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Revisiting Safe Biological Limits in Fisheries

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Abstract

Fisheries management reference points used for stocks in the Northeast Atlantic were investigated as to the appropriateness of their current levels based on three practical limits of exploitation in fisheries management: (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 maturity, i.e., the lowest age of captured fish that still allows for individual reproduction. SSB_{pa} is a widely used reference point for low population size. In 45% of the examined stocks, the official value for this reference point was found to be below the consensus estimates determined from three different methods. Additionally, the natural rate of mortality M is widely regarded as an upper limit for sustainable fishing pressure (F_{msy}) that can produce the maximum sustainable yield (*MSY*). However, the official estimates of F_{msy} exceeded the rate of natural mortality in 76% of the stocks. Finally, there is wide agreement that age at maturity is a lower limit for age at first capture. However, age at first capture was below maturity in 74% of the stocks. No official estimates of the stock size (SSB_{msy}) that can produce *MSY* are available for the Northeast Atlantic. However, an analysis of stocks from other areas confirmed that twice SSB_{pa} provides a reasonable preliminary estimate. Using this proxy with Northeast Atlantic stock sizes in 2013 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 Northeast Atlantic in order 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.

Keywords: safe biological limits, maximum sustainable yield, natural mortality, fisheries reference points, Northeast Atlantic

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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 maturity, i.e., the lowest age of captured fish that still allows for individual reproduction. This study explores the adherence to these common sense limits in the management of fish stocks of the Northeast 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, e.g. 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 (Figure 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. Figure 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.

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, i.e., 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 longstanding consensus in fisheries science (e.g. Gulland 1971; Shepherd 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 U.S., 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 Northeast 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 analyzed. 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/.

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

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

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

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 (Figure 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). Since 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.

