

**Stock name:** Coastal cod South

**Latin name:** *Gadus morhua*

**Geographical area:** South Norway, south of Stad (62°N) (ICES subarea 4)

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### Stock Sensitivity Attributes

**HABITAT SPECIFICITY:** Recent studies suggest the presence of a pair of coexisting Atlantic cod (*Gadus morhua*, Gadidae) ecotypes in coastal areas, one being an offshore ecotype (NS ecotype hereafter), another being a coastal ecotype (fjord ecotype hereafter) (André et al., 2016; Jorde, Synnes, et al., 2018; Knutsen et al., 2018; Sodeland et al., 2016). These coexisting ecotypes are characterized by distinct lifestyles, with highly migrating oceanic (offshore) individuals generally foraging along the coast (although some occur also inside the fjords) possibly returning to North Sea or offshore Skagerrak spawning sites and a more sedentary coastal ecotype remaining close to the coast in more sheltered locations that spawn locally (Espeland et al., 2008; Knutsen et al., 2007; Neuenfeldt et al., 2013; Rogers et al., 2014). Previous genetic studies of Atlantic cod from this area have shown an overall low level of genetic divergence, revealing strong gene flow, with a superimposed complex of slightly divergent components or populations. Population components include (1) large oceanic spawning aggregates in the North Sea (NS) (Heath et al., 2014; Hemmer-Hansen et al., 2013), where pelagic eggs and larvae are transported into coastal Skagerrak (Knutsen et al., 2003, 2018; Spies et al., 2018; Stenseth et al., 2006), and (2) geographically fine-scaled genetically differentiated components along the coast (Barth et al., 2019; Jorde et al., 2007; Knutsen et al., 2003), which are spatially separated within fjords (Knutsen et al., 2011; Sodeland et al., 2016), displaying fine-scaled population dynamic (Rogers et al., 2017) and fine-scaled life history patterns (Roney et al., 2016). Despite potential gene flow and the fact that both ecotypes occur together along the coast, there is evidence that genetic structuring is maintained by (i) retention of pelagic early-life stages (eggs and larvae) in fjords (Ciannelli et al., 2010; Jorde, Kleiven, et al., 2018; Knutsen et al., 2007), (ii) reduced migration of older fish (Knutsen et al., 2011; Rogers et al., 2014), and (iii) genomic and behavioural barriers to gene flow (Barth et al., 2019). There is also evidence for adaptive differences among coastal cod in fitness-related phenotypic characters (Olsen et al., 2008). The southern coastal cod population complex (South Norway, south to Stad) thus comprises a mixture of local, coastal cod sub-stocks (typically in sheltered coastal regions), that co-occur with oceanic cod, i.e. from the NS stock (typically outer coastal regions). It has been shown that some of the NS ecotypes leave the coast after some years, but the frequency of those leaving is unclear (Svedäng et al., 2007). Although local sub-stocks are confined to smaller areas, their general habitat is continuously distributed along the Norwegian coast (Aglen et al., 2016). Recent analyses using acoustic transmitters show that the NS ecotype have slightly shallower depth preferences compared to the coastal 'fjord' ecotype that stays deeper in the coastal zone (Barth et al., 2019). There is also evidence for more active and more freely moving individuals among the NS ecotype (Kristensen, personal communication).

**PREY SPECIFICITY:** Like in other parts of the Atlantic cod distribution range, adult North Sea/Skagerrak/coastal cod is a top/apex predator in the ecosystem, constituting a key ecological role. In comparison with the other major gadoids of the North Sea, i.e. haddock, saithe, pollack and whiting, cod has a much more diverse diet with a wide range of benthic and fish prey, including cannibalism (Daan, 1989; Hislop, 1996; Hislop et al., 1997, 2015). The departure of cod from the fish assemblage is likely to have profound effects on the ecosystem. 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 (ELS) are dependent on the presence of spring-spawning copepods. During the recent decades of increasing temperature, the number of the copepod *C. finmarchicus* has declined substantially. 0-group gadoids, including cod feed 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 cod larvae and the 0-group rely on sufficient supplies of *C. finmarchicus* from the northern entrance of the North Sea (Sundby, 2000) or by local sources inside fjords (e.g. Risør). With ocean warming during recent decades, boreal copepod species including *C. finmarchicus*, have been displaced northwards (Beaugrand et al., 2003; Beaugrand & Kirby, 2010). The Norwegian Trench is the main gateway of the *C. finmarchicus* influx from the Norwegian Sea to the North Sea (Sundby, 2000). Hence, decreasing abundances of *C. finmarchicus* will first appear along the trench adjacent to the Skagerrak coast. Reduced *C. finmarchicus* influx into the fjords is, therefore, expected to first appear in the fjords in southeastern Norway, while the fjords in western Norway are still close to the source population in the Norwegian Sea. There is some evidence that periods of lowered abundance of *C. finmarchicus* are correlated with weak recruitment of cod in coastal Skagerrak (Johannessen et al., 2012).

