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Lumpfish (*Cyclopterus lumpus*) in the Barents Sea: development of biomass and abundance indices, and spatial distribution

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Little is known about lumpfish (*Cyclopterus lumpus*) ecology, especially its distribution in the open Barents Sea. This paper describes fluctuations in abundance and biomass indices of lumpfish based on pelagic trawl catches. This long-term monitoring survey has been conducted between August and September since 1980. Investigations show that lumpfish is widely distributed in the pelagic waters of the Barents Sea. Relative biomass and abundance indices were calculated for the period 1980–2012. The mean annual biomass was estimated to be 48 000 t, with a maximum of 143 000 t; the estimated mean annual abundance was 53 million individuals, with a maximum of 132 million individuals. There were more juveniles than adults, with juveniles comprising 40–80% of the total abundance (average 60%). The largest concentrations of both juveniles and adults were in years with warm temperatures. The majority of fish were found in waters of 5–7°C (60% of juveniles) and 4–7°C (70% of adults), indicating a strong association with Atlantic water masses in the Barents Sea. Regulations on the Norwegian and Russian fisheries for prespawning lumpfish are based only on after-the-fact fishery data and, therefore, have been insufficient in preventing negative effects on the lumpfish resource from fishing. Understanding the stock fluctuations and the use of fishery-independent data may improve the precautionary approach to fishery management. The use of lumpfish indices from the scientific surveys in the Barents Sea should be implemented to strengthen the current stock assessment.

Keywords: abundance, Barents Sea, biomass, lumpfish, thermal habitat.

Introduction

Lumpfish of the North Atlantic (*Cyclopterus lumpus*) belong to the Cyclopteridae family and are semi-pelagic. They are widely distributed in the North Atlantic, including the open part of the Norwegian and Barents seas (Davenport, 1985; Holst, 1993; Ignashev and Rusyaev, 1999; Kudryavzeva, 2008). Breeding sites in the eastern part of their distributional area are located from Hudson Bay to Labrador. Breeding sites in the western part of their distributional area are found from the Bay of Biscay to the Murman coast (Andriashev, 1954; Bagge, 1964; Davenport, 1985). In the Barents Sea, mature fish migrate from offshore areas to spawning areas along the coast during late winter and early spring (February–May). Lumpfish spawn in shallow water, mainly along the Nordland, Troms and Finnmark, and Murman coasts (Ignashev and Rusyaev, 1999). After fertilization, eggs are guarded and cared for by males until hatching (Davenport, 1985). The incubation period decreases when temperature increases (Soin and Mikulin, 1974; Novikov, 2000). Larvae and juveniles are then found in both shallow coastal water and the open sea (Daborn and Gregory, 1983). Juveniles prey mostly on copepods, gammarids and polychaetes (Zvetkov and Kalyakina, 1987). The diet of the adults depends on the area, but crustaceans, ctenophores, jellyfish and polychaetes are the dominant prey (Kudryavzeva, 2008).

A commercial fishery for lumpfish in the northern part of Norway has existed since the 1950s. Mature females are mainly caught in the spawning grounds with gillnets and small vessels. The fishery is based on the catch of prespawned fish and is, therefore, highly seasonal: generally 5–6 weeks from April to mid-June (Bertelsen, 1994) and from mid-March to the end of May/early June (Torstensen, 1988). Every year, 200–800 boats participate in the lumpfish fishery, with vessel quotas of ~1.5–2.5 t of roe. In 1940, the Russian catch was ca. 15 000 t of lumpfish (Rusyaev, 2000). Today, the Russian coastal fishery in the Barents Sea and the White Sea is relatively low, with the total amount usually lower than 15–50 t annually.

Although highly prized for its roe, lumpfish is a poorly studied species, and little is known about its biology and ecology. This is especially true for younger fish, which are distributed in the open sea. The current Norwegian and Russian stock assessment uses fishery data based on the catch of prespawning fish along the coast. Information about the population structure of the lumpfish stock is lacking.

