Received: 11 January 2023 | Revised: 18 August 2023 | Accepted: 20 August 2023

DOI: 10.1111/faf.12789

ORIGINAL ARTICLE

FISH and FISHERIES WILEY

Including older fish in fisheries management: A new age-based indicator and reference point for exploited fish stocks

Christopher A. Griffiths | Henning Winker | Valerio Bartolino | Håkan Wennhage | Alessandro Orio | Massimiliano Cardinale

Department of Aquatic Resources, Institute of Marine Research, Swedish University of Agricultural Sciences, Lysekil, Sweden

Correspondence
Christopher A. Griffiths. Department of Aquatic Resources, Institute of Marine Research, Swedish University of Agricultural Sciences, Turistgatan 5, SE-453 30, Lysekil, Sweden.
Email: christopher.griffiths@slu.se

Funding information
Havs- och Vattenmyndigheten, Grant/Award Number: 01068-2022

Abstract

Larger and older fish contribute disproportionately to spawning and play an important role in the replenishment of exploited stocks. Fishing often removes specific size- and age-classes, with direct impacts on stock productivity and population resilience. Despite this, fisheries advice is commonly based on estimates of spawning stock biomass (SSB) and fishing mortality (F) and makes little reference to the importance of size and/or age structure. Consequently, there is a need for indicators of size and/or age structure to better inform fisheries management and help assess global sustainability goals. Here, we introduce a new age-based indicator ABI_{MSY} that monitors age structure relative to the equilibrium age structure at F_{MSY}. We apply this new indicator to 72 commercially important stocks in the Northeast Atlantic, covering 26 species, which collectively contributed 86% of all commercial catches in the region in 2019. We estimate that 62% (45 stocks) currently have proportionally fewer older fish relative to F_{MSY} conditions, whereas 38% (27 stocks) have proportionally more older fish; we also note patterns with respect to geographic area and taxonomic family. Simulation testing demonstrated that ABI_{MSY} is responsive to overfishing and generally tracks (with high sensitivity and specificity) a common measure of stock depletion, SSB relative to B_{MSY}. Throughout, we show that ABI_{MSY} provides information on the age structure of exploited stocks that is complementary to conventional reference points for SSB and *F*. Further, the framework used to estimate ABI_{MSY} make it well placed for integration into current advisory frameworks on fisheries management.

KEYWORDS
age structure, BOFFF fish, fisheries advice, good environmental status, maximum sustainable yield, stock assessment

1 | INTRODUCTION

The impacts of commercial fishing on marine fish populations are expected to be numerous and sometimes catastrophic (Halpern et al., 2008; Jennings & Kaiser, 1998). The effect of fishing extends well beyond direct and indirect mortality, with fishing activities being linked to reductions in fish body size (Darimont et al., 2009; Swain et al., 2007), earlier maturation times (Law, 2000; Olsen et al., 2004), altered sex-ratios (Shepherd et al., 2010), as well as the degradation of habitats and ecosystems (Rijnsdorp et al., 2020; Turner et al., 1999). Fisher behaviour and gear selectivity further impact fish populations, with the tendency to target larger, older and more economically profitable fish (Pauly et al., 1998), causing truncations in the size and age structure of commercially important stocks (Barnett et al., 2017; Blanchard et al., 2005; Hsieh et al., 2010).

The management of commercial fisheries typically aims to ensure that fishing occurs at sustainable levels, whereby total allowable catch (TAC) is set at values that both maximise yield and minimise the likelihood of long-term stock collapse (i.e. the theoretical Maximum Sustainable Yield; MSY; Dichmont et al., 2010; Mace, 2001; Rindorf et al., 2017). Key to this process is the application of analytical stock assessment models (e.g. Methot & Wetzel, 2013; Nielsen & Berg, 2014) that provide an informed description of stock status, and forecast how the biomass (*B*) or spawning stock biomass (SSB) of a stock may respond to a given exploitation level, i.e. fishing mortality (*F*). Also key to this process are reference points, which provide important thresholds for stock status classification. For instance, F_{MSY} (the *F* that yields MSY) and B_{MSY} (the biomass at MSY), are used in most of the world's major fisheries to evaluate *F* and B respectively. Put simply, if a stock is estimated to be both below F_{MSY} and above B_{MSY}, it is deemed to be in a good and healthy state, and is expected to be capable of producing MSY in the long term. Consequently, these reference points translate into aims and objectives for managers and decision makers (ICES, 2022a), and are implemented in policies like the EU Common Fisheries Policy (CFP; EU., 2013), the EU Marine Strategy Framework Directive (MSFD; EU-COM, 2008), the Magnuson-Stevens Fishery Conservation and Management Act (MSFMCA, 2007), the Fisheries and Oceans Canada's (DFO) Fishery Decision-Making Framework Incorporating the Precautionary Approach (PA Policy; DFO, 2009) and the Harvest Strategy Standard for New Zealand Fisheries (Ministry of Fisheries, 2008).

To further direct fisheries management, policies like the CFP and MSFD, as well as regional sea conventions like OSPAR (the Oslo-Paris Convention; OSPAR, 2017) and HELCOM (the Helsinki-Commission; HELCOM, 2018), often implement a pressure-state indicator framework in order to gain a more holistic assessment of the marine environment (Probst et al., 2016). In this framework, a pressure indicator will directly affect a state indicator in some mechanistic way (Jennings, 2005). For instance, SSB and *F* are widely considered as state and pressure indicators, respectively, as a change in *F* is expected to cause a predictable change in SSB.

Recently, the MSFD, via its descriptor 3 criteria 3 (D3C3) of good environmental status (GES), have extended this F-SSB indicator framework and requested that exploited fish stocks exhibit 'a population age and size distribution that is indicative of a healthy stock' (EU-COM, 2008, 2017). This is because not all fish contribute equally to the productivity and resilience of fish stocks. In a number of species and taxa (especially longer lived species), Big Old Fat Fecund Female fish (the BOFFF hypothesis) are expected to produce larger and better quality eggs (i.e. greater lipid composition of the yolk) than first or second-time spawners (Hixon et al., 2014; Rideout et al., 2005; Trippel, 1998). These larger and better quality eggs result in faster growth

at early life stages, larger sizes at hatching, and ultimately higher survival rates. Relative fecundity (i.e. number of eggs produced per unit body mass) also increases with female body weight (Cooper et al., 2013), and larger individuals have been shown to have higher spawning frequencies than smaller individuals (Marshall et al., 2022), thus allowing older and larger fish to contribute disproportionately to stock productivity (Barneche et al., 2018). In addition, older fish have been shown to spawn over longer spawning windows, providing a population with greater resilience to environmental variation via potential shifts in phenology (Brander, 2005; Fitzhugh et al., 2012; Lowerre-Barbieri et al., 2011; Wright & Trippel, 2009).

Age and size structure also have implications for the spatial distribution of fish stocks (Planque et al., 2011). Older and larger fish have broader ecological niches, greater energetic reserves and can make use of marginal habitats. They are also thought to pass on information on migratory routes and habitat use to younger fish via mechanisms of stock collective memory (Corten, 2002; Petitgas et al., 2006). This phenomenon might be particularly relevant for schooling species, as proposed for Atlantic herring (*Clupea harengus*, Clupeidae), whereby wintering site selection has been linked to local-scale environmental factors as well as population size and age structure (Corten, 1999; Macdonald et al., 2017). Such findings call into question the common assumption of stock assessment and fisheries management that the biomass of mature fish of different ages contributes equally (proportional to their mass) to stock replenishment. Moreover, as larger and older fish are expected to play a pivotal role in the productivity, persistence and resilience of wild fish populations to stressor effects, there is emerging concern that management of fisheries based purely on *F* and SSB might overlook key aspects of stock status, namely their age and size structure. This is highlighted in the recent work of Marshall et al. (2021) who showed that stock assessment approaches that use proportional to mass assumptions for spawning potential without considering age and/or size structure may result in recommended catch levels that are higher than those that sustain target levels of replenishment (but see also He et al., 2015). Further, attempts to use proxies of fecundity and spawning output (e.g. numbers of mature females) as opposed to SSB (to capture aspects such as changes in fertility, egg viability and sex-ratio) have been shown to impact the estimation of stock status and reference points (Minte-Vera et al., 2019). Albeit, Kell et al. (2015) found that using total egg production (which incorporates greater realism on reproductive biology) did not improve spawner-recruit analysis relative to SSB. Thus, a single best approach is yet to be agreed upon and such proxies have not been applied operationally in stock assessment and advice.

The age and size structure of a fish stock can be assessed using age-based indicators (ABIs) or length-based indicators (LBIs) (Probst et al., 2013a, 2013b; Shin et al., 2005; Trenkel et al., 2007). As a direct response to D3C3, the scientific community has proposed several indicators that aim to inform on the abundance and/or proportion of larger and older fish (Brunel & Piet, 2013; Froese, 2004; ICES, 2016, 2017a; Vasilakopoulos et al., 2020). Two such LBIs that have gained support are the 95th percentile of the fish-length distribution (L_{95}) and the proportion of fish larger than the mean size at maturation (P_{mat}) (EU-COM, 2017). However, both these indicators share some common limitations. They have been shown to be sensitive to recent recruitment with large incoming year classes causing uninformative skews in indicator values (Probst et al., 2013a). Importantly, the also lack established reference points that are critical for managerial applications (Probst et al., 2021). These limitations impair the use of L_{95} and P_{mat} beyond academic endeavours and have fuelled calls for further work by the scientific and managerial community. Thus, there is a clear need for ABIs and LBIs that provide direct information on larger and older fish, are insensitive to recent recruitment, and have reference points that fit within the policy objectives.

Here, we address the need for ABIs for exploited fish stocks and propose a new ABI: age structure relative to the estimated age structure at F_{MSY}. We call our ABI 'age structure relative to F_{MSY}' and give it the acronym ABI_{MSY}, and use them interchangeably throughout the text. Moreover, to provide an additional reference metric for the assessment of GES, we also calculate age structure relative to a no fishing scenario, F_0. We apply the proposed ABI_{MSY} to 72 commercially important fish stocks throughout the Northeast Atlantic. These stocks include 26 species (representative of 10 taxonomic orders) and provided 86% (~7 million tonnes) of all reported commercial catch in the region in 2019 (ICES, 2021a). Throughout, we show that ABI_{MSY} provides novel information on the age structure of exploited stocks that is complementary to estimates of SSB and *F*. Further, using simulation testing, we evaluate the ability of ABI_{MSY} to correctly classify 'true' stock status with respect to a biomass threshold at 80% of B_{MSY} (a target commonly used to infer a healthy stock; MSFMCA, 2007; DFO, 2009; Sharma et al., 2021), thus providing a clearly defined link between the age structure of exploited stocks and current policy objectives.

2 | MATERIALS AND METHODS

2.1 | Assessment data

A unique dataset of stock assessment inputs and outputs for 81 stocks covering the entire Northeast Atlantic was collated and used in this study (Table S1). The dataset is formed of stock objects of the 'FLStock' class as defined in the FLR framework (ICES, 2022a; Kell et al., 2007). All 81 stocks are classified and assessed by ICES (International Council for the Exploration of the Sea) as Category 1 stocks (i.e. age-based analytical stock assessments) and have a final assessment year of 2019 (n = 12), 2020 (n = 63) or 2021 (n = 6). In the following text, stocks are referred to by their ICES stock IDs (https://sid.ices.dk), with details on the assessment inputs and outputs of all stocks provided in the form of an external open access Shiny application (https://maxcardinale.shinyapps.io/Indicators/). The Shiny App also contains a range of plots that visualise various aspects of each stock's population dynamics and demographic characteristics. The dataset also contains ICES reference point values for each stock (e.g. F_{MSY}, F_{lim}, B_{MSY}, MSY $B_{trigger}$ and B_{lim}; Table S2), whereby MSY $B_{trigger}$ (hereafter referred to as $B_{trigger}$) is the biomass reference point used by ICES and is commonly the biomass above which *F* is set at F_{MSY} as part of stock's harvest control rule (ICES, 2023a).

A graphical summary of our dataset is provided in Figure 1. Briefly, the dataset contains 25 bony fish species (representative of 12 taxonomic families and 9 taxonomic orders) as well as one crustacean, northern shrimp (*Pandalus borealis*, Pandalidae; pra.27.3a4a). It also contains harmonised assessment of inputs and outputs from 12 different age-structure stock assessment frameworks (see Table S1 and S3 for more details) of which SAM (n = 35; Nielsen & Berg, 2014) and Stock Synthesis (SS3; n = 14; Methot & Wetzel, 2013) are the most frequent. The majority of the stocks occur in the North Sea (n = 19) and surrounding areas (e.g. Celtic Seas (n = 8) and Irish Sea (n = 7)), however, some stocks have a wide spatial distribution that spans multiple ecoregions (e.g. Blue whiting, *Micromesistius poutassou*, Gadidae, in the Northeast Atlantic and adjacent waters; whb.27.1–91, 214).

