

Standardizing blue ling landings per unit effort from industry haul-by-haul data using generalized additive models

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Haul-by-haul data derived from skippers' personal logbooks, from the French deep-water fishery to the west of the British Isles, were used to calculate standardized blue ling (*Molva dypterygia*) landings per unit effort (lpue) for the period 2000–2008. Lpue values were estimated using generalized additive models with depth, vessel, statistical rectangle, area, and year as explanatory variables. Because of their statistical distribution, landings were modelled by a Tweedie distribution, which allows datasets to contain many zeros. To investigate how to track stock trends reliably, lpue values were estimated in five areas for different subsets of the data. The subsets consisted of hauls during the spawning season (when blue ling aggregate), outside the spawning season, and hauls in which blue ling was only a bycatch. The results suggest that blue ling lpue values have been stable over the period 2000–2008, and that the declining trend previously observed for the stock has been halted. This finding is consistent with stable mean lengths in the landings during the same period. The study demonstrates the greater suitability of haul-by-haul data than EC logbook data for deriving abundance indices for deep-water stocks.

Keywords: abundance indices, fishing strategy, GAM, *Molva dypterygia*, tallybook.

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Introduction

Accurate assessments are crucial to fishery management, but assessments of deep-water stocks in European waters have been mostly exploratory (Basson *et al.*, 2002; ICES, 2008). Limitations to accurate assessment are the lack of data on deep-water fish populations globally, including basic knowledge of biological parameters and spatial distributions. Stock management units are delineated either based upon hypothetical considerations or upon the distribution of fisheries, and they may not correspond to biological populations. Fishery statistics are not always reported at a sufficient spatial resolution for deep-water species. Although depth is a strong structuring factor for abundance distributions and one single statistical rectangle often encompasses depths from 200 to 2000 m (Figure 1a), haul depth is not reported in EC logbooks and cannot be taken into account in standard landings per unit effort (lpue). Therefore, lpue values based upon EC logbook data should be considered as crude at best, usually. Nevertheless, they are often used as a basis for assessment and advice because more detailed data are generally not available.

For blue ling (*Molva dypterygia*), there is no agreed scheme for age estimation, so annual age–length keys are not collected routinely. Nevertheless, the species is thought to recruit to the fishery at an age of 6–8 years and to have a growth rate and natural mortality similar to typical gadoid species such as cod (*Gadus morhua*) or saithe (*Pollachius virens*; Ehrich and Reinsch, 1985; Moguedet, 1988; Magnússon and Magnússon, 1995; Magnussen, 2007). Blue

ling seasonally aggregate to spawn between March and May, and they are considered to be mainly scattered during the rest of the year (Large *et al.*, 2010). ICES Division Vb and Subareas VI and VII are assumed to be a stock unit for assessment purposes, but there is insufficient information to evaluate the stock structure (ICES, 2007). Blue ling have been fished to the west of the British Isles from 1973 and possibly earlier. Although no archive of landings by ICES Areas before the 1970s exists, earlier landings have been reported by Norway and Germany, aggregated at the scale of the Northeast Atlantic. From 1950 to 1970, ~5000 t of blue ling were landed annually (FAO fisheries catch statistics, <http://www.fao.org/fishery/statistics/en>). In those early years, Norwegian catches were mainly bycatch from longliners targeting ling (*Molva molva*) and tusk (*Brosme brosme*), and an unknown part of the catch was from the northern North Sea and Norwegian Sea (Bergstad and Hareide, 1996). The distribution of German catches is also unknown, but the organization of exploratory research cruises for new fishing grounds to the west of the British Isles from the mid-1970s (Ehrich, 1983) suggests that these grounds were not fished previously and that German catches of blue ling came from the North Sea and Norwegian Sea.

In the 1970s, landings of blue ling from the Faroe Plateau, the slopes of the Rockall Trough, Rockall, and Hatton Bank (ICES Divisions Vb and Subareas VI and VII) increased sharply. Those areas have remained the main area where blue ling have been targeted since then (ICES, 2009), and the French fleet landed more