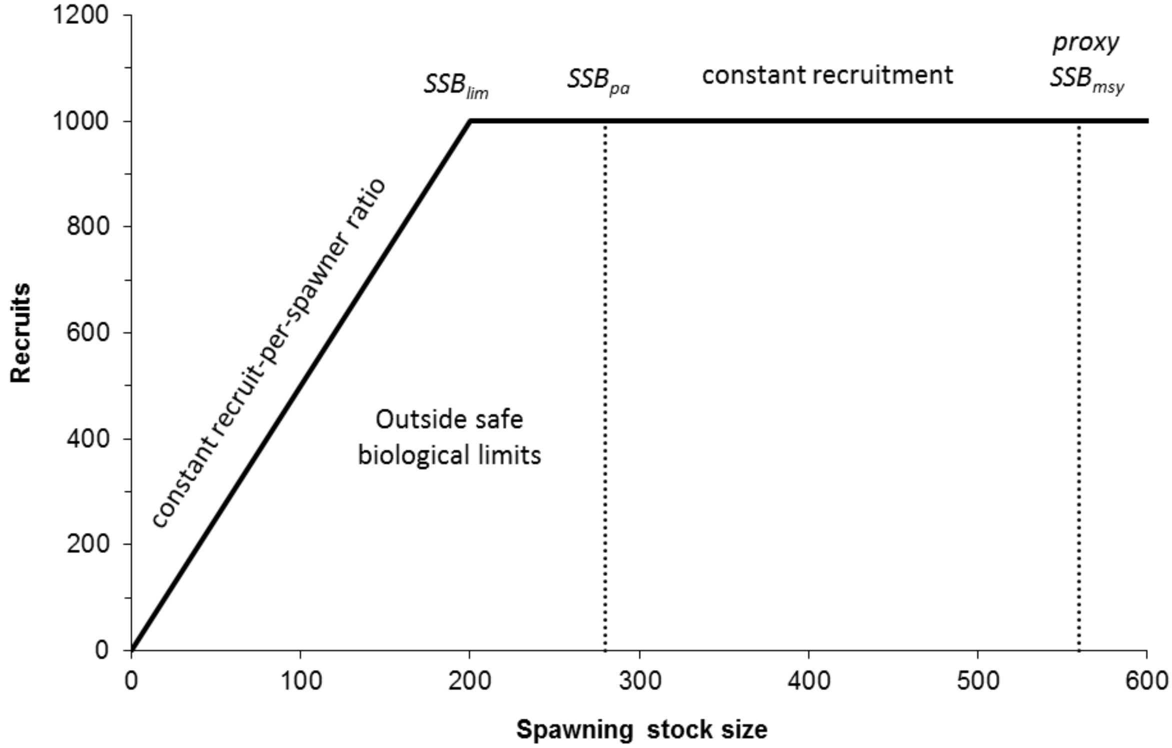

Figure 1. Conceptual drawing of the hockey stick relationship between spawning stock size and recruitment. SSB_{lim} marks the border below which recruitment declines, SSB_{pa} marks a precautionary distance to SSB_{lim}, and 2 * SSB_{pa} can be used as a proxy for SSB_{msy}, the stock size that can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

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).

