Demersal fish biodiversity: species-level indicators and trends-based targets for the Marine Strategy Framework Directive.

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The maintenance of biodiversity is a fundamental theme of the Marine Strategy Framework Directive. Appropriate indicators to monitor change in biodiversity, along with associated targets representing "good environmental status", are required to be in place by July 2012. A method for selecting species-specific metrics to fulfil various specified indicator roles is proposed for demersal fish communities. Available data frequently do not extend far enough back in time to allow GES to be defined empirically. In such situations, trends-based targets offer a pragmatic solution. A method is proposed for setting indicator-level targets for the number of species-specific metrics required to meet their trends-based metric-level targets. This is based on demonstrating significant departures from the binomial distribution. The procedure is trialled using North Sea demersal fish survey data. Although fisheries management in the North Sea has improved in recent decades, management goals to stop further decline in biodiversity, or to initiate recovery, have still to be met.

Keywords: species-specific metrics, metric-level targets, indicator-level targets, binomial distribution, "sensitive" species

(1) Introduction

Emerging concerns about the impact of fishing on marine ecosystems (Jennings and Kaiser, 1998; Hall, 1999; Omerod, 2003) precipitated the need for an ecosystem approach to management (EAM) (Gislason *et al.*, 2000; Sainsbury and Sumaila, 2001; Hall and Mainprize, 2004; Jennings, 2004; Cury and Christensen, 2005; Garcia and Cochrane, 2005). Although tasked with developing ecological objectives for the North Sea, the Oslo/Paris Commission (OSPAR) does not have the legislative competence to manage fisheries where such management might be necessary to achieve these objectives (Misund and Skjoldal, 2005; Johnson, 2008; Heslenfeld and Enserink 2008). The European Union Marine Strategy Framework Directive (MSFD) is intended to "*... contribute to coherence between different policies and foster the integration of environmental concerns into other policies, such as the Common Fisheries Policy, ...*" (EC, 2008). The MSFD therefore explicitly requires fishing activity to be managed, through the Common Fisheries Policy, so that conservation objectives for the broader marine ecosystems might also be achieved.

Descriptor 1 (D1) of the MSFD requires "good environmental status" (GES) with regard to "the maintenance of biodiversity" to be achieved by 2020 (EC, 2008). Indicators were stipulated at species, habitat and ecosystem ecological levels (EC, 2010; Table 1). Demersal fish communities consist mainly of mobile species so neither the habitat-level indicators, nor the single species distribution indicator explicitly directed at "sessile/benthic species" (1.1.3) are pertinent. Genetic variability has been examined

in a few commercial fish populations (Mork *et al.*, 1985; Giæver and Forthun 1999; Shaw *et al.*, 1999; Nesbø *et al.*, 2000; Hutchinson *et al.*, 2001; Nielsen *et al.*, 2009), but temporal variation has rarely been assessed (e.g. Poulsen *et al.*, 2006), so appropriate fish biodiversity metrics could not be derived to support this D1 indicator. We will consider ecosystem-level indicators and targets in a future analysis and focus here on selecting species-specific metrics (SSMs) to fulfil the function of the remaining four species-level indicators (SLIs) (Table 1). We suggest a procedure for setting trends-based metric-level targets (MLTs) for individual SSMs, and setting indicator-level targets (ILTs) for the number of SSMs required to meet their MLTs (see Table 2 for a summary of terminology, definitions and acronyms used in this paper).

(2) Assessment survey data

Groundfish surveys have been carried out for decades (Heessen, 1996; Heessen and Daan, 1996), generating abundance-at-length data that are ideal for determining metrics to populate the four SLIs (Trenkel and Cotter, 2009). The first quarter (Q1) international bottom trawl survey (IBTS) is used to calculate the North Sea Large Fish Indicator (LFI) on which the current OSPAR EcoQO is based (Greenstreet *et al.*, 2011; 2012; Heslenfeld and Enserink, 2008). We use the same data set to exemplify its potential in supporting MSFD D1 indicators. Sampling variation affects biodiversity-related metrics (Greenstreet and Piet, 2008), so groundfish survey data generally require "standardisation" prior to analysis (Jouffre *et al.*, 2010). Data from a "standard" survey area were therefore analysed (Supplementary Annex 1).

(3) Species-specific metric (SSM) selection

The proportion of ICES statistical rectangles surveyed each year in which particular species were recorded can be used as a SSM of "variation in distributional range" (SLI 1.1.1; Table 1). SSMs of "species abundance and/or biomass" (SLI 1.2.1; Table 1) can be generated directly from abundance-at-length data (e.g. Greenstreet et al., 2012). The mean:variance ratio (an index of dispersion/contagion: Southwood, 1978) of ICES rectangle species abundance/biomass data in occupied rectangles can be used as a SSM of "distributional pattern within the occupied range" (SLI 1.1.2; Table 1). Spawning stock biomass, used to monitor variation in the "state" of commercial fish stocks (e.g. Piet and Rice, 2004), is not routinely assessed for non-target species. However, knowing length-at-first-maturity for all species recorded in the Q1 IBTS (Supplementary Annex 2), the proportion of species' population biomass exceeding its length-at-first-maturity can provide an estimate of the fraction of each species' population that is sexually mature. This can fulfil the "population demographic indicator" role (SLI 1.3.1; Table 1).

(4) Management goals – recovery

(4.1) Derivation of metric-level targets (MLTs)

Fish landings into the UK increased three-fold through the first half of the 20th century then declined to a level in 2008 lower than at any time in the previous 120y. Landings per unit fishing power, an indicator of fish abundance, declined by >90% between 1890 and 1980 with little change since (Thurstan *et al.*, 2010). Marked fishing-induced changes in North Sea demersal fish community structure were apparent by the middle of the 20th century (Greenstreet and Rogers, 2006). Species with "slow-type" life-history traits (large-bodied, slow growing, late age and large size at first maturity, low fecundity, etc) are particularly sensitive to fishing mortality (Jennings *et al.*, 1998; Gislason *et al.*, 2008; Le Quesne and Jennings, 2012), and by the 1970s populations of such species had declined markedly (Frisk *et al.*, 2001; Greenstreet and Hall, 1996; Greenstreet *et al.*, 1999; Philippart, 1998; Rijnsdorp, *et al.* 1996; Walker and Hislop 1998; van Strien *et al.*, 2009), causing a shift towards "faster" life-history trait composition among the demersal assemblage as a whole (Jennings *et al.*, 1999; Greenstreet and Rogers, 2000). Predatory fish biomass in North Atlantic marine ecosystem also declined markedly by the 1960s (Christensen *et al.*, 2003).

Although the longest-running North Sea groundfish survey still operating, the Q1 IBTS only commenced in 1983, well after major changes in the demersal fish community had occurred. When absolute target values cannot be derived empirically because data to assess indicator values prior to anthropogenic change are not available, setting trend directions provides a pragmatic alternative (Jennings and Dulvy, 2005; Link, 2005; Shin *et al.*, 2005). The current "state" of the North Sea demersal fish community is

clearly unsatisfactory, particularly in respect of "sensitive" species with "slow-type" life-history traits, and even though the satisfactory state cannot be precisely defined, improvement is obviously necessary. Life-history trait analysis was used to identify 33% of the 119 demersal fish species sampled by the Q1 IBTS with the "slowest-type" traits (Supplementary Annex 2) for inclusion in the SLI assessment. Anticipating positive mitigation trends, trends-based MLTs can then be set for each of these 40 "sensitive" species' SSMs (Table 3).

For many species, metric trends were not monotonic invalidating the use of standard parametric trend analysis techniques. An alternative non-parametric approach is to treat each SSM's entire time-series as the "reference period". MLTs can then be set for the last year in the time-series, or "current assessment year". For example, '*The "current assessment year" SSM value should be in the upper 25 percentile of all SSM values in the full time-series "reference period"'* (see Table 2). Figure 1a illustrates such a MLT applied to three "sensitive" species' "population abundance" SSMs. Two species, halibut (*Hippoglossus hippoglossus*) and spotted ray (*Amblyraja radiata*), would meet their MLTs, but after first increasing the anglerfish (*Lophius piscatorius*) SSM then declined so that in the "current assessment year" it would fail to meet its MLT. Other upper-percentile ranges (e.g. upper 15%, upper 35%, or upper 50%) might also be considered as potential MLTs depending on the level of "ambition" considered desirable for each SSM.

(4.2) Derivation of indicator-level targets (ILTs)

How many individual SSMs need to meet their MLTs to conclude that ILTs for each SLI had successfully been achieved? Assessing compliance with the North Sea EcoQO for commercial fish species, "*Spawning stock biomass of commercial fish species in the North Sea should be above precautionary reference points for commercial fish species where these have been agreed by the competent authority for fishery management*" (Heslenfeld and Enserink, 2008), presented a similar dilemma. 17 stocks met the definition, but how many needed to exceed precautionary biomass reference points for the overall EcoQO to be achieved? Given a false alarm rate of 25%, setting a compliance target of 100% presents a high risk of apparent failure, even if all stocks were indeed above precautionary biomass levels. A target of 80% reduces the risk of failing the EcoQO simply through false alarms (Piet and Rice, 2004). So, for any given number of SSMs for each SLI, how might the ILT, the number of SSMs needing to meet their upper percentile MLTs, be determined?

Knowing the probability of an event happening, the number of such events occurring in a given number of trials is predicted by the binomial distribution. A Brownian random-walks model, incrementing the simulated SSM value by a normally distributed (with mean of 0) random number at each of 20,000 time steps, was used to estimate the probability of the last datum in an auto-correlated time-series falling in any specified upper percentile range under the null hypothesis of a random step progression (Maxwell and Jennings, 2005). For each potential upper percentile range MLT, the random-walks model was repeated 200,000 times to estimate the corresponding probabilities (Table 4). The binomial distribution can now be used to ascertain how many such events should be observed among any given number of SSMs for there to be a less than 5% probability of this happening by chance (Table 4). Demonstrating significant departure from the binomial distribution therefore represents the ILT; if these numbers of SSMs, or more, meet their MLTs, then the SLI has met the ILT (see Table 2).

Varying the upper-percentile range MLTs clearly influences the number of SSMs required to meet their MLTs for departure from the binomial distribution to be statistically significant (Table 4). Exploration of this balance point could allow the most risk-averse (of false alarms) strategy to be determined. For a given number of SSMs, making the MLTs more ambitious reduces the proportion of SSMs required to meet their MLTs in order for ILTs to be achieved (Table 4). It seems counter-intuitive, but increasing MLT ambition makes meeting the ILT easier. This is because variance of the binomial distribution is determined as $np(1-p)$, where n is the number of "sensitive" SSMs and p the probability of each SSM achieving its MLT, so variance increases appreciably as p increases, particularly at smaller n (Table 4). The more ambitious the individual species-specific MLTs, and so smaller value of p, the greater the statistical power to demonstrate a significant departure from the binomial distribution. This could be a key consideration when determining appropriate MLTs (Nicholson and Jennings, 2004; Maxwell and Jennings, 2005). Politically one might wish to set more ambitious MLTs for the individual SSMs, but at the same time not want the overall ILT to appear less stringent. To counter this, the significance level for

assessing departure from the binomial distribution could simply be adjusted, from 5% to the 1% probability level.

(5) Management goals – prevent further decline

Recovery responses to remedial management may involve long time-lag delays; for example LFI responses to varying fishing mortality in both the North and Celtic Seas were lagged by >10y (Daan et al, 2005; Greenstreet *et al.*, 2011; 2012; Shephard *et al.*, 2011). Fishing mortality in the North Sea started to decline in 1986 so real improvement in D1 metrics might only be expected from around 2000 onwards. The reduction in fishing mortality has also been gradual: a 60% decline over 22y. A range of species responses is therefore likely; the least "sensitive" species recovering soonest with only minimal reductions in mortality necessary to initiate recovery, and the most "sensitive" species, those with the "slowest" life-history traits, requiring a larger reduction in fishing mortality before commencing any recovery. Recovery in populations of the more "sensitive" species would therefore have been more recent, and fishing mortality rates may still remain too high for some of the most "sensitive" species in the community (Le Quesne and Jennings, 2012). Although fishing mortality across the targeted species in the community may have declined since 1986, levels of fishing effort remained almost unchanged until 2000, when the implementation of specific management action brought about a 40% reduction by 2004 (Greenstreet *et al.*, 2009). Fishing pressure on many non-target species may only have eased with this reduction in fishing effort (Piet *et al.*, 2009).

