ICES Journal of
Marine Science

ICES Journal of Marine Science (2020), doi:10.1093/icesjms/fsaa051

The use and performance of survey-based pre-recruit abundance indices for possible inclusion in stock assessments of coastal-dependent species

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Le Pape, O., Vermard, Y., Guitton, J., Brown, E. J., van de Wolfshaar, K. E., Lipcius, R. N., Støttrup, J. G. , and Rose, K. A. The use and performance of survey-based pre-recruit abundance indices for possible inclusion in stock assessments of coastal-dependent species. – ICES Journal of Marine Science, doi:10.1093/icesjms/fsaa051.

Received 29 April 2019; revised 4 March 2020; accepted 5 March 2020.

We reviewed the use of survey-based pre-recruit abundance indices in short-term recruitment forecasts for fish species relying on coastal habitats at the juvenile stage and that are assessed by ICES. We collated information from stock assessment reports and from a questionnaire filled out by the stock assessors. Among the 78 stocks with juvenile coastal dependence, 49 use short-term forecasts in stock assessment. Survey-based pre-recruit abundance indices were available for 35 of these stocks, but only 14 were used to forecast recruitment. The questionnaire indicated that the limited use of survey-based pre-recruit abundance indices was primarily due to sampling inefficiency, which may preclude reliable recruitment estimates. The sampling is inefficient because the juvenile coastal distribution is outside the geographical area covered by large-scale surveys or targeted coastal surveys are conducted on limited spatial and temporal scales. However, our analysis of the relationship between survey-based pre-recruit indices and assessment-generated recruitment indices revealed that survey-based pre-recruit abundance indices were sufficiently accurate to provide useful information for predicting future recruitment. We recommend expansion of the use of survey-based indices of pre-recruit abundance in stock assessment and recruitment forecasting, and consideration of how to include juveniles in ongoing and future surveys.

Keywords: coastal nursery, forecast, juvenile habitat, recruitment, stock assessment, survey

Introduction

Recruitment variability of many marine and coastal fish species is the main driver of fluctuations in population abundance and critically depends on the highly variable mortality rates of early life stages (Levin and Stunz, 2005; Juanes, 2007; Archambault *et al.*, 2014). Forecasting future recruitment has long been a focus of fisheries management (Hilborn and Walters, 1992; Needle, 2001) and continues to be an essential part of evaluating fishery management strategies (Kimoto *et al.*, 2007; Stige *et al.*, 2013; Punt, 2019). Stochastic processes that occur at the egg and larval stages generate high mortality rates (typically 99.9% for eggs and larvae; Le Pape and Bonhommeau, 2015), which can also be density dependent and can vary greatly from year to year, thereby generating large fluctuations in recruitment (Houde, 2008; Cury *et al.*, 2014; Szuwalski *et al.*, 2015). Accordingly, egg and larval abundances estimated from ichthyoplankton surveys are often poorly correlated to future recruitment success. In contrast, after a "critical" stage or size (Cowan *et al.*, 2000; Dingsor *et al.*, 2007; Houde, 2008), juvenile fish experience considerably lower and more consistent mortality rates than eggs and larvae. Abundance, whether absolute or relative (index), can be estimated during the juvenile stage for many species (Le Pape and Bonhommeau, 2015), without major discrepancies arising from the highly variable mortality rates typical of earlier life stages. In stock assessment, pre-recruitment is considered the life stage after the transition from the highly variable early stages (eggs, larvae, and often early juveniles) to when natural mortality is largely stable (Lorenzen and Camp, 2019) but before individuals fully join the adult stock. Survey-based pre-recruit abundance indices could therefore provide reliable information on recruitment and future year-class strength (Helle *et al.*, 2000; Zhang *et al.*, 2010; Stige *et al.*, 2013).

Indices estimating pre-recruit abundance can provide projections of recruitment and can inform fisheries management, especially for stocks whose exploitation is highly dependent on the juvenile stage. Such stocks depend on recruitment for determining harvest, either due to their biology (short-lived species, like small pelagics) or because high exploitation rates reduce the age of the fish harvested. For example, high exploitation rates of Atlantic cod *Gadus morhua* in the North Sea during the last 5 years (2012–2016) of the assessment resulted in immature fish constituting an average of 71% of the international landings in number (ICES, 2017c).

Coastal zones are biologically productive areas that serve as juvenile habitat for numerous marine species (Beck *et al.*, 2001). For example, considering the species for which ICES provides advice, one-third is dependent on coastal habitats during their juvenile stage (Seitz *et al.*, 2014) and these species account for 66% of the total landings of ICES-evaluated stocks (Brown *et al.*, 2018a). Scientific surveys at the population scale are usually designed to estimate density and age structure of post-recruited fish. Many surveys focus on post-recruitment fish for specific management purposes and, therefore, are not designed nor appropriate for estimating pre-recruit abundance. In addition, such post-recruitment surveys most often do not provide adequate coverage of coastal habitat on which juveniles rely (Ralph and Lipcius, 2014). When juveniles aggregate in coastal areas, survey designs that cover suitable shallow coastal habitats are required to produce reliable estimates of pre-recruit density. The timing within the year of the surveys is also important to give sufficient time for the recruits to settle in the juvenile habitats and to pass the early juveniles stages that incur highly variable survival (van der Veer, 1986; Wennhage, 2002; Nash *et al.*, 2007). Surveys designed for other purposes may not cover the time period that is optimal for estimating recruitment from pre-recruits. Even when the surveys focus on juveniles before recruitment, they tend to be spatially localized, thereby creating challenges to extrapolate the results to the broader spatial domain of the managed stock. A valid reason for why surveys are not used to generate pre-recruit indicators is simply that the surveys were well designed for other purposes and provide insufficient coverage of the spatial and temporal scales of the juveniles (Albert *et al.*, 2001; Ralph and Lipcius, 2014).

This article focuses on the use of survey-based pre-recruit abundance indices and the degree of agreement between survey-based and stock assessment estimates of annual recruitment for species with juvenile coastal dependence. Accurate short-term forecasts of recruitment could improve the management advice in the stock assessment of species with juvenile coastal dependence. We focused on those ICES-assessed species whose juveniles rely on coastal habitats (see definitions in Seitz *et al.*, 2014) and reviewed the use of survey-based pre-recruit abundance indices for short-term forecasts. For all ICES-assessed stocks whose juveniles use coastal habitats, we collated information from stock assessment reports and from a complementary questionnaire, which we designed for completion by the lead fisheries scientist for each stock assessment. The goals of our analysis were to: (i) assess the frequency of the use of survey-based pre-recruit abundance indices in recruitment forecasts in the framework of ICES stock assessment working groups (WGs); (ii) identify factors that influence when survey-based pre-recruit abundance indices are used; (iii) determine the level of accuracy (agreement with stock assessment estimates) when survey-based pre-recruit abundance indices are used to indicate recruitment; and (iv) suggest possible factors that influence the accuracy of the survey-based estimates. Our focus was on goals (i) and (iii) because we had relatively high confidence in the underlying information, and they provide important results about the frequency of use of pre-recruit surveys and their overall performance. The reliability of information to achieve goals (ii) and (iv) was uncertain, as it is difficult to judge a survey programme for generating pre-recruit information when the survey was designed for other purposes (goal ii) and our sample size of surveys was too small for assessing which factors influence accuracy (goal iv).