(**Equation 2**)

```
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) {
      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 modeled, given the observed value of *log.R*[j] and the priors. The anti-log of the mean of the medians of these distributions then gives the central values for SSB_{lim} and for R_{inf}. The anti-log 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.

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/.

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.

Stock ID	ICES		Fisheries Library			Rule-Based			Bayesian			Median	Proxy	*SSB*
	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
cod-2532	**63**	**88.2**	199	237	283	184	327	373	230	402	316	**327**	**654**	180
cod-347d	**70**	**150**	174	239	1,077	127	177	1,144	138	174	1,127	**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	1,986
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	1,361	21,264	1,244	1,742	22,725	725	922	20,517	**1,361**	**2,722**	717
her-3a22		**110**	148	295	3,389	119	167	4,317	107	180	3,263	**180**	**360**	106
her-47d3	800	1,300	819	1,078	48,403	749	1,098	53,693	501	616	48,131	1,049	**2,098**	1,996
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	**2,500**	5,000	3,812	6,285	68,616	3,332	4,665	48,567	2,696	6,255	68,595	**6,255**	**12,510**	5,080
her-riga		**60**	87	**175**	2,810	62	87	2,865	73	88	2,894	**88**	**176**	77

her-vasu	**200**	**300**	294	424	673	294	412	911	264	545	706	424	**848**	541
her-vian	50		433	**865**	3,330	107	285	2,881	179	308	1,968	**308**	**616**	102
hom-west			955	1,909	2,913	1,156	1,618	2,982	952	2,069	2,933	**1,909**	**3,818**	1,660
mac-nea	1,670	2,300	1,667	2,274	3,901	1,682	2,355	3,307	1,211	2,479	3,913	2,355	**4,710**	2,556
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
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**	**1,150**	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	1,275	78,948	354	496	79,837	256	463	64,459	496	**992**	883
whb-comb	**1,500**	**2,250**	4,648	6,144	22,032	2,191	3,067	23,195	2,362	7,260	16,931	**6,144**	**12,288**	5,130
whg-47d			363	587	4,792	275	385	4,776	242	439	4,352	**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

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

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 Northeast 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.

Table 4. Estimates of natural mortality *M*, fishing mortality reference point *Fmsy*, fishing mortality *F* estimated for the year 2013, and the ratio of fishing mortality and natural mortality. Stock ID 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

Discussion

Performance of hockey stick models

Since 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 Figure 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 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 Figure 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, Figure 4 shows the fitted hockey sticks for mackerel (*Scomber scombrus*, Scombridae) in the Northeast 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, i.e., they are probably overestimated.

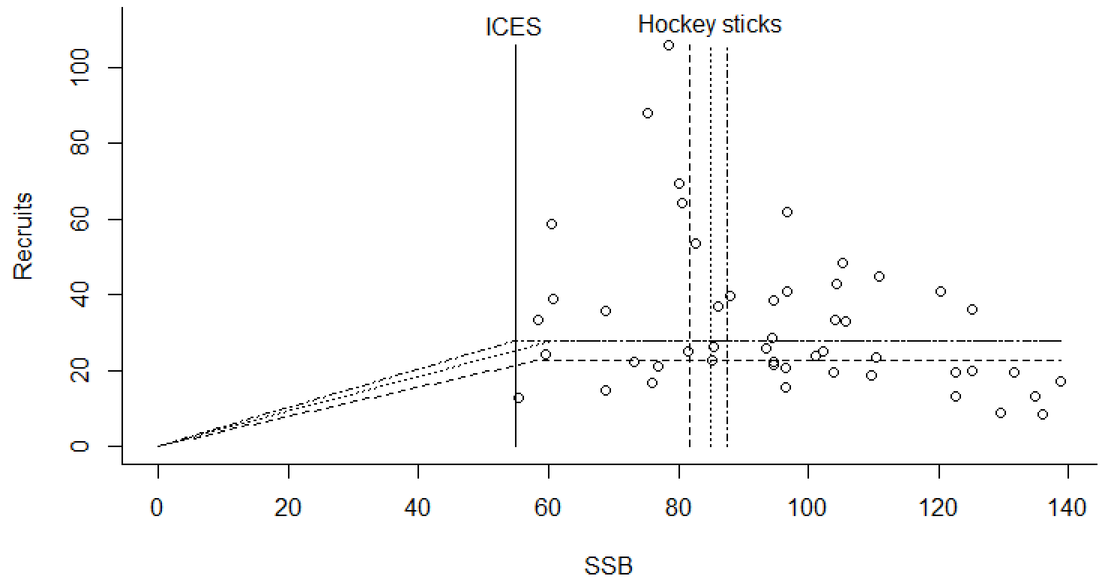

