Stock Annex: Mackerel (*Scomber scombrus*) in subareas 1-7 and 14 and divisions 8.a-e, 9.a (the Northeast Atlantic and adjacent waters)

Stock specific documentation of standard assessment procedures used by ICES.

Stock: Mackerel

Working Group: Working Group on Widely Distributed Stocks (WGWIDE)

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Last updated: September 2021

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A. General

A.1. Stock definition

Atlantic mackerel (*Scomber scombrus*) occurs on both sides of the North Atlantic and has traditionally been grouped into five spawning components, some of which have been thought to be isolated natal homing populations. Previous studies have provided no evidence of cross-Atlantic migration and no, or weak, support for isolated spawning components within either side of the North Atlantic (Jansen and Gislason, 2013).

ICES currently uses the term "Northeast Atlantic (NEA) mackerel" to define the mackerel present in the area extending from the Iberian Peninsula in the south to the northern Norwegian Sea in the north, and Iceland in the west to the western Baltic Sea in east.

In the Northeast Atlantic, mackerel spawn from the Portuguese waters in the south to Iceland in the north and from Hatton Bank in the west to Kattegat in the east. Spawning starts in January/February in Iberian Peninsula waters and ends in July to the northwest of Scotland and in the North Sea (ICES, 2013a). While spawning varies locally from day to day (Bakken, 1977; Iversen, 1981), it seems to form one large spatio-temporal continuum on the larger scale. However, relatively low levels of spawning in the English and Fair Isle channels separates the main spawning areas in the North Sea from the western areas along the continental shelf edge (Johnson, 1977). Recent studies on distribution, eggs distribution and abundance and mark–recapture experiments (Reid *et al*., 1997; Uriarte and Lucio, 1996; Uriarte *et al*., 2001) have questioned the limits of previously established stocks and proposed to consider NEA mackerel as one single stock divided into three spawning components. These components are not completely independent but reproductive exchanges occur, and no differences were observed between these components outside the spawning season (Jansen and Gislason, 2013). Despite this lack of complete spatial or temporal separation, NEA mackerel is divided into three distinct entities, namely the Southern, Western and North Sea spawning components (ICES 1977; 2013a). Catches cannot be allocated specifically to spawning area components on biological grounds, but by convention; catches from the Southern and Western components are separated according to the areas in which these are taken:

Mackerel in the Northeast Atlantic			
Mainly distributed and fished in ICES Subareas and Divisions 2.a, 3.a, 4, 5, 6, 7, 8, and 9.a			
Spawning component	Western	Southern	North Sea
Main spawning areas	6, 7, 5, 3.a,b,d,e,	8.c, 9.a	4, 3.a

The Western component is defined as mackerel spawning in the western area (ICES Divisions and Subareas 6, 7, and 8.a,b,d,e). This component currently accounts for ~75% of the entire Northeast Atlantic stock. Similarly, the Southern component (~22%) is defined as mackerel spawning in the southern area (ICES Divisions 8.c and 9.a). Although the North Sea component has been at an extremely low level since the early 1970s, ICES considers that the North Sea component still exists as a discrete unit (~3%). This component spawns in the North Sea and Skagerrak (ICES Subarea 4 and Division 3.aN).

Jansen and Gislason (2013) recently reviewed the concept of spawning components on the basis of spawning and age distribution data. Spawning intensities, proxied by larval abundances, were found to be negatively correlated between the North Sea and Celtic Sea, which indicates that the two spawning components may be connected by substantial straying. This finding was based on unique larvae samples collected before the collapse of North Sea component, thus showing that the exchange is not a recent phenomenon due to the collapse. Furthermore, analyses of old as well as more recent age distributions showed that strong year classes spread into other areas where they spawn as adults (i.e., "twinning"). The authors found that this was in accordance with the lack of solid evidence of stock separation from previous analyses of tagging data, genetics, ectoparasite infections, otolith shapes, and blood phenotypes. Because no method has been able to identify the origin of spawning mackerel unequivocally from any of the traditional spawning components, and in the light of their results, they concluded that straying outweighs spatial segregation. Jansen and Gislason (2013) therefore proposed a new model where the population structure of mackerel was described as a dynamic cline, rather than as connected contingents. Temporal changes in hydrography and mackerel behaviour may affect the steepness of the cline at various locations (Jansen, 2014; Jansen and Gislason, 2013; Jansen *et al.*, 2013).

The most recent genetic publication using microsatellite methodology on mackerel support that there is no specific structuring in the mackerel stock; i.e., give no support to the suggestion that the three spawning components North Sea, Western and Southern represent specific populations (Gislason *et al.*, 2020). However, in order to get to the bottom on this with final conclusions future effort should be put on full genome sequencing based on an appropriate sampling regime as they have for herring, where they have found hundreds of loci underlying ecological adaptation to different geographic areas and spawning conditions (Han *et al.*, 2020). Still, for herring such differences are more expected as they are more adapted to specific spawning grounds with preferred gravel and spawning condition than the mackerel apparently is. The idea that the NEA mackerel is a large dynamics single fish stock distributing over a large area and shifting spawning grounds over periods also within year classes is supported by recent development of the international egg surveys (ICES WGMEGS), now concluding that mackerel presumably belonging the western component now migrates further north and east, extending its spawning into northern North Sea. The only recent tagging experiment in the North Sea 2011 supports that mackerel growing up in that area show no signs of adapting a migration pattern of a supposed North Sea component. The experiment demonstrated that young mackerel ages 1-2 developed their migration pattern in the same way as the rest of the stock, being recaptured off Iceland, in the Norwegian Sea, wintering off Shetland, and migrating southwards along British Isles in January-February (ICES, 2021b WD06). Despite the increased knowledge on mackerel population structure in recent years, ICES still have management decisions with basis in the concept of three spawning components. Hence WGWIDE 2021 recommends that a group is set up to carefully revisit the population structure in this stock with the aim to finally conclude we should move away from the three components concept, and if current management considerations should be revised accordingly.

A.2. Fishery

As a widely distributed and migratory species, NEA Mackerel is exploited over a wide geographic range throughout the year. Significant fisheries extend from the Gulf of Cadiz, along the western and northern Iberian costs, through the Bay of Biscay, S, W and N of the United Kingdom and Ireland, into the northern North Sea and the Norwegian Sea and, in more recent years as far north as 72°N and west into Icelandic and east Greenland waters.

The fishery is international and, as such it is exploited by several nations using a variety of techniques determined by both the national fleet structure and the behaviour of the mackerel. At the onset of the spawning migration, large mackerel shoals move out of the northern North Sea initially to the west before moving south down the west coast of Scotland and Ireland. The timing of this migration is variable but generally occurs around the end of quarter 4 and the start of quarter 1. During this time, they are targeted primarily by Scottish and Irish pelagic trawlers with RSW tanks and also by freezer (factory) vessels (primarily Dutch and German). Prior to the onset of this migration the mackerel are overwintering, relatively static and are targeted by a large Norwegian purse-seine fleet. During summer, the mackerel are more widely dispersed as they feed in Northern waters. At this time Russian pelagic freezer trawlers and, in more recent times, Icelandic, Faroese and Greenlandic pelagic vessels are active. The southern fishery takes place at the start of the spawning season upon completion of the spawning migration. The Spanish fleet is comprised of both bottom and pelagic trawlers and also a large artisanal fleet. There are other smaller scale fisheries such as a Norwegian gillnet fleet and an English handline fleet that operates in the otherwise restricted area known as the Cornwall box.

There are a number of national and international agreements to control the exploitation of the NEA Mackerel stock. Targeted fishing is prohibited in the North Sea with the purpose of protecting the North Sea stock component which has failed to recover from extremely heavy exploitation during the 1970s. The Cornwall box is an area off the SW coast of England that is a known juvenile area. It supported a very large fishery prior to its introduction in the early 1980s after which the only permitted fishing in this area is by handliners. A number of countries have discard prohibition. Unfortunately, there has been no overarching agreement in the most recent period which would permit control of the overall exploitation and catches have exceeded advice. Since 2015 within the EU a landing obligation came into force, under this new law all species managed through TACs and quotas must be landed. It was gradually implemented, affecting initially the EU pelagic and industrial vessels but since 2019 it affects all European commercial fisheries.

A.3. Ecosystem and behavioural aspects

A.3.1. Feeding

Post larval mackerel feed on a variety of zooplankton and small fish. They are a visual predator that ingest prey either by filter or particulate feeding and prefer larger over smaller prey items (Pepin *et al*., 1987; Langoy *et al*., 2006). The diel feeding varies with the diel pattern and availability prey (Jansen *et al*., 2019). Feeding patterns vary seasonally, spatially and with size (Trenkel *et al*., 2014; Óskarsson *et al*., 2016). The formation of feeding schools seems to follow prevailing currents (Nøttestad *et al*., 2016a). The shoal formation and movement during feeding vary, but are relatively unknown (Thomsen *et al*., 2020) Mackerel stops feeding almost completely during winter in some regions.

Main zooplankton prey species in the North Sea are copepods (mainly *Calanus finmarchicus*), euphausiids (mainly *Meganyctiphanes norvegica*), while fish prey species such as sandeel, herring, sprat, and Norway pout also contributes to the diet (Walsh and Rankine, 1979; Mehl and Westgård, 1983; ICES, 1989; ICES, 1997). In the Norwegian Sea euphausiids, copepods (mainly *C. finmarchicus* and *Oithona*), *Limacina retroversa, Maurolicus muelleri,* amphipods, Appendicularia and capelin are the main diet during the summer feeding migration (Langoy *et al.,* 2006; Prokopchuk and Sentyabov, 2006; Langoy *et al*., 2010). As for other northern areas, *C. finmarchicus* also constitutes most of the diet in Icelandic waters, but also euphausiids, amphipods and large crustaceans play an essential role (Óskarsson *et al*., 2016; Kvaavik *et al*., 2019).