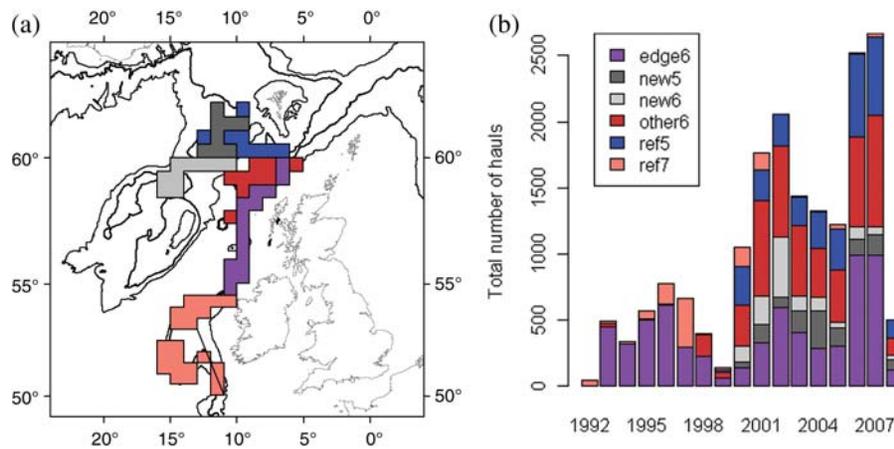


Figure 1. (a) Reference areas (statistical rectangles) used to calculate French lpue for blue ling and (b) the number of hauls per area in the full dataset. Dark grey, new grounds in ICES Subarea V (new5); light grey, new grounds in Subarea VI (new6); red brown, others in Subarea VI (other6); purple, edge in VI (edge6); blue, reference in Subarea V (ref5); pink, all grounds in Subarea VII (ref7). Depth contours are for 200, 1000, and 2000 m.

than half the total. Up to the late 1980s, the main species in the French landings from these areas were shelf gadoids, primarily saithe, but then French trawlers started to exploit mid-slope species at greater depth (Figure 2; Charuau *et al.*, 1995).

Blue ling lpue values derived from aggregated EC logbook data of the French fishing fleet displayed a declining trend from 1985 to about 1995, but then stabilized (Figure 3a). These lpue values were based upon an aggregated catch and effort by month and ICES Division for several fleets (Lorance and Dupouy, 2001). Although there is no doubt that blue ling and other gadoid abundance declined in the 1980s and that this was a reason for French vessels to move to other resources (Charuau *et al.*, 1995), there are several issues regarding the appropriateness of EC logbook data for calculating blue ling lpue. These issues are (i) changing fishing strategies, (ii) inaccurate effort data, and (iii) lack of information on haul depth.

Fishing strategies changed in the 1990s as fishing in deeper water developed, and might have changed again in the 2000s in response to

the introduction of management measures for deep-water fisheries. In the 1980s, the fishery was mainly operating on aggregations, and was particularly active during the spawning season. When the exploitation of other deep-water species started, in the early 1990s, trawlers moved to deeper water, some blue ling fishing grounds were no longer exploited and, in addition to being a target species, blue ling also became a bycatch of fishing operations for mid-slope species. The catch then became much less seasonal (Lorance and Dupouy, 2001). From 1995 deep-water fishing effort was regulated [Council regulation (EC) No 2027/95], and a licensing system was introduced in 2003 [Council regulation (EC) No 2347/2002]. Total allowable catches (TACs) for blue ling in ICES Division Vb and Subareas VI and VII were introduced in 2003, then reduced in 2005, 2007, and 2008. Additionally, technical measures were introduced and fishing companies also set some rules for their vessels to comply with annual quotas. From 2007, landings by EU vessels were limited to 25 t per fishing trip [Council regulation (EC) No 2015/2006]. One of the fishing companies reduced the landings per trip further, to 20 t in 2006 and 2007, and to 15 t in 2008, to avoid quota overrun (in relation to the decreasing TAC).

Effort data in EC logbooks might be less reliable than catch data, because an accurate effort reporting would require explicit guidelines whereas catch reporting is more straightforward. Reporting rules may have varied between skippers and over time. For example, because of the long shooting and hauling times, there are significant differences between the total time of one haul and the time during which the trawl is in contact with the seabed. In addition, French fishery statistics effort by day was often reported to be 24 h, i.e. including steaming time.

Fishing depth is not available from EC logbooks, although it is a major explanatory factor for blue ling catches (Ehrich, 1983; Gordon and Duncan, 1985). The average fishing depth increased when exploitation of roundnose grenadier (*Coryphaenoides rupertis*) and other mid-slope species started, then varied over time (Pawlowski and Lorance, 2009).

Collaboration with the fishing industry has led to the use of data from skippers' personal logbooks (tallybooks) for deriving standardized lpue (Dobby *et al.*, 2008). A partnership between the French fishing industry involved in the deep-water fishery and the research and advisory establishment (Ifremer) was

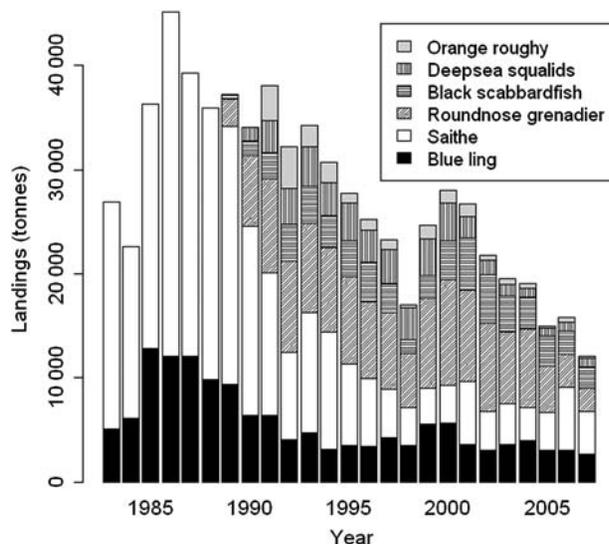


Figure 2. Landings from French trawlers (freezer-trawlers excluded) in ICES Subareas V–VII from 1983 to 2007.