(5.1) Derivation of metric-level targets (MLTs)

Rather than setting MLTs associated with demonstrating recovery, perhaps initial steps should be to demonstrate no further decline. Individual species-specific MLTs can be reworded to reflect this, e.g. '*The "current assessment year" SSM value should not fall in the <u>lower</u> 25 percentile of all values in the full time-series "reference period"*'. This is illustrated using the same three "sensitive" species (Figure 1b). Rarely over recent years has the recovering halibut failed to meet a MLT aimed at "stopping further decline". It is also clearer that prospects for the more variable spotted ray have indeed improved; not only has this species met a MLT for recovery in the last "current assessment year" (Figure 1a), but over the last 8y the frequency at which it failed to meet a MLT for "stopping further decline" has reduced. However, this alternative MLT, underlines the seriousness of the anglerfish situation. This species would now fail this "stop further decline" MLT. Again, depending on desired level of ambition, other lower-percentile ranges (e.g. lower 15%, lower 35%, or lower 50%) might be considered.

(5.2) Derivation of indicator-level targets (ILTs)

In using the binomial distribution to set ILTs for this alternative MLT two aspects need to be considered. Firstly, should the number of SSMs falling into the stipulated lower-percentile range be a significant departure from the binomial distribution on the high side, this would constitute strong evidence that current management was actively driving "sensitive" fish species in the wrong direction: clear evidence of continued over-exploitation. For this scenario, then the data given in Table 4 provide the required information. Consider an example of 40 individual "sensitive" SSMs, and a stipulated "stop further decline" MLT of '*The "current assessment year" SSM value should not fall in the <u>lower</u> 25 percentile of all values in the full time-series "reference period"*' the probability of this occurring in respect of each individual SSM would again be 0.332. So should we observe 19 "current assessment year" SSM values lying within the lower 25 percentile of the "reference period" ranges, then this would imply ongoing over-fishing at a level that was actively continuing to reduce demersal fish biodiversity.

However, to demonstrate successful management to stop further decline, what is needed is the converse of this. How large does the number of species that lie <u>outside</u> the specified lower-percentile range have to be in order for this to be a significant departure from the binomial distribution? If the probability of the "current assessment year" SSM value lying within the lower 25 percentile of its full time-series range of values is 0.332, then the probability of it lying outside the lower 25 percentile, i.e. in the upper 75% percentile, is $1.0 – 0.332 = 0.668$, and so on for other potential lower-percentile ranges and associated probabilities. For any given number of "sensitive" SSMs analysed, and applying the 1-p probabilities (Table 5), the number of "current assessment year" SSM values needing to fall outside the specified lower-percentile range for this to be a significant departure (at $P<0.05$) from the binomial distribution can be determined (Table 5). Seeing this would be strong evidence that further decline had been stopped among a significant fraction of the "sensitive" species assessed. It is worth noting that in both tables 4 and

5, because the probabilities illustrated were either *p* or 1-*p*, the variances in both sets of examples were the same.

(6) Case study: demersal fish in the Greater North Sea

This protocol is now applied to Q1 IBTS data to assess recent trends in six SSMs (see Table 3) in the North Sea demersal fish assemblage.

(6.1) Selection of "sensitive" species for which to derive SSMs

Based on the criterion that species should be recorded in at least half of the years of the time-series, data were considered adequate for reliable assessment for only 27 of the 40 "sensitive" species. Consequently, 13 of perhaps the rarest and potentially most threatened species in the community were not assessed. We examined the possibility that this might bias our analysis; that the 27 species assessed might be amongst the least sensitive of the 40 "sensitive" species. However, ranking the 40 "sensitive" species from least to most sensitive and determining where in this ranking the 27 species we analysed lay suggested no indication of bias (χ^2 = 0.406, 3 d. f., p ≈ 0.9, n. s.). The 27 species sampled well enough to support assessment were an adequate sub-sample of the full suite of 40 potential "sensitive" species, so there was no reason to believe that the 13 "sensitive" species we did not assess might behave substantively differently to the 27 "sensitive" species that we did.

(6.2) Management goals – recovery

Each year in turn from 2001 to 2008 was considered the "current assessment year", and in each case the "reference period", used to define the upper 25 percentile range MLT, was the full time series from 1983 up to and including the year in question. Similar consistent trends were apparent for four SLIs, distributional range, population abundance, population biomass and population demographic characteristics, with variable but low numbers of SSMs meeting their MLTs over the period 2001 to 2006, followed by a marked increase in 2007 and 2008 (Figure 2). However, the number of MLTs being met did not constitute a significant (*p*<5%) departure from the binomial distribution; although the trend is moving in the right direction, ILTs have yet to be met. Both "distribution pattern within range" SSMs were highly variable, and on occasion the number of SSMs meeting their MLTs was sufficient to achieve statistical significance with respect to the ILT (Figure 2). However, the trends were not consistent. At present we do not consider performance of the mean:variance metric to be well enough understood for it to support statutory commitments and be used as a D1 metric to implement the MSFD. Either further developmental work is required to make mean:variance metrics operational, or alternative metrics should be used (e.g. Blanchard *et al.*, 2005; Rindorf and Lewy, 2012).

(6.3) Management goals – prevent further decline

Figure 3 shows the number of individual SSMs meeting the alternative MLT of '*The "current assessment year" SSM value should not fall in the lower 25 percentile of all values in the full time-series "reference period"*' (i.e. the plots show the numbers of SSMs falling in the upper 75 percentile of all values). The two "distribution pattern within range" SLIs frequently met their ILTs over the period 2001 to 2008. However, having just declared a lack of confidence in the mean:variance ratio metric, we direct attention to the four remaining SLIs. Here the situation is less convincing, with only one SLI meeting its ILT once in the eight annual assessments (1.2.1 "Population abundance": Figure 3d). On the basis of these four SLIs, we have no evidence at present to suggest that remedial management has successfully prevented further decline among a significant proportion of the 27 "sensitive" species assessed.

Whilst we cannot demonstrate that the current management regime is actually preventing decline, the question can be turned around; is the current management regime actually causing ongoing deterioration in biodiversity, i.e. are current fishing mortality levels sufficiently high as to still be causing declines among a significant fraction of "sensitive" fish species? Or in other words, does the number of SSM values actually falling in the lower 25 percentile of all values in their full time-series "reference periods" represent a significant departure from the expected number predicted by the binomial distribution? Figure 4 shows that this is not the case; there is therefore no evidence to suggest that the current management regime in the North Sea is actually responsible for an ongoing reduction in fish biodiversity.

At present, therefore, we appear to be in an equivocal situation. We have no evidence to demonstrate that remedial management is actually preventing decline, but equally there is no evidence to suggest that the

current levels of exploitation are actually causing ongoing decline. This illustrates the importance of the precise phrasing of the binomial experiment being undertaken. It also emphasises the need for both analyses. In this case study, the first analysis suggests that we have not yet definitely achieved a solution, but the second implies that we no longer definitely have an ongoing problem.

In Figure 2, the upward inflection in the number of SSMs meeting their specified upper percentile MLTs tended to occur in the last two assessment years, while in Figure 3, a similar inflection tended to occur in the first or second year of assessment. Remedial management first brings about a cessation of further decline, before initiating actual recovery in metric and indicator values. Whilst seeming trivial, this observation could be important in gauging the time-scales of responses to remedial management (Nicholson and Jennings, 2004; Maxwell and Jennings, 2005). In situations of ongoing decline, setting MLTs and ILTs associated with demonstrating significant recovery may take many years to achieve, while targets based on stopping further decline may be more achievable in the short-term, and prove to be a moral-boosting first step along a long road to eventual recovery.

(6.4) Persistently failing species

Being unable to demonstrate a cessation of further decline among a significant fraction of the 27 "sensitive" demersal fish SSMs analysed, despite more than 20y of declining fishing mortality and 10y of reduced fishing effort in the North Sea (Greenstreet et al., 2009; Greenstreet et al., 2011), prompted us to examine the data to look for species that persistently failed to meet their MLTs. This was rare among the two "distribution pattern within range" SSMs, but more common among the four other SSMs. Three species, catfish (*Anarhichas lupus*), cod (*Gadus morhua*), and spurdog (*Squalus acanthias*), persistently failed the MLT for the two "population size" SSMs and the "distributional range" SSM (Figure 5), and ongoing declining trends were clearly the cause. Lumpsucker (*Cyclopterus lumpus*), ling (*Molva molva*), torsk (*Brosme brosme*), pollack (*Pollachius pollachius*), and Norway haddock (*Sebastes viviparus*) also regularly failed their MLTs for one or other of these SSMs, but not all three. A slightly different suite of species regularly failed the "population demographic" (proportion of biomass greater than length-at-first-maturity) MLT, and again declining trends were apparent among at least four of these species (Figure 6). Despite progress made in reducing the impact of fishing on North Sea demersal fish, mortality rates for some "sensitive" species remain sufficiently high that SSM values continue to decline.

(6.5) Alternative upper- (or lower-) percentile MLTs

The effect of adopting alternative upper- and lower- percentile MLTs, e.g. those illustrated in Tables 4 and 5, was examined. This had negligible effect on our results or conclusions. As expected, increasing MLT ambition reduced the number of SSMs meeting their MLTs, but at the same time the number of SSMs required to meet their MLT in order to demonstrate a significant departure from the binomial distribution was also reduced. These changes tended to counter-balance one another so that there was negligible effect on the frequency of occasions that ILTs were achieved.

(7) Discussion

(7.1) Generality of method application

We have used a North Sea case study to exemplify our proposal for selecting SSMs, setting trends-based MLTs for these SSMs, and setting ILTs for the number of SSMs required to meet their MLTs. A major strength of the North Sea situation was the availability of near-regional scale survey data and the relatively long duration of its time-series. In other regions where the MSFD applies, relatively recent data may only be available for comparatively short periods. Short time-series do not preclude application of the method we propose; even with a 10y time-series it would still be possible to set upper percentile ranges as SSM trends-based MLTs. Provided a sufficient number of sensitive species can be identified to fulfil the SSM roles, then the procedure to establish the number of SSMs required to meet their MLTs that represents a significant departure from the binomial distribution is still applicable. If relatively short recent time-series are all that is currently available, these time-series will only get longer as monitoring proceeds. The MSFD requires that GES be attained by 2020, if only 10y of data are available now then by 2020 the time-series would cover 18y. Long time-lags for recovery (e.g. Greenstreet *et al*., 2011; Shephard *et al*., 2011) suggest that if management measures are only implemented in 2016, the need for ongoing monitoring, assessment and remedial management could continue long past 2020. Provided the required monitoring programmes are established immediately, their fitness-for-purpose can only improve.

Our approach need not only be restricted to the assessment of fish biodiversity under the MSFD. We can think of no reason why it should not be equally applicable to other marine taxa. The only requirements are adequate monitoring data and a theoretically sound *a priori* reason for setting a trends-based target for the species concerned.

(7.2) Representativeness of the 27 assessed "sensitive" species

The 27 "sensitive" species we assessed proved to be an unbiased sub-sample of the total of 40 "sensitive" species recorded in the Q1 IBTS. This implies that, if in the future management measures were to achieve increases in abundance among a significant fraction of the 27 assessed species, then a similar proportion of the 13 non-assessed species should be similarly affected, raising the probability of their "detection" in the survey. Eventually, with each additional survey, this would result in some of these 13 species being sampled in more than the 50% of surveys, which was our criterion for selection for assessment. Meeting ILTs for abundance and biomass should therefore result in an increase in the number of SSMs available for assessment. The converse of this is that some of the 13 non-assessed species maybe so sensitive that they continue to undergo population declines (e.g. Le Quesne and Jennings, 2012). If data for such species are deemed inadequate to support target setting and monitoring programmes today, then ongoing declines will not improve their situation. The data for these species will remain inadequate and we will not be able to assess changes in their status. However, the sub-sample of 27 analysed "sensitive" species did include species with continuing declining SSM trends. Our assessed sub-sample was therefore also representative of this situation; failure to halt declines in some of these representative species is indeed indicative of continuing problems among some of the non-assessed species.