In the North Sea, mackerel and horse mackerel are responsible for virtually all of the predation on 0-group herring as well as a large part of the consumption of 0-group Norway pout and of all ages of sandeel (ICES, 2008; Engelhard *et al*., 2014). Mackerel has also fed opportunistically on available Norwegian spring-spawning herring larvae along the continental shelf coast of Norway (Skaret *et al*., 2014; Allan *et al*., 2021). This may have a significant impact on the herring larval survival rate, and largely depends upon the degree of overlap in time and space, which can vary from year to year.

Spatial and temporal overlap between NEA mackerel and Norwegian spring-spawning herring particularly in the outskirts or periphery of mackerel distribution (northern Faroese, Icelandic and Jan Mayen waters) may cause increased interspecific competition between mackerel and herring for preferred food such as *Calanus finmarchicus* (Debes *et al*., 2012; Langøy *et al*., 2012; Óskarsson *et al*., 2012; Bachiller *et al*., 2016; Óskarsson *et al*., 2016). Mackerel may partly outcompete herring during summer because mackerel are generally larger, faster, more enduring when migrating and more effective plankton eaters, including a wider food niche (wider diet breadth) than herring (Nøttestad *et al*., 2012). In addition, the weight-at-length and growth rate of Northeast Atlantic mackerel over a period of three decades (1984-2013) was negatively influenced by both mackerel stock size and herring stock, which might imply that carrying capacity for the system was reached during this period (Óskarsson *et al*., 2016).

The mackerel seems to be very opportunistic, and from one year to the next they may exploit any available oceanic areas for feeding purposes (Langøy *et al*., 2012). A westwards and northwards expansion have been observed in the Nordic Seas in recent years (since 2007), as far as Icelandic and south Greenlandic waters in the west and as far north as Spitzbergen (Olafsdottir *et al*. 2019). Historically, expansions into Icelandic waters are known to coincide with periods of warm waters (Astthorsson *et al*., 2012).

The dynamics and environmental drivers of the mackerel summer distribution are not yet entirely uncovered. Surveys indicate substantial interannual variation and provides hypothesis on relations to temperature and food (Holst and Iversen, 1992; Holst and Iversen, 1999; Gill *et al*., 2004; ICES, 2006; ICES, 2007; ICES, 2009). When the mackerel stock is large (as in the recent years) and plankton abundance is low, mackerel has to spread out further to the north and to the west to forage on suitable plankton aggregations. The expansion of mackerel during the summer feeding season have been driven by increasing stock size, but constrained by availability of preferred temperature (as defined by water temperatures above 5-6°C) and abundance of mesozooplankton (Hughes *et al*., 2011; Nøttestad *et al*., 2012; Jansen *et al*. 2016; Olafsdottir *et al*. 2019). Moreover nutrient-driven migration might also play a role in the expansion (Pacariz *et al*., 2016). Most recently, although constraint by low temperatures, the summer feeding migration seem to be driven by prevailing currents, where the swimming direction of feeding schools in the Norwegian Sea follow the northward Atlantic current towards productive areas (Nøttestad *et al*., 2016a).

A.3.2. Spawning

Even though spawning occurs widely on the shelf and shelf edge from the Bay of Biscay to the southern Norwegian Sea, most of the egg production is concentrated in two core spawning areas (Figure A.3.2.1). One elongated area along the shelf break from Spanish and Portuguese waters in January to March, and one around southwest Ireland to the west of Scotland where spawning peaked in April (Beare and Reid, 2002; Iversen, 2002) but the spawning peak has shifted to March in the most recent years. In the central North Sea spawning takes place in May–July.

Spawning activity along the shelf edge has varied to the north and to the south at various times over the decades since the 1980s although the centre of gravity of spawning has remained relatively stable off the southwest of Ireland over this period (Hughes, 2013; Beare and Reid, 2002) In the North Sea there is a westward shift in the main spawning area from the central part of the North Sea in the early 1980s to the western part in recent years (2005 and 2008) (Anon, 2009).

In the recent period (since the 2007 survey) an expansion of the spawning distribution for the western spawning component has been observed (ICES, 2013b). Spawning occurs now further to the west (up to 20° of latitude west) and to the north (up to the southern Norwegian Sea) (ICES, 2013b; Nøttestad *et al*., 2012; 2013). However, most of the egg production of the western component remains in the traditional spawning grounds, located on the shelf edge in the southwest of Ireland to the west of Scotland. The egg production in the new areas remains marginal. The causes of this geographical expansion of spawning remain unclear, but are suspected to be triggered by the increase in the stock size (i.e., density-dependent space occupation) coupled with changes in the potential spawning habitat linked to environmental conditions (ICES, 2013b). As a consequence of this expansion of spawning to the North, juveniles 0-group mackerel are now found in the Nordic seas (Iceland, Barents Sea; ICES, 2013a).

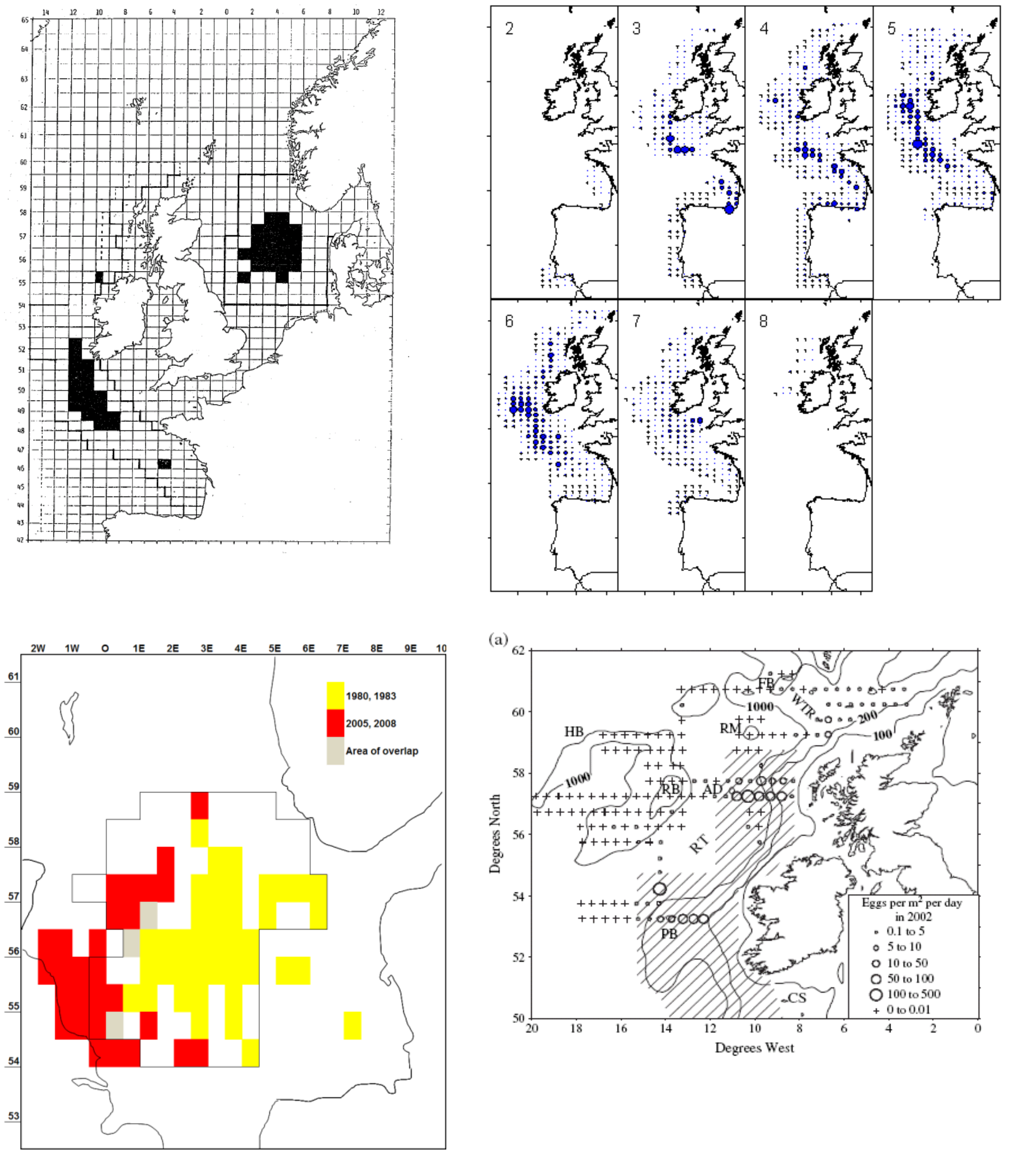

Figure A.3.2.1. NEA mackerel spawning areas. Upper left: Shaded areas indicate 100 eggs/m² in at least two of the years in the period 1977–1988 (from ICES, 1990). Upper right: Average distribution of mackerel eggs by ICES statistical rectangle in 1992–2007, each map represents a survey between February and August (from Anon, 2009). Lower left: North Sea spawning area defined by a daily egg production of at least 50 mackerel eggs per m2 of sea surface in any of the years 1980, 1983, 2005 and 2008 (from Anon, 2009). Lower right: Experimental survey in May 2002 (from Dransfeld *et al.*, 2005).

A.3.3. Migration

Within their geographical distribution range, mackerel perform extensive seasonal migration between southern spawning grounds, northern feeding grounds and overwintering areas, northern North Sea, and British Isles shelf areas (Jansen *et al*., 2012; Trenkel *et al*., 2014; Nøttestad *et al*., 2016b; ICES, 2020a).