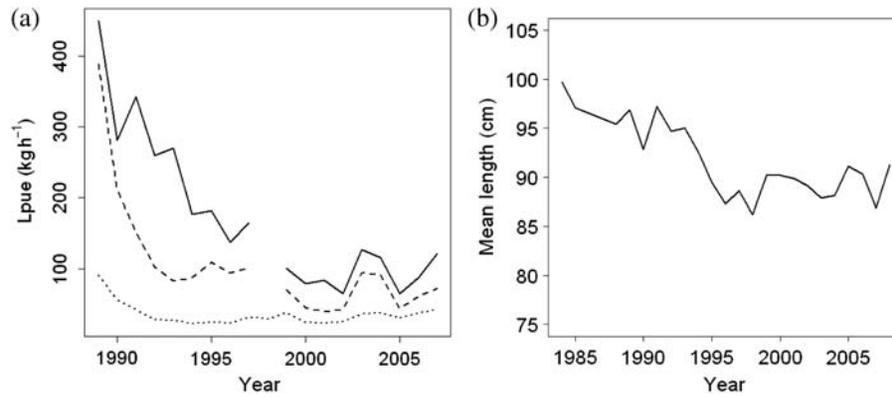


Figure 3. (a) Blue ling lpue values for French trawlers fishing in ICES Division Vb and Subareas VI and VII, from EC logbook data. Dotted line, all vessels; dashed line, reference fleet of large high-sea trawlers; solid line, directed lpue of the reference fleet (landings for fishing trips where blue ling represents >10% of total landings). Redrawn from ICES (2008). (b) Annual mean length of French landings of blue ling, 1985–2008.

initiated in 2001. The industry created a database with landings per species and haul information, including the fishing depth of a panel of volunteer trawlers since the late 1990s. Moreover, some skippers' personal logbooks have been retrieved back to 1992, so a database from 1992 to 2008 (first half) was available to us. Preliminary analysis showed that several ecological and fishing-strategy-related factors had an effect on deep-water fish lpue (ICES, 2009). Compared with the survey data obtained from a standardized sampling design, commercial fishing data suffer from being obtained by preferential sampling, i.e. sampling locations and the process of interest are not independent (Diggle et al., 2010). In that case, design-based abundance estimators cannot be used, and modelling has to be used to control for the various factors.

Here, statistical modelling was carried out to calculate the standardized blue ling lpue. Generalized additive models (GAMs) were fitted to extract the main factors and to identify trends over time assuming a Tweedie distribution (see below), which has already been used to model the lpue of yellowfin tuna (*Thunnus albacares*) and silky shark (*Carcharhinus falciformis*; Shono, 2008), and Patagonian toothfish (*Dissostichus eleginoides*; Candy, 2004).

Material and methods

Data

The deep-water tallybook (DWTB) database contains information on hauls and vessel characteristics from 30 French deep-water trawlers operating in the Northeast Atlantic during the period 1992–2008 (Figure 4). The data come from volunteer vessels,

which provided information for all hauls during a given period. For each haul location, the mean fishing depth, effort (haul duration), and landings (weight) by species were reported. For our purpose, location was aggregated to statistical rectangle. Vessels were identified with a numerical code, and engine power was also available. There were fewer hauls in the DWTB database for years before 2000 (Figure 1b), because the participation of vessels varied over time and the fleet composition changed as a consequence of decommissioning, vessels moving to other fisheries, and construction of new vessels. The modelling was restricted therefore to the years 2000–2008, to allow the area and vessel effects to be estimated; before 2000, data were primarily available for area edge 6 (Figure 1b), and no vessel participated throughout the whole period (Figure 4).

Several data subsets were created for the analysis. The full dataset contains 14 191 hauls with haul duration between 30 and 600 min and haul depth between 200 and 1100 m. The spawn subset consisted of hauls during the spawning season (when blue ling aggregate, March–May, $n = 3761$). The rest (for resting) subset consisted of hauls outside the spawning season (so March–May were excluded, $n = 10 430$). Finally, several blue ling bycatch data subsets were created by selecting hauls where blue ling was not a target species, corresponding to hauls with less than 20, 30, 40, or 50% of total landings attributable to blue ling ($n = 11 119$ for the 50% threshold).

