Received: 24 June 2019 | Accepted: 4 June 2020
DOI: 10.1111/nrm.12276

Natural Resource Modeling WILEY

Spatial and temporal distributions in the Norwegian cod fishery

Tannaz Alizadeh Ashrafi[1] | **Arne Eide**[1] | **Øystein Hermansen**[2]

[1]Norwegian College of Fishery Science, The Arctic University of Norway (UiT), Tromsø, Norway

[2]The Norwegian Institute of Food, Fisheries and Aquaculture Research (NOFIMA), Tromsø, Norway

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

Abstract

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

Recommendations for Resource Managers

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

1 | INTRODUCTION

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

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

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

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

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

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

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

2 | METHOD

2.1 | Theoretical framework

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

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

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

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

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

2.2 | Frequency-domain analysis

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

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

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

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

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

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

This allow us to modify the Fourier transformation to

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

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

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

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

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

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

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

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

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

3 | DATA

3.1 | Fishery areas and geographical distinction

Cod (*G. morhua*) is a commercially valuable fish species found throughout the shelf seas of the North Atlantic (Godø & Michalsen, 2000; Maslov, 1972). It is a population-rich species that exhibits migratory behavior (Neuenfeldt et al., 2013; Rose, 1993; Sundby & Nakken, 2008). In Norwegian waters cod is traditionally classified into two types: coastal and Northeast Arctic (NEA) cod. NEA cod, the cod considered here, migrates from the Barents Sea, aggregating during the period of mid-January to late February at particular geographical locations, mainly along the northern coast of Norway, to spawn (Mello & Rose, 2005b; Neuenfeldt et al., 2013; Rose, 1993). The migratory pattern and congregation in the same spawning field occurs every year in succession, representing a seasonal distribution pattern (Godø & Michalsen, 2000). Spawning migrations of NEA cod towards the coastal areas of Norway gives rise to a winter fishery. After spawning, NEA cod swims to offshore areas where it is available to the high seas cod fisheries. Figures 1 and 2 show the spatial and temporal distribution of trawling activities over a period of 6 years (2011–2016), including a total of 64,747 single trawl hauls (including both single and double trawls).

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

As it can be seen from Figure 2, effort allocation shows opposite patterns in the two regions. At the beginning of fishing season, effort is concentrated in region A, with its peak in January. The pattern is followed by a sudden drop in the fifth fortnight (March), and then it displays a plateau towards the end of the year. Whereas fishing effort in region B is dominantly concentrated at the end of the annual fishing season with its peak in December. A complete halt of production and effort allocation in the winter months for region B is observable, probably due

