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An approach to assess exploited fish stocks compliant to the requirements of the Marine Strategy Framework Directive (MSFD) including criterion D3C3

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ABSTRACT

The Marine Strategy Framework Directive (MSFD) complements European fish stock assessments under the Common Fisheries Policy (CFP). CFP assessments separately assess fishing mortality (F) and spawning stock biomass (SSB). Contrary, within its third descriptor (D3) of good environmental status (GES) the MSFD requires to assess exploited fish stocks against three criteria, which are F (D3C1), SSB (D3C2) and the age or size structure (D3C3) within the stock. Further, the MSFD requires to integrate the status of all three criteria to determine whether a stock has achieved GES. The full implementation of MSFD compliant stock assessments has been impaired by the lack of operational indicators for age/size structure. This study presents an approach to assess D3C3 by analysing two indicators i.e. recruitment (R) and SSB/R using time series-based assessments. R and SSB/R reflect the small and large components of a stock and are used as proxy indicators for stock productivity and realised growth potential. Using stock assessment data from 20 North East Atlantic fish stocks, a RandomForest model validated the sensitivity of SSB/R against F and two selectivity indicators. Further, this study introduces an approach to integrate the assessment outcomes of the three D3-criteria by stock. The here demonstrated approach of assessing fish stocks according to D3 of the MSFD relies only on data available from stock assessment summary sheets and is thereby easy to implement for all stocks with analytical stock assessments. The implications of and future direction for assessing D3C3 are discussed.

1. Introduction

The Marine Strategy Framework Directive (MSFD) implements an ecosystem-based approach to fisheries management (EBFM) within waters of the European Union (EU) (Lassen et al., 2013). While many different acronyms for EBFM with different meanings exist (Link and Browman, 2014), the essence of EBFM is to not only consider the impacts of fisheries on the target species, but also on affected by-catch species and habitats as well as the impacts of environmental conditions on yield (Garcia et al., 2003; Pikitch et al., 2004).

The MSFD addresses EBFM in several descriptors of good environmental status (GES), of which Descriptor 3 (D3) addresses the status of targeted fisheries resources and therefore requires a comprehensive assessment of exploited fish (and shellfish) stocks. The MSFD thereby complements current fish stock assessments performed under the Common Fisheries Policy (CFP) of the EU, which usually assess fishing mortality (F) and spawning stock biomass (SSB), by requiring to assess the age (or size) structure within a stock (Probst et al., 2021; Vasilakopoulos et al., 2022). Consequently, D3 of the MSFD aims to assess exploited fish stocks against three criteria, and further, to integrate the status of all three criteria to determine whether a stock has achieved GES (EU-COM, 2017, Table 1).

The size- and age distribution of exploited stocks is affected by the combination of fishing intensity and the selectivity of applied gears (Brunel and Piet, 2013). Many fisheries usually target larger and older individuals of a stock, thereby reducing their abundance and ecological functions, such as productivity or their role in the food web, while simultaneously impacting the phenotypic and genotypic structure within the stock. Large individuals within a stock produce a disproportional higher number of offspring, which often have better chances of survival due to so called parental effects (Hixon et al., 2013; Rideout et al., 2004; Trippel, 1998). Many fish species alter their diet throughout their ontogeny with larger individuals becoming predators on fish or benthos. Hence the abundance of large individuals affects the structure of and energy transfers in marine food webs (Rombouts et al., 2013). Further, selective fishing of larger individuals affects the genetic

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Table 1
The structure of Descriptor 3 (D3) of the Marine Strategy Framework Directive (MSFD) according to EU Commission decision 2017/848/EU (EU-COM, 2017).