In the Barents Sea, lumpfish have been recorded as part of the joint Norwegian–Russian surveys since 1980, although the data have never been quality checked and analysed owing to split databases (national/international). In 2009, the joint Norwegian–Russian database underwent a complete revision of all recorded species, including lumpfish, and was quality checked (Eriksen *et al.*, 2009). In this paper, data obtained from the quality-checked joint database were used. Data from ~10 000 stations over 30 years (1980–2012) from surveys in the Barents Sea taken in August–September were used to calculate relative biomass and abundance indices for lumpfish. The objective of this paper is to determine the core thermal habitat for younger and adult lumpfish in the Barents Sea and to determine how climate variability may influence their density and geographical spatial distribution.

Material and methods

Survey

Since 1965, the Norwegian–Russian 0-group fish survey in the Barents Sea has been carried out annually in August–September. The survey has been part of a Joint Norwegian-Russian Barents Sea ecosystem survey since 2003. During this long-term monitoring (1980–2012), all captured species were recorded, and their lengths and weights were measured. Since 1980, the trawling procedures during the survey have been standardized. Data from this survey have yielded several publications on long-term fish stock fluctuations (Ottersen and Loeng, 2000; Hylen *et al.*, 2008; Eriksen *et al.*, 2011, 2012).

The standard gear is the "Harstad trawl", a pelagic trawl with a 20 × 20 m mouth opening, seven sections, and a codend. Mesh size varies from 100 mm in the first section to 30 mm in the last. Standard trawling procedure consists of predetermined tows at three or more depths, each of 0.5 nautical miles, with the headline at 0, 20 and 40 m and with a trawling speed of 3 knots. Additional tows at 60 and 80 m, also of 0.5 nautical miles, are made when a dense concentration of fish is recorded deeper than 40 m on the echosounder. However, the proportion of these deep hauls is small and has varied among areas and years.

Biological data

More than 10 000 pelagic trawl stations were conducted for 0-group fish over the study period (1980–2012). Lumpfish individuals were measured (length and weight) except in 1981, 1983 and 1987.

Abiotic data

Temperature data were obtained from conductivity, temperature, and depth sensors (CTD) samples taken at each 0-group trawl station in 1980–2012. Water temperature was measured at standard depths (5, 10, 20, 30, 40 m . . .) either before or after trawling. Temperature was measured at a total of 6115 CTD stations. There were no data from the last three years (2010–2012).

Temperature conditions were characterized by the annual mean temperature at the Fugløya–Bear Island (FB, 71°30′N 19°48′E–73°30′N 19°20′E) section covering the 50–200 m water layer (Figure 1). The annual mean temperature in 1980–2008 was 5.5°C

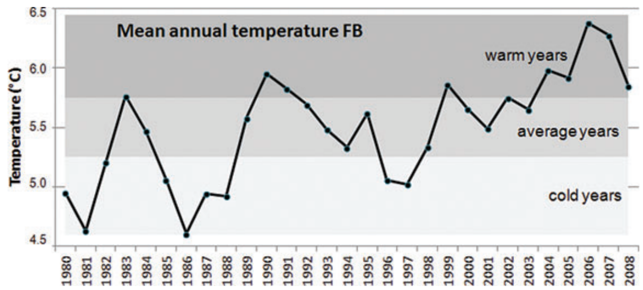

Figure 1. Annual fluctuations in temperature at the Fugløya–Bear Island (FB) section for the period 1980–2008. Years with different temperature conditions are shown with different colours.

(min = 4.6°C; max = 6.4°C) (http://www.imr.no/sjomil/index.html, last accessed December 2013). Years were categorized into three groups, and each group represented one-third of the temperature spectrum (see Figure 1): cold (4.6–5.3°C), average (5.31–5.8°C) and warm (5.81–6.4°C).

