superscript 1 in Equation (11) refers to the first step of the estimation procedure. The superscript $r$ refers to the intra-temporality equations.

$$e^{*\,r}_{iat} = \phi^{r\,1}_{i} + \theta^{r1}_{t} + \omega^{r1}_{a} + \beta^{r1}_{1a} fp_t + \beta^{r1}_{2a} cc_t + \beta^{r1}_{3a} ic_t + \sum_{j\in J} \beta^{r1}_{1j} CPUE_{ajt} + \sum_{k\in A} \beta^{r1}_{ak} sc_{iakt} + \varepsilon^{r1}_{iat}\,. \tag{11}$$

$$D^{r}_{iat} = \begin{cases} 1\ if\ e^{*r}_{iat} > 0 \\ 0\ otherwise \end{cases}. \tag{12}$$

$\phi^{r1}_{i}$ represents the individual vessel fixed effect. $\theta^{r1}_{t}$ and $\omega^{r1}_{a}$ are period and area fixed effects, respectively. $fp_t$ refers to the fuel price, which approximates the cost of travelling to the considered location. $cc_t$ indicates the total landings of cod by the coastal fishers and is a proxy for the possible congestion effect of the coastal boats on trawlers' harvest strategy. $ic_t$ shows the ice coverage in the Barents Sea. We allow the coefficients on these area-specific costs to vary across different areas to estimate the intra-temporal effects as the equation (8) indicates. $CPUE_{ajt}$ is the calibrated catch per unit of effort across 61 vessels (the calibration procedure is explained in Section 3.3.1). $sc_{iakt}$ refers to the switching cost. It is a lagged dummy variable indicating the location of the vessel in the previous period. For example, if a trawler has operated in region A at time $t-1$, the dummy variable is 1 for time $t$. We have used $k$ to refer to the effort allocation in previous location and $a$ for the current area. More precisely, if a trawler stays at the same region during successive periods, $k = a$. $\varepsilon^{r1}_{iat}$ refers to the residuals.

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

$$\ln e_{iat} = \phi^{r2}_{i} + \theta^{r2}_{t} + \omega^{r2}_{a} + \beta^{r2}_{1a} fp_t + \beta^{r2}_{2a} cc_t + \beta^{r2}_{3a} ic_t + \sum_{j\in J} \beta^{r2}_{1j} CPUE_{ajt} + +\varepsilon^{r2}_{iat}\,. \tag{13}$$

## Estimation of the inter-temporal effort allocation

The estimating equation for the inter-temporal substitution is based on the theoretical result expressed in Equation (10). Since the inter-temporal effort allows for time variation, we also include the prices of fish species in our model. The superscript $z$ refers to the inter-temporality.

$$e^{*z}_{iat} = \phi^{z1}_{i} + \theta^{z1}_{t} + \omega^{z1}_{a} + \sum_{\tau=t-2}^{t} \Big[ \beta^{z1}_{1\tau} fp_\tau + \beta^{z1}_{2a\tau} cc_\tau + \beta^{z1}_{3a\tau} ic_\tau + \sum_{j\in J} \Big( \beta^{z1}_{4j\tau} Price_{j\tau} + \beta^{z1}_{5j\tau} CPUE_{aj\tau} \Big) \Big] + \beta^{z1}_{6a} sc_{ia,t-1} + \varepsilon^{z1}_{iat}\,. \tag{14}$$

$$D^{z}_{iat} = \begin{cases} 1\ if\ e^{*z}_{iat} > 0 \\ 0\ otherwise \end{cases}. \tag{15}$$

The key differences from the first-step equation of the intra-temporal substitution [see Equation (11)] are the inclusion of the current period and the two previous periods ($\tau = t-1,\ t-2$) as well as the prices of the target species. In this specification, we focus on the inter-temporal effect of area-specific cost variation, hence we only estimate the coefficient on congestion cost ($cc_t$) for area $a = \mathrm{B}$, and the coefficient on the ice coverage ($ic_t$) for area $a = \mathrm{A}$. $Price_{jt}$ refers to the price of target species $j$ at time $t$. $\varepsilon^{z1}_{iat}$ refers to the residuals. The second-step estimation equation for the inter-temporal substitution is specified in Equation (16).

$$\ln e_{iat} = \phi^{z2}_{i} + \theta^{z2}_{t} + \omega^{z2}_{a} + \sum_{\tau=t-2}^{t} \Big[ \beta^{z2}_{1\tau} fp_\tau + \beta^{z2}_{2a\tau} cc_\tau + \beta^{z2}_{3a\tau} ic_\tau + \sum_{j\in J} \Big( \beta^{z2}_{4j\tau} Price_{j\tau} + \beta^{z2}_{5j\tau} CPUE_{aj\tau} \Big) \Big] + \varepsilon^{z2}_{iat}\,, \tag{16}$$

$\varepsilon^{z2}_{iat}$ refers to the residuals.