2.2 | Equilibrium age structure at F_{MSY} and F_0

The rationale behind ABI_{MSY} builds on the methods used in stock assessment and the estimation of reference points (e.g. F_{MSY} and B_{MSY}). Reference points are commonly calculated using either equilibrium

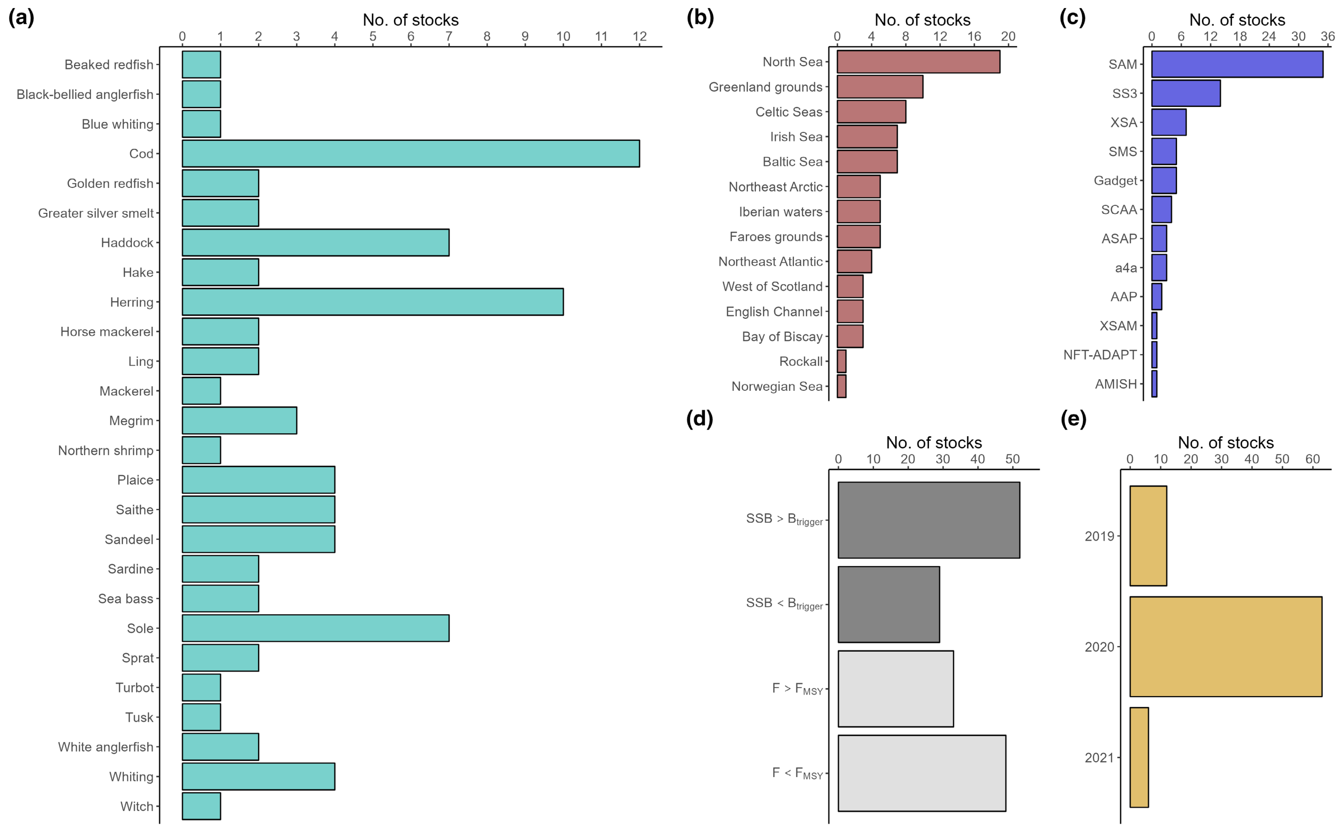

FIGURE 1 Graphical summary of the dataset used in this study. The dataset contains 26 species (a) from 14 different areas (b), whereby area is a broad characterisation based on ICES areas and ecoregions. All 81 stocks are assessed using age-structured analytical assessment frameworks (c), the details of which can be found in Tables S1 and S3. A summary of current stock status (i.e. in the final assessment year) in relation to SSB/$B_{trigger}$ and F/F_{MSY} is presented (d), as is the final assessment year of each stock (e). Panels D and E are aggregated across all 81 stocks; each stock's SSB and F values are presented in Table S1. Reference points (e.g. $B_{trigger}$ and F_{MSY}) for each stock are detailed in Table S2.

assumptions (e.g. Punt et al., 2014) or stochastic forecasting (e.g. EQsim; ICES, 2017a), whereby forecasts are made (typically many years into the future) to achieve equilibrium conditions under a fixed *F*. These forecasts are typically conditional on the current state of the stock, that is, they consider recent selectivity, an underlying stock-recruit (SR) function and other assumptions about the stock's biology. Multiple Fs are evaluated in the forecasts and, subject to some underlying long-term criteria (e.g. probability of SSB failing below B_{lim} should not exceed 5% in any given year; ICES, 2021b), reference points are calculated.

When stocks are assessed using age-structured models (as is the case here), this approach can be tailored to approximate a stock's age structure at equilibrium under a fixed F, and this forms the basis for ABI_{MSY}. For each stock, we ran deterministic long-term forecasts (~200 years) with a constant *F* that is equal to ICES official F_{MSY} reference points (Table S2) or is equal to 0 (the F_0 case). In the F_0 case, the stock cannot be considered 'unfished' but is instead forecasted forward conditional on its current biological characteristics and an absence of fishing. Once equilibrium is attained (when SSB achieves steady-state dynamics), we then extract the corresponding age structure at F_{MSY} and F_0.

Several assumptions are made about the biology and fishing selectivity of a stock when forecasting. Here, we set weight-at-age, maturity-at-age, mortality-at-age and selectivity to be the average of the last 3 years to reflect the recent biology and exploitation pattern of each stock. To implement the projection in FLR, we have also chosen to use a stock recruitment relationship (SRR) in the form of a segmented regression with the breakpoint fixed at ICES B_{lim}. We note, however, that because the age structure at equilibrium is based on the relative age-composition, it is not, in principle, affected by the choice of the SRR, and could also be derived from per-recruit analysis. That said, the code provided alongside this study is designed to be both general and flexible (see Data Availability Statement) and allows users to implement any chosen SRR or demographic/selectivity assumptions for any given stock.

As not all stocks have formally accepted F_{MSY} reference points for advice (Table S2), age structure at equilibrium under F_{MSY} could only be derived for 72 stocks. Thus, nine stocks were removed from our analysis.

2.3 | ABI calculation

Once the age structure of a stock at F_{MSY} has been approximated at equilibrium, we can use the resultant numbers-at-age distribution to calculate the reference proportion of older fish that is expected

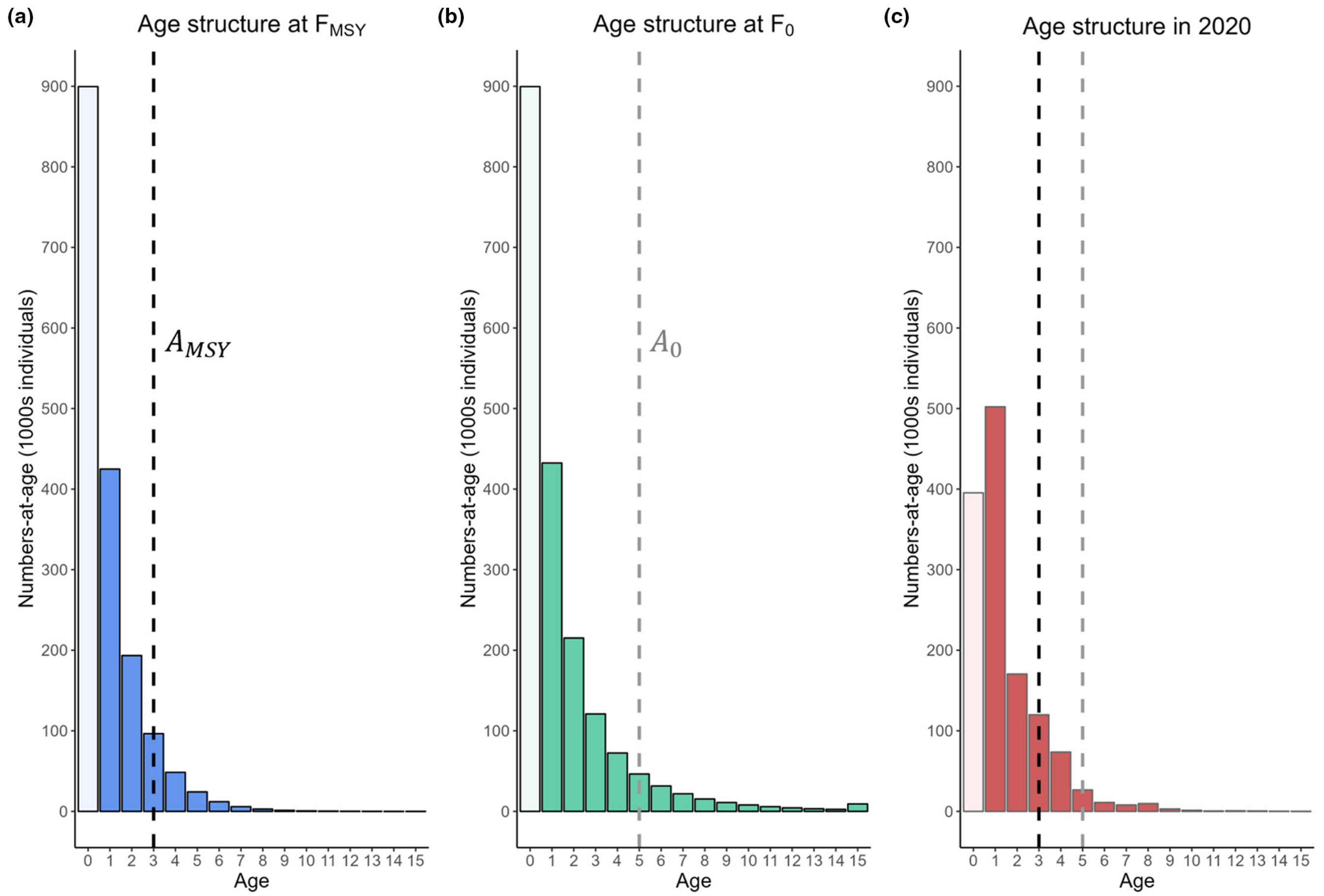

FIGURE 2 Graphical example of the methods used to calculate ABI_{MSY} and age structure relative to F_0 (ABI_0) Shown is the theoretical age structure at equilibrium under F_{MSY} (a) and F_0 (b) conditions, as well as the estimated age structure in the final year of the assessment (c). All three age structures (a–c) relate to the hake (*Merluccius merluccius*, Gadidae) stock (hke.27.3a46-8abd) in the Greater North Sea, Celtic Seas, and the northern Bay of Biscay. Dashed vertical lines illustrate the reference age under F_{MSY} (black; A_{MSY}) and F_0 (grey; A_0) conditions, whereby the reference age is the closest age to the 90th percentile of the fish numbers-at-age distribution. Age 0 (the first age class for this stock) is shown in all three panels with greater transparency but is removed prior to the calculation of ABI_{MSY} and ABI_0.

to be in a population under constant F_{MSY} exploitation levels. This reference proportion can then be directly compared, in relative terms, to the realised proportion of older fish in the population (in any given year) and therefore provides us with an ABI of the age structure relative to F_{MSY}. Thus, ABI_{MSY} represents a relative metric of how the age structure of a stock compares to what should be expected under F_{MSY} management targets in the long term, subject to assumptions outlined in the previous section.

For any given stock (e.g. hke.27.3a46-8abd; Figure 2), we calculated ABI_{MSY} in the following way. First, we removed the first age class to limit the potential impact of incoming recruitment (R) on ABI_{MSY}. We then calculated the 90th percentile of the fish numbers-at-age distribution at F_{MSY}, rounding to the nearest integer age which we term A_{MSY} (e.g. age 3 in Figure 2; see Table S5 for A_{MSY} values for each stock). We then calculated P_{MSY}, which is the realised percentage of the numbers-at-age distribution above A_{MSY}. In our graphical example, P_{MSY} = 11.9%.

For any given year t (e.g. 2020 in Figure 2), we then identified A_{MSY} in the estimated numbers-at-age distribution and calculated the proportion of fish above (>A_{MSY}) this age, P_t. ABI_{MSY} is then calculated such that:

$$ABI_{MSY_t} = \frac{P_t}{P_{MSY}} \qquad (1)$$

This process was then repeated for all years (e.g. 1978–2020 for hke.27.3a46-8abd) and all stocks, producing a stock-specific time series of ABI_{MSY}.

The same steps were taken for age structure relative to F_0 (ABI_0). In this case, the reference age, A_0, increases under $F=0$ (e.g. age 5 in Figure 2), as the absence of fishing permits older (and larger) fish to be retained at higher rates in the population (see Table S5 for A_0 values for each stock).

The choice of the percentile threshold for computing the proportion of older fish generally determines the responsiveness (inertia) of ABIs, with higher thresholds generally leading to improved responsiveness. The initial choice of using the 90th percentile is in line with levels commonly used for LBIs (e.g. the 95th percentile of the fish-length distribution; EU-COM, 2017). Moreover, simulation testing (see Section 2 below) indicated that the 90th percentile performed best across a range of simulated stocks with respect to proportional changes in the 'true' simulated SSB (Figure S1), whereas lower thresholds tended to underestimate the magnitude of changes in 'true' SSB (meaning the ABI is hyperstable). In addition, a sensitivity analysis revealed that small changes (85%–95%) in the percentile value used to calculate A_{MSY} yielded comparable ABI_{MSY} values, both in terms of trends through time and any inference gained, albeit the absolute values in the final assessment year do differ (Table S6 and Figure S2).

2.4 | Correlation analysis and visualisation

To investigate the relationship between ABI_{MSY} and other metrics of stock status (F, SSB and R) we used correlation analysis. Correlation analysis was used because it allows us to explicitly measure (via estimated correlation coefficients (r)) both the strength (value) and the direction (positive or negative) of any relationship. Our prior expectation is that F will have a strongly negative relationship with age structure, as increases in F are expected to reduce the likelihood of survival to older ages. We also expect to observe a positive relationship between ABI_{MSY} and SSB, as larger stock sizes are predicted to have a larger proportion of older fish. A directional relationship between ABI_{MSY} and R is not expected; however, the strength and direction of this relationship could depend on the strength of incoming year classes and may vary through time.

Specifically, we applied Spearman's rank correlation method using the *cor()* function in *R* (R Core Team, 2021). We tested for statistical significance using the *cor.test()* function and opted for a non-parametric analysis (i.e. the Spearman method as opposed to the more common Pearson's correlation method) due to the presence of non-linearity.

Metrics of stock status were considered as relative values throughout: SSB/MSY $B_{trigger}$ (hereafter SSB/$B_{trigger}$), F/F_{MSY} and R/R_0. This is to remove the need for standardisation across stocks. R_0 is the recruitment produced by the stock under no-fishing conditions. Here R_0 was computed by fitting a segmented regression (Hockey–Stick function) to stock recruitment data with the breakpoint fixed at B_{lim} (see Table S2). In practice, this means that R_0 represents the maximum recruitment for stock sizes above the breakpoint.

In all cases, we tested the relationship between ABI_{MSY} in the final assessment year (the terminal year) and the average value of SSB/$B_{trigger}$, F/F_{MSY} and R/R_0 taken from a recent temporal window. The correlation was evaluated for temporal windows from the terminal year (y) sequentially across y, $y-1$, ..., $y-8$, thus a total of 9 correlation analyses were conducted for each metric. A maximum of 9 years was used as it equals the average generation time of all species in our analysis (average = 9.3 years; see Table S1). For ease, in the rest of the text, we report the relationship between ABI_{MSY} and metrics of stock status averaged over the period y to $y-5$ (i.e. the last six assessment years). The choice to concentrate on a 6-year window is based on the inflection point between ABI_{MSY} and SSB/$B_{trigger}$, and ABI_{MSY} and F/F_{MSY}, after which estimated correlation coefficients show little or no deviation (see Figure S3).

In addition to the above-mentioned metrics of stock status, we also considered the percentage of years that a stock has been exploited at $F < F_{MSY}$ during the last 15 years. This metric was used to test for a mechanistic relationship between F and ABI_{MSY}.

All data manipulation, visualisation and analyses were conducted in *R* (R Core Team, 2021). Data extraction from our FLR dataset used the *FLCore* package (Kell et al., 2007; flr-project.org).

