

Marine fish mortality considerations as part of maximum sustainable yield calculations

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ABPmer

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Contents

1.	Crynodeb gweithredol	6
2.	Executive summary	8
3.	Introduction.....	10
4.	Fish stock assessment	11
4.1.	Maximum sustainable yield	122
4.2.	Reference points	133
4.3.	Setting TACs	133
5.	Natural mortality Error! Bookmark not defined.	4
5.1.	Definition	144
5.2.	Components of natural mortality.....	155
5.2.1.	Abiotic factors	155
5.2.2.	Biological factors	155
5.2.3.	Anthropogenic factors	166
6.	Natural mortality estimates in North Sea and Irish Sea stock assessments	177
6.1.	M=0.2.....	177
6.2.	Lorenzen (1996).....	18
6.3.	North Sea multi-species model.....	199
6.4.	Irish Sea benchmarking process	20
6.5.	Individual species.....	211
6.5.1.	Cod and Whiting.....	211
6.5.2.	Herring	233
6.5.3.	Sprat	24
6.5.4.	Sandeel.....	244
6.5.5.	Mackerel	255
7.	Assessing the significance of mortality from anthropogenic activities.....	266
8.	Conclusions	27
9.	References	288
10.	Abbreviations and acronyms.....	32
	Data Archive Appendix	34

List of figures

Figure 1 Schematic representation of fish stock dynamics	11
Figure 2 Schaefer model of surplus production showing the maximum sustainable yield	12
Figure 3 The process of data collection, stock assessment, testing a management rule and identification of recommended catch or effort levels.....	14
Figure 4 John Pope's parody of the derivation of $M=0.2$	18
Figure 5 Estimated M -at-age for whiting in 7.a (solid black line). Ranges of M (red broken line) were estimated for the mean $\pm$ s.d. wet weight. The previously assumed level of M (0.2) is shown (black broken line)	23

List of tables

Table 1 Mortality-weight model parameter estimates for juvenile and adult fish in different natural ecosystems and aquaculture systems, and latitudinal effects.....	19
Table 2 Natural mortality estimates for cod, haddock, whiting and herring since 2000 from the North Sea SMS model, reported in 2016.....	20
Table 3 Lorenzen natural mortality estimates for cod in the Irish Sea.....	22
Table 4 Estimates for natural mortality for Irish Sea whiting based on Lorenzen (1996).....	22
Table 5 Natural mortality estimates for herring with age (expressed in number of winter rings) in the Irish Sea.....	24

1. Crynodeb gweithredol

Mae Cyfoeth Naturiol Cymru (CNC) yn ceisio cael dealltwriaeth o'r amcangyfrifon marwoldeb naturiol ac anthropogenig sydd wedi'u hymgorffori mewn asesiadau stoc pysgod môr gan y Cyngor Rhyngwladol Archwilio'r Môr (ICES). Nod asesiad stoc pysgod yw asesu statws presennol stoc pysgod a rhagfynegi beth fydd yn digwydd o ran cynnyrch yn y dyfodol, lefelau biomas a chyfaint (neu werth) y ddalfa, ar gyfer lefelau penodol marwoldeb pysgota. Defnyddir yr amcanestyniadau hyn i bennu mesurau rheoli priodol, fel cyfanswm y ddalfa a ganiateir, yn seiliedig ar yr amcanion rheoli (e.e. i fanteisio ar stoc yn unol â'r cynnyrch cynaliadwy mwyaf). Mae'r adroddiad hwn yn adolygu cydrannau marwoldeb naturiol sy'n cael eu hymgorffori mewn asesiadau stoc pysgod, ac yn benodol ar gyfer penfras, gwyniad môr, pennog, corbennog, llymrien a macrell ym Môr y Gogledd a Môr Iwerddon.

Mae marwoldeb naturiol yn newidyn allweddol yn y modelau asesu stoc ac felly caiff ei ddefnyddio i amcangyfrif pwyntiau cyfeirio cynnyrch cynaliadwy mwyaf a chynghor ynghylch cyfanswm y ddalfa a ganiateir. Ystyrir bod marwoldeb naturiol yn cynnwys pob ffynhonnell marwolaeth stoc pysgod y tu allan i'r hyn a achosir gan bysgota. Felly mae'n cynnwys marwolaeth o ganlyniad i ysglyfaethu gan bysgod, adar a mamaliaid morol eraill, marwolaeth o ganlyniad i ffactorau biotig ac anfiotig (tymheredd, clefyd) a marwolaeth sy'n deillio o weithgareddau anthropogenig. Mae'r amcangyfrif o lefel y marwoldeb naturiol wedi symud ymlaen o ragdybiaeth gyffredinol o $M=0.2$, i amcangyfrifon sy'n benodol i oedran, ac amcangyfrifon sy'n ystyried lefelau marwolaeth o ganlyniad i ysglyfaethu yn benodol.

Mae marwoldeb naturiol yn uwch ar gyfer oeddrannau iau (meintiau llai) a chyfnodau larfaol, a chaiff hyn ei adlewyrchu'n gynyddol mewn asesiadau stoc (megis yn yr amcangyfrifon a ddiwygiwyd yn ddiweddar ar gyfer penfras a gwyniad môr ym Môr Iwerddon) gydag amcangyfrifon sy'n dibynnu ar oedran. Ar wahân i farwoldeb pysgota, un o'r prif ffynonellau marwolaeth yw marwolaeth o ganlyniad i ysglyfaethu, ac mae datblygu modelau aml-rywogaeth sy'n ystyried y rhyngweithio rhwng ysglyfaethwr ac ysglyfaeth yn golygu bod modd amcangyfrif lefelau marwolaeth o ganlyniad i ysglyfaethu yn seiliedig ar fomas rhywogaethau lefel uwch-droffig. Mae'r amcangyfrifon hyn yn cael eu cynnwys yn yr asesiadau ar gyfer rhywogaethau Môr y Gogledd (penfras, gwyniad môr, corbennog, llymrien). Nid yw model aml-rywogaeth ar gael eto ar gyfer Môr Iwerddon, ond bydd gweithgor yn cael ei gynnull i archwilio'r gwaith o ddatblyguun yn yr hydref 2018.

Ystyrir bod cyfrif yn cael ei roi am ffynonellau marwolaeth eraill (e.e. oherwydd clefyd, gweithgareddau anthropogenig megis tynnu dŵr gan orsafoedd pŵer, gosod seilwaith cynhyrchu ynni ar y môr) yn y marwoldeb naturiol cefndirol. Os yw lefel y marwoldeb naturiol o'r ffynonellau eraill hyn yn newid yn sylweddol, byddai proses meincnodi asesu stoc Cyngor Rhyngwladol Archwilio'r Môr (sy'n cael ei gynnal bob pum mlynedd yn fras) yn arwain at ddiweddarau'r amcangyfrif o farwoldeb naturiol. Byddai'r broses o feintoli lefel y marwolaethau o ffynhonnell benodol (e.e. gweithgaredd anthropogenig penodol) ond yn cael ei feintoli ar wahân pe bai tystiolaeth i awgrymu ei fod yn sylweddol a'i fod yn gallu bod yn fwy na'r amcangyfrif marwoldeb cefndirol sy'n bodoli eisoes. Nid yw dylanwad digwyddiadau eithafol (tymheredd ac ati) ar farwolaethau'n cael ei gynnwys fel arfer mewn amcangyfrifon o farwoldeb naturiol, ond mae'r rhain yn gyffredinol yn effeithio'n anghymesur ar y

cyfnodau larfaol a physgod ifanc (cyn aeddfedrwydd neu recriwtio i'r bysgodfa), a rhoddir cyfrif amdanynt yn yr amcangyfrif o gryfder dosbarth blwyddyn mewn modelau asesu.

