Received: 19 March 2020 | Revised: 28 May 2020 | Accepted: 1 June 2020
DOI: 10.1111/faf.12485

ORIGINAL ARTICLE

FISH and FISHERIES WILEY

Management of transboundary and straddling fish stocks in the Northeast Atlantic in view of climate-induced shifts in spatial distribution

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Funding information
Directorate of Fisheries (Norway): Post-Retirement Contract of Employment (P.G.); Institute of Marine Research (Norway): Post-Retirement Contract of Employment (S.S.); Norwegian Fisheries Research Sales Tax System (FFA): CLIMRATES (Climate and Vital Rates of Marine Stocks), Institute of Marine Research (Norway), Project no. 15205 (O.S.K.)

Abstract
The introduction of 200 n.m. exclusive economic zones (EEZs) in the late 1970s required increased collaboration among neighbouring coastal states to manage transboundary and straddling fish stocks. The established agreements ranged from bilateral to multilateral, including high-seas components, as appropriate. However, the 1982 United Nations Convention on the Law of the Sea does not specify how quotas of stocks crossing EEZs should be allocated, nor was it written for topical scenarios, such as climate change with poleward distribution shifts that differ across species. The productive Northeast Atlantic is a hot spot for such shifts, implying that scientific knowledge about zonal distribution is crucial in quota negotiations. This diverges from earlier, although still valid, agreements that were predominately based on political decisions or historical distribution of catches. The bilateral allocations for Barents Sea and North Sea cod remain robust after 40 years, but the management situation for widely distributed stocks, as Northeast Atlantic mackerel and Norwegian spring-spawning herring, appears challenging, with no recent overall agreements. Contrarily, quotas of Northern hake are, so far, unilaterally set by the EU despite the stock's expansion beyond EU waters into the northern North Sea. Negotiations following the introduction of EEZs were undertaken at the end of the last *cooler* Atlantic Multidecadal Oscillation (AMO) period, that is, with stock distributions generally in a *southerly* mode. Hence, today's lack of management consensus for several widely distributed fish stocks typically relates to more *northerly* distributions attributed to the global anthropogenic signal accelerating the spatial effect of the current *warmer* AMO.

KEYWORDS
climate change, negotiations, poleward shift, quota allocation, shared stocks, zonal attachment

All three authors contributed equally to this work.

1 | INTRODUCTION

Fisheries management operates at scales ranging from local to multinational schemes. This is because marine organisms display large diversity in their habitats—from stocks retained within coastal or reef areas to ocean basin-wide distributions. One of the first examples of an international effort to regulate exploitation of a living marine resource was the International Pacific Halibut Commission (IPHC) Convention, established in 1923 between Canada and the United States of America, when larger engine-powered vessels moved intensified fishing beyond the national three-nautical-mile (Thompson & Freeman, 1930). The status of the stock in international waters (or high seas) was considered of little importance to the management of the stock (IPHC, 2019); therefore, this historic bilateral agreement refers to a transboundary stock (i.e., a stock that crosses EEZ boundaries of one or more coastal states) (Munro, Van Houtte, & Willmann, 2004). However, migration over vast distances, including to high seas ("straddling"), is certainly the case for some species, such as tunas (Kampas, 2015), implying the need for multilateral agreements. A prime example is the International Commission for the Conservation of Atlantic Tunas (ICCAT), initiated during the 13th Session FAO Conference in 1965 and established the year after. ICCAT considers the entire Atlantic Ocean and consists of 48 member nations (ICCAT, 2019). Another well-known multilateral body is the Commission for the Conservation of Antarctic Marine Living Resources (CCAMLR), which was founded in 1982 by 23 member nations (CCAMLR, 2019; Constable, 2002). CCAMLR arose out of concerns among researchers about the large-scale harvest of Antarctic krill (*Euphausia superba*, Euphausiidae), given the history of overexploitation of several other resources in the Southern Ocean (Constable, 2002).

The establishments of exclusive 200 n.m. economic zones (EEZs), in parallel to the ongoing negotiations of the Third United Nations Conference on the Law of the Sea (1973–1982) (UNCLOS, 1982), predominately entailed the need for new or revised management agreements. In short, EEZs simplified the management of spatially confined (local) fish stocks but mandated strengthened international management cooperation regarding broadly distributed stocks. Examples of such stocks also include those that utilize distant habitat areas across life phases, from spawning migration, denatant drift of offspring to nursery grounds and adult feeding migrations (Harden Jones, 1968; Petitgas et al., 2013; Secor, 2002). Some EEZs clearly benefit much more than others with a markedly higher offspring inflow than outflow. In a recent global review, Russia was ranked as the country most dependent upon *inflow* of fish offspring produced within adjacent EEZs; nearby Norway was ranked sixth (Ramesh, Rising, & Oremus, 2019) (Figure 1). The seventh ranked for inflow was Japan, which also had the largest *outflow* to other EEZs followed by Alaska and China. Although such network simulations demonstrate fisheries as interconnected, the actual allocation of quota refers to life stages showing active rather than passive displacements, often with a pronounced seasonal pattern (e.g., Nøttestad et al., 2016).

Stressors significantly affecting fish stock productivity are fishing and climate fluctuations and change (Skern-Mauritzen et al., 2016), the latter with an apparent, increasing trend over the last decades (Bindoff et al., 2019; Hoegh-Guldberg et al., 2014) (Figure 2). In the late 1970s, fisheries were, in general, insufficiently regulated (Gullestad et al., 2014). Although the current universally adopted routines for good governance of fish stocks (FAO, 2018) are effective (Ye & Gutierrez, 2017), overfishing is still increasing globally (FAO, 2018). Highly migratory, transboundary and straddling stocks are overrepresented among overfished stocks, particularly those associated with high seas (Ye et al., 2013). Yet some regions have shown significant progress towards sustainable harvest over the last decades, such as in waters of the United States, Australia and in the Northeast Atlantic and adjacent seas (FAO, 2018). An intrinsic part of the sustainable development in the Northeast Atlantic has been the continuing efforts from the late 1980s to reach coastal state agreements for stocks occurring across *several* EEZs, including stocks that straddle the *high seas* (Gullestad et al., 2014) (Figure 1). Climate change generally affects stock distributions (Poloczanska et al., 2013), creating another critical point in today's negotiations,

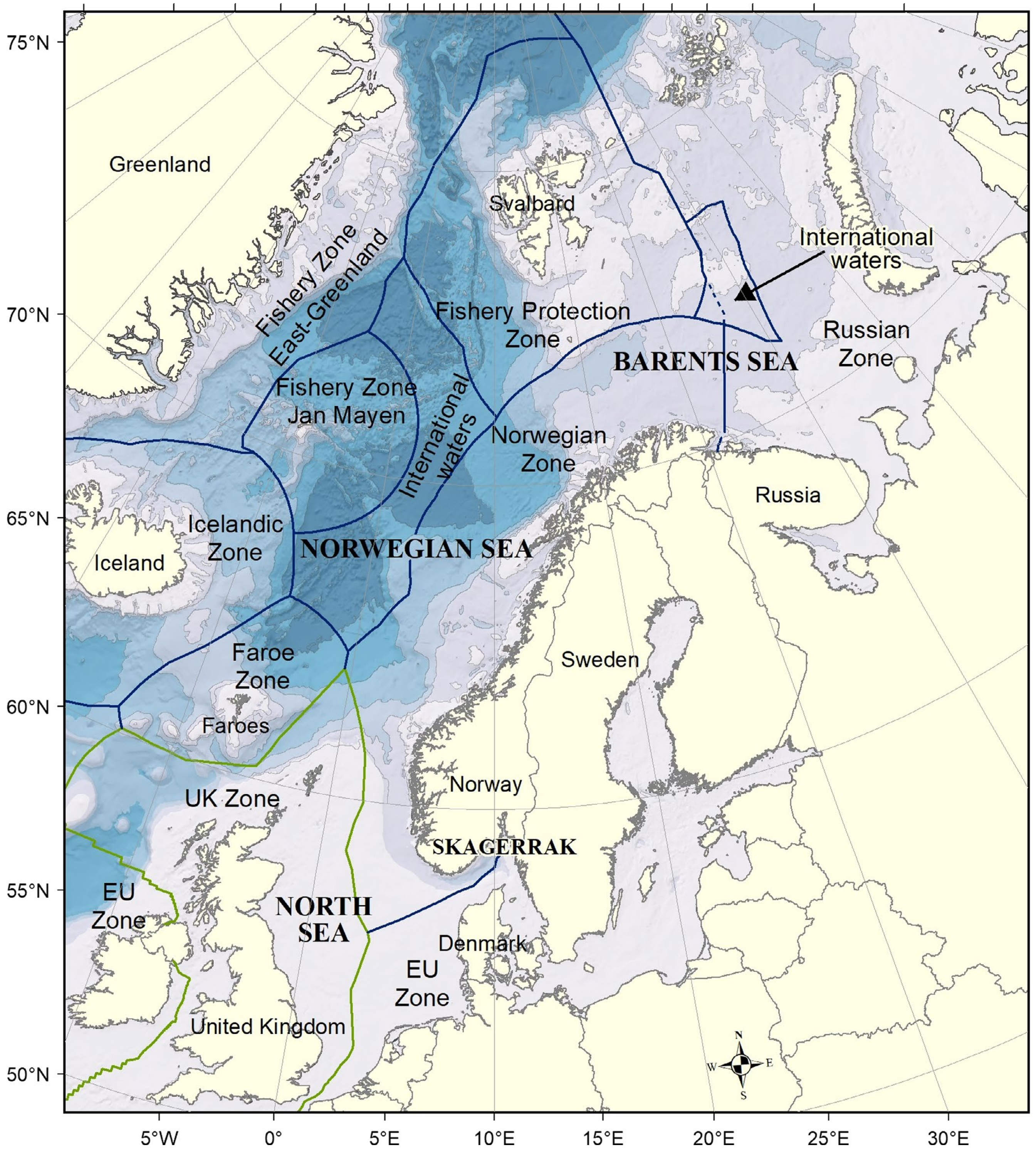


FIGURE 1 Exclusive economic zones (EEZs, blue line) in the Northeast Atlantic, where the UK EEZ following Brexit is marked (green line), and annotations of the three presently addressed large marine ecosystems (including depth contour): Barents Sea, Norwegian Sea, and North Sea including Skagerrak. The international waters (high seas) in the Barents Sea and the Norwegian Sea are commonly referred to as "the Loophole" and "the Banana Hole," respectively