2.5 | Simulation testing

A biomass target often used by managers and policy makers when assessing stock status is B_{MSY}, or some proxy of B_{MSY}. For instance, the FAO (Food and Agriculture Organization of the United Nations) and Canada both use 80% of B_{MSY} as a threshold to classify stock status as 'sustainably fished' (Sharma et al., 2021) and within a 'Healthy Zone (Green)' (DFO, 2009) respectively. This is based on the underlying principle that if fishing occurs at F_{MSY}, it is expected that stock biomass will naturally fluctuate around B_{MSY}. Consequently, 80% of B_{MSY} is used because it reflects the lower precautionary threshold of this fluctuation.

Consistent with recent performance evaluations of LBIs (Kell et al., 2022a), we used simulation testing to evaluate the skill of ABI_{MSY} to correctly classify if a stock has an age structure capable of producing B_{MSY}. Simulations were conducted on a selected number of case study stocks representing a wide range of fisheries and life histories. Specifically, the following six stocks were used: sardine (*Sardina pilchardus*, Clupeidae) in the Cantabrian Sea and Iberian waters (pil.27.8c9a), northern shrimp in the Skagerrak, Kattegat and northern North Sea (pra.27.3a4a), Atlantic herring in the North Sea, Skagerrak and Kattegat, and eastern English Channel (her.27.3a47d), European plaice (*Pleuronectes platessa*, Pleuronectidae) in the North Sea and Skagerrak (ple.27.420), Atlantic cod (*Gadus morhua*, Gadidae) on the Icelandic grounds (cod.27.5a) and white anglerfish (*Lophius piscatorius*, Lophiidae) in the Cantabrian Sea and Iberian waters (mon.27.8c9a). The life span of these stocks ranges from 6 years for sardine to 30 years for white anglerfish.

Age-structured simulation models were developed for each stock using FLR (Kell et al., 2007), specifically the FLR packages: *FLCore*, *FLRef*, *FLBRP* and *FLSRTMB* (flr-project.org). Each simulation model was conditioned based on stock-specific parameters: natural mortality, weight-at-age, maturity-at-age, and selectivity. All stock-specific parameters were set as the average of the last 3 years. For generality and in line with comparable simulation studies (e.g. Fischer et al., 2021a; Kell et al., 2022a; Mildenberger et al., 2021), we assumed a Beverton and Holt SRR (Beverton & Holt, 1993) to govern the underlying stock dynamics. The Beverton and Holt SRR was conditioned on the stock recruitment time-series of each stock and was based on the procedures described in ICES's Workshop on ICES reference points (WKREF1; ICES, 2021a), which involved the use of priors for steepness parameters that were sourced from

FishLife (Thorson, 2020). In the case of pra.27.3a4a, estimates of steepness were instead taken directly from the most recent assessment of the stock (ICES, 2022b). The steepness parameter estimates for the Beverton and Holt SRR represented a fairly broad coverage ranging from 0.5 for pil.27.8c9a to 0.94 for mon.27.8c9a.

Similar to Kell, Minto, and Gerritsen (2022), historical exploitation was simulated such that each stock was initially exploited for 100 years at F_{MSY}, therefore ensuring that each simulation started from the same point (i.e. with biomass oscillating around B_{MSY}). These initial 100 years were subsequently removed as 'burn-in'. For the first 25 years of the following 100-year evaluation horizon, exploitation was maintained at F_{MSY} and then was gradually increased to three times F_{MSY} (over a 25-year period). At this point, each stock can be considered overfished; during the following 25 years F was gradually brought back down to 80% of F_{MSY} and kept at that level for the last 25 years of each simulation. This time-varying pattern of exploitation provides contrasting periods of maximum sustainable, over- and under-exploitation, and allows us to investigate the sensitivity of ABI_{MSY} to changes in F. Moreover, to test for the effect of variability in recruitment (σ_R) on the classification skill of ABI_{MSY}, simulations were run across two levels of σ_R, 0.4 and 0.7, which are intended to mirror a relatively low and a relatively high rate respectively (Kolody et al., 2019). For clarity, these σ_R values refer to variability in log recruitment deviations (around the SRR relationship) and not just a measure of variability around estimated recruitment. All simulations were run using 1000 iterations over the 100-year evaluation horizon (i.e. 25 years at F_{MSY} and 50 years under a changing F and 25 years at 80% of F_{MSY}). In total, the simulations yielded 100,000 observations per stock for which we calculated 100,000 ABI_{MSY} values (using the methods described above) and extracted corresponding SSB values relative to the 'true' SSB at MSY, denoted as B/B_{MSY}.

2.6 | Receiver operating characteristics and evaluation of skill

To have good classification skill, ABI_{MSY} must have two properties: (1) high sensitivity that is equal to a high true-positive rate (TPR) for correctly identifying a stock as healthy ($B > 0.8\,B_{MSY}$) and (2) high specificity that is equal to a high true-negative rate (TNR) for correctly classifying a stock is overfished ($B < 0.8\,B_{MSY}$). The indicator's sensitivity and specificity emerge due to nature of binary classification, whereby the detection that a stock is above (a positive outcome; P) or below (a negative outcome; N) a given reference point (here 80% of B_{MSY}) leads to four possible outcomes:

1. True Positive (TP): ABI_{MSY} & $B/B_{MSY} > 0.8$
2. False Positive (FP): $ABI_{MSY} > 0.8$, but $B/B_{MSY} < 0.8$
3. True Negative (TN): ABI_{MSY} and $B/B_{MSY} < 0.8$
4. False Negative (FN): $ABI_{MSY} < 0.8$, but $B/B_{MSY} > 0.8$

where $\mathrm{TPR} = \mathrm{TP} / (\mathrm{TP} + \mathrm{FN})$ and $\mathrm{TNR} = \mathrm{TN} / (\mathrm{TN} + \mathrm{FP})$.

To visualise how the classification skill of ABI_{MSY} differs by stock and σ_R, we used Receiver Operating Characteristic (ROC; Green & Swets, 1966) curves. ROC curves are useful when evaluating classifiers and visualising their performance, and are being increasingly used in medical-decision making, machine learning and pattern recognition (Fawcett, 2006), as well as fisheries science (Kell et al., 2022a, 2022b). To generate ROC curves, we first sorted the estimated values of ABI_{MSY} from high to low for each simulated scenario and then computed the associated TPRs and TNRs with respect to the 'true' binary outcome for $B > 0.8\,B_{MSY}$. The ROC curves were then generated by plotting a cumulative probability curve of the false-positive rate (FPR = 1-TNR) on the x-axis against the corresponding cumulative TPRs on the y-axis. The top left-hand corner of the plot at TPR = 1 and FPR = 0 represents perfect classification, while the 1:1 line between FPR and TPR represents the randomisation line that would be theoretically generated by randomly tossing a coin.

Quantifying sensitivity and specificity allows us to determine the true skill statistic (TSS; Allouche et al., 2006) of using $ABI_{MSY} > 0.8$ as indicator for $B > 0.8\,B_{MSY}$, such that $\mathrm{TSS} = \mathrm{Sensitivity} + \mathrm{Specificity} - 1$. An indicator is said to have good classification skill if the TSS > 0 and thus better than random coin toss, whereas perfect classification would attain a TSS of 1. ROC curves and TSS values were computed for all simulated stocks and at both levels of σ_R. For the purpose of this simulation evaluation, we made the choice of using a threshold of 80% of B_{MSY} (DFO, 2009; Sharma et al., 2021), but any other threshold could be used in principle.

3 | RESULTS

Examples of ABI_{MSY} plotted through time alongside other metrics of stock status for two stocks, her.27.5a (Atlantic herring on the Icelandic grounds) and ple.27.21–23 (European plaice in the Kattegat, Belt Seas and the Sound), are shown in Figures 3 and 4 respectively. These examples illustrate how ABI_{MSY} is complementary to existing indicators, namely SSB, F and R, and how it could help provide additional information on stock status and advice.

For her.27.5a (Figure 3), ABI_{MSY} was historically low but has since recovered and has exceeded 1.0 since 2009. This demonstrates that the proportion of older fish is currently higher than under F_{MSY} conditions. ABI_0 shows a similar temporal trend, however, it remains low. F has declined through time and has been below or close to F_{MSY} since 2016. R is variable with a large incoming year class in 2020. SSB peaked in 2006 but has since then declined steadily through time. In 2020, SSB was between B_{lim} and $B_{trigger}$. These trends illustrate that the stock is in a relatively poor state compared to ICES reference points or to historical levels of SSB. However, the stock's age structure has a high proportion of older fish, and it is estimated to be above the level capable of producing MSY (i.e. B_{MSY}).

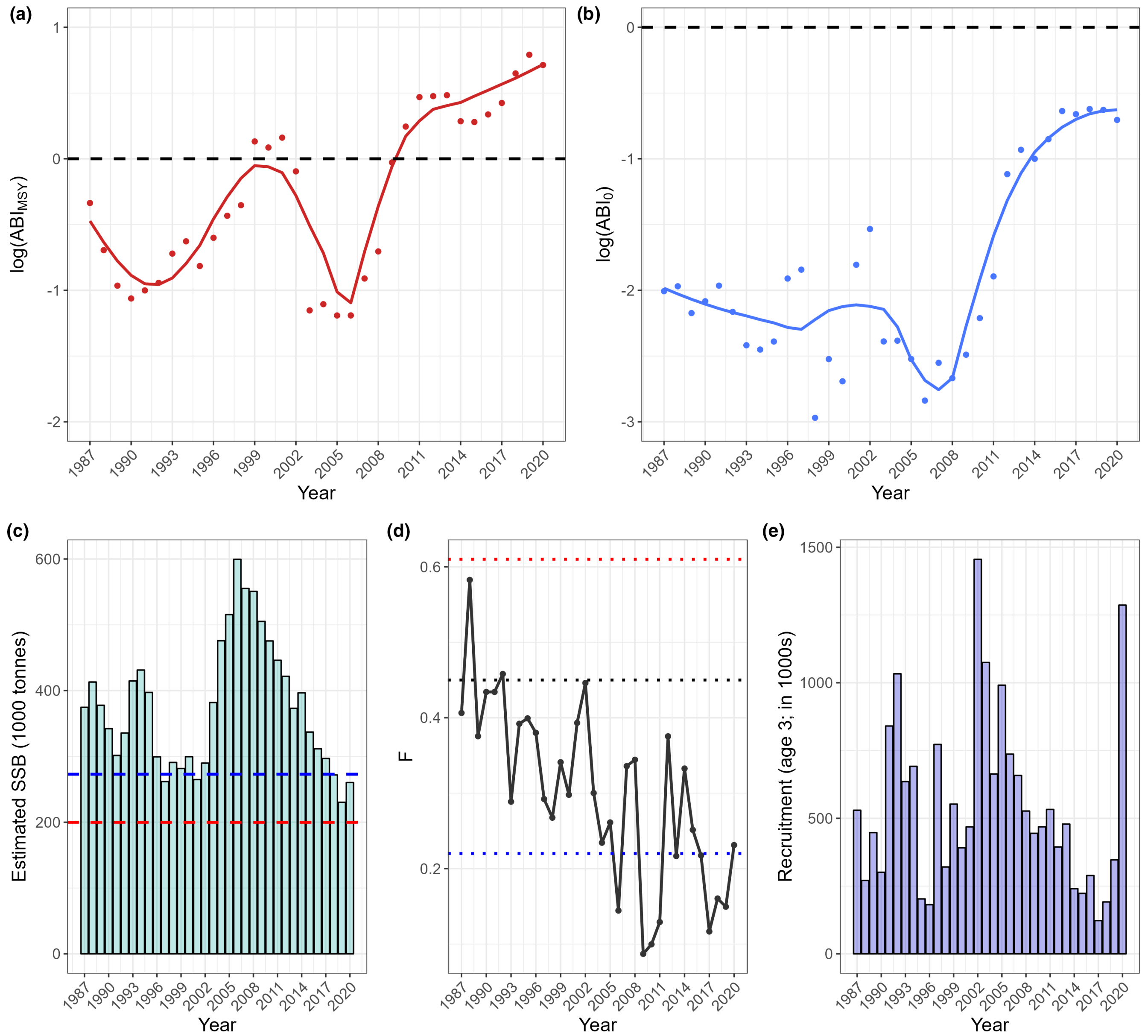

FIGURE 3 Summary of age structure and stock status for summer spawning Atlantic herring (*Clupea harengus*, Clupeidae) on the Icelandic grounds (her.27.5a). Time series of age structure relative to F_{MSY} and age structure relative to F_0 are shown in panels A and B respectively. A loess smoother with a default smoothing span has been fitted to provide a visualisation of any underlying trend. This smoother is used for visualisation and is not used in the calculation or evaluation of age structure. The black dotted line in panels A and B demonstrates the point at which the 90th percentile of the numbers-at-age distribution of the stock is equivalent to the 90th percentile of the numbers-at-age at equilibrium under F_{MSY} and F_0 conditions respectively. ABI$_{MSY}$ and ABI$_0$ have been plotted on the log scale to ensure consistency with Figures 5 and 6. The estimated SSB, *F* and recruitment are shown in panels C, D and E respectively. Recruitment is assumed to be the number of individuals in the youngest age class of the assessment. The coloured lines in panels C and D represent the following reference points: B_{lim} (red dashed) and $B_{trigger}$ (blue dashed), F_{lim} (red dotted), F_{pa} (black dotted) and F_{MSY} (blue dotted). Reference points for each stock are detailed in Table S2. Data and plots for all 72 stocks are available upon request or can be generated using the code provided (see Data availability statement for more details).

In ple.27.21–23 (Figure 4), both ABI$_{MSY}$ and ABI$_0$ are low and have remained so through time. In comparison, SSB and *R* are high, with 2020 being the highest on record for both metrics. *F* was historically high but has declined through time and is currently estimated to be below F_{MSY}. These trends illustrate that the stock is in a good state in relation to SSB reference points, however, the proportion of older fish remains low.