Ar raddfa stoc mewn basn môr (e.e. Môr y Gogledd, Môr Iwerddon) neu stoc sydd wedi'i ddosbarthu'n eang, mae effaith marwolaeth o ganlyniad i ddatblygiad anthropogenig lleol penodol yn debygol o fod yn ddibwys a rhoddir cyfrif amdani yn yr amcangyfrifon o farwoldeb naturiol. Ar gyfer stociau lleol sydd wedi'u cyfyngu'n ofodol yn eu dosbarthiad, lle credir y gallai marwolaethau anthropogenig gael effaith fwy arwyddocaol, gallai hyn gael ei asesu ar gyfer y datblygiad unigol o dan ofynion Asesiad o'r Effaith Amgylcheddol.

2. Executive summary

Natural Resources Wales (NRW) is seeking an understanding of the natural and anthropogenic mortality estimates incorporated in marine fish stock assessments by the International Council for the Exploration of the Sea (ICES). Fish stock assessments aim to assess the current status of a fish stock and predict what will happen in terms of future yields, biomass levels and volume (or value) of the catch, for specific levels of fishing mortality. These projections are used to determine appropriate management measures, such as total allowable catches (TACs), based on the management objectives (e.g. to exploit a stock in line with maximum sustainable yield, MSY). This report reviews the components of mortality incorporated in fish stock assessments, and specifically for cod, whiting, herring, sprat, sandeel and mackerel in the North Sea and Irish Sea.

Natural mortality is a key variable in stock assessment models and thus is used in the estimation of MSY reference points and TAC advice. Natural mortality is considered to include all sources of mortality of a fish stock outside of that caused by fishing. It therefore includes mortality from predation by other fish, birds and marine mammals, mortality from biotic and abiotic factors (temperature, disease) and importantly mortality arising from anthropogenic activities. The estimation of the level of natural mortality has progressed from a general assumption of $M=0.2$, to age-specific estimates, and estimates that take account of levels of predation mortality specifically.

Natural mortality is higher for younger ages (smaller sizes) and larval stages, and this is increasingly reflected in stock assessments (such as in the recently-revised estimates for Irish Sea cod and whiting) with age-dependent estimates. Aside from fishing mortality, one of the key sources of mortality is predation mortality, and the development of multi-species models that consider predator-prey interactions that allow predation mortality to be estimated based on the biomass of upper-trophic level species. These estimates are included in the assessments for North Sea species (cod, whiting, sprat, sandeel). A multi-species model is not yet available for the Irish Sea, but a working group will be convened to explore the development of one in autumn 2018.

Other sources of mortality (e.g. from disease, anthropogenic activities such as power station water intakes, installation of offshore energy production infrastructure) are considered to be accounted for in the background calculation of natural mortality. If the level of natural mortality from these other sources changes significantly, the ICES stock assessment benchmarking process (carried out roughly every five years) would result in the estimate of natural mortality being updated. Quantification of the level of mortality from a specific source (e.g. a certain anthropogenic activity) would only be quantified separately if there was evidence to suggest that it was substantial and could exceed the existing estimate of background natural mortality. The influence of extreme events (temperature etc.) on mortality is not usually incorporated into estimates of natural mortality, but these generally disproportionately affect the larval stages and juveniles (before maturity or recruitment to the fishery), and would be accounted for in the estimate of year class strength in assessment models.

At the scale of a stock in a sea basin (e.g. North Sea, Irish Sea) or a widely-distributed stock, the impact of mortality from a specific local anthropogenic development is likely to be insignificant and accounted for in the estimates of natural mortality. For local stocks that are spatially limited in their distribution, where it is thought that anthropogenic mortality may have a more significant impact, this can be assessed for the individual development under Environmental Impact Assessment requirements.

3. Introduction

NRW is seeking an understanding of the natural and anthropogenic mortality estimates incorporated in marine fish stock assessments by the International Council for the Exploration of the Sea (ICES). This report reviews the process and components of mortality considered in these assessments with specific detail provided on cod, whiting, herring, sprat, sandeel and mackerel.

In the North East Atlantic Region, ICES provide advice on marine policy and management issues related to the impacts of human activities on marine ecosystems and the sustainable use of living marine resources, and in particular on the management of the exploitation of living marine resources (ICES, 2016a). The latter includes stock assessment and the generation of recommended fishing opportunities to meet management targets. Scientific advice is provided on around 200 stocks in the Baltic Sea and North East Atlantic Ocean, including the overall level of Total Allowable Catch (TAC) and general technical measures (such as mesh sizes, closed areas for juveniles, spawning etc.). Expert groups are convened to prepare the scientific basis for the advice, in response to either regular (recurring) or specific requests for advice from ICES clients (the European Union, the North Atlantic Salmon Conservation Organization (NASCO), and the North East Atlantic Fisheries Commission (NEAFC)), the Helsinki Commission (HELCOM), the Oslo-Paris Convention Commission (OSPAR) and ICES Member Countries). Stocks that are distributed exclusively within the 12 nm limit of a single coastal state are assessed and managed by the competent authorities of that state.

The approach used by ICES for developing advice on fishing opportunities depends on:

- The model used for stock assessment, and the availability of data and knowledge on the stock (ICES classifies stocks into 6 categories, on the basis of available knowledge (ICES, 2012)); and
- The existence of a management plan or strategy consistent with the precautionary approach, and the availability of defined (F_{MSY}) reference points (see Section 4.2). In the absence of an internationally-agreed management plan, advice is provided on the basis of the ICES MSY framework.

The European Union's Common Fisheries Policy (CFP) (Regulation (EU) No 1380/2013) introduced a legal requirement to manage fish stocks to achieve maximum sustainable yield (MSY) by 2015 where possible and, on a progressive, incremental basis for all stocks by 2020. The Marine Strategy Framework Directive (2008/56/EC) also requires all commercially exploited fish and shellfish stocks to be within safe biological limits. ICES applies the MSY concept to single stocks as well as to groups of stocks in the context of biological interaction and mixed fisheries, where stocks are caught together in a fishery.