## Correction of potential econometric issues

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

### Inter-calibration of the CPUE across the trawl vessels

Within research on fisheries, the CPUE is a commonly employed index to assess the average stock size (Hilborn and Walters, 1992;

**Table 2.** Estimation results of the first and second steps from Equations (11) and (13).

| | 1st stage | | 2nd stage |
|---|---|---|---|
| | Estimates | Marginal effects | Effort hours |
| Fuel price, baseline | 0.022 | 0.009 | $-0.133^{***}$ |
| Fuel price, region B | $-0.085^{*}$ | $-0.033^{*}$ | 0.060 |
| Fuel price, region C | $0.085^{*}$ | $0.033^{*}$ | $0.180^{***}$ |
| Coastal landing (1000$t$), baseline | $-0.032^{***}$ | $-0.013^{***}$ | $0.048^{***}$ |
| Coastal landing (1000$t$), region B | $-0.001$ | 0.000 | $-0.050^{***}$ |
| Coastal landing (1000$t$), region C | $0.072^{***}$ | $0.028^{***}$ | $-0.048^{***}$ |
| Barents Sea ice coverage, baseline | $-2.603^{***}$ | $-1.007^{***}$ | 0.291 |
| Barents Sea ice coverage, region B | $2.720^{***}$ | $1.052^{***}$ | 0.346 |
| Barents Sea ice coverage, region C | $3.328^{***}$ | $1.287^{***}$ | $-0.180$ |
| Cod: CPUE | $-0.005^{**}$ | $-0.002^{**}$ | $-0.004$ |
| Saithe: CPUE | $0.024^{***}$ | $0.009^{***}$ | $-0.007$ |
| Haddock: CPUE | $-0.063^{*}$ | $-0.024^{*}$ | $-0.018$ |
| Switch from A to A | $1.505^{***}$ | $0.542^{***}$ | |
| Switch from A to B | $-2.304^{***}$ | $-0.522^{***}$ | |
| Switch from A to C | $-2.487^{***}$ | $-0.538^{***}$ | |
| Switch from B to B | $0.958^{***}$ | $0.364^{***}$ | |
| Switch from B to A | $-1.091^{***}$ | $-0.343^{***}$ | |
| Switch from B to C | $-1.752^{***}$ | $-0.456^{***}$ | |
| Switch from C to C | $1.168^{***}$ | $0.436^{***}$ | |
| Switch from C to A | $-1.560^{***}$ | $-0.432^{***}$ | |
| Switch from C to B | $-2.082^{***}$ | $-0.497^{***}$ | |
| Inverse mills ratio | | | $-0.624^{***}$ |
| $R^2$ | | | 0.234 |

The marginal effects show the magnitude of effort displacement in the intra-temporal analysis. $^{*}p < 0.1$, $^{**}p < 0.05$, and $^{***}p < 0.01$.

Maunder *et al.*, 2006). To calculate the values of the CPUE, the total catch of each haul is divided by the corresponding fishing effort. In this article, we are dealing with the effort allocation decisions of 61 individual trawl vessels over the period 2011–2016. Even if trawlers coexist at the same time and in the same location and are exposed to the same level of fish abundance, the effort allocation decisions and, subsequently, the catch sizes might be different. To take this heterogeneity into account, we construct a vessel-specific index for the CPUE of each trawler to implement it in the estimation equations.

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

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

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

## Endogeneity problem of the cod price

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

As a large portion of the Norwegian cod catch is exported to foreign countries (Asche *et al.*, 2002a, 2002b), the global wholesale market price for cod is expected to affect the international buyers' evaluation of the fish market, but it is not affected by the weekly cod landings (i.e. the definition of the instrumental variable). To correct the endogeneity problem of the cod price to obtain unbiased and consistent estimations, we first estimate the cod prices by instrumenting the global wholesale market prices for cod. Thereafter, we implement the estimated cod prices in the estimation equations.