Fishing area definition was based on ICES (2006), in which reference fishing grounds exploited since the 1990s were defined in ICES Subareas V, VI, and VII (ref5, ref6, and ref7, respectively),

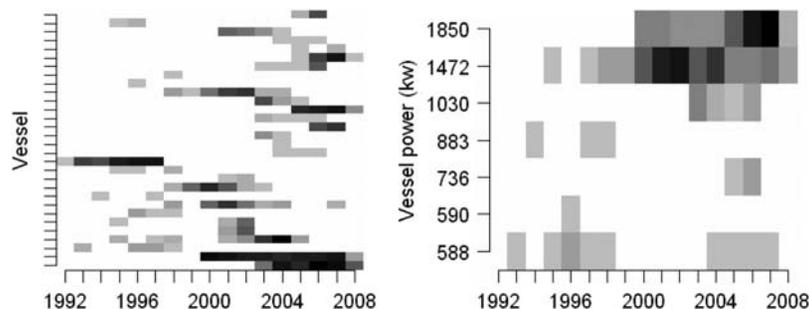


Figure 4. Number of hauls in tallybooks by (left) vessel (range 2–756 hauls) and (right) vessel power category (range: 9–2424 hauls). Grey scale from low (light) to high (dark) numbers.

and new fishing grounds exploited in the 2000s were defined in Subareas V and VI (new5 and new6, respectively). Additionally, ref6 was further split between statistical rectangles from the slope to the west of Scotland, along the Rockall Trough, here referred to as edge6, and other rectangles, referred to here as other6 (Figure 1a). The number of hauls per fishing area for the full dataset is shown in Figure 1b. Most hauls in the DWTB database come from the edge6 area.

Modelling

Data on landings or catches are often characterized by a large number of zero observations (Maunder and Punt, 2004), and a common way to handle this problem in standardization is to use the delta-approach in which presence-absence and quantity when present are modelled separately (Stefánsson, 1996). Zero and non-zero observations can be modelled together, but this approach has been used less frequently. In certain cases, the Poisson distribution (Dobby *et al.*, 2008) or the inflated Poisson is an option (Maunder and Punt, 2004). The Tweedie distribution offers a family of distributions with the Poisson distribution as a special case and Poisson-Gamma mixtures as another. In the latter case, it has a positive mass at zero and a continuous Gamma distribution for positive values.

For the creation of *lpue* indices per area, GAMs were fitted to the blue ling landings per haul for each data subset. All models included (i) a smooth term of haul duration, (ii) an interaction for year and area (i.e. a different year effect was fitted per area with no general year or area effect), (iii) depth as a smooth function, (iv) a factor for vessel identity, and (v) a factor for statistical rectangle.

The models had the form

$$\log(E[\text{landings}]) = s(\text{haul duration}) + s(\text{depth}) + \text{vessel.id} \\ + \text{rectangle} + \text{year:Area}, \quad (1)$$

where $E[\cdot]$ denotes the expected value, $s(\cdot)$ indicates a smooth non-linear function (cubic regression spline), vessel.id the vessel identity, and year:area is an interaction term. All models were fitted assuming a Tweedie distribution of the dependent variable with a log-link function, using the mgcv package in R (Wood, 2006). The Tweedie distribution has mean μ and variance $\varphi\mu^p$, where φ is a dispersion parameter and p is called the index. As we used a Poisson-Gamma compound distribution, $1 < p < 2$, the index p could not be estimated simultaneously with the model parameters, so a detailed study was carried out for the bycatch subset. Subsequently, $p = 1.3$ was fixed for all analyses. Model fit and assumptions were judged by visual inspection of residual plots.

To obtain predictions on the scale of the landings (not the log-scale) for each area and year, predictions were carried out for a given rectangle in the first month of the data subset (January or March), a haul duration of 300 min at 700 m depth, and a vessel that fished in most areas and during the whole study period. Given this selection, model predictions in each area were relative, not absolute, so for each area, the annual *lpue* estimates were standardized by dividing them by the predicted value for the first year. Confidence intervals for these predictions were obtained assuming normal distributions.

Other indicators of population dynamics

In some situations, *lpue* values may not track the actual stock abundance trend. Therefore, other indicators need to be used to complement the diagnostics derived from *lpue*. Mean length is one such indicator, the changes of which are caused by variations in fishing mortality, recruitment, and growth (Trenkel *et al.*, 2007). The consistency of trends in *lpue* and mean length of the landings was checked.

Results

For the DWTB database to represent the area exploited by the fishery, there should be data available for all rectangles in which blue ling were caught. The five areas for which we estimated standardized *lpue* (see below) totalled 50 rectangles. According to EC logbooks, the number of rectangles in which blue ling was caught by French trawlers in the years 2000–2008 ranged from 36 to 49. Tallybook data were available for 80–100% of those rectangles, except the year 2000, for which only 75% of rectangles were represented in the DWTB database. The DWTB included hauls in ICES rectangles where blue ling was not caught, in particular along the slope southwest of Ireland. The area where blue ling was caught remained the same (Figure 5; not all years shown).