Figure 2. Analysis of stock-recruitment data for Faroe Plateau Saithe (sai-faro), with number of recruits in millions and spawning stock biomass in thousands of tonnes. The three fitted hockey sticks give very similar results for the precautionary biomass limit (SSB_{pa}, vertical lines above SSB = 80,000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

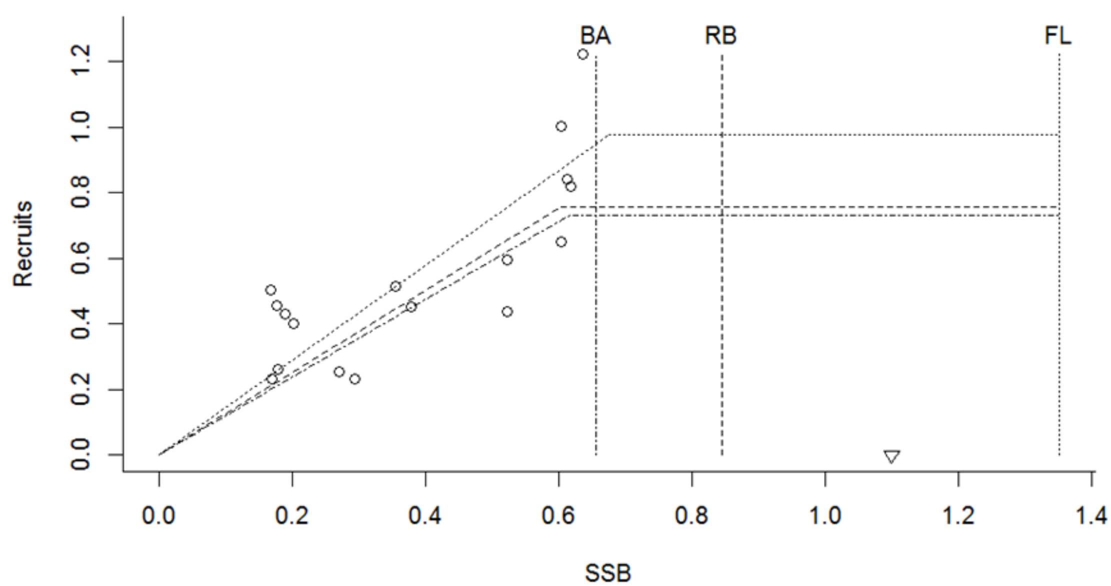

Figure 3. Analysis of stock-recruitment data for plaice in the Celtic Sea (ple-celt) with Bayesian (BA; dashed-dotted line), rule-based (RB; dashed line) and Fisheries Library (FL; dotted line) hockey stick functions. Because all biomass data are less than the lowest estimate of SSBpa (vertical lines),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

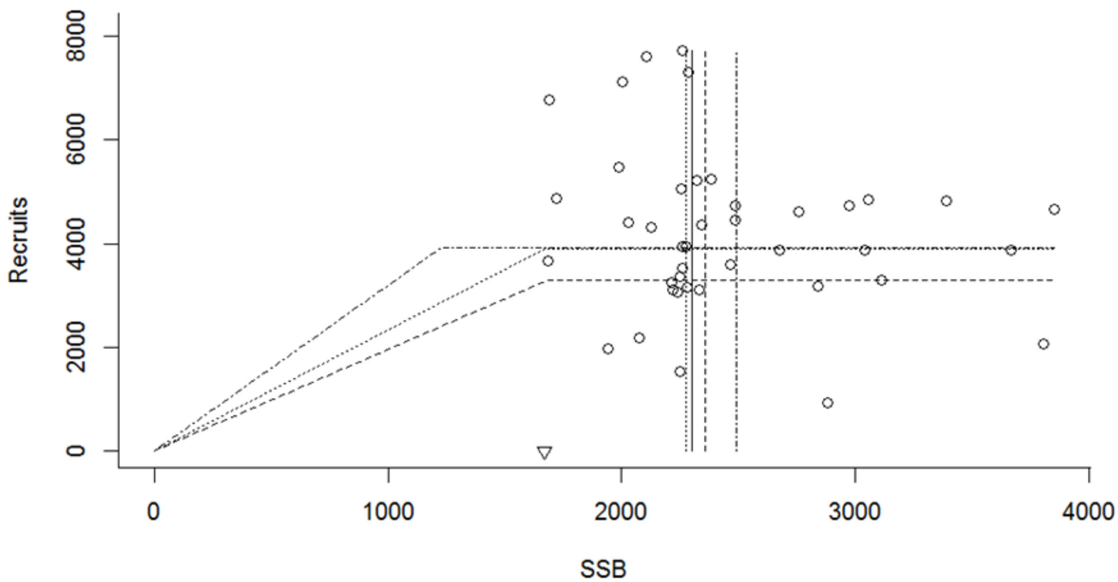

Figure 4. Analysis of stock-recruitment data for mackerel in the Northeast Atlantic (mac-nea). Because all biomass data are greater than the largest estimate of SSBlim (bends in the hockey sticks), this analysis is probably biased upwards and the biomass reference points should be considered as extra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

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 sub-sample 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 leveling-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 Figure 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 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.

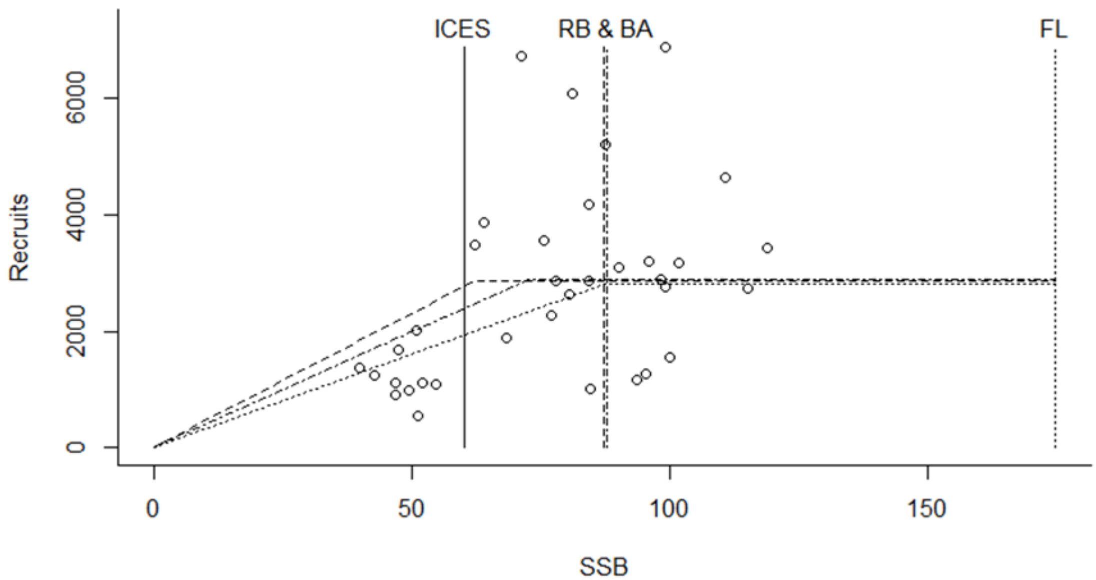

Figure 5. Analysis of stock-recruitment data for herring (her-riga) in the Gulf of Riga, with number of recruits in millions and spawning stock biomass in thousands of tonnes. The vertical lines indicate the precautionary biomass limits (SSB_{pa}) estimated by ICES and by the three hockey-stick implementations.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

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 leveling-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 favored (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 Figure 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_0 (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_0 (Fox 1975) and 0.5 B_0 (Schaefer 1954). If $SSB_{pa} \approx 0.2\ B_0$ 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, i.e., the proposed factor of 2 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).

Table 6. 30 NOAA stocks and 1 Billfish Working Group stock with recruitment data and estimates of SSBmsy. The median ratio *SSBmsy/SSBpa* 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	Northwest Atlantic Coast	392,000	157,000	0.4
Eopsetta jordani	PetraleSole_PC	Pacific Coast	3,631	8,107	2.23
Epinephelus niveatus	SnowGrouper_Satl	South Atlantic	260	2,092	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	4,713	10,051	2.13
Hippoglossoides platessoides	American plaice_GoMGB	Gulf of Maine/Georges Bank	8,450	21,940	2.6
Kajikia audax	SMarlin_NP	North Pacific	1,429	2,713	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	6,093	27,400	4.5
	Yellowtail flounder_CCGoM	Cape Cod / Gulf of Maine	938	7,080	7.55
	Yellowtail flounder_GB	Georges Bank	11,691	43,200	3.7
	Yellowtail flounder_SNEMA	Southern New England / Mid-Atlantic	6,093	2,995	0.49
