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Revisiting safe biological limits in fisheries

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Abstract

The appropriateness of three official fisheries management reference points used in the north-east Atlantic was investigated: (i) the smallest stock size that is still within safe biological limits (SSB_{pa}), (ii) the maximum sustainable rate of exploitation (F_{msy}) and (iii) the age at first capture. As for (i), in 45% of the examined stocks, the official value for SSB_{pa} was below the consensus estimates determined from three different methods. With respect to (ii), the official estimates of F_{msy} exceeded natural mortality M in 76% of the stocks, although M is widely regarded as natural upper limit for F_{msy}. And regarding (iii), the age at first capture was below the age at maturity in 74% of the stocks. No official estimates of the stock size (SSB_{msy}) that can produce the maximum sustainable yield (*MSY*) are available for the north-east Atlantic. An analysis of stocks from other areas confirmed that twice SSB_{pa} provides a reasonable preliminary estimate. Comparing stock sizes in 2013 against this proxy showed that 88% were below the level that can produce *MSY*. Also, 52% of the stocks were outside of safe biological limits, and 12% were severely depleted. Fishing mortality in 2013 exceeded natural mortality in 73% of the stocks, including those that were severely depleted. These results point to the urgent need to re-assess fisheries reference points in the north-east Atlantic and to implement the regulations of the new European Common Fisheries Policy regarding sustainable fishing pressure, healthy stock sizes and adult age/size at first capture.

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Introduction

Fish in the sea are a common good, the exploitation of which needs to be limited to avoid overharvesting and destruction (Hardin 1968). Three practical limits of exploitation in fisheries management can be defined as (i) the smallest size of the fished stock that is considered to be within safe biological limits (SSB_{pa}), (ii) the maximum sustainable rate of exploitation (F_{msy}) and (iii) the age at first capture resulting from the selectivity of legal gears, which should allow for individual reproduction. This study explores the adherence to these common sense limits in the management of fish stocks of the north-east Atlantic.

Hockey sticks and lower limit of spawning biomass

The lower limit of biomass below which the production of recruits may be compromised is a commonly accepted limit of exploitation (Beddington and Cooke 1983; Myers *et al.* 1994; ICES 2010). The International Council for the Exploration of the Seas (ICES) defines this point as the biomass below which recruitment becomes impaired or the dynamics of the stock are unknown (ICES 2010). This stock size (SSB_{lim}) can be derived from an analysis of recruitment and spawning stock biomass data, for example, by fitting stock–recruitment functions such as the widely used Beverton and Holt (1957) or Ricker (1954) functions. These curved functions have been criticized because at low population sizes, they predict an increase in number of recruits-per-spawner (Barrowman and Myers 2000), basically assuming highest productivity when the stock has collapsed. Also, these functions make assumptions about a continuing increase (Beverton and Holt 1957) or decline (Ricker 1954) of recruitment at large stock sizes, although data to support such assumptions are typically missing. Simple hockey-stick functions can overcome these problems by assuming a constant recruit-per-spawner ratio at low population sizes and constant recruitment at large population sizes (Clark *et al.* 1985; Barrowman and Myers 2000; O'Brien *et al.* 2003). Such hockey sticks are segmented regressions with the first segment (the blade of the hockey stick) anchored in the origin of a stock–recruitment plot. The break-point beyond which the second segment of the regression runs parallel to the x-axis marks SSB_{lim} and the height of the second segment (the shaft of the hockey stick) represents the average recruitment over the range of large stock sizes (Fig. 1). However, stock–recruitment data are notoriously noisy, and even a simple hockey-stick function may be difficult to fit or may provide unrealistic estimates of SSB_{lim} (see e.g. Fig. 3). In such situations, ICES stock assessment working groups have applied methods such as B_{loss} (ICES 2007, 2010), where the lowest observed spawning stock biomass that still produces some recruitment is taken as a proxy for SSB_{lim}, and a precautionary buffer zone is obtained by multiplying SSB_{lim} by 1.4 to obtain the precautionary biomass SSB_{pa} (e.g. ICES 2013a). But such proxy estimates of SSB_{pa} are often unrealistically low, thus defeating the purpose of providing a high probability that recruitment is not impaired and that the stock is within safe biological limits.

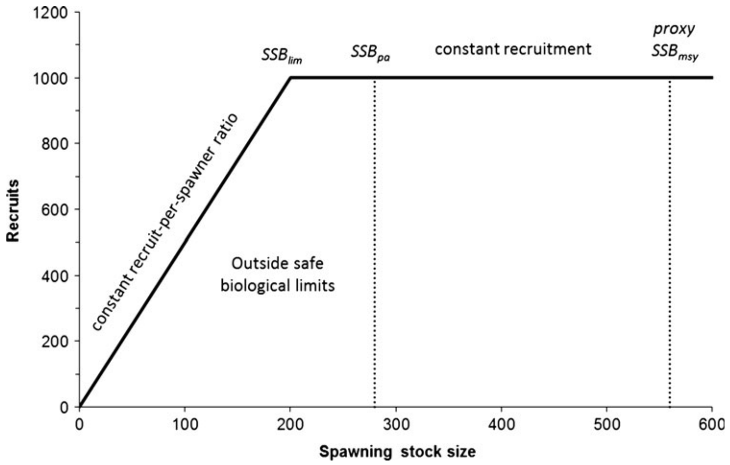

Figure 1 Conceptual drawing of the hockey-stick relationship between spawning stock size and recruitment. SSB_{lim} marks the border below which recruitment declines, SSB_{pa} marks a precautionary distance to SSB_{lim}, and 2 × SSB_{pa} can be used as a proxy for SSB_{msy}, the stock size that can produce the maximum sustainable catch.

Here, three implementations of the hockey-stick function fitted to stock–recruitment data are explored. The first implementation makes use of the segmented regression function in the *Fisheries Library in R* (http://www.flr-project.org, Kell *et al.* 2007), a standard toolbox in stock assessment, which is developed for use in R (R Development Core Team 2013). The second implementation is a rule-based hockey stick where the rules are derived from textbook principles of stock assessment. Interpretation of highly variable data such as stock recruitment data can benefit from the combination of formal analysis with expert knowledge. The third implementation is therefore a Bayesian inference fit of the hockey stick, where the analysis of the data is informed by general knowledge about stock–recruitment relationships. The results of these three methods were then compared to the biomass reference points used in the management advice documents produced by ICES, which are used by the European Commission to assess the status of European fish stocks (EC 2013).