Criterion	Description
D3C1	The *Fishing mortality* rate of populations of commercially exploited species is at or below levels which can produce the maximum sustainable yield (MSY). Appropriate scientific bodies shall be consulted in accordance with Article 26 of Regulation (EU) No 1380/2013.
D3C2	The *Spawning Stock Biomass* of populations of commercially exploited species are above biomass levels capable of producing maximum sustainable yield. Appropriate scientific bodies shall be consulted in accordance with Article 26 of Regulation (EU) No 1380/2013.
D3C3	The age and size distribution of individuals in the populations of commercially exploited species is indicative of a healthy population. This shall include a high proportion of old/large individuals and limited adverse effects of exploitation on genetic diversity. Member States shall establish threshold values through regional or subregional cooperation for each population of species in accordance with scientific advice obtained pursuant to Article 26 of Regulation (EU) No 1380/2013.

structure of fish stocks by selecting for slower growth and earlier onset of maturity (Jørgensen et al., 2007).

Multiple indicators for the assessment of age and size structure have been proposed in the scientific literature, attempting to capture the annual age or size distribution on the stock (Probst et al., 2013a; Probst et al., 2013b; Shin et al., 2005). Among these indicators the mean age (A_{mean}) in the stock, the proportion of mature individuals ($\%_{mat}$) or the 95 % of the length frequency distribution (L_{95}) have been proposed (EU-COM, 2017, 2022; Piet et al., 2010). However, several of these indicators have been demonstrated to be sensitive to recruitment i.e. the indicator value is pointing towards a degraded state in years with above-average recruitment (Probst et al., 2013b). For example, in years with high recruitment the mean age in the stock is lower than in years with low recruitment, even though the absolute abundance of mature and old individuals may not have changed.

Another and even more substantial problem of size- and age-based indicators (SBI, ABI) is the lack of agreed assessment benchmarks, which proved to be difficult to derive based on scientific concepts (ICES, 2016a; Piet et al., 2010). This is contrary to D3C1 and D3C2, which are based on the concept of maximum sustainable yield and a precautionary approach based on the spawner-recruit relationship (Lassen et al., 2014). Hence currently the most feasible method to assess SBI and ABI can be found in time-series based assessment approaches (Lindegren et al., 2012; Probst and Stelzenmüller, 2015; Trenkel and Rochet, 2009).

Due to the lack of agreed SBI/ABI and/or associated assessment benchmarks, the process of coordinated implementation of D3 has been stalled (Probst et al., 2021). Consequently, D3C3 has been implemented only by some EU member states (MS) in their D3 assessments in 2018, and approaches of implementations differed (Vasilakopoulos et al., 2021; Vasilakopoulos et al., 2022). This study presents an approach to assess D3C3 for stocks with analytical stock assessments, for which assessment benchmarks for F, SSB and times series of SSB and R are available. This approach addresses D3C3 by two indicators to account for the influence of recruitment while considering potential impacts of size and age selective fishing. Further, an integration scheme for all three criteria of D3 is presented to achieve an MSFD compliant GES assessment of exploited fish stocks.

2. Materials & methods

2.1. Rational for the assessment of D3C3

A “healthy” fish population should be productive and provide individuals the opportunity to grow and spawn, preferably multiple times throughout their life-cycle (Froese, 2004; Hixon et al., 2013; Myers and Mertz, 1998). Therefore, a high abundance of recruits and old individuals alike can be considered to reflect a healthy stock structure that reflects high productivity and an environment that provides ample opportunity to grow and mature. Consequently, the here presented approach for assessing D3C3 combines time series of two indicator metrics i.e. recruitment (R) as a proxy for stock productivity and mean age (A_{mean}) as a proxy for growth potential.

