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Fisheries

Distinct stocks of Atlantic cod face different climate change challenges

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Reproductive success of the population is vulnerable to warming oceans

The authors investigated the life history, focusing on reproductive ecology, of three spatially distant populations of Atlantic cod in the Irish/Celtic Seas-English Channel Complex, North and Barents Seas, under past and projected climate. Results show that North Atlantic cod stocks are stressed by different factors of varying management severity under climate change.

The reproductive success of marine ectotherms (organisms that rely on environmental heat sources, not their internal physiological sources of heat, to control body temperature) is especially vulnerable in warming oceans due to alterations in adult physiology, as well as embryonic and larval survival prospects. These vital responses may, however, differ considerably across the species' geographical distribution.

This article – summarized from the **original publication** (https://doi.org/10.1111/faf.12728) (Kjesbu, O.S. 2023. Latitudinally distinct stocks of Atlantic cod face fundamentally different biophysical challenges under on-going climate change. *Fish and Fisheries* Vol. 24, March 2023) – reports on a study that investigated the life history, focusing on reproductive ecology, of three spatially distant populations (stocks) of Atlantic cod (*Gadus morhua*) in the Irish/Celtic Seas-English Channel Complex, North and Barents Seas, under past and projected climate).

The study objectives were to 1. Precisely and accurately define temperatures at which reproductive failure takes place in Atlantic cod and explore the underlying physiological modes of action, with particular reference to reproductive investment (oocyte growth) and egg release coinciding with natural "warm waves" (i.e., seeing relatively extreme environmental temperatures over a limited period of time) as detected in experimental facilities; 2. Identify cod stocks likely to be subject to such detrimental thermal impacts; and 3. Determine other specific factors that may limit cod future reproductive success in this marine realm, placing special emphasis on fine-scale changes in zooplankton biography but also any heightened migration costs.

To synthetize a greater understanding of the reproductive ecology of Atlantic cod in view of climate change, multiple streams of data and models were utilized. For detailed information on the methods and data used, consult the original publication.

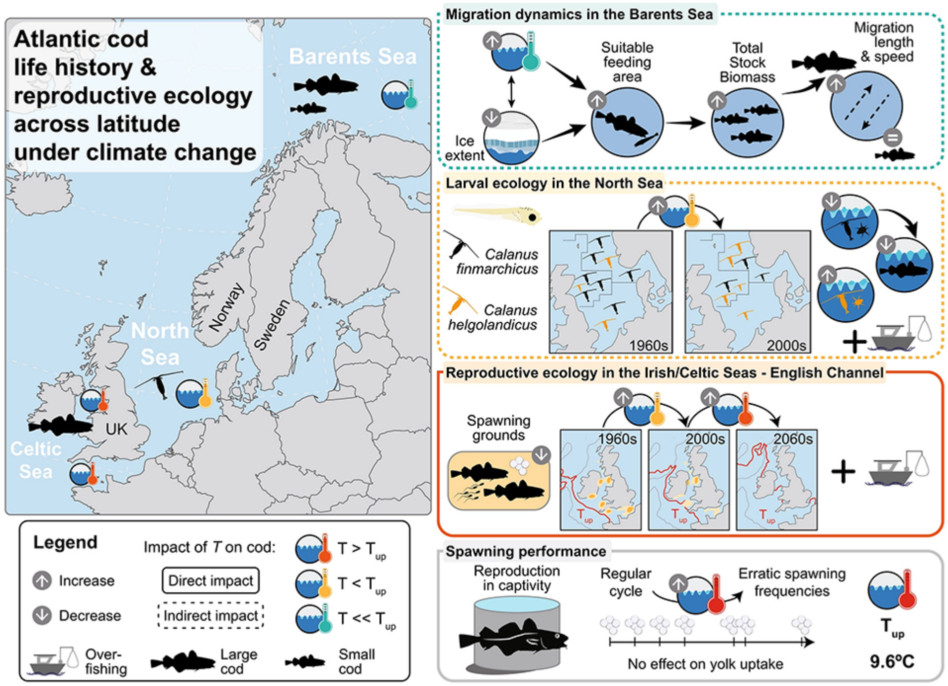

Fig. 1: Overview of study region including ocean basins, the four research topics addressed, and the main findings in this investigation on life-history and reproductive challenges encountered by Northeast Atlantic cod stocks under ongoing climate change. Adapted from the original.

Study results and discussion

We believe that the approach and methodology used in this study on Atlantic cod might serve as a template for future studies exploring thermal limitations of teleost reproduction. Our results show that experimental tracking of spawning behavior evidenced that the cod ovulation cycle is highly distressed at ≥9.6 (±0.25) degrees-C. Cod in the Celtic Sea-English Channel are, therefore, expected to show critical stock dispensation [effect on a population whereby, due to certain causes, a decrease in the breeding population leads to reduced production and survival of eggs or offspring] over the next decades as spawning grounds warm above a certain temperature, with Irish Sea cod subsequently at risk.

Also, in the relatively cooler North Sea, the northward retraction of important food items like various copepod species limits cod larvae feeding opportunities, particularly in the southernmost subarea. However, the contrasting increase in some copepods does not counteract this negative effect, likely because cod larvae hatch ahead of their abundance peaks. And that in the still relatively cold Barents Sea, the sustainably harvested cod benefit from improved food conditions in the recent ice-free polar region but at the energetic cost of lengthier and faster spawning migrations. Consequently, under climate change local stocks are stressed by different mechanistic factors of varying management severity.