Fishing mortality and natural mortality

A second limit of exploitation is the maximum sustainable rate of fishing, that is the maximum amount of fish that can be caught on a permanent basis relative to the amount of fish in the water. In fisheries science, this rate is expressed as the fishing mortality F and the United Nations Fish Stock Agreement (UNFSA 1995) defines the respective limit reference point as the fishing mortality F_{msy} that will result in the biomass that can produce the maximum sustainable catch or yield (MSY). There are a variety of methods to obtain estimates of F_{msy}, but there is also long-standing consensus in fisheries science (e.g. Gulland 1971; Sheperd 1981; Beddington and Cooke 1983; Clark *et al.* 1985; Beverton 1990; Patterson 1992; Thompson 1993; Walters and Martell 2002, 2004; MacCall 2009; Pikitch *et al.* 2012) that the mortality caused by fishing F shall not exceed the average rate of natural mortality (M) of the exploited phase of the stock, resulting from the sum of natural causes such as predation, diseases, hazards or old age. In other words, F may not exceed F_{msy}, which may not exceed M. In a practical application of this consensus, the National Oceanic and Atmospheric Administration (NOAA) in the United States uses M as proxy for F_{msy} for data-limited stocks (NOAA 2013). Here, the estimates of F_{msy} used in the official management advice documents of ICES are compared with the rate of natural mortality.

Age and size at maturity

A third limit of exploitation is given by the smallest acceptable size or age of fishes targeted by the fishery. It is long known that yield per recruit can be increased if fishing starts at a later age and thus targets larger sizes of fishes (Beverton and Holt 1957), up to about two-thirds of maximum length, where the theoretical maximum catch can be obtained with infinite effort (Holt 1958), or where a given catch has the lowest impact on cohort biomass (Froese *et al.* 2008). Also, it has been formally shown that a stock is unlikely to become overfished if all individuals are allowed to spawn at least once (Myers and Mertz 1998). Thus, the size and age where most fish have reproduced at least once marks the third limit reference point chosen in this study.

In summary, the purpose of this study was to compare biomass, fishing pressure and selectivity reference points used in north-east Atlantic fisheries management with international standards and to evaluate the status of the fish stocks against these reference points.

Material and methods

Data sources

Stock–recruitment data, natural mortality at age, proportion mature at age and fishing mortality at age were obtained from the ICES Stock Summary database (downloaded from http://ices.dk in July 2013) for 50 fully assessed stocks. Family assignments, scientific names and common names follow FishBase (Froese and Pauly 2014) and are given together with stock identifiers in Table 1. Doubtful values were checked against assessment reports available from http://ices.dk, and some errors in the database were corrected and reported to ICES. Spawning stock biomass and fishing mortality in 2013 were obtained from ICES advice documents in 2013, available from http://ices.dk. The full URLs are indicated in the respective spreadsheets available as online material at http://oceanrep.geomar.de/25749/.

For the purpose of comparing estimates of SSB_{pa} with estimates of the biomass that can produce the maximum sustainable yield SSB_{msy}, data for 31 stocks managed by other agencies (mostly NOAA) were analysed. These were selected from stocks with recent assessments where the range of stock sizes in the respective time series included one-half of SSB_{msy}, because analysis of stocks which have never been depleted or which have never been outside the depletion area cannot yield reliable estimates of SSB_{pa}. Also, in some cases, data from years before 1960, where recruitment was derived from model assumptions rather than observations, were excluded from the analysis. The full results of this analysis and the used data set are available from http://oceanrep.geomar.de/25749/.

Fisheries Library hockey stick

To obtain independent estimates of the biomass below which recruitment may be impaired, three different models were fitted to stock–recruitment data, with recruitment offset by the age of recruits. The Fisheries Library hockey stick was fitted by the segreg() function available in the FLCore

Table 1 Families, scientific names, common names and stock identifiers used in Tables 2, 4 and 5.

Family	Species	Common name	Stocks
Ammodytidae	*Ammodytes tobianus*	Small sandeel	san–
Carangidae	*Trachurus trachurus*	Atlantic horse mackerel	hom–
Clupeidae	*Clupea harengus*	Atlantic herring	her–
	Sardina pilchardus	European pilchard	sar–
	Sprattus sprattus	European sprat	spr–
Gadidae	*Gadus morhua*	Atlantic cod	cod–
	Melanogrammus aeglefinus	Haddock	had–
	Merlangius merlangus	Whiting	whg–
	Micromesistius poutassou	Blue whiting	whb–
	Pollachius virens	Saithe	sai–
	Trisopterus esmarkii	Norway pout	nop–
Nephropidae	*Nephrops norvegicus*	Norway lobster	nep–
Pleuronectidae	*Pleuronectes platessa*	European plaice	ple–
Scombridae	*Scomber scombrus*	Atlantic mackerel	mac–
Soleidae	*Solea solea*	Common sole	sol–

library of the Fisheries Library for R (Kell 2011). This routine uses the function:

$$R = \text{ifelse}(SSB <= SSB_{lim}, slope \times SSB, slope \times SSB_{lim}) \quad (1)$$

where R is the number of recruits, SSB is the spawning stock biomass of their parents, SSB_{lim} is the limit spawning stock biomass below which recruitment is reduced, and *slope* is the slope of the hockey-stick blade. The upper 95% confidence limit of SSB_{lim} was derived iteratively as described in Kell (2011). This upper confidence limit was used as the SSB_{pa} estimate of the Fisheries Library hockey stick.

Rule-based hockey stick

The hockey-stick function assumes that at stock sizes above a certain biomass threshold, recruitment fluctuates with a log-normal distribution around a central value, which is the height of the shaft of the hockey stick, parallel to the biomass axis. Below the threshold, recruitment declines linearly with biomass, with a constant recruit-per-spawner ratio, representing the slope of the blade of the hockey stick with its tip in the origin of a stock–recruitment plot (Fig. 1). The rule-based hockey stick tries to capture this general knowledge by applying the following rules:

1. An arbitrary boundary to large stock sizes is obtained as the mid-point of the range of available biomass data. The geometric mean of recruitment above that mid-point gives the rule-based height of the hockey-stick shaft RB_R_{inf};
2. A boundary to reduced recruitment RB_SSB_{lim} is determined as the biomass below which all observations of recruitment are smaller than RB_R_{inf};
3. A precautionary buffer to the boundary of reduced recruitment RB_SSB_{pa} is obtained by one of the three methods described below. The method that provides the largest biomass estimate is chosen.
    a. An empirical buffer is applied by increasing SSB_{lim} by 40% with RB_SSB_{pa} = 1.4 RB_SSB_{lim};
    b. RB_SSB_{pa} is determined as the biomass below which all observations of recruitment are smaller than the upper 95% confidence limit of RB_R_{inf};
    c. Stocks are assumed prone to reduced reproductive capacity if their biomass falls below 20% of the unexploited biomass (Beddington and Cooke 1983; Myers *et al.* 1994). As the largest biomass in a time series of fisheries data is unlikely to be larger than the unexploited biomass, it follows that RB_SSB_{lim} may not be smaller than 20%, and RB_SSB_{pa} not smaller than 1.4 RB_SSB_{lim} => 28% of the largest observed biomass.