but environmental information has so far rarely been directly included in operational fisheries management (Skern-Mauritzen et al., 2016).

While many science articles on transboundary and straddling stock management challenges have been produced, little has been written about actual experiences since the introduction of EEZs. In the following synopsis addressing these operational advancements in management practices, we focus on the Northeast Atlantic, covering several defined large marine ecosystems (LMEs) (Figure 1). Due to the number of nations surrounding these waters, the region

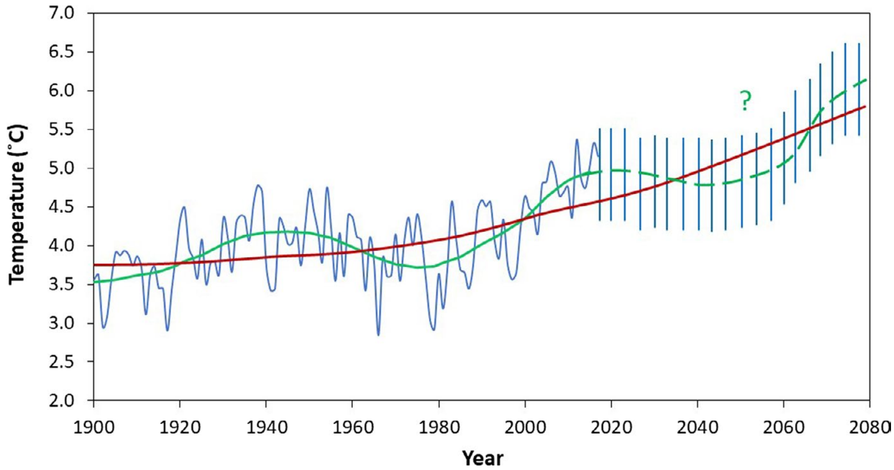


FIGURE 2 Observed and predicted ocean climate in the Northeast Atlantic represented by the Atlantic water masses in the Barents Sea. Thin (blue) line: annual mean temperature observations (stations 4–7, 0–200 m depth) of the Kola Section, Barents Sea (source and courtesy: PINRO [now VNIRO Polar Branch], Murmansk, Russia). Thick, undulating (green) line: 30-year low-pass filter of the annual mean temperature observations depicting the processes linked to Atlantic Multidecadal Oscillation (AMO). Thick, positive trend (red) line: the long-term temperature trend including prediction on anthropogenic climate change for the Barents Sea (IPCC B2 Scenario, corresponding to an in-between RCP 2.6 and 4.5 Scenario) (Furevik et al. (2002). Stippled (green) line: future multidecadal climate signal under the assumption (cf. mark of interrogation) that amplitude and periodicity continue as during the past century. Bars (blue): range of interannual variability as during the past century

includes many EEZs, and additional nations may claim fishing rights because the region includes high seas (Figure 1). The Northeast Atlantic is not only of particular interest because of the many stakeholders involved in the governance of the region, these waters have been subjected to most rapid climate-induced shifts in fish stocks (Peck & Pinnegar, 2018)—from "subtropicalisation" of the southern parts (Montero-Serra, Edwards, & Genner, 2015) to "borealisation" of the northernmost parts (Fossheim et al., 2015). Notably, increased scientific knowledge about zonal distribution has been a key point in quota negotiations for several decades (Hamre, 1993). One might ask whether these circumstances and insights have affected agreed quota allocations. In addition, eco-labelling and sustainability certification have become an influential factor (MSC, 2019a).

Here, we summarize information for three Northeast Atlantic LMEs, present five key stocks as case-studies and discuss the potential effects of long-term fish distribution changes on joint management of shared Northeast Atlantic fish stocks over the last 40 years. We conclude with general principles that likely speak for improved or successful management of transboundary and straddling stocks, in the hope that these frameworks and lessons learned are of interest where joint management of shared stocks has not yet started or is at an early phase.

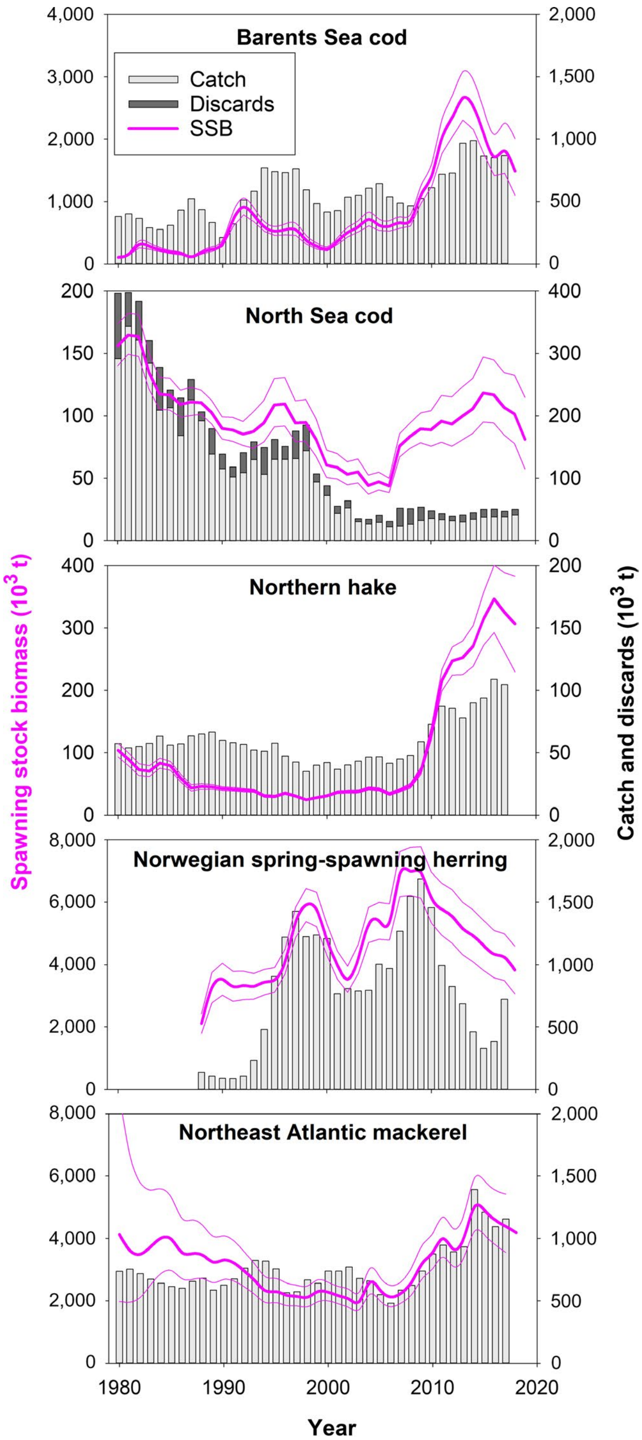
2 | SOURCES OF INFORMATION

In addition to peer-reviewed articles, this synopsis consulted directorate and governmental papers, minutes from negotiations, working group reports and trustworthy sources on the Internet, all properly cited. In the Appendix S1, we elaborate on development of management of other shared stocks in the Northeast Atlantic and formally define management-related terms (Table S1). The function and history of the mentioned organizational bodies are also outlined (Table S2). Lastly in the Appendix S1, we illustrate the extensive work efforts that might be involved in attempts to solve management problems related to quota allocation, with reference to the North-East Atlantic Fisheries Commission (NEAFC).