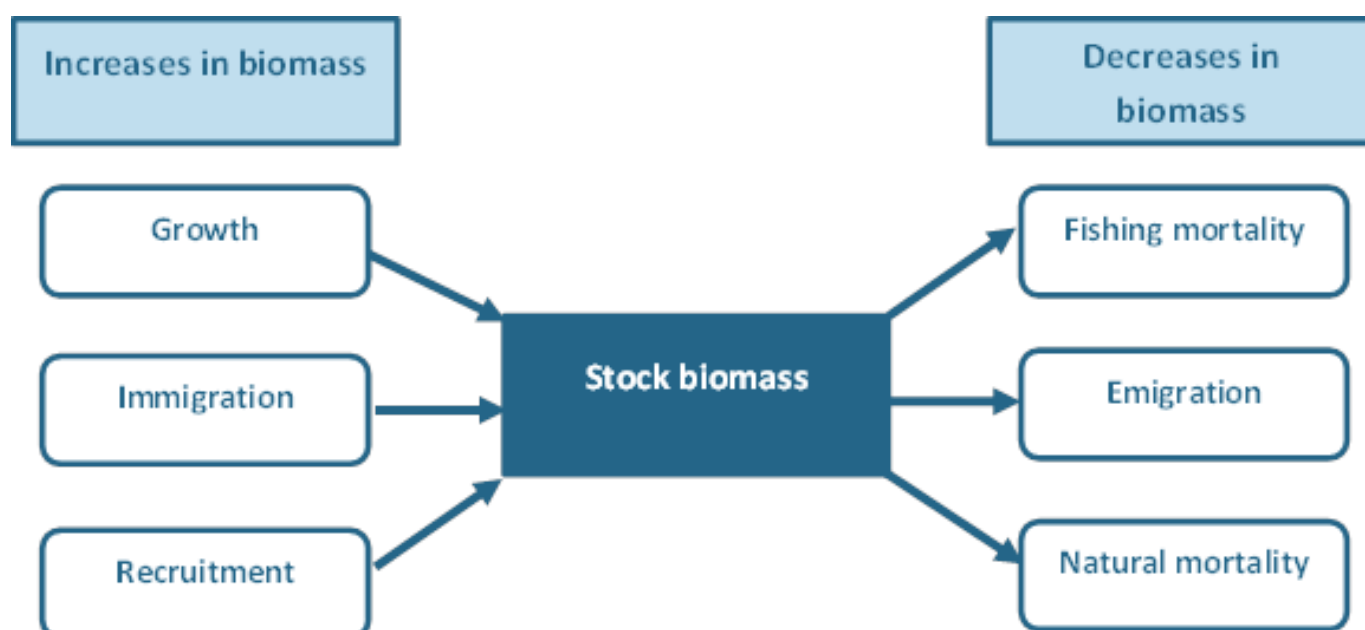
This report does not go into the details of individual stock assessment models, but instead addresses the concepts of fishing mortality, natural mortality and stock biomass in a general manner that is applicable across stock assessment models.

4. Fish stock assessment

Fish stock assessment aims to assess the current status of a fish stock and predict what will happen in terms of future yields, biomass levels and volume (or value) of the catch, for specific levels of fishing effort (FAO, 1998). It integrates all relevant information to best describe the dynamics of a fish stock. Projections from the stock assessment model are used in determining appropriate management measures, based on the management objectives (e.g. to exploit a stock in line with MSY (see Section 4.2), or in line with maximum economic yield, MEY¹).

Fish stock assessment is based on population dynamics, with the stock biomass being dependent on factors that increase it (the growth of individual fish, immigration of fish into the area, and recruitment) and factors that decrease it (mortality from fishing, emigration of fish, and natural mortality) (Figure 1).

Figure 1 Schematic representation of fish stock dynamics



Source: Adapted from Ives, 2011

Fishing directly affects fish stocks through the catch and removal of fish. The fishing mortality (F) is the proportion of the number of fish that is taken by fishing during one year, and is a reflection of the overall level of pressure on the stock from fishing. Stock biomass can influence the productivity of the stock, with the spawning stock biomass (SSB) affecting potential recruitment (through the production of eggs and larvae). Fishing can also affect the size structure of the stock (the proportion of different ages or sizes of fish within the stock) which can have an effect on recruitment (ICES, 2016a).

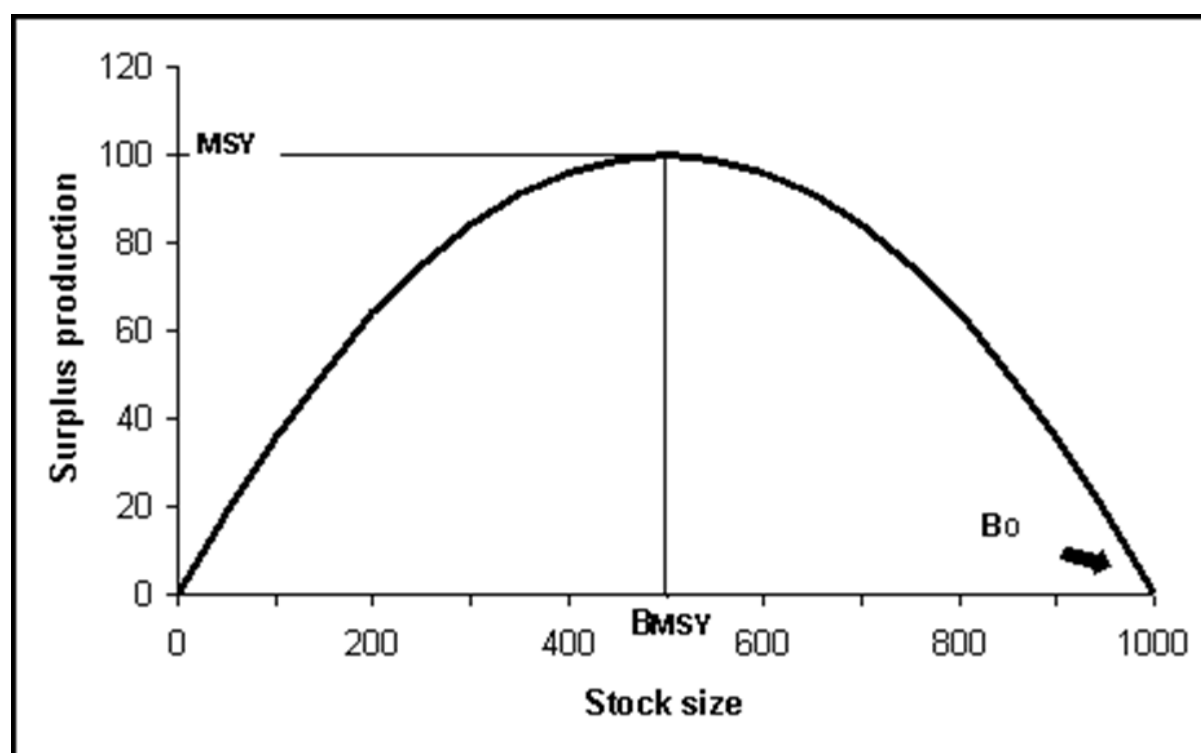
¹ MEY aims to maximise the expected economic profits in a fishery over the long term, based on the level of output and corresponding level of effort. In most cases, this results in yields and effort levels that are less than at MSY and in stock biomass levels greater than at MSY (

Fish stock assessment is a process in which data on stock dynamics, the level of fishing effort (of different fleets and gear types) and catches, are brought together in a structured model to assess the state of the stock (in terms of biomass and level of exploitation), and to carry out projections of future stock biomass and catches under different scenarios (e.g. different levels of fishing mortality, effort or catches). These are used to assess the probability of meeting management targets (e.g. 95% chance of the stock being within limit reference points, see Section 4.2).

4.1 Maximum sustainable yield

The maximum sustainable yield (MSY) concept is based on a model called a surplus production or biomass dynamic model which assumes that the annual growth in biomass of a stock increases up to a point at which this net growth, or surplus production, reaches a maximum (the MSY) (Figure 2). It is a broad conceptual objective, aimed at achieving the highest yield over the long term. The fishing mortality that will achieve it is referred to as F_{MSY} and the biomass that results is referred to as B_{MSY} . As biomass increases above B_{MSY} , density-dependent factors such as competition for food or space and cannibalism on smaller individuals start to reduce the net growth, which decreases until the biomass reaches the carrying capacity of the stock (B_0) (FAO, 2002). ICES' interpretation of MSY is the maximisation of average long-term yield from sustainable stocks and also reduces the risk of low biomass (ICES, 2016a).