Bayesian hockey stick

Bayesian inference combines existing knowledge (the prior information) with the analysis of new data in an appropriate model (the likelihood function) to obtain updated posterior knowledge. Prior information must be described by a probability distribution of the respective parameters, based on previous knowledge. Here, the definitions of the hockey stick and of SSB_{lim} are used to obtain priors for the central values of the distribution of the height of the hockey stick and the point where it connects to the blade. In other words, the prior knowledge that the height of the shaft will be near the geometric mean of recruitment at large stock sizes and that the blade connects near the point below which recruitment is less than the geometric mean at large stock sizes is incorporated into the analysis of the data at hand. This is similar to the recommended practice of normalizing observations by subtracting the mean (Kruschke 2011). Prior knowledge would then be expressed as the expected type and width of a prior distribution with a central value of zero. In this study, the rule-based estimates of RB_R_{inf} and RB_SSB_{lim} were accepted as prior central values for the Bayesian hockey stick. The width of the respective distributions was obtained from independently observed variability across the 50 stocks in Table 2. In particular, log-normal distributions were assumed for R, R_{inf}, SSB, SSB_{lim} and SSB_{pa}. The central values and relative standard deviations used for the priors for SSB_{lim} and R_{inf} are given in Table 3. The JAGS software (Plummer 2003) was used to estimate the Bayesian posterior distributions by means of a Markov Chains Monte Carlo simulation (Smith and Roberts 1993). A light-weight guide to JAGS is included among the online material (Coro 2013). The JAGS model is shown as Equation (2).

Table 2 Biomass reference points as used by ICES and as resulting from hockey-stick analysis with the Fisheries Library, the rule-based, and the Bayesian hockey stick, where SSB_{lim} and SSB_{pa} are biomass reference points and R_{inf} indicates the height of the hockey-stick shaft. ICES estimates of SSB_{lim} or SSB_{pa} that are below the lowest estimate of the three hockey sticks are bolded. Fisheries Library biomass estimates above maximum *SSB* are bolded. The median SSB_{pa} and the proxy estimate of SSB_{msy} are bolded if *SSB* in 2013 was below these levels. Stock ID are the codes used by ICES for the respective stocks. Weights are given in 1000 tonnes, R_{inf} in millions of recruits, except for stocks marked with an asterisk, where *SSB* and R_{inf} are given as index.

	ICES		Fisheries library			Rule-based			Bayesian					
Stock ID	SSB_{lim}	SSB_{pa}	SSB_{lim}	SSB_{pa}	R_{inf}	SSB_{lim}	SSB_{pa}	R_{inf}	SSB_{lim}	SSB_{pa}	R_{inf}	Median SSB_{pa}	Proxy SSB_{msy}	*SSB* 2013
cod-2532	**63**	**88.2**	199	237	283	184	327	373	230	402	316	**327**	**654**	180
cod-347d	**70**	**150**	174	239	1077	127	177	1144	138	174	1127	**177**	**354**	72
cod-7e-k	7.3	10.3	14	27	7.14	5.4	7.5	6.4	5.4	6.8	5.1	7.5	15	22
cod-arct	**220**	460	280	423	622	233	326	722	253	341	616	341	682	1986
cod-farp	**21**	40	33	51	14	25	34	13	28	44	13	**44**	**88**	24
cod-iceg	**125**		244	300	200	188	263	191	158	330	176	300	**600**	478
cod-scow	14	22	20	39	17	11	17	15	13	18	14	**18**	**36**	1.7
had-34	100	140	63	125	17 640	180	252	13 235	106	180	18 319	180	**360**	258
had-7b-k		**7.5**	5.9	12	272	15	22	153	12	17	292	17	**34**	24
had-arct	**50**	80	275	**549**	341	56	79	234	72	153	164	153	**306**	255
had-faro	22	35	48	76	18	22	30	16	23	35	16	**35**	**70**	15
had-iceg	**45**		64	99	56	59	83	50	55	90	56	90	**180**	90
had-rock	**6.0**	9.0	23	45	29	7.0	10	45	6.9	8.9	27	**10**	**20**	5.8
had-scow	22	30	29	53	83	21	29	103	22	33	81	**33**	**66**	30
her-2532-gor	**430**	**600**	901	1361	21 264	1244	1742	22 725	725	922	20 517	**1361**	**2722**	717
her-3a22		**110**	148	295	3389	119	167	4317	107	180	3263	**180**	**360**	106
her-47d3	800	1300	819	1078	48 403	749	1098	53 693	501	616	48 131	1049	**2098**	1996
her-irls	26	44	46	66	443	24	34	484	29	45	410	45	90	156
her-nirs	**6.0**	**9.5**	25	42	385	31	44	390	10	13	250	**42**	**84**	22
her-noss	**2500**	5000	3812	6285	68 616	3332	4665	48 567	2696	6255	68 595	**6255**	**12 510**	5080
her-riga		**60**	87	**175**	2810	62	87	2865	73	88	2894	**88**	**176**	77
her-vasu	**200**	**300**	294	424	673	294	412	911	264	545	706	424	**848**	541
her-vian	50		433	**865**	3330	107	285	2881	179	308	1968	**308**	**616**	102
hom-west			955	1909	2913	1156	1618	2982	952	2069	2933	**1909**	**3818**	1660
mac-nea	1670	2300	1667	2274	3901	1682	2355	3307	1211	2479	3913	2355	**4710**	2556
nep-8ab *			15	**31**	27	12	17	27	15	18	28	**18**	**36**	15
nop-34	90	150	149	225	52 895	92	144	44 706	83	150	50 123	150	**300**	192
ple-celt *	1.1	1.8	0.7	**1.4**	1.5	0.6	0.8	0.8	0.6	0.7	0.7	**0.8**	**1.7**	0.4
ple-eche	5.6	8.0	4.5	5.5	19.0	3.2	4.5	16	3.6	4.1	16	4.5	**9.0**	7.0

Table 2 Continued.