Melanogrammus aeglefinus	Haddock_GB	Georges Bank	57,058	124,900	2.19
	Haddock_GoM	Gulf of Maine	4,018	4,904	1.22
Pagrus pagrus	RedPorgy_Satl	South Atlantic Ocean	3,689	4,254	1.15
Pomatomus saltatrix	Bluefish_AC	Atlantic Ocean Coast	102,689	147,052	1.43
Pseudopleuronectes americanus	Winter flounder_GB	Georges Bank	4,866	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	2,819	5,491	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

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 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, i.e., 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). 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, 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 Northeast 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 Northeast Atlantic.

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References

Barrowman, N.J.; Myers, R.A. (2000) Still more spawner-recruitment curves: the hockey stick and its generalizations. *Canadian Journal of Fisheries and Aquatic Sciences* 57, 665–676.

Beddington, J.R. and Cooke, J. (1983) The potential yield of previously unexploited stocks. *FAO Fisheries Technical Paper* No. 242, 63 pp.

Beverton, R.J.H. and Holt, S.J. (1957) *On the dynamics of exploited fish populations*. (Fisheries Investigation Series, II). 19, Her Majesty's Stationary Office, London.

Beverton, R. (1990) Small marine pelagic fish and the threat of fishing; are they endangered? *Journal of Fish Biology* 37 (Suppl A), 5-16.

CFP (2013) Regulation (EU) No 1380/2013 of the European Parliament and of the Council of 11 December 2013 on the Common Fisheries Policy, amending Council Regulations (EC) No 1954/2003 and (EC) No 1224/2009 and repealing Council Regulations (EC) No 2371/2002 and (EC) No 639/2004 and Council Decision 2004/585/EC. *Official Journal of the European Union* L 354, 22-61.

Clark, C.W., Charles, A.T., Beddington, J.R., Mangel, M. (1985) Optimal capacity decisions in a developing fishery. *Marine Resource Economics* 2, 25-54.

Coro, G. (2013) A lightweight guide on Gibbs sampling and JAGS. ISTI-CNR, Technical Report cnr.isti/2013-TR-036, Pisa, Italy. Available online at http://puma.isti.cnr.it/linkdoc.php?idauth=1&idcol=1&icode=2013-TR-036&authority=cnr.isti&collection=cnr.isti&lanver=it

EC (2013) Communication from the Commission to the Council concerning a consultation on fishing opportunities for 2014. COM(2013) 319 final. Retrieved from http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=COM:2013:0319:FIN:EN:PDF in September 2013.

FEU (2009) Treaty on the Functioning of the European Union. OJ C 115 of 9.5.2008:47–200. Retrieved from http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:C:2008:115:0047:0199:EN:PDF in January 2010.

Fox, W.W. (1975) Fitting the generalised stock-production model by least-squares and equilibrium approximation. *Fishery Bulletin* 73, 23-26.

Froese, R. and Pauly, D. Editors (2014) FishBase. World Wide Web electronic publication. www.fishbase.org, version (04/2014), accessed at www.fishbase.org in May 2014.

Froese, R. and Proelss, A. (2010) Rebuilding fish stocks no later than 2015: will Europe meet the deadline? *Fish and Fisheries* 11, 194-202.