The inclusion of recruitment into D3C3 is an amendment to the requirements of the EU-Commission Decision 2017/848/EU (EU-COM, 2017) which states that *“D3C3 shall reflect that healthy populations of species are characterised by a high proportion of old, large individuals”*. Accordingly, previous studies aiming to capture the features of a stocks’ age or size distribution were focusing on single indicator metrics representing the abundance or proportion of large individuals (ICES, 2016c; ICES, 2016d; Probst et al., 2021; Probst et al., 2013a; Probst et al., 2013b; Shin et al., 2005). Looking only at the abundance of old and large individuals, however, neglects the importance of recruits. An example of this is provided by North Sea cod *Gadus morhua* (cod.27.47d20) in 2021 (ICES, 2021c). Due to low recruitment, spawning stock biomass of North Sea cod is not recovering to former levels of the last century, but due to reduced fishing mortality, the age-based indicator metric that represent the proportion of mature and old individuals show an increase (see supplementary material S1, p.mat and ssb.r). The “healthy” age structure of cod is hence a result of low fishing pressure and low recruitment, with the former being a wanted and the latter an unwanted stock status. A healthy age or size structure within a stock therefore cannot be represented by the proportion of old and large individuals alone, but also needs to consider the abundance of recruits.

Due to a lack of reference points for both indicators R and A_{mean}, a time series-based assessment approach was chosen to obtain minimum reference points that indicate significant deviation from any previously observed minima (Probst and Stelzenmüller, 2015). This is in line with the surveillance indicator approach by Shephard et al. (2015), when deviations from the observed value ranges in the past trigger additional management actions. Accordingly, the integration of D3C3 was designed to complement, but not to overrule the assessment outcomes of D3C1 and D3C2 (see below).

2.2. D3C3 indicators

The two initial indicators for D3C3 were time series of recruitment (R) and mean age (A_{mean}), which was considered as an easy-to-calculate metric from numbers-at-age matrices. However, during exploratory analysis, a strong generic correlation between A_{mean} and SSB/R was detected (Fig. 1). Hence SSB/R was considered as an adequate proxy for A_{mean}, having the advantage to be easily extractable from ICES stock summary tables (which are accessible through the R-package icesSAG) and which are available for a wider range of stocks allowing for more comprehensive D3 assessments without having to manually pull out data from working group reports.

2.3. Sensitivity analysis with real stock data

Data from twenty fish stocks from the North Atlantic and Baltic Sea, which were assessed by ICES in 2021 and 2022 were extracted from the reports by the ICES working groups WGBFAS, WGDEEP, WGNSSK, WGWIDE and HAWG (ICES, 2021b, 2021c, 2022a, 2022b, 2022c) (Table 2). Stocks were selected based on the availability of age structured data in the according reports to extract numbers-at-age, fishing-mortality-at-age, weight-at-age and time series of spawning stock biomass (SSB), R and mean fishing mortality of the targeted age classes (F_{bar}). Data on annual biomass-at-age were created by multiplication of the *n*-at-age and weight-at-age-matrices. Data on asymptotic length from the vonBertalnffy-growth-equation (L_{inf}) was obtained from Fishbase (https://www.fishbase.org) on 18.11.2022.

The pressure-state relationship between F and SSB is intrinsic to the stock assessment models and has been verified statistically (Jennings et al., 2001; Probst et al., 2012). R was not considered to be directly

