Short Communication

Evidence of fjord spawning by southern Norwegian Atlantic halibut (Hippoglossus hippoglossus)

Andrew C. Seitz1, Kathrine Michalsen2, Jennifer L. Nielsen3, and Mark D. Evans1*

1School of Fisheries and Ocean Sciences, University of Alaska Fairbanks, PO Box 757220, Fairbanks, AK 99775, USA
2Institute of Marine Research, PO Box 1870, Nordnes, 5817 Bergen, Norway
3South Sound Research Institute, Longbranch, WA 98351, USA

*Corresponding author: tel: +1 907 322 9008; fax: +1 907 474 7204; e-mail: mdevans@alaska.edu


Received 7 August 2013; accepted 2 December 2013; advance access publication 18 January 2014.

Atlantic halibut (Hippoglossus hippoglossus) in a Norwegian fjord were tagged with pop-up archival transmitting (PAT) tags to investigate whether they join offshore spawning events with halibut from other regions. All fish (n = 4) remained in the fjord throughout the spawning season, suggesting that they may be reproductively segregated from other stocks.

Keywords: Atlantic halibut, depth occupancies, fjord spawning, PSAT tag, skip spawning.

Introduction

Atlantic halibut (Hippoglossus hippoglossus) has long been a highly valued, commercially important fish species in Norway. Once abundant in the surrounding ocean, the species was overharvested in the late 1930s to the point of commercial extinction (Devold, 1938; Haug and Tjemsland, 1986), and while there has been some recovery of the stock north of 62°N, catches in southern Norway have remained low (Høines et al., 2009). Fishery managers would like to rebuild sustainable local stocks of Atlantic halibut in southern Norway, but little baseline knowledge about the ecology and behaviour of the animal exists, which may hinder the design of stock/fishery recovery plans.

Marine fish species often have complex population structures that may include several spatially or temporally segregated spawning components (Stephenson, 1999), and a single-unit stock management approach may fail to recognize the impact of localized overfishing of these spawning components on the overall spawning–stock biomass (Stephenson, 1999; Frank and Brickman, 2001). Therefore, in order to formulate effective recovery plans for Atlantic halibut, it is important to gain insights into the species’ reproductive ecology.

Upon reaching maturity, Atlantic halibut are assumed to spawn annually during winter at discrete deep-water locations on the continental slope, where large aggregations of fish from several summer feeding areas convene (Devold, 1938; Neilson et al., 1993). Genetic studies of H. hippoglossus have found no significant hereditary variation between southern Norwegian halibut and those from Greenland and the Faroe Islands (Fevolden and Haug, 1988; Foss et al., 1998), indicating that there is substantial gene flow among these regions. Greenlandic and Faroese halibut spawn in deep-water areas off the continental slope southwest of the Faroe Islands from January to March (Jakupsstovu and Haug, 1987). In contrast, in northern Norway, there is evidence that halibut may spawn within several deep-water fjords from December to February (Devold, 1938; Olsen, 1969; Kjørsvik et al., 1987; Van der Meeren et al., 2013).

The purpose of this study was to track the movements of tagged halibut from one of Norway’s southern fjords to investigate whether evidence exists that they join the large offshore spawning aggregations with other stocks, as their genetic homogeneity would suggest or, if not, whether evidence exists to support possible spawning within the fjord, as northern Norwegian halibut are believed to do.

The study

The study was conducted in Sognefjorden, Norway’s longest and deepest fjord, located on the southwest coast (Figure 1). It has a length of 175 km, a maximum depth of 1308 m, and a sill at its mouth with a depth of 165 m. The water mass is typical of fjords, with stable conditions below the sill depth. Above sill depth, there are strong vertical temperature and salinity gradients that increase
 Evidence of fjord spawning by Hippoglossus hippoglossus

with proximity to the fjord head (Svendsen, 2006). The mouth of the fjord is located ∼ 650 km from known halibut spawning grounds in Faroese waters.