Methods

Data collection

Of the 61 species for which ICES carried out stock assessments in 2017 and 2018, 18 species (Table 1) had juveniles with coastal dependence (Seitz *et al.*, 2014). These 18 species encompass 78 distinct stocks. Information about the use of survey-based pre-recruit abundance indices for these ICES-assessed 78 stocks was collated. The information came from the ICES stock assessment WG reports (ICES, 2017a, b, c; ICES, 2018a, b, c, d, e, f), and the questionnaire completed by the lead fisheries scientists in charge of each stock assessment. The ICES WG reports, questionnaire responses, and follow-up communications with WG members provided the following information on the 78 stocks that rely on coastal habitat:

(i) ICES data-limited stocks (DLS) category (ICES, 2012). The categories spanned from DLS category 1 (data-rich stocks with quantitative assessments) to DLS category 3 (stocks for which survey-based assessments indicate trends) to DLS categories 4–6 (data-poor stocks without quantitative assessments).

(ii) Whether pre-recruit surveys were used for short-term estimation and prediction of recruitment. In ICES stock assessment WG terminology, recruitment estimation means projecting the youngest assessed year-class strength for years y and $y + 1$. The term recruitment prediction is used in WGs to calculate total allowable catch (TAC) advice when recruitment is projected 2 years ahead. In the present

Table 1. The 18 species assessed by ICES in 2017–2018 whose juveniles rely on coastal habitats, and their general vertical habitat use [after Seitz *et al.* (2014) and updated in Brown *et al.* (2018a)].

Species	Vertical position
Ammodytes	Demersal
Anguilla anguilla	Demersal
Clupea harengus	Pelagic
Dicentrarchus labrax	Demersal
Engraulis encrasicolus	Pelagic
Gadus morhua	Demersal
Limanda limanda	Benthic
Merlangius merlangus	Demersal
Mullus surmuletus	Demersal
Platichthys flesus	Benthic
Pleuronectes platessa	Benthic
Pollachius pollachius	Demersal
Pollachius virens	Demersal
Psetta maxima (historic name)	Benthic
Scomber scombrus	Pelagic
Scophthalmus rhombus	Benthic
Solea solea	Benthic
Sprattus sprattus	Pelagic

analysis, we pooled these two situations and considered the use of pre-recruit surveys both for recruitment estimation or prediction (hereafter called "short-term forecasts of recruitment"). Performing recruitment estimation is the minimum required and is mandatory for DLS category 1 but is highly unusual for the other categories.

(iii) Availability of survey-based abundance estimates for pre-recruits. The expertise of the lead fishery scientist involved with the assessment was the key source for these estimates. Indeed, WG reports only mention survey-based abundance indices when used in stock assessment. When they are not accounted for, expertise is the only means to investigate whether such indices exist.

(iv) When used, how were the short-term survey-based pre-recruit abundance indicators combined with the stock assessment? Survey-based pre-recruit abundance indices are typically used in two ways in ICES stock assessments: (i) *post hoc* short-term forecasts of year-class strength by calibration–regression analysis of recruit index series (e.g. RCT3; Shepherd, 1997) and then used to account for future recruitment after a matrix model-based stock assessment is completed [e.g. extended survivors analysis (XSA); Shepherd, 1999]; or (ii) state-space modelling [e.g. state-space assessment model (SAM); Nielsen and Berg, 2014] that integrates the survey-based pre-recruit abundance indices directly into a stock assessment. We analysed both uses of survey indices.

When survey-based pre-recruit abundance was available as an index [positive response to item (iii) above], additional information was collated for that subset of stocks:

(v) Sampling gear (i.e. acoustic, trawl, or net) used in the survey to derive the pre-recruit index.

(vi) Spatial scale of the survey as one of the four possibilities: (i) stock scale that included juvenile habitats; (ii) stock scale that did not include juvenile habitats; (iii) stock spatial distribution partially covered with the area covered including juvenile habitats; and (iv) stock distribution partially covered and juvenile habitats not sampled.

(vii) Average number of samples in the annual survey.

(viii) Age group represented in the survey-based recruitment estimate and the youngest age group included in the stock assessment.

Finally, when responses indicated that a stock assessment included short-term forecasts of recruitment and a pre-recruit survey was available but not used to forecast recruitment:

(ix) The fisheries scientist for that stock assessment was asked why the survey was not used. Four possible responses were offered in the questionnaire: (i) the pre-recruit index time series was incomplete; (ii) the pre-recruit survey was carried out too late in the year to be available for the ICES stock assessment WG; (iii) the potential use of the survey-based pre-recruit abundance indices had not been evaluated; or (iv) pre-recruit survey-based indices were investigated (e.g. during the benchmark procedure), but a decision was made to exclude them from analysis.

Analysis: Availability and use of survey-based pre-recruit abundance indices for short-term forecasting in assessment

The frequency of the use of short-term forecasts of recruitment in stock assessment and the availability and use of survey-based pre-recruit abundance indices to forecast recruitment were estimated from the WG reports and questionnaires collated for each stock. Starting with the 78 (18 species) ICES-assessed stocks, we categorized these by habitat (demersal, benthic, pelagic). These stocks were further subdivided into those that used short-term forecasts in their assessments and either did or did not use available pre-recruit survey-based indices. For the subset of stocks that did not use the survey-based pre-recruit indices, the reasons for disuse by the WG assessors were noted. Another subset of stocks, which relied on short-term recruitment forecasts and also used pre-recruit survey results to generate short-term forecasts, was further analysed for accuracy of the survey-based predictions.