3 | THE LMEs AND THEIR BIOPHYSICS

The three considered Northeast Atlantic LMEs—the Barents Sea, the North Sea, including Skagerrak, and the Norwegian Sea—display diversity in their ecosystem structures, but several common features are apparent across their dominant fish species. The same cold-temperate (boreal) fish species are found throughout nearly the whole region, including Atlantic cod (*Gadus morhua*, Gadidae), haddock (*Melanogrammus aeglefinus*, Gadidae), saithe (*Pollachius virens*, Gadidae), Norway pout (*Trisopterus esmarkii*, Gadidae), redfish (*Sebastes* spp., Sebastiane), herring (*Clupea harengus*, Clupeidae) and sand eel (*Ammodytes* spp., Ammodytidae) because of the physiologically acceptable thermal range (Pörtner & Peck, 2010). The southern fringe, that is, the southern North Sea, forms their upper thermal limit, whereas the northern fringe, that is, the northern Barents Sea, forms their lower thermal limit (Sundby, 2000). The same principle applies to warm-temperate species, represented by Northern hake (*Merluccius merluccius*, Merlucciidae) and Northeast Atlantic mackerel (*Scomber scombrus*, Scombridae), but with far more southerly distributions and seasonally lengthy migrations northwards.

FIGURE 3 Development over the last 40 years in stock size, represented by spawning stock biomass (SSB) (thick line), with uncertainty indicted (95% confidence interval) (thin lines), and associated catches of the five case-study stocks (histogram): Barents Sea and North Sea cod (demersal, cold-temperate species at high and middle latitudes, respectively), Northern hake (demersal, warm-temperate species), Norwegian spring-spawning herring (pelagic, cold-temperate, widely distributed species), and Northeast Atlantic mackerel (pelagic, warm-temperate, widely distributed species). For North Sea cod stock, discards are a major issue and therefore indicated. Note that the y-axis scale varies across panels. All data were extracted in July 2019 from the ICES database (http://ices.dk/marine-data/assessment-tools/Pages/stock-assessment-graphs.aspx)



3.1 | The Barents Sea

The high-latitude Barents Sea (Figure 1) is influenced by winter ice cover in the northern and eastern region and hosts Arctic species of zooplankton through to marine mammals, whereas the southern and western region is dominated by the inflow of warmer Atlantic water masses and hosts boreal species of zooplankton and fish (Loeng, 1989). As a large shelf sea (≈1,400,000 km^2), the Barents Sea is dominated by demersal fish (Jakobsen & Ozhingin, 2011).

3.2 | The North Sea including Skagerrak

The North Sea (Figure 1) is a shallow shelf sea (≈570,000 km^2) influenced by the inflow of Atlantic water, mainly from the northern entrance between Scotland and Norway. The North Sea is also influenced by freshwater run-off along the eastern coasts, particularly from the Rhine and Elbe rivers but also by outflow from the brackish Baltic Sea (Fox et al., 2016). The North Sea ecosystem is dominated by groundfish (demersal fish), particularly gadoid species in the deeper central and northern parts, and by flatfish in the southern and shallowest area (Sundby et al., 2017). The Norwegian Trench differs from the other parts of the North Sea as it is inhabited by deep-water fish species only found in this part of the North Sea (Sundby et al., 2017). It is debatable whether the Skagerrak (≈47,000 km^2) should be merged with the North Sea as an LME. The merger is supported by its relatively limited geographical extension and related ecosystem dynamics (Knutsen et al., 2004).

3.3 | The Norwegian Sea

The Norwegian Sea (Figure 1) is constrained by the inflow of warm Atlantic water in the southeast and by Arctic water masses in the north–western areas (Blindheim, 1989). This deep oceanic area (≈1,400,000 km^2) east of the Mid Atlantic Ridge is dominated by pelagic and deep-water species, except along the shelf region of the Norwegian coast, where demersal species are also important for fisheries and for the ecosystem structure (Blindheim, 1989).

4 | CASE-STUDIES ILLUSTRATING HOW CLIMATE MAY IMPACT STOCK DISTRIBUTION

Following an outline on important environmental drivers, the ecology under climate fluctuations and change is reviewed for five, commercially valuable fish stocks: Barents Sea (Northeast Arctic) cod, North Sea cod, Northern hake, Norwegian spring-spawning herring, and Northeast Atlantic mackerel (Figure 3).

4.1 | Progress in the understanding of fisheries oceanography in the Northeast Atlantic

The attempt to understand fish stock fluctuations in relation to environmental drivers has continued since the beginning of the previous century (Helland-Hansen & Nansen, 1909; Hjort, 1914). The development of long time series for fish stocks (e.g., Toresen & Østvedt, 2000) and the environment (Boitsov, Karsakov, & Trofimov, 2012) (Figure 2) has become the backbone towards this understanding. Impacts of persistent changes in climate were discussed as early as the late 1940s, when ICES arranged a conference addressing the impacts of the warmer North Atlantic during the first half of the 20th century (Rollefsen & Tåning, 1949; Tåning, 1949, 1953) (Figure 2), and later reviewed by Drinkwater (2006). Surprisingly, the subsequent long-term cooler period that occurred until the early 1980s (Figure 2) received much less scientific attention. However, it later became apparent that fish stocks of the North Atlantic had retreated southwards during this period; the onset of the most recent long-term warmer period, subsequent to the mid-1980s, caused the stocks to again extend northwards (Drinkwater et al., 2014; Sundby & Nakken, 2008). These long-term climate fluctuations are now known as the Atlantic Multidecadal Oscillation (AMO), which has a periodicity of 60–80 years and spatially extends across the entire North Atlantic Ocean (Sutton & Hodson, 2005) (Figure 2). Tree-ring analyses in Europe and North America, representing a proxy for the North Atlantic scale temperature, indicate that such multidecadal oscillations have occurred at least back to the 1550s (Gray, Graumlich, Betancourt, & Pederson, 2004).

In essence, the AMO during the 20th century demonstrated a cooler phase until the 1920s, a warmer phase between the 1930s and 1950s, a new cooler phase during the 1960s to 1980s, and finally, a recent warmer phase (Figure 2). This cyclicity is not only reflected by the species distribution shifts but also by stock biomass changes (Drinkwater et al., 2014; Hollowed & Sundby, 2014; Sundby & Nakken, 2008). Importantly, the international negotiations of quotas on shared stocks, in response to the extension of EEZs to 200 n.m. during the late 1970s (see Section 1), were thus conducted at the end of the last *cooler* AMO period, when North Atlantic fish stocks were, in general, distributed in a *southerly* mode. Since then, the positive phase of the AMO, combined with the increasing global anthropogenic signal, has led to a stronger temperature increase than during the previous warm period between the 1930s and the 1950s (Figure 2). Poloczanska et al. (2013), who examined shifts in 1735 marine species worldwide over recent decades, found that most of the species (81%–83%) were displaced polewards according to the expected response to climate change. However, some of the species showed the opposite displacement, that is, equatorward, particularly in the North Sea, where cooler winter temperatures appear in the south.

4.2 | Barents Sea cod

Barents Sea cod is a highly seasonal-migratory stock with spawning areas along the Norwegian coast during spring and summer feeding stretching northward to the ice edge in the Barents Sea (Johannesen et al., 2012). It is currently by far the largest of the Atlantic cod stocks. Based on NAFO and ICES statistics (Table S2), its long-term average spawning stock biomass (SSB) is equivalent to the combined SSB of the second- and third-ranked cod stocks: Icelandic cod and Northern (Newfoundland) cod, respectively. During the last decade, the biomass of Barents Sea cod has increased considerably (Figure 3), so that the recent 10-year average SSB is twice the sum of all the other Atlantic cod stocks. This record-high situation has been ascribed to a combination of higher ocean temperatures and good management (Kjesbu et al., 2014). Behind these two overarching factors, there are additional large-scale climate processes as well as historic management decisions founded in the Joint Norwegian-Russian Fisheries Commission (Table S2). The recent increase in stock size had already begun by 1983, subsequent to the interdecadal cooling during the 1960s and 1970s (Ellertsen, Fossum, Solemdal, & Sundby, 1989; Sætersdal & Loeng, 1987) (Figure 2). Improved recruitment (year-class formation) from 1983 was ascribed to higher temperatures that provided better food conditions for the early stages of cod, hence leading to increased survival (Ellertsen et al., 1989). However, an increased SSB was also found to contribute equally to year-class formation (Ottersen & Sundby, 1995). As the temperature increased in the Barents Sea, the adult part of the stock was displaced towards the north-east (Ottersen, Michalsen, & Nakken, 1998), and the ice cover in the northern part of the Barents Sea retreated, resulting in summer feeding occurring at higher and higher latitudes. Consequently, the habitat of cod has expanded and been displaced towards the north and east along with the retreating ice edge (Kjesbu et al., 2014). As the spawning migration distance of Barents Sea cod is extraordinary long compared to other Atlantic cod stocks, it appears that spawning areas have been displaced towards the north-east along the Norwegian coast (Langangen et al., 2019; Sundby & Nakken, 2008). Subsequent to the millennium shift, ice cover in the northernmost and Arctic parts of the Barents Sea has been very low during summer (Årthun et al., 2018), which enabled cod to feed to the shelf edge in the Arctic Ocean, north of Svalbard (Fossheim et al., 2015). No other Atlantic cod stock has a similar dynamic variability in the extent of habitat caused by climate variations, except perhaps the West Greenland stock (Storr-Paulsen, Wieland, Hovgård, & Rätz, 2004).