## Results

We estimate Equations (11), (13), (14), and (16) using the comprehensive panel data set discussed in Section 2.2. Table 2 shows the estimation results for the intra-temporal effort allocation, while Table 3 refers to the inter-temporal analysis, using Heckman's two-step estimator. The tables report the estimations based on the first step—participation decisions (probit regression). They also provide the magnitude of effort displacement by marginal effects. The marginal effects show how the probability of participation in the area changes for a one-unit change in the explanatory variables. Tables 2 and 3 also present the estimation results based on the second step—trawling hours—conditional on the participation decisions. The first-step estimates are used to calculate the inverse Mills ratio, which is used to estimate the second step. Region A is the reference group.

**Table 3.** Estimation results of the first and second steps from Equations (14) and (16).

| | First step | | Second step |
|---|---|---|---|
| | Estimates | Marginal effects | Effort hours |
| Fuel price | 0.138 | 0.051 | $-0.044$ |
| Fuel price, *t*-1 | 0.179 | 0.065 | 0.241 |
| Fuel price, *t*-2 | $-0.074$ | $-0.027$ | 0.052 |
| Coastal landing (1000*t*) | $-0.018^{***}$ | $-0.007^{***}$ | $-0.004$ |
| Coastal landing (1000t), *t*-1 | $-0.001$ | 0.000 | 0.001 |
| Coastal landing (1000t), *t*-2 | $-0.001$ | 0.000 | $0.007^{*}$ |
| Sea Barents ice coverage | $-5.642^{***}$ | $-2.065^{***}$ | 1.246 |
| Sea Barents ice coverage, *t*-1 | $-2.671^{***}$ | $-0.978^{***}$ | 0.154 |
| Sea Barents ice coverage, *t*-2 | $3.386^{***}$ | $1.239^{***}$ | $-1.491^{**}$ |
| Cod: Price | 0.114 | 0.042 | 0.032 |
| Cod: Price, *t*-1 | $-0.090^{*}$ | $-0.033^{*}$ | 0.074 |
| Cod: Price, *t*-2 | $-0.006$ | $-0.002$ | $-0.006$ |
| Saithe: Price | 0.019 | 0.007 | $-0.161^{***}$ |
| Saithe: Price, *t*-1 | $-0.024$ | $-0.009$ | $-0.019$ |
| Saithe: Price, *t*-2 | 0.025 | 0.009 | $-0.001$ |
| Haddock: Price | $-0.014$ | $-0.005$ | 0.026 |
| Haddock: Price, *t*-1 | 0.018 | 0.007 | 0.016 |
| Haddock: Price, *t*-2 | $-0.033^{**}$ | $-0.012^{**}$ | $-0.003$ |
| Cod: CPUE | $0.029^{***}$ | $0.011^{***}$ | $-0.004$ |
| Cod: CPUE, *t*-1 | $-0.011$ | $-0.004$ | $-0.035^{**}$ |
| Cod: CPUE, *t*-2 | $-0.005$ | $-0.002$ | $-0.041^{**}$ |
| Saithe: CPUE | $0.022^{*}$ | $0.008^{*}$ | $-0.008$ |
| Saithe: CPUE, *t*-1 | 0.018 | 0.007 | $-0.004$ |
| Saithe: CPUE, *t*-2 | $-0.064^{***}$ | $-0.023^{***}$ | 0.002 |
| Haddock: CPUE | $-0.230^{**}$ | $-0.084^{**}$ | $-0.007$ |
| Haddock: CPUE, *t*-1 | 0.031 | 0.011 | $0.347^{***}$ |
| Haddock: CPUE, *t*-2 | $-0.372^{***}$ | $-0.136^{***}$ | $-0.215^{*}$ |
| Switch cost | $-1.105^{***}$ | $-0.397^{***}$ | |
| Inverse Mills ratio | | | $-1.102^{***}$ |
| $R^2$ | | | 0.302 |

The marginal effects show the magnitude of effort displacement in the inter-temporal analysis. $^{*}p < 0.1$, $^{**}p < 0.05$, and $^{***}p < 0.01$.

## Results of the intra-temporal effort allocation

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

The results presented in Table 2 shows that, overall, the coefficients are all of the expected sign. The combination of the result for the coefficients of the fuel price shows that the displacement of participation from region B to region C when the fuel price becomes high. The baseline coefficient is small in magnitude and statistically insignificant. The negative and significant coefficient of the fuel price in region B ($0.022 - 0.085$) (i.e. the true effect is the sum of the coefficient of the reference group and the coefficient of region B) and the positive and significant coefficient of the fuel price in regions C ($0.022 + 0.085$) in the first step increases the likelihood of effort substitution from region B to C. Moreover, the results from the second step show that, once trawlers have decided to fish with higher fuel prices, the effort is congested in region C. This harvesting behaviour is justifiable. When the travel cost increases, fishing region near the shore is preferable (region C).