Analysis: Accuracy of survey-based pre-recruit abundance indices to forecast recruitment

Time series of survey-based recruitment predictions were obtained from ICES WG reports for each of the stocks that used survey-based pre-recruit indices for forecasting short-term recruitment in the assessment (ICES, 2017a, b, c; ICES, 2018a, b, c, d, e, f). For these stocks, time series of model-based recruitment short-term forecasts were obtained from the ICES database (ICES, 2018g). Complementary analyses were performed to assess the potential for autocorrelation between survey-based and model-based short-term forecasts of recruitment, because for some stocks, the survey was also used within the assessment. When survey-based pre-recruit abundance indices were not used in the stock assessment modelling, but rather to make short-term forecasts post-assessment, the survey-based and stock assessment-based indices were inherently independent and could be directly compared. However, when the survey-based pre-recruit abundance indices were used within the stock assessment, they influenced the assessment-based recruitment indices and could result in artificial agreement between the two short-term forecasts of recruitment because they were no longer independent.

Two alternative options were used to reduce or to remove this potential for artificial agreement between the two short-term forecasts (survey and assessment) of recruitment: (i) elimination of the last 2 years from the analysis and (ii) rerun of the stock assessment without the survey index included to generate assessment-based recruitment not influenced by the survey results:

(i) The influence of survey results on assessment-generated estimates of recruitment can be significant, especially for the last years in a stock assessment (Hilborn and Walters, 1992). The influence of the survey results diminishes over time, as other sources of information in the stock assessment (e.g. catch-at-age and survey data on the older ages) inform the estimated recruitment values. To partially account for dependence between the survey- and model-based estimates, we eliminated the last 2 years of recruitment estimates for those stocks that used the survey-derived estimates as a part of their stock assessment modelling. This elimination was done either manually or because the last 2 years were dropped when matching the two recruitment indices (i.e. there were no survey estimates available to match recruitment for the last 2 years of the assessment). To test the robustness of these modelling options, we employed two methods, both of which focus on the accuracy of the correlation results from stocks that used survey indices in their assessments: the first was a comparison between the four stocks with independent survey and assessment estimates of recruitment and the remaining ten stocks that included the survey index in their assessment. The second was a windowing approach to compute correlations between survey and assessment estimates of recruitment to assess the influence of the last years in correlations (see details in Supplementary Material S2).

(ii) The best way to address this potential for artificial agreement is to rerun the stock assessments without the survey-derived indices and then compare the new assessment-based estimated recruitments with the, now independent, survey-derived estimates of recruitment. Such an approach is obviously the most attractive in theory, but each assessment varies among the different stocks and cannot been tuned from the ICES database without the expertise of the stock assessment WG. To do so, the fisheries scientists in charge of these stock assessments were asked to rerun the stock assessments without the survey-derived indices and some of them kindly did so. These new time series of model-based recruitment were collated and used separately from the potentially correlated estimates in analyses. This subset of comparisons allowed us to evaluate the robustness of results based on the potentially correlated estimates. For standardization purpose, we also eliminated the last 2 years of the recruitment estimates from these series, either manually or naturally.

To assess the accuracy of the survey-based predictions of recruitment compared to assessment-based estimates, we computed the Pearson correlation coefficient (r) between the survey-based recruitment estimates and the stock assessment model-based abundance for the youngest year group. This was done for all stocks (r_1, using model-based data from ICES database) and for the subset of stocks that the assessment estimates were independent of the survey (r_2, from stocks whose assessment did not use survey or from re-run assessment models). We assumed that the model-based estimates were a realistic value and thus the closer the correlation of the survey-based prediction to the model-based value, the higher the accuracy of the survey-based value. Because the true value of recruitment is unknown, we refer to this as apparent accuracy. While agreement between the two estimates of recruitment suggests higher confidence in the survey-based estimates, without knowing the true values of recruitment we cannot access whether either is or both are biased.

For the stocks for which correlation coefficient r_1 (model-based data from ICES database) and r_2 (for rerun assessment estimates) were available, we first compared their respective levels to highlight potential lack of independence and caution about the interpretation of r_1. From this preliminary analysis (r_1 vs. r_2 for rerun stocks only), we determined if we would use the r_2 values (truly independent estimates) rather than the r_1 in subsequent analyses.

Another proxy (r_3) was designed to approximate how short-term recruitment forecasts can be used in stock assessments that do not have a source of year-specific short-term forecasts. The geometric mean of the model-based abundances for the youngest year class during the previous 5 years was computed. When year-specific forecasts of recruitment are not used, geometric mean of model-based recruitment estimates is frequently used in forecasting for ICES stock assessments. To estimate the improvement of the forecast linked to the use of survey-based pre-recruit abundance indices, r_1 or r_2 and r_3 were compared. We used a one-way analysis of variance, after an arcsine transformation, to compare r_1 or r_2 to r_3 values. The arcsine transformation is appropriate to normalize the data from the original $[-1,1]$ distribution of correlation coefficients (Sokal and Rohlf, 1995). A higher value of r_1 or r_2 (for the survey-based estimates) compared to r_3 (geometric mean of the assessment-based estimates) indicates that survey estimates agree with assessment values better than average recruitment agrees with the assessment values. In this way, r_3 is an approximate proxy of the contribution of survey-based pre-recruit indices to estimate future recruitment over and above the use of a 5-year average.

We explored whether various factors influenced the magnitude of r_1 or r_2, including species vertical guild (Table 1), sampling gear, scale of the survey, number of samples in the survey, age group in the survey-based pre-recruit abundance indices, youngest age group in the stock assessment, difference between these two ages, and length of the time series.

Results

Stocks of coastal dependent species

ICES performed stock assessments for 185 stocks in 2017–2018 that spanned 61 species. Eighteen of these species (30%), which involved 78 stocks (42%), depend on coastal juvenile habitat (Table 2; Supplementary Table S1). These 78 stocks are widespread in the North East Atlantic (from Iberian waters to Greenland in latitude and from the North Sea to Greenland in longitude) and in the Baltic Sea (Supplementary Table S1). The habitat use of these species and stocks with juvenile coastal dependence were: demersal (9 species; 39 stocks), benthic (6 species; 23 stocks), and pelagic (3 species; 16 stocks). Among these 78 stocks, most (87%) were well-assessed stocks (ICES categories 1

Table 2. The number of species and stocks assessed by ICES in 2017–2018 based on progressive sub-setting: coastal dependent, use of short-term recruitment forecasts in assessment, existence of surveys with possible estimate of pre-recruitment, and use of the survey values as the predictor of recruitment in the assessment.