Five Atlantic halibut from Sognefjorden were captured and tagged with pop-up archival transmitting (PAT) tags. The fish were caught on longline gear in the upper part of the fjord in November, prior to the start of the putative spawning season (December–March). Circle hooks were used to minimize harm to the animals, and the soak-times of the longline sets were all less than 12 h to reduce hook-restraint times. Only fish >105 cm were retained for tagging because larger fish have a higher probability of being sexually mature (Haug, 1990), and this size has proven to be the minimum size acceptable for PAT tagging of Pacific halibut (Hippoglossus stenolepis), a closely related congener (Seitz et al., 2003).

The tags were externally attached to the fish by inserting a surgical-grade titanium dart through the skin and pterygiophores (bony fin ray supports), ∼ 2.5 cm medially from the dorsal fin on the eyed-side.

Figure 1. Depth contours of the area between Sognefjorden and documented halibut spawning grounds (⊗) southwest of the Faroe Islands. In order to occupy winter depths >900 m, the fjord fish would have to transit ∼265 km of relatively shallow shelf waters, movement not recorded in the archived tag data. Inset of the fjord shows pop-up or capture locations of the four tagged halibut (⊕) and their release location (Δ). Bathymetric data provided by the Norwegian Hydrographic Service.
of the fish, where the body began to taper towards the tail. This tag position ensured a firm anchor for the dart while minimizing muscular damage caused by drag from the tag (Seitz et al., 2003). The tagging procedure took 60–90 s and, after the tags were securely attached, the fish were gently released head first back into the fjord.

The tags used in the study were MK-10 pop-up archival transmitting (PAT) tags (Wildlife Computers, Redmond, Washington, USA). They were 21 mm in diameter, 175 mm in length, and weighed 75 g in air. Each tag contained sensors that measured and recorded ambient water temperature, pressure, and light intensity every 2 min. The tags were pressure-rated to 1750 m, although the sensor read a constant depth of 980 m. On preprogrammed dates, the tags were designed to release from the fish, float to the surface of the ocean (i.e. “pop up”), and transmit data to Argos satellites, during which an accurate location of the transmitting tag would be determined. Satellite-transmitting tags were chosen for the project because they are fishery independent, and the tagged animal does not have to be recaptured to recover the data. Due to the large amount of data collected by the tags and limited data reception by Argos satellites, only low-resolution, summarized data would be transmitted to satellites.

Because of the exploratory nature of this research and the compromise between tag-deployment duration and successful reporting, two pop-up dates were chosen to investigate seasonal dispersal. Four tags were programmed to pop up on 1 July 2004 to determine locations of fish during presumed, post-spawning summer feeding. Data from these tags were summarized in 12-h bins that included minimum and maximum depths and temperatures. The objective of this dataset was to examine the animal’s range of vertical movement in a 12-h period. One tag was programmed to pop up on 1 September 2004 to determine the latest summer location of this fish. Because of this tag’s longer time at liberty, it was programmed to summarize its minima and maxima in 24-h bins to reduce the number of unique data packets, thus decreasing the likelihood of gaps in the data record (Seitz et al., 2003).

Four of the five tags successfully measured and recorded data during the time that they were at liberty (Table 1). The one unsuccessful tag prematurely detached from the fish on the day it was released and did not provide useful data, although it did transmit as scheduled on 1 July 2004. Of the four successful tags, three tags released from their host fish and reported to satellites, and one tag was physically recaptured in April when the host fish was caught in a gillnet. Qualitative movement and behaviour of these tagged halibut were inferred from their end locations (pop-up or recapture) and from examining depths and temperatures experienced by the fish in relation to the fjord’s unique bathymetric and oceanographic characteristics.

The end locations of three tags were within the fjord and, while one was just outside the fjord entrance (Figure 1), the depth records indicate that all of the fish likely occupied deep water within Sognefjorden during the spawning season. This inference relies on the assumption that halibut, a demersal fish, can be expected to be in contact with the sea floor at least once during each 12-h summary period. Therefore, it is reasonable to assume that the maximum depth recorded by the tag represents the depth of the sea floor in the area occupied by the fish. The maximum depths occupied by all four fish from December to March (>900 m) are found in ~ 65% of the fjord (Dahl and Forsberg, 1998), but not in offshore waters adjacent to the fjord. Rather, to occupy equivalent water depths offshore, the fish would have to traverse at least 250 km of relatively shallow, continental shelf in any direction from the fjord entrance. This shallow-water transit was not documented in the tags’ depth records; therefore, it is unlikely that any of the fish left the fjord during winter and occupied deep water offshore.