Figure 2 Schaefer model of surplus production showing the maximum sustainable yield



Source: FAO, 2002

In the surplus production model, B_{MSY} is at a point lower than the unexploited biomass, at which the intrinsic rate of increase of the stock (through growth and recruitment) is maximised. In reality, stock size and productivity will tend to fluctuate because of environmental variability, and in fisheries management, MSY is considered to be more appropriate for setting a limit to catches, rather than as a target to be achieved (FAO, 2002). For data-poor stocks, proxies can be used where it is not possible to establish MSY reference points (e.g. F_{MSY} proxy, $F_{0.1}$).

4.2 Reference points

Fishing mortality is the only output variable from a stock assessment that can be directly controlled by fisheries management — fisheries management cannot directly control the stock size (biomass), it can only influence it through the fishing mortality. Fishing mortality is difficult to use as a management tool, therefore it is translated into the corresponding level of catch (as TACs and quotas) or fishing effort.

Target reference points define the level of fishing mortality or biomass which allow a long-term sustainable exploitation of the stock, in line with management objectives (e.g. to maximise catches, or to maximise economic profits) (Cadima, 2003). These might be $F_{0.1}$, F_{MSY} , or F_{max} .

Limit reference points are maximum values of fishing mortality which must not be exceeded, or minimum levels of biomass that stocks must not fall below, in order to avoid endangering the stock (e.g. F_{lim} , B_{lim}). Due to the uncertainty around such estimates, precautionary reference points (e.g. F_{pa} or B_{pa}) are established to ensure that probability of the limit reference points being reached is kept below a defined threshold (Cadima, 2003).

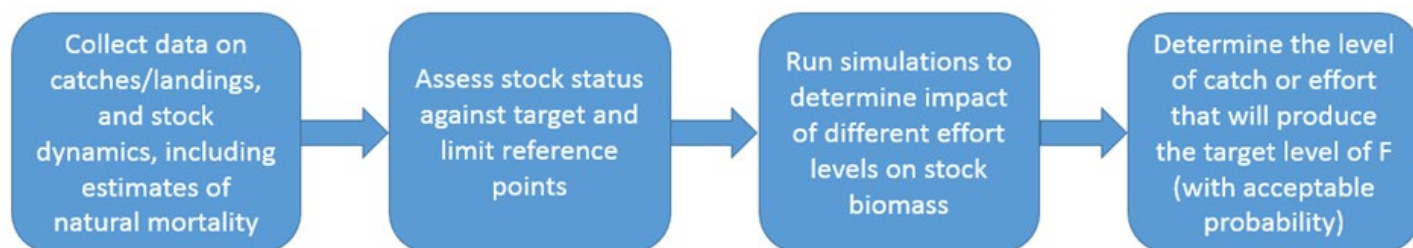
When there are any changes or updates to the biological parameters (e.g. growth rate, natural mortality) or changes or corrections to the exploitation pattern (e.g. catchability of different gear types on fish of different sizes), the biological reference points need to be updated and will change (Cadima, 2003).

4.3 Setting TACs

For the purposes of management, the level of fishing mortality estimated to produce the MSY is converted into a corresponding value of fishing effort or catch (Cadima, 2003). For stocks managed by output controls (e.g. the amount of catches or landings from the fishery used as the means of controlling the level of exploitation of the stock), this will be the TAC. Correspondingly, for stocks managed by input controls (e.g. the level of fishing effort used as the means of controlling the level of exploitation of the stock), the fishing mortality will be converted into an allowable level of fishing effort (e.g. number of vessel days, taking into account vessel power and gear efficiency). Fisheries on some types of fish (particularly schooling fish) cannot be managed by effort control as the ability to catch them is independent of their biomass. The process of data collection and stock assessment to produce advice on the appropriate level of fishing effort or catch is shown in Figure 3.

The setting of the TAC therefore takes into consideration the underlying stock dynamics as represented in the stock assessment model, incorporating the growth rates of the stock and level of natural mortality.

Figure 3 The process of data collection, stock assessment, testing a management rule and identification of recommended catch or effort levels



5. Natural mortality

5.1 Definition

Based on the description of the stock assessment approach and TAC-setting process in Section 4, it is therefore necessary to consider in more detail where the estimates of natural mortality (M) derive from and what components of mortality are incorporated in the estimates of natural mortality.

Natural mortality (commonly represented as 'M' in stock assessment models) is defined as:

*'deaths of fish from all causes except fishing (e.g. ageing, predation, cannibalism, disease and perhaps increasingly pollution). It is often expressed as a rate that indicates the percentage of fish dying in a year; for example, a natural mortality rate of 0.2 implies that approximately 20% of the population will die in a year from causes other than fishing.'*²

Source: Cochrane & Garcia, 2009.

Natural mortality (M) is a key variable and source of uncertainty in the estimation of MSY reference points and associated F_{MSY} catch forecasts. As the estimated values of M increase, estimates of recruitment and biomass from catch-based assessments increase substantially, and fishing mortality estimates are consequently reduced for a given catch³ (ICES, 2017a).

² The number of individuals surviving to the next time period is calculated as $\exp^{-M}$, thus for values of M below approximately 0.3, the proportion dying roughly equates to the value of M. Higher values of M (including values above 1) equate to progressively larger proportions of the population dying.

³ As the estimate of natural mortality for a population increases, the estimate of the population biomass (and initial recruitment) must increase to account for the observed biomass of the different age classes given the high level of natural mortality. Fishing mortality is expressed as a rate of mortality, so if the population biomass is estimated to be larger, then a specific catch from fishing will represent a smaller proportion of the overall population biomass.

The natural mortality plus fishing mortality represents the total mortality (Z) of the stock. The estimated total mortality is then used in the assessment models that are used for stock assessments and form the basis for TAC advice to the EU and other recipients of advice.

5.2 Components of natural mortality

As natural mortality is defined to include all mortality except fishing mortality, it has the potential to include anthropogenic sources of mortality as well as those considered 'natural' in the sense of predation, ageing and disease etc. Possible sources of natural mortality include:

- Physical (abiotic conditions): temperature, hostile environmental conditions;
- Biological: predation from other fish, mammals, seabirds etc.; cannibalism from own species; parasitism, infectious and non-infectious diseases; starvation; and
- Anthropogenic: marine developments and disturbance; pollution; recreational fishing (unless included in stock assessment as fishing mortality, which is increasingly common).

The estimate(s) of natural mortality used in each stock assessment reflect expert opinion or model output on the main sources of natural mortality and their potential variability between years.

For stocks that display variability in their abundance and distribution, such as forage fish (small pelagic species that occupy an important place in marine food webs, being preyed on by larger fish, birds and marine mammals), a dynamic approach that adjusts the estimate of natural mortality over time can help management respond to fluctuations in abundance (Dickey-Collas *et al.*, 2014).

5.2.1 Abiotic factors

Abiotic factors such as particularly harsh winters may cause higher levels of mortality, particularly for larval stages or smaller size classes. A particularly cold winter killed many North Sea common sole one year. Generally, whilst the time series of estimates of natural mortality are not usually adjusted to take account of specific events such as these, the effect is likely to be greater on the estimation of smaller size classes than on the estimation of exploitable size classes. Fluctuations in mortality at the young ages (before maturity or recruitment to the fishery) due to particular events usually lead to stock assessment models that assume constant natural mortality adjusting downwards the estimates of abundance for the youngest ages. However, once the year class reaches exploitable age/size, additional survey or catch data will lead to more accurate estimates of abundance of the older fish in the year class (Dr D.C.M. Miller, *pers. comm.*).