Tagging studies (Uriarte and Lucio, 1996; Belikov *et al*., 1998; Uriarte *et al*., 2001; Tenningen *et al.,* 2011) have demonstrated that mackerel travel from both the western and southern spawning grounds north up into the North Sea and Nordic Seas. The migration can be considered as having two elements:

1) A post-spawning migration from the spawning areas along the western European shelf edge (Uriarte *et al*., 2001) to feeding grounds in Nordic Seas and North Sea (Tenningen *et al*., 2011; Slotte *et al.*, 2020)
2) A pre-spawning migration from feeding grounds in Nordic Seas and North Sea to the spawning grounds further south (Walsh *et al*., 1995; Reid *et al*., 1997). This pre-spawning migration includes shorter or longer halts that sometimes are referred to as overwintering.

The most pronounced change in migration and geographical distribution, since the early 2000´s, is a westward expansion and retraction of summer feeding migration in Nordic Seas (Olafsdottir *et al*., 2019; ICES, 2021b WD09). From the mid-2000s to mid-2010s, mackerel summer distribution expanded in two directions from the traditional feeding area in the central Norwegian Sea. Westwards, along the south coast of Iceland and towards the east coast of Greenland by approximately 1500 km, and northward towards Svalbard by approximately 500 km (Berge *et al*., 2015; Jansen *et al*., 2016; Nøttestad *et al*., 2016a). In summer 2019, mackerel enter Greenlandic waters in negligible numbers (ICES, 2019) and abundance in Icelandic waters has been limited to the southeast and east coast of Iceland since 2020 (ICES 2020a; 2021b WD09).

Temperature is a dominant factor impacting distribution of mackerel in Nordic Seas as mackerel is a temperate fish which inhabits warm Atlantic water masses and avoids cold Polar waters, limited mackerel abundance encountered in waters < 8-9 °C (Nikolioudakis *et al*., 2018; Olafsdottir *et al*., 2019). Range expansion was also related to increasing stock size and prey (mesozooplankton) abundance (Olafsdottir *et al*., 2019). Range retraction in the western area concurred with declining stock size (ICES, 2021a; b WD09). More research is needed to understand the mechanism impacting observed changes in summer feeding distribution of mackerel in Nordic Seas. It is likely that other factors such as spawning location and timing, predator avoidance, surface layer stratification, and nutrient depletion (Pacariz *et al*., 2016) could impact the summer feeding migration.

Tagging has shown that juveniles of the southern/western component do not migrate as far as the adults (Uriarte *et al.*, 2001). The larger fish reaches furthest to the north and west during the feeding migration in summer (Holst and Iversen, 1992; Nøttestad *et al.*, 1999; Anon., 2009; ICES, 2009; Tenningen *et al.*, 2011; Nøttestad *et al.*, 2016a). This effectively results in a spatial gradient in the mean length of the fish measured during the IESSNS (ICES WGWIDE 2012-2021), with larger mean length in the north and west, and smaller mean length to the southeast. Similarly, the large mackerel also arrive to the feeding areas (observed in eastern Danish waters) before and leave later than small mackerel (Jansen and Gislason, 2011). This can be explained by swimming speed during migration being positively related to fish length (Pepin *et al.*, 1988).

When the NEA mackerel return in late summer and autumn from the feeding areas on the European shelf and in the Nordic Seas, they aggregate through autumn and early winter along the continental shelf edge, where they are targeted by commercial trawlers and purse-seiners. Later in winter the commercial fleets and the fisheries-independent bottom-trawl survey find the mackerel further towards the southwest. The path of the migration, as suggested by the location of commercial and survey catches coincides with the location of the relatively warm high saline eastern Atlantic water flowing north-eastwards on and along the continental shelf edge, flanked by cooler water masses. The mackerel population is found further upstream in warmer waters as the current cools through winter and this process is associated via climatic variability, with large impacts on the mackerel migration and fisheries (Jansen *et al.*, 2012; Walsh and Martin, 1986; Reid *et al.*, 2003; Walsh *et al.*, 1995; Reid *et al.*, 1997; Reid *et al.*, 2001).However, other factors than temperature preferences, such as oceanic and coastal current systems, prey concentrations, feeding competition from other pelagic fish species and predation pressure are all affecting the mackerel behaviour, including schooling behaviour, and can in different scenarios have different weights (see ICES, 2020b WD09; Nøttestad *et al.*, 2016b; Olafsdottir *et al.*, 2016; 2019; Nikolioudakis *et al.*, 2019).

Timing of overwintering, spawning migration and spawning of the NEA mackerel has previously been linked to temperature, with, e.g., earlier overwintering and spawning related to increased temperatures (Reid *et al.*, 1997; Jansen *et al.*, 2012; Punzón and Villamor, 2009; Jansen and Gislason, 2011).

B. Data

B.1. Commercial catch

Data Compilation and Archiving

Prior to the annual assessment WG, national data submitters are responsible for submitting details of commercial catch and the associated sampling (carried out under the DCF in EU countries) to the stock coordinator. This information is supplied aggregated to ICES subarea and quarter. The data are usually detailed in an Excel spreadsheet (known as the 'exchange format') and also uploaded to InterCatch. InterCatch is a web-based data portal which is hosted by ICES and has the advantage of acting as a central repository for the data. Information on misreported catches, unallocated catches and discards can also be included in the submission. An up-to-date fleet description and a breakdown of catch by ICES statistical rectangle by month are also requested.

Upon completion of error checking, the stock coordinator will compile the data in order that it can be used in the assessment. A key step in this process is the allocation of samples to unsampled catches. The stock coordinator will choose appropriate samples (and their relative weightings) on the basis of fleet type, quarter and geographic area. Once the samples have been assigned the stock coordinator will produce a vector of catch numbers, weights and lengths in addition to the total catch. This was traditionally done using a bespoke software application known as *sallocl* (Patterson, 1998). Presently, this is run in parallel with InterCatch. Frequent comparisons are made using both approaches as a quality check.

Discards

The working group has estimated the level of discards since 1978. However, this is based on estimates provided by only a few countries and is routinely identified as being an underestimate. The level of underestimation is variable and unknown. The discard information that is included in the assessment of Northeast Atlantic mackerel comes mainly from observer programs.

The primary reason for the discarding or slipping (where the entire catch is released prior to being brought on board) of mackerel is on the basis of size. Other possible reasons include lack of quota, storage or processing capacity and when mackerel is taken as bycatch.

The discarding of high proportions of the total catch resulted in the establishment of the Cornwall box catch restrictions around the SW coat of England. Small mackerel is also often caught in the horse mackerel directed fishery, primarily in the English Channel, and is subsequently discarded either because of quota restrictions or unfavourable market conditions. Widespread discarding of fish weighing under 600 g also occurred in the early

1990s in response to the high prices paid for large fish which has been proposed as a possible reason for the low abundance of some year classes.

Data quality

If they are in possession of supplementary information, national data submitters can identify misreported catches. Often, catches will be transferred from one ICES area to another to account for information on misreporting. While not considered to be an issue in recent years, there is evidence of large-scale misreporting between ICES Subareas 4a and 6.a and 4.a and 2.a in the past.

A significant proportion of the complete catch time-series is considered to be of relatively poor quality in that it is believed that there is a significant underreporting of catch. A study into unaccounted mortality (Simmonds, 2007) suggested significant unaccounted mortality equivalent to 1.6 to 3.4 times the reported catch. This unaccounted mortality could be the result of unreported discards and slipping, fish that escape but subsequently die or unreported catch. Improved monitoring and stricter reporting requirements have resulted in improved confidence in recent years.

B.2. Biological

B.2.1. Weighting of spawning components

The spawning–stock biomass (SSB) estimates from the egg surveys in the North Sea and the western/southern area are used to compute the proportion of the NEA mackerel represented by each of the three spawning components. For a complete time-series of proportion of each component, see the report of the 2014 Benchmark Workshop on Pelagic Fish (ICES, 2014a) and the WGWIDE reports since then.

B.2.2. Weight-at-age in stock

The mean weights-at-age in the stock are based on available samples from the area and season of spawning of each of the spawning components.

For the southern component, stock weights are based on the samples from the Portuguese and Spanish catch taken in 8.c and 9.a in the 2nd quarter of the year, complemented by egg survey samples when available. For the Western spawning component, samples come from commercial catches, and when available, the egg survey for the areas and months corresponding to spawning (Table 2.2.1). In addition, fish sampled during the May tagging experiments by Norway in the northwest of Ireland are also included. For the North Sea spawning component, mean weights-at-age were calculated from samples of commercial catches collected from Area 4.a in June combined with data collected during the North Sea egg survey in May–June when available.

There are occasional years with missing data in the mean weights per spawning component (especially age 1). Since trends are present in the mean weights at age, it was considered appropriate to fill these gaps using the local average (among the 5 neighbouring years), which are more likely to be representative of the weight of the specific year with missing data than, for instance, a mean over the whole time series.

The mean weights-at-age for the total stock are then calculated as weighted mean of the weights in each component, where the weighting is the egg survey-based estimate of SSB in the three components. For a complete time-series on mean weights-at-age in the three components see the report of the 2017 Benchmark Workshop on Pelagic Fish (ICES, 2017b) and the WGWIDE reports since then.

Table 2.2.1. Areas and month corresponding to the core spawning used for the selection of samples to compute mean stock weights-at-age in the western component. Establish based on egg survey results (see ICES, 2017b).