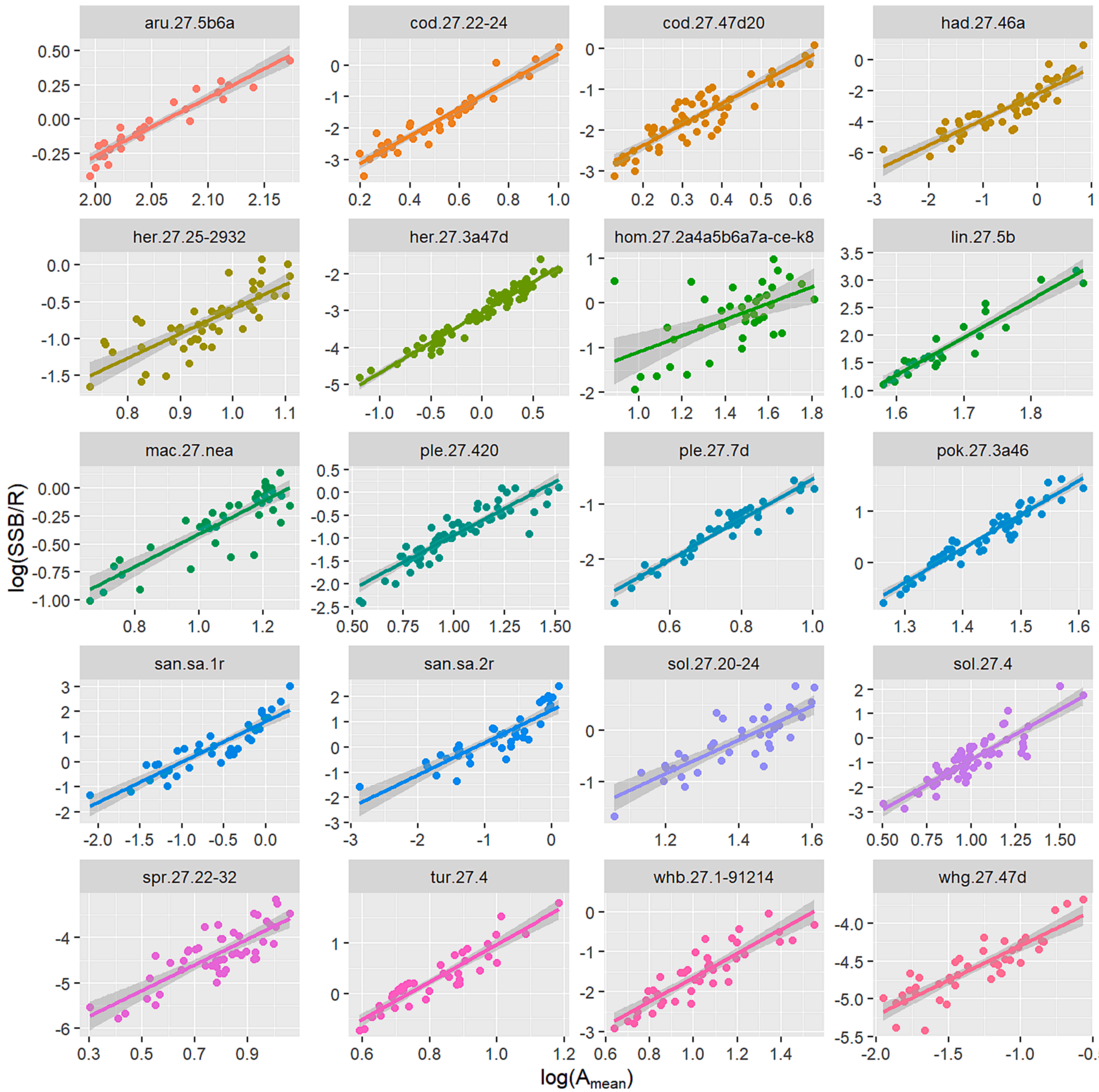

Fig. 1. Relationships between mean age (A_{mean}) and SSB/R for nine fish stocks from the North Sea. Note the logarithmic scale on both axes.

influenced by F_{bar} or selectivity, but rather was considered as a direct indicator for the productivity of the stock. Hence only the sensitivity of SSB/R vs fishing pressure indicators was tested with a RandomForest model. For this purpose, two pressure indicators representing selectivity for each year *i* were calculated:

- The ratio between fishing mortality of immatures (F_{imt}) of the assessment vs fishing mortality of adults (F_{bar}) according to Vasilakopoulos et al. (2020), who calculated F_{rec}/F_{bar} as F of the first recruited age class divided by F_{bar}. In this study, F_{rec} was slightly modified as the arithmetic mean of F on all juvenile age classes. This was preferred, because for some stocks F on the smallest age class was always close to zero and by-catch of juveniles occurred in older age classes. Age classes were classified as juvenile or mature based on mean age-at-maturity (A_{mat}), which was estimated from proportions of mature individuals within each age class as indicated in the working group reports. The smallest age class in which the proportion of mature individuals was ≥50 % was defined as A_{mat} (Table 2).
- A selectivity index S as mean-age weighted by f-at-age (Fy) across all *y* age classes divided by the number of age classes (N_{AC}) used in the assessment:

$$S = \frac{\sum_{y=A_{min}}^{y=A_{max}} Age_y * F_y}{\sum_{y=A_{min}}^{y=A_{max}} F_y} * \frac{1}{N_{AC}} \quad (1)$$

S thereby is a proxy for the age with the highest F. It is standardised by NAC to unify the scale for different stocks with different age classes.