5.2.2 Biological factors

Predation is the dominant source of fish mortality (Lorenzen, 1996), and fish stock assessments have been attempting to improve the quantification of this source of

mortality. In the North Sea, fishing mortality for many stocks has been successfully reduced, and natural mortality is becoming an increasingly dominant source of mortality (ICES, 2013a).

In ICES, the Working Group on Multispecies Assessment Methods (WGSAM) develops estimates of predation between different species in the North Sea and Baltic Sea, and these are used in many stock assessments to inform their choice for natural mortality. This allows the incorporation of ecosystem interactions in stock assessments (e.g. increasing biomass of cod resulting in increased predation of herring and sprat).

Some assessment models also incorporate adjustments to the estimates of natural mortality to take account of specific sources of mortality, such as:

- The model for North-East Arctic cod incorporates cannibalism in the assessment model (Dr M. Dickey-Collas, *pers. comm.*); and
- The Icelandic spring-spawning herring assessment accounts for higher levels of natural mortality during outbreaks of *Ichthyophonus* (a fish parasite, particularly of haddock, plaice and herring (ICES, 2013b)) (Dr D.C.M. Miller, *pers. comm.*).

5.2.3 Anthropogenic factors

Mortality arising from local marine developments (e.g. power station water intakes, dredging, installation of offshore energy production infrastructure) would in most cases be unlikely to have a notable effect on overall natural mortality at the population (or stock) level – for a stock that ranges over thousands of square kilometres, the effect of a local marine development covering a few kilometres would likely be negligible or difficult to discern (Dr D.C.M. Miller, *pers. comm.*); a development that affects a small percentage of the total stock abundance would not have a significant effect when compared to fishing mortality that might affect ten or twenty percent of the stock. Mortality arising from such local developments is considered to be incorporated as part of the overall estimates of natural mortality in the stock assessment.

For small stocks with limited distribution ranges, such factors could be relevant at a local scale. For other stocks like eel, which is currently in a poor state, some national eel management plan reports incorporate other sources of mortality such as mortality from hydropower intakes and pumping stations (ICES, 2015).

Some anthropogenic developments have specifically considered the significance of the impact of potential mortality on the stock, under statutory assessment processes such as Strategic Environmental Assessment (SEA), Environmental Impact Assessment (EIA) or Habitats Regulations Assessment (HRA). Further detail is provided in Section 7.

6. Natural mortality estimates in North Sea and Irish Sea stock assessments

In ICES, most stock assessments use an annually fixed level of natural mortality (i.e. M does not change from year-to-year). In age-structured models⁴, most use a level of M that changes with age, reflecting the reducing levels of natural mortality with increasing age (size). Some of these models use estimates of M based on Lorenzen (1996). However, some models still use a standard fixed level of natural mortality for all ages, often $M=0.2$, a long-standing assumption of the level of natural mortality. Increasingly, ecosystem models of predator-prey interactions are being used to derive estimates of natural mortality based on the abundance of different ecosystem components.

These different approaches to natural mortality generally reflect improvements in its estimation, and hence decreasing levels of uncertainty, moving from $M=0.2$, through age-based estimates of M , to estimates that incorporate predator-prey interactions.

6.1 $M=0.2$

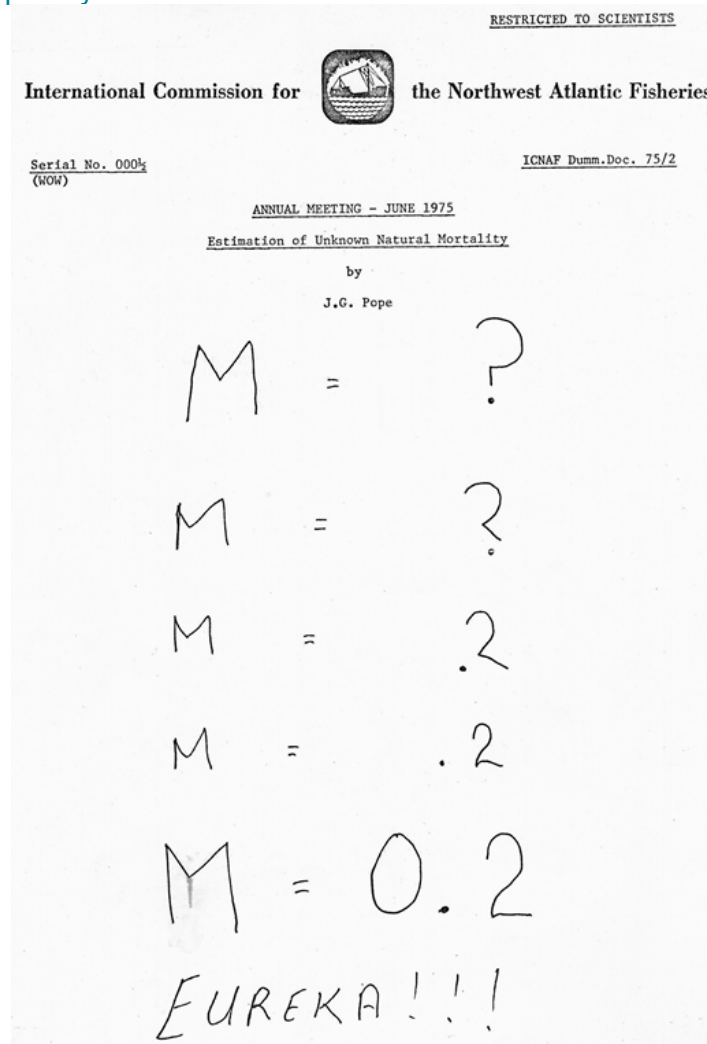
At one of the Assessments Subcommittee meetings of the International Commission for the Northwest Atlantic Fisheries (ICNAF), John Pope produced a humorous 'Dummy Document' demonstrating a contrived derivation of $M=0.2$ by progressively manipulating the "?" in his initial " $M = ?$ " until it became ".2" (Figure 4). This parody poked fun at the way in which many estimates of natural mortality, particularly the commonly-used $M=0.2$, were derived.

Stock assessments for many of the most commercially-important stocks have moved away from the assumption of $M=0.2$, increasingly recognising the higher levels of natural mortality on younger age classes, and taking account of changing levels of predation according to the population abundance of predators (and availability of food sources according to the population abundance of their prey).

Natural mortality is known to be a large uncertainty in stock assessment models, and is reviewed as part of the ICES benchmark reviews for each stock (roughly every 5 years) (see Section 6.4). This process may result in the estimate of natural mortality being updated, if the data demonstrate that the level of natural mortality has changed. If natural mortality is thought to vary substantially between years for the ages of fish targeted by a fishery, it would be important to re-consider estimates of natural mortality and potentially vary the level of natural mortality in the models from year-to-year.

⁴ Age-structured models take into account growth between different age classes of fish, and the catchability of each age class according to the fishing gears used.

Figure 4 John Pope's parody of the derivation of $M=0.2$



Source: Anderson, 2015

6.2 Lorenzen (1996)

Lorenzen's 1996 paper analysed the relationship between body weight and natural mortality in juvenile and adult fish in different aquatic ecosystems (lakes, rivers, the ocean, and pond, cage and tank aquaculture systems), with natural mortality modelled as a power function of weight:

$$M_W = M_u W^b$$

Where M_W is the natural mortality rate at weight W , M_u is the natural mortality rate at unit weight, and b is the allometric scaling factor. Mortality rates are annual, and the unit of weight is 1 g.