Biomass index calculation

Abundance and biomass indices were calculated using the stratified sample mean method of swept-area estimates (Dingsør, 2005; Eriksen *et al.*, 2009). Abundance and biomass per unit area were estimated using catch, effective wingspread of the trawl, total distance trawled at the station, and number of depth layers at the station. A number of depth layers of one indicated that the trawl was towed 0.5 nautical miles at the surface (0-m depth), and that the water layer between 0 and 20 m was covered by the trawl. A number of depth layers of two indicated that the trawl was towed 0.5 nautical miles at 0–20 m depth, then 0.5 nautical miles at 20–40 m depth, and so on if more layers were used. The stratified swept-area abundance/biomass estimate (E) is given by:

$$E = \sum_{i=1}^{N} A_i \bar{y}_i, \qquad (1)$$

where N is the number of area-strata, A_i is the area covered in the ith stratum, and $\bar{y}_i$ is the average abundance/biomass density in stratum i given by:

$$\bar{y}_i = \frac{1}{n_i} \sum_{s=1}^{n_i} EA_s. \qquad (2)$$

where n_i is the number of stations in stratum i.

Capture efficiency of the sampling trawl differs between species but is unknown for lumpfish. Because of fish avoidance behaviour in the trawl, it is possible that the abundance and biomass indices are underestimated and should be interpreted as minimum biomasses. However, this inaccuracy should have been consistent over time because the data were collected in a constant and standard manner, allowing the use of the time-series as a whole to examine interannual changes.

Fish length varied between 3 and 60 cm, and length distributions exhibited two peaks (Figure 2). We divided the data into two groups: fish <20 cm (hereafter referred to as juveniles) and fish >20 cm (hereafter referred to as adults, even though some individuals were not sexually mature). Abundance (in million individuals) was calculated separately for these two groups, while biomass (in thousand tonnes) was calculated for the entire pelagic component of the population.

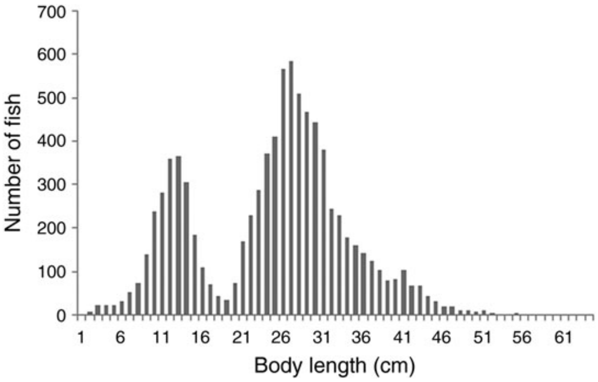

Figure 2. Lumpfish length–frequency distributions for the period 1980–2012. Lumpfish were taken by pelagic trawls in the Barents Sea during the months of August–September.

Statistical modelling

Stations with no lumpfish observations were excluded in our analyses of the response of the two groups of lumpfish (juveniles and adults) to temperature. The calculations were done in R (version 2.12.2) using the mgcv package (Wood and Augustin, 2002). Fish densities (D_i) of each group in a sample i (i.e. station) were fitted to the covariate according to the following model:

$$D_i = s(T) + \text{year}_i + e_i, \tag{3}$$

where the predictors included the smoothed fits (s) of T (mean temperature at 0–50 m) of sample i. Year was entered as a random variable, and e_i denotes the error for sample i. We used the dataset without "0" catches to consider the influence of temperature on observed fish only.

The model was checked by Akaike information criterion (AIC) and genuine cross validation (GCV).

A temperature range, the core thermal habitat (CTH), was estimated from the model as the temperatures corresponding to fish densities larger than the mean modelled fish density. By this approach, the calculation of the CHT included ~70% of the observations and covered the temperature range occupied by ca. 80% of the fish.