	ICES		Fisheries library			Rule-based			Bayesian			Median	Proxy	SSB
Stock ID	SSB_{lim}	SSB_{pa}	SSB_{lim}	SSB_{pa}	R_{inf}	SSB_{lim}	SSB_{pa}	R_{inf}	SSB_{lim}	SSB_{pa}	R_{inf}	SSB_{pa}	SSB_{msy}	2013
ple-echw		1.7	1.6	2.2	7.8	1.6	2.3	7.1	1.6	1.7	6.3	2.0	4.0	4.6
ple-nsea	160	**230**	173	279	938	182	255	986	153	264	942	264	528	663
sai-3a46	106	200	107	171	134	111	155	144	98	165	135	165	**330**	169
sai-arct	136	220	118	153	176	117	164	180	108	163	175	163	**326**	225
sai-faro		**55**	61	85	28	58	82	23	54	88	28	**85**	**170**	72
sai-icel	61	**65**	66	105	34	66	92	33	61	103	33	103	**206**	158
san-ns1	160	**215**	157	314	203 315	214	299	295 548	140	228	214 149	**299**	**598**	186
san-ns2	70	100	139	278	56 573	58	81	42 904	61	96	45 293	**96**	**192**	79
san-ns3	100	195	147	294	114 072	81	145	76 188	85	140	105 832	**140**	**280**	88
sar-soth			442	744	13 348	306	428	13 238	287	575	12 957	**575**	**1150**	192
sol-bisc		**13**	15	**30**	28	12	17	27	14	17	28	17	**34**	16
sol-celt		2.2	1.6	2.0	6.0	1.6	2.3	3.8	1.6	1.7	4.7	2.0	**4.0**	3.3
sol-eche		**8.0**	7.1	9.8	24.9	7.6	10.6	25	7.2	9.0	25	10	**20**	11
sol-echw	**1.3**	**1.8**	3.6	5.9	5.8	2.7	3.8	5.3	3.0	3.4	4.8	**3.8**	**7.7**	3.5
sol-iris	**2.2**	**3.1**	4.6	6.4	6.6	2.8	4.1	6.6	2.9	3.3	5.6	**4.1**	**8.2**	1.0
sol-nsea	25	35	28	41	98	23	33	84	22	33	95	33	**66**	51
spr-2232	410	570	774	1275	78 948	354	496	79 837	256	463	64 459	496	**992**	883
whb-comb	**1500**	**2250**	4648	6144	22 032	2191	3067	23 195	2362	7260	16 931	**6144**	**12 288**	5130
whg-47d			363	587	4792	275	385	4776	242	439	4352	**439**	**878**	282
whg-7e-k	**15**	**21**	18	25	69	18	25	63	16	23	68	25	50	59
whg-scow	**16**	**22**	38	57	237	27	38	185	20	26	223	**38**	**76**	8.5

```
model{
      # priors
      log.Rinf.ran ~ dnorm(pr_log.Rinf, pr_tau.logRinf)
      log.SSBlim.ran ~ dnorm(pr_log.SSBlim, pr_tau.log.SSBlim)
      SD.logR ~ dnorm(pr_SD.log.Rinf, pr_tau.SD.log.Rinf)
      tau.log.R < - pow(SD.log.R, -2)
      # data model and likelihood
      for(j in 1 : J){                                                    (2)
        logyh[j] < - ifelse(log.SSB[j] < log.SSBlim.ran,
        log.SSB[j] * log.Rinf.ran/log.SSBlim.ran,
        log.Rinf.ran)
        log.R[j] ~ dnorm(loghy[j], tau.log.R)
      }
      }
```

where the first two priors contain random normal distributions of R_{inf} and SSB_{lim}, and the third prior contains the random normal distribution of the standard deviation SD of log(R). The prefix tau indicates that precision is used instead of standard deviation, as required by JAGS, with tau = SD^{-2}. The data model is the same as used in Equation (1), only that the slope is expressed as R_{inf}/SSB_{lim}. For every biomass observation *log.SSB*[j], the likelihood of the predicted *logyh*[j] is modelled, given the observed value of *log.R*[j] and the priors. The antilog of the mean of the medians of these distributions then gives the central values for SSB_{lim} and for R_{inf}. The antilog of the upper 95% confidence limit of log SSB_{lim} gives the estimate of SSB_{pa}.

Other data and reference points

Estimates for fishing mortalities F and F_{msy} and for natural mortality M were used as published by ICES. Gear selectivity was estimated from fishing mortality at age as given by ICES. For the purpose of this study, an age class was regarded as having entered the fishery if F exceeded 33% of the maximum F value given for any age class. Age at full maturity was estimated from proportion mature as given by ICES. For the purpose of this study, the age class with more than 90% mature individuals was considered as fully mature. In two cases (had-7b-k, sol-eche) where knife-edge selection resulted in unrealistically low ages at first maturity, the subsequent age class was chosen as fully mature.

Table 3 Means, coefficient of variation (CV) and number of stocks used for defining the log-normal distributions of the priors in the Bayesian hockey-stick analysis.

Priors	Mean	CV	SD	Stocks
log(SSB_{lim})	log(RB_SSB_{lim})	0.071	0.078	50
log(R), log(Rinf)	log(RB_R_{inf})	0.15	0.18	50

Availability of code and data

The stock–recruitment data, the R-code and the results of the analysis are available online from http://oceanrep.geomar.de/25749/.

Results

Comparison of biomass reference points

Estimates of SSB_{lim} and SSB_{pa} as used by ICES in the advice provided in 2013 and as derived in this study are shown in Table 2 for 50 stocks of the north-east Atlantic. Median SSB_{pa} across the three methods and twice that median as proxy for SSB_{msy} are indicated. Table 2 also shows the ICES estimate of spawning stock biomass in 2013, for comparison against the reference points. Of the 38 stocks where ICES provided estimates of SSB_{lim}, 17 estimates (45%) were below the lowest estimate provided by the three hockey-stick functions. Of the 43 stocks where ICES provided estimates of SSB_{pa}, 19 estimates (44%) were below the lowest estimate provided by the hockey sticks. Using the median as a consensus estimate of SSB_{pa} across the three methods and comparing it with SSB estimates for the year 2013 shows that 26 of the 50 stocks (52%) were below the threshold and thus outside of safe biological limits. Only six of the 50 stocks (12%) were above the proxy MSY biomass level SSB_{msy}.

Comparison of fishing mortality and natural mortality

Table 4 shows, for 45 stocks of the north-east Atlantic, the official estimates of F, F_{msy} and M. In 29 of 38 stocks (76%) with available data, the limit reference point F_{msy} exceeded natural mortality by 86% on average. Actual fishing mortality in 2013 exceeded M in 33 of 45 (73%) stocks. Mortality caused by fishing was on average 75% higher than natural mortality.