Raw tallybook indices

Raw averages of catch rates may be misleading because blue ling are found only within a certain depth range, and probably within other habitat ranges more restricted than those fished by high-sea trawlers. Separate estimation of the proportion of hauls with blue ling (positive hauls) and the catch rate in positive hauls may provide a better representation of blue ling abundance in its habitat. The proportion of positive hauls displayed similar trends for the full, rest, and bycatch datasets (Figure 6). In particular, area edge6 showed an increasing proportion of hauls catching blue ling, from ~20% in 1993 to ~80% in the years 2006–2008. The trend was mainly stable, but it increased slightly in area other6 for the spawn and bycatch datasets. There was no trend in the new grounds in V and VI (new5 and new6), where the proportion of hauls with blue ling has been close to unity in all years. The trend observed in area ref7 may not be reliable because it is based upon a small number of hauls. The proportion of positive hauls during the spawning season (Figure 6c, left) was high, and virtually stable over time.

The highest raw *lpue* values for positive hauls (Figure 6, right) were in new fishing grounds (new5, new6) in some of the years. Interannual variations were large in those areas, probably as a result of the small number of hauls in some years. Raw positive *lpue* values showed increasing trends in area edge6 for the full and rest datasets, but no clear trend for the spawn and bycatch data subsets. Bycatch *lpue* values were much lower than for any other data subset. The bycatch data subset includes roughly half of the total number of hauls of the full dataset, and more than the spawn subset. High bycatch *lpue* observed in new5 and new6 should be regarded with caution owing to small haul numbers in that year. In other6, the 2007 value was the highest in the time-series (1992–2008) and was derived from >500 hauls. There was no clear trend for any other area/dataset.

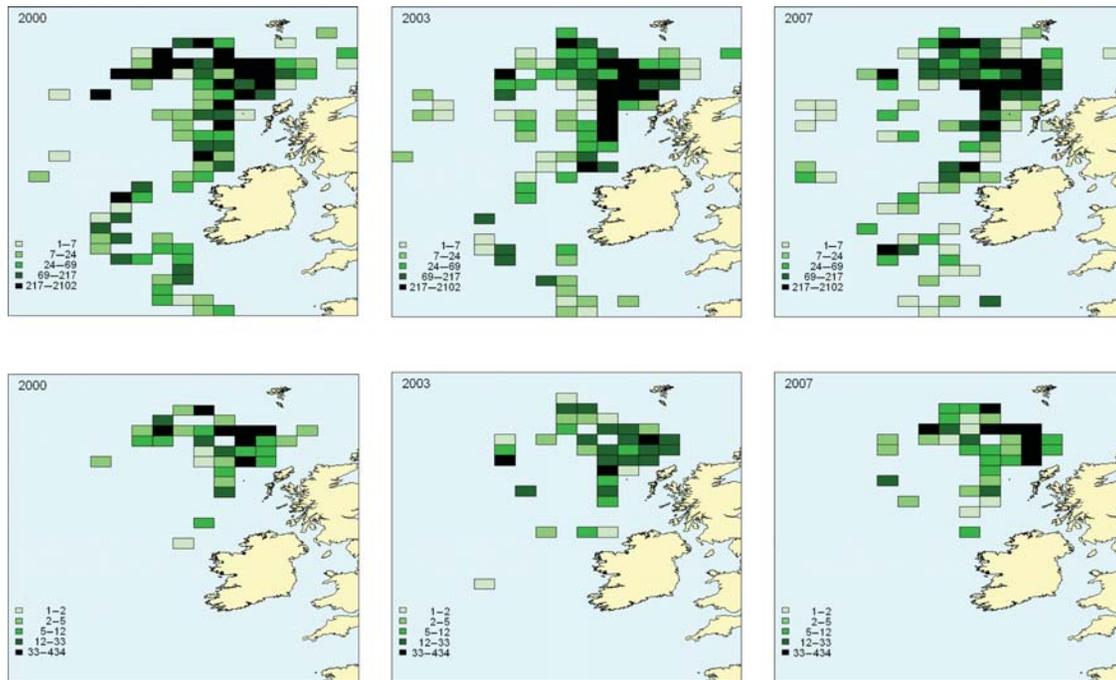


Figure 5. Distribution of total effort (top, h fishing) and blue ling catch (bottom, t) reported in the tallybook database in 2000, 2003, and 2007.

Standardized lpue

Standardized lpue could not be estimated for area ref7, because of the small number of hauls. In the five other areas, all explanatory factors were significant ($p < 0.001$) for the full dataset, and all subsets and models explained $\sim 50\%$ of the deviance in all cases. Landings increased nearly linearly with haul duration, generally increasing with depth down to about 350 m, then fluctuated without trend (results not shown). Residual diagnostics showed that all model fits were satisfactory.

