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Research Paper

Migration patterns of the Faroe Plateau cod (*Gadus morhua*, L.) revealed by data storage tags

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A R T I C L E I N F O

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A B S T R A C T

Spawning cod were tagged in March 2002, 2003 and 2004 on the Faroe Plateau with Data Storage tags, recording temperature and depth. Migration routes were reconstructed for 23 recaptured individuals using a state-space model and analysed focusing on horizontal and vertical migration behaviour in relation to spawning, feeding and areas closed to trawling. The state-space model is constrained by homogeneous temperatures and depths however the Faroe Plateau is ideal in this regard. Although our inference is based on limited data we here demonstrate a proof of concept.

Regarding horizontal movement, a log-normal distribution of daily displacement was found with a significantly higher daily displacement during spawning than during feeding season. This indicates a clear distinction between spawning and feeding behaviour. However, while food availability did not affect the migration routes cod did avoid the trawled areas. Regarding vertical behaviour, cod stayed within 10 m from the bottom more than 90% of the time. Yet, individuals caught with longline had a stronger affinity to the bottom than cod taken by other gears such as trawl, suggesting that the use of trawl as survey gear should be continued in this area.

The information, available from the simulated migration routes is a great improvement compared to the information achieved from conventional tagging when studying individual fish behaviour. The results can be used to support fisheries data, i.e. survey, logbook, stock assessment or acoustic data that lack resolution to evaluate individual fish.

1. Introduction

To ensure fitness, animals need to be efficient feeders, avoid predators and to reproduce. Natural habitats do not always provide locations where all these needs are simultaneously fulfilled and occasional migration is therefore advantageous despite energetic costs (Nikolsky, 1963; Sutherland, 1996). Harden Jones (1968) describes fish migration by a migration triangle where spawning, nursery and feeding areas represent the three corners. However the latest period of advances in technology has showed that migration behaviour is more diverse (Secor, 2015). Many fish populations migrate distances of more than 1000 km (Bergstad et al., 1987; Harden Jones, 1968; Opdal, 2010; Opdal and Jørgensen, 2015), however this paper focuses on Faroe Plateau Atlantic Cod (*Gadus morhua*), where distances between known spawning, feeding and nursery areas are of the order of 50 km (Joensen et al., 2005).

The Faroe Plateau, here defined as the area around the Faroe Islands shallower than ∼500 m, is approximately 40 thousand square kilometres and has a spatial extent of approximately 220 × 200 km (Hansen, 2006). Strong tidal currents with a clockwise residual flow dominate the plateau. The Faroe Shelf Front, located on 80–130 m depth, separates the always well mixed and relatively cold central shelf water from the outer, seasonally stratified water masses (Larsen et al., 2008, 2002). Inside the front the temperature varies from 6 to 11 °C between March and August. Outside the front, the sea surface temperature is higher by 0.5–1 °C (Larsen et al., 2008).

Many fish species spawn just inside the tidal front where appropriate food for the larvae is abundant and the risk that eggs and larvae are flushed away is low (Gaard and Steingrund, 2001). The 500 m isobaths is usually considered an approximate outer boundary for the

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Faroe Plateau cod (Joensen et al., 2005; Steingrund et al., 2009; Strubberg, 1933, 1916; Tåning, 1940) and the cod are distributed over the entire plateau, albeit scarcely distributed in areas deeper than 200 m (Tåning, 1940). The main spawning areas are located at two specific areas north and south west of the islands, between 80 and 150 m depth (Tåning, 1943) (Supplementary material, Fig. S1).

Cod in this region spawn between February and May with peak spawning in the second half of March (Jákupstovu and Reinert, 1994). Cod, spawning in the northern spawning area, move eastward or westward after spawning, and eventually distribute all over the plateau during the feeding season. Generally, cod spawning in the south western spawning area, move south after spawning and distribute on the southern part of the plateau during the feeding season, although deviations from this pattern have been observed (Joensen et al., 2005; Steingrund et al., 2009; Tåning, 1940). Faroe Plateau cod show a strong site fidelity to both spawning and feeding area (Steingrund et al., 2009; Tåning, 1940) and are therefore classified as 'accurate homers' (Robichaud and Rose, 2004). Even though cod is known to navigate by spatial memory of landmarks and bathymetry (Robichaud and Rose, 2002), this has so far not been demonstrated for Faroe Plateau cod. During the feeding season cod are distributed over the entire Plateau, however they are very stationary (Joensen et al., 2005; Strubberg, 1933, 1916). In areas shallower than 200 m, cod feed primarily on sandeels and benthic crustaceans, with sandeels being the preferred prey. In deeper waters cod feed primarily on norway pout and blue whiting (du Buis, 1982; Rae, 1967).

