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Genetic management of mixed-stock fisheries “real-time”: The case of the largest remaining cod fishery operating in the Atlantic in 2007–2017

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ABSTRACT

Fish stocks represent fundamental units in fisheries management, and their identification, especially in mixed-fisheries, represents one of the primary challenges to sustainable harvest. Here, we describe the first “real-time” genetic management program used to manage a mixed-stock fishery of a non-salmonid and commercially significant marine fish, the Atlantic cod (*Gadus morhua* L). Based upon the analysis of > 18 000 fish sampled from the commercial catch in Lofoten (Norway), which represents the largest remaining cod fishery in the Atlantic, we estimated the fraction of North East Arctic cod (NEAC), and Norwegian Coastal cod (NCC), just 24 h post-landing. These estimates, based upon the analysis of the *Pantophysin* gene, were performed weekly in the winter and spring of each year in the period 2007–2017. The program has successfully permitted the Norwegian Directorate of Fisheries to actively manage the commercial exploitation of the highly abundant NEAC stock, while simultaneously limiting exploitation of the fragile NCC stock, both of which overlap at the spawning grounds. Data from this program have also revealed a distinct temporal increase in the fraction of NEAC on the spawning grounds in this region, which is consistent with the overall increased abundance of this stock as estimated by ICES.

1. Introduction

Harvest from the world’s oceans has remained stable between 80–90 million tonnes/annum since the mid-1980s, and many of the world’s fisheries are either fully or over-exploited, depleted, or recovering from depletion (FAO, 2016). In addition, illegal, unreported and unregulated (IUU) fishing represents a major challenge to the sustainable harvest of marine resources (Agnew et al., 2009). Increasing the sustainability of harvest from the marine realm is vitally important given the current state of many fisheries, and the continued increase in the human population and its expanding requirements for food.

DNA methods provide unprecedented knowledge of population genetic structure for many of the exploited marine resources, including fish. In many cases, independent stocks and management units within fisheries have been identified using this approach (Hauser and Carvalho, 2008; Reiss et al., 2009). There are also examples of genetic methods being implemented in the active regulation of fisheries (Nielsen et al., 2001; Ogden, 2008; Glover, 2010; Glover et al., 2012; Flannery et al., 2010). Nevertheless, widespread integration of genetic data into fishery policy has been slow, and explicit and quantitative inclusion of genetic data into fisheries models is still relatively rare (Waples et al., 2008; Reiss et al., 2009).

One of the challenges to sustainable fisheries management is when two or more stocks, that are morphologically very similar or identical and thus impossible to differentiate in the fishery, overlap in time and space. In such cases, harvesting potentially leads to under- and over-exploitation of the separate components of the fishery (Allendorf et al., 2008). Mixed stock fisheries may occur where separate populations partially or completely overlap in their spawning areas. This is for example the case for the Northeast Atlantic cod (*Gadus morhua*) (NEAC) and Norwegian coastal cod (NCC) which have and continue to form the basis of major fisheries along the coast of Norway, and especially the Lofoten Islands (Fig. 1). Mixed stock-fisheries may also occur when multiple populations overlap on the feeding grounds. For example, Atlantic salmon (*Salmo salar* L.) originating from multiple distinct populations on both the west and east Atlantic meet on the high seas and

Abbreviations: IUU, illegal, unreported and unregulated; ICES, International Council for Exploration of the Sea; NEAC, North East Arctic cod; NCC, Norwegian coastal cod; IMR, Institute of Marine Research; NDF, Norwegian Directorate of Fisheries

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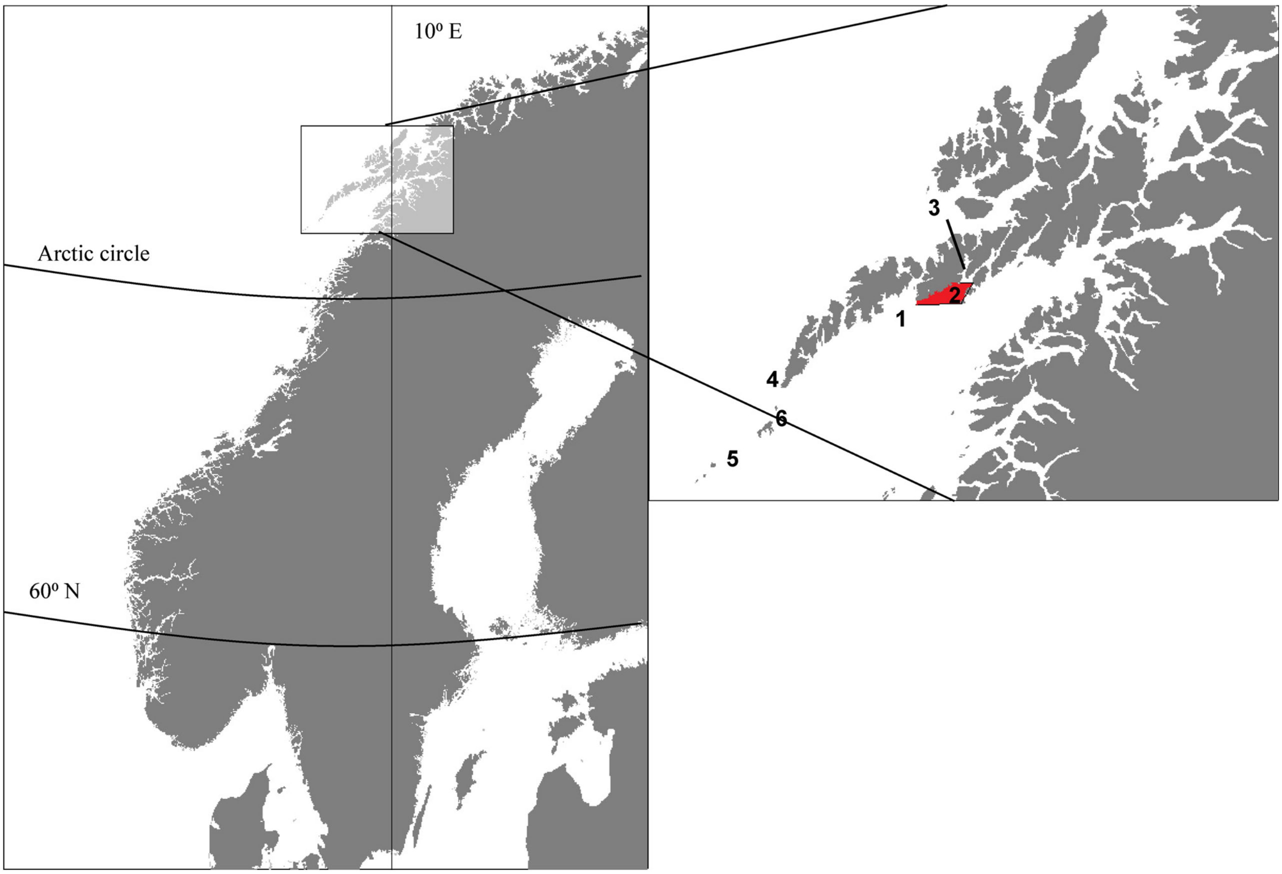