3.1 | Age structure relative to F_{MSY}

Across the 72 stocks, 45 stocks (62%) have ABI$_{MSY}$ values below 1.0 in the final year of their assessment, with 22 stocks (31%) below 0.5, meaning they currently have proportionally fewer older fish than under F_{MSY} conditions (Figure 5). Amongst these stocks, cod in the English Channel (cod.27.7e-k), haddock (*Melanogrammus aeglefinus*,

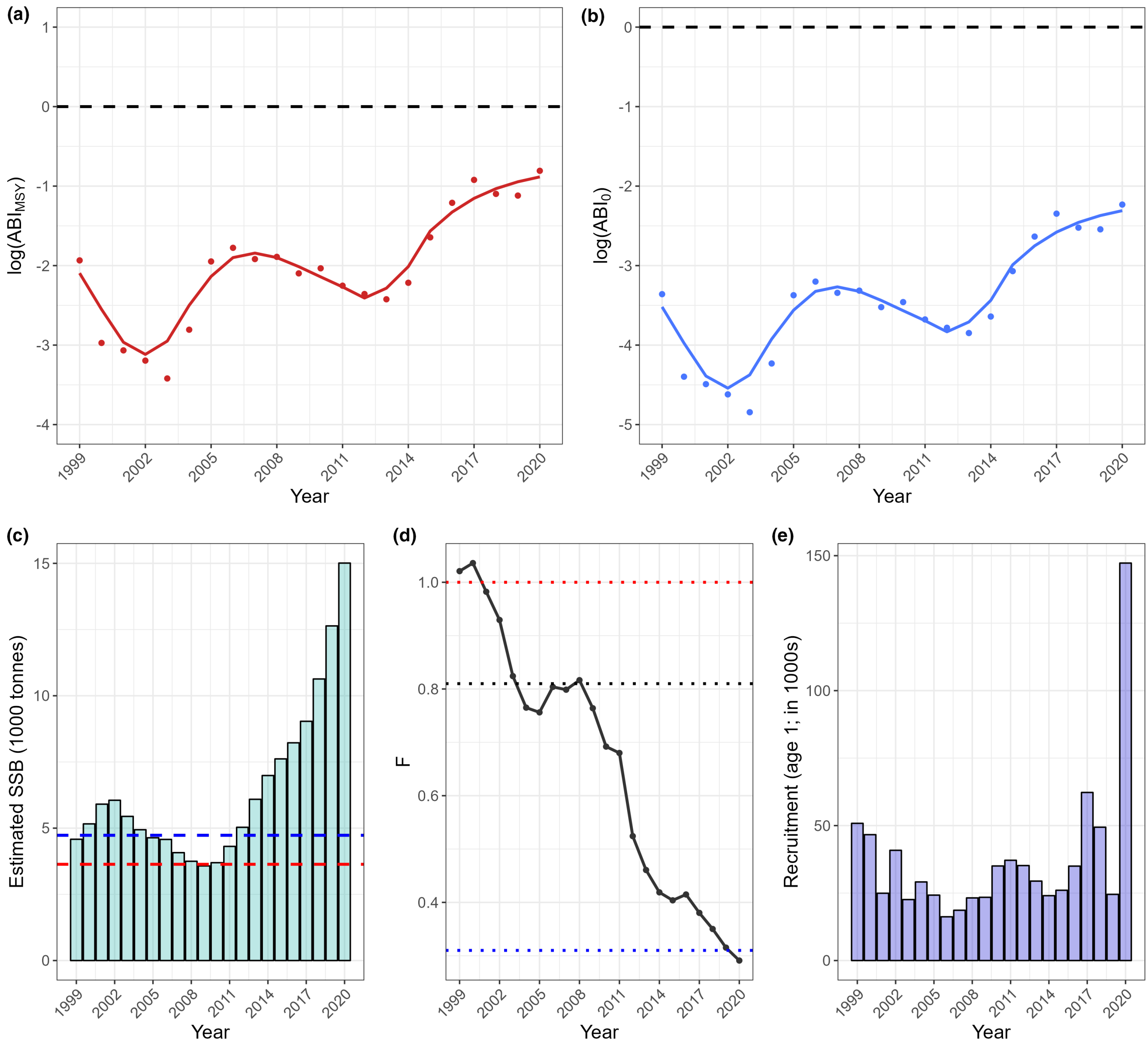

FIGURE 4 Summary of age structure and stock status for European plaice (*Pleuronectes platessa*, Pleuronectidae) in the Kattegat, Belt Seas and the Sound (ple.27.21–23). See Figure 3 for further details.

Gadidae) around Rockall (had.27.6b) and sole (*Solea solea*, Soleidae) in the North Sea (sol.27.4) have the lowest ABI_{MSY} values. These are closely followed by haddock in the North Sea, West of Scotland and in the Skagerrak (had.27.46a20), haddock in the Faroes grounds (had.27.5b) and cod in the western Baltic Sea (cod.27.22–24). In terms of stocks status, the two cod stocks have low (<1) $SSB/B_{trigger}$ values and high (>1) F/F_{MSY} values. All three haddock stocks have estimated SSB that are above or close to their respective $B_{trigger}$ reference points, with SSB seemingly increasing in all three stocks (current $SSB/B_{trigger}$ estimate represents the maximum observed in the last 5 years). Sol.27.4 is estimated to have low SSB and an F that is close to F_{MSY}.

In comparison, 27 stocks (38%) have ABI_{MSY} values above 1.0 in the final year of their assessment, meaning they have proportionally more older fish than under F_{MSY} conditions. Notable examples include Atlantic herring autumn spawners in the North Sea, Skagerrak and Kattegat and eastern English Channel (her.27.3a47d), white anglerfish in the Cantabrian Sea and Atlantic Iberian waters (mon.27.8c9a) and mackerel (*Scomber scombrus*, Scombridae) in the Northeast Atlantic and adjacent waters (mac.27.nea). Another noteworthy stock is cod in the Irish Sea (cod.27.7a) which despite having very low estimates of $SSB/B_{trigger}$ and R/R_0 (0.59 and 0.27 in 2021 respectively), seems to have an age structure that is skewed towards older fish (Figure S4).

When split by area and taxonomic family, several patterns emerge (Figure 6; Tables S7 and S8). In the North Sea, 11 out of 14 stocks (79%) have current ABI_{MSY} values below 1.0, with an average of 0.80. Similarly low values exist in the Celtic Seas (0.68), in the Faroes grounds

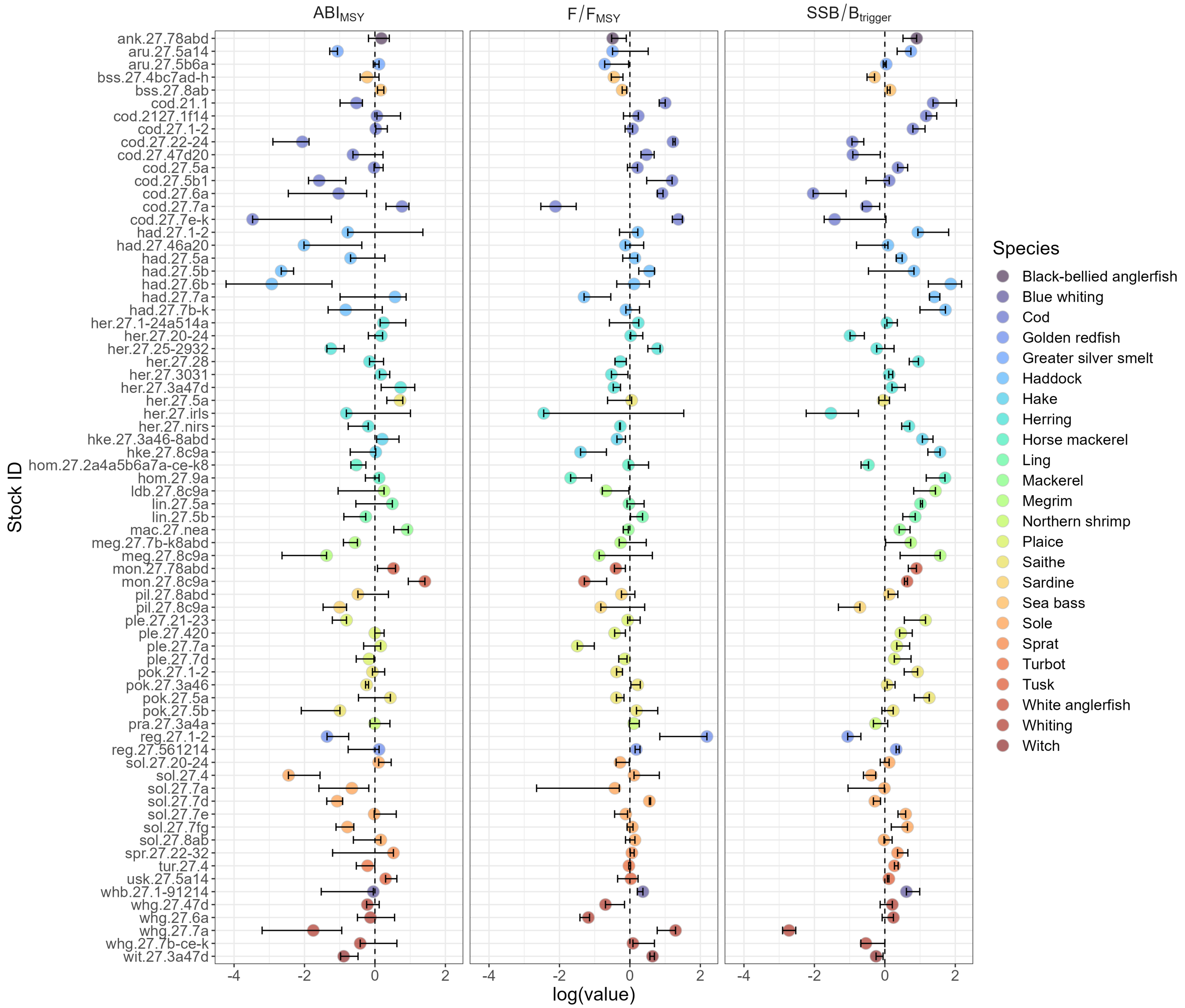

FIGURE 5 ABI_{MSY}, F/F_{MSY} and $SSB/B_{trigger}$ for all 72 stocks. Points represent the value in the final year of the assessment, with error bars the minimum and maximum values observed over the last 5 years of the assessment. The choice to use minimum and maximum as opposed to a measure of deviation was to provide a graphical representation of where each stock is now, based on where it has recently been. In most stocks, this 5-year period spans 2016–2020 ($n=63$), whereas in others it spans 2017–2021 ($n=6$) or 2015–2019 ($n=12$). Black dashed line in each panel signifies equivalence between the reference point and the value of interest (e.g. $SSB=B_{trigger}$). F_{MSY} and $B_{trigger}$ values for each stock are detailed in Table S2. Values are presented on the log scale to aid visualisation.

(0.51) and in the Baltic Sea (0.89). In fact, the number of stocks with ABI_{MSY} values that exceed 1.0 is less than 50% in 9 out of 13 areas.

Amongst the taxonomic families investigated, Pleuronectidae (80%), Gadidae (75%) and Scophthalmidae (75%) have the largest percentage of stocks with current ABI_{MSY} values below 1.0. In comparison, Lophiidae has an average ABI_{MSY} value of 2.34.

3.2 | Age structure relative to F_0

Only one stock currently has an age structure relative to F_0 that exceeds 1.0—cod in the Irish Sea (cod.27.7a; Figure S5). Amongst the other 72 stocks, the majority of stocks have ABI_0 values between 0 and 0.40 (67 stocks; 93%). Other notable stocks are plaice (ple.27.7a) and haddock (had.27.7a) in the Irish Sea, and whiting (*Merlangius merlangus*, Gadidae) in the waters west of Scotland (whg.27.6a), which have current ABI_0 values of 0.48, 0.84 and 0.44 respectively.

3.3 | Correlations

ABI_{MSY} is found to be strongly negatively correlated with F/F_{MSY} ($r=-0.71$; p-value$<.001$; Figure 7; Table S9). ABI_{MSY} is also found to be positively correlated with $SSB/B_{trigger}$ ($r=0.36$; p-value$=.002$) and Years at $F<F_{MSY}$ ($r=0.57$; p-value$<.001$). No clear correlation exists between ABI_{MSY} and R/R_0 ($r=-0.03$; p-value$=.83$).

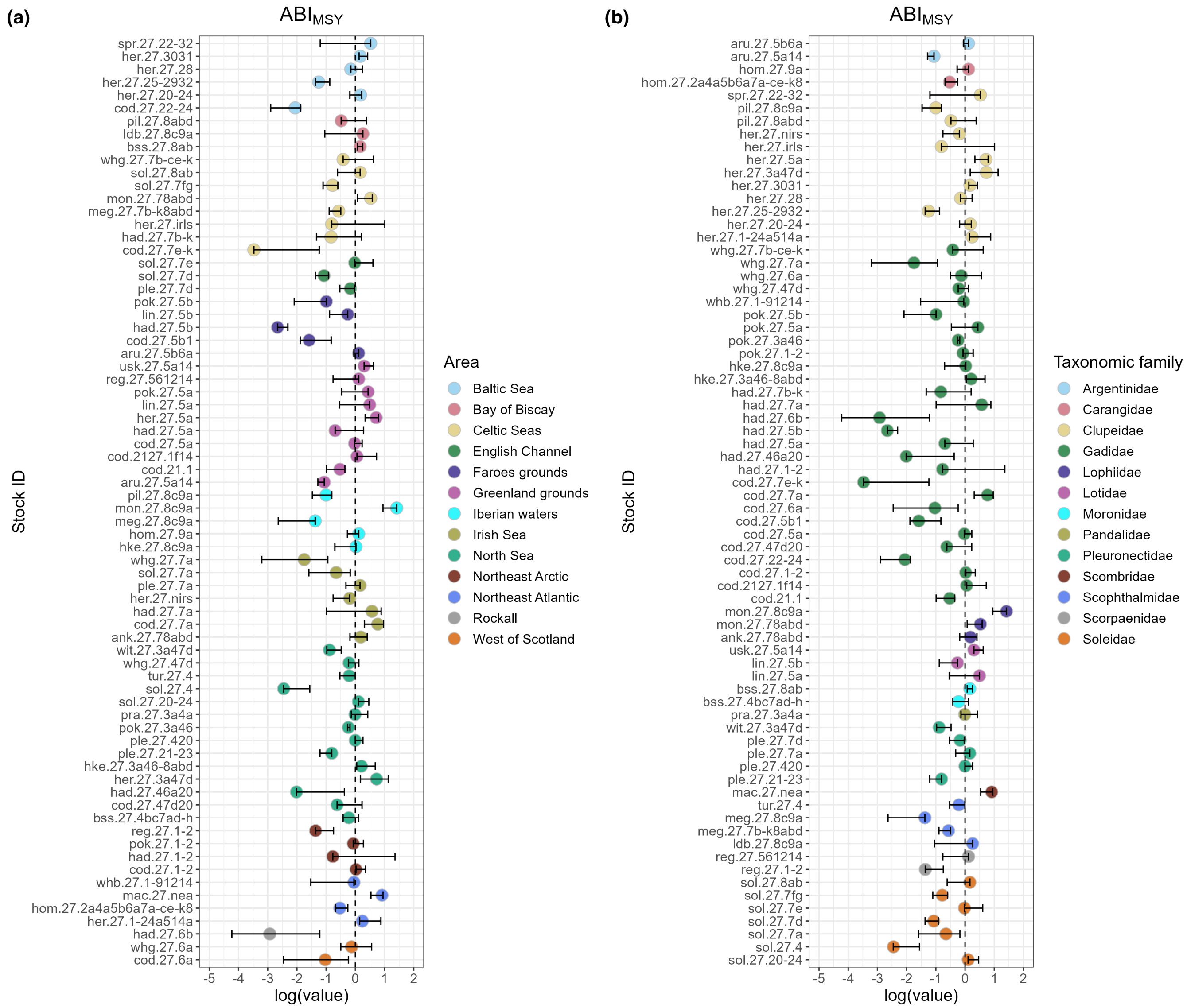

FIGURE 6 ABI_{MSY} plotted by area (a) and taxonomic family (b). As in Figure 5, points represent the value in the final year of the assessment, with error bars the minimum and maximum values observed over the last 5 years. The black dashed line in each panel signifies equivalence between the 90th percentile of the numbers-at-age distribution of the stock and the 90th percentile of the numbers-at-age distribution at equilibrium under F_{MSY} conditions. Areas are broadly characterised based on ICES divisions and ecoregions. Taxonomic information for each species was sourced from FishBase (Froese & Pauly, 2022). Details of area and taxonomic family by stock are provided in Table S1. Values are presented on the log scale to aid visualisation.