**ADULT MOBILITY:** Coastal cod perform shorter migration distances than the oceanic populations (Espeland et al., 2007, 2008). Individuals move on average less than a few hundred meters inshore, and farther in coastal areas (Rogers et al., 2014). Recently, long-term acoustic tagging studies have demonstrated home-range (space in which fish periodically lives and move) behaviour and repeatability of individual movement behavioural traits (Olsen et al., 2012; Villegas-Ríos et al., 2018). Coastal cod display strong spawning site fidelity (Espeland et al., 2007; Skjæraasen et al., 2011) and pronounced natal homing behaviour (André et al., 2016; Bonanomi et al., 2015; Svedäng et al., 2007) that could further aid differentiation of coastal and oceanic ecotypes by reducing potential gene flow.

**DISPERSAL OF EARLY LIFE STAGES:** A large portion of the eggs transported into and larvae settling along the Skagerrak coast (also inside fjords) seem to originate from spawning aggregations in the North Sea or offshore Skagerrak areas (Huserbråten et al., 2018; Stenseth et al., 2006). Modelling cod egg transport and dispersion from the main spawning sites of North Sea cod west of the Norwegian Trench (Sundby et al., 2017) show that a smaller fraction of pelagic juveniles reaches the Skagerrak coastline and the coastline of western Norway between Hordaland and Møre after 3-4 months. Using genetic tools, these ELS are later detected as juveniles that occur together with recruits originating from local spawners (Knutsen et al., 2018). In addition, eggs are spawned within fjords and sheltered areas along the coast. Generally, eggs from Norwegian coastal cod are neutrally buoyant at salinity from around 30.5 to 33 depending on the specific subpopulation (Stenevik et al., 2008). Eggs will, hence, float mainly in the surface layer (Sundby, 1983), while eggs in fjords may sink below the low-saline upper layer in the fjords (Sundby, 1991) where surface salinity during spring is outside the range where eggs are neutrally buoyant. As a consequence, the estuarine circulation may enhance egg retention inside the fjord (Ciannelli et al., 2010; Myksvoll et al., 2011). After hatching, cod larvae perform a vertical migration behaviour that prevents occurrences in the upper 10 meters of the water column (Ellertsen et al., 1984; Kristiansen et al., 2014), independent of being offshore or inside a fjord. The general estuarine circulation in fjords form typical offspring retention processes. The extent of the retention mechanism is variable depending on the position of spawning areas and the topography of the fjord (Ciannelli et al., 2010; Knutsen et al., 2007). The degree of retention/transport differs along the coast (Myksvoll et al., 2014), with higher retention rates when spawning occurs in inner fjords, and in fjords with sills. Hence, the dispersal of ELS differ among local populations.

**EARLY LIFE HISTORY SURVIVAL AND SETTLEMENT REQUIREMENTS:** Cod larvae have specific requirements for prey (copepods, *Calanus*) in a short window of time after hatching (mismatch). They grow and recruit into the populations across a wide range of environmental gradients along the coast (see above).

**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, hence, may be able to use energy from different sources for gonad maturation and production. The ambient temperature of the southernmost part of its range 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 may reach critical levels for gonad maturation, first in the southernmost part of the North Sea and gradually propagating northwards.

**SPAWNING CYCLE:** Cod is a long-lived species (20-30 years) reaching sexual maturation in  $\approx$  2-6 years, depending on the ambient temperature and the fishing pressure. Cod mainly reproduces in spring throughout the North Atlantic. Over this period females typically spawn 15-20 batches. There is evidence that cod is able to shift between being spring- and autumn spawning, such as cod off Nova Scotia (McKenzie, 1940). Cod spawning south of 62 °N is reported to occur 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 is synchronized with the spring bloom (Brander, 1994). It remains unclear whether cod may be able to adjust spawning to a change of the phenology of the spring bloom in the course of climate change. It is also unknown whether cod may extend the spawning season to match with abundant food sources that are available year around such as *Calanus helgolandicus*. It is assumed that *C. helgolandicus* may remain abundant under climate change in the northern North Sea. However, this is probably constrained by the seasonal light cycle (Sundby et al., 2016).

**SENSITIVITY TO TEMPERATURE:** The stocks are distributed along the coast of Norway at a depth range of 5-400 m with temperature between 0 and 18 °C. Optimal growth rates are assumed at around 13 °C (Sundby, 2000). However, spawning and gonad maturation require lower temperatures  $\leq$ 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 future.