Our investigation on the life history and reproductive ecology of the cold-temperate *G. morhua* reveals that local persistence under climate change is constrained by (1) uncertain ovulation requirements; (2) altered larval prey biogeography, and (3) energetically costlier spawning migrations, illustrated by the Irish/Celtic Seas-English Channel Complex, North Sea and Barents Sea scenario, respectively. Hence, each of these three addressed causal mechanisms is highly habitat specific.

Obviously, a series of other stressors are involved too, such as harvest rate and lower trophic level productivity due to strengthened sea stratification (at least in the southern domain covered in the study), but the performance of the currently addressed traits are fundamental for continued stock persistence. Our research complements related studies that either address the consequences of one single stressor or on the other end of the scale, undertake expert scorings of multiple stressors for both data-poor and data-rich stocks.

To circumvent the overriding investigative problem attributed to 'extremely scarce' reproductive data for teleosts (bony fishes members of a large and extremely diverse group of ray-finned fishes) in general, and especially in view of ocean warming, we addressed relevant, basic reproductive physiology aspects of Atlantic cod as an example, given that this is a relatively well-studied species. The resulting experimentally observed, spawning frequency (Sf) data clearly did not fit into the conventional thermal performance curve. The key deviation was the presence of both high and low Sf for a given individual past a rather moderate temperature corresponding to 9.6 (±0.25) degrees-C. Also very important, and validated by field observations, is that the existence of a knife-edge threshold during spawning is strongly supported by data storage tag information.

We contend – irrespective of the future development of the zooplankton (cod larval prey) community in the Irish/Celtic Seas-English Channel Complex) – that the projected increase in temperature in this area will seriously disturb local cod egg release. However, any healthy cod eggs transported into these waters might possibly survive at even higher temperatures.

Altogether, our work highlights the high importance of long time series, documenting as a clear example that the abundance of *Calanus finmarchicus* (a species of copepods found in enormous amounts in the northern Atlantic Ocean, and a key component in the food web of the North Atlantic, providing sustenance for a variety of marine organisms including fish, shrimp, and whales) and other species in the North Sea are today in a dire state. However, more worrying is the reduced recruitment of North Sea cod since the late 1990s, although there are indications of a recent but weak improvement in spawning stock biomass. In any case, infrequent incidences of highly successful recruitment play a paramount role for any subsequent rebuilding of stock size.

Photoperiod regulation inhibits spawning, promotes growth in Atlantic cod

Research has shown that an extended photoperiod for Atlantic cod females leads to reduced gonadal growth, faster body growth and shorter grow-out production periods.

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The switch in latitudinal position of large and small cod between summer and winter is explained by the fact that large cod migrate out of the Barents Sea in late winter to spawn on the coast. The environmental temperature was an inadequate reflection of ambient temperature, so the indirect effect of ocean warming on fish displacement distance (DD) and speed (UD) was not only totally dominating but also functioned as a cascading effect, seen by a reduced ice extent, an enlarged suitable feeding area (SFA), a larger total stock biomass (TSB) and then a pronounced increase in both DD and UD. However, in line with the general concept of lower migration costs per unit body mass when body size increases, a statistically significant relationship between either DD or UD and TSB only applied for large cod. Because of this major contribution of TSB to DD and UD, an increase in TSB from, for instance, 1.5–4.5 million tons, will increase DD and UD by a factor of 1.64 and 1.72, respectively.

These accelerated migration costs might negatively affect reproductive investment, such as fecundity. This consideration is also related to the fact that spawning migratory cod do not feed to any significant extent. Another factor to consider is that the proximate player in question is total stock biomass, TSB, a density-dependent factor, which is intimately linked to the adopted stock management regime, on top of the warmer climate. Conversely, examples of extremely long Barents Sea cod migration southwards in historic cold periods may well relate to other causal mechanisms, such as better recruitment in relatively warmer waters translating to a gradual strengthening of the southernmost spawning grounds along the Norwegian coast.

However, the location of the ice edge and thereby of the polar-front-associated Barents Sea capelin (*Mallotus villosus*) – a key cod food item – is certainly an issue. All aspects considered, our results of this high-latitude example illustrate that any further increased migration distance and speed to coastal spawning grounds may turn energetically supercritical under the current extreme northward displacement of feeding areas.

Perspectives

Results of this study show that understanding and predicting (or projecting) population (stock) persistence under anthropogenic climate change should be based on revealing the key, local regulatory mechanisms. This viewpoint is further underlined in this article by concentrating on the life-history trait-based 'weak link' (critical sensitivity attribute) – using Atlantic cod as a template species – within each of the three Northeast Atlantic regions (50–80° N) currently addressed.

Such an approach might, however, be criticized in cases where a series of sensitivity attributes in combination turn critical rather than each singularly, a common argument in climate impact assessments using expert scorings. Thus, our work should be considered as an alternative, where the strength lies in thorough, quantitative investigations of key traits and their drivers resulting in findings of clear importance for future cod stock productivity.

These novel results were made possible by running dedicated experiments, consulting extensive databases and accessing and building upon a wealth of knowledge gathered by generations of researchers within different branches of marine science.

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