The poleward displacement combined with the increase in stock size since the late 1980s is not a unique event in the history of Barents Sea cod. The extended time series of stock abundance, spawning areas and climate conditions show that the stock abundance has oscillated in concert with multidecadal climate oscillations (i.e., AMO) throughout the 20th century (Drinkwater & Kristiansen, 2018; Hollowed & Sundby, 2014), and the spawning habitats have accordingly shifted northwards and southwards along the Norwegian coast (Sundby & Nakken, 2008). During the previous warmer phase of the AMO, from the 1930s to the 1950s, marine species of the North Atlantic, including Atlantic cod, were displaced polewards (Drinkwater, 2006; Tåning, 1949, 1953). The spawning areas of Barents Sea cod were even found in Storfjorden, the oceanic area between Bear Island and West Spitsbergen (Svalbard) (Iversen, 1934). The present warming, however, has exceeded the previous warmer period of the 1930s to 1950s due to the additional and steadily increasing influence of anthropogenic climate change (Alexander, Kilbourne, & Nye, 2014). Yet, it remains to be determined whether cod has resumed spawning as far north as Storfjorden.

4.3 | North Sea cod

North Sea cod is among the major Atlantic cod stocks and is found at the upper range for temperature habitats of this species (Sundby, 2000). The underlying mechanistic details are not presented here, but it is known that increasing temperature is detrimental to recruitment for those Atlantic cod stocks living at the upper temperature range, for example, North Sea cod, while increasing temperature is beneficial to recruitment for those Atlantic cod stocks living at the lower temperature range, for example, Barents Sea cod (see Sundby, 2000, and references therein). The biomass of North Sea cod was at its peak abundance during the last cool period of the 1960s and 1970s. This was described as the "Gadoid Outburst" in the North Sea (Cushing, 1984) and influenced not only cod but also haddock, whiting (*Merlangius merlangus*, Gadidae), saithe and Norway pout. The North Sea cod stock began to steadily decrease from the early 1980s to around 2005 (Hislop, 1996; Hislop et al., 2015) (Figure 3). Hence, the decline coincided with the combined warmer phase of the AMO and the global anthropogenic increase in temperature, but was also due to persistent overfishing (Bannister, 2004). However, not only the biomass has declined; for example, Sundby et al. (2017) and Wright, Regnier, Gibb, Augley, and Devalla (2018) showed that the distribution of the adult stock as well as the spawning areas have been displaced towards the north-east during the same time interval, as cod spawning areas prior to the 1990s were spread over most of the North Sea (Brander, 1994). It should, however, be emphasized that it may be difficult to quantitatively assess the separate effects of climate and fishing, as demonstrated in these waters by Engelhard, Righton, and Pinnegar (2014). The major spawning areas are now found at the shelf near the western slope of the Norwegian Trench and in the northernmost part of the North Sea in the waters off Scotland and Shetland (Sundby et al., 2017; Wright et al., 2018). This cod spawning ground displacement might also be an indirect effect of higher temperatures; the main abundance of *Calanus finmarchicus* (Calanidae), the key prey for the cod larvae (Beaugrand, Brander, Lindley, Souissi, & Reid, 2003), now appear in the same region of the North Sea (Sundby, 2000). Subsequent to 2005, SSB had been rising (although currently declining) (Figure 3), but only in the northern half of the North Sea (ICES, 2017), which is influenced by the inflow of Atlantic water masses from the north. In the southern half of the North Sea, SSB has continued its decreasing trend (ICES, 2017).

4.4 | Northern hake

Traditionally, the main habitat of European hake has been located south of the North Sea, although this species is generally widely distributed—from the Mediterranean, along the Iberian and French coast, west of the British Isles and Irish Sea to the North Sea, and further northwards to the Norwegian coast around 64° N and westward towards Iceland (Heessen & Murua, 2015; Werner, Staby, & Geffen, 2016). It is uncertain whether the European hake is divided into sub/metapopulations, but within ICES, it is managed as one southern and one northern stock unit, divided at the Cap Breton Canyon in the Bay of Biscay (ICES, 2012). The major catches of Northern hake have been taken west of Ireland and Scotland (Baudron & Fernandes, 2015; Heessen & Murua, 2015). In the North Sea, the catches have undergone multidecadal variations (Baudron & Fernandes, 2015); low catches were taken at the beginning of the 20th century, but catches increased from the 1920s to reach a peak around 1950, except for a temporary reduction during the Second World War. Post-1950, catches declined dramatically. From the 1980s, when stock abundance estimates became available (Figure 3), SSB remained very low until the beginning of the 2000s, probably due to very high fishing mortality (between 0.8 and 1.1) during 1985–2005 (Baudron & Fernandes, 2015). SSB then increased and, around 2010, North Sea catches reached the same level as during the record-high period in the 1950s.

The mentioned multidecadal pattern in hake catches in the North Sea seems to be inverse to that of boreal gadoids (cod, haddock, whiting, Norway pout, and saithe) in the same region. The centre of gravity of catch rates for Northern hake since the cooler 1970s has been displaced towards the north-east, subsequently towards the northern entrance of the North Sea and thereafter southwards with the Atlantic inflowing water masses (Sundby et al., 2017). There are indications that AMO might be an explanatory forcing of this displacement. Subsequent to the recent substantial increase in SSB, major spawning areas were established after 2014 along the western slope of the Norwegian Trench in the North Sea (Sundby et al., 2017; Werner et al., 2016). Thus, with ongoing climate change, there are indications that Northern hake is taking over much of what used to be the central role of North Sea cod in the northern North Sea, although there is no evidence that hake is actually outcompeting the cod. Competitive relationships may exist with other species; however, the present hake distribution overlaps with the distribution of saithe in the North Sea and they share preference for some of the same prey (Cormon, Loots, Vaz, Vermard, & Marchal, 2014). Lastly, since hake was practically absent from the North Sea until rather recently, it is often considered an "invasive species." The catch history indicates that the stock should be considered an endemic species to the North Sea. The northern limit for egg release is around 64° N, reflecting lesser spawning ground habitat exists along the Norwegian coast (Werner et al., 2016). Northward expansion of spawning areas is uncertain given the species' year-round spawning activity (Serrat et al., 2019), because spring-spawning behaviour is a necessary adaptation at latitudes higher than 66–67 N due to the restricted timing of blooming of suitable prey for the fish larvae (Sundby, Drinkwater, & Kjesbu, 2016).

4.5 | Norwegian spring-spawning herring

As for boreal fish stocks, the Norwegian spring-spawning herring has undergone major multidecadal-scale changes in SSB (Toresen & Østvedt, 2000). Unlike most other stocks in the Northeast Atlantic, this stock does *not* display a poleward shift in distribution in parallel with the positive phases of AMO. This might possibly be due to that its ambient temperature is still near the optimal (dos Santos Schmidt et al., 2020) and that its feeding is strongly linked to the distribution of *Calanus finmarchicus* that still has its core abundance in the Norwegian Sea proper (Melle et al., 2014; Sundby, 2000). The most apparent link with changes in habitat extent is related to stock abundance rather than coupled to temperature, or climate in a broader sense of the word. Further to this, abrupt changes in overwintering areas appear closely linked to the ratio of young to older individuals, that is, when the former category dominates (cf. strong year classes) (Huse, Fernø, & Holst, 2010). Subsequent to the stock collapse during the 1960s, the summer feeding habitat extent in the Norwegian Sea also collapsed back to a small area along the Norwegian coast in the vicinity of the spawning areas (Dragesund, Johannessen, & Ulltang, 1997), apparently because the coastal areas had sufficient amounts of copepods to feed the small herring stock. Moreover, overwintering areas were also confined to minor Norwegian coastal regions that were adjacent to spawning areas. Only when the stock started recovering during the late 1980s, was summer feeding throughout the Norwegian Sea resumed (Dalpadado, Ellertsen, Melle, & Dommasnes, 2000). The science community is increasingly becoming aware of another factor that complicates the dynamics of summer feeding distribution in the Norwegian Sea, namely the density-dependent interactions with the two other main planktivorous players: blue whiting (*Micromesistius poutassou*, Gadidae) and Northeast Atlantic mackerel (dos Santos Schmidt et al., 2020; Huse et al., 2012; Utne & Huse, 2012).

4.6 | Northeast Atlantic mackerel

Northeast Atlantic mackerel comprises the third component of the "Pelagic Complex" that summer feeds in the Norwegian Sea, the other two being Norwegian spring-spawning herring and blue whiting. The main part of this mackerel stock is found in the open ocean to the west of the British Isles (ICES, 2015). The Northeast Atlantic mackerel has a seasonal migration potential that strongly exceeds that of the two other stocks. During recent years of warming, that is subsequent to 1995 (Uriarte & Lucio, 2001), the stock has occupied an increasingly larger portion of the Nordic Seas during summer feeding (Astthorsson, Valdimarsson, Gudmundsdottir, & Óskarsson, 2012; Langøy, Nøttestad, Skaret, Broms, & Fernö, 2012; Nøttestad et al., 2016; Uriarte & Lucio, 2001) but might comprise a southern, western and North Sea component, with the latter much smaller than the other two. These various components apparently mix during summer feeding (Ellis & Heessen, 2015). The recent advancement of mackerel far into the Nordic Seas is not a novel phenomenon; the northward–southward shift appears in concert with AMO oscillations (Astthorsson et al., 2012). Although the SSB is currently high (i.e., exhibiting "the second wave" since the 1980s), the most recent abundance estimates provide further support for a declining trend (ICES, 2019) (Figure 3).