Ethics statement

The Fisheries Commission gives authorization for field studies as part of the international monitoring programme. Apart from this general permission, specific permission for the work described in this paper was not required, as the work conducted and the material collected are part of the national (Russian and Norwegian) duties according to international law for managing living marine resources and monitoring environmental changes. The field studies did not involve endangered or protected species. Fish taken by pelagic trawling were killed immediately after removing them from the sea. The work is part of routine work at sea by international certified institutions, which has been approved by the IACUC.

Results

Lumpfish abundance and biomass estimates were generally low during the 1980s, increased in the 1990s, and were highest during the 2000s (Figure 3). The lowest biomass (212 t) and abundance indices (36 million) were recorded in 1986, while the highest

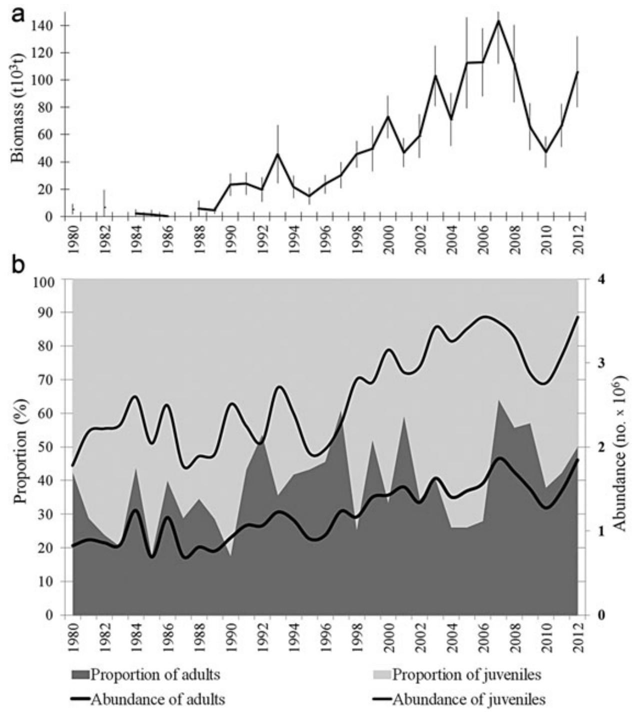

Figure 3. Biomass (1000 t) and abundance (no. in millions) estimates for both juveniles and adult lumpfish during the period 1980–2012 in the Barents Sea. The proportions of juveniles and adults are shown in light and dark grey, respectively.

biomass (143 000 t) and abundance indices (143 million) were recorded in 2007.

Lumpfish were observed widely in the Barents Sea from 67–80°N and from 6–57°E. However, denser concentrations were observed in a narrow geographic area between 15 and 49°E and 71 and 76°N. Spatial distribution varied between years, and areas of concentration were smallest during cold years and widest during warmer years (Figure 4). Lumpfish were found in a broad range of temperatures from 0–11°C (Figure 5). However, the majority of fish were found in a much narrower temperature range of 5–7°C (60% of juveniles) and 4–7°C (70% of adults). Furthermore, the data were divided into cold, average and warm years before we carried out new log-linear model runs. The selected models showed that the predicted fish densities for both juveniles and adults differed between cold, average and warm years (Figure 5, Table 1), and the predicted fish densities were higher during warmer years.

Discussion

The biomass of lumpfish varied considerably during the last three decades and was lowest during the 1980s, increased in the 1990s, and was highest in the 2000s. The Barents Sea climate varied from a cold period in the late 1970s and early 1980s, to moderately warm in the 1990s, and to the warmest recorded temperatures in the 2000s (Levitus *et al.*, 2009). The area of concentration of the lumpfish varied over years and was larger (ca. 20%, corresponding to 70 000 nautical miles^2) during warm years than cold years. During the 2000s, warm water had spread farther north, thereby increasing the warm Atlantic part of the Barents Sea (Johannesen *et al.*, 2012), and higher zooplankton biomass has been observed in the Barents Sea (Dalpadado *et al.*, 2002; Orlova *et al.*, 2005, Eriksen