With regard to the effect of the congregation of coastal fleet during the winter months on the harvest strategy adopted by the trawlers, the almost zero magnitude of the coefficient on the region B indicates that the negative effect is as much as the region A as the true effect is the sum of the baseline coefficient and the coefficient on the region B. The positive sign in region C indicates that the intensity of participation of coastal boats shifts the effort allocation of the trawlers to region C to target saithe. For the participating trawlers, the effort hours increase in the region A as the baseline coefficient shows, but the net effects on the regions B and C are very small. The substitution due to congestion is adjusted by internal margin (effort time) for the region A, but it is adjusted by external margin (participation) for the region C.

Unsurprisingly, the presence of thicker sea ice in the Arctic area (region A) increases the likelihood that trawlers will participate in regions B and C and avoid region A. This is expected as the Arctic areas have the thickest ice density in the wintertime (see Figure 7), which discourages trawlers from fishing in region A and causes them to reallocate their fishing effort to the ice-free regions B and C. For the participating trawlers, the effort hours increase in the region A and B, but the estimates are statistically insignificant, suggesting that the effects of ice coverage on the internal margin adjustment are not strong. This is reasonable because operating in the region covered with sea ice is very costly and the trawlers would respond to the changes of sea ice by participation rather than the effort hours.

The coefficients of CPUEs show that they are affecting external margins rather than effort hours, but the interpretation of the signs is not straightforward. The negative signs on the cod and haddock do not necessarily mean that the trawlers avoid these species as they are the main target species. However, in this intra-temporal model, the choice of location may not be based on the abundance of the target species in the given period. As the coefficients on the saithe

CPUE is positive and significant, the region C is chosen due to the saithe abundance, but the choice of A or B are made based on the area-specific costs rather than the stock abundance. The negative signs may be due to the confounding factors that are not captured in the model such as ocean conditions in finer scales. In addition, the trawlers are not actually "target" haddock but rather treat it as beneficial bycatch of cod. The importance of the CPUE is also discussed in the section for inter-temporal effort allocation.

The results from switching cost disclose that switching fishing location influences the probability of participation as well as the trawling duration. Shifting between fishing locations is costly, and the magnitude is greater when switching from A or B to C than switching between A and B.

### Results of the inter-temporal effort allocation

The results in Table 3 shows how trawlers allocate their fishing effort over time in a given region.

An increase in the fuel price in a given month and the previous two months does not strongly affect the decision to allocate fishing effort to a given location in the current month. Combined with the intra-temporal results, we see that the trawlers respond to the increase in fuel price by shifting between the available locations within a time period, rather than adjusting between different points in time at the same location. Unlike environmental fluctuations, fluctuations in fuel prices are not seasonal and are difficult to predict, and hence the dynamic adjustment is limited.

The increased activity of coastal fishers in the current month in region B decreases the probability of fishing effort allocation, but no intertemporal shift is indicated. As we discussed in the previous section, the displacement of participation due to the coastal fishing activity is substituted with the different locations in the same period.

Unsurprisingly, the denser sea ice in the current month and the previous month in region A is associated with a lower probability of allocating fishing effort to region A in the current month. However, the two-month-lagged variable for sea ice positively affects the effort allocation to this region in the current month. This refers to inter-temporal effort substitution. For the trawlers who have already decided to travel to region A to fish for cod and haddock, the thickness of the ice in the last two months negatively affects the amount of fishing effort that they allocate to that region.

Prices do not seem to strongly affect the inter-temporal allocation of effort in both participation and haul hours. The effect of the current price of cod is positive for participation decision, but not statistically significant. The negative effect of price in the previous period is theoretically expected, and is probably due to intertemporal substitution, which adjusts the next period for increased effort when prices are high, but not for prices of two previous periods. The current price of saithe has a negative impact on the internal margin. Price of saithe is almost invariant and its price reaches the highest level in March (see Figure 6). This is the time when saithe aggregates to spawn. Catching congregated saithe requires less fishing time, but the aggregated CPUE at the monthly level may not capture all the variations due to the congregation, and the timing of the price variation may coincidently explain the short effort time.

The CPUE of cod and saithe in the current period have positive and significant coefficients, suggesting that the trawlers are targeting these two species. While the intra-temporal model revealed that the trawlers do not choose the location with the highest CPUE in a given period. This result shows that the trawlers choose the best timing of cod CPUE in a season. This is consistent with the exhaustion of the individual quotas of cod and saithe. The unintuitive signs for haddock CPUE may be due to "beneficial bycatch." As shown in Figure 2, the trawlers participate in the region A to target cod when the cod CPUE is high, but haddock CPUE is not necessarily high.

