Stock name: North Sea cod
Latin name: *Gadus morhua*
Geographical area: North Sea (ICES subarea 4)
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Stock Sensitivity Attributes

HABITAT SPECIFICITY: Prior to 1990s cod (*Gadus morhua*, Gadidae) was widely distributed throughout the entire North Sea in terms of feeding areas (Hislop et al., 2015) as well as spawning areas (Brander, 1994). The increasing temperature during the recent 30 years has caused stock abundance to be reduced substantially (Hislop et al., 2015), although stock size has increased again after 2005 (ICES, 2017), however, only in the north part of the North Sea. In the southern part cod has continued to decrease. Also, the spawning areas are now concentrated and displaced towards the northern and northeastern part of the North Sea adjacent to the Norwegian Trench (Sundby et al., 2017).

PREY SPECIFICITY: As in other habitats of Atlantic cod, adult North Sea cod is a top predator in the ecosystem. In comparison with the other major gadoids of the North Sea, i.e. haddock, saithe, and whiting, cod has a much more diverse diet with a wide range of fish including cannibalism (Daan, 1989; Hislop, 1996; Hislop et al., 1997, 2015). Also, during the juvenile stages, cod diet is relatively diverse. However, the early stages have been shown to be dependent on particular spring-spawning copepods species (Rothschild, 1998), mostly *Calanus finmarchicus*, but also high abundances of *Paracalanus/Pseudocalanus*.

SPECIES INTERACTION: The early life stages are dependent on the presence of spring-spawning copepods. During the recent decades of increasing temperature, the important spring-spawning copepod *C. finmarchicus* has declined substantially. 0-group gadoids, including cod feed substantially on *C. finmarchicus* (Bromley et al., 1997), but the larger fraction of the 0-group is increasingly feeding on other small fish. This implies that the larvae and 0-group fish are dependent on influx/supply of *C. finmarchicus* from the northern entrance of the North Sea (Sundby, 2000). As the ocean climate has been warming during recent decades, boreal copepod species, including *C. finmarchicus*, have been displaced farther northwards (Beaugrand et al., 2003; Beaugrand & Kirby, 2010).

ADULT MOBILITY: The North Sea circulation pattern and the location of the cod spawning areas implies that transport and dispersion of the pelagic offspring occur towards southeast (Turrell, 1992). Recently, the transport of the gadoid species cod, Norway pout, and saithe has been modelled (Sundby et al., 2017). The drift pattern from the spawning area was to the south and east, apart from northeastern drift at the Tampen/Vikingbanken spawning area. Although also from this spawning area the major transport direction was towards south, a certain fraction of the eggs and larvae was lost out of the North Sea towards northeast and the Møre Plateau. In conclusion, it implies that the cod offspring retain in the North Sea with minor possibilities to escape towards north as climate continues to warm. The life cycle of North Sea cod is closed within the North Sea.

DISPERSAL OF EARLY LIFE STAGES: The stock has very low abilities to colonize new areas under climate change as the offspring is transported in the "wrong" direction towards south and warmer waters. For details, see the explanation above (Sundby et al., 2017; Turrell, 1992). We have seen that major part of fish stocks world-wide expand poleward under global climate change (Poloczanska et al., 2013). However, in the North Sea a large fraction of the fish species has been displaced equatorwards, probably because of the prevailing inflow of warm Atlantic water through the northern entrance between Scotland and Norway. It implies that the North Sea as an ecosystem is poorly structured for cold-temperate (boreal) fish species to expand polewards to cooler climate under global climate change.

EARLY LIFE HISTORY SURVIVAL AND SETTLEMENT REQUIREMENTS: See the two previous sensitivity attributes: the only alternative for cod to utilize new areas is to become transported towards northeast to the Mid Norwegian shelf (Sundby et al., 2017). However, under such conditions it is an open question whether it could be considered as a North Sea stock, as the fraction of offspring transported to the Mid Norwegian shelf would have a larger potential to mix with Norwegian coastal cod and Northeast Arctic cod.

COMPLEXITY IN REPRODUCTIVE STRATEGY: With the wide prey range utilized by cod (Daan, 1989; Hislop, 1996; Hislop et al., 1997, 2015) it is considered that cod is very robust against food limitation, and, may be able to use energy from different sources for gonad maturation and production. The ambient temperature of the southernmost part of North Sea is, however, approaching the critical temperature of 9.5-10.0 °C for gonad maturation in Atlantic cod. Above this temperature the egg quality drops (van der Meeren & Ivannikov, 2006). Under continued ocean warming, temperature will limit capacities for gonad maturation, first in the southernmost part of the North Sea and gradually propagating northwards.

SPAWNING CYCLE: Cod is mainly a spring-spawning species throughout the North Atlantic. There are some few examples of cod stocks that can switch between spring and autumn spawning, such as cod off Nova Scotia (McKenzie, 1940). Cod spawns in the North Sea between January and May with peak spawning in January-February in the southern North Sea and in March at Vikingbanken of the northern North Sea (Sundby et al., 2017). It is assumed that the spawning season is synchronized with the spring bloom (Brander, 1994). It is an open question whether cod would be able to shift spawning season in the northern North Sea from spring-spawning to more widely stretched spawning season if climate change would result in more year-around spawning copepods like *Calanus helgolandicus*, i.e. provided such species are continuing to become abundant in the northern North Sea under climate change. However, this is probably constrained by the seasonal light cycle that will not change with climate change (Sundby et al., 2016).