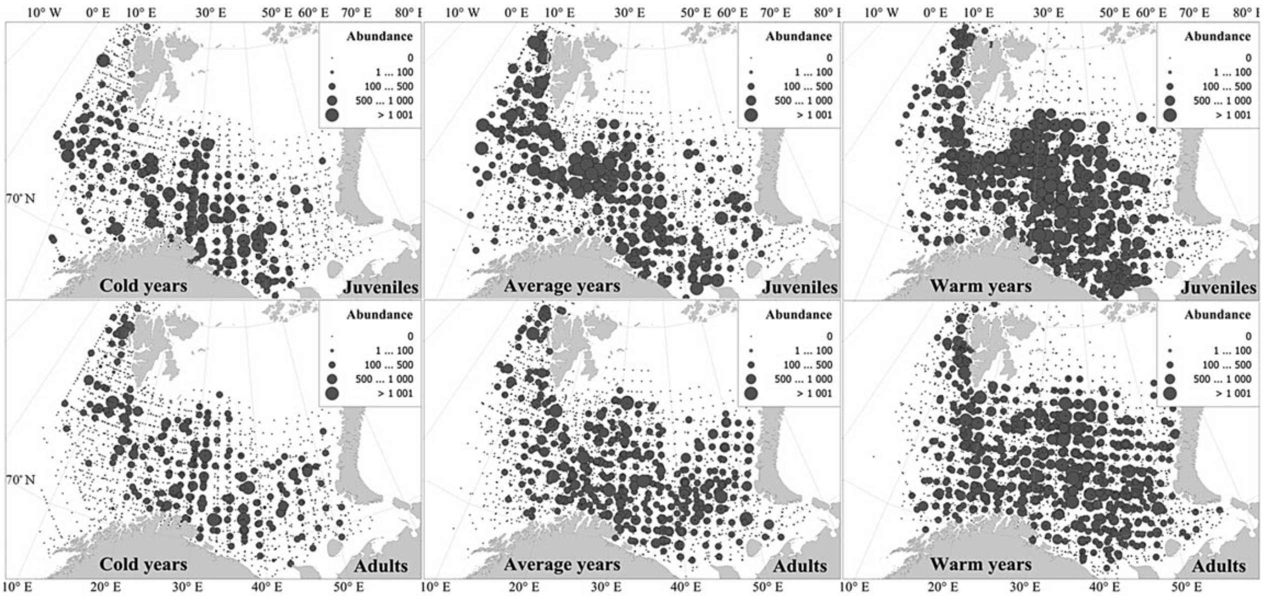

Figure 4. The spatial and temporal distribution of juvenile and adult lumpfish in the Barents Sea during years with cold, average and warm temperature conditions. The points denote the stations. Abundance estimates per nautical mile^2 are size-coded: from the smallest points (no catch) to largest (catch >1000 individuals).

and Dalpadado, 2011). Juveniles were at higher densities and occupied the largest areas observed during warmer years. This can be explained by the larger inflow of warm, plankton-rich Atlantic water, which brings more larvae and small fish into the Barents Sea, thus offering a wider suitable habitat for lumpfish (Eriksen *et al.*, 2011; Johannesen *et al.*, 2012). This result is supported by earlier findings (Ignashev and Rusyaev, 1999; Nikiforov and Rusyaev, 2004) that showed that the numbers of lumpfish in the Barents Sea depended on oceanographic conditions and were higher during warmer years.

