NORTH EAST ARCTIC COD

Stock name: North east Arctic cod (NEA cod)
Latin name: *Gadus morhua*
Geographical area: Barents Sea (juvenile and adult feeding grounds) and coast of Northern and Mid Norway (spawning grounds) (ICES subareas 1 and 2)
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Stock Sensitivity Attributes

HABITAT SPECIFICITY: Adult Northeast Arctic cod (*Gadus morhua*, Gadidae), located in the Barents Sea, is found at temperatures ranging from 7 down to -0.5 °C (Nakken & Raknes, 1987; Ottersen et al., 1998). These are temperatures found along the western shelf break between the Barents and Norwegian Seas (highest temperature) and to the Polar front in the northern part of the Barents Sea (lowest temperature). As a demersal species, it is primarily restricted to the continental shelf (< 500 m) (Christiansen et al., 2016; Strand et al., 2017; Sundby, 2000). There are, however, examples that specimens have been observed over deeper waters than mentioned, i.e. when crossing basins in the Norwegian Sea or deep trenches off Northern Norway (O. R. Godø & Michalsen, 2000). As the main prey is Barents Sea capelin, at least for adult cod, feeding migrations are undertaken to the Polar front of the Barents Sea, where the capelin stock stays most of the year (Fossheim et al., 2015; Haug et al., 2017). It is yet little evidence of Northeast Arctic cod entering the Polar Basin, although it has been at some occasions found over deep water (> 2,800m) in the Fram Strait (Ingvaldsen et al., 2017). The so-called "suitable feeding area" is defined as bottom temperatures > 0 °C (Kjesbu et al., 2014), but it has been observed feeding on capelin in the upper Arctic waters of temperatures down to -1 °C for limited periods of time (Mehl et al., 1985). During the pelagic juvenile stage through spring and late summer the ambient temperature may range from more than 11 to less than 1 °C (Sundby, 2000). The present range of ambient temperatures for Northeast Arctic cod in the Barents Sea is well within the tolerable ranges for the species. Under future climate change it has a wide potential to expand its habitat farther eastward into the Kara Sea and at the same time maintain its present distribution in the Barents Sea (Stenevik & Sundby, 2007). However, the southernmost spawning areas along the coast of Mid Norway would most likely no longer be used (Sundby & Nakken, 2008).

PREY SPECIFICITY: The diet of Northeast Arctic cod changes with age; younger individuals feed mostly upon macronekton while those somewhat older turn mostly piscivorous, including examples of cannibalistic behaviour on preceding year classes (Holt et al., 2019). The adults are fully piscivorous and feeding generalist choosing a wide range of prey species, but capelin is a preferred prey (Bogstad et al., 2000; Bogstad & Gjøsæter, 2001; Bogstad & Mehl, 1997; Mehl, 1989; Mehl & Yaragina, 1992; Orlova et al., 2005). In some periods of very low or very high capelin abundance the cod growth rate has been affected (Mehl & Sunnanå, 1991).

SPECIES INTERACTION: Cod is the main piscivorous fish species in the Barents Sea and thus there is little competition from other fish species. There is, however, competitions from marine mammals, notably minke whale and harp seal. A recent study shows that cod seems to utilize food resources better than harp seals and minke whales when competing for food (Bogstad et al., 2015).