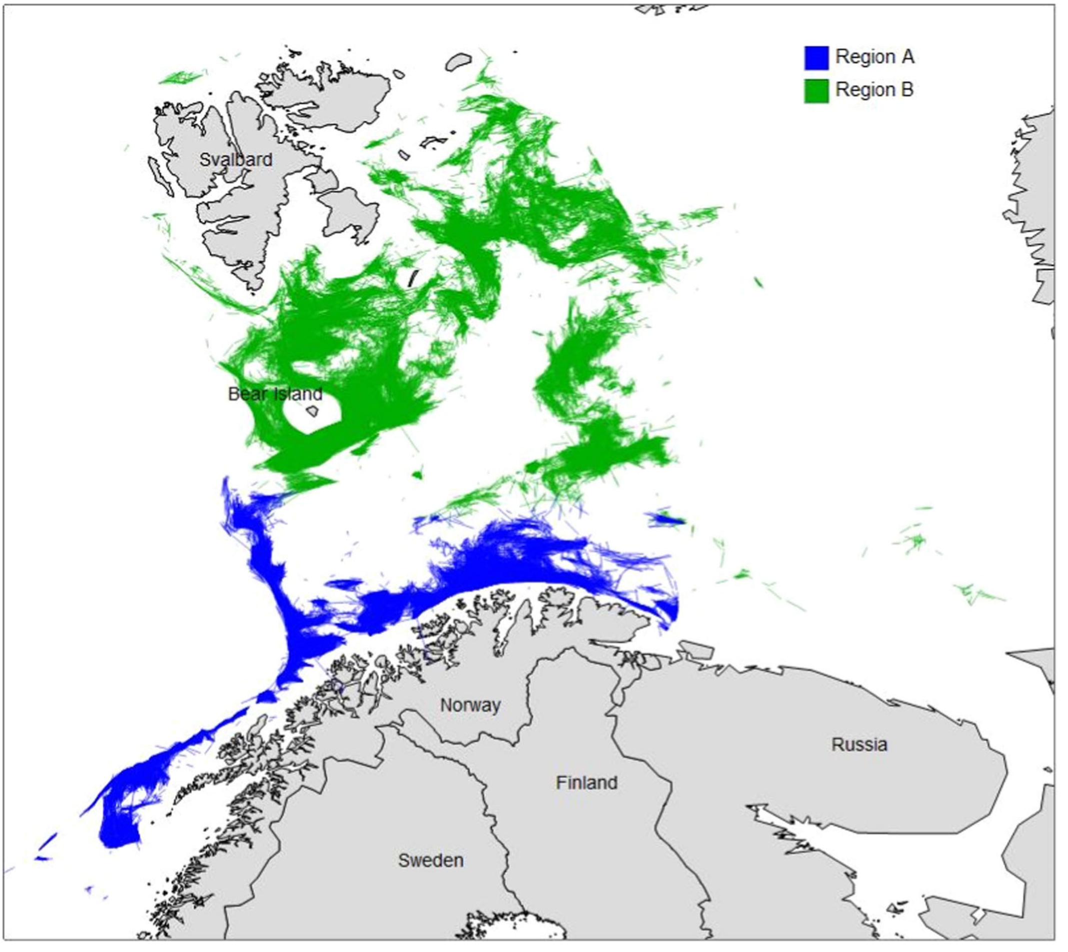

FIGURE 1 Positions (geolocations) of 64,747 individual tows by 54 Norwegian registered trawl vessels during 2011–2016 (Figure 1 excludes exceptionally short or long hauls and abnormal catch sizes). *Source:* Norwegian Directorate of Fisheries

to the harsh climate with extreme wind chill. Lack of fishing activities during the first quarter could be also attributed to the fact that trawlers are more attracted to region A due to cod assemblage and lower cost of fishing.

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

In figure 3, we graph cod catches in thousand tonnes per fortnight broken down by years (2011–2016). The catch also includes cod that incidentally was caught as bycatch in fisheries targeting, for example, saithe or haddock. The pattern of catch is reasonably similar to the pattern of fishing effort evident in Figure 2. Not surprisingly, for region A, monthly catch is highest at the

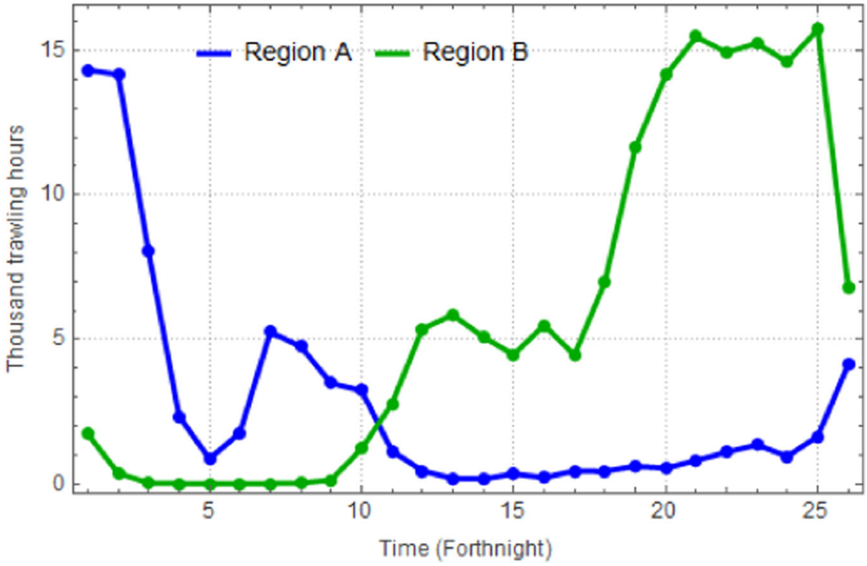

FIGURE 2 Total trawling time per fortnight spent on targeting cod in the two regions during the period 2011–2016. *Source:* Norwegian Directorate of Fisheries

