POLAR COD

Stock name: Polar cod
Latin name: *Boreogadus saida*
Geographical area: Arctic Ocean including the Barents Sea (ICES subarea 1)
Expert: Elena Eriksen, Frode Vikebø
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Stock Sensitivity Attributes

HABITAT SPECIFICITY: Adult Polar cod (*Boreogadus saida*, Gadidae) is located in the entire Arctic Ocean, including both shelf sea and across deep ocean, defined as semi-pelagic by its vertical distributed (Boitsov et al., 2013; Hop & Gjøsæter, 2013). It inhabits waters down to -1.8 °C, enabled by antifreeze proteins in the blood. Spawning occurs mainly under ice and it is anticipated that the ice shelters the large fragile eggs from mechanical tear (Boitsov et al., 2013; Eriksen et al., 2015, 2017; Eriksen, Huserbråten, et al., 2020). In the Barents Sea there is an additional component of Polar cod at the head of the Porsangen in northern Norway. Genetic studies of East-Greenland and Svalbard Polar cod show that there are genetic differences among specimens indicating the existence of sub-populations (Madsen et al., 2016). Similar studies in the Barents Sea are ongoing but the hypothesis is already supported by dispersal and connectivity studies based on numerical dispersal models and *in situ* data from ecosystem studies in the Institute of Marine Research (Norway) from autumn and winter cruises (H. Gjøsæter et al., 2020). With retreating sea ice, suitable spawning areas under ice covered areas are displaced towards the Kara Sea and the north-eastern of Svalbard with high uncertainty on the further melting of the ice as ocean heat content seems to increase at an unprecedented rate (Eriksen, Huserbråten, et al., 2020; Huserbråten et al., 2019).

PREY SPECIFICITY: The diet of young Polar cod consists of a variety of *Calanus* spp. including *C. glacialis*, *C. hyperboreus* and *C. finmarchicus*, and with increase in fish size hyperiid species begin to dominate in the diet. Older Polar cod prey also on fishes (Bouchard et al., 2016; Hop & Gjøsæter, 2013; Kortsch et al., 2015; Planque et al., 2014). A decrease of Arctic habitats and Arctic prey items such as *C. glacialis* and *Themisto libellula* may have negative consequences on feeding conditions. However, Polar cod forage also on boreal (*Meganyctiphanes norvegica*, Euphausiidae) and arcto-boreal (*Themisto inermis*) euphausiids and therefore could to some degree compensate the decrease of the Arctic species (Eriksen, Benzik, et al., 2020).

SPECIES INTERACTION: Polar cod plays a key role in the Arctic ecosystem (Boitsov et al., 2013; Hop & Gjøsæter, 2013). Polar cod is known to feed on *Themisto* (*T. libellula*), but also forage on copepods (*C. glacialis, Metridia longa*), euphausiids and some other prey (Dolgov et al., 2011; Hop & Gjøsæter, 2013; E. Orlova et al., 2005; E. L. Orlova et al., 2009). Many fish species such as *Amblyraja hyperborean* (Rajidae)*, Osmerus dentex* (Osmeridae)*, Gadus morhua, Reinhardtius hippoglossoides* (Pleuronectidae)*, Melanogrammus aeglefinus, Hippoglossoides platessoides* (Pleuronectidae) and other prey on Polar cod (Eriksen, Benzik, et al., 2020). Polar cod is an important prey for marine mammals such as ringed seal (*Pusa hispida*, Phocidae), narwhal (*Monodon monoceros*, Monodontidae), white whale (*Delphinapterus leucas*, Monodontidae) and seabirds, e.g. Brünnich's guillemot (*Uria lomvia*, Alcidae), black guillemot (*Cepphus grylle*, Alcidae), and Northern fulmar (*Fulmarus glacialis*, Procellariidae).

ADULT MOBILITY: The Polar cod is not confined to shelf seas. Their habitat is pushed north with retreating ice and warming oceans their presence in the Barents Sea is expected to decline. However, a main predator, the Northeast Arctic cod, migrating northwards, is dependent on shelf seas, and may not follow farther into the Arctic Ocean.