ADULT MOBILITY: As the Northeast Arctic cod is primarily restricted to high-latitude continental shelf areas, the space for displacement is principally defined. However, these continental shelf areas are significant in size (the Barents Sea is about 1.4 million km^2). Over the last decade the Northeast Arctic cod have moved north-eastwards in the Barents Sea, reporting catches as far north as 80 °N (Haug et al., 2017; Kjesbu et al., 2014). As the 500 m isobath is currently considered the ultimate border for expansion, the above outline situation indicates that the adults may stay longer periods farther north in the Barents Sea during the year but also to a larger extent be inhabiting north-eastern areas (Kjesbu et al., 2014). In simple phrases the adults of Northeast Arctic cod typically show a predominately north-south migration whereas younger age classes a gradual displacement from east to west in the Barents Sea (Langangen et al., 2019; Michalsen et al., 1998; Nakken & Raknes, 1987; Ottersen et al., 1998). The length of migration of adults is defined by the geographical distance between feeding area and spawning ground, the latter primarily found along the coast of Northern Norway (Sundby & Nakken, 2008). There are, however, some surprising exceptions: spawning was found in Storfjorden between Bear Island and West Spitsbergen in the early 1930ies (Iversen, 1934), and cod spawning was in 2019 observed around Jan Mayen, this cod seems to be a mix of Barents Sea and Icelandic cod, with Icelandic cod dominating (Bogstad, 2019). A few specimens of young cod originating from the Barents Sea have also recently been found on the Northeast Greenland shelf (Andrews et al., 2019; Christiansen et al., 2016), individuals that are likely to have been transported from the Norwegian/Barents shelf as pelagic juveniles/0-group fish (Strand et al., 2017). In principle, the Northeast Arctic cod has the potential to inhabit other Arctic shelf regions under future climate change, like the Kara Sea and even the Siberian shelf farther east. However, due to the vast and extended areas of these regions it would be expected that such expansions must result in establishment of new metapopulations or subpopulations, since the distances in spawning migration and pelagic juvenile drift would be too long to occupy such large areas during one reproduction season (Sundby & Nakken, 2008).

DISPERSAL OF EARLY LIFE STAGES: The starting point for denatant advection of early life stages (ELS) of Northeast Arctic cod is the location of the spawning grounds along the Norwegian coast. These are found as far south as the Møre region (62 °N) but the main one is at Lofoten (68 °N) (Sundby & Nakken, 2008; Vikebø et al., 2005). Under a warmer regime the spawning grounds are displaced northwards and vice versa under a cooler regime (Sundby & Nakken, 2008). Hence, there is a fine-tuned mechanism regarding location of spawning grounds. Nevertheless, the Lofoten area, placed in the middle of the spatial distribution of spawning grounds, seems little affected by these climate-mediated effects. Spawning at the Møre region implies a more westerly settlement of the 0-group in the Barents Sea (cf. “Svalbard cod” and the western branch of the Atlantic current) whereas ELS stages originating from northern grounds are to a larger extent advected into the middle-eastern part of the Barents Sea (cf. “true” Northeast Arctic cod and the eastern branch of the Atlantic current) (O. Godø, 1984). Taken together, under climate change the eastern and northern parts of the Barents Sea are expected to become increasingly important as nursery grounds. Generally, these Arctic-dominated waters are less productive systems. However, the borealisation of these waters under climate change is expected to increase the productivity with larger fraction of boreal zooplankton on the cost by reducing the fraction of Arctic zooplankton (Ellingsen et al., 2008). Northeast Arctic cod has the longest spawning migration of all Atlantic cod stocks and has been shown to be very dynamic in its selections of spawning habitat under varying climate conditions (Sundby & Nakken, 2008).

EARLY LIFE HISTORY SURVIVAL AND SETTLEMENT REQUIREMENTS: It is well established that ELS are crucial in determining year class strength. The associated daily mortality rate is immense; typically, 0.17 (0.12 – 0.22) day^{-1} during the egg stage (Sundby et al., 1989). Only a few percent of the larvae are still alive 30 days post hatch (predation is considered the main explanatory factor) (Sundby et al., 1989). There are reasons to believe that first-time (recruit) spawners show a higher degree of natural egg mortality (in the order of 20% during the whole length of incubation) than established (repeat) spawners (Solemdal, 1997). The synchrony with the short spring bloom is considered critically important; the cod larvae need to successfully prey upon *Calanus* nauplii and early copepodites around the period of yolk sac reabsorption (Ellertsen et al., 1989). This match is defined by the time of spawning of the cod and the appearance of the spring bloom (Ellertsen et al., 1989; Kjesbu et al., 1996; Solemdal, 1997). The start of the spring bloom at such high latitudes is largely defined by day length (which does not vary between years) (Eilertsen et al., 1993; Racault et al., 2012) whereas the Northeast Arctic cod spawning time (March/April) is a function of environmental conditions (primarily temperature) during the period of maturation (from October onwards) (Kjesbu et al., 2010) and thereby might be considered more variable. High growth (Suthers & Sundby, 1993) and survival (Ellertsen et al., 1989) during the larval and early pelagic juvenile stage ("post larvae") has some correlation with ambient temperature during these stages. However, it is still unclear about the mechanistic link, but high temperature is considered a proxy for the availability of high abundance of zooplankton prey (Ellertsen et al., 1989; Sundby, 2000; Suthers & Sundby, 1993).