beginning of the year (January) due to high densities of cod. Similar to the pattern of effort allocation in graph 2, there is a sudden drop in catch in February and March, even though cod stock density is still high. Compared with Figure 2, catch size starts to rise in region B by May (fortnight number 10). Trawling is predominant in this region until the end of the fishing year.

Figure 4 shows monthly average CPUE pertaining to regions A and B over the course of a year. The scores on the radar plot are on the scale of 0–8 in steps of 2, showing values of CPUE. From Figure 4, it can be seen that there is substantial variation in the magnitude of CPUE

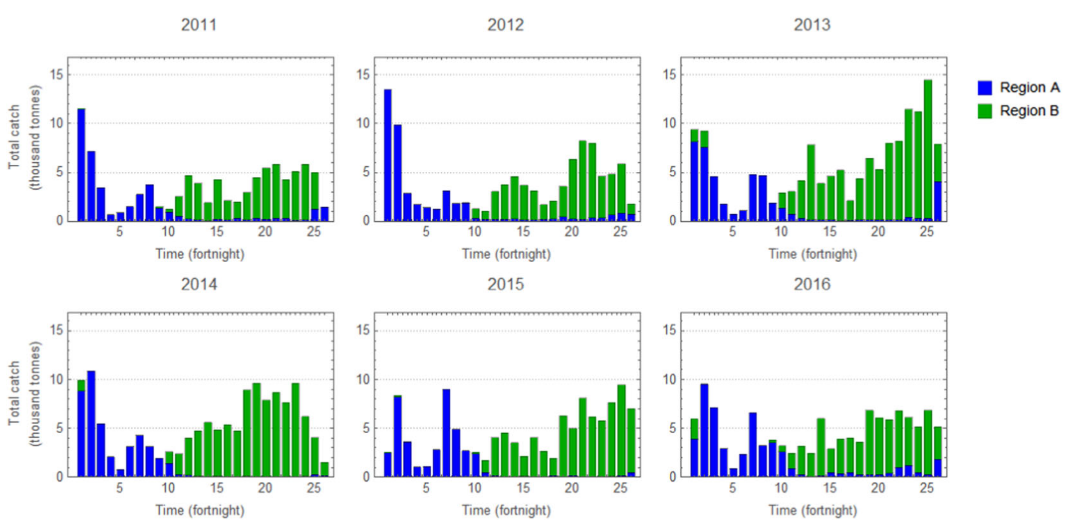

FIGURE 3 Fortnight cod catches (thousand tonnes) in the two areas during 2011–2016. Bycatch of cod when targeting other species is also included. *Source:* Norwegian Directorate of Fisheries

between the two regions. CPUE in region A displays a significant degree of variation where it reaches its peak in March. Looking at Figure 3, we see that even though in March (5th and 6th fortnight) catch size is considerably low, CPUE has the highest value of approximately 6 tonnes/hr of trawling, on average. The high value of CPUE arises because trawlers require less amount of fishing effort to catch cod when the stock is dense. Hence, reduction in trawling hour determines high CPUE in March. By April, when NEA cod migrates back to the high sea areas to feed, CPUE starts to decline considerably in region A. Since higher/lower values of CPUEs are related to the time when the stock is congregated/dispersed, this could offer some insight about the reason for seasonality in region A.

It is worth mentioning that initially we split the high sea area into two separate regions: a western and an eastern region. Since it was detected a strong resemblance between the level of CPUEs in the two regions, the regions were merged, recognizing them as one (region B). The rise in CPUE in region B occurs when NEA cod swims back to the Barents Sea. At this point in time, sea ice melts and weather becomes suitable in high north areas, encouraging fishers to redirect their fishing effort from region A to B. Productivity reaches its highest score in July and January with approximately 4 tonnes of cod per 1 hr of operation in region B. If we leave winter months (February and March) aside, CPUE is almost steady for the rest of the year. As pointed out earlier, when assuming a bilinear catch equation, CPUE is proportional to stock (see Equation 2). Invariability in CPUE could drive the lack of seasonality in the high sea areas.