(7.3) Independence of species-specific metrics

In using the binomial distribution to determine the number of SSMs required to meet their individual MLTs, and thus achieve the ILT, there is an underlying assumption of independence among the individual SSMs. But the species analysed have been selected because of their "sensitivity" to additional mortality caused by human activities. In setting the trends-based MLTs, the underlying assumption is that they should all respond in a particular way to remedial management (Table 3). Does this undermine the assumption of independence between the SSMs? We argue not. The manipulation of human pressure on demersal fish biodiversity, through varying the management regime (little restriction through to considerable restriction on landings and/or effort), can be considered as the "variable treatment" in an "experiment". We hypothesise that "varying the treatment" in a particular way should cause the SSMs to respond in a predictable and uniform manner, and we test this hypothesis using the binomial distribution. The question really is whether, in the absence of any human intervention (no fishing and so no fisheries management) the 27 (in this case) "sensitive" species might be expected to vary independently? In reality we have little evidence to suggest that they shouldn't, and lots to suggest that they might.

Demersal fish species have their own particular habitat requirements in terms of preferred temperature regime, depth range and sediment characteristics (Greenstreet *et al.*, 1997; Dulvy *et al.*, 2008; Magnussen, 2002; Perry *et al.*, 2005; Hinz, *et al.*, 2006; Righton *et al.*, 2010), giving rise to distinct differences in species' distributions (Heessen and Daan, 1996; Hinz *et al.*, 2003; Hedger *et al.*, 2004), so that different species are subjected to quite different hydro-dynamic regimes (Turrell, 1992; Berx and Hughes, 2009). Diets vary between different demersal fish species so that they are affected in different ways by variation in the abundance of different prey (Hislop, 1997; Greenstreet *et al.*, 1998; Floeter *et al.*, 2005; Floeter and Temming 2005). Reproductive mode and spawning period vary between different demersal fish so that their larvae experience quite different hydro-dynamic environments and respond differently to different environmental drivers; temporal variation in recruitment across species is therefore rarely correlated (Philippart *et al.*, 1996). Finally, "sensitive" species also vary in their vulnerability to fishing pressure, so that the responses of different species to particular changes in fishing pressure are also expected to differ (Le Quesne and Jennings, 2012).

(7.4) Failure to demonstrate recovery or cessation of decline

Le Quesne and Jennings (2012) estimate that fishing mortality in the Celtic Sea may remain sufficiently high as to place many of the more sensitive species in the community below conservation reference points. The same may be true in the North Sea, despite declines in fishing mortality in recent decades (Greenstreet *et al.*, 2011). In using the binomial distribution to set ILTs, we assume that the species involved all have the same probability of meeting their MLTs. In reality this is clearly not the case;

mortality rates in some of the species assessed are still too high, causing continued population decline or preventing recovery. This makes it more difficult to demonstrate a significant departure from the binomial distribution and meet the ILT. Consider a MLT of "*The "current assessment year" SSM value should lie within the upper 25 percentile of the full time-series "reference period" range*". Table 4 indicates that, with 25 SSMs, 13, or 52%, need to meet this MLT for there to be a <5% probability of observing such a result simply by chance, so demonstrating a significant departure from the binomial distribution. But if in reality, five species have no hope of recovering because their mortality rates remain too high, then a higher recovery rate of 62% would be required among the other 20 species in order for the ILT to be achieved.

As mortality is gradually reduced, more and more "sensitive" species will benefit as mortality rates progressively decline to levels that each successive species can sustain (Le Quesne and Jennings, 2012). However, if mortality rates applied to "commercial" and "sensitive" species can not be decoupled, safeguarding the most sensitive species in the Celtic Sea fish community may require up to 65% of potential yield-per-recruit to be sacrificed (Le Quesne and Jennings, 2012). The reduction in fishing mortality necessary to allow the most sensitive species in the community to recover could therefore be unsustainable as far as the economics of the fishing industry is concerned. This may be politically unacceptable and contrary to the intent of the MSFD to promote continued "*sustainable use of marine goods and services by present and future generations*". However, sustainable use has to be compatible with achieving GES, such that "*the capacity of marine ecosystems to respond to human-induced changes is not compromised*" (EC, 2008, Chapter 1, Article 1, paragraph 3). The MSFD is not intended to be a legislative tool to restrict human activities in marine ecosystems to such low levels that the original pristine state might be restored. If economic sustainability of the fishing industry into the future requires relatively high levels of yield-per-recruit, then loss of the most sensitive species in the demersal fish community could be the price that has to be paid. A further question then is how many of these "sensitive" species can we afford to lose before the capacity of marine ecosystems to respond to human-induced changes is threatened?

Unless technical measures can be introduced to decouple mortality rates applied to "sensitive" and "commercial" species, providing succour to the fishing industry and permitting fishing mortality rates that are higher than can be tolerated by some of the most "sensitive" demersal fish species comes at the cost of making it more difficult to achieve ILTs. Greater measures may be necessary to promote recovery among the "sensitive" species that are capable of sustaining such levels of mortality, or further reductions in mortality may be required in order to stimulate recovery in one or two more of these most "sensitive" species. Additional protection to safeguard remnant populations of especially sensitive and depleted species could help to stop further decline; for example, spatial measures (marine protected areas: MPAs) to protect remnant populations of large mature female common skate. However, establishment of such MPAs would not devolve member states of their obligation to address the issue of unsustainable human pressure on marine ecosystems at regional scales.

Politically, it would be desirable if the "state" indicators used in support of the MSFD could reflect the beneficial (or otherwise) effects of management measures over time-scales of one to four years (Nicholson and Jennings, 2004; Maxwell and Jennings, 2005). But "state" indicators monitor change in the status of different marine ecosystem components, and if these changes only occur over long periods (Daan *et al*., 2005; Greenstreet *et al*., 2011; 2012; Shephard *et al*., 2011), then this could be a forlorn hope. In adopting an EAM and implementing the MSFD in European waters, politicians may have no alternative but to adopt a long-term perspective.

(7.5) Trends-based targets and GES
Because the individual SSM MLTs are trends-based, achieving the ILT does not necessarily mean that GES has been achieved in respect of any particular SLI. We still do not know what the GES state actually looks like. What meeting each ILT does imply is that the number of sensitive demersal fish species now on recovery trajectories is significantly more than the number expected simply by chance. This is evidence that management measures to mitigate human impact on the demersal fish assemblage are successfully moving the sensitive species component of the community in the right direction. It is evidence of "improved environmental status". However, setting recovery-related trends-based MLTs in perpetuity is also nonsensical; at some point over-shooting GES is inevitable, almost certainly associated

with unnecessarily stringent restriction of human activities. Since the MSFD is just as concerned that marine resources are utilised to their full sustainable potential, this should also be avoided.

Other indicators, for example the ecosystem-level indicator (1.7.1: Table 1), or achieving the OSPAR EcoQO for the LFI (Greenstreet et al., 2011; Shephard et al., 2011), might be used to assess when GES for the whole demersal fish community had been achieved. Making a "leap of faith", one might assume that if the state of the fish community as a whole meets GES, then GES should also have been achieved for its constituent species. If so, then from this point forward, trends-based MLTs for individual SSMs might be relaxed from "striving for improvement" to just "maintaining *status quo*". However, the nature of the relationship between the status of whole communities and the status of the individual species of which they are comprised has yet to be properly explored. At present therefore, such an approach should not be considered operational. Adopting the trends-based approach that we propose would, in the short term, ensure that the remedial management necessary to bring about recovery was implemented immediately; thereby buying more time to determine what GES for "sensitive" fish species might actually look like.

(8) Supplementary material

The following supplementary material is available at the *ICESJMS* online version of this article:

Annex 1 presents the results of an assessment of variation in spatial coverage by the Q1 IBTS in order to determine a "standardised" sampling area.

Annex 2 presents the results of an analysis of the life-history traits of 119 demersal fish species sampled by the Q1 IBTS in order to derive "sensitivity" scores for each species, enabling these species to be ranked by their "sensitivity" to additional mortality associated with fishing activity.

(9) Acknowledgements

(10) References

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Descriptor	Level	Criterion	Indicator Class
1	Species	1.1 Species distribution	**1.1.1 Distributional range**
			1.1.2 Distributional pattern within the latter, where appropriate
			1.1.3 Area covered by the species (for sessile/benthic species)
		1.2 Population size	**1.2.1 Population abundance and/or biomass, as appropriate**
		1.3 Population condition	**1.3.1 Population demographic characteristics (e.g. body size or age class structure, sex ratio, fecundity rates, survival/ mortality rates)**
			1.3.2 Population genetic structure, where appropriate
	Habitat	1.4 Habitat distribution	*1.4.1 Distributional range*
			1.4.2 Distributional pattern
		1.5 Habitat extent	*1.5.1 Habitat area*
			1.5.2 Habitat volume, where relevant
		1.6 Habitat condition	*1.6.1 Condition of the typical species and communities*
			1.6.2 Relative abundance and/or biomass, as appropriate
			1.6.3 Physical, hydrological and chemical conditions
	Ecosystem	1.7 Ecosystem structure	<u>1.7.1 Composition and relative proportions of ecosystem components (habitats and species)</u>

Table 1. Levels, criteria and broad indicator classes proposed for Descriptor 1 "Biological diversity is maintained" of the Marine Strategy Framework Directive (EC 2010). Italicised text indicates habitat-level indicators, or indicators explicitly directed towards benthic invertebrates and other sessile species, considered here to be of little relevance to fish communities. Underlined text indicates the ecosystem-level indicator addressed elsewhere. Plain text indicates the single species-level indicator for which insufficient information is available to develop a fish community species-level biodiversity indicator. Bold text indicates the four species-level indicators considered in this paper.

1. The EC Decision document (EC 2010) defines indicators at three ecological levels for Descriptor 1: species, habitats and ecosystems. To fulfil the function of each "*species-level indicator*" (SLI), "*species-specific metrics*" (SSMs) are required.
   - Thus SLI 1.2.1 is "population abundance (or biomass)", so SSMs of abundance for a defined list of species are required; cod (*gadus morhua*) abundance would be one SSM, saithe (*Pollachius virens*) abundance a second SSM, spurdog (*Squalus acanthias*) abundance a third SSM, and so on.

2. For each SSM, a "*metric-level target*" (MLT) must be set. Ideally the MLT would be an absolute SSM value representing "*good environmental status*" (GES).
   - Thus, for cod, if a population abundance of 5.6×10^9 was considered to represent GES, this abundance value would be set as the MLT for the cod SSM.

3. But where absolute SSM values representing GES cannot be determined empirically for particular SSMs, trends-based MLTs are a pragmatic alternative. Here a non-parametric approach to setting trends-based MLTs is used. For each individual SSM, a trends-based MLT for recovery, such as '*the "current assessment year" SSM value should be in the upper 25 percentile of all SSM values in the full time-series "reference period"*' might be set.
   - So if the cod abundance time series started in 1983 and the "current assessment year" is 2008 (usually the last year for which data are available) cod abundance in 2008 should be amongst the top 25% of all cod abundance values recorded from 1983 to 2008 for the cod abundance MLT to be met.

4. Each SLI is then the number of associated SSMs actually meeting their MLTs.
   - Thus of the defined list of species, the 1.2.1 population abundance SLI would be the number (or proportion) of individual population abundance SSMs meeting their specified upper percentile range MLTs.