With regard to the switching cost, we should bear in mind that this variable shows the location of the vessel in the previous period. Obviously, the increase in switching cost to other locations/fisheries negatively affects the participation likelihood in a new location/fishery.

## Discussion

Our empirical results are informative about how trawlers respond to the changes in the location-specific costs, such as the fuel price to travel to the fishing grounds (i.e. including switching cost), the intensity of coastal fishers' participation in region B, and the ice congestion in region A. Since our results reveal that region-specific costs have a substantial effect on the decisions underlying the effort allocation, we narrow the focus of our discussion on this matter.

With regard to the fuel price, intra-temporal substitutions in the allocation of fishing effort was detected. The increased fuel prices discouraged trawlers from fishing in region B due to possibly high travel cost to reach to the port to land the fish. With higher fuel price, trawlers choose region C to fish saithe. The landing site for saithe is located in region C (Ålesund port) instead of the base port located in northern Norway (Tromsø port); hence, trawlers incur less fuel expenditure. This is to say that trawlers may compensate increasing fuel costs by choosing nearshore locations. This result shows that the cost, through the spatial allocation of effort, influences the allocation of individual quotas. This result is in agreement with the results from the study by Poos *et al.* (2013) where they argue that fishers fish closer to port when the fuel price is higher. Once trawlers have decided to participate, the amount of fishing effort is decreased in region A and increased in region C. The reduction in trawling hours in region A may be related to the fact that offshore vessels with active gears such as bottom trawling technique are very sensitive to fuel cost (Poos *et al.*, 2013). For this reason, trawlers' fishing behaviour can be influenced by the increase in fuel price. The adaptive responses of the trawl fishers to rising fuel cost could be reduction in towing speed or towing length (Abernethy *et al.*, 2010; Beare and Machiels, 2012; Poos *et al.*, 2013). Our results confirm the reduction in trawling hour in region A when fuel price is higher. In addition, a possible rationale for insignificance of inter-temporal effect when fuel price is higher could be related to the time constraint embedded in quota constraint. Based on the Norwegian fisheries regulations, quotas must be fished within a fishing year. Hence, even with high fuel prices, fishers have to go fishing to exhaust the quota portfolio by the end of the fishing year.

The negative effect of the congestion of the coastal fleet on trawlers' decision-making regarding their effort allocation is irrefutable. The congregation of the coastal boats persuades trawlers to redirect the fishing effort to region C and consume saithe quota. Based on our results, the intensified fishing activities of coastal fishers reduces the magnitude of the effort allocation in region B. Lofoten fishery takes place in the winter months when cod, saithe, and haddock aggregate to spawn along the west coast of Norway. The cost per harvested fish is lower during the winter due to the availability of dense stocks (Hannesson, 2007; Sandberg, 2006). The lower cost of production together with the limited geographical mobility of the coastal fleet persuades coastal fishers to fish for a big portion of their quotas (i.e. to exhaustion) at this time. Up to 80% of the cod quota belongs to the coastal fishers (Asche *et al.*, 2014; Birkenbach *et al.*, 2020); hence, as a result of the large supply of cod, the price of cod that it is received by the trawlers drops (Alizadeh Ashrafi *et al.*, 2020; Hermansen and Dreyer, 2010) (see also Figure 6). Thus, it is economically irrational for trawlers to fish for the cod quota in region B when the price is low. In connection with this, Boyce (1992) mentioned that individual fishers consider the congestion effect of their counterparts when choosing to participate in a specific location.

After spawning, when cod and haddock swim back to the Arctic to feed, the prices start to rise (see Figure 6) due to the smaller landings as the coastal fleet has already filled its quotas during the winter (Asche *et al.*, 2015; Hermansen and Dreyer, 2010). At this time, trawlers utilize the remaining cod and haddock quotas in the sub-Arctic areas (see Figure 4). Shifting the production to other times of the year when cod price is higher indicates that the Norwegian trawlers are profit oriented. This result is in line with that of the study by Alizadeh Ashrafi *et al.* (2020), which found that the magnitude of the reduction in the cod price in the winter fishery outweighs the reduction in the cost of fishing; hence, trawlers reserve the cod quota for the time when the cod price starts to rise towards the end of the year.