The mortality-weight relationships were calculated for all natural ecosystems (lakes, rivers and the ocean) and for latitudinal zones (Table 1). These relationships form the basis for the estimates of natural mortality of each age group (or size class) used in many ICES assessments.

Table 1 Mortality-weight model parameter estimates for juvenile and adult fish in different natural ecosystems and aquaculture systems, and latitudinal effects

System (S) or Zone (Z; latitudinal zone/natural ecosystems)	<i>n</i>	Weight exponent <i>b</i>	Mortality at unit weight <i>Mu</i> [year ⁻¹]
S: Lakes	121	−0.291 [−0.356, −0.224]	3.37 [2.94, 3.85]
S: Rivers	74	−0.289 [−0.360, −0.230]	2.53 [2.29, 2.96]
S: Ocean	113	−0.305 [−0.351, −0.257]	3.69 [2.84, 4.49]
S: Ponds	154	−0.382 [−0.442, −0.342]	2.23 [1.75, 2.77]
S: Cages	59	−0.461 [−0.583, −0.339]	2.04 [1.06, 2.94]
S: Natural	308	−0.288 [−0.315, −0.261]	3.00 [2.70, 3.30]
S: Ponds/cages	213	−0.423 [−0.475, −0.370]	2.24 [1.82, 2.71]
Z: Tropical	29	−0.210 [−0.356, −0.111]	3.08 [1.87, 4.48]
Z: Temperate	269	−0.309 [−0.342, −0.278]	3.13 [2.79, 3.46]
Z: Polar	10	−0.292 [−0.450, −0.151]	1.69 [0.87, 3.12]

Notes: Theil estimates with 90% confidence intervals.
Tropical = 0–30°, temperate = 30–60°, polar = 60–90°.

Source: Lorenzen (1996).

6.3 North Sea multi-species model

In the North Sea, the stochastic multi-species (SMS) assessment model (Lewy & Vintner, 2004) is used to estimate predation mortality on cod, haddock, whiting, herring, sprat, Norway pout and sandeels (among others) (ICES, 2013a). It is a multi-species stock assessment model that includes biological interactions between species. Predation interactions are size-dependent (the size class(es) of fish that are eaten by different predators are taken into account) and stomach contents data are used to determine the interactions and their magnitude. Predation mortality is driven by the biomass of predators such as cod, saithe, seals, birds etc. (Neils Hintzen, *pers. comm.*). The model is fitted to observations of total catches, survey catch-per-unit-effort and stomach contents for the main stocks in the North Sea.

The following predator and prey stocks are incorporated in the model:

- Predators and prey (cod, whiting, haddock);
- Prey only (herring, sprat, northern and southern sandeel, Norway pout);
- Predator only (saithe and mackerel);
- No predator prey interactions (sole and plaice); and
- ‘External predators’ (eight seabird species, starry ray, grey gurnard, North Sea horse-mackerel, western horse-mackerel, hake, grey seals and harbour porpoise).

The model explicitly estimates predation mortality (‘M2’) by simulating the upper trophic North Sea food web. In addition, other residual or background natural

mortality ('M1') accounts for all the other mortality that may occur (e.g. disease, starvation, other anthropogenic activities such as power station developments, dredging), with natural mortality, M, being the sum of M1 and M2. However, M1 is estimated and is set to 0.2 per year in most cases.

Other sources of mortality (in addition to predation) are thus implicitly taken into account, although individual sources of mortality are not quantified specifically. If there was evidence to suggest that mortality from other specific sources was more substantial and could exceed the M1 estimate, stock assessment scientists would try to quantify it specifically as extra source of mortality.

Table 2 shows examples of the natural mortality (M) estimates for selected stocks in the North Sea derived from the SMS model.

Table 2 Natural mortality estimates for cod, haddock, whiting and herring since 2000 from the North Sea SMS model, reported in 2016

Age	Cod	Haddock	Whiting	Herring
0	1.172	-	-	-
1	1.180	1.272	1.313	0.787
2	0.888	0.495	0.729	0.380
3	0.234	0.321	0.610	0.353
4	0.200	0.294	0.604	0.335
5	0.200	0.276	0.568	0.315
6	0.200	0.236	0.568	0.311
7	0.200	0.216	0.568	0.304

Source: ICES, 2017a

6.4 Irish Sea benchmarking process

The Irish Sea regional benchmarking is a multi-year process to consider the impact of ecosystem and environmental drivers on Irish Sea fisheries management as part of a regional ecosystem assessment. It focusses on improving single-species stock assessments (principally cod, haddock, whiting, plaice and herring), incorporating a mixed fisheries model, and developing the integration of ecosystem aspects and working towards an integrated assessment and advice. Four workshops have been conducted:

- WKIrish1 (ICES, 2016b) aimed to enable information exchange between management stakeholder groups, fishermen, scientists, regulators and other interested parties to improve understanding of the key issues involved and questions to be addressed;
- WKIrish2 (ICES, 2017b) included review and recommendation of life history parameters (e.g. growth parameters, maturity ogives, fecundity, natural mortality) for use in assessments;

- WKIrish3 (ICES, 2017a) developed methods to determine stock status and short-term outlook and to propose biological reference points for the Irish Sea stocks of cod, haddock, herring, plaice and whiting; and
- WKIrish4 (ICES, 2018) on stakeholder input and parameterisation of ecosystem and foodweb models.

A fifth workshop WKIrish5 is planned for late 2018 to develop integrated ecosystem assessment and advice. This will look at the development of multi-species models incorporating the effects of predation (as in the North Sea SMS model).

WKIrish2 (ICES, 2017b) developed various estimates of natural mortality for several stocks in the Irish Sea, including cod and whiting (see Section 6.5.1), and WKIrish 3 (ICES, 2017a) carried out sensitivity testing on the estimates to determine which was the best description of natural mortality in the population.

6.5 Individual species

6.5.1 Cod and Whiting

North Sea cod and whiting

In the assessments of North Sea cod and whiting, natural mortality estimates are extracted from the SMS model (Dr A. Kempf, *pers. comm.*), and therefore explicitly include predation mortality as well as other background mortality. Mortality arising from anthropogenic activities (such as dredging, power stations) is not quantified specifically but is implicitly included in the estimate of background natural mortality (M1).

Irish Sea cod

There are no direct estimates of natural mortality for cod and whiting in the Irish Sea (e.g. from tagging, multispecies assessments or other methods) (ICES, 2017a). Assessments of demersal species (e.g. cod, haddock, whiting) in the Irish Sea previously used age-invariant natural mortality estimates (i.e. the same value of M across all ages) set at historically assumed values (0.2 for cod) (ICES 2017b). However, recent research has indicated that natural mortality is higher in cod in the Irish Sea and likely to be dependent on temperature. The Irish Sea benchmarking process therefore tested a range of different methods to estimate M and found that M may have been underestimated, helping to explain why fishing mortality has not responded as expected to reductions in fishing. The calculated estimates of M ranged from 0.193 to 3.651, with higher levels of mortality for the younger age classes. The process recommended the use of age-specific natural mortality using Lorenzen and Gislason methods (ICES, 2017b), and the 2017 advice for Irish Sea cod used these fixed natural mortality estimates which are based on generic relationships between size and mortality following Lorenzen (1996) (ICES, 2017c) (Table 3). The estimates are time independent (values do not vary from year-to-year). However, inter-year variation in the mortality at the youngest ages would be reflected within the models by the estimates of recruitment strength.