5. The "*indicator level target*" ILT is set such that, knowing the number of individual SSMs analysed (e.g. the specified list of species) and the probability of any individual SSM meeting its MLT, observing such an SLI value would represent a statistically significant (e.g. less than 5% chance) departure from the binomial distribution.
   - Thus if the specified list contained 25 species for which population abundance SSMs could be determined and the SLI was 13 (i.e. SSMs for 13 of the species had met their MLTs), then this would represent a significant departure from the binomial distribution (see Table 4), leading to the conclusion that the ILT for the 1.2.1 population abundance SLI had been met.

Table 2. Summary of terminology and acronyms, and over-view of logic underlying the derivation of non-parametric trends-based *metric-level targets* (MLTs) for each *species-specific metric* (SSM), which then determines effective *species-level indicators* (SLIs) as the number of SSMs meeting their MLTs, and use of the binomial distribution to set objective *indicator-level targets* (ILTs) for each SLI.

EC Indicator	Metric	Perturbed state condition	Trend target direction
1.1.1 Distributional range	Proportion of surveyed ICES rectangles occupied	Depressed – population reduced and only prime habitat sites occupied	positive
1.1.2 Distributional pattern within range	Mean:variance ratio of abundance in occupied rectangles by numbers	Depressed – Density remains high in prime habitat site, but few occupied marginal habitat sites hold low densities leading to high variance	positive
1.1.2 Distributional pattern within range	Mean:variance ratio of abundance in occupied rectangles by biomass	Depressed – Density remains high in prime habitat site, but few occupied marginal habitat sites hold low densities leading to high variance	positive
1.2.1 Population abundance and/or biomass	Abundance	Depressed – population abundance reduced by unsustainable mortality	positive
1.2.1 Population abundance and/or biomass	Biomass	Depressed – population biomass reduced by unsustainable mortality	positive
1.3.1 Population demographic characteristics	Proportion of biomass greater than length-at-first maturity	Depressed – spawning component in slow growing late maturing species reduced by unsustainable mortality	positive

Table 3. Derivation of trends-based MLTs for each SSM applied to "sensitive" demersal fish species in the North Sea.

Number of assessed "sensitive" species	Metric values in "current assessment year" should lie within the upper (or lower):			
	15% of all values ($P = 0.253$)	25% of all values ($P = 0.332$)	35% of all values ($P = 0.403$)	50% of all values ($P = 0.500$)
10	6 (60%) *1.890*	7 (70%) *2.218*	8 (80%) *2.406*	9 (90%) *2.500*
15	8 (53%) *2.835*	9 (60%) *3.327*	10 (67%) *3.609*	12 (80%) *3.750*
25	11 (44%) *4.725*	13 (52%) *5.544*	15 (60%) *6.051*	18 (72%) *6.250*
35	14 (40%) *6.615*	17 (49%) *7.762*	20 (57%) *8.421*	23 (66%) *8.750*
40	16 (40%) *7.560*	19 (48%) *8.871*	22 (55%) *9.624*	26 (65%) *10.000*
50	19 (38%) *9.450*	23 (46%) *11.089*	27 (54%) *12.030*	32 (64%) *12.500*

Table 4. For a given number of "sensitive" species analysed, the number (and percentage in parenthesis) of SSMs required to meet specified upper (or lower) percentile MLTs for the probability of observing such a departure from the binomial distribution to be less than 5%. If the indicated numbers of SSMs lie in the upper percentile range then this provides evidence that introduced management measures have achieved a recovery among a significant fraction of the "sensitive" SSMs analysed. If the indicated numbers of SSMs lie in the lower percentile range then this provides evidence that continued overfishing is negatively impacting a significant fraction of the "sensitive" SSMs analysed (see text for details). Figures in italics indicate calculated variance of the binomial distribution for each combination of the number of assessed "sensitive" species and probability associated with the "current assessment year" SSM value lying within the specified upper- or lower-percentile MLT ranges.

Number of "sensitive" species	Metric values in "current assessment year" should lie outside the lower:			
	15% of all values ($P = 0.747$)	25% of all values ($P = 0.668$)	35% of all values ($P = 0.597$)	50% of all values ($P = 0.500$)
10	10 (100%) *1.890*	10 (100%) *2.218*	9 (90%) *2.406*	9 (90%) *2.500*
15	15 (100%) *2.835*	14 (93%) *3.327*	13 (87%) *3.609*	12 (80%) *3.750*
25	23 (92%) *4.725*	21 (84%) *5.554*	20 (80%) *6.015*	18 (72%) *6.250*
35	31 (89%) *6.615*	29 (83%) *7.762*	27 (77%) *8.421*	23 (66%) *8.750*
40	35 (88%) *7.560*	33 (83%) *8.871*	30 (75%) *9.624*	26 (65%) *10.000*
50	43 (86%) *9.450*	40 (80%) *11.089*	36 (72%) *12.030*	32 (64%) *12.500*

Table 5. For a given number of "sensitive" species analysed, the number (and percentage in parenthesis) of SSMs required to lie outside specified lower percentile MLTs for the probability of observing such a departure from the binomial distribution to be less than 5%. Observing such numbers, or more, of the individual SSMs lying outside the specified lower percentiles provides evidence that introduced management measures have stopped declines in SSM values among a significant fraction of "sensitive" SSMs analysed. Figures in italics indicate calculated variance of the binomial distribution for each combination of the number of assessed "sensitive" species and probability associated with the "current assessment year" SSM value lying outside the specified lower-percentile MLT ranges.
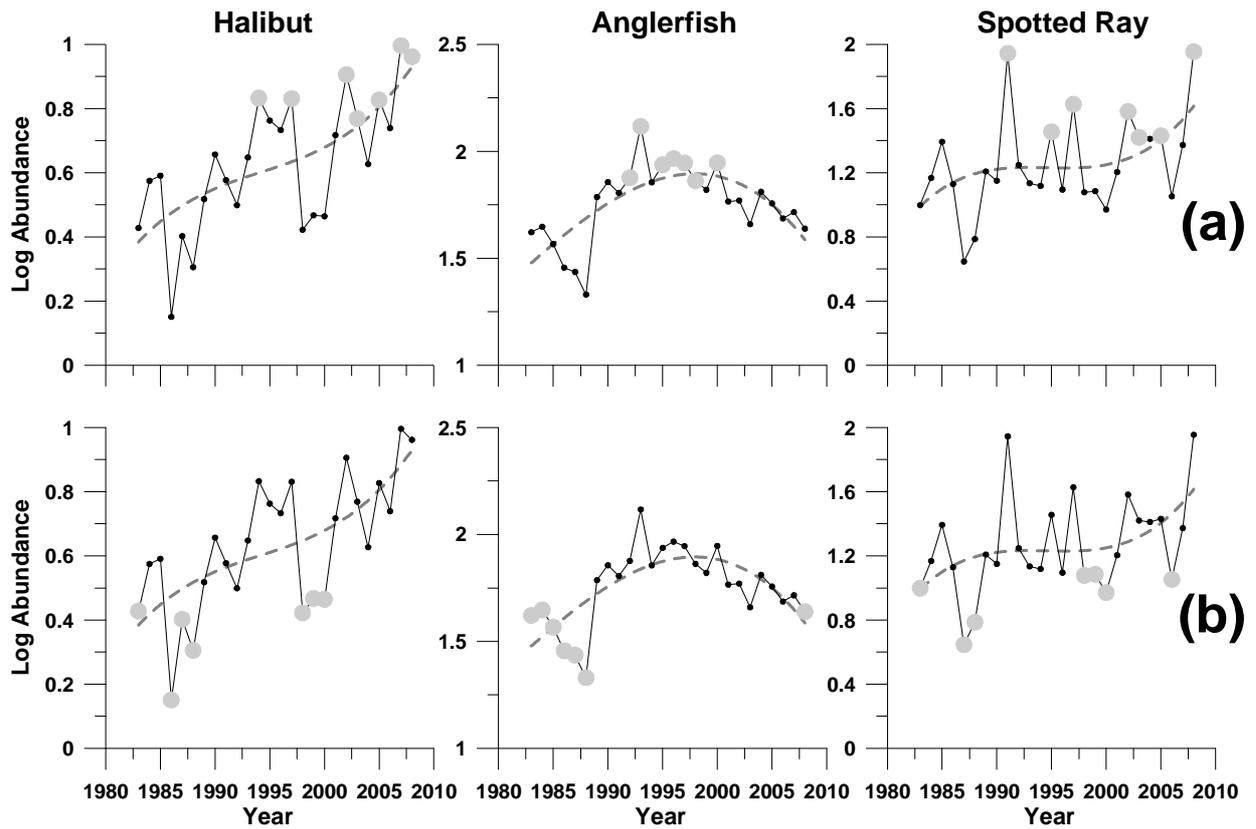
Figure 1. Variation in "population abundance" *species-specific metric* (SSM) values for three "sensitive" species in the North Sea derived from Q1 IBTS data. Grey dashed lines are 3rd degree polynomials fitted to highlight the different underlying trends. Large light grey dots indicate: a. SSM values falling in the upper 25 percentile of all values in the whole time-series "reference period"; b. SSM values falling in the lower 25 percentile of all values in the whole time-series "reference period".
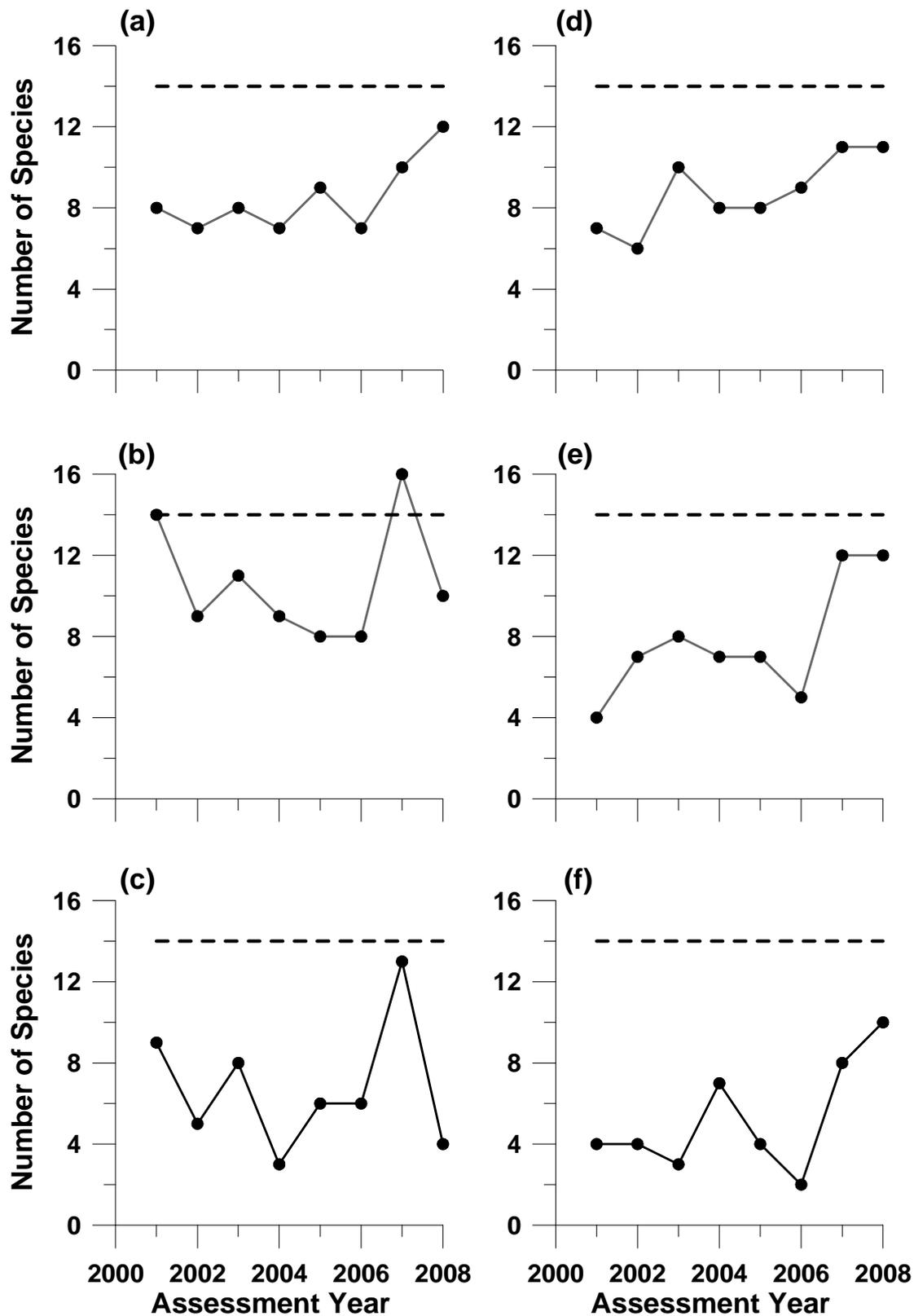
Figure 2. Number of individual SSMs meeting their "recovery" MLTs '*The "current assessment year" SSM value should be in the top 25 percentile of all values in the full time-series "reference period"*' for each SLI class evaluated: a. 1.1.1 Distributional range; b. 1.1.2 Distributional pattern within range (by numbers); c. 1.1.2 Distributional pattern within range (by biomass); d. 1.2.1 Population abundance; e. 1.2.1 Population biomass; f. 1.3.1 Population demographic characteristic (proportion of biomass greater than length-at-first-maturity). Dashed horizontal line indicates the ILT, the number of SSMs meeting their MLTs that represents a significant departure ($P<0.05$) from the binomial distribution. North Sea case study analysing data for 27 "sensitive" species monitored using Q1 IBTS data.
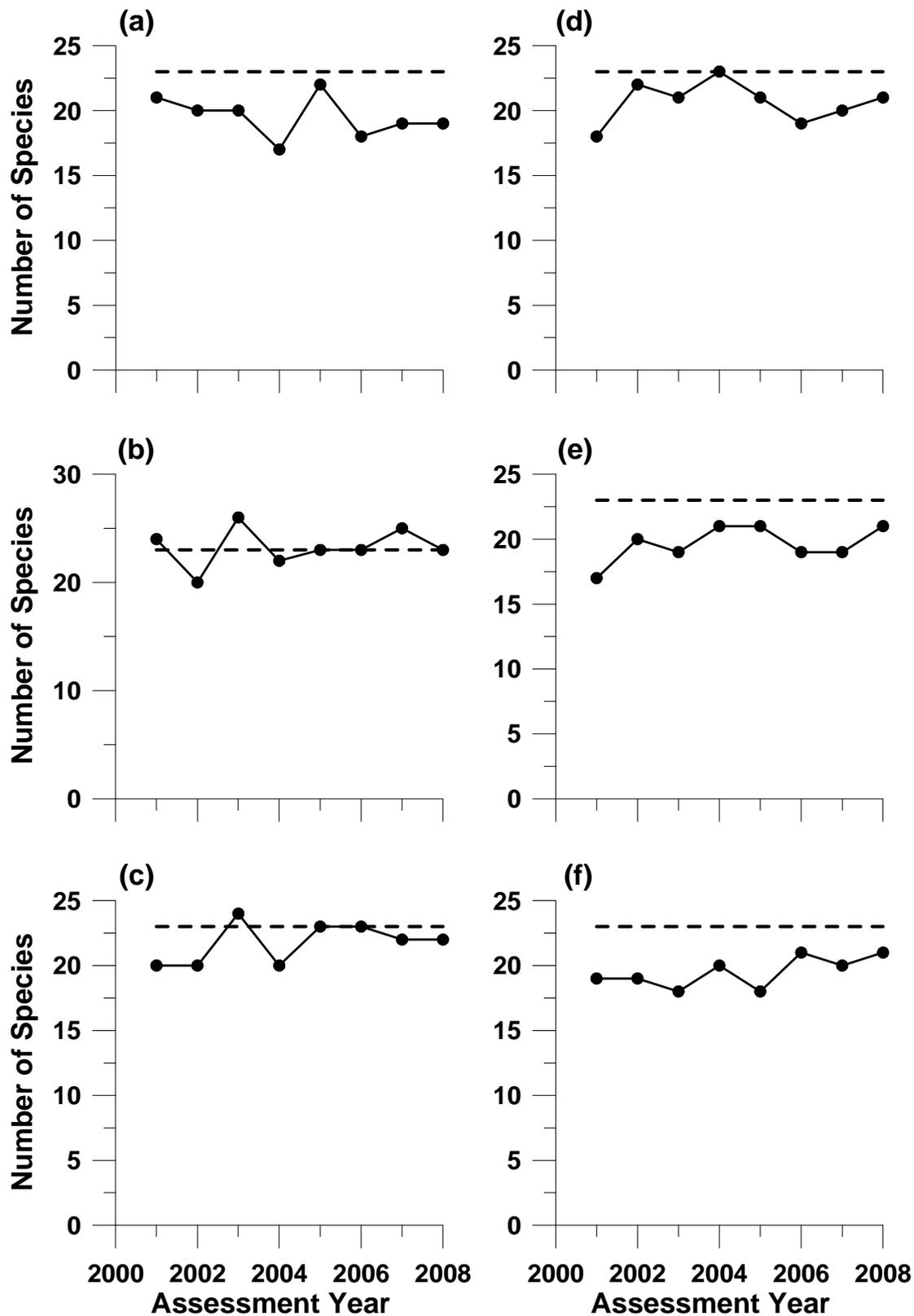
Figure 3. Number of individual SSMs meeting their "prevent further decline" MLTs '*The "current assessment year" SSM value should not fall in the <u>lower</u> 25 percentile of all values in the full time-series "reference period"*' (i.e. number of SSM falling in the upper 75% percentile of all metric values in the time-series) for each SLI class evaluated: a. 1.1.1 Distributional range; b. 1.1.2 Distributional pattern within range (by numbers); c. 1.1.2 Distributional pattern within range (by biomass); d. 1.2.1 Population abundance; e. 1.2.1 Population biomass; f. 1.3.1 Population demographic characteristic (proportion of biomass greater than length-at-first-maturity). Dashed horizontal line indicates the ILT, the number of SSMs meeting their MLTs that represents a significant departure (P<0.05) from the binomial distribution. North Sea case study analysing data for 27 "sensitive" species monitored using Q1 IBTS data.