COMPLEXITY IN REPRODUCTIVE STRATEGY: The fact that Northeast Arctic cod undertake long spawning migrations (in contrast to most of the other cod stocks) is a central component in the reproductive strategy of this stock (Jørgensen et al., 2008). This, because this migration is highly energetically demanding, can lead to "skipping" of spawning as a regular phenomenon (Jørgensen et al., 2006; Skjæraasen et al., 2012; Yaragina, 2010). The decision to skip or not is dependent on the energetic status and taken around the months of October/November which marks the first part of the reproductive cycle compromising individual invest in body maintenance (Skjæraasen et al., 2009). The degree of skipping in Northeast Arctic cod is well developed, i.e. comparably in magnitude to the spawning stock biomass (SSB) (Skjæraasen et al., 2012). Hence, numerous sexually mature individuals (but with "resting" gonads) stay in the Barents Sea during wintertime instead of migrating to the coast of Norway to spawn (Skjæraasen et al., 2012). There are reasons to believe that the prevalence of skipping will increase during climate change due to increased metabolic costs, both during the spawning migration in warmed Atlantic water and longer migrations back and forth to the northernmost part of the Barents Sea.

SPAWNING CYCLE: Generally, Northeast Arctic cod is spawning too late in the season compared to the appearance of the spring bloom. This might be explained by that a high number of members of this stock encounter extremely cold temperatures during the feeding period which overlaps with gonad development (Kjesbu et al., 2010). Hence, ocean warming will cause accelerated gonad development (if not arrested, see comment above regarding "skippers") and thereby likely a higher degree of match with the spring bloom. This might underlie the well-known statement that "a higher temperature is a requirement but not a sufficient one for better recruitment of Northeast Arctic cod" (Ellertsen et al., 1989; Sundby, 2000). Nevertheless, successful recruitment is a complex series of factors that need to play in well-tuned concert. Each female cod shed in the order of 15 egg batches at an interval of about 3 days (Kjesbu, 1989; Kjesbu et al., 1996). Hence, a Northeast Arctic cod female spawns over several weeks introducing millions of eggs to the water column, characteristically in the transition layer between the cool coastal water and the warmer Atlantic water in a typical temperature range from 3 to more than 6 °C and which depth position varies between 50 and 200 m depth on temporal and spatial scales (Ellertsen, Furnes, et al., 1981; Ellertsen, Solemdal, et al., 1981; Furnes & Sundby, 1981). The spawning season last from beginning of March to early May, with peak spawning around 1st of April (Ellertsen et al., 1989; Pedersen, 1984; Sundby & Bratland, 1987), a spawning cycle that is shared with most other high-latitude species (Sundby et al., 2016). The eggs ascend to the upper, mixed layer and are transported by the Norwegian coastal current northwards (Ådlandsvik & Sundby, 1994; Sundby, 1983; Sundby et al., 1989). As likely for many other marine fishes, the ovulation process is highly sensitive to environmental conditions; cod in general is known to spawn between 0 and 9.6 °C (Brawn, 1962; Kjesbu et al., 2010; van der Meeren & Ivannikov, 2006).

SENSITIVITY TO TEMPERATURE: As mentioned above, spawners of Northeast Arctic cod are in principle sensitive to temperature influences, i.e. show a narrow thermal window of about 3-6 °C. The thermal window for ELS is considerably wider as it is exposed to the upper pelagic layer from March to August, typical from 11 down to about 1 °C (Sundby, 2000). Sub-zero temperatures are avoided; Northeast Arctic cod is probably not producing antifreeze proteins as seen in Northern cod (Goddard et al., 1992). Bottom temperatures >0 °C mark Northeast Arctic cod feeding areas in the Barents Sea (Kjesbu et al., 2010). Nevertheless, cod in the Barents Sea have been frequently observed down to -0.5 °C and at (probably short) occasions even down to -1 °C (Ottersen et al., 1998). The freezing point of internal body fluid is about -0.63 °C (S=11). Northeast Arctic cod may migrate up into even colder surface Arctic water during summer feeding on capelin for a short period of time and, thereafter, migrate down below into warmer waters to digest the food (Mehl et al., 1985).