Moreover, as our intra-temporal results show, in the winter fishery, trawlers are less likely to participate in region A, probably because of the harsh climatic conditions of the Arctic during the winter (see Figure 7). Therefore, trawlers are left with the only option, which is to fish for their saithe quota in region C. Substitution of cod and haddock with saithe during winter is also confirmed by Birkenbach *et al.* (2020). They argued that, due to the high value of cod, the landings of this species should be spread over the fishing year to take advantage of the downward-sloping demand. In contrast, the saithe quota should be fished in the short period of winter due to its lower price and insensitivity of price to the landings volume. However, we have a different reason for this substitution. Our results show that saithe is targeted during the short period of winter because of the region-specific cost inflicted by the congestion of coastal boats and is not necessarily because of the low commercial value of saithe.

For the trawlers who have already decided to fish in region A during winter, the increased trawling hour in region A might be due to the fact that participating trawlers in region A have already incurred steaming cost to reach to region A. Therefore, they increase trawling hour to make best use of the cost that they have already incurred to reach region A. Another relevant justification to increase trawling hour in region A is that early in the fishing season, cod is still plentiful in the Arctic area as the cod reach the spawning grounds along the north-west coast no earlier than March (Olsen *et al.*, 2010; Trout, 1957).

With regard to the inter-temporal effort allocation, the intense fishing of coastal fishers in a given month reduces the probability of allocating effort in region B in that month. However, the intensified fishing activities of coastal fishers in the previous two months has no effect on probability of allocating fishing effort in the current month in region B. This could mean that the congestion of the coastal fleet and the price reduction in cod and haddock during the winter are a transient phenomenon, and, as time elapses, the negative impact of the congestion of coastal boats will eventually fade away and the price of cod and haddock will rise (see Figure 6).

Another component of the region-specific cost is the extent of the Barents Sea ice. Trawlers redirect their fishing effort to the ice-free regions of B and C when the ice is thicker in region A. However, region C is preferred to region B to catch saithe. The reason behind the preference for region C to region B could be the presence of coastal fishers during the winter months in region B. Catching saithe during winter to maximize profit is confirmed by Birkenbach *et al.* (2020). They explain that due to the flat demand curve for saithe, the saithe quota should be fished in winter. In contrast, since the price of cod fluctuates, trawlers should spread cod landings over the course of a year to take advantage of fluctuation in the market conditions to maximize profit. Our intra-temporal result provides another mechanism for observing this harvest strategy. During the winter months, it is rational to avoid region A to catch cod due to the increased hazard of fishing, stemmed from harsh climatic conditions of the Arctic areas. Trawlers are reluctant to fish in region B as well because the prices of cod and haddock are low (see Figure 6). Hence, they are left with only one option and that is to fish saithe in region C.

In the case of the inter-temporal allocation of effort in the presence of ice in region A, the thicker ice at times $t$ and $t-1$ reduces the likelihood of participation at times $t$. In contrast, the presence of thicker ice at time $t-2$ is associated with higher probability of participation at time $t$. This could mean that, as time passes, the climatic condition of region A becomes more desirable for fishing. This intertemporal substitution suggests another reason to "spread" the cod supply over the season. The forward-looking harvesters know the availability of cod in region A when the ice extent decreases; hence, the shadow cost of harvesting cod early in region B is large. This is still aligned with seasonal profit-maximizing behaviour by reducing the region-specific cost and taking the shadow cost into account, but it is captured by allowing the spatial choice in the model.

Another locational-specific cost was the cost related to the shift between different fishing locations. Our results show that the effect of switching cost is indisputable in allocation of fishing effort to maximize profit. Fishers increase the trawling hour when they decide to remain in the same fishing locations. In contrast, the trawling hours are reduced when fishers switch between locations as displacing fishing effort to a new area is costly and decreases the profit.

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

## Conclusion

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

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

Despite the fact that these fisheries have long been studied, the knowledge of fishing effort allocation is underdeveloped. In this regard, the present article aims to extend the insights into the spatio-temporal allocation of fishing effort in the trawl fishery and its profit-maximizing harvest strategy. Basically, our empirical model investigates the fishing effort allocation across the three species and three regions over the course of a year. We defined location heterogeneity in terms of the fish availability, fish prices, fuel cost to traverse, coexistence of the coastal fleet, and ice congestion.