Category	Number of species	Number of stocks
ICES evaluated	*61*	185
& coastally dependent juveniles	*18*	78
& with short-term forecast		49
& with potential existing survey-based pre-recruit indices		35
& using survey-based indices in forecast		14

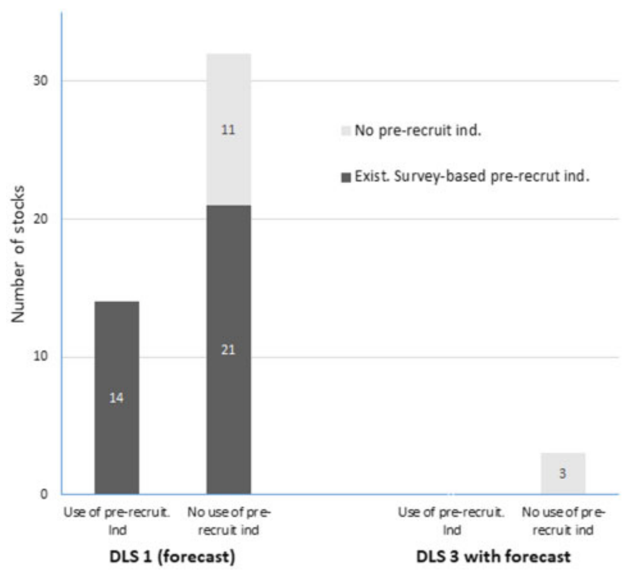

Figure 1. Number of stocks by DLS category that used short-term forecasted recruitment in their assessment, categorized by whether a pre-recruit survey exists or not, and if it exists, whether it was used to predict recruitment. A total of 49 stocks were used that were species that rely on coastal habitats and for which ICES assessments used short-term forecasted recruitment.

and 3), whereas 10% were data-poor stocks, all of which were demersal species (Supplementary Table S1).

Use of recruitment forecasts and pre-recruit surveys in assessment

Among the 78 stocks from species with juvenile coastal dependence, 49 (Table 2) used short-term recruitment forecasts (from any source) in their assessments. Most of these 49 stocks (46) were designated as DLS category 1, with the remaining three stocks being DLS 3. Survey-based pre-recruit abundance indices were available (used and not used in the assessment) for 35 (71%) of these 49 stocks, which were all designated as DLS category 1 (Table 2 and Figure 1). For these 35 (of 78) stocks with both survey-based pre-recruit abundance indices available and that use short-term recruitment forecasts in their assessment (Table 2), the pre-recruit indices were derived mainly (Supplementary Table S1) from trawl surveys for demersal species (12 of 18 stocks) and benthic species (9 of 9 stocks) and from acoustic surveys for pelagic species (5 of 8 stocks).

While survey-based pre-recruit abundance indices were available for 35 of the 49 stocks that generated recruitment forecasts in their assessments, only 14 of these 35 stocks (40%; Table 2; Figure 1) actually used the indices in their assessments. For the majority of stocks (21 of 35), the indices were not used for short-term forecasts of recruitment. The underutilization of survey-based indices was noteworthy for stocks of demersal species (12 of 18 stocks did not use the indices; Supplementary Table S1).

Six stocks with unused indices reported that the available time series were not yet sufficient or because the results would not be available in time for consideration by the WG (Table 3), but the most commonly reported reason for not using the survey-based indices (11 of 21) was that the use of the indices had not been thoroughly evaluated (Table 3; Supplementary Table S1). The remaining four stocks with unused indices had attempted to use the indices, but a decision was made to not use them because the surveys were not designed to estimate pre-recruit abundance in the spatial domain of the stock (Table 3). A partial explanation for not using the survey-based indices when they were sufficient and available (15/21) was that these surveys were not designed to cover both the spatial scale of the stock and/or coastal juvenile habitats (Table 3).

Fourteen stocks used the survey-based pre-recruit indices in their forecasts. These 14 stocks are distributed in the North East Atlantic (from Bay of Biscay to Greenland in latitude and from the North Sea to Greenland in longitude) and in the Baltic Sea (Table 4). For these 14 stocks, seven of the indices were derived from surveys covering both the stock scale and coastal nurseries, four indices were from surveys that partially cover the stock's spatial extent and include coastal nurseries, and three indices were calculated from surveys done at the stock spatial scale but which do not include coastal juvenile habitat (Table 4).

Apparent accuracy of survey-based pre-recruit indices

For 12 of 14 stocks (Table 4), one pre-recruit abundance indices was used in the assessments. These were either derived from a single survey (eight stocks) or were combined into a single recruitment index as part of the assessment by the ICES WG (four stocks, North Sea cod and sole, Irish Sea plaice and Celtic Sea whiting; ICES, 2017c). Two (of 14) stocks used two survey-based pre-recruit abundance indices for short-term forecasting (Table 4): Iceland cod (ICES, 2018c) and North Sea whiting (ICES, 2017c). Our analysis of the relationship between the survey-based pre-recruit abundance indices and the model-based abundance for the youngest year class (r_1 and r_2) considered a single survey-based pre-recruit abundance index of recruitment per stock. For North Sea whiting, the lead fishery scientist (T. Miethe, pers. comm.) for the stock assessment (ICES, 2017c) indicated that the index in Autumn (IBTSQ3) is considered as the reference pre-recruit abundance index. For Iceland cod, we

Table 3. The reasons for rejection, and spatial scale of the survey for the 21 stocks of species that rely on coastal habitats and for which survey-based pre-recruit abundance indices exist but are not presently used in short-term forecasts in ICES assessment.

Reason to reject	Number of stocks	Scale of the survey
Incomplete time series	2	–
Too late to be used	4	–
Not investigated, nor tested	11	Stock scale, not including nurseries (2)Stock distribution partially covered, including coastal nurseries (6)Stock distribution partially covered, not including coastal nurseries (3)
Investigated and rejected	4	Stock distribution partially covered, including coastal nurseries (2)Stock distribution partially covered, not including coastal nurseries (2)

initially analysed both indices separately (surveys SMB and SMH had correlation coefficients of 0.75 and 0.8 with model-based indices, respectively); given the similarity of the results, the SMH index derived from the fall survey was selected (Table 4).

Among these 14 stocks, 4 used survey-based pre-recruit abundance indices only in forecasting and 10 used these indices in both stock assessment and forecasting (Table 4). Of these ten, only five required manual deleting of two recent years. The other five stocks, which used the survey indices in their assessments, had sufficient lag between the age of fish in the survey and the age of recruitment (youngest age) in the assessment. This meant that the two most recent years of recruitment from the stock assessment would not be auto-correlated with their survey index for our comparisons (i.e. "Natural removal", Table 4).

