Calanus finmarchicus

Stock name: *Calanus finmarchicus*
Latin name: *Calanus finmarchicus*
Geographical area: Norwegian Sea and Barents Sea (ICES subarea 2)
Expert: Cecilie Broms, Geir Huse
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Stock Sensitivity Attributes

HABITAT SPECIFICITY: The core distribution areas of the copepod *Calanus finmarchicus* (Calanidae) are the North Atlantic basins of the Labrador Sea and the Norwegian Sea and adjacent areas (Aksnes & Blindheim, 1996; Marshall & Orr, 1955; Melle et al., 2014). *C. finmarchicus* is the dominant species of the mesozooplankton in the Norwegian Sea (Melle et al., 2004). *Calanus* is vital to many of the planktivorous fish species including Norwegian spring spawning (NSS) herring (*Clupea harengus*), blue whiting (*Micromesistius poutassou*), and Atlantic mackerel (*Scomber scombrus*, Scombridae), which enter the Norwegian Sea during summer to utilize the abundant zooplankton resources (Bachiller et al., 2018; Langøy et al., 2012). In addition to these migrating predators, there are large standing stocks of invertebrates and mesopelagic fish that feed on different stages of *C. finmarchicus* (Dalpadado et al., 1998). Its life cycle consists of overwintering at depth mainly as copepodite stages 4 (C4) or 5 (C5), ascent towards the surface during early spring, maturation, and subsequent commencement of egg production prior to and during the spring phytoplankton bloom (Marshall & Orr, 1955; Melle et al., 2014). The new generation stays in the upper waters and grows to stage C5. At this point, individuals may continue to mature and produce a new generation, or build up fat reserves and descend for overwintering (Hirche, 1996a). The present range of ambient temperatures for *C. finmarchicus* in the Norwegian and Barents Seas is well within the tolerable ranges for the species (Strand et al., 2020). Under future climate change it has a wide potential to expand its habitat farther north and west in the Nordic Seas, eastward and at the same time maintain its present southwesterly distribution in the Barents Sea. However, the southernmost spawning areas in the North Sea is expected to become greatly reduced (Beaugrand & Reid, 2003; Fromentin & Planque, 1996; Heath et al., 1999; Planque & Fromentin, 1996). By 2081-2100, average *C. finmarchicus* density projections show a decrease by as much as 50% under a high greenhouse gas emissions scenario (Grieve et al., 2017). These decreases are particularly pronounced in the spring and summer in the Gulf of Maine and Georges Bank (Grieve et al., 2017).

PREY SPECIFICITY: The species feeds on both microzooplankton such as ciliates, and phytoplankton such as diatoms and flagellates, and constitutes an important link between the phytoplankton and the higher trophic levels in the food chain (Aksnes & Blindheim, 1996; Irigoien et al., 1998; Melle et al., 2004; Nejstgaard et al., 1997).

SPECIES INTERACTION: The stock is probably experiencing feeding competition as several other herbivorous zooplankton species are found in the same area (Melle et al., 2004). It is also hypothesized that zooplankton in the Norwegian Sea can graze down the phytoplankton, resulting in a low chlorophyll maximum, but a prolonged phytoplankton production season. However, many of the other zooplankton species utilize other depths in the water column which may reduce special overlap and competition for the same food. *C. finmarchicus* is an important prey for the pelagic fish stock in the Norwegian Sea, for fish larvae of several fish species, and for carnivorous zooplankton (Huse et al., 2012; H. Skjoldal et al., 2004; H. R. Skjoldal et al., 2004). Herring, mackerel and blue whiting together have been estimated to consume 53-83 million tonnes of copepods annually (Bachiller et al., 2018).

ADULT MOBILITY: *C. finmarchicus* is planktonic and is unable to uphold its horizontal position. Its life cycle includes overwintering at 500-1,500 m depth affecting the horizontal movement of the stock (Bryant et al., 1998; Hirche, 1996a). Large part of the population is transported out of the Nordic Seas and into adjacent areas like the Barents Sea (Aksnes & Blindheim, 1996). The horizontal location within the Nordic Seas is important regarding the retention of individuals (Søiland & Huse, 2012; Torgersen & Huse, 2005).