MONTHS	ICES SUBDIVISION
March	7.b,j,h, 8.a,b
April	6.a, 7.b,c,j,h, 8.a
May	6.a, 7.b,c,j,k, 8.a,d

B.2.3. Proportions of individuals mature at age

The proportions of individuals mature at age are based on the following information:

North Sea component: The present proportions mature were calculated in 1984 on the basis of analysis of Norwegian biological samples from June–August 1960–1981. This revealed that 74% of the two year-old mackerel, which appeared in the catches, were sexually mature. By comparing fishing mortalities for II-group mackerel with the fishing mortalities for the 3-group the year after, when they are fully recruited to the spawning stock, it seems that about 50% of the II-group mackerel are available to the fishery. Assuming that only the spawning component of the stock is available in the fishery, maturity ogive for the North Sea stock was estimated (ICES, 1984).

Western component: Since the 2014 mackerel benchmark (ICES, 2014a) time varying proportions of individuals mature at age are calculated based on samples from the Dutch, Irish, German and UK commercial catches collected from February to July. Proportions of mature fish at age were calculated grouping the data in blocks of five years, and moving this five-year window from 1980 to the terminal year in the assessment. Due to the scarcity of samples for age 1 fish, the time varying estimate for this age is replaced by the mean across all years.

Catch data for the western component originate from different areas. Analysis done during the 2017 benchmark (ICES, 2017b) have shown that the proportion of juveniles is higher in some areas (Celtic Sea, English Channel) than others (Bay of Biscay, West of Ireland, West of Scotland). Since the proportion of the data coming from these different areas vary over time, this can introduce changes in the proportion of individual mature at age, not linked to actual changes in maturation schedules, but to variation in the proportion of the samples coming from areas of higher juvenile concentration. It was therefore decided, as a way of standardizing for potential variations in the spatial origin of the samples, to compute separate maturity ogives for each of 5 geographical zones (see table below), and to take the average of these ogives, weighted by the respective size (in km^2) of these geographic areas.

GEOGRAPHICAL AREAS	ICES SUBDIVISIONS	WEIGHT
Bay of Biscay	8.ab	7.3%
Eastern Celtic Sea	7.a,e-h	20.7%
West Ireland	7.b,c,j,k	26.7%
West Scotland	6.ab	42%
English Channel	7.d	2.9%

Southern component: Based on a histological analysis of mackerel samples collected during the 1998 Egg Survey (ICES, 2000; Perez *et al.*, 2000).

The proportions of mature mackerel-at-age for the total stock are calculated as the mean of the proportions in the three spawning components weighted by the respective size of each component (as estimated by the egg surveys).

B.2.4. Natural mortality and proportion of F and M before spawning

Natural mortality (M) has been fixed at 0.15 for decades. This value was calculated based on estimates of total mortality derived from tagging data combined with catch data (Hamre, 1980). The first mackerel working group report where this value was given in was 1983 (ICES, 1984).

Given the variability of the time of spawning, time varying proportions of F and M before spawning are used. The time of spawning is calculated for both the western and southern spawning component in each egg survey year as the Julian day where 50% of the total egg production has occurred. The time of spawning for the whole stock is then taken as the average of the time in these two components (weighted by their respective size). Assuming that natural mortality is constant through the year, the proportion of M occurring before spawning is equal to the proportion of the year before spawning time.

The proportion (per age group) of the catches taken before spawning time are calculated for each survey year as the sum of the quarter 1 catches plus the necessary proportion of the quarter 2 catches (if spawning time occurs in the second quarter) or as the necessary proportion of the catches in the first quarter (if spawning time occurs in the first quarter). Proportions of fishing mortality before spawning (F_{prop}) per age group are then estimated using an optimizer to find the F_{prop} value which minimizes the (square of the) difference between the observed proportion of catches before spawning, and the proportion of catches before spawning calculated based on the M_{prop} value and F at age values from the last available assessment. In order to reduce the effect of the noise in the data, average F_{prop} values are calculated by groups of age-classes: ages 1–2, ages 3–4 and ages 5 and older. F_{prop} for age 0 is by convention set to 0.

Time-series of M_{prop} and of F_{prop} at age based on linear interpolation between survey years are used as input to the assessment model. The M_{prop} and F_{prop} values of the latest survey are used for the most recent years, but these values are updated using linear interpolation when a new survey is carried out.

B.3. Surveys

B.3.1. Mackerel Egg surveys (MEGS: I4189 - Northeast Atlantic -, I1582 - North Sea-)

The working group on mackerel and horse mackerel egg surveys (WGMEGS) coordinates the mackerel egg surveys since 1977.These surveys cover Northeast Atlantic and the North Sea spawning grounds (Lockwood *et al*., 1981). These surveys are carried out triennially, although North Sea area survey is usually completed one year after the Western and Southern area surveys.

Since 1977 the annual egg production method (AEPM) has been used for estimation of NEA mackerel SSB (Lockwood *et al*., 1981; Lockwood, 1988) under the assumption that mackerel has a determinate fecundity. The AEPM estimates and combines total annual egg production (TAEP) and realized fecundity to calculate SSB (ICES, 2019b; c). With the AEPM, estimated egg production is integrated over the whole annual spawning season, using data from a series of surveys (sampling periods), and how many eggs are produced on average per unit mass of spawning female in the year. The entire spawning time of mackerel and horse mackerel is divided into different sampling periods.

The plankton samplers for use on these surveys used are mainly national variants of “Gulf high speed” plankton sampler (Gulf VII) or Bongo plankton nets with a mesh size of 280 µm. All samplers are towed in double oblique hauls at a speed of approximately 4 knots for Gulf type samplers and 2-3 knots for Bongo samplers. Recommended maximum sampling depth is to 200m, or to within 5m of the bottom where the bottom is less than 200m (ICES, 2019b). Next to the plankton samples pelagic trawl samples of adult fish are collected and collect ovary samples to estimate fecundity and atresia of female fish.

All eggs are sorted out and removed from plankton samples and identified to species. The mackerel eggs in the samples are staged according to development (Lockwood *et al*., 1981). The stage 1 eggs are used to estimate the daily egg production per sampling period. The stages in the estimation of annual egg production are:

- Estimating the daily egg production per rectangle.
- Estimating the period egg production for each survey period.

- Integrating the daily egg production using the histogram method, to estimate the total annual egg production (TAEP).
- Calculating the variance of the estimate of TAEP.

The mackerel SSB is estimated by dividing the total annual egg production by the realized fecundity of the females and multiplying by the sex ratio. The coordination of the surveys and SSB estimation are the responsibility of the working group for mackerel and horse mackerel egg surveys (WGMEGS). Preliminary results are reported by WGMEGS to WGWIDE in the year of the survey, the results of the survey are finalized and reported in the year after the survey.

B.3.2. International Bottom Trawl Surveys (IBTS: +ICES codes)

Observations from bottom-trawl surveys conducted between October and March from 1998 to the assessment year was compiled. Surveys conducted on the European shelf in the first and fourth quarters are collectively known as the International Bottom Trawl Survey (IBTS). All surveys sample the fish community on the continental shelf and upper shelf slope. IBTS Q4 covers the shelf from Spain to Scotland, excluding the North Sea, while IBTS Q1 covers the shelf waters from north of Ireland, around Scotland, and into the North Sea.

Trawl operations during the IBTS have largely been standardized through the relevant ICES working group (ICES, 2013c). Trawling speed was generally 3.5–4.0 knots, and trawl gear is also standardized and collectively known as the Grande Ouverture Verticale (GOV) trawl. Some countries use modified trawl gear to suit the particular conditions in the respective survey areas. In some cases, the standard GOV was modified, which was not expected to change catchability significantly. However, subsequent trawls deviated more significantly from the standard GOV type, namely the Spanish BAKA trawl, the French GOV trawl, and the Irish mini-GOV trawl. The BAKA trawl had a vertical opening of only 2.1–2.2 m and was towed at only 3 knots. This was considered substantially less suitable for catching juvenile mackerel and, therefore, was excluded from the analysis. The French GOV trawl was rigged without a kite and typically had a reduced vertical opening, which may have reduced the catchability of pelagic species like mackerel. Catchability was assumed to equal the catchability of the standard GOV trawl because testing has shown that the recruitment index was not very sensitive to this assumption (Jansen *et al*., 2015). Finally, the Irish mini-GOV trawl, used during 1998–2002, was a GOV trawl in reduced dimensions. The reduced wingspread and trawl speed were accounted for in the model (Jansen *et al*., 2015).

A geostatistical log-Gaussian Cox process model (LGC) incorporating spatio-temporal correlations was used to describe the catch rates of mackerel recruits over space and time. The modelled recruitment index (square root transformed catch rate because of density dependant catchability, see Jansen *et al.*

(2015)) surface in autumn year Y-1 and winter year Y was mapped every year.

The time series of spatially integrated recruitment index values are used in the assessment as a relative abundance index of mackerel at age 0 (recruits).

Data handling, modelling and post processing of the model output has been described in detail in Jansen *et al*. (2015).

B.3.3. International Ecosystem Summer Survey in Nordic Seas (IESSNS: A7806)

IESSNS is a swept-area surface trawl survey targeting the Northeast Atlantic mackerel stock as they feed in Nordic Seas, north of latitude 60 °N, and North Sea during summer (Nøttestad *et al.*, 2016b). The survey provides an age-segregated index of mackerel and is the only annual fishery independent tuning series used in the mackerel assessment (ICES, 2014a; ICES, 2017b; ICES 2019c). The survey was first executed in 2007 and annually since 2009. Faroe Islands and Iceland joined the survey in 2009, Greenland in 2014 and Denmark in 2018. Survey coverage gradually expanded westward and northward following geographical expansion of the mackerel stock and retracted in 2021 when Greenlandic waters and Icelandic waters, south of 62° 45′ N (strata 10, 11, 12) were not surveyed. North Sea was added to the survey in 2018 and has been surveyed annually since. Total survey coverage peaked at 3.2 million km^2 in 2019-2020 and declined to 2.5 million km^2 in 2021.