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

Figure 5 shows that the average CPUE and the number of trawling operations in the first quarter in region A are greater than those in region B. The opposite pattern is discernible for region B out of winter months. Excluding fortnights 4–7, we see that average values and interquartile ranges are reasonably similar in region B.

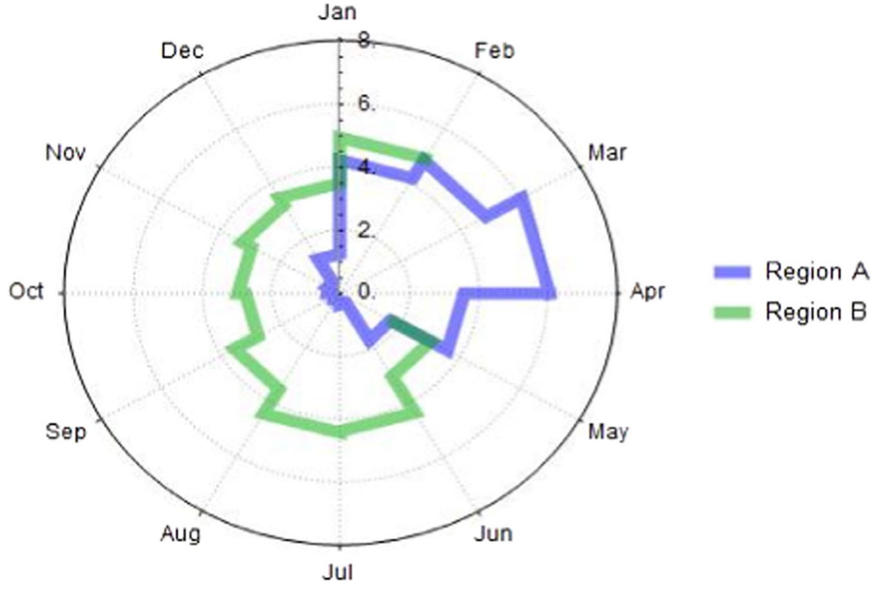

FIGURE 4 CPUE (tonne/hour) in the selected areas (2011–2016) with radial axes representing different months with center at zero in steps of 2. *Source:* Norwegian Directorate of Fisheries. CPUE, Catch per unit effort