Figure 4. Number of individual SSMs failing to meet their "prevent further decline" MLTs '*The "current assessment year" SSM value should not fall in the <u>lower</u> 25 percentile of all values in the full time-series "reference period"*' (i.e. number of SSM falling in the lower 25% percentile of all metric values in the time-series) for each SLI class evaluated: a. 1.1.1 Distributional range; b. 1.1.2 Distributional pattern within range (by numbers); c. 1.1.2 Distributional pattern within range (by biomass); d. 1.2.1 Population abundance; e. 1.2.1 Population biomass; f. 1.3.1 Population demographic characteristic (proportion of biomass greater than length-at-first-maturity). Dashed horizontal line indicates the ILT, the number of SSMs meeting their MLTs that represents a significant departure (P<0.05) from the binomial distribution. North Sea case study analysing data for 27 "sensitive" species monitored using Q1 IBTS data.

Figure 5. Temporal trends in the species-specific population abundance, population biomass and distributional range metrics of catfish, cod and spurdog.
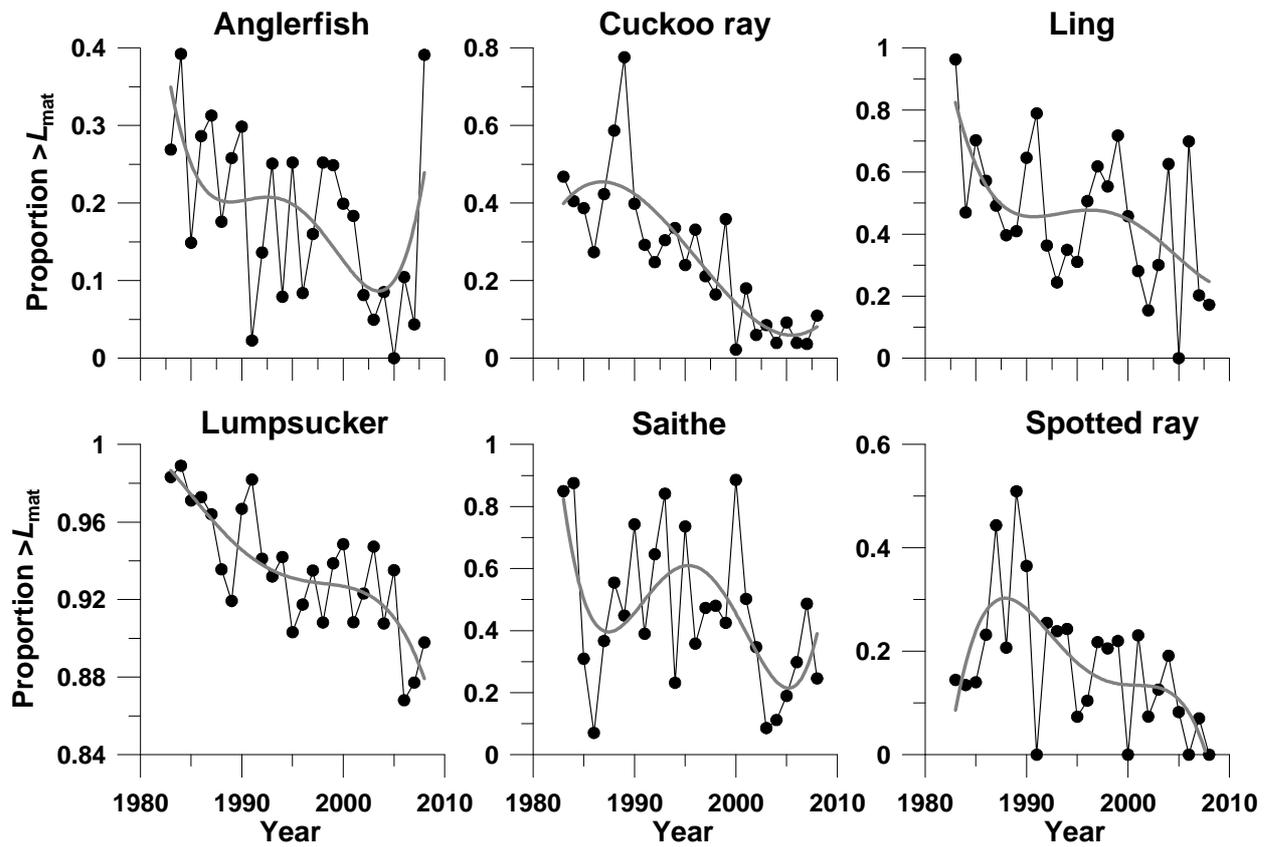
Figure 6. Temporal trends in the species-specific population demographic metric (proportion of biomass greater than the length of first maturity) of anglerfish, cuckoo ray (*Leucoraja naevus*), ling, lumpsucker, saithe (*Pollachius virens*) and spotted ray (*Raja montagui*). Grey lines show fitted 4th degree polynomial smoothers to highlight underlying trends in the data.

Supplementary Material Annex 1: Determining a "standardised" sampling area for determining demersal fish biodiversity metrics derived from the Q1 IBTS.