From the ten stocks utilizing survey-based indices in both stock assessment and forecasting, fisheries scientists in charge of assessments agreed to rerun the stock assessments without the survey-derived indices for six stocks (Table 4, r_2 in bold). For these stocks, correlations were higher for r_1 than for r_2 [Table 4, for the six stocks, average difference in Pearson correlation coefficient $r_1 - r_2 = 0.077$ (0, 0.19)]. These patterns confirmed the preliminary tests of robustness on the use of the correlation between the survey-based recruitment estimates and the stock assessment model-based abundance; i.e. low to moderate influence of autocorrelation when the last 2 years of the recruitment estimates are removed (detailed in Supplementary Material S2). These differences indicate a slight overestimation of r_1 through correlation induced by inclusion in the assessment. Hence, we selected r_2 for further analyses, which reduced the number of stocks to ten (four whose assessment did not use the index and six rerun assessments, Table 4).

When used, the survey-based predictions of recruitment (r_2) had a reasonable apparent accuracy (Table 4; Figures 2 and 3). Survey-based pre-recruit abundance indices had significantly higher correlations with the model-based recruitment estimates than the geometric means of the five previous years of model-based abundances (Figure 3; $p < 0.001$, after arcsine transformations of r_2 and r_3). No obvious patterns emerged from the factors (species habitat, survey design, Table 4) that could influence the accuracy of the survey-based pre-recruit abundance indices r_2, although the small size of the data set and many potential influential factors made the identification of associations difficult.

Discussion

We examined ICES-assessed stocks that both utilize coastal areas as juvenile habitat and use survey-based predictions of recruitment in their management assessments. Of the 78 stocks involving 18 species with juvenile coastal dependence, 49 also used short-term forecasts of recruitment in assessments. Most of these stocks (46 of 49) were designated as ICES DLS category 1 stocks. Indeed, short-term forecasts of recruitment are mandatory in the ICES protocol for this category. We analysed the existence and aspects of surveys and derived survey-based pre-recruit indices and how they are presently used in assessments for the 78 stocks, using data collated from WG reports, responses to a questionnaire from the lead fishery scientists for each stock, and communications with lead members of various stock assessment WGs. We sought to explore how surveys are used to generate recruitment indices as part of assessments, possible reasons for their omission, and the accuracy of predicted recruitment from survey-derived values.

The responses to the questionnaire as to why the survey information was available but not used (i.e. survey data on pre-recruit abundance were not used for 21/35 = 60% of the stocks for which they are available) indicated that there are opportunities for the determination of how the survey information, either as is or with some adjustments to the survey design, could be used in assessments. The most common response for why an available survey was not used was that its utility had not been rigorously evaluated, followed by issues of whether enough data were available and that the survey results were not available in time for assessments. These three reasons accounted for why 17 of 21 stocks were not using available surveys to forecast recruitment for assessment and suggested that surveys are available that, with proper evaluation, may be useful for generating recruitment indices.

Fishery-independent surveys are designed to answer specific questions, and their lack of use for other purposes is not indicative of a poorly designed survey. For our proposed use, to forecast recruitment, the coverage of coastal habitats and the effective sampling of pre-recruit juveniles are critical. Both the stocks that did not use surveys to predict recruitment and those that did confirmed the (perhaps obvious) importance of the spatial scales of the surveys. Half of the survey-based pre-recruit indices used in assessments covered both the stock scale and coastal juvenile habitat, while the other half covered either stock scale or juvenile habitats. In contrast, none of the unused survey-based pre-recruit abundance indices covered both the stock scale and the coastal juvenile habitat. 87% of the unused pre-recruit abundance survey-based indices covered only a fraction of the spatial extent of the stock, and 47% did not sample coastal juvenile habitat.

A major challenge for estimating pre-recruit abundance indices from surveys is to account for complex spatial and temporal variations in pre-recruit abundance (Denson *et al.*, 2017; Potts and Rose, 2018). Variation in abundance across successive juvenile stages could be driven by small-scale processes, leading to large spatial discrepancies among juvenile habitats (Scharf, 2000). The

Table 4. Characteristics of the 14 stocks of species relying on coastal habitats at juvenile stage, for which survey-based pre-recruit abundance indices are used in short-term forecasts in ICES stock assessments.

Stock description	Stock code	Area of juvenile survey	Survey name	Method of survey	Nb samples	Age group of the recruitment indices	Youngest age group in the stock assessment	Length of the time series	Assessment method	Incorporated in assessment and not in forecast only	Two last years removed	Value of correlation coefficient (r_1)	Value of correlation coefficient without survey-based index in stock assessment (r_2)
Anchovy (*Engraulis encrasicolus*) in subarea VIII (Bay of Biscay)	ane.27.8	Stock scale, including nurseries	Juvena	Accoustic	80	0	1	15	Specific SAM like	Yes	–	0.7	–
Cod (*Gadus morhua*) in division Va (Iceland grounds)	cod.27.5a	Stock scale, not including nurseries	SMH[a] and (SMB)	Trawl	800	1	3	21	Specific XSA like	No	–	0.8	*0.8*
Cod (*G. morhua*) in NAFO subarea 1, inshore (inshore west Greenland cod)	cod.21.1	Stock											
distribution partially covered, including nurseries	West Greenland inshore gill-net survey	Net	100	1	1	28	SAM	Yes	Manually	0.62			
Cod (*G. morhua*) in subarea IV and divisions VIId and IIIa West (North Sea, Eastern English Channel, Skagerrak)	cod.27.47d20	Stock scale, including nurseries	IBTS–Q1 + IBTS–Q3 combined	Trawl	200	1	1	35	SAM	Yes	Manually	0.91	
Cod (*G. morhua*) in subdivisions 22–24 (Western Baltic Sea)	cod.27.22-24	Stock scale, including nurseries	BITSQ4	Trawl	100	0	1	17	SAM	Yes	Manually	0.89	**0.7**
Herring in subarea IV and divisions IIIa and VIId (North Sea autumn spawners)	her.27.3a47d	Stock scale, including nurseries	IBTS (mik)	Trawl	567	0	0	27	FLSAM	Yes	Manually	0.94	**0.84**
Herring in subdivisions 25–29 (excluding Gulf of Riga) and 32	her.27.25-2932	Stock scale, not including nurseries	BIAS	Accoustic	49	0	1	24	XSA	No	–	0.92	*0.92*
Mackerel in the Northeast Atlantic (combined Southern, Western and North Sea spawning components)	mac.27.nea	Stock scale, including nurseries	IBTS	Trawl	1820	0	0	18	SAM	Yes	Natural	0.64	**0.58**