Fig. 1. Sampling areas in Lofoten. 1 – Henningsværstraumen, 2 – Henningsværboksen, 3 – Austnesfjorden, 4 – Bleiksegga, 5 – Røst, 6 – Værøy.

have been historically exploited in the fishery operated around the Faroe Islands (Gilbey et al., 2017). A similar situation exists for the many salmonid fisheries in the Northeast Pacific. Here, in contrast to the Atlantic salmon fishery around the Faroe Islands which has been suspended (ICES, 2016), oceanic salmon fishing is permitted despite capturing fish from multiple genetically distinct stocks. However, the fisheries are actively regulated with genetic methods to ensure that a sufficient number of adult salmon return to each river to ensure the river's spawning target is achieved (Seeb et al., 2004; Flannery et al., 2010). Similar approaches could be used to monitor other marine fisheries where possible.

Historically, the Atlantic cod has formed the basis of many economically significant fisheries operating on both sides of the Atlantic. However, over-exploitation in many regions has left highly depleted stocks and multiple fishery collapses. The best documented example of this being the total collapse of the cod stock in the Grand Banks fishery located off east Canada (Hutchings and Myers, 1994). In Norway, the numbers of NCC have also severely declined (ICES, 2003, 2014), however, the NEAC stock has remained relatively stable. NEAC undertakes long-distance migrations to the feeding grounds in the Barents Sea but spawn in coastal regions of Norway, primarily in the Lofoten and Møre area (Fig. 1, Bergstad et al., 1987; Sundby and Nakken, 2008). In contrast to NEAC, NCC displays a limited migratory behaviour, remaining in coastal areas throughout its life (Jakobsen, 1987; Svåsand, 1990; Michalsen et al., 2014). However, just like NEAC, NCC spawns in coastal regions of Norway, including the Lofoten area (Hylen, 1964; Berg and Albert, 2003). Therefore, these different stock components with different abundances may be observed on the same spawning grounds at the same time (e.g., Johansen et al., 2017). In turn, this creates a significant challenge for the sustainable exploitation of NEAC, while protecting NCC in that area.

NCC has been recognised as different from NEAC for more than 80 years (Rollefsen, 1933), and since 2001, ICES has provided management advice for coastal cod in the area north of 62°N. In the annual quota agreements between Norway and Russia since 2005, however, an expected catch of NCC has been added annually to the Norwegian NEAC quota. From the mid-1970s, until 2003, an expected annual catch of 40 000 t NCC was added to the 5–10 times bigger quota for NEAC. The total quota was thereafter driven primarily by the status of the NEAC stock, leading to an inherent risk of over-exploiting NCC. Due to the decline of NCC, ICES advised a zero catch of NCC for the years 2004–2011, and at the same time recommended establishing a recovery plan (ICES, 2003, 2014). However, stopping all commercial exploitation of NCC would require a closure of all coastal fisheries in Norway where NCC also formed part of the catch. As this was not considered feasible, the expected catch of NCC (still included in the total Norwegian cod quota) was reduced from 40 000 to 20 000 t, and technical regulations aimed at reducing NCC catches (and by-catches) were introduced. Instead of enforcing a separate quota for NCC the Norwegian authorities chose to reduce the fishing pressure on NCC by means of technical regulations. These included moving fishing effort from areas and seasons where NCC dominated the catches, to areas and seasons where NEAC dominated. One of the regulatory measures included closing all commercial fishery activities in one important NCC spawning area in Lofoten ("Henningsværboksen") during the spawning season (Fig. 1). However, this was done on the premise that if the sampling of catches along the border of the area proved that the fraction of NEAC was high, the authorities would consider a temporary reopening for fishery, under the argument that it is better to allow the fleet to fill their quota by NEAC rather than catching in NCC during other times of the year. Therefore, a sampling program was needed.

In Norway, otoliths have and continue to be used to differentiate between NEAC and NCC (Rollefsen, 1933). However, accurate otolith typing is dependent on trained personnel (Berg et al., 2005).