Gear selectivity and maturity

Table 5 shows a comparison of the age where 90% of the fish have reached maturity with the age where young fish are entering the fishery. In 74% of the stocks, fishing started before most fish could reproduce, with a difference of 1.4 years on average but up to 4 years in some late-maturing stocks.

Discussion

Performance of hockey-stick models

As one standard method and two new methods were applied to the estimation of biomass limits, the performance of these methods is discussed here in more detail. The concept of the hockey-stick function for the stock–recruitment relationship is shown in Fig. 1. Spawning stock sizes below the precautionary reference point SSB_{pa} are considered to be outside safe biological limits, because reduced recruitment cannot be ruled out with a high level of certainty (ICES 2007, 2010). Stock sizes above SSB_{pa} are thus considered safe from collapse, but high yields with less impact on the stocks can only be obtained at stock levels above the spawning stock biomass that can produce the maximum sustainable yield (SSB_{msy}).

Figure 2 shows an example of fitting the three hockey sticks to stock–recruitment data for saithe (*Pollachius virens*, Gadidae) from the Faroe Plateau (sai-faro). In this case, three implementations of

Table 4 Estimates of natural mortality M, fishing mortality reference point F_{msy}, fishing mortality F estimated for the year 2013 and the ratio of fishing mortality and natural mortality. Stock IDs are the codes used by ICES for the respective stocks. Note that in 33 of 45 stocks (73%), fishing mortality exceeded natural mortality, on average by 75%. With one exception (whg-scow), heavy fishing continued also in the six most depleted stocks, in bold.

Stock ID	M	F_{msy}	F_{2013}	F/M
cod-2532	0.20	**0.46**	0.37	1.85
cod-347d	0.20	0.19	0.39	1.95
cod-7e-k	0.26	**0.40**	0.43	1.68
cod-arct	0.20	**0.40**	0.23	1.15
cod-farp	0.20	**0.32**	0.41	2.05
cod-iceg	0.20		0.26	1.30
cod-scow	0.27	0.19	0.92	3.41
had-34	0.22	**0.30**	0.18	0.83
had-7b-k	0.43	0.33	0.72	1.68
had-arct	0.20	**0.35**	0.56	2.80
had-faro	0.20	**0.25**	0.32	1.60
had-iceg	0.20		0.34	1.70
had-rock	0.20	**0.30**	0.19	0.95
had-scow	0.20	**0.30**	0.24	1.20
her-2532-gor	0.24	**0.26**	0.15	0.64
her-3a22	0.20	**0.28**	0.39	1.95
her-47d3	0.34	0.27	0.27	0.79
her-irls	0.16	**0.25**	0.12	0.75
her-nirs	0.33	0.26	0.22	0.67
her-noss	0.15	0.15	0.13	0.87
her-riga	0.20	**0.35**	0.37	1.85
her-vasu	0.10	**0.22**	0.22	2.20
her-vian	0.14	**0.25**	0.20	1.45
hom-west	0.15	0.13	0.17	1.13
mac-nea	0.15	**0.22**	0.36	2.40
nop-34	0.42		0.31	0.74
ple-eche	0.10	**0.23**	0.29	2.90
ple-echw	0.12	**0.24**	0.40	3.33
ple-nsea	0.10	**0.25**	0.23	2.30
sai-3a46	0.20	**0.30**	0.37	1.85
sai-arct	0.20		0.33	1.65
sai-faro	0.20	**0.28**	0.51	2.55
sai-icel	0.20	**0.22**	0.21	1.05
sar-soth	0.35		0.45	1.29
sol-bisc	0.10	**0.26**	0.40	4.00
sol-celt	0.10	**0.31**	0.34	3.40
sol-eche	0.10	**0.29**	0.46	4.60
sol-echw	0.10	**0.27**	0.25	2.50
sol-iris	0.10	**0.16**	0.16	1.60
sol-nsea	0.10	**0.22**	0.24	2.40
spr-2232	0.36	0.29	0.29	0.81
whb-comb	0.20	0.18	0.18	0.90
whg-47d	0.61		0.15	0.25
whg-7e-k	0.20	**0.36**	0.33	1.65
whg-scow	0.54		0.07	0.13

Table 5 Age in years where more than 90% of the fish have reached maturity (t_{m90}), age of entry in the fishery (t_{F33} where fishing mortality exceeds 33% of the highest age-specific value) and difference between these ages (*delta t*).

Stock ID	t_{m90}	t_{F33}	*delta t*
cod-2532	5	3	−2
cod-7e-k	4	2	−2
cod-arct	9	6	−3
cod-farp	5	3	−2
cod-iceg	8	5	−3
cod-scow	4	4	0
ghl-arct	14	8	−6
had-34	5	3	−2
had-7b-k	3	3	0
had-arct	8	4	−4
had-faro	4	3	−1
had-rock	3	4	1
had-scow	3	1	−2
her-2532-gor	4	3	−1
her-3a22	5	1	−4
her-47d3	4	2	−2
her-irls	2	2	0
her-nirs	3	2	−1
her-noss	6	5	−1
her-riga	2	2	0
her-vian	3	2	−1
hom-west	5	1	−4
mac-nea	4	4	0
nep-8ab	4	3	−1
ple-celt	5	3	−2
ple-eche	4	2	−2
ple-echw	5	3	−2
ple-nsea	4	3	−1
sai-3a46	7	4	−3
sai-arct	8	4	−4
sai-faro	8	5	−3
sar-soth	2	1	−1
sol-bisc	4	3	−1
sol-celt	5	3	−2
sol-eche	4	3	−1
sol-echw	5	3	−2
sol-iris	4	3	−1
sol-nsea	3	3	0
spr-2232	2	1	−1
whb-comb	3	4	1
whg-47d	2	3	1
whg-7e-k	3	3	0
whg-scow	2	3	1

the hockey stick led to very similar estimates of SSB_{pa} between 80 000 and 90 000 tonnes despite the considerable scatter in the data. In contrast, the official SSB_{pa} estimate of ICES was taken as the lowest biomass in the time series at 55 000 tonnes (ICES 2013b).

Clearly, reasonable predictions of the spawning biomass below which recruitment declines can only be derived from data sets that include this threshold. In other words, time series where all biomass data are above or below SSB_{lim} will give biased results. If such a situation is visible in the stock recruitment plot, then no modelling should be attempted. An example for a depleted stock is shown in Fig. 3 for plaice (*Pleuronectes platessa*, Pleuronectidae) in the Celtic Sea (ple-celt). Because all biomass data are smaller than the lowest estimate of SSB_{pa}, the stock can be treated as outside the safe biological limits. Thus, the proposed reference points are probably biased downwards and should not be used. Similarly, Fig. 4 shows the fitted hockey sticks for mackerel (*Scomber scombrus*, Scombridae) in the north-east Atlantic (mac-nea). This stock has never been depleted, and therefore, the data do not contain information about limit reference points. This situation is less critical than the previous one, because the proposed biased reference points err on the precautionary side, that is, they are probably overestimated.