Our major finding is that the region-specific attributes, such as the proximity to shore and less steaming time, the presence of coastal boats during the winter, and the icy conditions of the sub-Arctic areas, have a substantial effect on the adopted harvest strategy of the trawlers' profit maximization. Another finding is that the decisions underlying the spatio-temporal effort allocation of trawlers are not made in a random or haphazard manner. Indeed, trawlers are capable of identifying the changes in the biological, environmental, and economic conditions in these regions within a fishing year and respond to these changes in an economically rational way. The technical advances of the trawl vessel (e.g. powerful engine and large size) offer them temporal and spatial flexibility, and this could explain the ability of fishers to make rational choices regarding effort reallocation.

The results of our study provide a broad picture of spatial dynamics and how variations in attractiveness of one location influence the effort allocation of the trawlers in alternative fisheries or areas. Moreover, the identification of the trawlers' harvest strategy and the potential factors that explain the effort allocation choices contribute to a better prediction of fishers' potential responses to the possible biological, environmental, economic, and regulatory changes across space. This information is useful in designing policy instruments to improve the fisheries regulations.

## Data availability statement

Raw catch and effort data are openly available in the Norwegian Directorate of Fisheries at https://www.fiskeridir.no/.

Fish prices are publically available in the Norwegian Fishermen's Sale Organization at https://www.rafisklaget.no/. The wholesale market prices for the Atlantic cod are available on request from the corresponding author, Tannaz Alizadeh Ashrafi.

Fuel price is available in the Guarantee Fund for Fishers at https://www.garantikassen.no/.

The Barents Sea ice coverage data are openly accessible in the European Organization for the Exploitation of Meteorological Satellites at https://www.eumetsat.int/.

## References

Abernethy, K. E., Trebilcock, P., Kebede, B., Allison, E. H., and Dulvy, N. K. 2010. Fuelling the decline in UK fishing communities? ICES Journal of Marine Science 67: 1076–1085.

Alizadeh Ashrafi, T., Eide, A., and Hermansen, Ø. 2020. Spatial and temporal distributions in the Norwegian cod fishery. Natural Resource Modeling 33: e12276.

Alizadeh Ashrafi, T., Syed, S., and Eide, A. 2021. Individual quotas and revenue risk of fishing portfolio in the trawl fishery. Fisheries Research 241: 105990.

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

Årthun, M., Eldevik, T., Smedsrud, L., Skagseth, Ø., and Ingvaldsen, R. 2012. Quantifying the influence of Atlantic heat on Barents Sea ice variability and retreat. Journal of Climate 25: 4736–4743.

Asche, F., Bjørndal, M. T., and Bjørndal, T. 2014. Development in fleet fishing capacity in rights based fisheries. Marine Policy 44: 166–171.

Asche, F., Chen, Y., and Smith, M. D. 2015. Economic incentives to target species and fish size: prices and fine-scale product attributes in Norwegian fisheries. ICES Journal of Marine Science 72: 733–740.

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

Asche, F., Gordon, D. V., and Hannesson, R. 2002. Searching for price parity in the European whitefish market. Applied Economics 34: 1017–1024.

Beare, D., and Machiels, M. 2012. Beam trawlermen take feet off gas in response to oil price hikes. ICES Journal of Marine Science 69: 1064–1068.

Bergstad, O., Jørgensen, T., and Dragesund, O. 1987. Life history and ecology of the gadoid resources of the Barents Sea. Fisheries Research 5: 119–161.

Birkenbach, A. M., Cojocaru, A. L., Asche, F., Guttormsen, A. G., and Smith, M. D. 2020. Seasonal harvest patterns in multispecies fisheries. Environmental and Resource Economics 75: 631–655.

Boyce, J. R. 1992. Individual transferable quotas and production externalities in a fishery. Natural Resource Modeling 6: 385–408.

Eide, A., Skjold, F., Olsen, F., and Flaaten, O. 2003. Harvest functions: the Norwegian bottom trawl cod fisheries. Marine Resource Economics 18: 81–93.

Flaaten, O., and Heen, K. 2004. Fishing vessel profitability and local economic link obligations—the case of Norwegian trawlers. Marine Policy 28: 451–457.

Garrod, D. 1967. Population dynamics of the Arcto-Norwegian cod. Journal of the Fisheries Research Board of Canada 24: 145–190.

Godø, O. R., and Michalsen, K. 2000. Migratory behaviour of north-east Arctic cod, studied by use of data storage tags. Fisheries Research 48: 127–140.

Hannesson, R. 2007. A note on the "stock effect." Marine Resource Economics 22: 69–75.

Heckman, J. J. 1976. The common structure of statistical models of truncation, sample selection and limited dependent variables and a simple estimator for such models. In Annals of Economic and Social Measurement, 5, pp. 475–492. National Bureau of Economic Research, Cambridge.