SENSITIVITY TO OCEAN ACIDIFICATION: This is a much-debated topic where both experimental designs and up-scaled model projections diverge (Browman, 2017). However, ocean acidification will seemingly reduce Northeast Arctic cod stock productivity by the end of the 21st century under the "business-as-usual" scenario, with particular reference to increased ELS mortality (Stiasny et al., 2016).

POPULATION GROWTH RATE: The stock has shown large fluctuation in stock size but is also the most productive of all Atlantic cod stocks (O. Godø, 2003). Growth dynamics of Northeast Arctic cod (age 1-10 years) apparently do not fit well to the von Bertalanffy equation as asymptotic total length-at-age is poorly detectable (Hamre et al., 2014). This being said, Northeast Arctic cod fall into the specific criteria tabled under "High" and "Very High", depending on which parameter is consulted, e.g. Northeast Arctic cod reach sexual maturity relatively late compared to other Northeast Atlantic cod stocks (Nash et al., 2010).

STOCK SIZE/STATUS: Biomass maximum sustainable yield (B_{MSY}) is not defined for this stock. However, SSB is well above the precautionary reference point for biomass (B_{pa}) and the total stock biomass is also above the post-World War II mean value (ICES, 2019). This has been the case for the last decade. Northeast Arctic cod is currently well managed, i.e. since the introduction of the harvest control rule, adopted in 2004 by the Joint Norwegian–Russian Fishery Commission and turned effective in 2007 following dedicated efforts to reduce illegal landings (Kjesbu et al., 2014).

OTHER STRESSORS: Northeast Arctic cod is experiencing one main stressor; fishing. So far climate change effects on this stock are considered positive and are thus at present not considered a stressor.

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 Northeast Arctic cod (*Gadus morhua*) in ICES subareas 1 and 2. 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.

Northeast Arctic cod (*Gadus morhua*) in ICES subareas 1 and 2

SENSITIVITY ATTRIBUTES	L	M	H	VH	$Mean_w$	Usage	Remark
Habitat Specificity	1	4	0	0	**1.8**		
Prey Specificity	1	3	1	0	**2.0**		
Species Interaction	3	2	0	0	**1.4**		
Adult Mobility	1	4	0	0	**1.8**		
Dispersal of Early Life Stages	4	1	0	0	**1.2**		
ELH Survival and Settlement Requirements	1	1	3	0	**2.4**		
Complexity in Reproductive Strategy	3	2	0	0	**1.4**		
Spawning Cycle	0	1	4	0	**2.8**		
Sensitivity to Temperature	1	2	2	0	**2.2**		
Sensitivity to Ocean Acidification	5	0	0	0	**1.0**		
Population Growth Rate	3	2	0	0	**1.4**		
Stock Size/Status	5	0	0	0	**1.0**		
Other Stressors	3	2	0	0	**1.4**		
Grand mean					**1.68**		
Grand mean SD					**0.55**		

CLIMATE EXPOSURE	L	M	H	VH	$Mean_w$	Usage	*Directional Effect*
Surface Temperature	0	0	0	0		N/A	
Temperature 100 m	0	2	3	0	**2.6**	3	1
Temperature 500 m	0	0	0	0		N/A	
Bottom Temperature	0	0	0	0		N/A	
O_2 (Surface)	3	2	0	0	**1.4**	2	-1
pH (Surface)	2	3	0	0	**1.6**	2	-1
Gross Primary Production	1	2	2	0	**2.2**	1	1
Gross Secondary Production	0	0	3	2	**3.4**	2	1
Sea Ice Abundance	0	0	2	3	**3.6**	3	1
Grand mean					**2.47**		
Grand mean SD					**0.91**		
Accumulated Directional Effect					**–**		**8.8**

***Accumulated Directional Effect*: POSITIVE**	**8.8**

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