5 | DEVELOPMENT OF QUOTA ALLOCATIONS FOR TRANSBOUNDARY AND STRADDLING STOCKS

As stocks may well extend beyond more than one LME, the below perspectives on progress in management refer principally to the stock units, grouped by the primary LME. Furthermore, we use the starting point for negotiations, either being political, based on historical catches, distribution of the fishable part of the stock, or zonal attachment (see definition below) as an overarching criterion, corresponding principally from the earliest to the most recent agreements in the Northeast Atlantic (Figure 4). Barents Sea cod, North Sea cod, Northern hake, Norwegian spring-spawning herring and Northeast Atlantic mackerel are key targets. However, as management development in these five stocks is intimately linked to similar or related progress in other stocks (Figure 4), the Appendix S1 provides complementary narratives and discussions for Iceland–Greenland–Jan Mayen capelin (*Mallotus villosus*, Osmeridae), Barents Sea capelin, Barents Sea (Northeast Arctic) Greenland halibut (*Reinhardtius hippoglossoides*, Pleuronectidae) and beaked redfish (*Sebastes mentella*, Sebastinae), North Sea herring, and blue whiting.

5.1 | The Barents Sea

The first management agreement in this high-latitude water has been in place for almost half a century and was based on a principle of equal sharing of quota between the two coastal states, Russia (the former Soviet Union) and Norway (Figure 4). This bilateral management agreement was rooted in politics, following a series of initial discussions between the two countries' Minister of Fisheries, despite the still ongoing "Cold War" (Hønneland, 2006). In preparation for the upcoming expansion to 200-nautical-mile zones, the Soviet Union and Norway signed an agreement to cooperate through the Joint Norwegian-Soviet Fisheries Commission (JNSFC, 1974), formally effectuated thereafter (JNSFC, 1976). The parties agreed to allocate the total allowable catch (TAC) of cod, and also haddock, evenly after setting aside an allocation for third parties fishing in the same area. The third-party states were the German Democratic Republic, the Faroe Islands, Poland, Portugal, Spain, and the European Community (EC) member states, France, the Federal

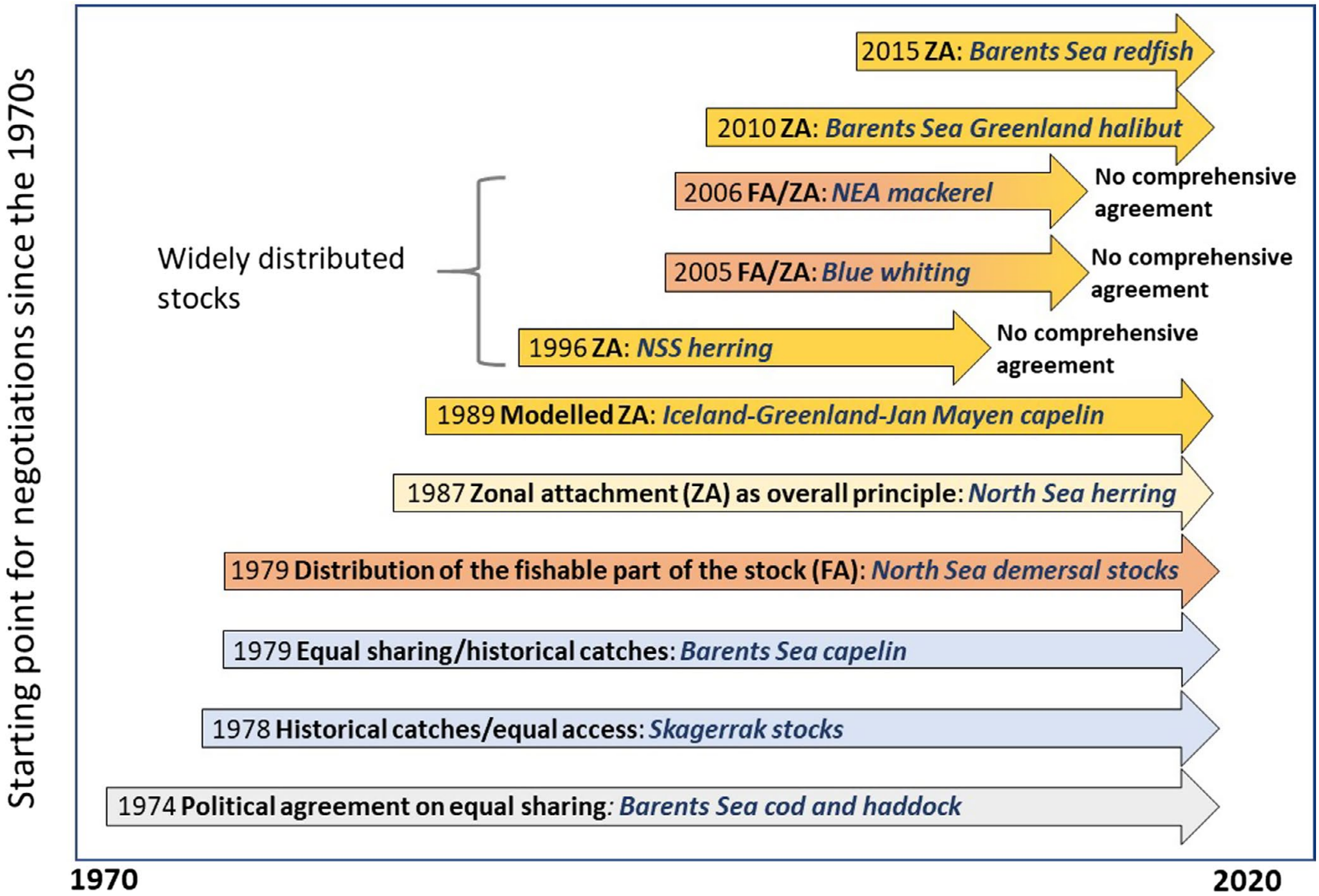


FIGURE 4 Principles that have been the starting point for negotiations on the sharing of transboundary and straddling stocks in the North East Atlantic in the period from around 1970 to 2020. Arrow length indicates duration of agreement. The advent of lack of management consensus is indicated as well for the stocks in question. Over this time frame, Northern hake, one of the five case-study stocks (Figure 3), has been unilaterally managed by EU and the state of affairs is therefore not shown here. The narratives for all five case-study stocks are presented in the main body of text whereas narratives for Barents Sea capelin, North Sea herring, Iceland–Greenland–Jan Mayen capelin, blue whiting, Barents Sea Greenland halibut and Barents Sea redfish appear in Appendix S1. FA: distribution (area) of the fishable part of the stock; NEA mackerel, Northeast Atlantic mackerel; NSS herring, Norwegian spring-spawning herring; ZA, zonal attachment

Republic of Germany and the United Kingdom. Today, all are members of the European Union (EU), except for the Faroe Islands, and the United Kingdom, which recently left the EU (Brexit). The Faroe Islands is an autonomous part of the Kingdom of Denmark, yet not a member of the EU.

Another important element of the agreement was the opportunity to fish in each other's waters to establish more sustainable fishing practices. As younger and immature year classes of cod dominated in the eastern parts of the Barents Sea, that is in the waters of the Soviet Union (Nakken & Raknes, 1987), joint fishing was agreed in Norwegian waters in the western Barents Sea where older year classes dominated. Not only did this increase the economic efficiency of the Soviet Union fishery, but the resulting exploitation pattern increased long-term yield to the benefit of both parties (Gullestad, Howell, Stenevik, Sandberg, & Bakke, 2018). There were several reasons why the parties quickly agreed to a fraternal sharing of TACs (Engesæter, 1993). Sufficiently good data on stock distribution were unavailable, and the parties disagreed on the delimitation line between their zones (agreement not reached until 2010; Lovdata, 2010). However, due to overfishing and the less favourable climate (see above), the parties saw an urgent need to establish a reconciled coastal state management regime for the entire Barents Sea (Hønneland, 2012). The equal sharing of cod and haddock between Norway and Russia has remained unchanged since 1977 (Hønneland, 2006; Joint Fish, 2020; Norwegian Government, 2019b). The third parties' share of fishing in the Barents Sea did, however, fluctuate until the turn of the century (www.ices.dk). In the Fishery Protection Zone around Svalbard (FPZS) (Figure 1), quotas of cod were granted to third parties with a historic record of fishing in the FPZS prior to its establishment in 1977. After some initial variability, this allocation has been stable at 4% of TAC, which corresponded to the share of total catches in the 10-year period prior to the FPZS. In addition, Norway and Russia enter into bilateral agreements with third parties (EU and the Faroe Islands) to exchange quotas of cod and haddock on a reciprocal, annual basis.