Hermansen, Ø., and Dreyer, B. 2010. Challenging spatial and seasonal distribution of fish landings—the experiences from rural community quotas in Norway. Marine Policy 34: 567–574.

Hersoug, B. 2005. Closing the Commons: Norwegian Fisheries from Open Access to Private Property. Eburon Academic Publishers, Utrecht.

Hilborn, R., and Walters, C. J. 1992. Quantitative Fisheries Ftock Assessment: Choice, Dynamics and Uncertainty. Chapman and Hall, New York.

Holland, D. S., and Sutinen, J. G. 1999. An empirical model of fleet dynamics in New England trawl fisheries. Canadian Journal of Fisheries and Aquatic Sciences 56: 253–264.

Holland, D. S., and Sutinen, J. G. 2000. Location choice in New England trawl fisheries: old habits die hard. Land Economics 76: 133–149.

Jakobsen, T., and Olsen, S. 1987. Variation in rates of migration of saithe from Norwegian waters to Iceland and Faroe Islands. Fisheries Research 5: 217–222.

Johnsen, J. P., and Eliasen, S. 2011. Solving complex fisheries management problems: what the EU can learn from the Nordic experiences of reduction of discards. Marine Policy 35: 130–139.

Korsbrekke, K. 1999. Variations in maturity of haddock in the Barents Sea in relation to year-class strength, age, size, sex and area. Journal of Northwest Atlantic Fishery Science 25: 37–45.

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

Maunder, M. N., Sibert, J. R., Fonteneau, A., Hampton, J., Kleiber, P., and Harley, S. J. 2006. Interpreting catch per unit effort data to assess the status of individual stocks and communities. ICES Journal of Marine Science 63: 1373–1385.

Misund, O. A., Heggland, K., Skogseth, R., Falck, E., Gjøsæter, H., Sundet, J., and Lønne, O. J. 2016. Norwegian fisheries in the Svalbard zone since 1980. Regulations, profitability and warming waters affect landings. Polar Science 10: 312–322.

Norwegian Directorate of Fisheries. 2019. Profitability Survey of the Norwegian Fishing Fleet. Norwegian Directorate of Fisheries, Bergen.

Olsen, E., Aanes, S., Mehl, S., Holst, J. C., Aglen, A., and Gjøsæter, H. 2010. Cod, haddock, saithe, herring, and capelin in the Barents Sea and adjacent waters: a review of the biological value of the area. ICES Journal of Marine Science 67: 87–101.

Pethon, P. 2005. Aschehougs Store Fiskebok: Norges Fisker I Farger. Ed. by Nyström, B. O. Aschehoug & Co, Oslo.

Pfeiffer, L., and Haynie, A. C. 2012. The effect of decreasing seasonal sea-ice cover on the winter Bering Sea pollock fishery. ICES Journal of Marine Science 69: 1148–1159.

Poos, J. J., Turenhout, M. N., AE van Oostenbrugge, H., and Rijnsdorp, A. D. 2013. Adaptive response of beam trawl fishers to rising fuel cost. ICES Journal of Marine Science 70: 675–684.

Rose, G. A. 1993. Cod spawning on a migration highway in the northwest Atlantic. Nature 366: 458.

Russo, T., D'Andrea, L., Franceschini, S., Accadia, P., Cucco, A., Garofalo, G., and Sabatella, R. F. 2019. Simulating the effects of alternative management measures of trawl fisheries in the central Mediterranean Sea: application of a multi-species bioeconomic modeling approach. Frontiers in Marine Science 6: 542.

Russo, T., Pulcinella, J., Parisi, A., Martinelli, M., Belardinelli, A., Santojanni, A., and Anderlini, L. 2015. Modelling the strategy of midwater trawlers targeting small pelagic fish in the Adriatic Sea and its drivers. Ecological Modelling 300: 102–113.

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

Smith, M. D., Sanchirico, J. N., and Wilen, J. E. 2009. The economics of spatial-dynamic processes: applications to renewable resources. Journal of Environmental Economics and Management 57: 104–121.

Standal, D., and Hersoug, B. 2015. Shaping technology, building society; the industrialization of the Norwegian cod fisheries. Marine Policy 51: 66–74.

Trout, G. 1957. *The Bear Island cod: m igrations and movement*. Ministry of Agriculture and Food Fisheries Investigations Series 2: 21.

Wooldridge, J. M. 2009. Introductory Econometrics: A Modern Approach, 4th edn. Cengage Learning, OH.

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