Predicted trends in standardized lpue varied over datasets and areas (Figure 7a–d). The full and rest datasets displayed similar patterns over time, with peaks and troughs in predicted lpue in the same years. The spawn and rest data subsets are non-overlapping, and together make up the full dataset. As there were more hauls in the rest subset, the trend for the full data was mainly driven by hauls from the rest subset. Hence, the similarity between the predictions of the two datasets is unsurprising. The spawn and the bycatch subsets had similar time-trends to the other two datasets for areas new5 and other6, and somewhat distinct trends for the other three areas. The bycatch subset showed stability over time in areas edge6, other 6, and ref5, and an increasing trend in new5 and new6.

In area edge6, there was no clear trend over time in the rest and bycatch subsets, whereas declining trends with time were apparent from the spawn and full datasets. In area new5, the full dataset and all subsets showed a more or less steady increase after the lowest values, in 2001. In contrast, in area new6, the four sets showed different patterns. The predictions were more consistent for area other6, with high levels in 2000 and 2003 and a low level in 2002, but overall there was no clear trend. In area ref5, the predicted lpue values had wide confidence intervals during the spawning season, owing to the small number of hauls. For the other datasets, there were no clear trends in predictions over time.

Overall, the results suggested an increasing trend in lpue in area new5 over the period 2000–2008, and no clear trends in the other areas. The trends from the spawn subset differed from the two other subsets and the full dataset for most areas except new5. There was little consistency in the years of high and low lpue across areas, which might indicate a metapopulation structure of the blue ling stock. On the other hand, high values of lpue appeared in 2003 at least in edge6, new6, and other6, and could suggest the existence of a single population.

The results for the bycatch subset presented above were obtained assuming a threshold value of $< 50\%$ blue ling in total landings. The sensitivity to the threshold value was tested by varying it from 50 (Figure 7d) to 20% (Figure 7e). The trends in most areas were insensitive to the change downwards. For area ref5, the trend was a decreasing one when the threshold was lowered. Note that at a threshold of 20%, the number of hauls was very small.

Other indicators

The mean length of the French landings in 1984 was about 100 cm, reduced by ~ 10 cm by 1995 and stable since (Figure 3b).

Discussion

Statistical modelling of the tallybook data allowed trends in blue ling lpue to be evaluated. This was achieved by combining information on the proportion of positive hauls and the lpue of positive hauls, and taking account of the changes in fishing strategy over time in different areas. Without modelling, the lpue values by haul were calculated by dividing landings by haul duration. For the two most fished areas, edge6 and other6, there was an increase in the proportion of positive hauls over time. This proportion was always close to 1 in ref5, new5, and new6; data were insufficient to comment in ref7. The average lpue values for positive hauls