Biodiversity metrics are notorious for their susceptibility to influence from sampling variability (Greenstreet and Piet 2008). Species richness metrics are affected by variation in sampling effort, which affects the probability of detecting rare species, and by variability in the area sampled, which affects the level of β (cross-habitat) diversity in the richness estimate. It is this latter aspect that would particularly affect the species-specific metrics analysed in this paper, which address species abundance/biomass, occupied range, distributional pattern within the range and proportion of biomass greater than the species-specific length-at-first-maturity. If the survey moved into habitats preferred by particular species, but avoided by others, then the potential for bias in all these metrics was high. Prior to any analysis therefore, the frequency of sampling in each ICES statistical rectangle in each year was examined to determine a criterion for "adequate sampling". For the ICES first quarter (Q1) International Bottom Trawl Survey (IBTS) applying a criterion of "rectangles must be sampled at least once in at least 24y (92%) of the 26y time series" resulted in a "standard survey area" that covered 158 ICES statistical rectangles. Analysing data from only this "standard survey area" eliminated any temporal trend in the extent of the area covered each year and markedly reduced between-year variation (Annex 1 Figure 1). Only data from this "standard survey area" were therefore used to derive the species-specific metrics analysed in the paper. This ensured that any observed metric variation reflected real variability in the status of each species, and could not be an artefact of sampling variability.

References

Greenstreet, S.P.R. and Piet, G.J. 2008. Assessing the sampling effort required to estimate alpha species diversity in the groundfish assemblage of the North Sea. Marine Ecology Progress Series, 364: 181-197.
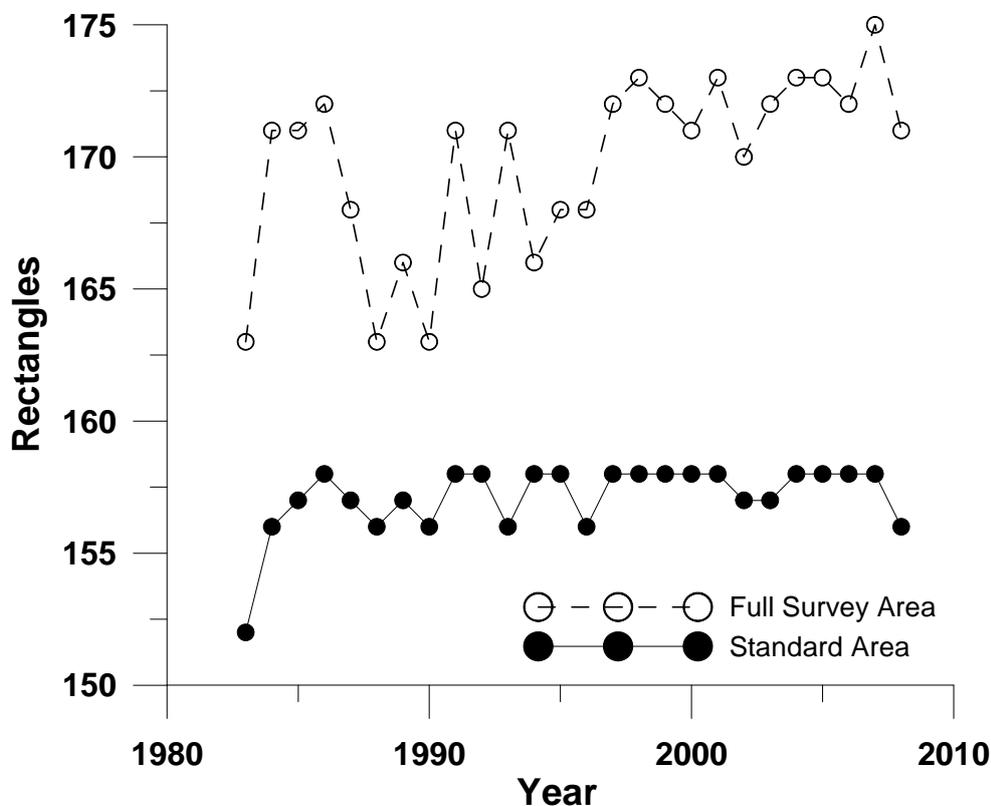
Annex 1 Figure 1. Temporal trends in the number of ICES statistical rectangles sampled in the full area covered by each year's first quarter International Bottom Trawl Survey of the Greater North Sea, and the number of rectangles sampled from a "standard" survey area defined by the criterion "rectangles must be sampled at least once in 24y (92%) of the 26y time series".

Supplementary Material Annex 2: Using life-history traits to assess the sensitivity status of 119 demersal fish species recorded in the Q1 IBTS between 1983 and 2008 and considered likely to occur in the Greater North Sea.

A species' life-history traits provide a good indication of its capacity to cope with additional mortality, and can therefore be used to assess its sensitivity to human activities that raise mortality rates above those normally associated with natural ambient environmental conditions (Jennings, *et al*. 1998; Jennings *et al*., 1999; Gislasson *et al*., 2008; Hobday et al., 2011; Le Quesne and Jennings, 2012). Life-history trait data are now widely available from a number of sources (see Jennings, *et al*. 1998; Jennings *et al*., 1999; Gislasson *et al*., 2008) and the *FishBase* website (www.fishbase.org) also provides data for numerous species. To derive "sensitivity" index values for all 119 species recorded in the Q1 IBTS and considered likely to occur in the Greater North Sea, information on the two von Bertalanffy growth equation parameters, ultimate body length (L_∞) and the growth parameter (K), and length- (L_{mat}) and age-at-first-maturity (A_{mat}) were compiled for each species. Where data were not available these were estimated using the following procedures.

A value for the maximum recorded length (L_{max}) is provided for all species in the *FishBase* website. A simple linear regression model was derived to estimate L_∞ for species where this was not known as a function of L_{max} using data for species where values for both variables were available (Annex 2 Figure 1). The two von Bertalanffy variables are known to be correlated (Gislasson *et al*., 2008), so a second regression model was developed to estimate K from L_∞ (Annex 2 Figure 1). The parameters derived from this second model fell well within the 95% confidence limits provided by Gislasson *et al*. (2008) for equivalent parameters. Gislasson *et al*. (2008) also estimate length-at-first-maturity (L_{mat}) as a function of von Bertalanffy ultimate body length (L_∞). Linear regression models to estimate length-at-first-maturity (L_{mat}) for species where this information was missing were developed using both maximum recorded length (L_{max}) and ultimate body length (L_∞) as the explanatory variable; the (L_∞) model was the more reliable, and hence this was the one used (Annex 2 Figure 2).

For most fish species, the incremental increase in length with each successive time-step follows the von Bertalanffy growth equation

$$L_{s,t} = L_{\infty,s}(1 - e^{-K_s(t-t_0)}),$$

where, for the species (s) in question, length at a given time (t, in years) is determined by two species specific parameters, $L_{\infty,s}$ and K_s. These are the two parameters considered as life-history trait variables in the paragraph above. Since t is relative to t_0, setting t_0 to zero allows the equation to be rearranged to find solutions for t at specified body lengths for any particular species,

$$t = \frac{Ln\left(1 - \dfrac{L_{s,t}}{L_{\infty,s}}\right)}{-K_s} .$$

Substituting estimates for length-at-first-maturity (L_{mat}) for $L_{s,t}$ then provides estimates of age-at-first-maturity (A_{mat}). However, these estimates of age-at-first-maturity also include the period of larval and post-larval development up to metamorphosis (a consequence of setting t_0 to zero). Since this phase of growth is not well described by the von Bertalanffy growth equation, this could potentially distort the age-at-first-maturity estimates. Gislasson *et al*. (2008) assume that fish generally go through their metamorphosis stage at a length of around 4cm (L_{met}). Such a length is appropriate for the fish that they modelled, but seems too large for some of the smaller fish species sampled by the Q1 IBTS. Here values of L_{met} = 4cm are assumed for all species with (L_∞) values of 15cm or more; for species where L_∞ <6cm, L_{met} is assumed to be 1.5cm; for species where L_∞ = 6 to <8cm, L_{met} is assumed to be 2.0cm; for species where L_∞ = 8 to <10cm, L_{met} is assumed to be 2.5cm; and for species where L_∞ = 10 to <15cm, L_{met} is assumed to be 3.0 cm. Substituting these L_{met} values into the equation provided estimates of the age of each species at metamorphosis. Subtracting these latter values from the former gives estimates of the age-at-first-maturity for each species that excludes the uncertain larval and post-larval stage. Estimates of age-

at-first-maturity derived in this way were found to be a close approximation to actual values for 51 species where reported age-at-first-maturity data were available (Annex 2 Figure 3). The linear regression obtained from this comparison was used to provide a final adjustment to the modelled estimates, to make the modelled estimates of age-at-first-maturity as similar as possible to those obtained from the literature.

For L_∞, L_{mat}, and A_{mat}, increasing values corresponded with increased sensitivity, but for K the reverse was true; increased sensitivity was associated with decreasing values of K. By taking reciprocals of K the direction of this relationship was reversed, ensuring that variation in all four life-history trait variables was positively related to sensitivity. Having determined values for each of the four life-history trait variables for all 119 species, these values were square-root transformed to reduce the spread in each set of data and to distribute the values more evenly within their ranges. The data for each variable were then standardised following

$$\Omega_{std,s} = \frac{\Omega_s - \Omega_{min}}{\Omega_{range}},$$

where Ω_s is the value for any of the four life-history trait variables for a particular species, Ω_{min} is the minimum value for that life-history variable observed among the 119 species and Ω_{range} is the range of values for that life-history variable observed across all 119 species. $\Omega_{std,s}$ is the standardised value for that life-history trait variable for the species in question. A single sensitivity index for each of the 119 species was then derived simply by determining the arithmetic mean of the four standardised life history trait variables. This index ranged between 0 representing the least sensitive, or most resilient, species and 1 representing the most sensitive species. Values for each of the life-history trait variables, and the resulting sensitivity index, are given for all 119 species in Annex 2 Table 1. The forty species in the upper 33 percentile and forty species in the lower 33 percentile were categorised as "sensitive" species and "resilient" species respectively (Annex 2 Table 1).