Trawl design, its operation, and sampling protocol are standardized between vessels and nations (ICES, 2013c). This includes a specifically designed and standardized pelagic trawl (Multpelt 832) towed in the surface at the speed of 5 nmi for 30 minutes using a curved tow track (ICES, 2013b; Valdemarsen *et al.*, 2014; Nøttestad *et al.*, 2016b). Trawl opening is approximately 30 m vertical height * 60 m horizontal spread. Trawl rigging maintains headline at surface during trawling. For details on trawl design, rigging and operational details see Valdemarsen *et al*. (2014), ICES (2013c) and Nøttestad *et al.* (2016b). Trawl catch sampling involves total catch weight, species composition determined from a subsample of total catch, and age is recorded for 10 – 25 individuals.

The survey is considered a "static point sampling survey" with a survey design focusing on representative sampling of mackerel and to prevent double counting of individuals. The design includes predetermined location of trawl stations and survey transects. Transects are from east to west, except in parts of the Icelandic exclusive economic zone (EEZ) where transects are across-shelf north and south of Iceland. The survey begins in the southern part of the Nordic seas, in the beginning of July, and heads northward as the 30-40 days survey period progresses. Three different methods have been used to determine transect/station location from 2007 to 2016:

- 2007 – 2011: distance between transects ranged from approximately 40-60 nmi and distance between stations on a transect ranged from 30-60 nmi. The first transect located in the middle of first rectangle (defined as the rectangle where the survey starts) and the first station manually located approximately 10 nmi from beginning of first transect. Other transects and stations located approximately at the predetermined distance from the first transect/station. Effort varies between different parts of the Nordic seas.
- 2012 – 2014: distance between transects ranged from approximately 40-60 nmi, but distance between stations varies (30 – 60 nmi) with latitude as the aim was to have one station in each rectangle (rectangle size: 1°latitude by 2°longitude). First station location, on transect, was manually selected with an aim to minimize sailing time. Other transects and stations located approximately at the predetermined distance from the first transect/station. Effort varies between different parts of the Nordic seas.
- 2015 onward: stratified random sampling within eight permanent and two dynamic strata implemented. Permanent strata are constant between years and cover the core mackerel distribution area in the Norwegian Sea and in the Icelandic EEZ. The dynamic zones are located at the westward and the northward distribution range periphery. Distance between stations varies between strata and ranges from 40 nmi to 80 nmi. Within each stratum, there is equal distance between all stations and transect. A combination of spatial variance in mackerel abundance, in years 2010-2014, and available survey time determines effort. Effort increase as abundance and spatial variability in abundance increases.

Stratum design changed in 2018 when the stratum for Greenlandic waters was split into two strata reflecting lower mackerel densities in the south compared to the north. Southern boundary of strata 5 and 6, west and south of Iceland, was set at latitude 62° 45′ N, a new stratum (number 12) as added south of Iceland, and the North Sea was added to the survey, stratum 13 (Figure B.3.3.1).

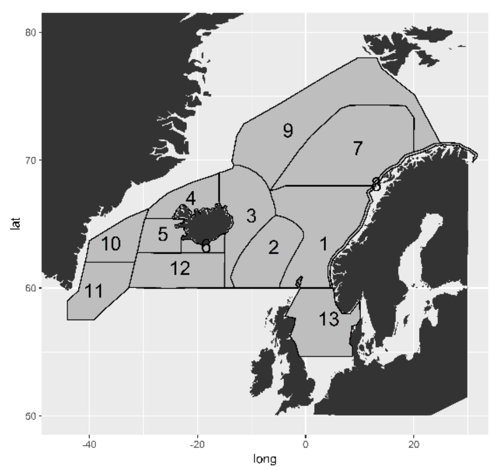

Figure B.3.3.1. Survey strata IESSNS 2018 onward.

The IESSNS index was first included in the mackerel assessment at the mackerel benchmark in February 2014 (ICES, 2014a). At the time, the index was calculated as an annual age-segregated density index including age 6 – 11, and year 2007 and from 2010 onwards. The density index was the total estimated biomass divided by the geographical survey area where mackerel was present. The index was calculated by gridding the survey area into rectangles (rectangle size: 1°latitude by 2°longitude in years 2007-2014, and 2°latitude by 4°longitude in 2015-2016) using a R-code. The area south of latitude 62 °N in the North Sea (east of longitude -2 °W) was excluded from further analysis (ICES, 2014a). Justification of index calculation method was apparent lower catchability of fish at age <6, variable and expanding coverage of the IESSNS survey coverage between years, uncertainty in catch efficiency with respect to vertical distribution of the stock in the North Sea, and the fact that the survey is only covering the oceanic part of the stock leaving out mackerel further south. Thus, the age-disaggregated indices constructed for analytical assessment purpose was spatially restricted to Nordic Seas, leaving out North Sea south of 62°N, delimited to age 6+ and scaled by the total area covered each year (number of fish per square km; equivalent to catch-per-unit-effort).

Prior to the benchmark in January 2017, it was decided to revise how the IESSNS index was calculated as three more years of IESSNS data had been collected. The revised index is an annual age-segregated abundance index including age 3 – 11, and year 2010 and from 2012 onwards (Olafsdottir *et al.*, 2017). The index is calculated using stratified approach in the StoX software (Salthaug *et al.*, 2017; Johnsen *et al.*, 2019). Survey coverage was acceptable for the included years; hence, the density index was replaced by an abundance index. Ages 3 to 5 were included as internal consistency has improved compared to the 2014 benchmark (ICES, 2014a), and a large proportion of the stock is in this age range. Years 2007 and 2011 were excluded due to limited spatial coverage of the survey compared to the other years (ICES, 2017b). Southern boundary of the survey area was set at latitude 60 °N as in the years 2010, and from 2012-2016, where there is sufficient coverage for the area north of 60 °N given the stratification method used to calculate the index. For details, see Olafsdottir *et al.* (2017).

Catch in the North Sea is excluded from the mackerel index used in the assessment because the 2017 mackerel benchmark stipulated that trawl stations south of latitude 60 °N be excluded from index calculations due to limited temporal coverage (ICES, 2017b). Results from the mackerel index calculations for the North Sea are presented in the cruise report which is available as a working document in the WGWIDE report (ICES, 2021 WD09). Denmark joined the IESSNS in 2018 and no problems applying the IESSNS methods in the North Sea were encountered. Area coverage, however, was restricted to the northern part of the North Sea at water depths larger 50 m (see ICES, 2021 WD09).

A new inter-benchmark on NEA mackerel was conducted 4-7 March 2019 (ICES, 2019d). It was then decided not to revise the IESSNS abundance index.

B.4. Commercial cpue

B.5. Other relevant data: Tagging data

Steel tags

The Institute of Marine Research in Bergen (IMR) has conducted tagging experiments on mackerel on annual basis since 1968, both in the North Sea and to the west of Ireland during the spawning season May–June. Information from steel-tagged mackerel tagged west of Ireland and British Isles was introduced in the mackerel assessment during ICES WKPELA 2014 (ICES, 2014a), and data from release years 1980-2004, and recapture years 1986-2006 has been used in the update assessments after this. The steel tag experiments continued to 2009, with recaptures to 2010, but this part of the data was at the time considered less representative and was excluded.

The steel tag methodology involved a whole lot of manual processes, demanding a lot of effort and reducing the possibility to scan larger proportions of the landings. The tags were recovered at metal detector/deflector gate systems installed at plants processing mackerel for human consumption. This system demanded external personnel to stay at the plants supervising the systems during processing. Among the typical 50 fish deflected, the hired personnel had to find the tagged fish with a hand-hold detector and send the fish to IMR for further analysis. It was decided in the end to go for a change in methodology to radio-frequency identification (RFID), which would allow for more automatic processes and increased proportion of scanned landings

RFID tags

The radio-frequency identification (RFID) tagging project on NEA mackerel was initiated in 2011, and replaced the manual method with steel tags, at the Institute of Marine Research, Bergen (IMR) in Norway. RFID is a technology that uses radio waves to transfer data from an electronic tag, called an RFID tag, through a reader for the purpose of identifying and tracking the object. The RFID tagging project has moved away from manual and expensive system to an automatic and cost-effective scanning system. The actual format of the tagging data used in the assessment is as numbers tagged of a year class in a specific year, the numbers recovered of this year class from that release year in all successive years, as well as the numbers screened by year class in all years.

In the WKPELA benchmark 2017 (ICES, 2017b) the RFID time series in terms of numbers per year class released, screened and recaptured per release year and recapture year was accepted for use in the assessment from 2017 onwards. The RFID tagging has continued annually since 2011. This includes an experiment off the Norwegian Coast on young mackerel in September 2011 as well as five experiments carried out in August in Iceland 2015-2019, none of which is included as input data in the assessment. In the assessment only data from the releases at the spawning grounds in May-June of Ireland and the Hebrides are included.

Mackerel are now recaptured at factories processing mackerel for human consumption in Norway, Scotland and Iceland. The project started with RFID antenna reader systems connected to conveyor belt systems at 8 Norwegian factories in 2012. Now there are 5 operational systems at 4 factories in UK (Denholm has 2 RFID systems) and 3 in Iceland. Norway has installed RFID systems at 8 more factories in 2017-2018, most of which with the purpose of scanning Norwegian spring spawning herring catches (IMR started tagging herring in 2016), but some also processing mackerel. More systems are also bought by Ireland (3), which up to now has been non-operational.

There is a web-based software solution that is used to track the different systems, import data on catch information, and biological sampling data of released fish and screened catches. Based on this information the system can estimate numbers released and screened by year class in a known biomass landed, which is used to estimate abundance by year class and totally. Research institutes, fisheries authorities or the industry need to provide additional data about catches screened through the RFID systems, such as total catch weight, position of catch (ICES rectangle), mean weight in catch, etc. Regular biological sampling of the catches landed at these factories is also needed. Altogether, these data are essential for the estimation of numbers screened per year class, which is needed as input to the tag data-table currently used in the SAM-assessment for steel tags.