Minimum depths and water temperatures experienced by the fish provide additional evidence that the fish did not leave the fjord during the spawning season. Because a sill that rises to a depth of 165 m gates the entrance to the fjord, any fish entering or leaving the fjord must swim above that depth in order to pass. Two fish (tags 678 and 688) never rose above sill depth and, therefore, never left the fjord. Two other tags (tags 675 and 679) recorded depths shallower than the sill depth, but based on water temperature, only one of them appears to have exited the fjord. When the fish with tag 675 experienced a minimum depth of 143 m on 6 March 2004, the minimum water temperature did not change, but the maximum water temperature increased from 7.5 to 8.1°C (Figure 2a), which is consistent with an ascent through the stratified waters of the inner fjord. In contrast, when the fish with tag 679 rose to a minimum depth of 60 m on 15 March 2004, the minimum water temperature decreased from 7.4 to 6.2°C (Figure 2b), which is consistent with moving over the fjord sill onto the continental shelf where colder, mixed waters occur. This observation is corroborated by the tag’s end location, which was immediately adjacent to the fjord entrance (Figure 1). However, it is unlikely that this fish spawned in deep continental slope spawning grounds outside of the fjord, such as around the Faroe Islands where H. hippocampus

Table 1. Deployment and data summary for four PAT tags on Atlantic halibut released in Sognefjorden, Norway.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Tag 675</th>
<th>Tag 678</th>
<th>Tag 679</th>
<th>Tag 688</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fish length (cm)</td>
<td>107</td>
<td>119</td>
<td>172</td>
<td>171</td>
</tr>
<tr>
<td>Estimated fish sex</td>
<td>Male</td>
<td>Male</td>
<td>Female</td>
<td>Female</td>
</tr>
<tr>
<td>Tag release date</td>
<td>12/11/03</td>
<td>12/11/03</td>
<td>10/11/03</td>
<td>10/11/03</td>
</tr>
<tr>
<td>Data recovery date</td>
<td>19/04/04</td>
<td>01/07/04</td>
<td>01/07/04</td>
<td>01/09/04</td>
</tr>
<tr>
<td>Days at liberty</td>
<td>159</td>
<td>232</td>
<td>234</td>
<td>296</td>
</tr>
<tr>
<td>Horizontal displacement (km)</td>
<td>30.0</td>
<td>37.2</td>
<td>144.3</td>
<td>12.7</td>
</tr>
<tr>
<td>Minimum depth (m)</td>
<td>33</td>
<td>201</td>
<td>4</td>
<td>280</td>
</tr>
<tr>
<td>Maximum depth (m)</td>
<td>953</td>
<td>980</td>
<td>980</td>
<td>980</td>
</tr>
<tr>
<td>Maximum vertical displacement (m) within summary period</td>
<td>520</td>
<td>96</td>
<td>424</td>
<td>416</td>
</tr>
<tr>
<td>Minimum temperature (°C)</td>
<td>7.1</td>
<td>7.1</td>
<td>5.8</td>
<td>7.4</td>
</tr>
<tr>
<td>Maximum temperature (°C)</td>
<td>10.7</td>
<td>7.5</td>
<td>8.4</td>
<td>11.4</td>
</tr>
<tr>
<td>Maximum temperature difference (°C) within summary period</td>
<td>1.2</td>
<td>0.2</td>
<td>2.5</td>
<td>1.0</td>
</tr>
</tbody>
</table>

*aThe first days after release are excluded from this analysis.*
Figure 2. Depth and temperature profiles of four Atlantic halibut tagged in Sognefjorden. Maximum (black solid line) and minimum (black dotted line) depths for each 12-h (a), (b), (c) and each 24-h (d) summary period are shown. Maximum (grey dotted line) and minimum (grey solid line) temperatures for the same periods appear in the bottom portion of the chart. The dashed horizontal line indicates the depth of the fjord entrance sill. Gaps in the lines reflect transmission gaps in the data.
spawns at depths greater than 700 m (Jakupsstovu and Haug, 1987), because its depth never exceeded 388 m after it left the fjord (Figure 2b).