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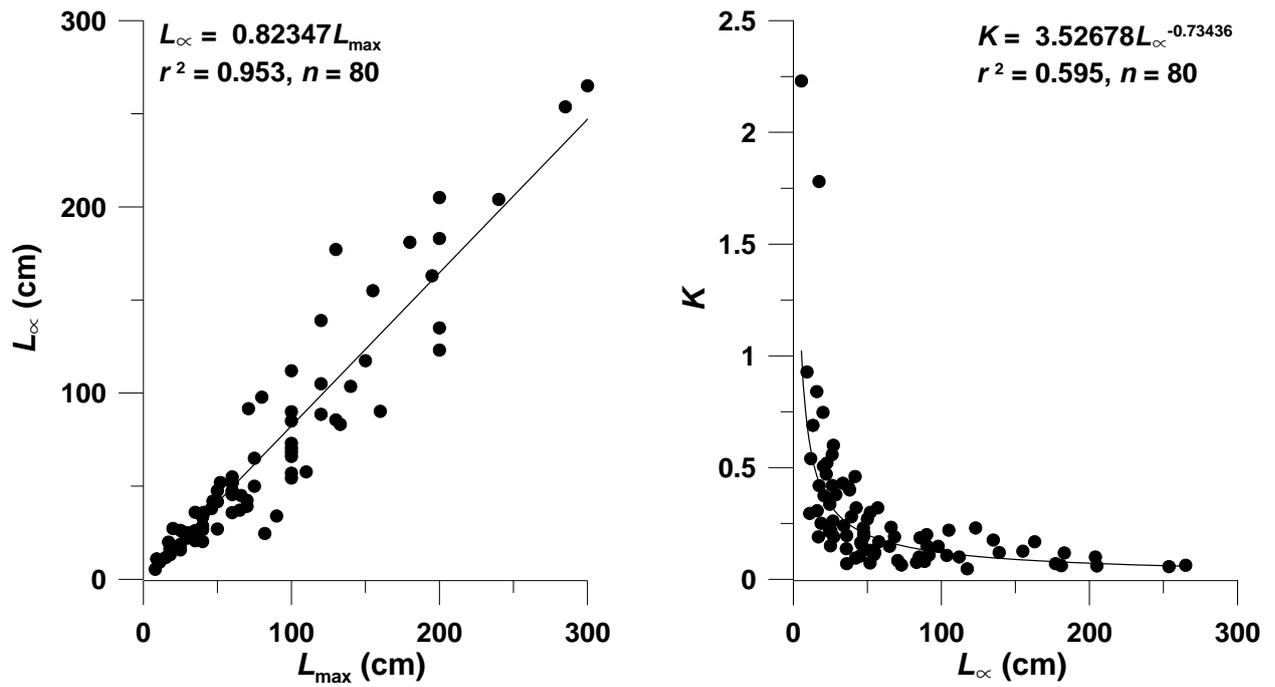
Annex 2 Figure 1. Linear regression models used to estimate ultimate body length (L_∞) from available data on maximum recorded body length (L_{max}), and to estimate the von Bertalanffy growth parameter (K) from ultimate body length (L_∞), for species where no information on the two von Bertalanffy growth equation parameters was available.
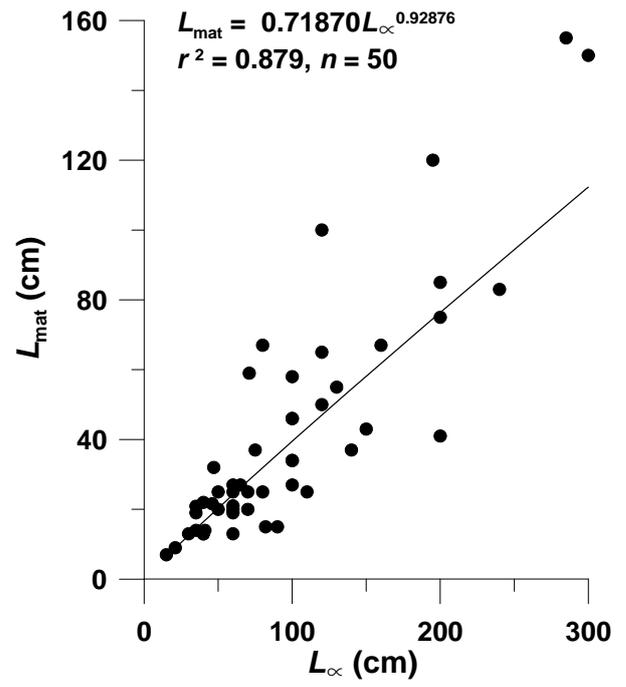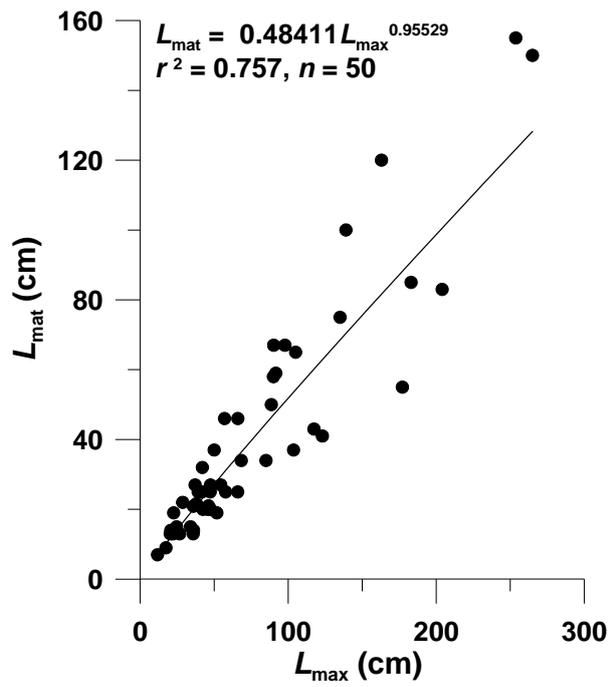
Annex 2 Figure 2. Linear regression models used to estimate length-at-first-maturity (L_{mat}) as functions of maximum recorded body length (L_{max}) and von Bertalanffy ultimate body length (L_∞).
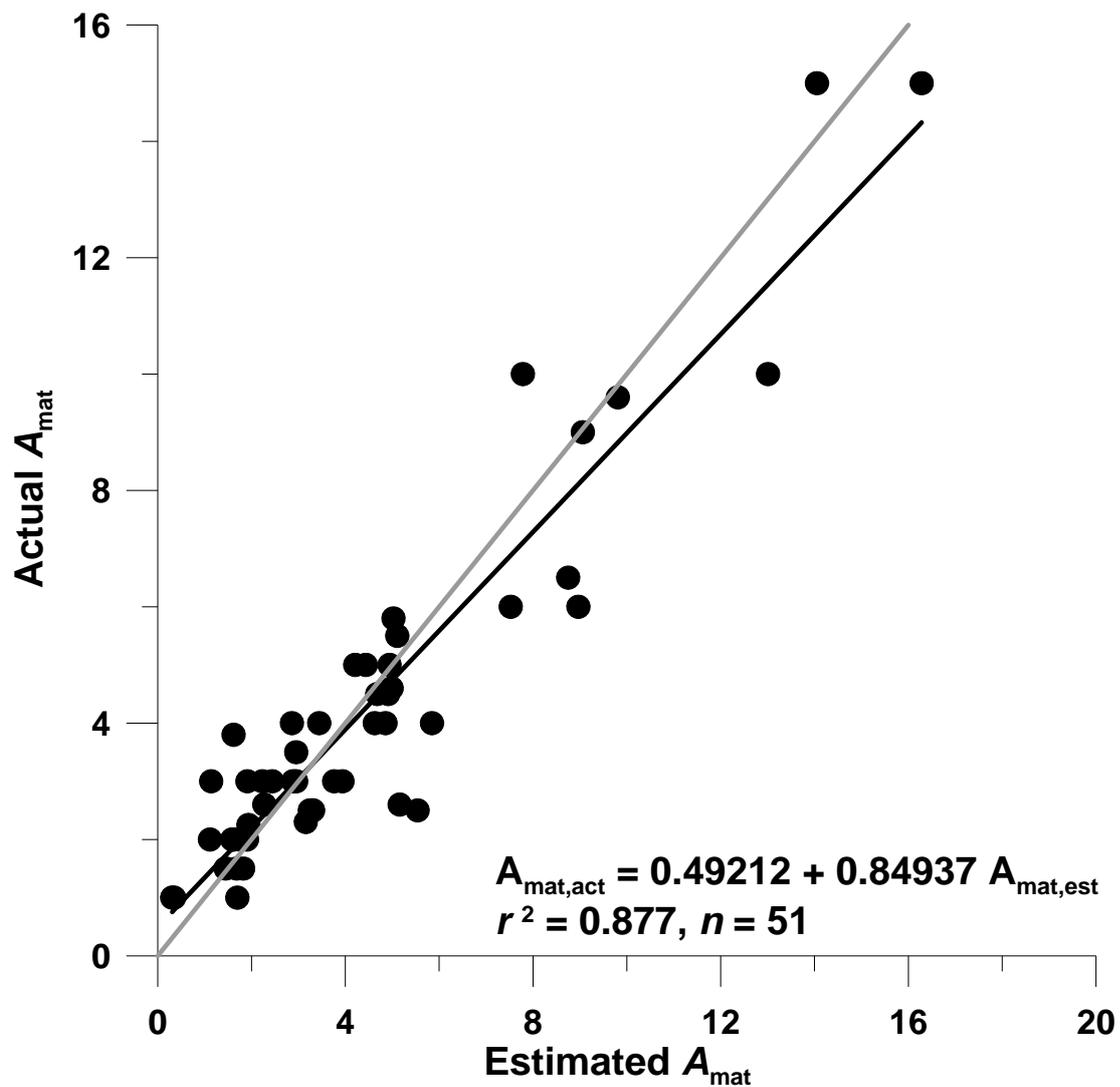
Annex 2 Figure 3. Comparison of estimates of age-at-first-maturity ($A_{mat,est}$) derived from substituting estimates of length-at-first-maturity and length-at-metamorphosis into the von Bertalanffy growth equation rearranged to provide solutions for time *t* and specified lengths (see text for details) with actual values of age-at-first-maturity ($A_{mat,act}$) provided in the literature or from *FishBase*. Grey line indicates the line of perfect prediction. Black line shows the fitted regression used to adjust the modelled estimates.

Scientific Name	Common Name	L_{max}	$L\infty$	K	L_{mat}	A_{mat}	Sensitivity Index	Sensitivity Category
Aphia minuta	Transparent goby	**8**	**5.4**	**2.230**	3.4	**1.0**	0.011	Resilient
Crystallogobius linearis	Crystal goby	**5**	4.1	1.247	2.7	0.9	0.011	Resilient
Diplecogaster bimaculata	Two-spotted clingfish	**6**	4.9	1.091	3.2	1.0	0.024	Resilient
Pomatoschistus pictus	Painted goby	**6**	4.9	1.091	3.2	1.0	0.024	Resilient
Taurulus lilljeborgi	Norway bullhead	**7.4**	6.1	0.935	3.9	1.0	0.035	Resilient
Pomatoschistus minutus	Sand goby	**11**	**9.2**	**0.928**	5.6	1.1	0.049	Resilient
Spinachia spinachia	Fifteen spined stickleback	**22**	**17.3**	**1.780**	10.1	**1.0**	0.058	Resilient
Callionymus reticulatus	Reticulated dragonet	**11**	9.1	0.699	5.6	1.3	0.064	Resilient
Liparis montagui	Montagu's sea snail	**12**	9.9	0.656	6.0	1.3	0.072	Resilient
Phrynorhombus norvegicus	Norwegian topknot	**12**	9.9	0.656	6.0	1.3	0.072	Resilient
Arnoglossus laterna	Scaldfish	**25**	**15.8**	**0.840**	9.3	1.1	0.075	Resilient
Lesueurigobius friesii	Fries's goby	**13**	10.7	0.618	6.5	1.3	0.076	Resilient
Centrolabrus exoletus	Small-mouthed wrasse	**18**	**13.2**	**0.689**	7.9	1.3	0.080	Resilient
Artediellus europaeus	Atlantic hook-ear sculpin	**15**	12.4	0.557	7.4	1.5	0.090	Resilient
Echiichthys vipera	Lesser weever	**15**	12.4	0.557	7.4	1.5	0.090	Resilient
Liparis liparis	Sea snail	**15**	12.4	0.557	7.4	1.5	0.090	Resilient
Syngnathus rostellatus	Nilsson's pipefish	**17**	**20.0**	**0.747**	11.6	1.2	0.095	Resilient
Callionymus maculatus	Spotted dragonet	**16**	13.2	0.531	7.9	1.5	0.097	Resilient
Ciliata mustela	Five-bearded rockling	**25**	20.6	0.383	11.9	**1.0**	0.111	Resilient
Ciliata septentrionalis	Northern rockling	**20**	16.5	0.451	9.7	1.6	0.116	Resilient
Leptoclinus maculatus	Spotted snake blenny	**20**	16.5	0.451	9.7	1.6	0.116	Resilient
Lycenchelys sarsii	Sar's wolf eel	**20**	16.5	0.451	9.7	1.6	0.116	Resilient
Triglops murrayi	Moustache sculpin	**20**	16.5	0.451	9.7	1.6	0.116	Resilient
Zeugopterus regius	Eckstrom's topknot	**20**	16.5	0.451	9.7	1.6	0.116	Resilient
Leptagonus decagonus	Atlantic poacher	**21**	17.3	0.435	10.1	1.7	0.122	Resilient
Callionymus lyra	Dragonet	**30**	**22.2**	**0.471**	13.0	**1.5**	0.125	Resilient
Gaidropsarus mediterraneus	Shore rockling	**50**	**27.0**	**0.600**	15.3	1.5	0.126	Resilient
Agonus cataphractus	Hooknose	**21**	**17.4**	**0.419**	**9.0**	**2.0**	0.129	Resilient
Syngnathus typhle	Broad-nosed pipefish	**35**	**26.2**	**0.558**	14.9	1.5	0.129	Resilient
Buglossidium luteum	Solenette	**15**	**11.7**	**0.540**	7.0	**3.0**	0.131	Resilient
Pomatoschistus microps	Common goby	**9**	**11.0**	**0.295**	6.7	2.3	0.134	Resilient
Trisopterus minutus	Poor cod	**40**	**20.3**	**0.506**	13.0	**2.0**	0.136	Resilient