Since the 2019 inter-benchmark process (ICES, 2019d), only a subset of the RFID data collected is used in the assessment. Investigation conducted at this benchmark indicated that the recapture rates of the given tagging experiment tended to decrease over time (most likely due to tag loss commonly found in other fish species tagged with these tags), which contributed to introducing spurious trend in the assessment, if the whole data set is used. To avoid this bias, only the first 2 years of recapture are used for each tagging experiment. In addition, other criteria were applied to the data that could be used; removing data from fish tagged as 4 years old or younger being few among the tagged fish, excluding the first two years of tagging experiments in 2011 and 2012 as the fishery was not covering the same distribution in 2012-2013 as in later years. However, the recent development in the time series suggests that this decision of filtering needs to be revisited, especially the potential of including data from ages 2-4 being abundant among tagged fish in the most recent years.

C. Historical stock development

The assessment model

SAM

A benchmark assessment for NEA Mackerel was carried out in 2014 during the Benchmark Workshop for Pelagic Stocks (WKPELA: ICES, 2014a). Following this benchmark investigation, the tool chosen for the assessment is SAM, the state–space assessment model (Nielsen and Berg, 2014). Since 2014, this method has been implemented using both the R package *stockassessment* and the online webpage interface on www.stokassessment.org.

In SAM, the "states" (fishing mortalities and abundances-at-age) are constrained by the survival equation and follow a random walk process. The variances of the random-walk processes on abundances and fishing mortalities are parameters estimated by the model.

SAM is a fully statistical model in which all data sources (including catches) are treated as observations, assuming a lognormal observation model. The corresponding variances, so-called observation variances, are also parameters estimated by the model. Observation variances can be used to describe how well each data source is fitted in the model and effectively correspond to the internal weight given by the model to the difference data sources.

The other parameters estimated are the catchabilities of the surveys.

Uncertainties (standard errors) are estimated for all parameters and for all states (Fs and Ns).

Modifications to SAM for the NEA mackerel assessment

In the SAM mackerel assessment, tagging–recapture data from the Norwegian tagging program are used as input data. In order to incorporate the tagging–recapture information, tag recoveries (per year and for each year class) were predicted from the model, based on the number of fish screened in the processing factories, the amount of tagged fish of the same year class released in the previous years, and the corresponding abundances of this year class in each release year estimated by the model, conditional to a post-release survival rate (time invariant and for all ages) which is a parameter estimated by the model. Given the nature of these data (count data with overdispersion) a negative binomial observation model is used.

Two distinct tagging recapture time series are used in the assessment. The steel tag series, providing information on the historical part of the assessment (recaptures until 2006) and the RFID tags time series, informing the model for the recent years (recaptures since 2014). Due to the differences in the two-time series with respected to tagging protocols, estimation of number recaptures and number scanned, the two series are used as two different datasets. This means, concretely, that the model estimates a post-release survival parameter for each series. Since the first time both were used together (ICES, 2017b), a large difference is observed in the estimated survival rates of the two tagging series, with around 40% and 15% survival for the steel tags and RFID tags, respectively. Part of the difference may indeed be explained by actual differences in survival, potentially due to the change in catching methods (hand jigging for the steel tags vs. automatic jigging for the RFID tags). However, the parameter called post release survival actually encompasses all processes happening after tagging, by which the concentration of tags in the population decreased comparted to the time of release. Processes such as tag loss, which are more likely to occur with RFID tags (ICES, 2019c) would contribute to a lower estimated survival rate. In addition, in the mathematical formulation of the expected recaptures, the survival rate appears together with other term (numbers scanned, number of tags detected in the factories). Any bias in these measurements would be confounded with the estimate of survival rate (ICES, 2019d).

At the 2019 inter-benchmark process (ICES, 2019d) several sources of potential bias were found in the way the RFID data was used in the 2014 benchmark. First, with more years of data, it became clear that the perception of the abundance of a year-class in a given tag release increased with the number of years separating release and recapture. This was assumed to be related to tag loss occurring along the years, progressively decreasing the concentration of tags in the population (and thereby indicating a larger abundance of the cohort at release). To avoid this source of bias, only tags recaptured after one and two years of liberty are now used in the model. There is also uncertainty about the degree to which fish tagged at a young age mix with the full population, as they may not undertake the same migrations as older fish. In addition, as younger fish may not have joined yet the spawning migration, there is a risk that the young fish tagged west of Ireland would belong only to a subpart of the population. In order to avoid these potential sources of bias, only fish tagged at an age of 5 or older are now used in the assessment. By applying, this selection on the RFID data, the number of data points used in the assessment has decreased drastically. This resulted in a decrease in the influence of the RFID data on the assessment. Before the 2019 IBP, the RFID had an excessive weight on the assessment, mainly due to the large size of the dataset.

Assessment model configuration

Catches for NEA mackerel for the period prior to 2000 are considered highly unreliable, due to a massive underreporting in the historical period. However, valuable information is available from other data sources (tags, egg survey) for the years before 2000. Instead of discarding all data prior to 2000, it was decided during the 2014 benchmark mackerel assessment to start the assessment in 1980, and reduce as much as possible the influence of the catches until 2000. This was done by arbitrarily down weighting the catches for the years prior to 2000, by imposing a high observation variance of these catches (equal to 1.35).

Furthermore, the model incorporates the steel and RFID tagging–recapture data, and three survey indices: the IBTS recruitment index, the mackerel egg survey SSB index and abundances indices from the IESSNS. In order to account for year effects (correlation of year-to-year variations across age-classes) in the IESSNS survey, the model has a AR1 observation error correlation structure for this survey.

More details on the input and on the survey indices incorporated in the assessment are given in the tables below (Y being the current year in which the assessment is carried out).

INPUT DATA TYPES AND CHARACTERISTICS:

Name	Year range	Age range	Variable from year to year
Catch in tonnes	1980–(Y-1)		Yes
Catch-at-age in numbers	1980*–(Y-1)	0–12+	Yes
Weight-at-age in the commercial catch	1980–(Y-1)	0–12+	Yes
Weight-at-age of the spawning stock at spawning time.	1980–(Y)	0–12+	Yes
Proportion of natural mortality before spawning	1980–(Y)	0–12+	Yes
Proportion of fishing mortality before spawning	1980–(Y)	0–12+	Yes (constant before 1989)
Proportion mature-at-age	1980–(Y)	0–12+	Yes
Natural mortality	1980–(Y)	0–12+	No, fixed at 0.15

*** Catches-at-age before 2000 are heavily down weighted which makes that in practice, they have little influence on the assessment.**

Tuning data:			
Type	Name	Year range	Age range
Survey (SSB)	ICES Triennial Mackerel and Horse Mackerel Egg Survey	1992, 1995, 1998, 2001, 2004, 2007, 2010, 2013, 2016,2019.	Not applicable (gives SSB)
Survey (abundance index)	IBTS Recruitment index (square root transformed)	1998–(Y-1)	Age 0
Survey (abundance index)	International Ecosystem Summer Survey in the Nordic Seas (IESSNS)	2010, 2012–Y	Ages 3-11
Tagging/recapture	Norwegian tagging program	Steel tags: 1980 (release year)–2006 (recapture year)	Ages 2 and older (age at release)
		RFID tags: 2013 (release year)–(Y-1) (recapture year)	Ages 5 and older (age at release)

Model configuration as defined during the 2019 inter-benchmark is given in the table below. In addition, the model has an age range from 0 to 12 and a plus group is set at 12 years. The reference fishing mortality, F_{BAR}, is calculated over the ages 4 to 8.

SAM parameter configuration:		
Setting	Value	Description
Coupling of fishing mortality states	0/1/2/3/4/5/6/7/7/7/7/7/7	Different F states for ages 0 to 6, one same F state for ages 7 and older
Coupling of catchability parameters	-1/-1/-1/-1/-1/-1/-1/-1/-1/-1/-1/-1/-1 0/-1/-1/-1/-1/-1/-1/-1/-1/-1/-1/-1/-1 1/-1/-1/-1/-1/-1/-1/-1/-1/-1/-1/-1/-1 -1/-1/-1/2/3/4/5/6/7/8/9/9/-1	No catchability parameter for the catches One catchability parameter estimated for the egg One catchability parameter estimated for the recruitment index One catchability parameter for each age group estimated for the IESSNS (age 3 to 11)
Power law model	-1/-1/-1/-1/-1/-1/-1/-1/-1/-1/-1/-1/-1 -1/-1/-1/-1/-1/-1/-1/-1/-1/-1/-1/-1/-1 -1/-1/-1/-1/-1/-1/-1/-1/-1/-1/-1/-1/-1 -1/-1/-1/-1/-1/-1/-1/-1/-1/-1/-1/-1/-1 -1/-1/-1/-1/-1/-1/-1/-1/-1/-1/-1/-1/-1	No power law model used for any of the surveys