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

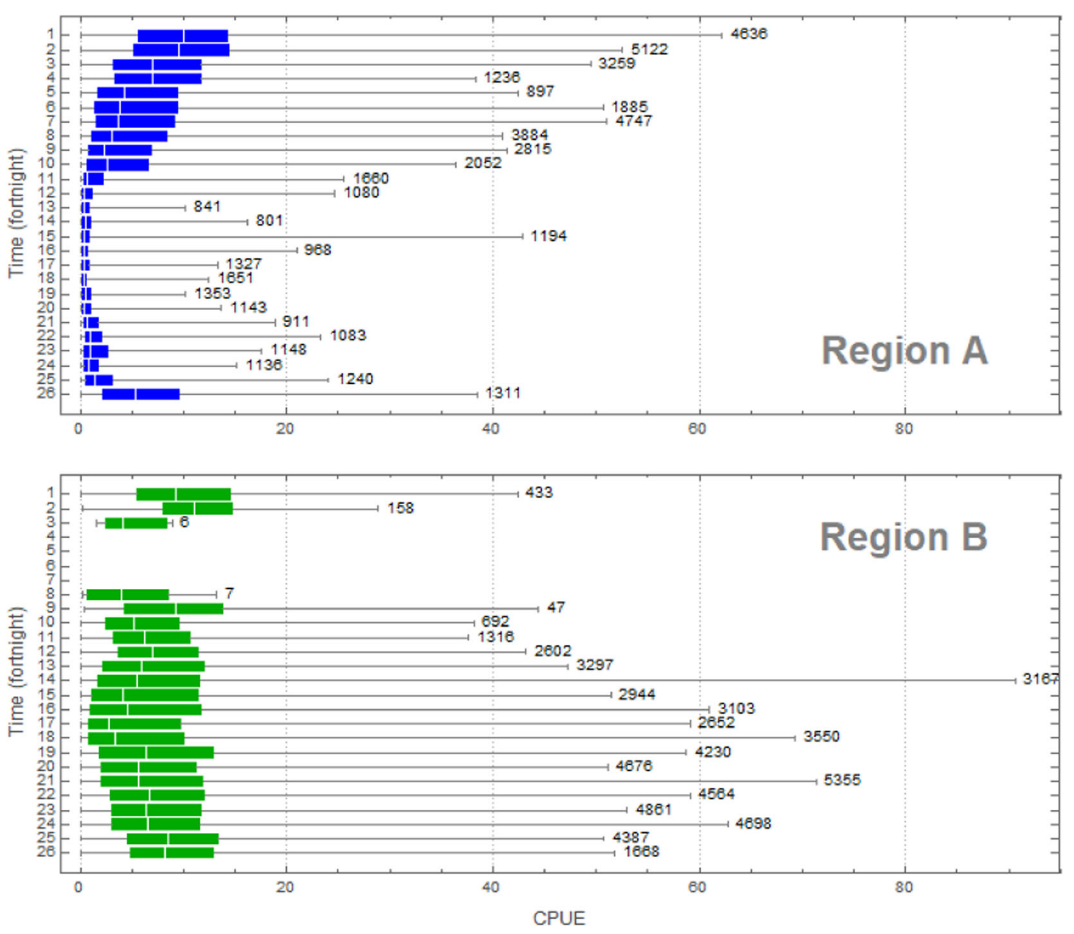

FIGURE 5 Comparative Box plot of fortnight distribution of CPUE (tonne/hour) in the selected areas (2011–2016) with the corresponding number of trawling operations. *Source:* Norwegian Directorate of Fisheries. CPUE, Catch per unit effort

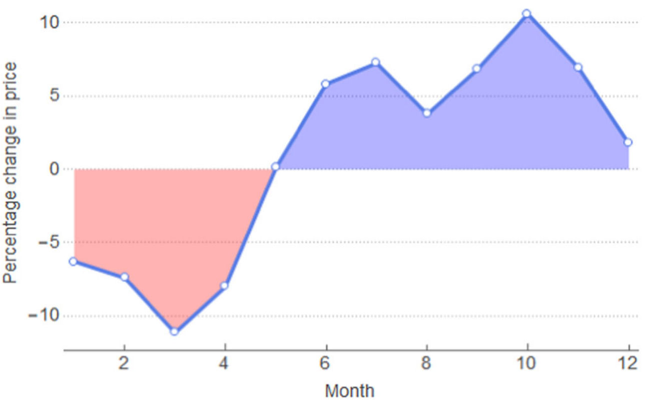

FIGURE 6 Percentage change in the frozen cod price in comparison to average price caught by trawl fleet in 2016. *Source:* Norwegian Directorate of Fisheries published data

3.2 | Fortnightly basis for estimation of CPUE

Time-series data of fisheries are inherently noisy. When the trawlers leave port they do not know with any degree of certainty, whether the catch will be good or poor. Unexpected failures in equipment, good or bad luck, weather conditions and other factors can introduce random variation into the magnitude of the catch (Kirkley, Squires, & Strand, 1995; Salvanes & Steen, 1994; Squires & Kirkley, 1999; Thorlindsson, 1994). One way to reduce the random variation in CPUE is to aggregate CPUE data by fortnight. The rationale behind choosing fortnight data resolution is to cancel out most of the positive and negative randomness in the CPUE. We believe that a 14-day period is long enough duration to offset positive and negative shocks of random occurrences in fishing activities. In this regard, our original data of 23,256 and 41,491 observations for CPUE for regions A and B, obtained from individual tows of 54 active vessels over 2011–2016, are reduced to 157 fortnight data sets over 2011–2016 for each of the two regions. The effort component of CPUE is measured in trawling hours, while catch is measured in tonnes. The CPUE values encompass fishing by single and double trawl operations. It is worth mentioning that since the chosen time resolution is fortnightly, fundamental periodicity T has fortnight units, hence fundamental frequency f shows the cycles made in a 2-week time resolution.