Continued

Table 4. continued

Stock description	Stock code	Area of juvenile survey	Survey name	Method of survey	Nb samples	Age group of the recruitment indices	Youngest age group in the stock assessment	Length of the time series	Assessment method	Incorporated in assessment and not in forecast only	Two last years removed	Value of correlation coefficient (r_1)	Value of correlation coefficient without survey-based index in stock assessment (r_2)
Plaice in division VIIa (Irish Sea)	ple.27.7a	Stock scale, not including nurseries	BTS combined	Trawl	58	1	1	24	SAM	Yes	Natural	0.67	
Plaice subarea IV (North Sea)	ple.27.420	Stock											
distribution partially covered, including nurseries	UKBTSQ4	Trawl	100	1	1	22	AAP	Yes	Manually	0.77	**0.77**		
Sole in subarea IV (North Sea)	sol.27.4	Stock											
distribution partially covered, including nurseries	DFS combined	Trawl	630	0	1	26	AAP	No	–	0.83	*0.83*		
Sprat in subdivisions 22–32 (Baltic Sea)	spr.27.22-32	Stock scale, including nurseries	BIAS	Accoustic		0	1	23	XSA	No	–	0.85	*0.85*
Whiting in ICES division VIIb, c, e–k	whg.27.7b-ce-k	Stock											
distribution partially covered, including nurseries	IGFS + EVHOE combined indices	Trawl	180	0	0	14	XSA	Yes	Natural	0.79	**0.68**		
Whiting subarea IV (North Sea) and division VIId (Eastern Channel)	whg.27.47d	Stock scale, including nurseries	IBTSQ3[a] and (IBTSQ1)	Trawl	310	1	1[a]	26	XSA	Yes	Natural	0.67	**0.67**

Characteristics shown are: description of the stock, name and information on survey design ([a]: the selected survey indices for the two stocks for which two were available), age of pre-recruit in survey-based abundance indices, youngest age in the associated stock assessment, length of the time series, assessment model used, whether the pre-recruit survey-based indices were used in the stock assessment or only for short-term forecasts, the method to eliminate the last 2 years of the recruitment estimates (either "manually" or "natural, i.e. natural elimination because the last 2 years were dropped when matching the two recruitment indices"), value of the correlation coefficients r_1 and r_2 [r_2: rerun models (in bold) and stocks for which survey indices are not incorporated in the assessment (in italic)]. Please refer to ICES (2017a–c and 2018a–f) for acrnonyms and further description.

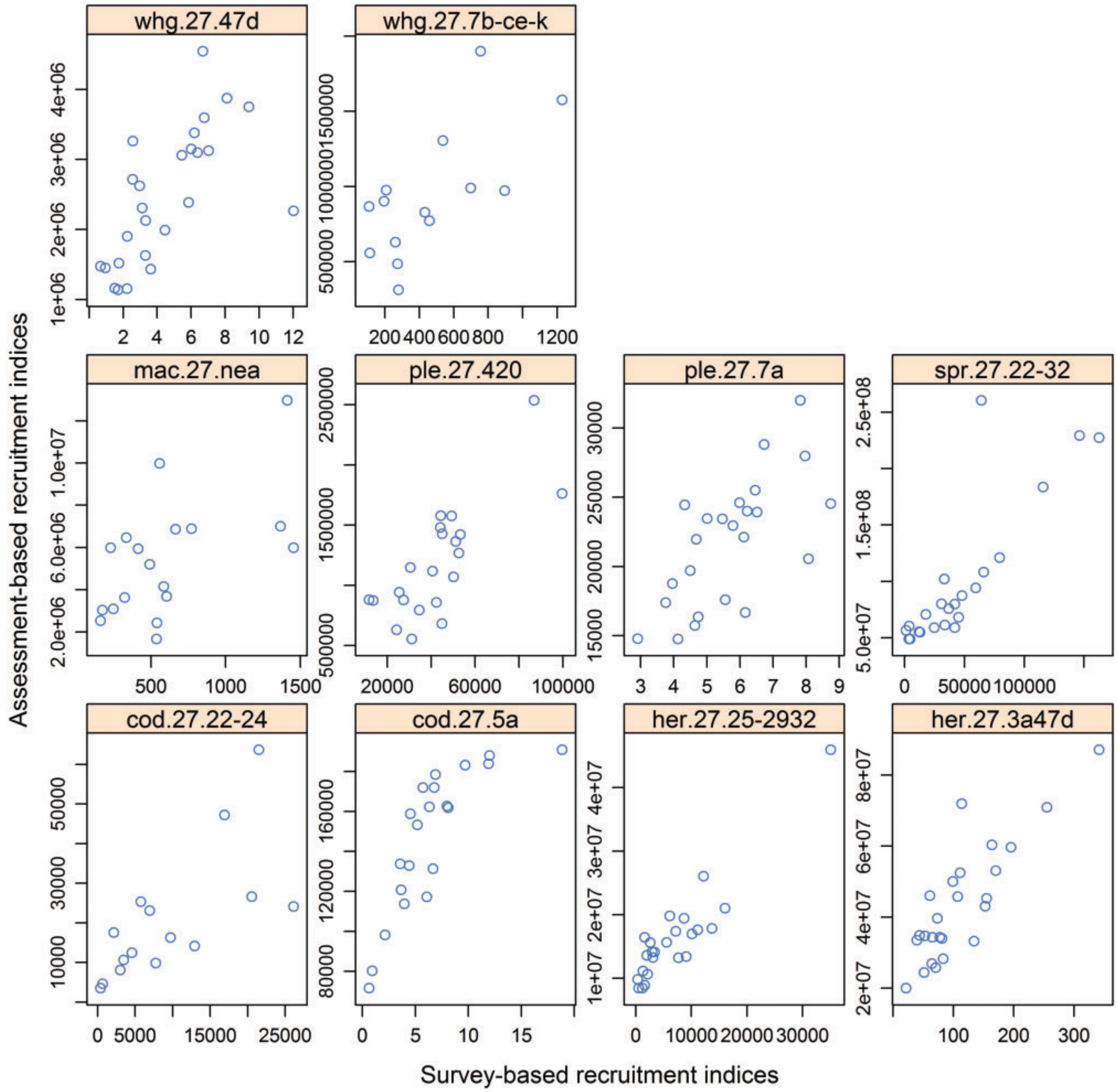

Figure 2. Scatter plot of survey-based (*x*-axis) and assessment-based (*y*-axis) recruitment (both in the unit used in the stock assessment WG) for the 14 coastal-dependent stocks for which survey-based pre-recruit abundance indices are used as short-term forecasts of recruitment in ICES assessments. Stock codes are defined in Table 4.

temporal (including inter-annual) variability in coastal habitat use of juvenile fish suggests that, to estimate recruitment, it is necessary to survey several juvenile habitats (Chittaro *et al.*, 2009). Both juvenile coastal distributions outside the geographical area covered by the surveys and regional patterns in recruitment variability (Denson *et al.*, 2017) may hinder the estimation of reliable recruitment estimates (Albert *et al.*, 2001; Ralph and Lipcius, 2014).