Coupling of fishing mortality random walk variances	0/1/2/2/2/2/2/2/2/2/2/2 -1/-1/-1/-1/-1/-1/-1/-1/-1/-1/-1/-1 -1/-1/-1/-1/-1/-1/-1/-1/-1/-1/-1/-1 -1/-1/-1/-1/-1/-1/-1/-1/-1/-1/-1/-1 -1/-1/-1/-1/-1/-1/-1/-1/-1/-1/-1/-1	Separate F random walk variances for age 0, age 1 and a same variance for older ages
Coupling of log abundance random walk variances	0/1/1/1/1/1/1/1/1/1/1/1	Same variance used for the log abundance random walk of all ages except for the recruits (age 0)
Coupling of the observation variances	0/1/2/2/2/2/2/2/2/2/2/2 3/-1/-1/-1/-1/-1/-1/-1/-1/-1/-1/-1 4/-1/-1/-1/-1/-1/-1/-1/-1/-1/-1/-1 -1/-1/-1/5/6/6/6/6/6/6/6/-1 -1/-1/-1/-1/-1/-1/-1/-1/-1/-1/-1/-1	Separate observation variances for age 0 and 1 than for the older ages in the catches One observation variance for the egg survey One observation variance for the recruitment index One observation variance for the IESSNS age 3 and one for the ages 4-11.
Type of error correlation structure	"ID", "ID", "ID", "AR"	Auto-regressive correlation structure for the IESSNS index, independent observations assumed for the other data sources
Specification of the error structure	NA/NA/NA/NA/NA/NA/NA/NA/NA/NA/NA/NA NA/-1/-1/-1/-1/-1/-1/-1/-1/-1/-1/-1 NA/-1/-1/-1/-1/-1/-1/-1/-1/-1/-1/-1 -1/-1/-1/0/0/0/0/0/0/0/0/-1 -1/-1/-1/-1/-1/-1/-1/-1/-1/-1/-1/-1	A single correlation coefficient between all pairs of neighbouring ages (◎$_{3-4}$ = ◎ $_{4-5}$, ...= ◎ $_{10-11}$) in the autocorrelation structure for the IESSNS
Correlated random walks for the fishing mortalities	0	F random walk of different ages are independent
Stock–recruitment model	0	No stock-recruitment model (random walk)

Due to the high uncertainty in the recruitment estimates for the terminal year, Y-1, for the NEA Mackerel, the value estimated by SAM is arbitrarily replaced by the output of RCT 3 (see short-term prediction section).

D. Short-term projection

In a given assessment year Y, advice is given on catches for the following year Y+1 based on deterministic projections three years ahead (Y to Y+2). These projections are based on an assumption of the current year's (also called intermediate year) catch (see section below on "Assumptions for the intermediate year catch") from which fishing mortality in the current year Y is inferred, and a range of management options for the advice year, Y+1 (fishing mortality in Y+2 being the same as Y+1), are provided.

Initial abundances at age

The survivors on the 1st of January of year Y estimated by SAM are used as starting abundances at age in the first year of the short-term forecast. The recruitment estimate at age 0 from the assessment in the terminal assessment year (Y-1) is considered too uncertain to be used, because this year class has not yet been fully recruited into the fishery. The last (Y-1) SAM recruitment estimate is therefore replaced by predictions from the RCT3 software (Shepherd, 1997). The RCT3 software performs a linear regression between the IBTS recruitment index and the SAM estimates over the period 1998 to Y-2, and, based on this regression, predicts the Y-1 recruitment from the Y-1 IBTS index value. The final Y-1 recruitment is the average between the prediction from this regression and a time tapered geometric mean of the SAM recruitments up to Y-2, weighted by the inverse of their respective prediction standard errors. The historic performance of the IBTS index thus determines the influence of the Y-1 index value on the Y-1 recruitment produced by RCT3. A weak correlation of the survey index with the SAM estimates brings the RCT3 estimate close to the SAM geometric mean, while a strong correlation brings it close to recruitment predicted from the IBTS index for the year Y-1. The "time tapered geometric mean" is a weighted geometric mean, where the most recent years are given the highest weights.

The abundance of the survivors-at-age 1 (in Y) used as starting values for the short-term forecast is then estimated by bringing forward recruitment-at-age 0 (in Y-1) applying the total mortality-at-age 0 in year Y-1 estimated by SAM.

Conditioning of the short-term forecast

Recruitment

The recruits at age 0 in year Y, Y+1 and Y+2 are set to the geometric mean from 1990 to Y-1.

Exploitation pattern

The exploitation pattern (relative selection pattern) used in the predictions from Y to Y+2 is defined as the average of the exploitation pattern of the last three years in the assessment (Y-3 to Y-1), obtained by dividing the fishing mortalities-at-age of those three years by the value of F_{BAR}4–8 in the corresponding years.

Maturity-at-age, weight-at-age in the catch and weight-at-age in the stock

The three-year average of Y-3 to Y-1 is used for the proportion mature-at-age as well as stock and catch weights-at-age.

Proportion of natural and fishing mortality occurring before spawning

The three-year average of Y-3 to Y-1 is used for the proportions F_{prop} and M_{prop}.

Assumptions for the intermediate year (Y)

The catch in the intermediate year (Y) is taken as a TAC constraint. The catch is estimated from declared quotas modified by e.g., paybacks (e.g., EU COMMISSION REGULATION (EC) No 147/2007), discards (assumed to be equal to the last reported discards in year Y-1), interannual transfers and expected overcatch. Scientists from the relevant countries present at the WGWIDE each year provide the information on interannual transfers and expected overcatch.

Management Option Tables for the TAC year

The different management options for the catch in Y+1 are presented, covering the ICES MSY approach and ICES precautionary approach, and the agreed management strategy (in case there is). The zero catch and constant catch options are also given for illustration

Software implementation

The deterministic projections are calculated in R using FLR, based on the function *stf()* from the library FLash (Kell, 2017). The output of the R script was compared with the output of the old ICES software MFDP and the results were found to be identical.

E. Medium-term projections

No medium-term projections are carried out at WGWIDE for this stock.

F. Long-term projections

No long-term projections are carried out at WGWIDE for this stock.

G. Biological reference points

A management strategy evaluation Interbenchmark Workshop on the assessment of northeast Atlantic mackerel (WKMSEMAC) was conducted in 2020 (ICES, 2020b) which resulted in the adoption of new reference points for NEA mackerel stock by ICES.

Precautionary reference points.

B_{lim} **-** There is no evidence of significant reduction in recruitment at low SSB within the time-series (ICES, 2019d) hence the previous basis for B_{lim} is retained. B_{lim} is taken as B_{loss}, the lowest estimate of spawning–stock biomass from the revised assessment (ICES, 2019e). This was estimated to have occurred in 2003; B_{loss} = 2.00 Mt.

F_{lim} **-** F_{lim} is derived from B_{lim} and is determined from the long-term equilibrium simulations (ICES, 2020b*)* as the F that on average would bring the stock to B_{lim}; F_{lim} = 0.46.

B_{pa} **-** The ICES basis for advice requires that a precautionary safety margin incorporating the uncertainty in actual stock estimates leads to a precautionary reference point B_{pa}, which is a biomass reference point designed to avoid reaching B_{lim}. Consequently, B_{pa} was calculated as B_{lim} * exp(1.645 σ_{SSB}) where σ_{SSB} = 0.14 was taken as the estimate of spawning biomass uncertainty in the most recent year (2019) as estimated by the updated assessment (ICES, 2019e); B_{PA} = 2.58Mt.

F_{pa} – The ICES basis for advice requires that a precautionary safety margin incorporating the uncertainty in actual stock estimates leads to a precautionary reference point F_{pa}, which is a fishing mortality reference point designed to avoid reaching F_{lim}. Following the updated Technical Guidelines on ICES fisheries management reference points for category 1 and 2 stocks in 2020, F_{pa} was set equal to $F_{p0.5}$ (0.36).

MSY reference points

A sequence of MSE simulations (ICES, 2020b) were conducted in line with ICES Technical Guidelines (ICES, 2017a) to derive an estimate for F_{MSY} of 0.26.

Recruitment was parameterised by a mixed model approach (30% Ricker, 20% Segmented Regression and 50% Beverton & Holt, percentages from the *msy* R package), fit to data points from the period 1998-2018 using maximum likelihood estimation, carried out within the FLR framework. Autocorrelation in recruitment was included within the simulation.

MSY $B_{trigger}$ is a biomass reference point that triggers a management response to avoid stock depletion when fishing at F_{MSY}. It is defined as the 5_{th} percentile on the distribution of SSB when fishing at F_{MSY}. However, fishing mortality on NEA Mackerel has been significantly greater than the F_{MSY} estimate for a number of years, and particularly in the most recent period. Thus, the B_{pa} value of 2.58Mt was selected as the appropriate value for MSY$B_{trigger}$.

A summary of the reference points is given below:

Type		Value	Technical basis
Management Plan	$SSB_{trigger}$	N/A	
	F target	N/A	
MSY Approach	MSY $B_{trigger}$	2.58 Mt	Bpa
	F_{MSY}	0.26	Stochastic simulation
Precautionary Approach	B_{lim}	2.00 Mt	Bloss from 2019 update assessment (ICES, 2019e)
	B_{pa}	2.58 Mt	B_{lim} * exp(1.654*σ_{SSB}), σ_{SSB}=0.15
	F_{lim}	0.46	The fishing mortality that, on average, leads to B_{lim}
	F_{pa}	0.36	F_{p05}

H. Other Issues

H.1. Management plans and evaluations

The management plan adopted in 2014 by three of the Coastal States (EU, NO and FO) was evaluated by ICES (ICES, 2014b) on the basis of the 2014 benchmark method.

The following benchmark assessments performed in 2017 (WKWIDE: ICES, 2017b) and 2019 (IBPNEAMac: ICES, 2019d) lead to a substantial revision of the perception of the stock. Consequently, the management plan required new revisions. Both in 2017 and 2020, on the request of the coastal states, ICES updated the tables that were presented in its response to the EU, Norway, and the Faroe Islands request to ICES to evaluate a multi-annual management strategy for mackerel in the Northeast Atlantic (ICES, 2014b). In 2017, the options that were precautionary and maximized the median long-term yield were F targets around 0.22–0.26 and $B_{trigger}$ values around 2.8 to 4.2 million t, with higher F targets being associated with higher $B_{trigger}$ values. With minor effect when incorporating a TAC constraint and where increasing the F_{target} or the $B_{trigger}$ values resulted in increased interannual variability in yield. Results from preliminary modelling of density-dependent weights suggested that higher target Fs would likely be possible while remaining precautionary. However, better scientific understanding of the link between stock size and growth and the development of an appropriate modelling approach would be needed before these types of changes in growth can be incorporated in the evaluation of the harvest control rule.