We also note positive correlations between $SSB/B_{trigger}$ and R/R_0 ($r = 0.56$; p-value $< .001$), and between $SSB/B_{trigger}$ and Years at $F < F_{MSY}$ ($r = 0.37$; p-value $= .001$). $SSB/B_{trigger}$ is also negatively correlated with F/F_{MSY} ($r = -0.41$; p-value $< .001$).

3.4 | Simulations and ROCs

The simulated trajectories of SSB, R, yield and ABI_{MSY} for the six selected stocks across two levels of recruitment variability are provided in Figure 8. These simulations show that ABI_{MSY} follows the inverse of F in all six stocks, independent of life history and recruitment variability. The simulations also show that differences in life history and σ_R do influence the uncertainty around ABI_{MSY} but not the temporal trend of ABI_{MSY}.

The ROC curves demonstrate that for most stocks and levels of σ_R, ABI_{MSY} is capable of correctly identifying a high number of cases when $B/B_{MSY} > 0.8$ (TSS values between 0.3 and 0.77; Figure 9). The only exceptions to this occur in sardine (pil.27.8c9a) and herring (her.27.3a47d) at relatively high levels of recruitment variability ($\sigma_R = 0.7$), for which the classification skill of ABI_{MSY} deteriorates to TSS values below 0.25.

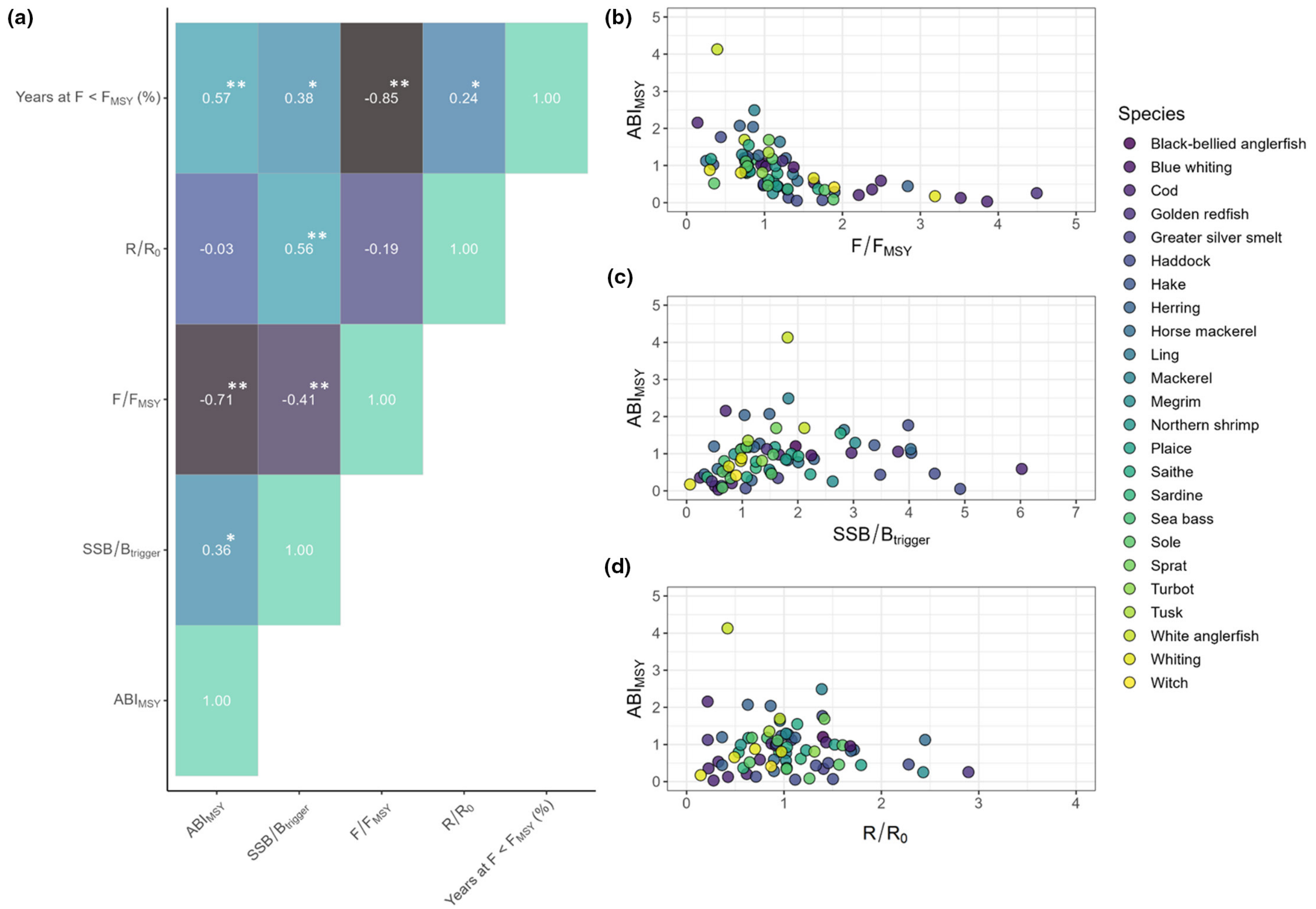

FIGURE 7 Correlation between ABI_{MSY} and several estimates of stock status. Correlation coefficients reported in panel A are non-parametric and were estimated using Spearman's rank correlation method. The estimated significance value of each correlation is reported as **highly significant ($p < .001$) or *significant ($p < .05$). Non-significance ($p > .05$) is illustrated by an absence of a symbol. In all cases, ABI_{MSY} refers to the indicator value in the final year of the assessment, whereas estimates of stock status (R/R_0, F/F_{MSY} and $SSB/B_{trigger}$) are averages taken from the last 6 years of the assessment (see Table S9 and Figure S3). Values for R_0, F_{MSY} and $B_{trigger}$ are provided for all stocks in Tables S2 and S4. Years at $F < F_{MSY}$ details the percentage number of years at which a stock has been exploited at levels lower than F_{MSY} over the last 15 years (Table S2). A 15-year period was used to ensure consistency across all 72 stocks.

4 | DISCUSSION

Larger and older fish (BOFFF fish) are expected to play an important role in stock productivity and population resilience (Barneche et al., 2018; Hixon et al., 2014; Macdonald et al., 2017; Marshall et al., 2022; Rideout et al., 2005; Wright & Trippel, 2009). Despite this, the importance of larger and older fish is often overlooked in fisheries management whereby TACs are advised based on the relation between SSB and F, and their respective reference points, with little or no consideration of age and/or size structure (Marshall et al., 2021). To help address this, we have introduced a novel age-based indicator (ABI_{MSY}) that aims to quantify departures from the expected age structure when fishing at F_{MSY}, with specific focus on the proportion of older fish. In this study, we applied ABI_{MSY} to 72 stocks in the Northeast Atlantic region. In doing so, we have shown that 45 stocks currently have proportionally fewer older fish relative to F_{MSY} conditions, whereas 27 stocks have proportionally more older fish.

ABI_{MSY} values vary by area and taxonomic family, with stocks in the North Sea, Celtic Seas and Baltic Sea, as well as stocks from the Gadidae, Soleidae and Pleuronectidae families found to have relatively low ABI_{MSY} values. Such findings match historic patterns of exploitation, whereby high levels of F and the targeting of larger and older fish in certain species and areas, has resulted in deteriorations in age structure (Barnett et al., 2017; Froese et al., 2016; Pauly et al., 1998). They also highlight that the achievement of EU MSFD D3 objectives, namely 'a population age and size distribution that is indicative of a healthy stock' (EU-COM, 2008, 2017) might require management action that varies not only by species and stock but also by area.

Based on previous work and guidelines on D3C3, three criteria have emerged for the development of operational ABIs and LBIs (EU-COM, 2017): (1) inform on the age and/or size structure of exploited fish stocks; (2) be insensitive to recent recruitment; and (3) have established reference levels that meet policy objectives. We have shown that ABI_{MSY} provides inference on the age structure of

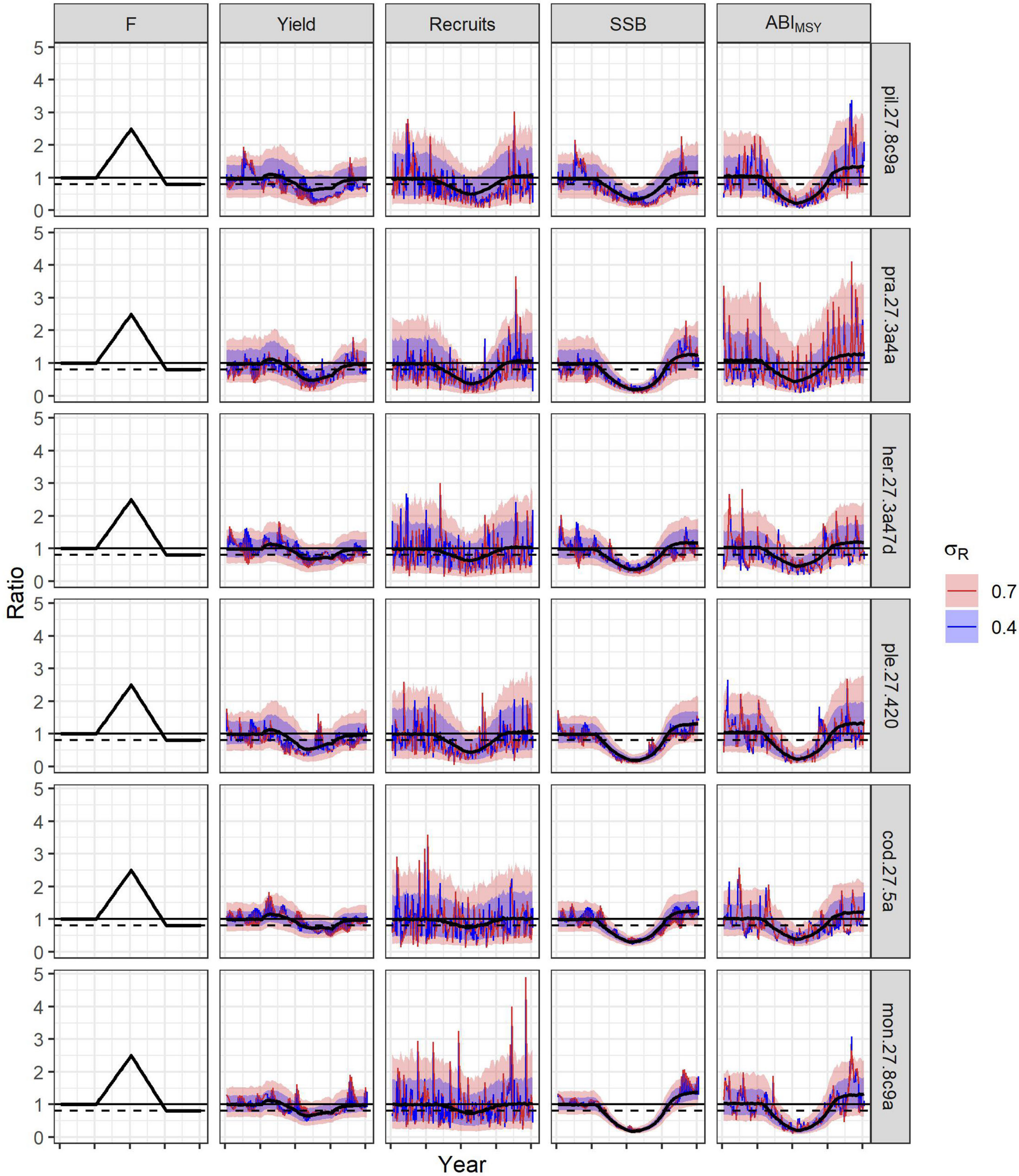

FIGURE 8 Simulated trajectories for the six selected stocks showing fishing mortality (F), yield, recruitment, SSB and ABI_{MSY}. SSB is presented as SSB relative to stock-specific B_{MSY} reference points (black line); the 80% B_{MSY} reference threshold used in the construction of the ROC curves (see Figure 9) is also shown (dashed line). *F* was initially fixed at F_{MSY} and then increased to three times F_{MSY}, after which *F* was reduced to bring *F* down to 80% of F_{MSY}. The simulations consider two different levels of recruitment variability (σ_R), 0.4 in blue and 0.7 in red, which represent a relatively low and a relatively high rate of recruitment variability respectively. The blue and red solid lines represent the medians across 1000 iterations for each recruitment scenario and the shaded areas show the corresponding 5th and 95th percentiles. The thin red and blue lines illustrate the first simulation iteration for each recruitment variability scenario respectively. The stocks are ordered by life span, which ranges from 6 years for the Iberian sardine (top) to 30 years for white anglerfish (bottom). B_{MSY} and F_{MSY} values are listed in Table S2.