Furthermore, it should be noted that, even though we have zero observations for catch and effort during fortnights 4–7 (see Figures 2 and 3) in region B, which yields no CPUE, we conduct linear interpolation to obtain values for CPUE to fill the observations. The rationale behind this is that by doing so, our assumption that CPUE is taken as an estimate of stock size is still valid as no values for CPUE confound indexes of abundance (see Equation 2). Second, interpolation enhances the fit of our model.

4 | EMPIRICAL RESULTS

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

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

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

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

$\bar{a}_d$ in Table 1 shows the periodic mean, while a_n, b_n, and ω represent the estimated coefficients for the period functions of cosine and sine, and angular frequency, respectively. On the basis of the p values, it can be concluded that the estimated coefficients are statistically

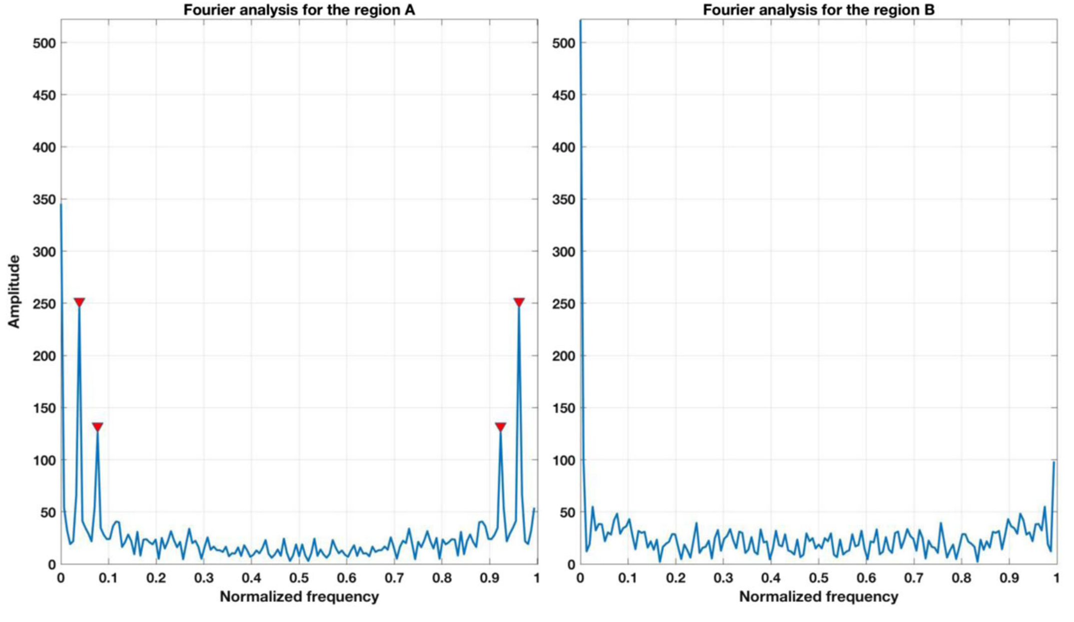

FIGURE 7 FFT of fortnight time-series of CPUE in regions A and B. It extracts dominant frequency $\left(\frac{1}{\text{fortnight}}\right)$ components in CPUE signal. Two detectable spikes are marked in region A, indicating seasonal behavior while no distinguishable spike is observed or marked for region B. CPUE, Catch per unit effort; FFT, fast Fourier transformation

significant. The estimated angular frequency for region A is $\omega = 0.2386$, which yields a period of 26.33 in fortnight units. This means that the cyclic pattern in cod stock aggregation repeats itself approximately every 26 fortnights, which is equal to 1 year. This result is consistent with the duration of the fishing year.