In 2019, ICES provided (F_{target}, $B_{trigger}$) combinations maximising the median annual yield in the long term and simultaneously minimising the risk of the stock falling below B_{lim}. These where, F_{target} values between 0.27 and 0.30, with $B_{trigger}$ values between 3 and 4.5 million tonnes. Where higher F_{target} values were associated with higher $B_{trigger}$ values. The maximum sustainable yield (MSY) was estimated to be 970 000 tonnes in the long-term, which corresponded to an F_{target} = 0.29 and a long-term median SSB at 4.5 million tonnes when simulated with $B_{trigger}$ = 4.25 million tonnes. The simulations suggested that long-term yields within 1% of MSY could be achieved with a lower F_{target}, that would result in higher SSB and less variation in the yield and SSB in the long-term. When additional management measures (limitation of TAC inter-annual variation and banking and borrowing) were applied in the harvest control rule (HCR), they had a limited influence on the median annual long-term yield or stock status. If future recruitment is lower than that observed from 1998 onwards, simulations show that this will result in both reduced yield and increased risk of SSB < Blim.

H.2. Data limited approach for NEA mackerel

Context

In 2013 ICES was required to provide advice for the mackerel stock on the basis of no agreed quantitative assessment and corresponding management target and reference points, an exploitation rate which was potentially above the previous reference levels and no international agreement on catches.

For other stocks for which no quantitative assessment was available ICES had previously employed the WKLIFE Data Limited Stocks (DLS) approach (ICES, 2012) to provide precautionary management advice. ICES considered the DLS Method 3.2 approach, which uses survey trend-based scaling of catches, applicable to the NEA mackerel. WKLIFE3 (ICES, 2013e) had evaluated the method using a simulated gadoid stock and concluded that for overexploited stocks without a defined management target, a precautionary buffer which reduced catch levels by 20% would be required to prevent increasing risk to the stock when the control rule was applied over the longer term; however, caveat scenarios in which the precautionary buffer might not be required were also discussed.

ICES ACOM eventually gave advice on NEA mackerel based on a recent catch, citing the preliminary nature of the most recent egg survey, the lack of good uncertainty estimates and the lack of agreement on whether a precautionary buffer (20% reduction in catches in the first year of application) should be applied. WKLIFE3 later examined the ICES NEA mackerel advice in 2013 and made the following comment:

"**<u>Mackerel in the Northeast Atlantic</u>**: In the 2013 advice season, ACOM treated this stock in an *ad hoc* way rather than as a data-limited stock proposed by their own ADG. The rationale for this is neither adequately nor clearly explained in any ICES document. On balance, WKLIFE do not understand the rejection of the DLS guidance and support the ADG's recommendation to treat this stock with a Category 3 method incorporating the *precautionary buffer*."

As a result of the uncertainty in the application of the ICES DLS Method 3.2 to mackerel, WKPELA (ICES, 2014a) agreed that a more detailed, stock-specific evaluation of the ICES DLS Method 3.2 application to the NEA mackerel should be conducted in order to provide guidance for management advice in the event that a quantitative assessment was not available.

NEA mackerel simulations

WKPELA (ICES, 2014a) used a MSE simulation framework in FLR, R version 2.10.1 (2009-12-14), Core package of FLR, fisheries modelling in R. Version: 2.3-644. Flash Version: 0.7.0. Evaluations were carried out based on a simulated mackerel stock with stock dynamics (growth, recruitment, etc.), single fleet exploitation and a single fishery-independent survey index.

Fishery-independent time-series

WKPELA considered that the triennial egg survey index of SSB with a CV of the order of 24% gave the only, more or less complete, index of SSB (the egg survey does not include egg mortality and so it is not considered an absolute SSB estimate).

Harvest control rule

As the survey is carried out triennially setting the catch for three years as multi-annual advice (y+1 to y+3) is appropriate and the DLS Method 3.2 becomes:

$$C_{(y+1,y+2,y+3)} = C_{(y)} * Fac \qquad \text{Equ. H.2.1}$$

where Fac is derived from DLS Method 3.2 such that with S(y) the survey index in year y

$$Fac = ((S_{(y)} + S_{(y-1)}) /2) / ((S_{(y-2)} + S_{(y-3)} + S_{(y-4)}) /3) \qquad \text{Equ. H.2.2}$$

Mackerel egg survey indices are available every three years so that $S_{(y-1)}$, $S_{(y-2)}$ and $S_{(y-4)}$ are derived by linear interpolation from the surveys in $S_{(y)}$, $S_{(y-3)}$ and $S_{(y-6)}$ such that after simplification:

$$Fac = 3/2 * (5*S_{(y)} + S_{(y-3)}) / (S_{(y)} + 7*S_{(y-3)} + S_{(y-6)})$$
Equ. H.2.3

Interannual variability, which could result from noise in the survey index series, is damped by the use of an uncertainty cap, such that:

$$Fac > 1.2 \Rightarrow Fac = 1.2 \qquad \text{Equ H.2.4a}$$

$$Fac < 0.8 \Rightarrow Fac = 0.8 \qquad \text{Equ H.2.4b}$$

In addition to the uncertainty cap, the application of ICES precautionary buffer margin of -20% for the first application of the rule was evaluated.

$C_{(y+1,y+2,y+3)} = C_{(y)} * 0.8 * Fac$ at the first application and Equ H.2.5a

$C_{(y+1,y+2,y+3)} = C_{(y)} * Fac$ for subsequent iterations Equ H.2.6b

DLS simulation results

Twelve scenarios were evaluated, four rule implementation options (with and without the PA buffer and the uncertainty cap) under three different stock starting conditions: historic fishing mortalities, F=0.22 (~F_{MSY}) and F=0.45 (~2*F_{MSY}). In all cases the stock was conditioned from 1981 to 2009 and DLS management simulated to start in 2009 with first year of catch under this regime in 2010.

The performance of the DLS method was considered in the context of ICES precautionary criteria by comparing the lower 5th percentile of SSB in each forecast year with a B_{lim} proxy (B_{loss}, Figure H.2.1). The inclusion of the precautionary buffer had a major influence on the likelihood that SSB had a greater than 5% probability of falling below B_{lim}. In all cases in which the precautionary buffer was not applied a substantially higher percentage than 5% of the stocks fall below B_{lim} and a significant proportion collapse; the inclusion of the PA buffer appears to prevent collapse in the medium term, independent of the starting conditions in the scenarios examined. This suggests that the application of the ICES DLS Method 3.2 as simulated, using triennial egg surveys to calibrate catch set for a period of three years is precautionary when the buffer is applied; it is not without the application of the buffer.

DLS method conclusions

WKPELA (ICES, 2014a) concluded that the simulations provided very clear guidance that exploitation using the ICES DLS Method 3.2 using the triennial egg survey based on equation H.2.3 would provide precautionary management advice for the provision of triennial multiannual TAC (three years) for the NEA mackerel stock in the absence of an agreed assessment.

The application of the ICES DLS Method 3.2 to the NEA mackerel requires the inclusion of the precautionary buffer at 20% in the first year of implementation (Equation H.2.4ab) and risk of SSB<B_{lim} is also reduced by the application of the uncertainty cap at 20% in each change of three year TAC (Equ H.2.5ab).

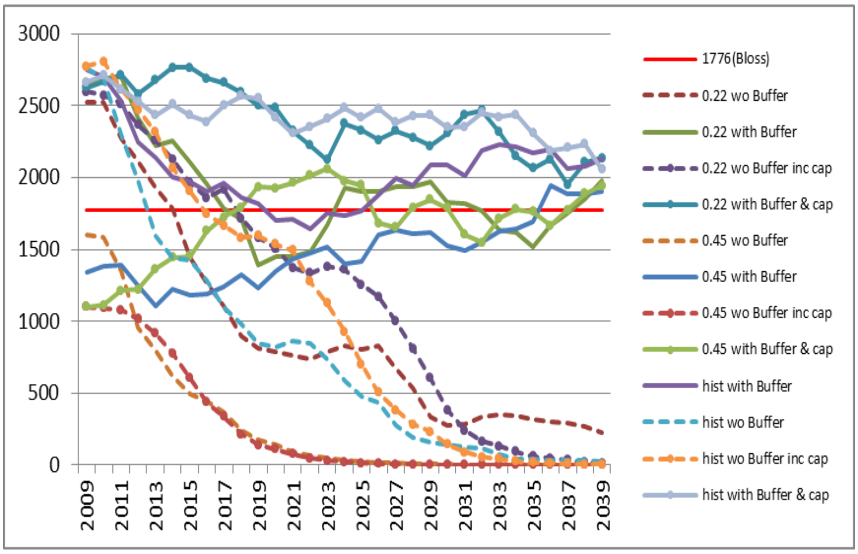

Figure H.2.1. Summary of NEA mackerel DLS Method 3.2 simulations in terms of ICES precautionary criteria. Three starting options 1) stable F=0.22, 2) stable F=0.45 and 3) historic state in 2009. Two options for calculating future catch are tested 1) PA Buffer included (solid lines) or not (dotted lines) 2) +/-20%cap on TAC change included (symbol on the line) or not (no symbol). These results demonstrate that it is essential to include the precautionary buffer if the lower 5% on SSB is to be kept above the assumed B_{lim}.

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