DISPERSAL OF EARLY LIFE STAGES: Polar cod is suggested to depend on ice for sheltering buoyant eggs from mechanical tear (Boitsov et al., 2013; Eriksen, Huserbråten, et al., 2020). However, the ice in the

Arctic Ocean is retreating (Lind et al., 2018), and climate prediction models point towards an ice-free Arctic within the 21st century (Intergovernmental Panel on Climate Change (IPCC), 2001). The southeastern Barents Sea is a main spawning site for Polar cod (Boitsov et al., 2013; Eriksen et al., 2015). Polar cod spawns also in even colder conditions around the Svalbard archipelago. Ocean currents transport eggs from the main spawning site northwards towards northcentral and northern areas along Svalbard, but prone to retention processes close to Svalbard due to clockwise currents (Eriksen et al., 2015; Eriksen, Huserbråten, et al., 2020). Spawning is also observed in the Kara Sea and some eggs are advected by currents drifting either into the Barents Sea or northwards along Novaya Zelmya (Boitsov et al., 2013). The early life stages of Polar cod have a relatively long pelagic duration, e.g. the development time of eggs is about 1.5-3 months (Kent et al., 2016). Hence, the potential for expansion is large.

EARLY LIFE HISTORY SURVIVAL AND SETTLEMENT REQUIREMENTS: Polar cod has a relatively short life span of < 5 years (Boitsov et al., 2013). Annual recruitment to the stock very much reflects stock size dynamics (Hop & Gjøsæter, 2013). Long duration in cold waters of early life stages assumes high vulnerability during these stages (Bouchard et al., 2016). Local requirements for sea ice for both spawning and early life stage feeding makes the stock strongly dependent on the early life history (Eriksen et al., 2015; Eriksen, Huserbråten, et al., 2020; Huserbråten et al., 2019). In this regard it is hypothesized that extensive feeding during larval and juvenile stages is required to reach sizes necessary for surviving the first winter (Bouchard et al., 2016), something which is not as important in the Barents Sea due to earlier hatching and longer feeding periods than in the Pacific Arctic (Eriksen, Huserbråten, et al., 2020). Polar cod juveniles move deeper during late autumn and winter exerting a semi-pelagic lifestyle (Boitsov et al., 2013).

COMPLEXITY IN REPRODUCTIVE STRATEGY: Polar cod spawns under ice (Ponomarenko, 1968) during December through March (Boitsov et al., 2013; Hop & Gjøsæter, 2013) and have eggs withstanding temperatures <0°C (Laurel et al., 2018). It is believed that the large buoyant eggs may be damaged by mechanical tear (Boitsov et al., 2013) (Copeman & Laurel, unpublished data) if present in open rough waters during winter storms. It has been shown (Huserbråten et al., 2019) that numerical back-tracked spawning intensity based on observed 0-group distribution and modelled daily mean 3D circulations correlates with the presence of ice. This is, however, not the case for the spawning around Svalbard. Note though, that it is the spawning in the southeastern Barents Sea that constitutes the main supply of recruits to the Barents Sea Polar cod – unless ongoing genetic studies indicate sub-populations (Eriksen et al., 2015).

SPAWNING CYCLE: Though the Polar cod is being pushed north and east out of its current Barents Sea habitat, the spawning season peaks during period of the highest ice extend in the Arctic so suitable areas for spawning will be available also in the future. This is, however, unlikely in the Barents Sea, and only for the entire Arctic (Huserbråten et al., 2019). The smaller 0-group individuals found near Svalbard compared to the ones occurring in the southeastern Barents Sea indicate a delayed spawning and slower growth (Boitsov et al., 2013; J. Gjøsæter, 1973). Along with the above-mentioned long temperature-dependent egg stage development, the spawning cycle seems to be already adapted to a highly variable environment. However, the recent reported changes in sea ice and heat content (Lind et al., 2018; Onarheim & Årthun, 2017; Serreze et al., 2007) is likely beyond the conditions the spawning cycle is adapted to.

SENSITIVITY TO TEMPERATURE: Polar cod has antifreeze proteins in its blood (Hop & Gjøsæter, 2013) and can therefore withstand ambient temperatures down to -1.8 °C providing a temperature refuge from predators. Although Polar cod can tolerate higher temperatures it generally prefers cold Arctic water masses. The majority of 0-group Polar cod in the Barents Sea is found at water temperatures between 2.0 and 5.5 °C, whereas adults have been observed between -5 °C and 5 °C (Eriksen et al., 2015; Hop & Gjøsæter, 2013). However, early life stages and particularly eggs are confined to cold water with eggs floating below the ice for a substantial time after spawning (Eriksen, Huserbråten, et al., 2020). Thermal stress due to increased summer-autumn temperatures, especially in the south eastern Barents Sea, and a reduction of ice cover result in a loss of suitable spawning habitats during the winter. This may have a negative effect recruitment, thereby leading to a further decline of Polar cod in the Barents Sea.