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

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

5 | DISCUSSION

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

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

TABLE 1 Estimated Fourier coefficient from aggregated fortnight hauls for region A

Parameters	Fourier coefficient	*p* Value
$\bar{a}_d$	1.211	0.001
α_1	0.712	0.001
b_1	0.845	0.001
α_2	−0.251	0.001
b_2	0.39	0.001
ω	0.2386	0.001
R^2	0.6478	–

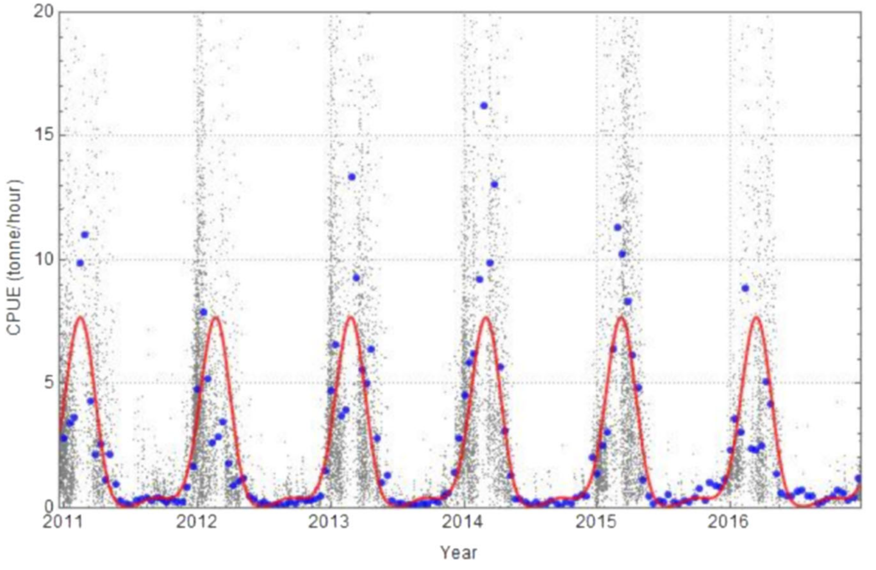

FIGURE 8 Scatterplot of fitted (red line) and actual observation of fortnightly CPUE (blue dots) in region A derived from model (5) by two harmonics. *Gray dots represent actual observation of CPUE for each individual haul. CPUE, Catch per unit effort

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

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

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

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

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

6 | CONCLUSION

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

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

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

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

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

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

ORCID

Tannaz Alizadeh Ashrafi http://orcid.org/0000-0001-6075-0282
Arne Eide http://orcid.org/0000-0002-8009-7177

REFERENCES

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

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

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

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

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

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

Bjørndal, T., & Gordon, D. V. (1993). The opportunity cost of capital and optimal vessel size in the Norwegian fishing fleet. *Land Economics*, *69*(1), 98–107.

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

Maurstad, A. (2000). To fish or not to fish: Small-scale fishing and changing regulations of the cod fishery in northern Norway. *Human Organization*, *59*(1), 37–47.

Mello, L., & Rose, G. (2005a). Seasonal cycles in weight and condition in Atlantic cod (*Gadus morhua* L.) in relation to fisheries. *ICES Journal of Marine Science*, *62*(5), 1006–1015.

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

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

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

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

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

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

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

Salvanes, K. G., & Steen, F. (1994). Testing for relative performance between seasons in a fishery. *Land Economics*, *70*(4), 431–447.

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

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

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

Schwalme, K., & Chouinard, G. A. (1999). Seasonal dynamics in feeding, organ weights, and reproductive maturation of Atlantic cod (*Gadus morhua*) in the southern Gulf of St Lawrence. *ICES Journal of Marine Science*, *56*(3), 303–319.

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

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

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

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

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

Trout, G. (1957). *The Bear Island cod: Migrations and movement* (Vol. 2, p. 21). Ministry of Agriculture and Food Fisheries Investigations Series.

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

How to cite this article: Alizadeh Ashrafi T, Eide A, Hermansen Ø. Spatial and temporal distributions in the Norwegian cod fishery. *Natural Resource Modeling*. 2020;e12276. https://doi.org/10.1111/nrm.12276