Stock name: North Sea autumn-spawning herring
Latin name: *Clupea harengus*
Geographical area: North Sea, English Channel and Skagerrak-Kattegat (ICES subarea 4, divisions 3.a and 7.d)
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Stock Sensitivity Attributes

HABITAT SPECIFICITY: This herring (*Clupea harengus*, Clupeidae) stock is at the southern limit of herring distribution in the Northeast Atlantic. Hence, it is bounded by its southern limit but also low salinity in the east. The mature part of the stock is mainly distributed on the North Sea plateau at a maximum depth of 200 m. The habitat area is therefore restricted and may be reduced if, e.g. a temperature increase causes the southern limit of the stock to move northwards. Herring is a demersal spawner which requires specific spawning habitats, like e.g. gravel.

PREY SPECIFICITY: Planktonic crustaceans mainly compose the diet of Atlantic herring by planktonic crustaceans (Arrhenius & Hansson, 1992; Dalpadado et al., 2000; Darbyson et al., 2003; Hardy, 1924; Möllmann et al., 2003). However, the diet of the North Sea herring varies by season and includes as major constituents copepods (*Calanus* spp*.*, *Temora* spp*.,* and *Pseudocalanus* spp.), juvenile sandeels (*Ammodytes* spp.), with fish eggs, amphipods, *Sagitta* spp., and *Oikopleura* spp. (Bainbridge & Forsyth, 1972; Daan et al., 1985; Hardy, 1924; Last, 1989; Segers et al., 2007). Spatial differences in the prey exist (Savage, 1937). The coincident herring distribution with that of zooplankton during summer feeding is secure by the interactions of predator and prey (Maravelias & Reid, 1997).

SPECIES INTERACTION: Herring is highly impacting most other fish stocks in the North Sea as both, prey and predator and thus is a key pelagic species in this area (Dickey-Collas et al., 2010). The M (natural mortality) estimates are variable along the time period covered by the assessment and are the result of predator–prey overlap and diet composition. The estimates come from a stochastic multi-species (SMS) model for the North Sea (ICES WGSAM).

ADULT MOBILITY: This herring stock is at its southern boundary and is also limited by depth in the north and east, salinity in the most eastern part towards the Baltic Sea as well as the shoreline. The adult stock has also specific requirements for spawning, as it is a demersal spawner requiring gravel or other type of hard substrates for spawning. The North Sea is heavily influenced by human activities, and the number of wind farms and oil rigs is high and increasing, and the ship traffic is also intense. It is not well understood how this might influence the mobility of herring, but it might restrict migration and spawning behaviour. However, fishing pressure might be reduced in areas with oil rigs and wind farms. The stock annex (ICES, 2017) and references therein provides further information.

DISPERSAL OF EARLY LIFE STAGES: The benthic eggs take about three weeks to hatch dependent on the temperature. In other regions there is evidence of large interannual variability in egg mortality (Richardson et al., 2011). The larvae at hatching are 6 to 9 mm long and rise, due to buoyancy changes, in the water column to become planktonic (Dickey-Collas et al., 2009). Their yolk sac lasts for a few days during which time they will begin to feed on phytoplankton and small zooplankton. Their planktonic larval duration lasts around three to four months during which time they are passively subjected to the residual drift which takes them to various coastal nursery areas on both sides of the North Sea and into the Skagerrak and Kattegat (Heath et al., 1997). The environmental impact during this phase is crucial to life cycle closure and probably controls the spawning season of the components (Hufnagl & Peck, 2011).

EARLY LIFE HISTORY SURVIVAL AND SETTLEMENT REQUIREMENTS: Herring spawning and nursery areas close to the coasts are particularly sensitive and vulnerable to anthropogenic influences (Röckmann et al., 2011). The general reduction in larval survival is generally attributed to associated changes in the physical and biological environment (ICES, 2006; Payne et al., 2009). Survival rate variation co-occurs with an increase in the mortality rate of the very early larval stages (Fässler et al., 2011). However, the reasons for this are unknown but mortality trends and residuals of the stock-recruit relationship, the stock biomass and temperature appear to be correlated. The reduced survival is also correlated with a reduction in larval growth rate (Payne et al., 2013). The authors attributed this result to changes in either the amount or quality of available food.

COMPLEXITY IN REPRODUCTIVE STRATEGY: Spawning typically occurs on coarse gravel (0.5-5 cm) to stony (8-15 cm) substrates and often on the crest of a ridge rather than in hollow groves. There are four spawning areas, with differing spawning times. The most northern spawning (Shetland-Orkney) happens in September-October, the central (Banks and Buchan) in October-November, and the most southern (Downs) in December-January. The prolonged spawning period may ensure resilience against changes in drift, food availability and predation of herring larvae. If temperature changes make one of them unsuitable, the stocks resilience may become reduced against variability. The stock annex (ICES, 2017) and references therein provides further information.

SPAWNING CYCLE: Herring spawning and nursery areas are particularly vulnerable to anthropogenic activities (see above) (Röckmann et al., 2011). However, the individual local spawning aggregations are typically grouped into four "spawning components" that exhibit different growth rates, meristic characteristics and recruitment patterns (Bjerkan, 1917; Cushing & Bridger, 1966) and spawn at four main locations. The productivity of these spawning components varies as the three northern components show similar population trends and differ from the most southern (Downs) component (Payne, 2010). This difference appears to be influenced by different environmental drivers (Fässler et al., 2011). Outside their spawning season, the different components mix and are exploited together. However, the components could be expected to have a unique population dynamics as each component remains probably a high degree of population integrity (Iles & Sinclair, 1982). The different spawning aggregations of this stock are genetically homogeneous (Mariani et al., 2005; Reiss et al., 2009).