Froese, R. and Quaas, M. (2012) Mismanagement of the North Sea cod by the European Council. *Ocean and Coastal Management* 70, 54-58.

Froese, R. and Quaas, M. (2013) Rio+20 and the reform of the Common Fisheries Policy in Europe. *Marine Policy* 39, 53-55.

Froese, R., Branch, T.A., Proelss, A., Quaas, M., Sainsbury K., Zimmermann, C. (2011) Generic harvest control rules for European fisheries. *Fish and Fisheries* 12, 340-351.

Froese, R., Stern-Pirlot, A., Winker, H., Gascuel, D. (2008) Size matters: how single-species management can contribute to ecosystem-based fisheries management. *Fisheries Research* 92, 231-241.

Gabriel, W.L. and Mace, P.M. (1999) A review of biological reference points in the context of the precautionary approach. *NOAA Technical Memorandum,* NMFS-F/SPO-40, 34-45.

Gascuel, D., Coll, M., Fox, C., Guénette, S., Guitton, J., Kenny, A., Knittweis, L., Nielsen, J.R., Piet, G., Raid, T., Travers-Trolet, M., Shephard, S. (2014) Fishing impact and environmental status in European seas: a diagnosis from stock assessments and ecosystem indicators. *Fish and Fisheries* DOI: 10.1111/faf.12090

Gulland, J.A. (1971) *The fisheries resources of the ocean*. Fishing News, London.

Hardin, G. (1968) The tragedy of the commons. *Science* 162, 1243-1248.

Holt, J.S. (1958) The evaluation of fisheries resources by the dynamic analysis of stocks, and notes on the time factors involved. *ICNAF Special Publication* I, 77-95.

ICES (2007) Report of the workshop on limit and target reference points (WKREF). *ICES CM 2007/ACFM:*05, 93 pp.

ICES (2010) Chair's report of the workshop on the form of advice (WKFORM), *ICES CM 2009/ACOM*:53, 15 pp.

ICES (2012) Marine Strategy Framework Directive – Descriptor 3 +. *ICES CM/ACOM*:62, 169 pp.

ICES (2013a) Cod in subdivisions 25-32 (Eastern Baltic Sea), advice May 2013. Downloaded in July 2013 from http://www.ices.dk/sites/pub/Publication%20Reports/Advice/2013/2013/cod-2532_201304112231.pdf

ICES (2013b) Saithe in Division Vb, advice June 2013. Downloaded in March 2013 from http://www.ices.dk/sites/pub/Publication%20Reports/Advice/2013/2013/sai-faro.pdf.

Kell, L.T., Mosqueira I., Grosjean P., Fromentin J.M., Garcia D., et al. (2007) FLR: An open-source framework for the evaluation and development of management strategies. *ICES Journal of Marine Science* 64, 640–646.

Kell, L.T. (2011) FLSR. Downloaded in July 2013 from http://tyflr.flr-project.org/

Kruschke, J.K. (2011) *Doing Bayesian data analysis: a tutorial with R and BUGS*. Elsevier, Amsterdam.

MacCall, A.D. (2009) Depletion-corrected average catch: a simple formula for estimating sustainable yields in data-poor situations. *ICES Journal of Marine Science* 66, 2267-2271.

MSFD (2008) Marine strategy framework directive. *Official Journal of the European Union 2008* L 164/19. http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:2008:164:0019:0040:EN:PDFS [accessed 20.07.12]

Myers, R.A., Rosenberg, A.A., Mace, P.M., Barrowman, N.J., Restrepo, V.R. (1994) In search of thresholds for recruitment overfishing. *ICES Journal of Marine Science* 51, 191-205.