IUU (illegal, unreported and unregulated fishing) became a serious problem from the early 1990s: the warmer climate implied cod were also available for harvest in international waters in the north-eastern part of the Barents Sea, i.e., in "the Loophole") (Figure 1). The IUU in the Loophole tailed off between 2006 and 2009 (Kjesbu et al., 2014), following persistent measures to stop this activity, including blacklisting of vessels (Norwegian Black List, 2019)[1] and effective cooperation with several European port states to deny such vessels the ability to land catches from the Barents Sea (FiskDir, 2015). The EU amended their regulations to include fishing in the Loophole in their existing quota arrangements for Barents Sea cod (EEC, 1992). With Greenland and Iceland as newcomers to fishing in the Barents Sea, Norway and Russia negotiated agreements giving vessels from these countries quotas of cod in Norwegian and Russian waters in exchange for fishing opportunities in their waters (Lovdata, 1992, 1999). The agreement with Iceland was finally concluded in 1999 (Lovdata, 1999), and since 2000, the total annual allocation of cod to third parties in the Barents Sea, including the allocation to be fished in the FPZS (see above), has remained stable at 14.15% of TAC (in protocols from the Joint Norwegian-Russian Fisheries Commission (JNRFC); Table S2).

5.2 | The North Sea including Skagerrak

The basic principle for fisheries management negotiations in this southernmost, comparatively smaller LME (Figure 1) is either historic landings or distributions of the fishable part of the stock, with special reference to Skagerrak in the first instance and to the North Sea in the last instance (Figure 4).

Because the three countries surrounding the Skagerrak, Denmark, Sweden and Norway have strong cultural ties dating back at least to the age of the Vikings, an emphasis on historical landings was a natural starting point for negotiations. In 1966, these Scandinavian states signed a fisheries agreement that gave fishers equal and reciprocal access, under flag state jurisdiction, to waters outside 4 n.m. (FiskDir, 1967). When quotas were introduced for three Skagerrak stocks in 1978, the allocations were based on historical catches, reflecting the principle of equal access from the 1966 agreement. The number of stocks regulated by quotas increased to six in 1980 and seven in 1991 (cod, haddock, whiting, plaice *Pleuronectes platessa* (Pleuronectidae), herring, sprat *Sprattus sprattus* (Clupeidae), and deep-water prawn *Pandalus borealis* (Pandalidae)), where the allocations again referred to historical catches. After some initial adjustments, the allocations stabilized and have remained unchanged (Norwegian Government, 2019a). The 1966 Skagerrak agreement was renegotiated in 2015 and brought in line with UNCLOS (see Section 1) (Lovdata, 2015). The establishment of a coastal state jurisdiction throughout the EEZs considerably strengthened the management regime in the Skagerrak. The EU is now party to the agreement on behalf of the EU member states, Denmark and Sweden (Norwegian Government, 2019c). Denmark and Sweden have been subject to the Common Fisheries Policy (CFP) of the EC/EU (EC, 2014) since they became members in 1973 and 1995, respectively.

The fisheries management situation in the North Sea is far more complex due to several transboundary stocks shared by multiple coastal states, who are all, except Norway, EU member states[2] and subject to the CFP. In 1979, the EC and Norway negotiated a framework agreement on future cooperation on fisheries management, which was formally signed in 1980 and underscored the parties' wish to cooperate in managing joint North Sea fish resources (Engesæter, 1993). The parties also emphasized their willingness to continue traditional fisheries in each other's waters on stocks that were not shared, at a scaled-down level, so that fishing opportunities were equal and balanced. According to historic catch statistics (www.ices.dk), fishers from EC member states had fished more in Norwegian waters than vice versa. In practice, this meant a reduction of EC (EU) fishing activity in Norwegian waters. Although no formal joint fisheries commission was established, the framework for cooperation resembles the cooperation between Russia and Norway (Table S2: JNRFC). On request from NEAFC (Table S2), ICES presented the following five relevant factors in establishing quota allocation of shared resources in the Northeast Atlantic (ICES, 1978): (a) the occurrence and migrations of the fishable part of the stock; (b) the occurrence of juvenile and pre-recruit fish; (c) the spawning areas and the distribution of eggs and larvae; (d) the history of the fishery, including the distribution of catch, rate of exploitation and fishery regulations; and (e) the state of exploitation of the stock. This report did not advise on how these factors should be weighted to reach an agreed quota allocation. Taking this report as the point of departure, a working group of EC and Norwegian research scientists and managers analysed the situation for several transboundary North Sea stocks. These experts proposed that, due to the lack of comprehensive and reliable data for several of the above-mentioned influential factors and challenges related to weighting factors, negotiations could be based on the distribution of the fishable part of the stock, including the zonal distribution of catches. With this starting point, EC and Norway agreed in 1979 on quota allocation for five North Sea demersal stocks: cod, haddock, plaice, saithe and whiting (Figure 4). These allocations have remained unchanged to date (Norwegian Government, 2019c).

Northern hake provides a prime example of a stock challenging established management regimes. This stock was predominately within EU waters but has undergone a substantial spatial expansion, including into the north-eastern part of the North Sea (see above) and thereby into the Norwegian EEZ (Figure 1). The corresponding

[1]The Norwegian Black List, first introduced in 1994 and modified in 1998 (Norwegian Black List, 2019), states that any enrolled physical vessel will not be granted a licence to fish in Norwegian waters regardless of future flag or ownership; the list is regularly updated. Blacklisting is now part of the monitoring, control and surveillance systems of several regional fisheries management organizations (RFMOs), including NEAFC (Table S2) and NAFO (Northwest Atlantic Fisheries Organization) (Table S2), as well as CCAMLR (see above).

[2]Brexit will inevitably lead to changes in the fisheries management regime of the North Sea, cf. the relatively large UK EEZ (Figure 1). The consequences for quota allocations are currently unclear (Shepherd & Horwood, 2019).

SSB has shown a nearly 10-fold increase since 2008 (Figure 3), resulting in ICES catch advice of ≈115 thousand tonnes in 2018, an increase of 37% over the previous year (ICES, 2018a). For Norway, landings of hake have been mainly as by-catch; however, as by-catches increased, Norwegian landings became 10 times higher in 2017 (≈5,300 tonnes) than in 2002 (≈530 tonnes).

5.3 | The Norwegian Sea

The Norwegian Sea stands out as particularly informative regarding management challenges in the context of climate-induced shifts of widely distributed stocks (Figure 4). Furthermore, the important model for zonal attachment (Hamre, 1993) originated from emerging, local management issues (Appendix S1: Iceland–Greenland–Jan Mayen capelin). Today this research-based model, used for the first time in 1989 on this capelin stock, is frequently applied in fisheries managements, as further specified and discussed below (Figure 4).

Following the appearance of the strong 1983-year class, the recovering Norwegian spring-spawning herring stock reoccupied its juvenile habitat in the Barents Sea, including the waters of the Soviet Union (Dragesund et al., 1997). In response, the Soviet Union claimed coastal state rights and fished 82 000 tons of juveniles in their EEZ (1984–1985) (www.ices.dk). The two parties reached an agreement the following year, when Norway granted the Soviet Union an annual quota of *adult* herring in Norwegian waters (Table S2; JNRFC); the parties concurrently agreed to a minimum length at catch of 25 cm. This had the effect of closing the Barents Sea, including Soviet waters, to the fishing of herring. By 1990, the 1983-year class left the Barents Sea and partially resumed the stock's adult feeding migration in the Norwegian Sea (Dragesund et al., 1997). In consequence, the stock became available for summer fishing in the EEZs of several coastal states adjacent to the Norwegian Sea but also in the “Banana Hole” (Figure 1). Five coastal states, Norway, Russia, Iceland, the Faroe Islands and the EU, agreed to a quota allocation (1996–2002) (Herring Agreement, 1996). Applying the principles outlined in Hamre (1993), zonal attachment was modelled and used as a starting point for these negotiations (Figure 4). The resulting model summed quarterly trawl-acoustic data for the zonal distribution of a representative year class throughout its lifetime. From this, bilateral agreements on access to waters were established. The quota allocation was under review 2002–2006, and a new key was adopted for 2007–2013. However, the five coastal states have *not* reached *consensus* on the quota allocation since then. Four of the five coastal states did reach an agreement on TAC and allocations between 2013 and 2014, failed to reach agreement for the years 2015–2016, but succeeded thereafter in terms of TAC (2017–2020) (Herring Agreement, 2019). Despite disagreements on quota allocations, the parties had already jointly decided on a management strategy in 1999, including a harvest control rule (HCR) for determining the TAC (ICES, 2000), which was recently updated (ICES, 2018b). With the lack of an agreed allocation, the parties set their national quotas unilaterally and related quota to the agreed TAC. Nonetheless, in all years without a full five-party agreement on allocation, the sum of the unilaterally set quotas has been *higher* than the advised TAC. In 2018 and 2019, the sum of the unilateral quotas amounted to 132% of the advised/agreed TAC (www.ices.dk). Despite this, the established schemes agreed through NEAFC (Table S2) on, for example technical regulations, electronic reporting systems (ERS), and control and protection of vulnerable habitats, have not been affected by the disagreement on the allocation. Similar allocation disagreements also occurred for the blue whiting (Appendix S1) and mackerel fisheries (elaborated on below).