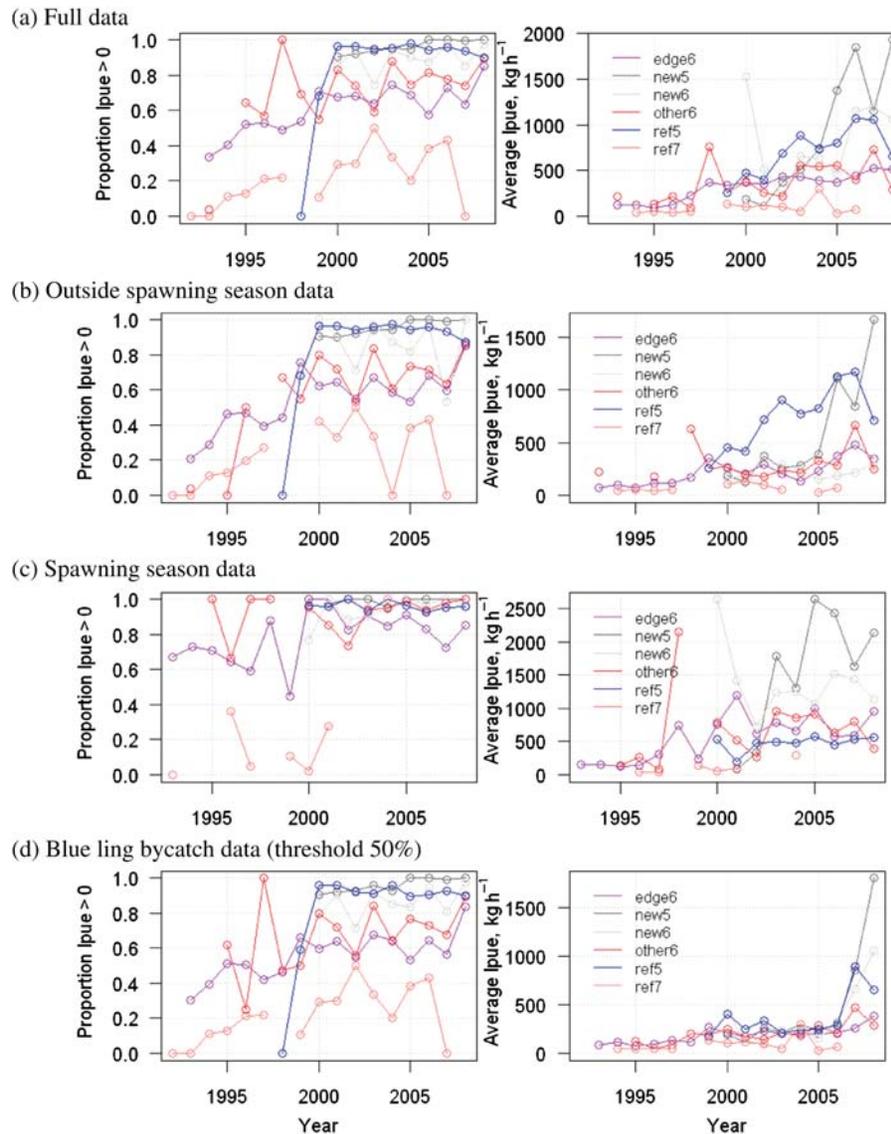


Figure 6. (Left) Proportion of positive (blue ling catch > 0) hauls and (right) average blue ling lpue for positive hauls for the different datasets.

showed consistent increases over time in all datasets. The model applied to each dataset accounted for (i) a non-linear effect of depth, (ii) a vessel factor effect, and (iii) a rectangle factor effect. Increasing trends from the raw lpue were not found consistently in the modelled lpue values across data subsets in all five areas, except new5. Therefore, the trends in the raw lpue might be primarily attributable to changes in fishing strategy accounted for by variables (i)–(iii) in the models.

The bycatch subset might be the most reliable in terms of assessing variations in blue ling density. As blue ling aggregate to spawn, using lpue values from the spawning season as abundance indices might lead to biased estimates. Problems with lpue values of aggregating species are well known (Hilborn and Walters, 1992; Maunder and Punt, 2004). Blue ling targeting might also have been impacted by the development of deeper water fishing and regulations. Our lpue model accounts for this, by including terms for fishing rectangle and depth. However, lpue values based upon the bycatch subset might be less sensitive to fishing strategy effects.

Although blue ling in the study area are thought to comprise a single population unit, our study showed different trends in abundance in the five areas, although they shared such common features as the high values in 2003. It is unclear whether differences in trends between areas are related to bio-ecological factors, to the effects of fishing, or to a combination of both. High values in the same years might reflect population connectivity, whereas different trends across areas might reflect the effect of fishing or spatial heterogeneity in population dynamics.

As the aggregated lpue decreased (Figure 3a), and also because of the risk of local depletion (ICES, 2008), it was judged precautionary to restrict the fishery for blue ling. One case of depletion of a blue ling spawning aggregation has been reported south of Iceland (Magnússon and Magnússon, 1995). Our study shows no sign of local depletion over the period 2000–2008: (i) standardized lpue values were stable in edge6, which is the area most intensively fished; (ii) new fishing grounds (new5 and new6) started to be exploited by the French fleet in the 2000s, but blue ling continued to be fished in previously exploited areas ref5,