Table 3 Lorenzen natural mortality estimates for cod in the Irish Sea

Age	0	1	2	3	4	5	6+
M	1.7	0.714	0.355	0.269	0.232	0.213	0.202

Source: ICES, 2017d

There is no multi-species model used for the Irish Sea⁵, so specific predator-prey interactions (M2) are not calculated – the natural mortality estimates do not vary with changes in the population abundance of other species. However, the Irish Sea stock assessments for cod use similar levels of natural mortality M to those estimated in the North Sea SMS model (where $M=M_1+M_2$), and therefore are consistent with natural mortality from predation being taken into account. Nevertheless, there could be differences in the upper trophic level food webs between the North Sea and Irish Sea. Development of a model specific to the Irish Sea would be expected to provide a more robust estimate.

Irish Sea whiting

WKIrish2 (ICES, 2017b) reviewed natural mortality estimates and data for whiting to improve the estimate across ages and include a measure of variability to develop a range for natural mortality. Lorenzen (1996) was used to estimate M for different ages (weights) from survey data, with a range calculated from the standard deviation. The resulting values (Table 4) were much higher than the previously-used 0.2 value (Figure 5), but lower than the values identified for whiting in the North Sea where predation was included in the estimation process (using the North Sea SMS model). The 2017 advice for whiting used the age-specific natural mortality estimates based on Lorenzen (ICES, 2017e).

WKIrish2 also investigated the potential to use values of M that vary from year-to-year, and found that this may be more biologically realistic, especially for the younger ages. However, further investigation in WKIrish3 concluded that there is too much uncertainty around M to justify estimating it for each year as this can potentially just add noise to the assessment (ICES, 2017a).

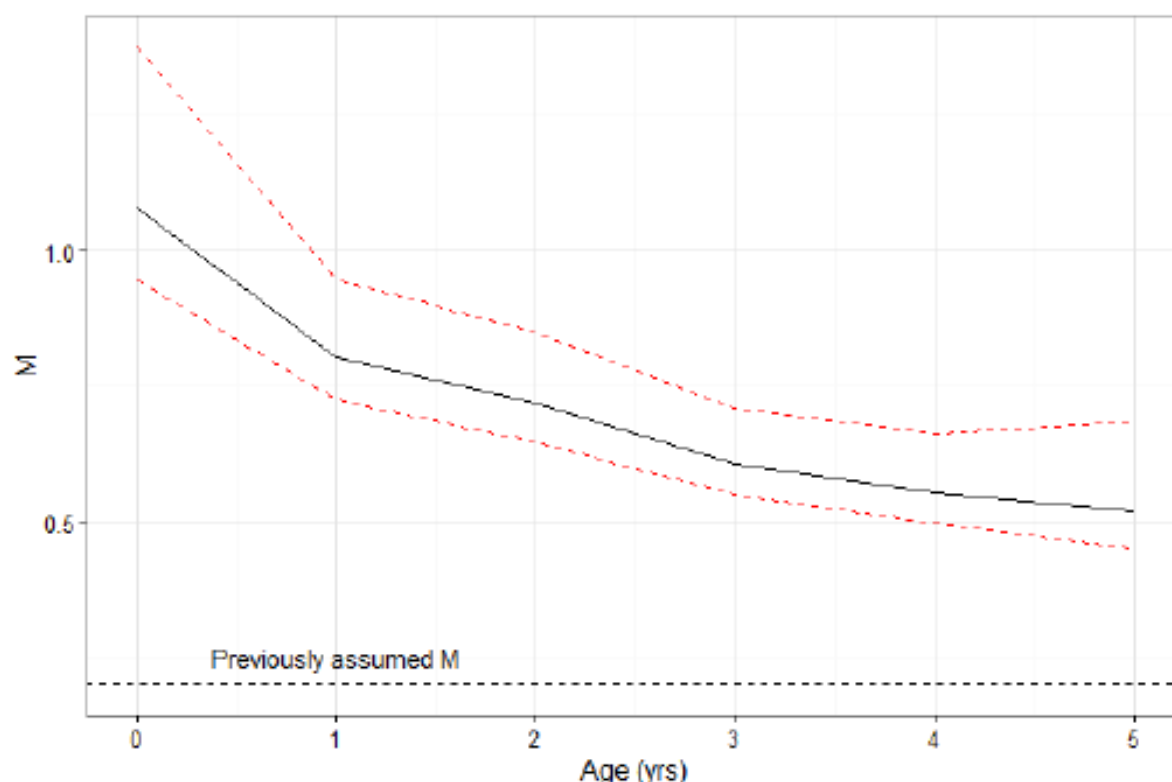
Table 4 Estimates for natural mortality for Irish Sea whiting based on Lorenzen (1996)

Age	0	1	2	3	4	5
M	1.078	0.803	0.718	0.608	0.554	0.518

Source: ICES, 2017b

⁵ WKIrish5 will explore the development of a multi-species model for the Irish Sea in autumn 2018.

Figure 5 Estimated M-at-age for whiting in 7.a (solid black line). Ranges of M (red broken line) were estimated for the mean $\pm$ s.d. wet weight. The previously assumed level of M (0.2) is shown (black broken line)



Source: ICES, 2017b

6.5.2 Herring

North Sea herring stocks

The stock assessments for herring in the North Sea now use time-varying natural mortality which aim to take into account changes in the ecosystem that affect the herring stock size (through changes in the level of predation). In 2016, new natural mortality estimates were derived from the North Sea SMS model (ICES, 2016c). This led to a change in perception of the stock and mortality and the reference points were updated (ICES, 2017f). As with the cod and whiting assessments, the predation mortality derived from the SMS model forms part of the estimate of natural mortality, together with other background mortality (natural mortality (M) = predation mortality M2 + background mortality M1).

As such, other anthropogenic activities are accounted for in the background mortality component of natural mortality, which ranges from illness to power-station mortality. The effect of physical or abiotic factors (e.g. cold winters) are not specifically considered, but these are most relevant only for the youngest larvae which are not being targeted by the assessment models (and would be accounted for in the estimate of year class strength).

Irish Sea herring stocks

There are no direct estimates of M for Irish Sea herring. Age-dependent estimates of M for North Sea herring from the SMS model runs for the North Sea have been used in the Irish Sea herring stock assessment since 2012 (ICES, 2017a; ICES, 2017g) (Table 5). The use of these values is considered to be preliminary until stock-specific estimates can be obtained.

Table 5 Natural mortality estimates for herring with age (expressed in number of winter rings) in the Irish Sea

Rings (age)	1	2	3	4	5	6	7+
M	0.787	0.380	0.353	0.335	0.315	0.311	0.304

Source: ICES, 2017g

6.5.3 Sprat

Sprat in the Irish Sea is an ICES category 5 stock (data poor, including stocks for which only catch data are available). The stock assessment is therefore limited, with advice based on the most recent advised catch (ICES, 2017h). Predation mortality of sprat is estimated through the North Sea SMS model. The stock structure of sprat populations in the Celtic Seas ecoregion is not clear and management units are not defined (ICES, 2017i).

6.5.4 Sandeel

Sandeel is a short-lived species. Recruitment is highly variable and influences the spawning stock and total biomass rapidly. The default ICES approach to MSY-based management for short-lived species is an escapement strategy⁶, i.e. to maintain SSB above $MSY_{Bescapement}$ after the fishery has taken place.

North Sea

In the North Sea, sandeel assessments estimate natural mortality for different assessment areas, based on a sliding 3-year average (ICES, 2017j). This is based on estimates of predation rates carried out by the WGSAM every three years and estimated through the North Sea SMS model.