DISPERSAL OF EARLY LIFE STAGES: *C. finmarchicus* is spawning throughout its distributional area and is not restricted to specific spawning areas (Melle et al., 2014). However, it has a rather low fecundity with short larval spans. Average number of eggs spawned per female per day is ca. 20-60 depending on different areas in the North Atlantic (Melle et al., 2014). In the Norwegian Sea individual egg production rate is ca. 20 eggs during the spring bloom period (Stenevik et al., 2007). *C. finmarchicus* is batch spawner, and the spawning may continue for weeks or until the adults are eaten. Duration of larval stages depends on temperature, and development-time from egg to C5 (near adult) at 8 °C is 32 days (Campbell et al., 2001). It is therefore considered to have a moderate dispersal ability.

EARLY LIFE HISTORY SURVIVAL AND SETTLEMENT REQUIREMENTS: The production of *C. finmarchicus* is about 5-7 times higher than the standing stock (H. Skjoldal et al., 2004). The annual variation in this is not clear, but there has been substantial variation in the abundance of *C. finmarchicus* in the core area in the Norwegian Sea. There was previously a link between the abundance of *C. finmarchicus* and climate through the North Atlantic Oscillation (NAO), but this has broken down in recent years. In waters with low temperature towards the limit of distributional area, there is probably a mismatch between the larvae (nauplii and early copepodite stages) development and food availability (Broms et al., 2009; Melle & Skjoldal, 1998). The recruitment mechanisms of *C. finmarchicus* is poorly understood.

COMPLEXITY IN REPRODUCTIVE STRATEGY: *C. finmarchicus* has a complex life cycle like most crustaceans with an egg stage, six nauplii stages and six copepodite stages. The duration of a generation cycle is highly temperature and food dependent and varies from about 20-60 days (egg to C5) (Campbell et al., 2001). So, while the species can cope under rather broad environmental conditions, the productivity is likely to vary considerably dependent on the conditions. *C. finmarchicus* is a batch-spawner, which may be an advantage in a changing environment and to secure that some of the offspring are released at suitable environmental conditions. An average female may produce ca. 20 eggs per day and ca. 600 eggs during the spring bloom, and the prolonged spawning may be an adaptation to the shifting conditions at high latitudes and may “stabilize” the population size (Hirche, 1996a, 1996b).

SPAWNING CYCLE: After the diapause in deep waters, *C. finmarchicus* ascend towards the surface mainly as stage C5 and develop into the adult stage before spawning. The spawning is temporally linked to the seasonal development of the phytoplankton, and in the Norwegian Sea the population spawning rate is high both in the pre-bloom and the spring bloom due to high abundance of females and high individual spawning rates, respectively (Broms & Melle, 2007; Stenevik et al., 2007). Owing to differences in the timing of the pre-bloom and spring bloom between areas in the Norwegian Sea, the spawning of *C. finmarchicus* varies between areas. Gonad maturation and egg production of *C. finmarchicus* may be fuelled by diverse energy sources: internal fat reserves, feeding on heterotrophic microplankton and grazing on algae (Irigoien et al., 1998; Niehoff et al., 1999; Ohman & Runge, 1994; Plourde & Runge, 1993). To be able to spawn based on internal fat reserve may largely detach the egg production from changes in food supply due to climate change, however a positive correlation between number of eggs produced and chlorophyll concentrations in surrounding waters have been shown (Head et al., 2013). Temperature may not affect the number off eggs spawned, except at very low temperatures at the distributional limits of the stock (Head et al., 2013). The stock spawns at more than one season, but the second spawning is carried out by a new generation.

SENSITIVITY TO TEMPERATURE: *C. finmarchicus* in the Norwegian Sea is found at least in the temperature range <0-14 °C. At temperatures below 0 °C the concentration of *C. finmarchicus* is rapidly reduced. At the upper part of this temperature range, the concentration of the stock is also reduced. Highest abundance in the area of interest is between 5 and 9 °C (Strand et al., 2020).

SENSITIVITY TO OCEAN ACIDIFICATION: There have been several experimental studies on the effects of ocean acidification (OA) on *C. finmarchicus*. There appears to be low or no effects of OA on the growth and development of copepodites of *C. finmarchicus*, but the hatching success is reduced at OA levels expected as the worst-case scenario for year 2300. At higher levels *C. finmarchicus* can be affected, among others by reduced survival (Mayor et al., 2007, 2012; Pedersen et al., 2013; Wu et al., 2014). It has been pointed out that longer-term experiments at more moderate CO_2 levels are necessary before the possibility that growth and development may be affected below 2000 ppm CO_2 (the highest CO_2 level expected by the year 2300) can be ruled out (Pedersen et al., 2013). Acidification in the depth of overwintering *C. finmarchicus* may affect the population in the future.