The substantial north- and westward extensions of summer and autumn feeding areas of Northeast Atlantic mackerel after the mid-1990s (see above) negatively affected the possibility for management consensus among the parties taking part in this fishery, historically or just recently joining (see Mackerel Agreement, 2014, 2015, 2017) (Figure 5). This being said, no comprehensive quota regulations existed before this “mackerel era.” The fisheries were regulated uni- or bilaterally or were carried out without quantitative restrictions, where bilateral arrangements at that time (1977–1998) referred to the recognized coastal states EU, Norway and the Faroe Islands (Figure 5). Subsequently, these states annually entered into trilateral ad hoc agreements on the TAC and allocation (1999–2009) (Figure 5). A share was allocated to third parties to be fished in international waters (Figure 5) to be managed through NEAFC (Table S2). From 2006, the SSB gradually increased and fishable concentrations became available during summer in Icelandic waters (Astthorsson et al., 2012), and from 2013, the stock extended into Greenlandic waters (Nøttestad et al., 2016). This new constellation of parties was unable to reach agreement (Figure 5); the Faroe Islands claimed a larger share, and furthermore, Iceland claimed a share as a coastal state. With this background, the EU and Norway entered into a 10-year bilateral framework agreement on the management of the stock, including allocation and mutual access to each other's waters (2010–2020) (Figure 5). Between 2010 and 2013, the four parties negotiated extensively without success. The following year, the EU, Norway and the Faroe Islands managed to agree on a trilateral 5-year framework agreement, later extended until 2020 (Figure 5). On this basis, the three parties have annually agreed on the TAC and allocation, including mutual access to each other's waters. Iceland has thus far decided not to join this agreement. Greenland also participated in these consultations based on zonal attachment considerations. This lack of an overall agreement on the distribution of TAC resulted in the sum of unilateral quotas for 2018 amounted to 122% of the TAC as agreed upon by the EU, Norway, and the Faroe Islands (www.ices.dk). Further to this, these three parties embraced a management strategy and an HCR in 2015, revised in 2017, after a technical revision of the assessment method (see below). To complete, NEAFC has been actively involved in defining the criteria for the quota allocation for the three widely distributed, pelagic stocks of herring, mackerel and blue whiting. These discussions made progresses but also encountered difficulties, related, among other aspects, to the impact of Brexit. Because of this, the NEAFC Working Group, initiated in 2015, was temporarily suspended in 2017 (Appendix S1).

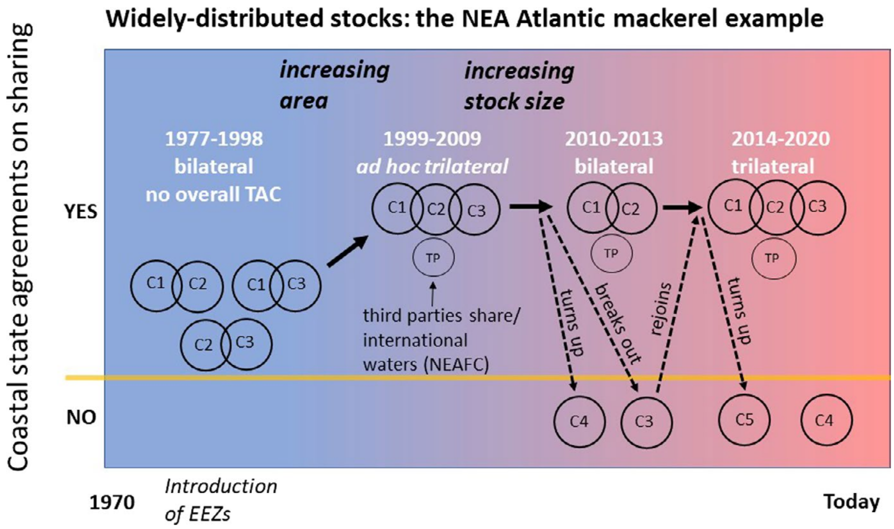


FIGURE 5 The unstable management situation for Northeast Atlantic mackerel since the late 1970s (i.e., from the introduction of exclusive economic zones [EEZs] through today). C1–C5: coastal states (see main body of text for further precision); NEAFC, North-East Atlantic Fisheries Commission; TP, third party. Colour grading (from blue to red) indicates a successively warmer climate. Shown are the type of agreements in place, and the time point when the distribution area and spawning stock size started to increase markedly. Horizontal line reflects whether the coastal state is part of the signed agreement

This unstable harvest of Northeast Atlantic mackerel caused suspension of eco-labelling certification (March 2019) issued by the Marine Stewardship Council (MSC) (Table S2). In the last 10–15 years, eco-labelling has become widespread in economically important European fisheries, and MSC is the leading player in this field. MSC noted: "The North East Atlantic mackerel stock had faced overfishing due to increased activity from fishing vessels outside of MSC certification. International agreements aimed at managing the stock had broken down and all MSC certificates were suspended." However, this underlying assessment of the Northeast Atlantic mackerel stock situation was encumbered with great uncertainty. Therefore, in March 2019, ICES conducted a new revision of the assessment method. It was concluded that the stock situation was more positive than previously assumed (ICES, 2019), but MSC certification has not been reinstated.

6 | DISCUSSION

The present synopsis demonstrates that the United Nations Convention on the Law of the Sea (UNCLOS, 1982) does not provide any *explicit* rule for allocation of quotas for transboundary and straddling fish stocks. This should be viewed in the light of that previously signed management agreements for such shared stocks were based on either political considerations or the geographical distribution of historical catches (Figure 4), while recently, agreements appear, to a larger extent, to be founded on zonal attachment model results (Figure 4). Zonal attachment, a more scientific approach, assesses stock distribution of different life-history stages for a representative year class (Hamre, 1993). Despite a series of accomplishments, management agreements might be seriously put to the test, when stock size and/or stock distribution are undergoing rapid change (Figures 3 and 5), as witnessed with IUU fishing in the Loophole for Barents Sea cod (Table S2: JNRFC; Kjesbu et al., 2014). The Northern hake stock has also significantly enlarged in size and spatially (Werner et al., 2016), although not into international seas but seeing the creation of a new independent coastal state, the UK (Shepherd & Horwood, 2019). In the case of Northeast Atlantic mackerel, the major north-westward extension was foreshadowed in the 1990s (Astthorsson et al., 2012) but materialized with the recent peak in stock abundance (dos Santos Schmidt et al., 2020; Nøttestad et al., 2016) (Figure 5). This synopsis emphasizes that both increased stock productivity and area extension relate closely to large-scale phenomena represented by the AMO reflecting cooler or warmer periods that last several decades (Sutton & Hodson, 2005). However, today's anthropogenic climate change (Figure 2) comes in addition to the positive phase of AMO, amplifying the impact of a climate-induced shift. Conversely, Norwegian spring-spawning herring seemed little impacted in this respect. This might be related to herrings, in general, being an ancient (primitive) species, phylogenetically speaking (Near et al., 2012), and thereby are likely well-adapted evolutionarily to highly fluctuating environmental stressors. Another explanation may be that the ambient temperature of the herring in the Norwegian Sea is still around the optimum for this species (dos Santos Schmidt et al., 2020). Therefore, for this stock, the management challenges refer principally to an increase in stock size post-collapse and the resulting area expansion. The current displacement of North Sea cod spawning grounds to the north-east North Sea (Sundby et al., 2017; Wright et al., 2018) is certainly attributed to climate change but accelerated by a parallel overfishing in the central-western North Sea (Engelhard et al., 2014). The overall stock situation is still poor (ICES, 2020) (Figure 3), although seeing recent positive trends locally in the proportion of larger cod greater than 40 cm corresponding with reductions in EU's bottom trawl efforts (Engelhard, Lynam, Garcia-Carreras, Dolder, & Mackinson, 2015). Moreover, the overfishing also seems to have influenced the genetics structure of the North Sea cod (Hutchinson, van Oosterhout, Rogers, & Carvalho, 2003), and such changes might be of more irreversible nature than the climate impacts. The present synopsis considers both warm- and cold-temperate species, the former represented by Northeast Atlantic mackerel and Northern hake, the latter by North Sea cod, Barents Sea cod and Norwegian spring-spawning herring (Sundby et al., 2016). Cold-temperate species in the far north and warm-temperate species thrive under the present set of environmental conditions (warming) whereas cold-temperate species in the south suffer, for example in terms of recruitment success. Ultimately, physiological responses (Pörtner & Peck, 2010) to current environmental conditions scale up to stock productivity (Petitgas et al., 2013), and, in cases, management challenges. Contemporary management challenges may, to some extent, be traced back to the time of EEZs being established under environmental conditions that largely deviated from those of today (Bindoff et al., 2019). More specifically, the AMO was in a cooler phase (Figure 2) and stock distributions were generally in a more southerly mode (see Section 4).

The above-outlined case-studies illustrate that the negotiation processes on quota allocation can be highly complicated and can take years before agreement is eventually reached. Increased scientific knowledge of stock distributions, however, has elevated the importance of zonal attachment as an input towards agreements on allocations. This article clarifies that negotiations involving a limited number of parties and relatively restricted interannual variation in stock migration dynamics (cf. cod in the North Sea or Barents Sea) produce agreements that are more stable than those for widely distributed, highly dynamic pelagic stocks, cf. Norwegian spring-spawning herring (Figure 4) and Northeast Atlantic mackerel (Figures 4 and 5). However, sustainable and successful fisheries management of transboundary and straddling stocks involves far more than quota allocations (cf. the mandate of JNRFC, NAFO and NEAFC; Table S2), and a comprehensive management regime, once established, may have a mitigating effect on potential future disagreement over allocations.