The segmented regression of the Fisheries Library provides its estimates based on the best fit of a hockey-stick function to the available data. This approach suffers from the general problem that even a very good fit may give misleading results if the data at hand are a biased subsample of the unknown 'true' distribution. Such bias is common in stock recruitment data because observations of recruitment at very small or at large stock sizes are typically missing. In this study, the segmented regression tended to overestimate SSB_{lim} if there was no clear levelling-off of recruitment at higher biomass values. Also, it tended to overestimate SSB_{pa} if there was high variability in recruitment. In six cases (12%; bolded in Table 2), the SSB_{pa} estimates of the Fisheries Library hockey stick far exceeded the largest biomass value in the time series. This is an unlikely result, as it would suggest that all observations in the time series were taken from a stock far outside safe biological limits. One such case is depicted in Fig. 5 for Baltic Herring (*Clupea harengus*, Clupeidae) in the Gulf of Riga (her-riga). A closer inspection of available time-series data for biomass and fishing mortality suggests that this stock was above SSB_{pa} at least in some years. This was also true for most of the other cases. In Norway lobster (*Nephrops norvegicus*, Nephropidae) (nep-8ab) and sole (*Solea solea*, Soleidae) in the Bay of Biscay (sol-bisc), biomass

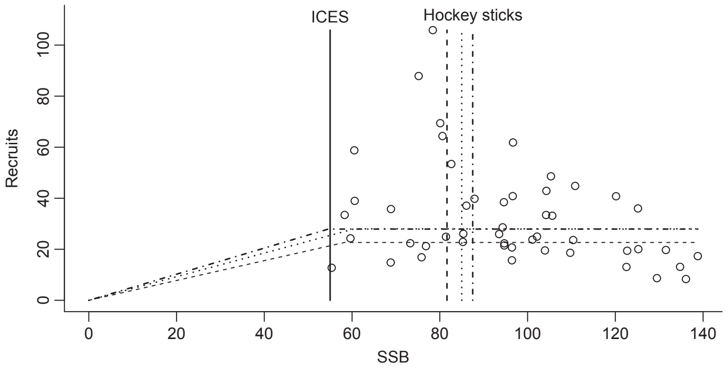

Figure 2 Analysis of stock–recruitment data for Faroe Plateau Saithe (sai-faro), with number of recruits in millions and spawning stock biomass in thousands of tonnes. The three fitted hockey sticks give very similar results for the precautionary biomass limit (SSB_{pa}, vertical lines above SSB = 80 000 tonnes). In contrast, the official ICES SSB_{pa} was set to the lowest biomass in the time series at 55 000 tonnes.

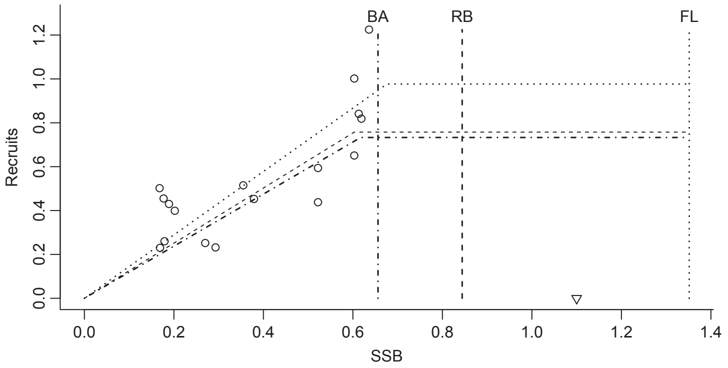

Figure 3 Analysis of stock–recruitment data for plaice in the Celtic Sea (ple-celt) with Bayesian (BA; dashed dotted line), rule-based (RB; dashed line) and Fisheries Library (FL; dotted line) hockey-stick functions. Because all biomass data are less than the lowest estimate of SSB_{pa} (vertical lines), BA and RB are probably biased downward and should not be used for management. The triangle indicates the estimate of SSB_{lim} used by the ICES working group.

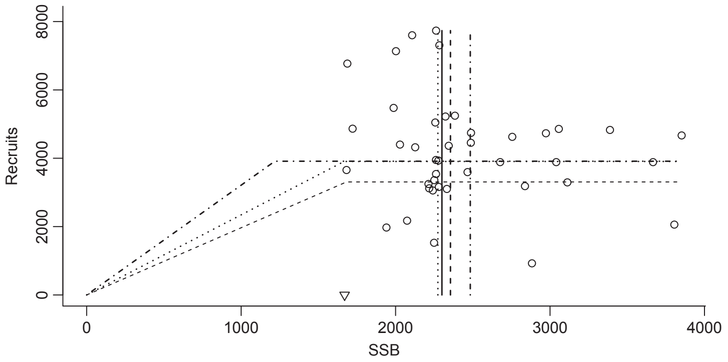

Figure 4 Analysis of stock–recruitment data for mackerel in the north-east Atlantic (mac-nea). Because all biomass data are greater than the largest estimate of SSB_{lim} (bends in the hockey sticks), this analysis is probably biased upwards and the biomass reference points should be considered as extra precautionary. The triangle indicates SSB_{lim} and the solid vertical line SSB_{pa} as used by the ICES working group.

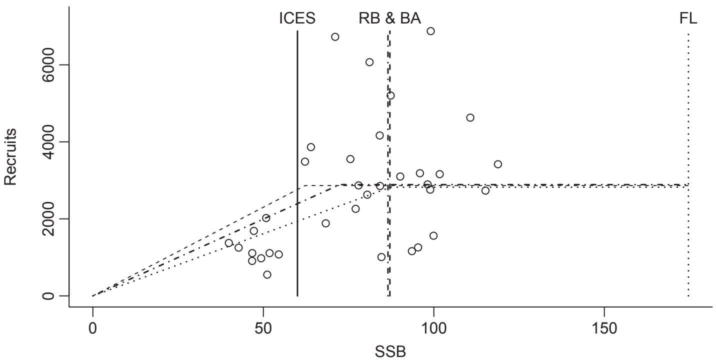

Figure 5 Analysis of stock–recruitment data for herring (her-riga) in the Gulf of Riga, with number of recruits in millions and spawning stock biomass in thousands of tonnes. The vertical lines indicate the precautionary biomass limits (SSB_{pa}) estimated by ICES and by the three hockey-stick implementations. The estimate of the Fisheries Library (FL) far exceeds the maximum observed biomass and appears unrealistic.

status was more difficult to judge, but the suggested precautionary level of twice the maximum biomass on record still seemed unlikely. These overestimates by the Fisheries Library hockey stick underline the need for additional models that draw on general knowledge about stock recruitment relationships, beyond the data at hand. Such additional knowledge is built into the rule-based hockey stick and the Bayesian hockey stick.