POPULATION GROWTH RATE: The growth of *C. finmarchicus* varies depending on temperature and the amount and quality of food (Campbell et al., 2001). This is clearly documented in experimental studies. Field studies have shown that there is a climate driven reorganization of the plankton community in the greater North Sea area whereby *C. finmarchicus* dominates in cold periods and *Calanus helgolandicus* (Calanidae) dominates in warmer periods (Beaugrand et al., 2002). The present productivity of *C. finmarchicus* is rather low in the southern part of the distribution area of the North Sea and the southern part of the Norwegian Sea. In a future warmer Norwegian Sea this trend can be expected to be strengthened. *C. finmarchicus* has a one-year life cycle and can also have more than one generation per year, thus age at maturity is also one year or less (Broms et al., 2009; Melle et al., 2004; Strand et al., 2020). Maximum length is 3 mm. The annual production of *C. finmarchicus* is about 5-7 times higher than the standing stock (Hjøllo et al., 2012; H. Skjoldal et al., 2004). The species is considered towards r-selected but have not a very high egg production.

STOCK SIZE/STATUS: *C. finmarchicus* has been harvested in trial fisheries since 2003, with a maximum quota at 5,000 tonnes per year that can be harvested in coastal water (Fiskeridirektoratet, 2016). In addition, a commercial fishery has recently opened, and the total quota in 2021 is 254,000 tonnes (Nærings- og Fiskeridepartementet, 2019). Of the commercial quota, 3,000 tonnes can be harvested between the Norwegian coastline and 1,000 m depth isobaths. A management plan has been developed and the established quotas have been estimated not affecting the *C. finmarchicus* population (Broms et al., 2016; Fiskeridirektoratet, 2016). At maximum, 1,300 tonnes have been harvested per year so far.

OTHER STRESSORS: *C. finmarchicus* is negatively affected by climate change in the southern part of the distribution area as documented previously for the North Sea (Beaugrand et al., 2002; Planque & Fromentin, 1996; Sundby, 2000). The abundance in the southeastern part of the Norwegian Sea has declined since the year 2000, however the timeseries has not been analysed after 2012. The reason for this is not understood (Dupont et al., 2017). A reduction in abundance in the southwestern part of the Norwegian Sea has been reported and linked to less Arctic water inflow from the west (Kristiansen et al., 2016, 2019). The total zooplankton biomass in the Norwegian Sea, which mainly consists of *C. finmarchicus*, has been stable the last 10 years and increased in certain sub-areas (ICES, 2020).

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 *Calanus finmarchicus* stock in ICES subarea 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.

Calanus finmarchicus in ICES subarea 2

SENSITIVITY ATTRIBUTES	L	M	H	VH	Mean_w	Usage	Remark
Habitat Specificity	4	1	0	0	**1.2**		
Prey Specificity	3	2	0	0	**1.4**		
Species Interaction	0	2	3	0	**2.6**		
Adult Mobility	5	0	0	0	**1.0**		
Dispersal of Early Life Stages	3	2	0	0	**1.4**		
ELH Survival and Settlement Requirements	0	5	0	0	**2.0**		
Complexity in Reproductive Strategy	0	5	0	0	**2.0**		
Spawning Cycle	0	2	3	0	**2.6**		
Sensitivity to Temperature	0	5	0	0	**2.0**		
Sensitivity to Ocean Acidification	2	0	3	0	**2.2**		
Population Growth Rate	3	2	0	0	**1.4**		
Stock Size/Status	5	0	0	0	**1.0**		
Other Stressors	2	3	0	0	**1.6**		
Grand mean					**1.72**		
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	1	4	0	0	**1.8**		1
Temperature 500 m	0	0	0	0		N/A	
Bottom Temperature	0	0	0	0		N/A	
O_2 (Surface)	5	0	0	0	**1**		0
pH (Surface)	1	3	1	0	**2**		-1
Gross Primary Production	0	3	2	0	**2.4**		1
Gross Secondary Production	4	1	0	0	**1.2**		0
Sea Ice Abundance	4	0	1	0	**1.4**		1
Grand mean					**1.63**		
Grand mean SD					**0.53**		
Accumulated Directional Effect					**–**		**3.6**

***Accumulated Directional Effect*: POSITIVE**	**3.6**

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