SENSITIVITY TO TEMPERATURE: The criterion for "low" is a "large temperature range". The species occurs in a wide range of temperatures (>15 °C) or is found across 3 or more provinces". This herring stock is distributed over a large area, from the northern part of the North Sea to the English Channel, and from UK in the west to the Baltic Sea in the east. This area covers more than 3 provinces.

SENSITIVITY TO OCEAN ACIDIFICATION: As for Norwegian-spring spawning herring also addressed in this climate impact assessment analysis, this is a much-debated topic where both experimental designs and up-scaled model projections diverge. However, there is no reason to doubt that ocean acidification (OA) will reduce the herring stock productivity if the "business-as-usual" scenario continues, with particular reference to increased early-life stages (ELS) mortality. However, recent studies have shown that indirect effects of OA might be positive for survival of herring larvae (Sswat et al., 2018), and there is a need to include food web effects of OA before projections of the effect of OA can be done.

POPULATION GROWTH RATE: The fecundity is length related and varies between approximately 10,000 and 60,000 eggs per female (van Damme et al., 2009). This is a relatively low fecundity for a teleost. The age of first maturity is three years old (2-ringers), but the proportion mature-at-age may vary from year to year, dependent on growth. Over the past 15 years the proportion of mature at age three years (2-ringers) has ranged from 47% to 86% and for four-year-old fish (3-winter ringers) from 63% to 100%. Above that age, all individuals are considered to be mature. M is estimated by the SMS model to be around 0.8 for 0-wr (winter rings), 0.6 for 1-wr, 0.35 for 2-wr, 0.28 for 3-wr and steadily decreasing with age to around 0.2 for 8-wr. Over the past century, herring abundance and distribution has been mostly influenced by human in the North Sea. In the late 1940s, estimation of the spawning stock biomass (SSB) which was of around 4.5 million tonnes declined to less than 100,000 tonnes in the late 1970s (Mackinson, 2002; Mackinson & Daskalov, 2007; Simmonds, 2009). In spite of recruitment levels being adversely affected, robustness in relation to recovery from such low levels has been observed in the species, once fishing mortality is limited (Nash et al., 2009; Payne et al., 2009). From 1940 to 1980, North Sea herring fish size has been increasing, possibly due to a decrease of competition for food while the stock collapsed (Burd, 1984; Saville et al., 1984). Large year-classes may have a slower body growth rate than average ones resulting from intra-cohort competition (ICES, 2008). In addition, body growth is affected by environmental factors such as plankton production (Shin & Rochet, 1998) and temperature (Brunel & Dickey-Collas, 2010). Finally, maturation seems to be closely related to body growth.

STOCK SIZE/STATUS: The criterion for low is biomass/ biomass maximum sustainable yield (B_{MSY}) ≥ 1.2 (or proxy). The current B_{MSY} estimate is 1.4 million tonnes, and the spawning stock biomass (SSB) estimate for the autumn 2018 is 1.87 million tonnes (ICES, 2019b). This gives a B/B_{MSY} = 1.34, which is larger than 1.2. The spawning stock status is good, despite low recruitment since around 2000. This has been achieved by regulating the fishing pressure by considering the recent low recruitment.

OTHER STRESSORS: Sand and gravel extraction, as well as wind farms, especially construction, might negatively influence the spawning sites of this demersal spawner. Increasing temperatures might shift the southern limit of this stock and also the size of its distribution area, as well as the zooplankton community in the North Sea, i.e. the food of herring, as already experienced in the regime shift in the late 1980s and again around 2000 (Beaugrand, 2004; ICES, 2019a). In addition, the fishery is another important stressor, as well as predation. So, altogether: sand and gravel extraction / wind farms → spawning sites; temperature → zooplankton (food); fishing.

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 herring (*Clupea harengus*) in ICES subarea 4, divisions 3.a and 7.d. 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 herring (*Clupea harengus*) in ICES subarea 4, divisions 3.a and 7.d

SENSITIVITY ATTRIBUTES	L	M	H	VH	$Mean_w$	Usage	Remark
Habitat Specificity	0	1	4	0	**2.8**		
Prey Specificity	0	4	1	0	**2.2**		
Species Interaction	0	3	2	0	**2.4**		
Adult Mobility	0	1	4	0	**2.8**		
Dispersal of Early Life Stages	5	0	0	0	**1.0**		
ELH Survival and Settlement Requirements	0	1	4	0	**2.8**		
Complexity in Reproductive Strategy	0	2	3	0	**2.6**		
Spawning Cycle	0	4	1	0	**2.2**		
Sensitivity to Temperature	4	1	0	0	**1.2**		
Sensitivity to Ocean Acidification	5	0	0	0	**1.0**		
Population Growth Rate	0	4	1	0	**2.2**		
Stock Size/Status	5	0	0	0	**1.0**		
Other Stressors	0	5	0	0	**2.0**		
Grand mean					**2.02**		
Grand mean SD					**0.72**		

CLIMATE EXPOSURE	L	M	H	VH	$Mean_w$	Usage	*Directional Effect*
Surface Temperature	0	0	0	0		NA	
Temperature 100 m	0	4	1	0	**2.2**		1
Temperature 500 m	0	0	0	0		NA	
Bottom Temperature	0	0	0	0		NA	
O_2 (Surface)	5	0	0	0	**1.0**		-1
pH (Surface)	0	0	0	0		NA	
Gross Primary Production	3	2	0	0	**1.4**		1
Gross Secondary Production	2	3	0	0	**1.6**		1
Sea Ice Abundance	0	0	0	0		NA	
Grand mean					**1.55**		
Grand mean SD					**0.50**		
Accumulated Directional Effect					**–**		**4.2**

***Accumulated Directional Effect*: POSITIVE**	**4.2**

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