By design, the rule-based method cannot propose SSB_{lim} estimates below the minimum or above the maximum biomass in the time series. Compared with the other two models, it tended to underestimate SSB_{lim} if there was a single high recruitment event at very low biomass, or if there was no clear levelling-off of recruitment at larger stock sizes. However, despite its simplicity, the rule-based method provided reasonable estimates that were, in the majority of cases, close to the estimates provided by the other two methods (see Table 2).

The Bayesian hockey stick combined prior knowledge about stock–recruitment relationships and about the general variability of the parameters with an analysis of the stock-specific data at hand. Thus, not surprisingly, it was often intermediate to the SSB_{pa} estimates of the Fisheries Library and of the rule-based hockey stick. However, all three methods provided minimum or maximum SSB_{pa} estimates in some cases and therefore selecting the most appropriate SSB_{pa} estimate in these instances was not straightforward. The precautionary principle holds that in the case of uncertainty, the result with the least potential harm for the stock is to be favoured (FEU 2009; Froese *et al.* 2011). Thus, in cases where the three methods provided different estimates for SSB_{pa}, the highest estimate should be chosen. However, as pointed out above, there were cases where the validity of the highest estimate was doubtful. As a pragmatic implementation of these considerations, the median of the available estimates was chosen as representative of a consensus SSB_{pa}. The median has the advantage that it is insensitive to outliers.

Comparison of biomass limit estimates

The main purpose of this study was to compare official reference points for fisheries management with independent estimates. With regard to biomass, nearly half of the official values were below estimates derived with three independent methods in this study. Figures 2 and 5 show two examples of such cases. Of the 15 stocks where ICES did not provide estimates of SSB_{lim} or SSB_{pa}, such estimates were available from the hockey sticks. We appreciate that ICES stock assessment working groups will have reasons for setting biomass reference points as they did, or for not providing such estimates. But, we would like to point out that the available data and the methods used in this study allowed an estimation of reference points for all examined stocks and that these independent estimates were often more precautionary than the official reference points.

For example, the precautionary reference point SSB_{pa} is used to identify stocks that are outside of safe biological limits (EC 2013). This study found 52% (26 of 50) of the stocks in that danger zone. This is considerably more than the 33% (14 of

43) resulting from the official SSB_{pa} reference points. Using ICES reference points with a slightly different set of stocks, the European Commission concluded that 41% of the European stocks (17 of 41) were outside of safe biological limits (EC 2013), which is closer to, but still below the independent estimate obtained in this study.

A proxy for the biomass that can produce the maximum sustainable yield

As indicated in Fig. 1, the precautionary biomass limit to reduced reproduction, SSB_{pa}, can be used as a proxy for the biomass that can produce the maximum sustainable yield, SSB_{msy}. This follows from the common assumption that the probability of reduced recruitment is increasing at stock sizes below 20% of the unexploited biomass, B_O (e.g. Beddington and Cooke 1983; Myers *et al.* 1994; Gabriel and Mace 1999), whereas production models place the biomass that can produce *MSY* between 0.37 B_O (Fox 1975) and 0.5 B_O (Schaefer 1954). If $SSB_{pa} \approx 0.2\ B_O$, it follows that $2\ SSB_{pa} \approx SSB_{msy}$. Such relationship also follows from the ICES definition of $SSB_{trigger}$, which is supposed to mark the lower range of biomass candidates for SSB_{msy} (ICES 2010), and which was set by ICES working groups equal to SSB_{pa} in the stocks we have examined (ICES 2012). If we assume a precautionary uncertainty range of +/− 50% around SSB_{msy}, then we again obtain $SSB_{msy} \approx 2\ SSB_{pa}$. Other agencies provide estimates of SSB_{msy} for their fully assessed stocks. For 31 stocks with such estimates and available recruitment time-series data, we applied the three methods for fitting hockey sticks and compared the median estimate of SSB_{pa} with the respective estimates of SSB_{msy} (Table 6). The median ratio was 2.2, with 95% confidence limits of 1.6–2.6, that is the proposed factor of two falls within the confidence limits and is thus empirically confirmed. The median of the SSB_{pa} estimates was therefore used to calculate proxy estimates of SSB_{msy} for the 50 ICES stocks (Table 2).

Comparing biomass in 2013 against the proxy SSB_{msy} derived in this study, only 12% of the stocks were above the biomass level that can produce the maximum sustainable yield, the threshold set in the reformed European Common Fisheries Policy (CFP 2013) and in descriptor 3.2 of the Marine Strategy Framework directive for good environmental status of European seas (MSFD 2008). Of the stocks that were below the threshold, five were close enough ($SSB_{2013} > 80\%\ SSB_{msy}$) to reach SSB_{msy} in 2014 if fishing was strongly reduced in that year. Most of the other stocks would be able to reach SSB_{msy} within several years if fishing was reduced to adequate rebuilding levels (Froese and Quaas 2013). However, six (12%) of the considered stocks, such as cod (*Gadus morhua*, Gadidae, cod-347d) in the North Sea, were so depleted ($SSB_{2013} < 20\%\ SSB_{msy}$) that rebuilding plans are needed to prevent their collapse (Froese and Quaas 2012).

Fishing mortality versus natural mortality

The reformed European Common Fisheries Policy (CFP 2013) and descriptor 3.1 of the Marine Strategy Framework directive for good environmental status of European seas (MSFD 2008) require that mortality caused by fishing does not exceed the level (F_{msy}) that can produce the maximum sustainable yield. ICES provides estimates of F_{msy} for most of the fully accessed stocks, but how good are these estimates? In the introduction, it was pointed out that the rate of natural mortality can be seen as a 'natural' upper limit to F_{msy}. Setting $F = M$ in effect doubles the mortality in the exploited part of the population and reduces adult life expectancy and average duration of the reproductive phase by half. Because fish grow throughout their life, reducing average life expectancy also shrinks the biomass of the stock by about half as the numbers and weight of fish are reduced. In other words, setting $F = M$ results in a strong impact on the stock that may overstretch the productivity of the stock, and thus, $F = M$ is not a target but a limit reference point, with candidate values for long-term sustainable fishing pressure being somewhere below that level (Beddington and Cooke 1983; Walters and Martell 2002, 2004; MacCall 2009; Pikitch *et al.* 2012).