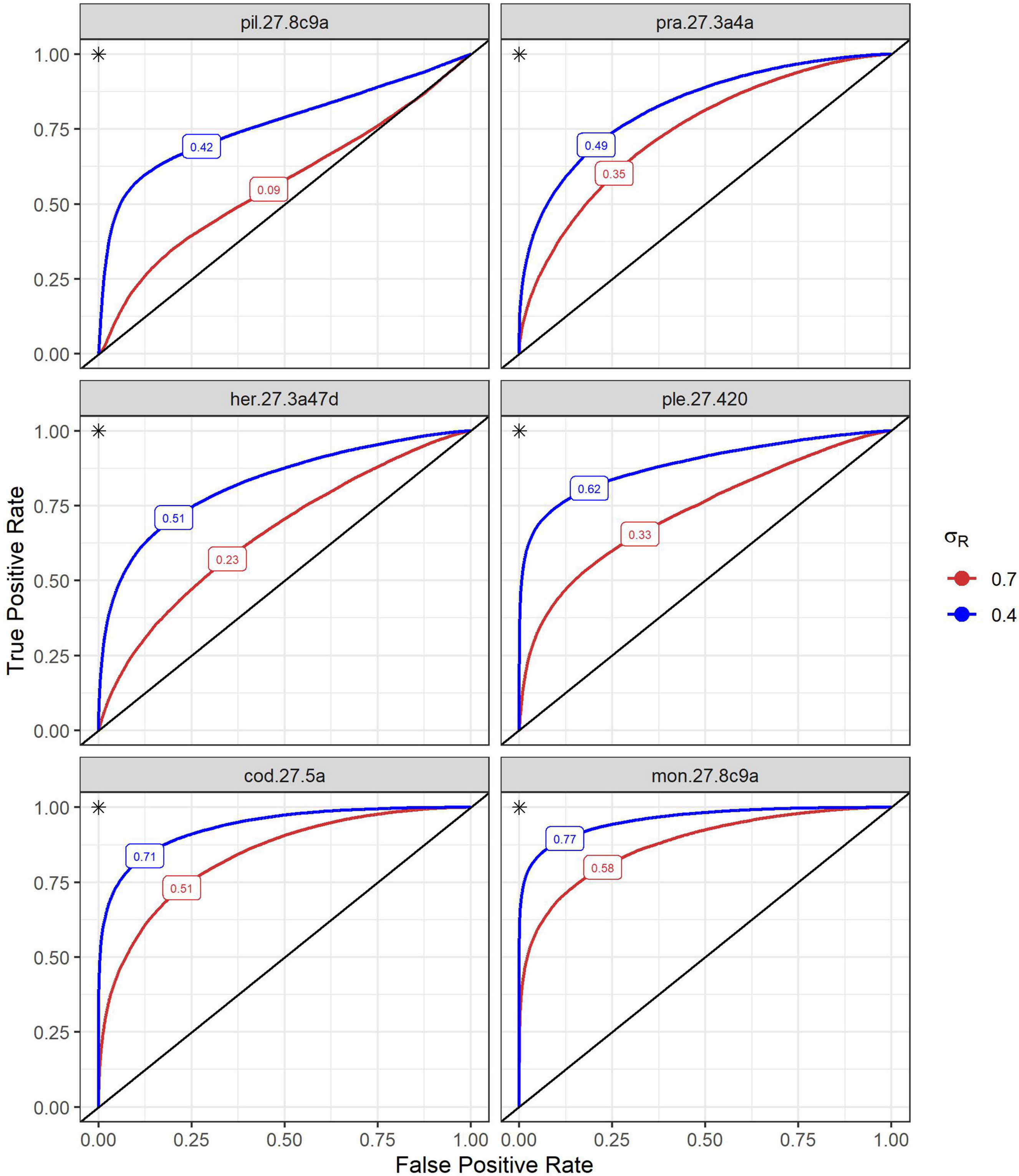

FIGURE 9 Receiver operating characteristics (ROC) curves detailing the classification skill of ABI_{MSY} for the 80% reference threshold of B/B_{MSY}. The true-positive rate (TPR) is the proportion of positive cases correctly identified and false-positive rate (FPR) is the proportion of negative cases incorrectly identified as being positive. The blue (0.4) and the red (0.7) lines correspond to the two different levels of recruitment variability (σ_R). The numeric value detailed in each plot corresponds to the true skill statistic (TSS) estimate for each stock and σ_R. The black 1:1 line is the randomisation line equivalent to a coin toss and the star in the left top corner signifies perfect classification skill of TSS = 1 (TPR = 1, FPR = 0).

commercially important stocks and thus provides information that is complementary to the current F-SSB pressure-state indicator framework. This is highlighted by the examples of European plaice in the Baltic Sea (ple.27.21–23) and Atlantic herring on the Icelandic grounds (her.27.5a). In both of these cases, an assessment of stock status based on SSB and F would leads to conclusions and advice that might not necessarily fit with each stock's estimated age structure. For instance, in ple.27.21–23 a high SSB and R, and a low F, would likely lead to a conclusion that the stock is in a good state and an advised increase in TAC. In fact, the 2021 assessment of this stock recommended a 70% increase in TAC (ICES, 2021c). However, ABI_{MSY} suggests that the stock currently has an abundance of young fish and that there is, proportionally, fewer older fish than under constant F_{MSY} conditions. Increases in catch could therefore lead to growth overfishing, whereby fish are removed before they have had a chance to reach their full growth potential (Jennings et al., 2001). Moreover, in trawl fisheries for plaice that target larger and older fish, and have an elevated discard survival rates (~15%–60% across studies; Morfin et al., 2017; van der Reijden et al., 2017), any large increase in TAC could result in a skewed removal of older fish and a greater truncation of the stock's age structure. In comparison, in her.27.5a we observe a low SSB and a high F compared to their respective reference points and this might suggest a poor stock status (ICES, 2021b). Conversely to this assessment, ABI_{MSY} suggests that the stock has an age structure that is above F_{MSY} reference levels and therefore has a high proportion of older fish. This is most likely linked to recent F values that have been around F_{MSY} for several years and have allowed the age structure of the stock to rebuild over time. In fact, the absolute number of older fish above A_{MSY} is slightly larger than at equilibrium under F_{MSY}. Thus, the stock retains the potential to be productive (it has a large amount of older fish) in the coming years and has an age structure that could enhance recovery towards MSY levels, subject to the retention of those older fish in the population and the survival of recruits. Albeit, it is important to note that her.27.5a has experienced a consistent decline in recruitment over recent years, and we cannot exclude this may have had marginal effects on ABI_{MSY}. Such marginal effects highlight that ABI_{MSY} should not be used in isolation but alongside other estimates of stock status as suggested for other similar indicators (e.g. Fischer et al., 2020, 2021b).

The utility of ABI_{MSY} is also shown in the unique case of Atlantic cod in the Irish Sea (cod.27.7a). In fact, this stock is the only stock that currently has an age structure relative to F_{MSY} and F_0 value that exceeds 1.0 (Figure S5). This is somewhat of a surprising finding, especially considering the historic levels of exploitation for this stock (Figure S4) and the expectation that the age structure of an unfished population at equilibrium would have (on average) the largest quantity of older fish. The reasons why an ABI_0 value above 1.0 might arise are manifold and link directly to the stock assessment model used to assess the stock. Cod in the Irish Sea is widely considered to have collapsed (Christensen et al., 2003; ICES, 2022c; Kelly et al., 2006) and there are concerns that the current assessment model does not account for time-varied changes in natural mortality (assumed constant for the Irish Sea cod), the immigration/emigration of fish (thought to be substantial between Irish Sea, Celtic Sea and West of Scotland; Neat et al., 2014), and time-varying changes in carrying capacity (ICES, 2023b). All of these factors can contribute to change the age structure of stock and might cause estimated age structures to differ from those expected from simulations based on assessment outputs. Thus, this finding highlights two important points: (1) that research on Irish Sea cod might need to broaden and possibly redirect research efforts towards other drivers of low stock biomass and recruitment failures, such as Allee effects (Allee, 1938; Gascoigne & Lipcius, 2004) as the stock does not appear to be lacking older fish; and (2) that the quality of any indicator (including ABI_{MSY}) derived from stock assessment data will always be tied to the quality of the stock assessment model used to assess the stock.

Using correlation analysis we have also shown that ABI_{MSY} displays no clear trend with R/R_0, and exhibits a weak positive relationship with $SSB/B_{trigger}$ and a strong negative relationship with F/F_{MSY} (Figure 7). We have also shown that these relationships are consistent across a range of recent temporal windows (Figure S3). In reality, more work will be needed on the relationships between ABI_{MSY} and these metrics of stock status (especially recruitment) prior to implementation. For instance, it would be interesting to explore biologically motivated temporal lags linked to species-specific generation times or years to maturation. That withstanding, the observed findings already give us an indication on how ABI_{MSY} might inform management decisions. The observed relationship between ABI_{MSY} and F illustrates that exploitation levels that exceed F_{MSY} reference points result in the loss of older fish and cause a truncation in age structure. This is further reinforced by a strong positive relationship between ABI_{MSY} and years at $F < F_{MSY}$. These findings reflect established theory in fisheries science that small reductions in F below F_{MSY} will increase the number of larger and older fish in the population and facilitate greater stock productivity and resilience to environmental perturbations (Froese et al., 2008; Hixon et al., 2014; Wright & Trippel, 2009), at a cost of small reductions in long-term yield (Mace, 1994). Such links between positive stock status and exploitation slightly below F_{MSY} also mirror recent calls for MSY to be used as a limit, and not as a target, by fisheries managers (ICES, 2022a). In fact, this relationship is foundational to the concept of 'Pretty Good Yield' as proposed by Hilborn (2010) and others (Earle, 2021; Rindorf et al., 2017), and has even been extended in a multispecies context by Rindorf et al. (2017) to account for stock effects on ecosystems, sustainability and socio-economic benefits (Bastardie et al., 2022).

ABI_{MSY} also has an established reference point, namely age structure at equilibrium under F_{MSY}. When it comes to fisheries management, F_{MSY} reference levels provide a common currency, and therefore should allow the concept of ABI_{MSY} (i.e. an age structure that is close to that expected at equilibrium under F_{MSY}) to be incorporated within that same framework in the future. For example, advice on TACs in the Northeast Atlantic is regularly provided by ICES in the context of F_{MSY}, and we expect that ABIs with F_{MSY} reference levels are likely to be translational from scientists to managers, as well as from managers to policy makers. In addition to this, we have shown via simulation testing that ABI_{MSY} has generally a high classification skill (assessed using TSS) with respect to B/B_{MSY}. In particular, the simulation experiments showed that its classification skill only deteriorates under an assumption of relatively high recruitment variability for certain species. These findings suggest that in most cases having an ABI_{MSY} value that exceeds 0.8 means that a stock has an age structure that corresponds to biomass levels above a lower threshold of 80% of B_{MSY}, a threshold that is globally used to indicate a healthy stock status (DFO, 2009; Sharma et al., 2021). This potentially paves the way for age structure to be included among the stock characteristics contributing to long-term sustainability. For example, currently the main sustainable biomass threshold used by ICES is $B_{trigger}$, which for most stocks is set at B_{pa} (ICES, 2022a) that is a precautionary biomass reference point that provides a buffer to B_{lim}. Consequently, $B_{trigger}$ provides no direct means to assess whether a stock has a sufficiently healthy age structure comparable to B_{MSY} that is capable of producing average MSY in the long-term. For instance, a stock might have an SSB that exceeds $B_{trigger}$ but may still be recovering from past exploitation and, if exploited too soon, might not yet be capable of producing the expected long-term yield (i.e. it has not had time to rebuild its age structure). This temporal lag between SSB and F, and ABI_{MSY}, will require further investigation on a stock-by-stock basis prior to implementation. Moreover, it is noteworthy that our main fisheries management tool is to reduce F to increase the probability that strong recruitment occurs, but if this action is taken in response to a low ABI_{MSY} value, then we would expect a lag to occur between management action and a response in ABI_{MSY}.

When it comes to the assessment of GES, national government organisations might favour a more precautionary approach and, in this respect, comparisons to F_0 might provide additional insights for setting adequate thresholds. In this case, however, it is likely to be challenging to define tangible reference levels based on F_0. Thus, future development of our framework could move towards a percentage of F_0 as a suitable reference level for the assessment of GES (Ministry of Fisheries, 2011) such as using more precautionary MSY proxies, for example, the age structure at F_{B40}, which corresponds to the F that produces 40% of B_0 (Punt et al., 2014). This percentage is likely to vary on a stock-by-stock basis based on biological traits such as generation time, age-at-maturity, and productivity as proposed during WKREF1 (ICES, 2022a). Moreover, a prerequisite to this work might be to answer a fundamental question in this area, namely, what age and/or size structure is indicative of a healthy stock? Addressing this question holistically is beyond the scope of this study, and therefore we have chosen to use B_{MSY} or some percentage threshold of B_{MSY} to provide first evidence that ABI_{MSY} has good classification skill with respect to B/B_{MSY}.

In addition to F_{MSY} and F_0, our approach could consider any level of F when estimating a stock's age structure at equilibrium. This coupled with flexibility on the assumptions around a stock's demographic and selectivity parameters, would allow scientists and managers to conduct stock-specific management strategy evaluations (MSEs) that use age structure as an additional performance criterion alongside conventional targets for SSB and F. For instance, one might use such MSEs to test the responsiveness and recovery rate of a stock's age structure to future decisions on F and selectivity. Conceptually, this could mean that future harvest control rules could include an additional age structure dimension whereby a target F is reduced if a stock's age structure is below an established target. This is already used in harvest control rules where F is multiplied by the ratio between current the SSB and the value of MSY $B_{trigger}$. Such an approach might allow for the inclusion of age structure in the exploration of management options by fisheries managers, national government organisations and policy makers.

When forecasting the age structure of a stock forward to equilibrium under a given F, we have made several assumptions about how fundamental biological processes will occur in the future. For instance, for recruitment, we have assumed deterministic recruitment derived from a SRR. This assumption means that our reference levels are fixed and lack measures of uncertainty. In reality, natural variability in recruitment can be large, especially in short- and medium-lived species (Shephard et al., 2014), and is likely to be impacted by future environmental change (Kjesbu et al., 2022). Future work could consider running simulations with uncertainty in recruitment (e.g. stochastic variations around the SR function as used in Brunel & Piet, 2013) and should explore particular recruitment patterns like those observed in stocks like North Sea haddock (had.27.46a20) and Norwegian spring-spawning herring (her.27.1-24a514a), whereby recruitment is often characterised by the rare appearance of very large year classes (i.e. pulse recruitment events). Future simulations could also test higher levels of recruitment variability than those considered here (e.g. $\sigma_R > 0.7$) or the incorporation of stochasticity in other key biological parameters (e.g. weight, maturity and natural mortality) when estimating a stock's age structure under a given F. Any such stochastic simulations would result in an age structure that could be described by a median and a distribution, and allow reference levels (i.e. P_{MSY}) to be approximated as a distribution as opposed to a point estimate, an approach not dissimilar to that used in the stock assessment of northern shrimp in ICES Divisions 3a and 4a east (ICES, 2022b).

Past studies have also shown that fisheries selectivity is an important driver of age structure in fish populations (Brunel & Piet, 2013; Vasilakopoulos et al., 2011, 2020). Here, we have assumed that recent selectivity (as estimated from the last 3 years of assessment) will continue into the future. Selectivity will undoubtedly vary through time as fishers change their behaviour and fishing patterns (Jennings et al., 2001), as well as their gear in response to technological advancements and/or management actions (e.g. restrictions on mesh size; Wienbeck et al., 2011). Nevertheless, our assumptions on selectivity, biology and recruitment match those made routinely in stock assessments when running MSEs and estimating reference points (e.g. F_{MSY}, F_{lim}, $B_{trigger}$ and B_{lim}), thus our approach aligns well with current stock assessment methods within ICES and other scientific councils (e.g. ICCAT [International Commission for the Conservation of Atlantic Tunas] and PICES [North Pacific Marine Science Organization]). That said, to ensure consistency we advise that ABI_{MSY} should be calculated using the same stock-specific assumptions on biology and selectivity that are used for the calculation of other reference points. The use of recent selectivity assumptions is also part of the reason why we have chosen to focus on the current state of a stock (in the terminal year of the assessment) in most cases as opposed to discussing how ABI_{MSY} values have changed through time. That said, it remains unknown whether current selectivity can be considered representative of future selectivity, and therefore further work on the use of alternative selectivity assumptions would be highly informative. For example, such studies could build on the simulation work of ICES (2017b) and other authors (Kell et al., 2022a; Vasilakopoulos et al., 2020) and test the robustness of ABI_{MSY} to different selectivity assumptions and evaluate how future selectivity could be modified to achieve management objectives on age structure (EU-COM, 2008; STECF, 2021).