**SENSITIVITY TO OCEAN ACIDIFICATION:** This is a much-debated topic where both experimental designs and up-scaled model projections diverge. Ocean acidification (OA) may reduce coastal cod stock productivity if the “business-as-usual” scenario continues, with reference to increased ELS mortality. The saturation level of calcium carbonate (hereafter, *W*) increases under OA, implying that organisms depending on building solid calcium carbonate structures will suffer under OA. The changes in *W* will first be manifested in deeper layers of the water column (due to the additional influence of pressure on *W*). Most parts of the pelagic surface layer (except in the large eastern boundary upwelling ecosystems) are assumed to remain unaffected by the change in *W* under most emission scenarios. However, the OA itself will have the largest impact in the surface layers particularly on ELSs that are probably more vulnerable to OA than adults due undeveloped gills that allow for proper ion-regulation (Frommel et al., 2013). Experiments with cod larvae from the Baltic Sea and the Barents Sea showed increased larval mortality under the IPCC RCP8.5 scenario (comparing to atmospheric CO<sub>2</sub> of 1,100 ppm by the end of 21<sup>st</sup> century) (Stiasny et al., 2016), although no effects on Baltic cod larvae were seen because OA in the Baltic Sea naturally fluctuates stronger than in other North Atlantic regions (Frommel et al., 2013). This indicates high adaptational abilities to OA in the Baltic. North Sea cod, however, is assumed to be similar vulnerable to OA like the Barents Sea cod. Norwegian coastal cod larvae suffered tissue damage under high OA (Frommel et al., 2012). Moreover, strong OA was observed to hamper otolith calcification in Barents Sea cod larvae (Maneja et al., 2013). The RCP8.5 scenario seem devastating for the coastal cod stock. Less clear is how the more realistic IPCC scenario RCP4.5 would impact larval cod.

**POPULATION GROWTH RATE:** No biomass maximum sustainable yield ( $B_{MSY}$ ) is defined for this stock. The age structure indicates that the stock is heavily overexploited. Recent advice is to reduce fishing pressure considerably.

**STOCK SIZE/STATUS:** No  $B_{MSY}$  is defined for this stock. The age structure is truncated and indicates that sub-stocks are heavily overexploited. Tagging experiments conducted in coastal Skagerrak (2005-2013) and subsequent modelling suggest that in some years fishing mortality was entirely responsible for stock reduction for cod at  $\geq 40$  cm (Fernández-Chacón et al., 2015). Recent regulations in Skagerrak may reduce fishing pressure but rebuilding of age structure is less likely under the present management regime. In the near future, protection of habitats that are likely to harbour future temperature refugia and rebuilding of homogenous age structure should be prioritised.

**OTHER STRESSORS:** Successful recruitment of 0-group cod and survival to age 1 appear to have decreased over recent decades, although the 2019 year-class was particularly strong in Skagerrak. There is also decline in catches/landings of adult cod along the Skagerrak coast over the last decade. Besides unabated overharvesting there are several factors causing the decline, including habitat loss in nursery areas due to coastal hardening, increased summer temperatures, eutrophication and seasonal and/or permanent oxygen deprivation of deep water in fjords with sills.

**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 Coastal cod (*Gadus morhua*) stock in ICES subarea 4. L: low; M: moderate; H: high; VH: very high, Mean<sub>w</sub>: 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.

*Coastal cod (Gadus morhua) South in ICES subarea 4*

<b>SENSITIVITY ATTRIBUTES</b>	L	M	H	VH	Mean <sub>w</sub>	Usage	Remark
Habitat Specificity	1	3	1	0	<b>2.0</b>		
Prey Specificity	1	3	1	0	<b>2.0</b>		
Species Interaction	2	2	1	0	<b>1.8</b>		
Adult Mobility	1	2	2	0	<b>2.2</b>		
Dispersal of Early Life Stages	1	2	2	0	<b>2.2</b>		
ELH Survival and Settlement Requirements	0	2	2	1	<b>2.8</b>		
Complexity in Reproductive Strategy	4	1	0	0	<b>1.2</b>		
Spawning Cycle	0	1	3	1	<b>3.0</b>		
Sensitivity to Temperature	0	1	3	1	<b>3.0</b>		
Sensitivity to Ocean Acidification	4	1	0	0	<b>1.2</b>		
Population Growth Rate	5	0	0	0	<b>1.0</b>		
Stock Size/Status	5	0	0	0	<b>1.0</b>		
Other Stressors	0	1	2	2	<b>3.2</b>		
<b>Grand mean</b>					<b>2.05</b>		
<b>Grand mean SD</b>					<b>0.79</b>		

<b>CLIMATE EXPOSURE</b>	L	M	H	VH	Mean <sub>w</sub>	Usage	<i>Directional Effect</i>
Surface Temperature	0	0	0	0		N/A	
Temperature 100 m	0	0	2	3	<b>3.6</b>	3	-1
Temperature 500 m	0	0	0	0		N/A	
Bottom Temperature	0	0	0	0		N/A	
O <sub>2</sub> (Surface)	3	2	0	0	<b>1.4</b>	2	-1
pH (Surface)	3	2	0	0	<b>1.4</b>	2	-1
Gross Primary Production	3	2	0	0	<b>1.4</b>	2	0
Gross Secondary Production	0	2	2	1	<b>2.8</b>	3	-1
Sea Ice Abundance	0	0	0	0		N/A	
<b>Grand mean</b>					<b>2.12</b>		
<b>Grand mean SD</b>					<b>1.03</b>		
<b>Accumulated Directional Effect</b>					-		<b>-9.2</b>

<b>Accumulated Directional Effect: NEGATIVE</b>	<b>-9.2</b>
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