The 17 stocks with available surveys not being used and that have not been evaluated for use would need to be evaluated. The evaluation should consider whether the sampling design can generate sufficiently accurate predictions of recruitment and how easy it would be to maintain present sampling and make minor additions to better cover nursery areas (e.g. add stations in shallow juvenile habitat). Thus, there is an opportunity for further analyses to determine the feasibility and utility of these surveys for also generating short-term forecasts of recruitment, either as they are presently implemented or with minor changes that do not affect the use of the surveys for other purposes.

When survey-based predictions of recruitment were used in assessments, their apparent accuracy was reasonably high. The r_2 values averaged 0.76 across all ten stocks. Such degree of agreement was based on stocks with independent survey and assessment estimates and, therefore, was not influenced by the lack of

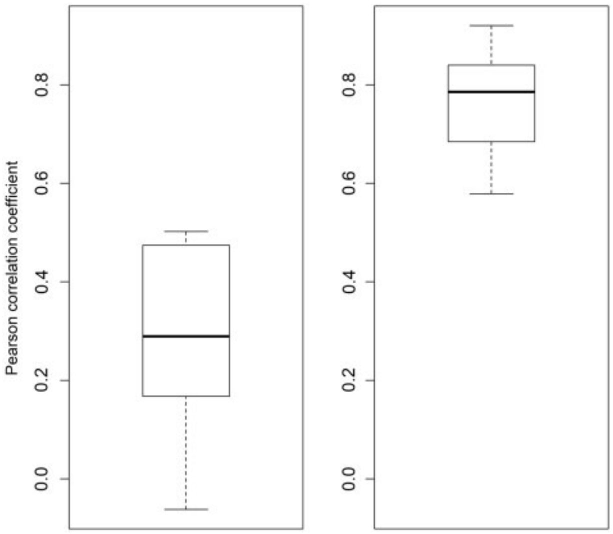

Figure 3. Box plot of the correlation coefficients between model-based recruitment indices, and (left panel) the geometric mean of the model-based recruitment indices during the last 5 years (r_3) and (right panel) the survey-based pre-recruit abundance indices (r_2). Each plot is based on the ten stocks that rely on coastal habitats at juvenile stage and for which the ICES assessments are truly independent from survey-based pre-recruit abundance indices but use these survey-based pre-recruit abundance indices for short-term forecasts of recruitment (thick line, median; box, from the 0.25 quartile to the 0.75 quartile; whiskers, 1.5 times the distance between the quartiles).

independence due to the use of surveys within assessments. Indeed, for four stocks, survey-based predictions of recruitment were originally independent of the assessments (Table 4). For the six remaining stocks, models were rerun after removing survey-based indices from the assessment. For these six stocks, differences between r_1 and r_2 depended at least partly on the availability of alternative information on recruitment strength used in stock assessment models. The difference was insignificant for North Sea plaice, for which several alternative data-based sources of information are used in the assessment model to infer pre-recruit abundance (including survey-based indices from other surveys; ICES, 2017c). Conversely, $r_1 - r_2$ reached 0.19 for the western Baltic Sea cod, for which recruitment is mainly informed by the survey-based index in the assessment model for young stages (ICES, 2018b). This difference illustrates autocorrelation between survey-based and model-based short-term forecasts of recruitment, i.e. for stocks where the survey-based recruitment indices informed the assessment models.

The degree of agreement between survey-based and survey-independent, model-based short-term forecasts was not due to a few influential points, as there was an average of 22 years in the various time series. Furthermore, the survey-based predictions outperformed the alternative using a 5-year geometric mean of model-based values.

Given the long history of attempts to predict recruitment in fisheries management, our results strongly suggest that juvenile surveys should be investigated for their potential use in assessments, a theme that has been emphasized by the analysis of other stocks (Helle *et al.*, 2000; Zhang *et al.*, 2010; Caputi *et al.*, 2014; Punt, 2019). Any possible use of survey results would need to be evaluated for the specifics of the survey data, the assessment methodology, and the life history of the species.

Deviations between survey-based and model-based short-term forecasts of recruitment may be due to several factors. First is the unknown estimation error in deriving recruitment estimates from surveys due to high spatio-temporal variation in abundance (Denson *et al.*, 2017; Potts and Rose, 2018). Quantifying and understanding the causes of these errors are central to obtain reliable recruitment estimates (Albert *et al.*, 2001; Ralph and Lipcius, 2014). Second, our assumption that the model-based estimates are accurate ignores how process and estimation errors in recruitment arise from stock assessment models (Hilborn and Walters, 1992). Estimates of recruitment time series are sensitive to model assumptions used in the assessments (Dickey-Collas *et al.*, 2015). Third, there may be high, density-dependent, and variable juvenile mortality (Nash *et al.*, 2007; Le Pape and Bonhommeau, 2015; Haggarty *et al.*, 2017) after the survey-based estimate of pre-recruit abundance. Given that these and other factors add noise to both survey-based and model-based short-term forecasts of recruitment, the degree of agreement we found between both predictors across diverse stocks and sampling programmes is encouraging.

The small (ten stocks) dataset precluded a comprehensive analysis of the driving factors of survey apparent accuracy. The correlation values did not indicate any obvious dependence on species habitat nor survey design. However, these and other factors, such as life history of the species, probably influence survey accuracy, which warrants analysis with more stocks. Two main issues complicated our ability to determine the factors that influenced the accuracy of survey-based pre-recruit estimates: (i) it is speculative to judge a survey programme for generating pre-recruit information when the survey was designed for other purposes and (ii) our sample size was too small for using the questionnaire results for assessing which factors influence accuracy. Given these caveats, the present analysis allows for some recommendations about survey design to ensure that the surveys provide sufficiently accurate pre-recruit abundance indices for advice about recruitment in the stock assessment of species with juvenile coastal dependence:

(i) Surveys should sample coastal juvenile areas at appropriate times, to avoid the high and variable mortality during the early juvenile stages (Nash *et al.*, 2007; Le Pape and Bonhommeau, 2015; Haggarty *et al.*, 2017).

(ii) Surveys should cover a large proportion of a stock's spatial domain to capture inter-annual variation in nursery habitat utilization (Albert *et al.*, 2001; Ralph and Lipcius, 2014).

(iii) Surveys should be carried out annually to avoid missing values in the pre-recruit abundance time series.

(iv) The juvenile portion of the survey should include an evaluation of the performance of the sampling gear (e.g. selectivities) and incorporate methods for quantifying variability.