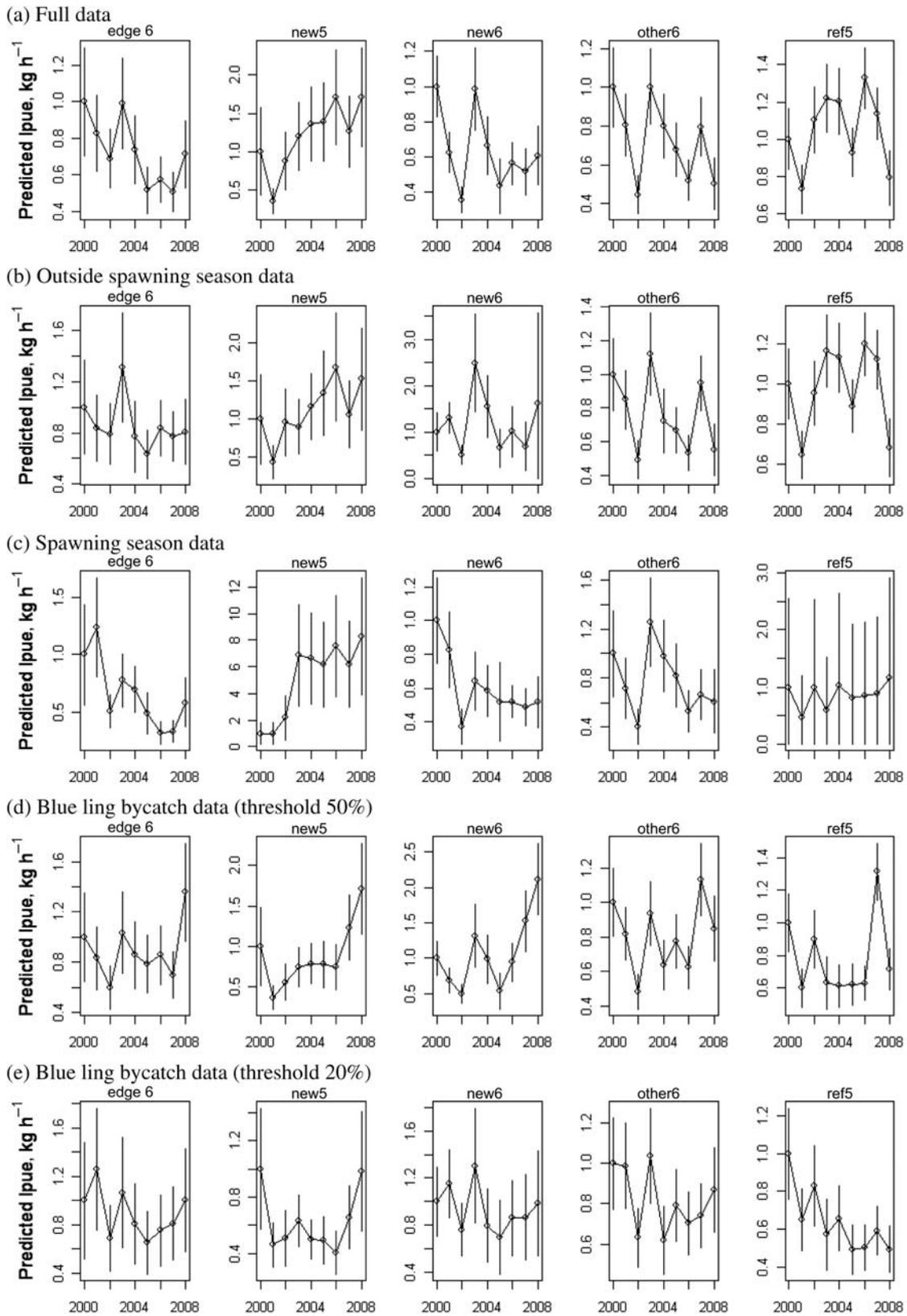


Figure 7. Predicted standardized relative blue ling $Ipue$ per dataset and area. Predictions are made for one vessel in January [March for (c)], 300 min fishing time, and 700 m depth.

edge6, and other6; and (iii) the distribution of catches per rectangle does not indicate a shift in the underlying distribution of blue ling. Therefore, if there was local depletion, it might have been at a scale spatially smaller than the size of statistical rectangles, because catches continued to be obtained from all rectangles fished.

The present work does not contradict the consensus view that the blue ling stock has declined since the 1980s. The decline of catches in Icelandic waters, the Norwegian Sea, the North Sea, and the Skagerrak in the late 1980s and early 1990s (ICES, 2008) is sufficient evidence that stocks were overfished. However, our analysis of blue ling in Division Vb and Subareas VI and VII in recent years shows that this decline is not continuing. Using the bycatch subset, standardized lpue values were stable in three areas and increasing in the other two. Compared with other deep-water species, the gadoid-like life history of blue ling might allow them to react more quickly to changes in fishing mortality. Blue ling catches are no longer driven by fleet capacity and strategy, but capped by a TAC. Management by TAC might be efficient for a species whose largest catches come from targeted hauls. Under TAC management with restricted landings per fishing trip, vessels may no longer fish at locations where they used to target the species and have high catch rates.

Past assessments of the blue ling stock have used aggregated lpue from EC logbooks of a reference French fleet (Figure 3a), which showed a declining trend in the early part and stability in recent years. Length distributions of the landings (Figure 3b) have rarely been used for assessment purposes. The mean length at the start of the time-series (1984) was similar to that during exploratory cruises made in 1973 and 1974, i.e. at the onset of major exploitation (Bridger, 1978). This suggests that in 1984 the fishery was still fishing unexploited grounds with a pristine size distribution. After that, exploitation reduced the mean length by 10 cm, i.e. ~10%, which is a moderate decline. Note that, unlike many shelf stocks, immature blue ling are not caught because they are not found on the fishing grounds. Discards do not occur, at least not to any significant level (ICES, 2008), so the mean length of the landings is virtually equivalent to the mean length of the catch.

The purpose of management of deep-water fisheries since 2000, including that for blue ling, has been to halt overexploitation. Assessments of deep-water stocks have been undermined by several sources of uncertainty, short time-series, and the perceived notion of a “one-way trip” in which only a monotonic harvest rate increase coupled with a decrease in abundance was observed. Such a situation is assumed to provide little information on population dynamics, although this is not always the case (Magnusson and Hilborn, 2007). Starting from levels of overexploitation (ICES, 2008), management now faces difficulty in detecting changes in stock status over time.

This work has provided a basis for developing abundance indices of blue ling in ICES subareas VI and VII and Division Vb. Whether or not the decline of blue ling abundance in these areas has stabilized through implementation of management measures can only be confirmed by analysis of future data. The reliability of an index of lpue for blue ling taken as bycatch will become essential, because fishing on spawning aggregations has been so regulated from 2009 that a component of the past fishery will disappear.

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