SENSITIVITY TO TEMPERATURE: Atlantic cod is distributed over a wide range of temperature from 0 to 18 °C with an optimal growth rate at around 13 °C (Sundby, 2000). However, spawning and maturation require temperatures below 10 °C (van der Meeren & Ivannikov, 2006). Presently, the southernmost part of the North Sea reaches temperature limits for successful spawning. Continued ocean warming is assumed to limit cod reproduction in the southernmost part of the North Sea in the future.

SENSITIVITY TO OCEAN ACIDIFICATION: Ocean acidification (OA) will occur first in deeper layers. The pelagic surface layer will be less influenced by OA. However, it is assumed that the early larval stages are more vulnerable to OA than the adults, assumably due to undeveloped gills without ion-regulatory capacities (Frommel et al., 2013). Experiments with cod larvae from the Baltic Sea and the Barents Sea shows increased mortality of both stock under the IPCC RCP8.5 scenario (comparing to atmospheric CO_2 of 1,100 ppm by the end of 21st century) (Stiasny et al., 2016), although no significant impacts on the Baltic cod larvae are seen (Frommel et al., 2013) as the Baltic Sea is naturally exposed to OA fluctuations inside low salinity and sub-oxic conditions. Baltic cod larvae indicate high adaptational capacities to OA. North Sea cod is expected to show the same degree of vulnerability as the Barents Sea cod. Also, Norwegian coastal cod larvae were observed to suffer tissue damage under high OA (Frommel et al., 2012). Moreover, high OA seem to influence otolith calcification in Barents Sea cod larvae (Maneja et al., 2013). The RCP8.5 scenario seem devastating for the North Sea cod stock. Less clear is how the more realistic IPCC scenario RCP4.5 would impact larval cod.

POPULATION GROWTH RATE: North Sea cod has shown a decreasing productivity since the “gadoid outburst" (Cushing, 1980, 1984), assumedly in response to ocean warming since the cool 1960s and 1970s. After 2005, the stock has increased again, but only in the northern part of the North Sea, probably as an adaptation to less abundant spring-spawning copepod *C. finmarchicus* in more southerly parts of the North Sea. In the southern North Sea, the stock abundance has continued to decrease, and the traditional spawning areas here seems to be skipped recently. Under future climate change North Sea cod productivity is expected to become under increasing stress. The question remains whether North Sea cod might continue with a limited population in the northeastern part of the North Sea.

STOCK SIZE/STATUS: North Sea cod has been overfished since the 1960s. Particularly, during the last two decades of the 20th century fishing mortality (F) was around 1 (ICES, 2017). Subsequent to year 2000, F started decreasing, and from 2014 F became below 0.4 and from 2016 the cod stock was considered as "sustainable harvested" (ICES, 2017). In conclusion, fishing has been unsustainably conducted since the 1960s. Only the recent 2-3 years fishing has become sustainable. It will remain to see whether this is a continuing trend.

OTHER STRESSORS: Although the stock has increased since 2005 and fishing has been sustainably conducted over the recent past 2-3 years, the increasing influence of global warming is expected to exert increasing environmental stress on the North Sea cod stock. It is therefore uncertain whether the recent years increasing trend in stock abundance since 2005 would continue.

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 North Sea cod (*Gadus morhua*) in ICES subarea 4. 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.

North Sea cod (*Gadus morhua*) in ICES subarea 4

SENSITIVITY ATTRIBUTES	L	M	H	VH	$Mean_w$	Usage	Remark
Habitat Specificity	0	5	0	0	**2.0**		
Prey Specificity	5	0	0	0	**1.0**		
Species Interaction	0	0	5	0	**3.0**		
Adult Mobility	0	0	5	0	**3.0**		
Dispersal of Early Life Stages	0	0	0	5	**4.0**		
ELH Survival and Settlement Requirements	0	0	0	5	**4.0**		
Complexity in Reproductive Strategy	0	0	5	0	**3.0**		
Spawning Cycle	0	0	0	5	**4.0**		
Sensitivity to Temperature	0	0	5	0	**3.0**		
Sensitivity to Ocean Acidification	0	5	0	0	**2.0**		
Population Growth Rate	0	0	5	0	**3.0**		
Stock Size/Status	0	5	0	0	**2.0**		
Other Stressors	0	0	5	0	**3.0**		
Grand mean					**2.85**		
Grand mean SD					**0.90**		

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)	3	2	0	0	**1.4**	2	0
pH (Surface)	2	3	0	0	**1.6**	2	-1
Gross Primary Production	4	1	0	0	**1.2**	1	1
Gross Secondary Production	0	0	2	3	**3.6**		-1
Sea Ice Abundance	0	0	0	0		N/A	
Grand mean					**2.28**		
Grand mean SD					**1.21**		
Accumulated Directional Effect					**–**		**-7.6**

***Accumulated Directional Effect*: NEGATIVE**	**-7.6**

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