To account for the influence of the two selectivity indicators, fishing

Table 2
Summary of stocks included into an analysis on stock assessment data. Amat = Age-at-mean-maturity. Estimates of L_{inf} are from https://www.fishbase.org (from 18.11.2022).

Species	*Stock ID*	*Order*	*Marine region*	A_{mat} *[years]*	L_{inf} *[cm]*	*ICES Working group*
Ammodytes spp.	san.sa.1r	Uranoscopiformes	North Sea	2	20.0	HAWG 2021
Ammodytes spp.	san.sa.2r	Uranoscopiformes	North Sea	2	20.0	HAWG 2021
Argentina silus	aru.27.5b6a	*Argentiniformes*	Celtic Sea	7	41.0	WGDEEP 2022
Clupea harengus	her.27.3a47d	*Clupeiformes*	North Sea	2	35.2	HAWG 2021
Clupea harengus	her.27.25-2932	*Clupeiformes*	Baltic Sea	2	35.2	WGBFAS 2022
Gadus morhua	cod.27.22-24	*Gadiformes*	Baltic Sea	2	106.0	WGBFAS 2022
Gadus morhua	cod.27.47d20	*Gadiformes*	North Sea	4	106.0	WKNSSK 2021
Melanogrammus aeglefinus	had.27.46a	*Gadiformes*	North Sea/Celtic Sea	3	70.0	WKNSSK 2021
Merlangius merlangius	whg.27.47d	*Gadiformes*	North Sea	2	41.3	WKNSSK 2021
Micromesistius poutassou	whb.27.1-91214	*Gadiformes*	North Atlantic	3	36.0	WGWIDE 2022
Molva molva	lin.27.5b	*Gadiformes*	North Atlantic [Faroe Grounds]	6	158.0	WGDEEP 2022
Pleuronectes platessa	ple.27.7d	*Carangiformes*	North Sea	3	54.4	WKNSSK 2021
Pleuronectes platessa	ple.27.420	*Carangiformes*	North Sea	2	54.4	WKNSSK 2021
Pollachius virens	pok.27.3a46	*Gadiformes*	North Sea/Celtic Sea	5	118.0	WKNSSK 2021
Scomber scombrus	mac.27.nea	*Scombriformes*	North Atlantic	2	42.0	WGWIDE 2022
Solea solea	sol.27.4	*Carangiformes*	North Sea	3	46.5	WKNSSK 2021
Solea solea	sol.27.20-24	*Carangiformes*	Baltic Sea	3	46.5	WGBFAS 2022
Sprattus sprattus	spr.27.22-32	*Clupeiformes*	Baltic Sea	2	13.2	WGBFAS 2022
Scophthalmus maximus	tur.27.4	*Carangiformes*	North Sea	4	54.7	WKNSSK 2021
Trachurus trachurus	hom.27.2a4a5b6a7a-ce-k8	*Carangiformes*	North Atlantic	3	40.4	WGWIDE

mortality, the year effect, L_{inf} and the stock, the formula of the random forest model was:

$$SSB/R \sim F_{bar} + F_{imt}/F_{mat} + S + year + L_{inf} + stock \quad (2)$$

The model grew 500 trees and selected three variables per tree (mtry = 3). Partial dependencies were calculated using the pdp-package version 0.7.0. The Boruta-package (v7.0.0) was applied to test the importance of single predictors (Kursa and Rudnicki, 2010). The Boruta-algorithm iteratively compares assesses whether single predictors have significantly more impact on the dependent variable than randomly created shadow variables.