Irish Sea

There is no sandeel stock assessment for the Irish Sea as there is no sandeel fishery. For Division VIa (West of Scotland), no stock assessment is carried out (ICES, 2016d), and the ICES advice indicated that it was not possible to define the

⁶ Where the target is to leave the reference spawning stock biomass to spawn the next year, used for short-lived species in the ICES MSY framework.

details of an approach suitable for this area, although information on incoming year-class strength is an important requirement.

6.5.5 Mackerel

Mackerel is a widely-distributed stock whose range spans several subareas and divisions in the North East Atlantic, and its distribution spans the waters of several different coastal states. Natural mortality is assumed to be equal to 0.15 for all ages, based on tagging studies from the early 1980s, and does not vary from year-to-year (ICES, 2017k; ICES, 2017m).

7. Assessing the significance of mortality from anthropogenic activities

The aim of Environmental Impact Assessment (EIA) is to protect the environment by ensuring that a decision-making authority, when deciding whether to grant permission for a project, which is likely to have significant effects on the environment, does so in the full knowledge of the likely significant effects, and takes this into account in the decision-making process. Where potentially significant effects are anticipated, mitigation measures are identified to minimise impacts. If an EIA is not required, there are other mechanisms that would be used (e.g. environmental appraisal for non-EIA projects, Habitats Regulations Assessment for projects that might impact on designated sites). An example of where fish mortality was specifically assessed in relation to a potential anthropogenic activity was the proposed Hinkley Point C power station. The impingement of juvenile fish at water intakes was identified as being a potentially significant impact, and so a more in-depth assessment was undertaken.

Mortalities of fish caused by power station cooling water intakes mainly involve the juveniles of a population, which are particularly vulnerable due to their presence in inshore nursery areas and poorer swimming ability compared to adults. The natural mortality of juveniles is higher than of adults of the same species, and the loss of a single juvenile does not equate to the loss of a breeding adult, as a proportion of the juveniles would be expected to be lost to natural mortality before maturity.

The assessment approach therefore calculated the 'Equivalent Adult Value' (EAV) as the corresponding adult biomass of fish that relates to the number of potentially impinged juveniles. This is based on life history information (growth parameters, natural mortality at size, size at age and age at maturity), together with information of the size distribution of fish potentially caught by the power station (based on monitoring data from Hinkley Point B) to calculate site-specific EAVs (Cefas, 2017a).

To assess the significance of the mortality from impingement, the EAVs were compared to the SSB of the local stock (based on stock assessment surveys and population biomass estimates, where data were available) or compared to local fishery catches. For sprat, this was based on acoustically-derived biomass estimates from the area, which were converted into an equivalent adult spawning stock biomass (as the aggregations monitored acoustically were composed of both juvenile and adult fish) (Cefas, 2017b).

Where the EAV was less than 1% of the SSB, the assessment considered the mortality from impingement to be insignificant.

8. Conclusions

Natural mortality is a key variable in stock assessment models and thus is used in the estimation of MSY reference points and TAC advice. Natural mortality is considered to include all sources of mortality of a fish stock outside of that caused by fishing. It therefore includes mortality from predation by other fish, birds and marine mammals, mortality from biotic and abiotic factors (temperature, disease) and mortality arising from anthropogenic activities. The estimation of the level of natural mortality has progressed from a general assumption of $M=0.2$, to age-specific estimates, and estimates that take account of levels of predation mortality specifically. These different approaches to natural mortality generally reflect improvements in its estimation (the exception being where constant M across ages has been confirmed through tagging and other studies). Time-varying estimates (which are updated periodically to reflect changes in the ecosystem) are also an improvement on estimates that remain fixed for decades or more.

Natural mortality is higher for younger ages (smaller sizes) and larval stages, and this is increasingly reflected in stock assessments (such as in the recently-revised estimates for Irish Sea cod and whiting) with age-dependent estimates. Aside from fishing mortality, one of the key sources of mortality is predation mortality, and the development of multi-species models (such as the SMS model for the North Sea) that consider predator-prey interactions allow predation mortality to be estimated based on the biomass of upper-trophic level species. These estimates are included in the assessments for North Sea species (cod, whiting, herring, sprat, sandeel). A multi-species model is not yet available for the Irish Sea, but a working group will be convened to explore the development of one in autumn 2018.

Other sources of mortality (e.g. from disease, anthropogenic activities such as power station water intakes, installation of offshore energy production infrastructure) are considered to be accounted for in the background natural mortality. If the level of natural mortality from these other sources changes significantly, the ICES stock assessment benchmarking process (carried out roughly every five years) would result in the estimate of natural mortality being updated. Quantification of the level of mortality from a specific source (e.g. a certain anthropogenic activity) would only be quantified separately if there was evidence to suggest that it was substantial and could exceed the existing estimate of background mortality. The influence of extreme events (temperature etc.) on mortality is not usually incorporated into estimates of natural mortality, but these generally disproportionately affect the larval stages and juveniles (before maturity or recruitment to the fishery), and would be accounted for in the estimate of year class strength in assessment models.

At the scale of a stock in a sea basin (e.g. North Sea, Irish Sea) or a widely-distributed stock, the impact of mortality from a specific local anthropogenic development is likely to be insignificant and accounted for in the estimates of natural mortality. For local stocks that are spatially limited in their distribution, where it is thought that anthropogenic mortality may have a more significant impact, this can be assessed for the individual development as the EAV of the potential mortality, compared to the spawning stock biomass or local fisheries landings data.

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10. Abbreviations and acronyms

CFP	Common Fisheries Policy
b	Allometric scaling factor
B_0	Carrying capacity of the stock
B_{lim}	Limit reference point for SSB
B_{MSY}	SSB that results from fishing at FMSY for a long time
B_{pa}	Precautionary reference point for spawning stock biomass (SSB)
EAV	Equivalent adult value
EIA	Environmental Impact Assessment
EU	European Union
F	Fishing mortality
$F_{0.1}$	The fishing mortality rate at which the marginal yield-per-recruit is 10 percent of the marginal yield-per-recruit on the unexploited stock
F_{lim}	Limit reference point for fishing mortality
F_{max}	Fishing mortality rate that maximises equilibrium yield per recruit
F_{MSY}	Fishing mortality consistent with achieving MSY
F_{pa}	Precautionary reference point for fishing mortality
HELCOM	Helsinki Commission
HRA	Habitats Regulations Assessment
ICES	International Council for the Exploration of the Sea
ICNAF	International Commission for the Northwest Atlantic Fisheries
M	Natural mortality
M_1	Residual or background natural mortality (excluding predation)
M_2	Predation mortality
MW	Natural mortality rate at weight W
M_u	Natural mortality rate at unit weight
MEY	Maximum economic yield
MSY	Maximum sustainable yield
$MSY_{Bescapement}$	Biomass reference point for short-lived species where the target is to leave the reference spawning stock biomass to spawn the next year
NASCO	North Atlantic Salmon Conservation Organization
NEAFC	North East Atlantic Fisheries Commission
OSPAR	Oslo-Paris Convention
SEA	Strategic Environmental Assessment

SMS	Stochastic multi-species (assessment model)
SSB	Spawning stock biomass
TAC	Total Allowable Catch
WGSAM	Working Group on Multispecies Assessment Methods
Z	Total mortality

Cardinal points/directions are used unless otherwise stated.

SI units are used unless otherwise stated.

11. Data Archive Appendix

No data outputs were produced as part of this project.