SENSITIVITY TO OCEAN ACIDIFICATION: Generally, PCO_2 would interact with other pressures in the system but multi-pressure experiments including ocean acidification (OA) are limited to only a few parameters e.g. food availability (Thor et al., 2018). Furthermore, it is believed that species affected by OA may compensate by increased energy demand. However, Arctic species live in low temperatures and have therefore less energy available for handling additional pressures than other temperate species. Zooplankton species utilized by Polar cod is only affected during the early copepodite stages and then mainly through growth (Thor et al., 2018). Polar cod have impaired swimming capabilities under elevated PCO_2 (1,170 μatm) (Kunz et al., 2018). Overall, the scientific basis through experimental work is currently insufficient to predict effects of OA on Polar cod.

POPULATION GROWTH RATE: The stock with a “good” estimate of age at maturity is in the range for a “high” score for the covered area (Barents Sea). However, an unknown part of the Polar cod population is outside of the surveyed area. Therefore, estimates include a high level of uncertainties.

STOCK SIZE/STATUS: During the last 10 years the Barents Sea stock size has reduced significantly from > 1 million tonnes (2 million in 2000) to a few hundred tonnes (357,000 in 2017). The data are uncertain because of the variable spatial distribution of Polar cod and unknown abundances under ice (ICES, 2018). The spawning stock biomass varies reflecting the short life span of the species and the annual variable recruitment. Hence, the current state of the stock is low, and it is anticipated that this is at least partly caused by climate change.

OTHER STRESSORS: The Polar cod is, as part of the Arctic community in the Barents Sea, pushed north by boreal species (Eriksen et al., 2017; Fossheim et al., 2015). A large cod stock extended into the northern areas increasing the overlap with Polar cod enhancing predation pressure (ICES, 2018). At the same time ice is retreating thereby reducing the spawning habitat to the northwest and southeast. Hence, climate change is the main driver for stock size variability and change. Indirect changes through OA and pollutants are moderate.

Scoring of the considered sensitivity attributes

Sensitivity attributes, climate exposure based on climate projections allowing the evaluations of impacts of climate change, and accumulated directional effect scoring for Polar cod (*Boreogadus saida*) in Arctic Ocean and ICES subarea 1. L: low; M: moderate; H: high; VH: very high, $Mean_w$: weighted mean; N/A: not applicable. Usage: this column was used to make ad hoc notes, including considerations about the amount of relevant data available: 1 = low, 2 = moderate; 3 = high. N/A = not applicable.

Polar cod (*Boreogadus saida*) in Arctic Ocean and ICES subarea 1

SENSITIVITY ATTRIBUTES	L	M	H	VH	$Mean_w$	Usage	Remark
Habitat Specificity	0	1	4	0	**2.8**		
Prey Specificity	0	1	4	0	**2.8**		
Species Interaction	0	0	0	5	**4.0**		
Adult Mobility	0	2	3	0	**2.6**		
Dispersal of Early Life Stages	4	1	0	0	**1.2**		
ELH Survival and Settlement Requirements	0	0	1	4	**3.8**		
Complexity in Reproductive Strategy	0	0	1	4	**3.8**		
Spawning Cycle	0	2	3	0	**2.6**		
Sensitivity to Temperature	0	0	0	5	**4.0**		
Sensitivity to Ocean Acidification	3	2	0	0	**1.4**		
Population Growth Rate	2	3	0	0	**1.6**		
Stock Size/Status	0	0	4	1	**3.2**		
Other Stressors	0	0	2	3	**3.6**		
Grand mean					**2.88**		
Grand mean SD					**0.99**		

CLIMATE EXPOSURE	L	M	H	VH	$Mean_w$	Usage	*Directional Effect*
Surface Temperature	0	0	0	0		N/A	
Temperature 100 m	0	0	2	3	**3.6**	3	-1
Temperature 500 m	0	0	0	0		N/A	
Bottom Temperature	0	0	0	0		N/A	
O_2 (Surface)	4	1	0	0	**1.2**	2	-1
pH (Surface)	2	3	0	0	**1.6**	2	-1
Gross Primary Production	2	3	0	0	**1.6**	1	0
Gross Secondary Production	0	0	3	2	**3.4**	2	-1
Sea Ice Abundance	0	0	2	3	**3.6**	3	-1
Grand mean					**2.50**		
Grand mean SD					**1.14**		
Accumulated Directional Effect					**–**		**-13.4**

***Accumulated Directional Effect*: NEGATIVE**	**-13.4**

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