(v) Where possible, juvenile surveys or the juvenile component of stock surveys should aim to be as consistent as possible with the survey of non-juvenile areas to provide commensurable data for combined analyses.

These conditions provide a general basis for examining how surveys can be initially evaluated for possible use for juveniles and pre-recruit indices. These recommendations can be applied to situations when surveys are being revised (surveys are presently done for multiple reasons) and new surveys are being designed.

Augmenting the survey-based pre-recruit abundance indices with other covariate variables, such as environmental drivers, may further improve the accuracy of recruitment predictions. Indices based on environmental drivers (e.g. Le Pape *et al.*, 2003 and Lagarde *et al.*, 2018 for Bay of Biscay sole; Denson *et al.*, 2017; ICES, 2018a for North East Arctic cod) alone, or in combination with pre-recruit abundance indices (Zhang *et al.*, 2010; Ralston *et al.*, 2013), could provide helpful information about recruitment trends and variability in the near term. However, changes in TAC recommendations lead to gains only when environmental predictors and survey-based pre-recruit abundance indices are accurately assessed (Basson, 1999; De Oliveira and Butterworth, 2005). The increase in accuracy that survey-based pre-recruit abundance indices can provide to catch advice suggests that existing surveys should be evaluated for their potential use.

Predictions of future short-term recruitment can influence management advice both for the assessment year and for the TAC year (ICES, 2015). Our analysis showed that, while a limited number of the total possible stocks that can use survey-based predictions actually use them, when survey-based predictions are used in the assessment, their apparent accuracy is reasonable. Survey-based pre-recruit abundance indices are being used for some stocks either explicitly in the SAM (e.g. Nielsen and Berg, 2014) or in a separate forecasting routine combined with stock assessment outputs (e.g. RCT3 routine post XSA model; Shepherd 1997; Shepherd, 1999). These indices inform the expected recruitment in future years. The scope of the present paper was focused on the usefulness of survey-based pre-recruit abundance indices for advice about recruitment, but not on the ways in which to utilize these indices in stock assessment procedures; this has been extensively discussed by others (Punt, 2019).

Tools for forecasting recruitment play an important role in fisheries management and decision-making, and all possible tools should be at least explored for their potential utility, if not utilized. When catches are highly dependent on recruitment (short-lived or over-exploited stocks; e.g. North Sea cod, ICES, 2017c), estimating recruitment and possible variability about the forecast is a priority to provide reliable information for management. However, the number of years for which short-term forecasts can benefit from survey-based abundance indices of pre-recruits obviously depends on the year-lag between the first age in the catch forecast and the age of the pre-recruit individuals in the survey. For the large proportion of stocks with only a 1-year lag (Supplementary Table S1), there is no observed recruitment survey index for more years ahead, and short-term forecast means a forecast for the next year only.

Even when they are not accounted for in stock assessment, survey-based pre-recruit abundance indices could be considered as quantitative evidence supporting or opposing predictions derived using average previous recruitment and used to provide a measure of the uncertainty in predicted recruitment. Indeed, when the survey-based pre-recruit abundance indices are not available during an assessment (e.g. Sandeel stocks, Supplementary Table S1; Table 3), some procedures allow their results to be considered *a posteriori*. For example, the advice for the main flatfish and round fish stocks in the North Sea has a procedure for reopening after the surveys are conducted in autumn (ICES, 2008; ICES, 2015). If pre-recruit abundance indices are estimated to differ significantly from assessment derived indices, re-evaluating management advice after surveys are completed should make the advice more robust (ICES, 2008). This procedure of re-evaluating management advice clearly shows the validity and importance of the recruitment indices. We recognize that these approaches introduce additional work for those delivering advice; thus, exploratory analyses to assess their potential benefits to assessments are a good first step. While our focus was on species that use coastal habitats, our evaluation approach is applicable to most species, including those that do not depend on coastal juvenile habitats (Kimoto *et al.*, 2007; Ralston *et al.*, 2013).

We focused our analysis on using existing surveys for stocks that use recruitment forecasts in their assessments. In addition to the use of survey-based pre-recruit abundance indices for forecasting recruitment, fishery-independent surveys can be evaluated for their potential use with other management goals. Examples include quantifying juvenile habitat for informing an ecosystem-based approach to fisheries management (Browman *et al.*, 2004), deriving indices of environmental drivers for further forecasting (Hidalgo *et al.*, 2016), and informing dynamic marine spatial plans that respond to changes in coastal habitats (Kininmonth *et al.*, 2019). Surveys can also be used to provide alerts on the impacts of anthropogenic disturbances affecting the survival of juveniles. A large proportion of coastal-dependent species is impacted by human activity other than fishing mortality when juveniles utilize coastal habitats (Brown *et al.*, 2018a). Regular monitoring of juvenile habitats to provide data for assessment can generate spatially explicit evidence for local productive areas to inform environmental management. Surveys can provide information on juvenile responses to both environmental drivers (Hermant *et al.*, 2010; Caputi *et al.*, 2014; Lagarde *et al.*, 2018; Brown *et al.*, 2019) and anthropogenic pressures (Rochette *et al.*, 2010; Archambault *et al*, 2018), which can influence future stock dynamics (Stige *et al.*, 2013). Habitat degradation can result in either overly optimistic or overly conservative assessments of stock status (Brown *et al.*, 2018b). Preserving or restoring the capacity of juvenile habitat is of major importance for improving adult biomass of populations relying on coastal juvenile habitat (Van de Wolfshaar *et al.*, 2011; Le Pape and Bonhommeau, 2015; Archambault *et al.*, 2018). Existing and planned surveys should be examined for possible leveraging of their results, in addition to their primary motivation and goals, thereby integrating fisheries and ecosystem-based management (Kraufvelin *et al.*, 2018).

Supplementary data

Supplementary material is available at the *ICESJMS* online version of the manuscript.

Acknowledgements

This work was developed within the context of the ICES working group WGVHES (Working Group on the Value of Coastal Habitats for Exploited Species). The authors thank both ICES and all participants of the working group 2017–2019. The authors also warmly thank Maria Lifentseva and Jette Fredslund (ICES) for their efficient help to connect us to scientists in charge of the 78 stock assessments. The authors thank Mark Dickey-Collas (ICES) and the scientists involved in stock assessments for their contributions. The authors specially thank Marianne Robert, Niels Hintzen, and Marie Storr-Paulsen who kindly and greatly contributed by re-tuning stock assessment models without the recruitment index data. Finally, the authors thank Stan Kotwicki, the editor, Niels Hintzen, and the two other anonymous reviewers for their constructive reviews that improved the article.

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Handling editor: Stan Kotwicki