The fishery for groundfish species on the Faroe Plateau can roughly be divided into two groups: trawlers primarily targeting saithe at depths from 100 to 150 m down to 500 m and longliners primarily targeting cod and haddock in shallower waters (ICES, 2016). The separation of the gear, trawl and longline, is enforced by a number of area closures, with exceptions, that are too complex to explain in detail here (Gaard et al., 2014). In addition there are specific area closures for longliners as well as trawlers during spawning time to protect the spawning of cod. Jiggers are, however, not constrained by any of these area closures. The area closures have been unchanged since the effort management system was introduced in 1996 (ICES, 2016). Despite area closures, there are no area that is closed to all types of fishing during the whole calendar year on the Faroe Plateau. This is especially true for cod that are caught by all gears, i.e. jigging, longline and trawl. In practice, longliners have traditionally taken 30–70% of the cod catches since 1985, and 50-60% during the tagging period 2002–2006(ICES, 2016).

Faroe Plateau cod enter the fishery at age 2 years and are fully recruited to the fishery at age 4 (ICES, 2016). The catch ranged between 18 and 40 thousand tons during nearly a century (1906–1990) but decreased to less than 10 thousand tons in 1991–1994 and in the period after 2006 (Supplementary material, Fig. S2).

Previous analyses of Faroe Plateau cod migration pattern rely on mark-recapture data, obtained using conventional tags, which only provide information on release and recapture location. Data Storage Tags (DSTs) continually record temperature and depth while attached to individual fish. As the spatial distribution of conventional and DST tagged cod has showed to be similar, these data can upon recapture be used to infer movements during the time at liberty (Righton et al., 2007).

This paper presents the first estimation of migration routes of Faroe Plateau cod using DSTs. Migration routes were reconstructed using a state-space model, in which observations of depth and temperature and vertical behaviour were used as input. We aim to describe the Faroe Plateau cod migration and to show the possibilities of this method by relating it to homing to spawning areas, potential navigational mechanisms, habitat use in relation to feeding and trawled areas, horizontal movement pattern (daily displacement), vertical migration into the water column and vulnerability to fishing gears (including survey gears).

2. Material and methods

2.1. Data storage tags and tagging

Cod were caught by RV "Magnus Heinason" on March 26th 2002 and March 20th and 21st 2004 and by a hired commercial trawler on March 28th and 29th 2003 (Supplementary material, Table S1). The cod were caught at the spawning areas north and south west of the islands at 102–113 m depths (Supplementary material, Table S1). The mesh size was 135 mm in the cod-end and all cod in good conditions were transferred to tanks with running seawater. The DSTs (DST-milli, Star-Oddi, Iceland) were implanted into the body cavity of 180 cod. The tags, which record temperature and depth with 0.2 °C and 2 m precision respectively, were set to log every ten minutes for the first two days and thereafter every third hour for the next 12 days. This routine was repeated every 14 days. Date, time, position, depth and fish length (rounded down to the nearest cm) were recorded for each tagged fish before release.

The tagging was announced in local newspapers and on the website of the Faroe Marine Research Institute. A reward of 100 DKK was paid for each tag returned and if tag and carcass were returned, 300 DKK and 20 DKK per kilo of the carcass were paid. An annual lottery of 10,000 DKK was arranged, where tags with a carcass had a threefold probability to win. Recapture date (registered either as a specific date or as a date interval), recapture position (a GPS position accompanied by an error estimate as a diameter in nautical miles) and recapture gear were recorded. For returned carcasses, length (rounded down to nearest cm), weight, gutted weight, liver weight, gonad weight, sex, maturity state and otolith age were also recorded.

Of the 36 cod recaptured (Supplementary material, Table S1), ten tags were disregarded due to poor data quality, data exceeding the model grid in time and space, or inability of the model to find optimal parameters (lack of convergence and therefore inability to produce a track). Moreover, three tags were excluded as the estimated migration routes proved to be sensitive to the choice of the parameter S, which defines the pelagic and demersal behavioural states (see model description). Thus, it was possible to estimate migration routes for 23 cod (Supplementary material, Fig. S3 and Table S2). Tag number 1445, 1483 and 1498 in 2002 all stopped logging before recapture. The average length of these was 67 cm at release and only three of the 23 cod were at liberty until the following year.

2.2. Model

We used a state-space model (SSM), including behaviour switching, to simultaneously estimate movement and behaviour of each individual fish (Pedersen et al., 2011). Overall, this model connects the release and recapture positions by fitting the time series of temperature and depth data, by using the restrictions set by the bathymetry (Simonsen et al., 2002) and a simulated temperature field (Rasmussen et al., 2014). For our study region we use bathymetric information resolved on a 300 × 300 m grid in the latitude longitude range: (59.11N–63.71N) (12.55W–14.5W). The code was run in Matlab based on a modification of the code from (Pedersen et al., 2008a).

The behavioural model has two states: in state one ($i = 1$) the fish is located close to the bottom and in state two ($i = 2$) the fish is located away from the bottom (pelagic). Thus, behaviour is interpreted in terms of vertical placement relative to the bottom.

The switching between the two behavioural states is governed by a Markov chain with transition probabilities p_{12} and p_{21}, i.e. the probabilities of switching from state 1 to state 2 and vice versa. The process equation describing the horizontal movement of the fish was a random walk given by

$$x_t = x_{t-1} + e_t,\ e_t \sim N(0, s^2),$$

where x_t is the horizontal location of the fish at time t and e_t is the