5 | CONCLUSIONS

Here, we have introduced a new ABI and framework for commercial fish stocks (ABI_{MSY}), aligned with MSY reference levels, and applied it to 72 stocks in the Northeast Atlantic region. In doing so, we have shown that some stocks currently have proportionally less older fish than under F_{MSY} levels, whereas others have more. We have also shown that ABI_{MSY} values vary by area and taxonomic family. Building on these findings, we have used examples to demonstrate how ABI_{MSY} can provide information on age structure that is both complementary to, and informative to current advisory frameworks on fisheries management. Moreover, using simulation testing, we have shown that ABI_{MSY} has high classification skill for a healthy stock status threshold of 80% of B/B_{MSY}, thus providing a clearly defined link between the age structure of exploited stocks and biomass at MSY.

Additionally, we suggest that ABI_{MSY} meets the required specifications for D3C3, that is, it provides information on older fish, initial investigations suggest it is not overly sensitive to recent recruitment, and it has reference levels that are in line with the MSY approach and the overarching objectives of policies like the CFP and the MSFD. In doing so, we have demonstrated that ABI_{MSY} responds effectively to changes in fishing intensity and temporal extent of past exploitation. This is a desirable characteristic for managers and policy makers, as it highlights a cause-and-effect relationship that could support decision making and aligns well with the current state-pressure indicator framework. In particular, it demonstrates that by controlling for fishing mortality (the pressure), proportions of older fish (the state) that are comparable to those under F_{MSY} conditions (the reference level) can be achieved. This will therefore pave the way for age structures that are more in line with management objectives and are able to produce MSY (i.e. B_{MSY}).

ACKNOWLEDGEMENTS

We thank our colleagues at SLU Aqua for their comments and collective input to this work, in particular Lena Bergström, Jens Olsson, Elisabeth Bolund and Max Lindmark. Thanks are also due to Christopher Lynam and Robert Thorpe at Cefas, Mark Taylor at the Thünen Institute, and Colm Lordan at the Marine Institute, as well as six reviewers, all of which provided insightful and constructive comments on our work. We would also like to thank all members of the ICES WKREF working group whose collation of a stock assessment dataset was foundational to this work. The work was funded by the Swedish Agency for Marine and Water Management (SwAM; contract code 01068–2022).

DATA AVAILABILITY STATEMENT

The original dataset of stock assessment inputs and outputs ($n=78$) is freely available via ICES as part of the WKREF working group. Updated data (including FLR stock objects for all 81 stocks) and *R* code to simulate a stocks' age structure at equilibrium, calculate ABI_{MSY} and ABI_0, and recreate figures are publicly accessible on GitHub at https://github.com/cagriffiths/ABIs-fish.

ORCID

Christopher A. Griffiths https://orcid.org/0000-0001-7203-0426
Henning Winker https://orcid.org/0000-0003-4774-4499
Valerio Bartolino https://orcid.org/0000-0002-4506-4329
Håkan Wennhage https://orcid.org/0000-0001-9631-5688
Alessandro Orio https://orcid.org/0000-0002-5566-6139
Massimiliano Cardinale https://orcid.org/0000-0003-1870-3882

REFERENCES

Allee, W. C. (1938). *Animal aggregations: A study in general sociology*. University of Chicago Press.

Allouche, O., Tsoar, A., & Kadmon, R. (2006). Assessing the accuracy of species distribution models: Prevalence, kappa and the true skill statistic (TSS). *Journal of Applied Ecology*, *43*, 1223–1232.

Barneche, D. R., Robertson, D. R., White, C. R., & Marshall, D. J. (2018). Fish reproductive-energy output increases disproportionately with body size. *Science*, *360*(6389), 642–645. https://doi.org/10.1126/science.aao6868

Barnett, L. A. K., Branch, T. A., Ranasinghe, R. A., & Essington, T. E. (2017). Old-growth fishes become scarce under fishing. *Current Biology*, *27*(18), 2843–2848.e2. https://doi.org/10.1016/j.cub.2017.07.069

Bastardie, F., Feary, D. A., Brunel, T., Kell, L. T., Döring, R., Metz, S., Eigaard, O. R., Basurko, O. C., Bartolino, V., Bentley, J., Berges, B., Bossier, S., Brooks, M. E., Caballero, A., Citores, L., Daskalov, G., Depestele, J., Gabiña, G., Aranda, M., … van Vlasselaer, J. (2022). Ten lessons on the resilience of the EU common fisheries policy towards climate change and fuel efficiency—A call for adaptive, flexible and well-informed fisheries management. *Frontiers in Marine Science*, *9*, 947150. https://doi.org/10.3389/fmars.2022.947150

Beverton, R. J. H., & Holt, S. J. (1993). *On the dynamics of exploited fish populations*. Springer.

Blanchard, J. L., Dulvy, N. K., Jennings, S., Ellis, J. R., Pinnegar, J. K., Tidd, A., & Kell, L. T. (2005). Do climate and fishing influence size-based indicators of Celtic Sea fish community structure? *ICES Journal of Marine Science*, *62*(3), 405–411. https://doi.org/10.1016/j.icesjms.2005.01.006

Brander, K. M. (2005). Cod recruitment is strongly affected by climate when stock biomass is low. *ICES Journal of Marine Science*, *62*, 339–343.

Brunel, T., & Piet, G. J. (2013). Is age structure a relevant criterion for the health of fish stocks? *ICES Journal of Marine Science*, *70*(2), 270–283. https://doi.org/10.1093/icesjms/fss184

Christensen, V., Guenette, S., Heymans, J. J., Walters, C. J., Watson, R., Zeller, D., & Pauly, D. (2003). Hundred-year decline of North Atlantic predatory fishes. *Fish and Fisheries*, *4*, 1–24.

Cooper, W. T., Barbieri, L. R., Murphy, M. D., & Lowerre-Barbieri, S. K. (2013). Assessing stock reproductive potential in species with indeterminate fecundity: Effects of age truncation and size-dependent reproductive timing. *Fisheries Research*, *138*, 31–41. https://doi.org/10.1016/j.fishres.2012.05.016

Corten, A. (1999). A proposed mechanism for the Bohuslän herring periods. *ICES Journal of Marine Science*, *56*(2), 207–220.

Corten, A. (2002). The role of "conservatism" in herring migrations. *Reviews in Fish Biology and Fisheries*, *11*, 339–361.

Darimont, C. T., Carlson, S. M., Kinnison, M. T., Paquet, P. C., Reimchen, T. E., & Wilmers, C. C. (2009). Human predators outpace other agents of trait change in the wild. *Proceedings of the National Academy of Sciences of the United States of America*, *106*(3), 952–954. https://doi.org/10.1073/pnas.0809235106

DFO. (2009). A fishery decision-making framework incorporating the precautionary approach. https://www.dfo-mpo.gc.ca/reports-rapports/regs/sff-cpd/precaution-eng.htm

Dichmont, C. M., Pascoe, S., Kompas, T., Punt, A. E., & Deng, R. (2010). On implementing maximum economic yield in commercial fisheries. *Proceedings of the National Academy of Sciences of the United States of America*, *107*(1), 16–21. https://doi.org/10.1073/pnas.0912091107

Earle, M. (2021). Maximum sustainable yield in the EU's common fisheries policy—A political history. *ICES Journal of Marine Science*, *78*(6), 2173–2181. https://doi.org/10.1093/icesjms/fsab037

EU. (2013). Regulation (EU) No 1380/2013 of the European parliament and of the council of 11 December 2013 on the common fisheries policy, amending council regulations (EC) No 1954/2003 and (EC) No 1224/2009 and repealing council regulations (EC) No 2371/2002 and (EC) No 639/2004 and council decision 2004/585/EC. *Official Journal of the European Union*, *L354*, 22–61.

EU-COM. (2008). Directive 2008/56/EC of the European Parliament and of the council of 17 June 2008 establishing a framework for community action in the field of marine environmental policy (marine strategy framework directive). *Official Journal of the European Union*, *L164*, 19–40.

EU-COM. (2017). Commission decision (EU) 2017/848 of 17 may 2017 laying down criteria and methodological standards on good environmental status of marine waters and specifications and standardised methods for monitoring and assessment, and repealing decision 2010/477/EU. *Official Journal of the European Union*, *L125*, 43–74.

Fawcett, T. (2006). An introduction to ROC analysis. *Pattern Recognition Letters*, *27*(8), 861–874.

Fischer, S. H., De Oliveira, J. A. A., & Kell, L. T. (2020). Linking the performance of a data-limited empirical catch rule to life-history traits. *ICES Journal of Marine Science*, *77*(5), 1914–1926.

Fischer, S. H., De Oliveira, J. A. A., Mumford, J. D., & Kell, L. T. (2021). Application of explicit precautionary principles in data-limited fisheries management. *ICES Journal of Marine Science*, *78*(8), 2931–2942.

Fischer, S. H., Oliveira, J. A. A., Mumford, J. D., & Kell, L. T. (2021). Using a genetic algorithm to optimize a data-limited catch rule. *ICES Journal of Marine Science*, *78*, 1311–1323.

Fitzhugh, G. R., Shertzer, K. W., Kellison, G. T., & Wyanski, D. M. (2012). Review of size- and age-dependence in batch spawning: Implications for stock assessment of fish species exhibiting indeterminate fecundity. *Fishery Bulletin*, *110*, 413–425.

Froese, R. (2004). Keep it simple: Three indicators to deal with overfishing. *Fish and Fisheries*, *5*(1), 86–91.

Froese, R., & Pauly, D. (2022). *FishBase*. World Wide Web electronic publication. www.fishbase.org

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

Froese, R., Winker, H., Gascuel, D., Sumalia, U. R., & Pauly, D. (2016). Minimising the impact of fishing. *Fish and Fisheries*, *17*, 785–802.

Gascoigne, J., & Lipcius, R. N. (2004). Allee effects in marine systems. *Marine Ecology Progress Series*, *269*, 49–59. https://doi.org/10.3354/meps269049

Green, D. M., & Swets, J. A. (1966). *Signal detection theory and psychophysics* (Vol. *1*). Wiley & Sons.

Halpern, B. S., Walbridge, S., Selkoe, K. A., Kappel, C. V., Micheli, F., D'Agrosa, C., Bruno, J. F., Casey, K. S., Ebert, C., Fox, H. E., Fujita, R., Heinemann, D., Lenihan, H. S., Madin, E. M. P., Perry, M. T., Selig, E. R., Spalding, M., Steneck, R., & Watson, R. (2008). A global map of human impact on marine ecosystems. *Science*, *319*(5865), 948–952. https://doi.org/10.1126/science.1149345

He, X., Field, J. C., Beyer, S. G., & Sogard, S. M. (2015). Effects of size-dependent relative fecundity specifications in fishery stock assessments. *Fisheries Research*, *165*, 54–62. https://doi.org/10.1016/j.fishres.2014.12.023

HELCOM. (2018). *State of the Baltic Sea—Second HELCOM Holistic Assessment* (Vol. *2011–2016*, p. 155). Baltic Sea Environment Proceedings.

Hilborn, R. (2010). Pretty good yield and exploited fishes. *Marine Policy*, *34*(1), 193–196. https://doi.org/10.1016/j.marpol.2009.04.013

Hixon, M. A., Johnson, D. W., & Sogard, S. M. (2014). BOFFFFs: On the importance of conserving old-growth age structure in fishery populations. *ICES Journal of Marine Science*, *71*(8), 2171–2185. https://doi.org/10.1093/icesjms/fst200

Hsieh, C., Yamauchi, A., Nakazawa, T., & Wang, W.-F. (2010). Fishing effects on age and spatial structures undermine population stability of fishes. *Aquatic Sciences*, *72*(2), 165–178. https://doi.org/10.1007/s00027-009-0122-2

ICES. (2016). Report of the workshop on guidance on development of operational methods for the evaluation of the MSFD criterion D3.3 (WKIND3.3i), 14–17 march 2016, Copenhagen, Denmark. ICES CM 2016/ACOM: 44, p. 99.

ICES. (2017a). Report of the workshop to consider FMSY ranges for stocks in ICES categories 1 and 2 in Western waters (WKMSYREF4), 13–16 October 2015, Brest, France. ICES CM 2015/ACOM: 58, p. 187.

ICES. (2017b). Report of the workshop on guidance on development of operational methods for the evaluation of the MSFD criterion D3.3 (WKIND3.3ii), 1–4 November 2016, ICES HQ, Copenhagen, Denmark. ICES CM 2016/ACOM: 44, p. 155.

ICES. (2021a). Official Nominal Catches 2006-2019. Version 15-10-2021. https://www.ices.dk/data/dataset-collections/Pages/Fish-catch-and-stock-assessment.aspx

ICES. (2021b). Northwestern working group (NWWG). *ICES Scientific Reports*, *3*(52), 766.

ICES. (2021c). Plaice (*Pleuronectes platessa*) in subdivisions 21–23 (Kattegat, Belt Seas, and the Sound). ICES Advice on Fishing Opportunities, Catch, and Effort Baltic Sea Ecoregion, Published 28 May 2021. https://doi.org/10.17895/ices.advice.7817

ICES. (2022a). Workshop on ICES reference points (WKREF1). *ICES Scientific Reports*, *4*(2), 70.

ICES. (2022b). Benchmark workshop on Pandalus stocks (WKPRAWN). *ICES Scientific Reports*, *4*(20), 249.

ICES. (2022c). Working Group for the Celtic Seas Ecoregion (WGCSE). *ICES Scientific Reports*, *4*(45), 931.

ICES. (2023a). Advice on fishing opportunities. In report of the ICES advisory committee, 2023. ICES advice 2023, section 1.1.1. https://doi.org/10.17895/ices.advice.22240624

ICES. (2023b). Benchmark workshop on North Sea and Celtic Sea stocks (WKNSCS). *ICES Scientific Reports*, *5*(4), 324. https://doi.org/10.17895/ices.pub.21558681

Jennings, S. (2005). Indicators to support an ecosystem approach to fisheries. *Fish and Fisheries*, *6*(3), 212–232.

Jennings, S., & Kaiser, M. J. (1998). The effects of fishing on marine ecosystems. *Advances in Marine Biology*, *34*, 201–212.

Jennings, S., Kaiser, M. J., & Reynolds, J. D. (2001). *Marine fisheries ecology*. Blackwell Science.