The majority of juveniles (60%) were found in a temperature range of 5–7°C, while the majority of adults (70%) were found in a temperature range of 4–7°C. Most fish were associated with Atlantic water, characterized by water temperature >3°C. The distribution of juveniles and adults in the western and southern areas was limited by water warmer than ca. 7°C (Figure 5); in the eastern and northern areas, it was limited by water colder than ca. 4°C, and these temperatures led to a decrease in fish density in these areas (Figure 4). An important change in the increasing lumpfish abundance trend occurred in the 2000s. Lumpfish abundance decreased, coinciding with record warm temperature conditions in the Barents Sea (Figure 3b). The additive effect of temperature on lumpfish was asymptotic, and there was no further increase in fish abundance above a certain temperature (6°C) (Figures 1 and 5). Some juveniles were found in cold water at temperatures lower than ca. 4°C. Juveniles have a limited swimming capacity compared with adults, and currents will, therefore, have a greater effect on their distribution. Johannessen *et al.* (2012) suggested that during recent decades, the area of Atlantic water increased, while the area occupied by Arctic water decreased. Therefore, lumpfish distribution will most likely expand if the area of Atlantic water continues to increase, but the change in distribution will not necessarily lead to increasing lumpfish abundance and biomass. Therefore, this study showed that this long-term time-series could significantly contribute to ecological studies of lumpfish habitat.

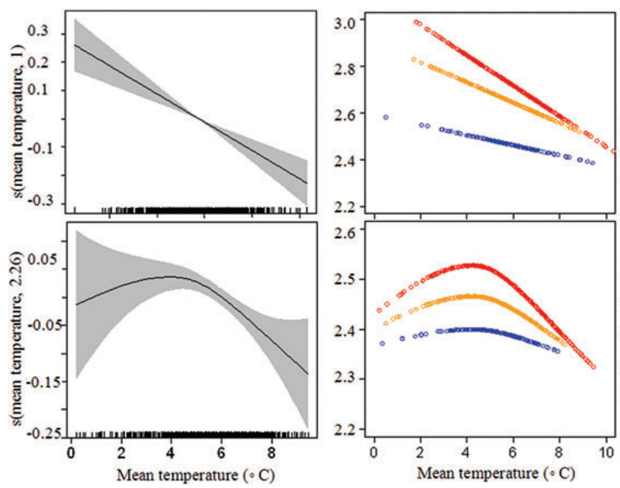

Figure 5. Estimated smoothing curves for the temperature effect on fish densities for models [juveniles (top), adults (bottom)], only including data with fish catches (left panel). The shaded regions indicate 95% point-wise confidence intervals. Predicted fish log-densities (right panel) during years with different temperatures: the blue line is for cold years, orange is for average years, and red is for warm years.

The Norwegian fishery targets prespawning lumpfish along the coast. Since 1990, the number of commercial vessels has decreased and was a record low in 2011 (173 vessels). Simultaneously, the amount of roe landed decreased; in 2011, it was 40% lower than in 2005–2010. Stock assessments of lumpfish in Norway have been based on commercial catches. Fishery-independent data from the Barents Sea has shown a strong decrease in adults and juveniles since 2007. Monitoring of the standing stock in the Barents Sea will improve our knowledge of population structure and thus offer a

Table 1. Additive models for temperature associations of juvenile and adult lumpsucker in the Barents Sea, with adjusted r^2 (i.e. proportion of variance explained) and genuine cross validation (GCV).

Models	s(MeanTemp)	*F*-value of *s*(MeanTemp)	*F*-value of *s*(years)	*F*-value of *s*(TempCond)	R^2 (Deviance explained)	GCV score (Scale est.)
Younger fish						
Density	1	31.8	5.65		0.16 (18.5)	0.13 (0.12)
Mean fish length	1.86	1 189		851	0.10 (10.5)	0.13 (0.13)
Adults						
Density	2.26	5.85	3.01		0.07 (9.28)	0.08 (0.79)
Mean fish length	3.23	508.3		1 026	0.02 (3.11)	0.08 (0.08)

All terms included in the models are statistically significant ($p \leq 0.001$). The models include non-zero data.

better tool for a precautionary approach to the management of this species.

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