Species	Common name							
Arnoglossus imperialis	Imperial scaldfish	**25**	20.6	0.383	11.9	1.9	0.142	Resilient
Zeugopterus punctatus	Topknot	**25**	20.6	0.383	11.9	1.9	0.142	Resilient
Ctenolabrus rupestris	Coldsinny wrasse	**18**	**16.1**	**0.307**	9.5	2.2	0.146	Resilient
Pholis gunnellus	Butterfish	**25**	**26.3**	**0.420**	15.0	**2.0**	0.154	Resilient
Raniceps raninus	Tadpole fish	**28**	23.1	0.352	13.3	2.1	0.156	Resilient
Trisopterus esmarkii	Norway pout	**35**	**22.6**	**0.520**	**19.0**	**2.3**	0.158	Resilient
Mullus surmuletus	Striped red mullet	**40**	**33.4**	**0.430**	18.7	1.9	0.164	Resilient
Capros aper	Boarfish	**30**	24.7	0.335	14.1	2.2	0.165	Resilient
Echiodon drummondii	Pearlfish	**30**	24.7	0.335	14.1	2.2	0.165	Intermediate
Parablennius gattorugine	Tompot blenny	**30**	24.7	0.335	14.1	2.2	0.165	Intermediate
Trisopterus luscus	Bib	**46**	**38.0**	**0.400**	**21.6**	**1.5**	0.165	Intermediate
Merlangius merlangus	Whiting	**70**	**42.4**	**0.320**	**20.0**	**1.5**	0.176	Intermediate
Microchirus variegatus	Thickback sole	**35**	**20.7**	**0.374**	**14.0**	**3.0**	0.176	Intermediate
Taurulus bubalis	Sea scorpion	**25**	**18.7**	**0.251**	10.9	2.6	0.176	Intermediate
Hippoglossoides platessoides	Long rough dab	**82**	**24.6**	**0.336**	**15.0**	**2.6**	0.177	Intermediate
Limanda limanda	Common dab	**40**	**26.7**	**0.261**	**13.0**	**2.3**	0.178	Intermediate
Chelidonichthys cuculus	Red gurnard	**50**	**41.7**	**0.460**	**25.0**	**2.0**	0.184	Intermediate
Myoxocephalus scorpius	Bullrout	**90**	**34.0**	**0.240**	**15.0**	**2.0**	0.187	Intermediate
Gobius niger	Black goby	**18**	**16.9**	**0.190**	9.9	3.2	0.200	Intermediate
Symphodus melops	Corkwing wrasse	**28**	**24.4**	**0.214**	14.0	3.2	0.210	Intermediate
Gobius cobitis	Giant goby	**27**	**25.3**	**0.217**	14.4	3.1	0.211	Intermediate
Solea vulgaris	Dover sole	**70**	**39.2**	**0.280**	**25.0**	**2.5**	0.217	Intermediate
Pegusa lascaris	Sand sole	**40**	**28.7**	**0.379**	**22.0**	**4.0**	0.222	Intermediate
Enchelyopus cimbrius	Four-bearded rockling	**41**	**36.0**	**0.196**	**14.0**	**3.0**	0.224	Intermediate
Spondyliosoma cantharus	Black sea bream	**60**	**52.0**	**0.300**	28.2	2.5	0.229	Intermediate
Triglops pingelii	Ribbed sculpin	**20**	**27.3**	**0.190**	15.5	3.5	0.232	Intermediate
Pagellus erythrinus	Pandora	**60**	**35.8**	**0.137**	**13.0**	2.6	0.233	Intermediate
Microstomus kitt	Lemon sole	**65**	**37.1**	**0.415**	**27.0**	**4.0**	0.235	Intermediate
Lampetra fluviatilis	European river lamprey	**50**	41.2	0.230	22.7	3.1	0.238	Intermediate
Syngnathus acus	Great pipefish	**50**	41.2	0.230	22.7	3.1	0.238	Intermediate
Lumpenus lampretaeformis	Snake blenny	**50**	**47.6**	**0.205**	**20.0**	**3.0**	0.243	Intermediate
Lycodes vahlii	Vahl's eelpout	**52**	42.8	0.223	23.5	3.2	0.244	Intermediate
Platichthys flesus	Flounder	**60**	**47.3**	**0.230**	**25.0**	**3.0**	0.246	Intermediate
Eutrigla gurnardus	Grey gurnard	**60**	**46.2**	**0.156**	**21.0**	**2.5**	0.248	Intermediate
Trachinus draco	Greater weever	**53**	43.6	0.220	24.0	3.2	0.248	Intermediate
Glyptocephalus cynoglossus	Witch	**60**	**45.5**	**0.165**	**20.0**	**3.0**	0.254	Intermediate
Mullus barbatus	Red mullet	**30**	**25.0**	**0.150**	14.3	4.3	0.257	Intermediate
Gaidropsarus vulgaris	Three-bearded rockling	**60**	**47.5**	**0.191**	**27.0**	**3.0**	0.259	Intermediate
Entelurus aequoreus	Snake pipefish	**60**	49.4	0.201	26.9	3.5	0.268	Intermediate
Etmopterus spinax	Velvet belly	**60**	49.4	0.201	26.9	3.5	0.268	Intermediate

Scientific name	Common name							
Myxine glutinosa	Hagfish	**80**	65.9	0.163	**25.0**	2.7	0.271	Intermediate
Melanogrammus aeglefinus	Haddock	**100**	**68.3**	**0.190**	**34.0**	2.5	0.273	Intermediate
Phycis blennoides	Greater forkbeard	**110**	**57.7**	**0.168**	**25.0**	3.5	0.283	Intermediate
Scophthalmus rhombus	Brill	**75**	**50.0**	**0.270**	**37.0**	4.5	0.289	Intermediate
Pleuronectes platessa	Plaice	**100**	**54.4**	**0.110**	**27.0**	2.5	0.290	Intermediate
Psetta maxima	Turbot	**100**	**57.0**	**0.320**	**46.0**	4.5	0.298	Intermediate
Amblyraja radiata	Starry ray	**100**	**66.0**	**0.233**	**46.0**	4.0	0.310	Intermediate
Lepidorhombus whiffiagoni	Megrim	**60**	**51.8**	**0.073**	**19.0**	2.6	0.311	Sensitive
Cyclopterus lumpus	Lumpsucker	**60**	**55.0**	**0.120**	**29.7**	**4.0**	0.322	Sensitive
Pollachius pollachius	Pollack	**130**	**85.6**	**0.186**	**44.8**	3.7	0.327	Sensitive
Chelidonichthys lucerna	Tub gurnard	**75**	**65.0**	**0.148**	**34.7**	4.5	0.331	Sensitive
Zoarces viviparus	Viviparous blenny	**52**	**52.0**	**0.130**	**28.2**	5.1	0.332	Sensitive
Gadus morhua	Cod	**200**	**123.1**	**0.230**	**41.0**	3.8	0.333	Sensitive
Merluccius merluccius	Hake	**140**	**103.6**	**0.107**	**37.0**	3.0	0.350	Sensitive
Labrus bergylta	Ballan wrasse	**66**	**45.0**	**0.104**	**24.7**	6.2	0.356	Sensitive
Lophius budegassa	Black bellied angler	**100**	**85.0**	**0.100**	**34.0**	4.0	0.362	Sensitive
Scyliorhinus canicula	Lesser spotted dogfish	**100**	**90.0**	**0.200**	**58.0**	5.0	0.367	Sensitive
Raja clavata	Thornback ray	**120**	**105.0**	**0.220**	**65.0**	**5.0**	0.377	Sensitive
Leucoraja circularis	Sandy ray	**120**	98.8	0.121	51.2	5.3	0.402	Sensitive
Leucoraja fullonica	Shagreen ray	**120**	98.8	0.121	51.2	5.3	0.402	Sensitive
Petromyzon marinus	Sea lamprey	**120**	98.8	0.121	51.2	5.3	0.402	Sensitive
Lophius piscatorius	Angler	**200**	**135.0**	**0.176**	**75.0**	5.0	0.415	Sensitive
Raja montagui	Spotted ray	**80**	**97.8**	**0.148**	**67.0**	**6.0**	0.416	Sensitive
Squalus acanthias	Spurdog	**160**	**90.2**	**0.150**	**67.0**	**6.5**	0.419	Sensitive
Sebastes viviparus	Norway haddock	**35**	**36.0**	**0.070**	**20.9**	9.6	0.425	Sensitive
Brama brama	Ray's bream	**100**	**70.5**	**0.084**	**37.4**	7.6	0.433	Sensitive
Mustelus asterias	Starry smooth hound	**140**	115.3	0.108	59.1	5.9	0.438	Sensitive
Raja undulata	Undulate ray	**100**	**112.0**	**0.100**	57.5	6.3	0.448	Sensitive
Molva dypterygia	Blue ling	**155**	**155.0**	**0.126**	77.8	5.0	0.450	Sensitive
Chimaera monstrosa	Rabbit ratfish	**150**	123.5	0.103	63.0	6.1	0.454	Sensitive
Anguilla anguilla	European eel	**133**	**83.2**	**0.076**	43.6	8.2	0.468	Sensitive
Leucoraja naevus	Cuckoo ray	**71**	**91.6**	**0.109**	**59.0**	**9.0**	0.471	Sensitive
Pollachius virens	Saithe	**130**	**177.1**	**0.070**	**55.0**	**4.6**	0.477	Sensitive
Molva molva	Ling	**200**	**183.0**	**0.118**	**85.0**	**5.5**	0.482	Sensitive
Helicolenus dactylopterus	Bluemouth	**47**	**42.0**	**0.095**	**32.0**	**15.0**	0.484	Sensitive
Scyliorhinus stellaris	Nurse hound	**170**	140.0	0.094	70.8	6.6	0.486	Sensitive
Brosme brosme	Torsk	**120**	**88.6**	**0.080**	**50.0**	**9.6**	0.492	Sensitive
Sebastes marinus	Redfish (marinus)	**100**	**73.0**	**0.064**	**38.6**	9.7	0.492	Sensitive
Anarhichas lupus	Catfish	**150**	**117.4**	**0.047**	**43.0**	**6.0**	0.502	Sensitive
Hippoglossus hippoglossus	Halibut	**240**	**204.0**	**0.100**	**83.0**	5.8	0.506	Sensitive

9

		L_{max}	L_∞	K	L_{mat}	A_{mat}		
Raja brachyura	Blond ray	**120**	**139.0**	**0.120**	**100.0**	9.3	0.531	Sensitive
Galeorhinus galeus	Tope	**195**	**163.0**	**0.168**	**120.0**	**10.0**	0.544	Sensitive
Anarhichas minor	Spotted catfish	**180**	**181.0**	**0.061**	89.8	9.7	0.605	Sensitive
Mustelus mustelus	Smooth hound	**200**	**205.0**	**0.060**	100.8	9.8	0.627	Sensitive
Conger conger	Conger eel	**300**	**265.0**	**0.063**	**150.0**	**10.0**	0.683	Sensitive
Dipturus batis	Skate	**285**	**253.7**	**0.057**	**155.0**	**15.0**	0.751	Sensitive
Somniosus microcephalus	Greenland shark	**730**	601.1	0.032	273.9	16.4	1.000	Sensitive

Annex 2 Table 1. List of 119 species recorded in the Q1 IBTS and likely to occur in the Greater North Sea giving species specific values for four life-history traits: the two von Bertalanffy growth equation parameters, ultimate body-length (L_∞) and growth rate (K), and length- (L_{mat}) and age-at-first-maturity (A_{mat}). Bold font indicates variable values obtained from the literature and *FishBase* website; other values were estimated using various modelling approaches (see text for details). Maximum recorded length (L_{max}) values for each species obtained from FishBase are also given as this was a key variable used to derive estimates for missing life-history trait data. The resultant sensitivity indices for each species, and each species classification to a sensitivity category, are provided.