Kell, L. T., Minto, C., & Gerritsen, H. D. (2022). Evaluation of the skill of length-based indicators to identify stock status and trends. *ICES Journal of Marine Science*, *79*(4), 1202–1216. https://doi.org/10.1093/icesjms/fsac043

Kell, L. T., Mosqueira, I., Grosjean, P., Fromentin, J.-M., Garcia, D., Hillary, R., Jardim, E., Mardle, S., Pastoors, M. A., Poos, J. J., Scott, F., & Scott, R. D. (2007). FLR: An open-source framework for the evaluation and development of management strategies. *ICES Journal of Marine Science*, *64*(4), 640–646. https://doi.org/10.1093/icesjms/fsm012

Kell, L. T., Nash, R. D. M., Dickey-Collas, M., Mosqueira, I., & Szuwalski, C. (2015). Is spawning stock biomass a robust proxy for reproductive potential? *Fish and Fisheries*, *55*, 1766–1783.

Kell, L. T., Sharma, R., & Winker, H. (2022). Artefact and artifice: Evaluation of the skill of catch-only methods for classifying stock status. *Frontiers in Marine Science*, *9*, 762203. https://doi.org/10.3389/fmars.2022.762203

Kelly, C. J., Codling, E. A., & Rogan, E. (2006). The Irish Sea cod recovery plan: Some lessons learned. *ICES Journal of Marine Science*, *63*(4), 600–610. https://doi.org/10.1016/j.icesjms.2005.12.001

Kjesbu, O. S., Sundby, S., Sandø, A. B., Allx, M., Hjøllo, S. S., Tiedemann, M., Skern-Mauritzen, M., Junge, C., Fossheim, M., Broms, C. T., Søvik, G., Zimmermann, F., Nedreaas, K., Eriksen, E., Höffle, H., Hjelset, A. M., Kvamme, C., Reecht, Y., Knutsen, H., … Huse, G. (2022). Highly mixed impacts of near-future climate change on stock productivity proxies in the north East Atlantic. *Fish and Fisheries*, *23*, 601–615.

Kolody, D. S., Eveson, J. P., Preece, A. L., Davies, C. R., & Hillary, R. M. (2019). Recruitment in tuna RFMO stock assessment and management: A review of current approaches and challenges. *Fisheries Research*, *217*, 217–234.

Law, R. (2000). Fishing, selection, and phenotypic evolution. *ICES Journal of Marine Science*, *57*(3), 659–668. https://doi.org/10.1006/jmsc.2000.0731

Lowerre-Barbieri, S. K., Ganias, K., Saborido-Rey, F., Murua, H., & Hunter, J. R. (2011). Reproductive timing in marine fishes: Variability, temporal scales, and methods. *Marine and Coastal Fisheries*, *3*, 71–91.

Macdonald, J. I., Logemann, K., Krainski, E. T., Sigurosson, B., Beale, C. M., Huse, G., Hjøllo, S. S., & Marteinsdottir, G. (2017). Can collective memories shape fish distributions? A test, linking space-time occurrence models and population demographics. *Ecography*, *41*(6), 938–957.

Mace, P. M. (1994). Relationships between common biological reference points used as thresholds and targets of fisheries management strategies. *Canadian Journal of Fisheries and Aquatic Sciences*, *51*(1), 110–122. https://doi.org/10.1139/f94-013

Mace, P. M. (2001). A new role for MSY in single-species and ecosystem approaches to fisheries stock assessment and management. *Fish and Fisheries*, *2*(1), 2–32.

Marshall, D. J., Barneche, D. R., & White, C. R. (2022). How does spawning frequency scale with body size in marine fishes? *Fish and Fisheries*, *23*(2), 316–323. https://doi.org/10.1111/faf.12617

Marshall, D. J., Bode, M., Mangel, M., Arlinghaus, R., & Dick, E. J. (2021). Reproductive hyperallometry and managing the world's fisheries. *Proceedings of the National Academy of Sciences of the United States of America*, *118*(34), e2100695118. https://doi.org/10.1073/pnas.2100695118

Methot, R. D., & Wetzel, C. R. (2013). Stock synthesis: A biological and statistical framework for fish stock assessment and fishery management. *Fisheries Research*, *142*, 86–99. https://doi.org/10.1016/j.fishres.2012.10.012

Mildenberger, T. K., Berg, C. W., Kokkalis, A., Hordyk, A. R., Wetzel, C., Jacobsen, N. S., Punt, A. E., & Nielsen, J. R. (2021). Implementing the precautionary approach into fisheries management: Biomass reference points and uncertainty buffers. *Fish and Fisheries*, *23*, 73–92.

Ministry of Fisheries. (2008). Harvest strategy standard for New Zealand fisheries. New Zealand Government. https://fs.fish.govt.nz/Page.aspx?pk=113&dk=16543

Ministry of Fisheries. (2011). Operational guidelines for New Zealand's harvest strategy standard. New Zealand Government. https://fs.fish.govt.nz/Doc/22847/Operational_Guide-lines_for_HSS_rev_1_Jun_2011.pdf.ashx

Minte-Vera, C. V., Maunder, M. N., Schaefer, K. M., & Aires-da-Silva, A. M. (2019). The influence of metrics for spawning output on stock assessment results and evaluation of reference points: An illustration with yellowfin tuna in the eastern Pacific Ocean. *Fisheries Research*, *217*, 35–45. https://doi.org/10.1016/j.fishres.2018.09.022

Morfin, M., Kopp, D., Benoit, H., Méhault, S., Randall, P., Foster, R., & Catchpole, T. (2017). Survival of European plaice discarded from coastal otter trawl fisheries in the English Channel. *Journal of Environmental Management*, *204*(1), 404–412.

MSFMCA. (2007). Magnuson-Stevens fishery conservation and management act (MSFCMA), public Law 94–265. 2007. As amended by the Magnuson-Stevens Fishery Conservation and Management Reauthorization Act (P.L. 109–479). U.S. Department of Commerce, National Oceanic and Atmospheric Administration, National Marine Fisheries Service.

Neat, F. C., Bendall, V., Berx, B., Wright, P. J., Ó Cuaig, M., Townhill, B., Schön, P.-J., Lee, J., & Righton, D. (2014). Movement of Atlantic cod around the British Isles: Implications for finer scale stock management. *Journal of Applied Ecology*, *51*, 1564–1574. https://doi.org/10.1111/1365-2664.12343

Nielsen, A., & Berg, C. W. (2014). Estimation of time-varying selectivity in stock assessments using state-space models. *Fisheries Research*, *158*, 96–101. https://doi.org/10.1016/j.fishres.2014.01.014

Olsen, E. M., Heino, M., Lilly, G. R., Morgan, M. J., Brattey, J., Ernande, B., & Dieckmann, U. (2004). Maturation trends indicative of rapid evolution preceded the collapse of northern cod. *Nature*, *428*(6986), 932–935. https://doi.org/10.1038/nature02430

OSPAR. (2017). Intermediate Assessment 2017. https://oap.ospar.org/en/ospar-assessments/intermediate-assessment-2017/

Pauly, D., Christensen, V., Dalsgaard, J., Froese, R., & Torres, F. (1998). Fishing down marine food webs. *Science*, *279*(5352), 860–863. https://doi.org/10.1126/science.279.5352.860

Petitgas, P., Reid, D., Planque, B., Nogueira, E., O'Hea, B., & Cotano, U. (2006). The entrainment hypothesis: An explanation for the persistence and innovation in spawning migration and life cycle patterns. *ICES CM*, *7*, 9.

Planque, B., Loots, C., Petitgas, P., Lindstrom, U., & Vaz, S. (2011). Understanding what controls the spatial distribution of fish populations using a multi-model approach. *Fisheries Oceanography*, *20*, 1–17.

Probst, W. N., Kempf, A., Taylor, M., Martinez, I., & Miller, D. (2021). Six steps to produce stock assessments for the marine strategy framework directive compliant with descriptor 3. *ICES Journal of Marine Science*, *78*(4), 1229–1240. https://doi.org/10.1093/icesjms/fsaa244

Probst, W. N., Kloppmann, M., & Kraus, G. (2013). Indicator-based status assessment of commercial fish species in the North Sea according to the EU marine strategy framework directive (MSFD). *ICES Journal of Marine Science*, *70*(3), 694–706. https://doi.org/10.1093/icesjms/fst010

Probst, W. N., Rau, A., & Oesterwind, D. (2016). A proposal for restructuring descriptor 3 of the marine strategy framework directive (MSFD). *Marine Policy*, *74*, 128–135. https://doi.org/10.1016/j.marpol.2016.09.026

Probst, W. N., Stelzenmuller, V., & Kraus, G. (2013). A simulation-approach to assess the size structure of commercially exploited fish populations within the European marine strategy framework directive. *Ecological Indicators*, *24*, 621–632.

Punt, A. E., Smith, A. D. M., Smith, D. C., Tuck, G. N., & Klaer, N. L. (2014). Selecting relative abundance proxies for B_{MSY} and B_{MEY}. *ICES Journal of Marine Science*, *71*, 469–483. https://doi.org/10.1093/icesjms/fst162

R Core Team. (2021). *R: A language and environment for statistical computing*. R Foundation for Statistical Computing. https://www.R-project.org/

Rideout, R., Trippel, E., & Litvak, M. (2005). Effects of egg size, food supply and spawning time on early life history success of haddock *Melanogrammus aeglefinus*. *Marine Ecology Progress Series*, *285*, 169–180. https://doi.org/10.3354/meps285169

Rijnsdorp, A. D., Hiddink, J. G., van Denderen, P. D., Hintzen, N. T., Eigaard, O. R., Valanko, S., Bastardie, F., Bolam, S. G., Boulcott, P., Egekvist, J., Garcia, C., van Hoey, G., Jonsson, P., Laffargue, P., Nielsen, J. R., Piet, G. J., Sköld, M., & van Kooten, T. (2020). Different bottom trawl fisheries have a differential impact on the status of the North Sea seafloor habitats. *ICES Journal of Marine Science*, *77*(5), 1772–1786. https://doi.org/10.1093/icesjms/fsaa050

Rindorf, A., Dichmont, C. M., Levin, P. S., Mace, P., Pascoe, S., Prellezo, R., Punt, A. E., Reid, D. G., Stephenson, R., Ulrich, C., Vinther, M., & Clausen, L. W. (2017). Food for thought: Pretty good multispecies yield. *ICES Journal of Marine Science*, *74*(2), 475–486. https://doi.org/10.1093/icesjms/fsw071

Sharma, R., Winker, H., Levontin, P., Kell, L., Ovando, D., Palomares, M. L. D., Pinto, C., & Ye, Y. (2021). Assessing the potential of catch-only models to inform on the state of global fisheries and the UN's SDGs. *Sustainability*, *13*(11), 6101. https://doi.org/10.3390/su13116101

Shephard, S., Rindorf, A., Dickey-Collas, M., Hintzen, N. T., Farnsworth, K., & Reid, D. G. (2014). Assessing the state of pelagic fish communities within an ecosystem approach and the European marine strategy framework directive. *ICES Journal of Marine Science*, *71*(7), 1572–1585. https://doi.org/10.1093/icesjms/fsu005

Shepherd, S. A., Brook, J. B., & Xiao, Y. (2010). Environmental and fishing effects on the abundance, size and sex ratio of the blue-throated wrasse, Notolabrus tetricus, on south Australian coastal reefs. *Fisheries Management and Ecology*, *17*, 209–220. https://doi.org/10.1111/j.1365-2400.2009.00697.x

Shin, Y.-J., Rochet, M.-J., Jennings, S., Field, J. G., & Gislason, H. (2005). Using size-based indicators to evaluate the ecosystem effects of fishing. *ICES Journal of Marine Science*, *62*(3), 384–396. https://doi.org/10.1016/j.icesjms.2005.01.004

STECF. (2021). Review of the technical measures regulation (STECF-21-07). Scientific, technical and economic Committee for Fisheries (STECF) – Review of the technical measures regulation (STECF-21-07). Publications Office of the European Union, Luxembourg, 2021, EUR 28359 EN, ISBN 978-92-76-45890-6, JRC127718.

Swain, D. P., Sinclair, A. F., & Mark Hanson, J. (2007). Evolutionary response to size-selective mortality in an exploited fish population. *Proceedings of the Royal Society B: Biological Sciences*, *274*(1613), 1015–1022. https://doi.org/10.1098/rspb.2006.0275

Thorson, J. T. (2020). Predicting recruitment density dependence and intrinsic growth rate for all fishes worldwide using a data-integrated life-history model. *Fish and Fisheries*, *21*(2), 237–251.

Trenkel, V. M., Rochet, M.-J., & Mesnil, B. (2007). From model-based prescriptive advice to indicator-based interactive advice. *ICES Journal of Marine Science*, *64*(4), 768–774. https://doi.org/10.1093/icesjms/fsm006

Trippel, E. A. (1998). Egg size and viability and seasonal offspring production of young Atlantic cod. *Transactions of the American Fisheries Society*, *127*(3), 339–359.

Turner, S. J., Thrush, S. F., Hewitt, J. E., Cummings, V. J., & Funnell, G. (1999). Fishing impacts and the degradation or loss of habitat structure: Degradation or loss of habitat structure. *Fisheries Management and Ecology*, *6*(5), 401–420. https://doi.org/10.1046/j.1365-2400.1999.00167.x

van der Reijden, K. J., Molenaar, P., Chen, C., Uhlmann, S. S., Goudswaard, P. C., & van Marlen, B. (2017). Survival of undersized plaice (*Pleuronectes platessa*), sole (*Solea solea*), and dab (*Limanda limanda*) in North Sea pulse-trawl fisheries. *ICES Journal of Marine Science*, *74*(6), 1672–1680. https://doi.org/10.1093/icesjms/fsx019

Vasilakopoulos, P., Jardim, E., Konrad, C., Rihan, D., Mannini, A., Pinto, C., Casey, J., Mosqueira, I., & O'Neill, F. G. (2020). Selectivity metrics for fisheries management and advice. *Fish and Fisheries*, *21*(3), 621–638. https://doi.org/10.1111/faf.12451

Vasilakopoulos, P., O'Neill, F. G., & Marshall, C. T. (2011). Misspent youth: Does catching immature fish affect fisheries sustainability? *ICES Journal of Marine Science*, *68*(7), 1525–1534. https://doi.org/10.1093/icesjms/fsr075

Wienbeck, H., Herrmann, B., Moderhak, W., & Stepputtis, D. (2011). Effect of netting direction and number of meshes around on size selection in the codend for Baltic cod (Gadus morhua). *Fisheries Research*, *109*(1), 80–88. https://doi.org/10.1016/j.fishres.2011.01.019

Wright, P., & Trippel, E. A. (2009). Fisheries-induced demographic changes in the timing of spawning: Consequences for reproductive succes. *Fish and Fisheries*, *10*, 283–304.

SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

How to cite this article: Griffiths, C. A., Winker, H., Bartolino, V., Wennhage, H., Orio, A., & Cardinale, M. (2024). Including older fish in fisheries management: A new age-based indicator and reference point for exploited fish stocks. *Fish and Fisheries*, *25*, 18–37. https://doi.org/10.1111/faf.12789