Comparing the official reference points for F_{msy} with the estimates of natural mortality showed that in about three-fourths of the stocks, F_{msy} values were substantially higher than *M*. Thus the proposed reference point for sustainable fishing allowed more fish to be killed via fishing than due to all other causes of mortality combined. Fortunately, decreasing trends in fishing mortality have been illustrated in northern European seas in recent years, and several stocks have responded with increases in biomass (Gascuel *et al.* 2014).

Table 6 30 NOAA stocks and one Billfish Working Group stock with recruitment data and estimates of SSB_{msy}. The median ratio SSB_{msy}/SSB_{pa} was 2.19 with 95% confidence limits of the median of 1.61–2.56.

Species	Stock ID	Region	SSB_{pa}	SSB_{msy}	Ratio
Atheresthes stomias	GOAatf	Gulf of Alaska	676 370	478 822	0.71
Clupea harengus	Atlantic herring_NWAC	North-west Atlantic Coast	392 000	157 000	0.4
Eopsetta jordani	PetraleSole_PC	Pacific Coast	3631	8107	2.23
Epinephelus niveatus	SnowGrouper_Satl	South Atlantic	260	2092	8.03
Gadus macrocephalus	EBSPcod	East Bering Sea	223 251	355 000	1.59
Gadus morhua	Cod_GB	Georges Bank	77 132	186 535	2.42
	Atlantic cod_GB	Georges Bank	77 132	148 084	1.92
Glyptocephalus cynoglossus	Witch flounder_NWAC	North-west Atlantic Coast	4713	10 051	2.13
Hippoglossoides platessoides	American plaice_GoMGB	Gulf of Maine/Georges Bank	8450	21 940	2.6
Kajikia audax	SMarlin_NP	North Pacific	1429	2713	1.9
Lepidopsetta polyxystra	BSAIrocksole	Eastern Bering Sea and Aleutian Islands	148 551	255 000	1.72
Limanda aspera	BSAIyfin	Eastern Bering Sea and Aleutian Islands	93 883	341 000	3.63
Limanda ferruginea	YTFlo_MA	Mid-Atlantic Ocean	6093	27 400	4.5
	Yellowtail flounder_CCGoM	Cape Cod/Gulf of Maine	938	7080	7.55
	Yellowtail flounder_GB	Georges Bank	11 691	43 200	3.7
	Yellowtail flounder_SNEMA	Southern New England/ Mid-Atlantic	6093	2995	0.49
Melanogrammus aeglefinus	Haddock_GB	Georges Bank	57 058	124 900	2.19
	Haddock_GoM	Gulf of Maine	4018	4904	1.22
Pagrus pagrus	RedPorgy_Satl	South Atlantic Ocean	3689	4254	1.15
Pomatomus saltatrix	Bluefish_AC	Atlantic Ocean Coast	102 689	147 052	1.43
Pseudopleuronectes americanus	Winter flounder_GB	Georges Bank	4866	11 800	2.42
	Winter flounder_SNEMA	Southern New England/ Mid-Atlantic	27 149	43 661	1.61
Sebastes alutus	BSAIpop	Eastern Bering Sea and Aleutian Islands	67 174	157 542	2.35
	GOApop	Gulf of Alaska	30 258	91 044	3.01
Sebastes fasciatus	Acadian redfish_GoMGB	Gulf of Maine/Georges Bank	35 925	238 000	6.63
Seriola dumerili	GreaterAmberjack_Satl	South Atlantic Ocean	2819	5491	1.95
Theragra chalcogramma	EBSpollock	East Bering Sea	882 904	2 034 000	2.3
	GOApollock	Gulf of Alaska	267 361	271 000	1.01
	Pollock_GoMGB	Gulf of Maine/Georges Bank	117 362	91 000	0.78
Urophycis tenuis	Whake_GoMGB	Gulf of Maine/Georges Bank	12 660	32 400	2.56
	White hake_GoMGB	Gulf of Maine/Georges Bank	12 660	32 400	2.56

However, in the six most depleted stocks where fishing should have been halted to allow recovery, the rate of fishing mortality in 2013 exceeded the rate of natural mortality by 102% on average, in effect increasing total mortality to three times its natural level and potentially causing the extirpation of these stocks.

Gear selectivity and age at maturity

Common sense, as well as long-established fisheries models (Beverton and Holt 1957), suggests that it is rational to let fish grow and reproduce before capture. Consequently, the reformed European Common Fisheries Policy (CFP 2013) and descriptor 3.3 of the Marine Strategy Framework directive for good environmental status of European seas (MSFD 2008) aim for a high proportion of old and mature fish as indicative of a healthy stock. However, in 74% of the examined stocks, fishing started well before most fish could reproduce. For a given fishing mortality, small size at first capture reduces catches, biomass and age-structure (Beverton and Holt 1957). Conversely, catching small juveniles requires the killing of many more fish than needed for a given allowed catch (Froese *et al.* 2008). Thus, the current selectivity of legal gears is not compatible with the expressed goals of European fisheries and ecosystem management.

Summary

Official fisheries management reference points used for stocks in the north-east Atlantic were investigated as to the appropriateness of their current levels. In 46% of the stocks, the official estimate of the precautionary biomass limit SSB_{pa} was found to be below the consensus estimate of three different methods. The official exploitation limit F_{msy} was found to exceed the rate of natural mortality in 76% of the stocks. Selectivity of official gears resulted in an age at first capture that was below the age of full maturity in 74% of the stocks.

The Law of the Sea (UNCLOS 1982), the Marine Strategy Framework of the EU (MSFD 2008) and the new Common Fisheries Policy of Europe (CFP 2013) require that fish stocks shall be rebuilt to and maintained above the biomass level (SSB_{msy}) that can produce the maximum sustainable yield. In its advice for 2014, ICES did not provide estimates of SSB_{msy}, which makes it difficult to judge where Europe stands with regard to these commitments (Froese and Proelss 2010). Using the proxy for SSB_{msy} developed in this study and looking at stock sizes in 2013, 88% were below the level that can produce the maximum sustainable yield, 52% were outside of safe biological limits, and 12% were severely depleted. The rate of fishing mortality in 2013 exceeded the rate of natural mortality in 73% of the stocks and fishing continued also in the severely depleted stocks. Thus, while the new Common Fisheries Policy (CFP 2013) of the European Community is widely regarded as a big step in the right direction, much remains to be done to rebuild healthy fish stocks and fisheries in the north-east Atlantic.

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