Considering these several lines of evidence, it is highly unlikely that the Sognefjord fish spawned outside the fjord, raising the possibility that they spawned inside the fjord. Although there is no record of H. hippoglossus larvae ever being detected in southern Norwegian fjords, a recent collection of four halibut larvae in Skjerstadfjorden, in northern Norway, suggests that inshore, deep-water fjords with shallow entrance sills can provide suitable spawning and nursery habitat for the species (Van der Meer et al., 2013).

During winter, the tagged Sognefjord fish conducted short-term, high-displacement, vertical forays. This short-term vertical activity is consistent with high-resolution depth profiles of Pacific halibut (H. stenolepis), that have shown deep-water residency and abrupt, regularly spaced ascents and descents of 100–200 m in magnitude, which is hypothesized to be spawning activity (Seitz et al., 2005; Loher and Seitz, 2008). Considering the recently shared common ancestry of H. hippoglossus and H. stenolepis (Grant et al., 1984), and the similarities of their depth records from PAT tags, it is possible that the halibut were spawning in Sognefjorden in January and/or February.

Fjord-spawning migratory fishes are not without precedent in Norway. Atlantic cod (Gadus morhua), e.g., occupies Norwegian waters as two distinct life history types. Northeast Arctic Atlantic cod has a life history type in which one large population migrates seasonally between spawning grounds on the Norwegian shelf and feeding grounds in the Barents Sea (Myksvoll et al., 2013). The other life history type, Norwegian coastal Atlantic cod, has a very different lifestyle in which several relatively small spawning components spawn and rear entirely within fjords, rarely intermingling and never interbreeding with the Northeast Arctic Atlantic cod (Jakobsen, 1987; Nordeide, 1998). Much like the Norwegian coastal Atlantic cod, it is possible that Atlantic halibut in southern Norway demonstrate a life history type that spawns within the fjord.

An alternative interpretation of the fjord residency demonstrated by the tagged fish is that these particular fish did not undertake a spawning migration to offshore areas because they skipped spawning during the winter of this study. By identifying individual spawning events in high-resolution electronic tag data, it has been proposed that up to 25% of mature Pacific halibut females either fail to migrate to the spawning grounds or fail to spawn once they arrive (Loher and Seitz, 2008). The only high-resolution data from this study capable of providing evidence of discrete spawning events, from tag 675, did not provide evidence that the host fish spawned, raising the possibility that Atlantic halibut may skip spawning as well.

Given the limitations of its small sample size, it is beyond the scope of this study to quantitatively address the population structure of Atlantic halibut in Norwegian waters. Nevertheless, the evidence presented here does support the possibility of a segregated spawning component of H. hippoglossus in Sognefjorden. If several small, independently breeding spawning components exist, rather than one large, panmictic population, then the species may be more susceptible to localized depletion, such as from overfishing (Hare, 2005). This warrants special attention when preparing rebuilding and management plans for H. hippoglossus or for other fisheries that might affect them.

Acknowledgements
The authors wish to extend special thanks to Torstein Halstensen for his tireless pursuit of the elusive Atlantic halibut, his skilful treatment of the fish, and for his unbounded enthusiasm for the preservation of halibut in Norwegian waters. The tagging was conducted under license from the Norwegian Animal Research Authority and complied with the 1974 Animal Welfare Act (supplemented by the provisions of the EU Directive 86/609/CEE). Protocols were reviewed and approved by University of Alaska Fairbanks Institutional Animal Care and Use Committee Assurance of Animal Care #02-62.

Funding
Funding for this project was provided by U.S. Geological Survey, Norway Institute of Marine Research, and Torstein Halstensen.

References
Evidence of fjord spawning by Hippoglossus hippoglossus


Handling editor: Emory Anderson