Myers, R.A. and Mertz, G. (1998) The limits of exploitation: a precautionary approach. *Ecological Applications* 8, S165–S169.

NOAA 2013. Fishery Management Plan for Groundfish of the Bering Sea and Aleutian Islands Management Area. North Pacific Fishery Management Council, Anchorage, Alaska, 142 pp. Accessible from http://www.npfmc.org/wp-content/PDFdocuments/fmp/BSAI/BSAIfmp613.pdf.

O'Brien, C.M., Kell, L.T., Smith, M.T. (2003) Evaluation of the use of segmented regression through simulation for a characterization of the North Sea cod (*Gadus morhua*) stock, in order to determine the properties of B_{lim} (the biomass at which recruitment is impaired). *ICES CM, 2003/Y*:10.

Patterson, K. (1992) Fisheries for small pelagic species: an empirical approach to management targets. *Reviews in Fish Biology and Fisheries* 2(4), 321–338.

Pikitch, E., Boersma, P.D., Boyd, I.L., et al. (2012) Little fish, big impact: managing a crucial link in ocean food webs. Lenfest Ocean Program, Washington, DC, 208 pp.

Plummer, M. (2003) JAGS: A program for analysis of Bayesian graphical models using Gibbs sampling. (Proceedings of the 3rd International Workshop on Distributed Statistical Computing (DSC 2003) March 20-22, Vienna, 2003) K. Hornik, F. Leisch, A. Zeileis eds. Vienna, pp 20–22.

R Development Core Team (2013) R: A Language and Environment for Statistical Computing. R Foundation for Statistical Computing. Vienna, Austria. http://www.r-project.org/.

Ricker, W.E. (1954) Stock and recruitment. *Journal of Fisheries Research Board of Canada* 11, 559-623.

Schaefer, M.B. (1954) Some aspects of the dynamics of populations important to the management of commercial marine fisheries. *Bulletin of the Inter-American-Tropical Tuna Commission* 1, 25-56.

Sheperd, J.G. (1981) Cautious management of marine resources. *Mathematical Biosciences* 55,179-181.

Smith, A.F.M. and Roberts G.O. (1993) Bayesian computation via the Gibbs sampler and related Markov chain Monte Carlo methods. *Journal of the Royal Statistical Society. Series B (Methodological)* 3–23.

Thompson, G.G. (1993) A proposal for a threshold stock size and maximum fishing mortality rate. In *Risk evaluation and biological reference points for fisheries management*. (eds. S.J. Smith, J.J. Hunt, D. Rivard) *Canadian Special Publication of Fisheries and Aquatic Sciences* 120, 303–320.

UNFSA (1995) Agreement for the implementation of the provisions of the United Nations Convention on the Law of the Sea of 10 December 1982, relating to the conservation and management of straddling fish stocks and highly migratory fish stocks. 2167 UNTS 88, 1995. Retrieved from http://www.un.org/Depts/los/convention_agreements/texts/fish_stocks_agreement/CONF164_37.htm in April 2013.

UNCLOS (1982) United Nations Convention on the Law of the Sea. Retrieved from www.un.org/Depts/los/convention_agreements/texts/unclos/closindx.htm in June 2010

Walters ,C. and Martell, S.J.D. (2002) Stock assessment needs for sustainable fisheries management. *Bulletin of Marine Science* 70(2), 629–638.

Walters, C.J. and Martell, S.J.D. (2004) *Fisheries ecology and management*. Princeton University Press, Princeton, UK.