The establishment of EEZs, in many ways, marked the beginning of the development of modern fisheries management. A wide range of measures to support sustainable management in the Northeast Atlantic has been developed since the 1970s, an iterative process that continues today. Measures adopted at the global or regional level have been incorporated in national legislation and management. To support this development, scientific cooperation has been extended bilaterally and through ICES (see above), the prime scientific adviser to coastal states in the Northeast Atlantic. Technical regulations on issues such as gear, selectivity, protection of juveniles, and discarding practices have been improved and harmonized bilaterally or through NEAFC, as appropriate (see above). Beginning in the late 1990s, the precautionary approach has been embedded in management strategies and HCRs that are aimed at the maximization of long-term sustainable yield (www.ices.dk). By 2020, most Northeast Atlantic transboundary/straddling stocks are managed according to agreed management strategies and HCRs. Standards and protocols for the collection and exchange of data from fisheries (satellite tracking and electronic logbooks) have been introduced and harmonized throughout the region. For its regulatory area, NEAFC has adopted a comprehensive Scheme of Control and Enforcement, which includes control measures, monitoring of fisheries, inspection at sea, port state control of foreign vessels, infringement procedures and measures to promote compliance by vessels from non-contracting parties (NEAFC, 2019). In addition, numerous bilateral agreements on cooperation for control have been concluded between relevant coastal, flag and port states; Norway alone is party to 13 such agreements (Norwegian Government, 2019d). Most coastal states in the region annually conclude bilateral fisheries agreements, including the exchange of fishing opportunities in each other's waters. This network of diverse measures and cooperation, developed over the past 40 years, is hardly affected by disagreements on quota allocations for certain stocks. It could be argued that this mutual dependence has a dampening effect on conflicts regarding allocation. During the last few decades, ecosystem considerations have been increasingly emphasized and will gradually be incorporated in fisheries management (Gullestad et al., 2017; Link, Huse, Gaichas, & Marshak, 2020; Skern-Mauritzen et al., 2016). Related measures can be seen in the adoption of a number of area closures in international waters to protect vulnerable marine ecosystems (VMEs) (NEAFC; Table S2) or the introduction of regulations to protect vulnerable by-catch species, for example sharks (Ellis et al., 2008). We believe that the four decades of Northeast Atlantic experiences and efforts should be relevant to the joint management of shared resources in other parts of the world.

The distributions of stocks vary for a series of intrinsic reasons, for example stock size and demography, but also competition between species, climate fluctuations and, now, climate change. The consequence of climate change, as suggested in the five case-studies above, will likely be to create *long-term* changes in distribution for many fish stocks and increase the complexity involved in management agreements, particularly in quota allocations for transboundary and straddling fish stocks. The rapid growth in scientific expertise understanding natural variability and climate influences on fish stock abundances (e.g., Free et al., 2019) and distributions (e.g., Pinsky, Selden, & Kitchel, 2020) could have the potential to clarify premises for negotiations and thus facilitate agreements in the future. Impacts of climate change on marine fish and ecosystems involve a number of variables in addition to sea temperature (Moloney et al., 2011), and even temperature, alone, impacts marine organisms directly as well as indirectly through the food web. Correlations between sea temperature and biotic variables may, therefore, have multiple mechanistic links making it complicated to track all causal relations. In consequence, the *persistence* of a climate/temperature signal generally has more profound impacts on ecosystems than the *amplitude* of the signal. This is also because spatial and temporal scales of climate signals are correlated

(Drinkwater et al., 2014) implying that multidecadal (i.e., persistent) climate signals like AMO are associated with large spatial scales (i.e., Atlantic basin scale) and, hence, involving processes across regional marine ecosystems. Interannual climate variations, on the hand, often involve spatial scale smaller than extents of marine organism's habitats, at least for highly migratory and transboundary fish stocks.

Agreements are the result of a series of compromises among parties, not simple responses to recommendations resulting from scientific models or copies of previous agreements, based on other species or other parties on the same species. Access to fish within a given water (on a stock component) is often an important element in reaching an agreement. Flexible access may contribute to reductions in the cost of fishing or increases in the value of the catch (e.g., Gullestad et al., 2018) through exploitation patterns that increase the long-term stock yield to the mutual benefit of all involved parties (www.ices.dk). Further to this, a series of international declarations and legal instruments that support sustainable development have been added to overlying considerations over the last 30 years, including the 1992 United Nations Convention on Biological Diversity (CBD, 1992), the 1995 United Nations Fish Stock Agreement (UNFSA, 1995), the 1995 FAO Code of Conduct for Responsible Fisheries (FAO, 1995), the 2002 Johannesburg Declaration on Sustainable Development, adopted at the 2002 World Summit of Sustainable Development (WSSD, 2002), and the 2009 FAO Agreement on Port State Measures (PSMA, 2009). By signing these declarations, each party has limited their ability to manoeuvre towards unsustainable fishing behaviour.

A comprehensive set of management measures that eventually bind the parties may help to mitigate the most negative effects of lack of agreement on quota allocation. With an agreement on a management strategy and HCR, it is difficult to imagine that responsible coastal states by 2020 should open up an unregulated fishery by vessels flying their flag. When negotiating quota allocation, the party's fishing industry is usually the least willing to compromise. For fisheries where eco-labelling (MSC; Table S2) is vital for access to well-paying markets (Agnew, 2019), labelling may become a promising tool and an important driving force for the industry's willingness to agree to compromises. Eco-labelling of the Namibian and South African hake fisheries may become the first African example in this regard. Until now, these fisheries have been managed unilaterally by the parties. The South African fishery was certified by MSC in 2004 and is presently under re-assessment, whereas the Namibian fishery is in the process of certification. However, recent scientific research has shown that one of the hake species, the deep-water hake (*Merluccius paradoxus*, Merlucciidae), is a transboundary stock between the two countries (Burmeister, 2005; Jansen et al., 2017; Strømme, Lipinski, & Kainge, 2016). On 30 September 2019, MSC stated that certification of the *M. paradoxus* fishery will be subject to the standards and requirements of transboundary stocks (MSC, 2019b). Eco-labelling has thus become an important driver for the two countries to cooperate in stock assessment and in management of their hake fisheries.

In conclusion, bilateral agreements on quota allocations, once made, have shown resilience over time. It has been much more difficult to agree on similar types of allocations for widely distributed pelagic stocks, not only because such stocks migrate across several zones and involve more parties, but also because they have highly variable habitat extents, a trait that will be even more noticeable in the future under continued climate change. Therefore, agreements for such stocks are often temporary. Bilateral agreements, on the other hand, tend to be more comprehensive in terms of stocks and management cooperation, which may contribute to a mutual beneficial long-term partnership. This synopsis clarifies that earlier agreements were largely based on political consultations or distribution of historical catch data, while recent agreements are becoming increasingly science-based, exemplified by the zonal attachment model. However, emerging zonal attachment issues typically link directly to management challenges caused by altered or dynamically changing stock distributions. Agreements following the introduction of EEZs in the late 1970s were established when the climate was in a cooler phase and stock distributions were thus in a southerly mode typically. Current climate drives stock distributions polewards, for many stocks, which may or may not influence management schemes depending on the strength of the cooperative partnership.

ACKNOWLEDGEMENTS

We would like to thank colleagues at the Norwegian Directorate of Fisheries (FiskDir) for their most valuable comments on earlier manuscript drafts: Inger-Anne Arvesen, Gunnstein Bakke, Sigmund Engesæter, Kjetil Gramstad, Ida Omenaas Flaageng, Terje Løbach and Snorri Palmason. We thank Karen Gjertsen and Kjell Bakkeplass, Institute of Marine Research (IMR), for making the map. Dr Jennifer Devine, National Institute of Water & Atmospheric Research Ltd (NIWA), Port Nelson, Nelson, New Zealand, is warmly acknowledged for quality assessing a late version of the manuscript. We are also grateful to the Editor Dr Paul Hart and the reviewers for constructive comments—identified as Dr Georg H. Engelhard, Centre for Environment, Fisheries and Aquaculture Science (Cefas), Lowestoft, United Kingdom, and Dr Myron Peck, University of Hamburg, Hamburg, Germany. This study is a contribution to Grand Challenge III (GCIII) of the international IMBeR project (www.imber.info), presented at the 2019 Future Oceans$_2$ IMBeR Open Science Conference in Brest, France.

AUTHOR CONTRIBUTIONS

O. S. K. established this transdisciplinary study. P. G., S. S., and O. S. K. wrote the manuscript. All authors provided feedback on earlier manuscript versions and developed the conclusions.

DATA AVAILABILITY STATEMENT

Data were freely extracted from ICES (www.ices.dk). No other research data were consulted or produced during this study.

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SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section.

How to cite this article: Gullestad P, Sundby S, Kjesbu OS. Management of transboundary and straddling fish stocks in the Northeast Atlantic in view of climate-induced shifts in spatial distribution. *Fish Fish*. 2020;21:1008–1026. https://doi.org/10.1111/faf.12485