2.4. Time series-based assessment of recruitment and SSB/R

Time series of R and SSB/R were assessed using breakpoint analysis as implemented in the R-package 'strucchange' (Probst and Stelzenmüller, 2015). This analysis identifies different stable time periods within a time series applying segmented regression (Bai and Perron, 1998; Bai and Perron, 2003). The minimum length of a segment was set to five. In the here applied time series-based assessment (TSBA) the lowest mean of a reference period was set as assessment benchmark, which was compared against the arithmetic mean of indicator values in the last six years (2016–2021). The reference period was defined by all time series values before 2004, as 2004 was considered as the starting year of the first assessment period of the first MSFD assessment cycle (first MSFD assessment cycle from 2004 to 2009, second MSFD assessment cycle from 20010 to 2015 and current MSFD assessment cycle from 2016 to 2021, EU-COM, 2022). If the mean of the last six years was equal or lower than the assessment benchmark, the indicator value was classified as "not good".

The averaging of time series values for the determination of reference and assessment values corresponds to the MSFD assessment cycles and allows the assessment of a mid-term perspective rather than a 'snapshot' of the most recent status (EU-COM, 2022; Probst et al., 2021).

2.5. Integration of indicators within D3C3

The assessment outcomes of R and SSB/R were integrated in a traffic light approach (Fig. 2). Thereby D3C3 obtained a green i.e. "good" assessment result when both R and SSB/R were above their assessment benchmark, an orange i.e. "intermediate" status, when either R or SSB/R failed their assessment benchmark and a red i.e. "not good" status if both indicators were below their assessment benchmark.

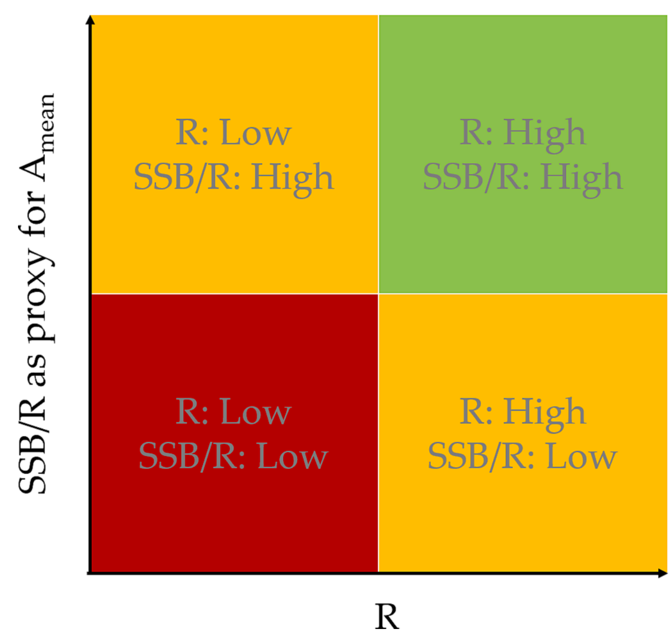

Fig. 2. Integration scheme of R and SSB/R within D3C3.

2.6. Integration scheme for D3C1, D3C2 and D3C3

D3C1 (F) and D3C2 (SSB) were assessed against their stock assessment benchmarks (F_{MSY} or F_{cap} for short lived stocks, here sand eels in the North Sea, and $MSY_{Btrigger}$) downloaded from the ICES stock data base using the R-package icesSAG (v.1.4.0).

Integration of the three D3 criteria D3C1, D3C2 and D3C3 was built on the rationales of the MSFD Article 8 guidance (EU-COM, 2022) that a stock cannot achieve good environmental status (GES) if either D3C1 or D3C2 fails a good status (Fig. 3, supplementary material S5). Further, GES cannot be achieved, if D3C2 is unknown. D3C3 will downgrade a stocks' status only to not-good when it is red, but otherwise will not affect the assessment outcomes of D3C1 and D3C2. This was applied to precautiously reduce the influence of D3C3 as a new indicator with metrics that have not been used in MSFD stock assessments before.

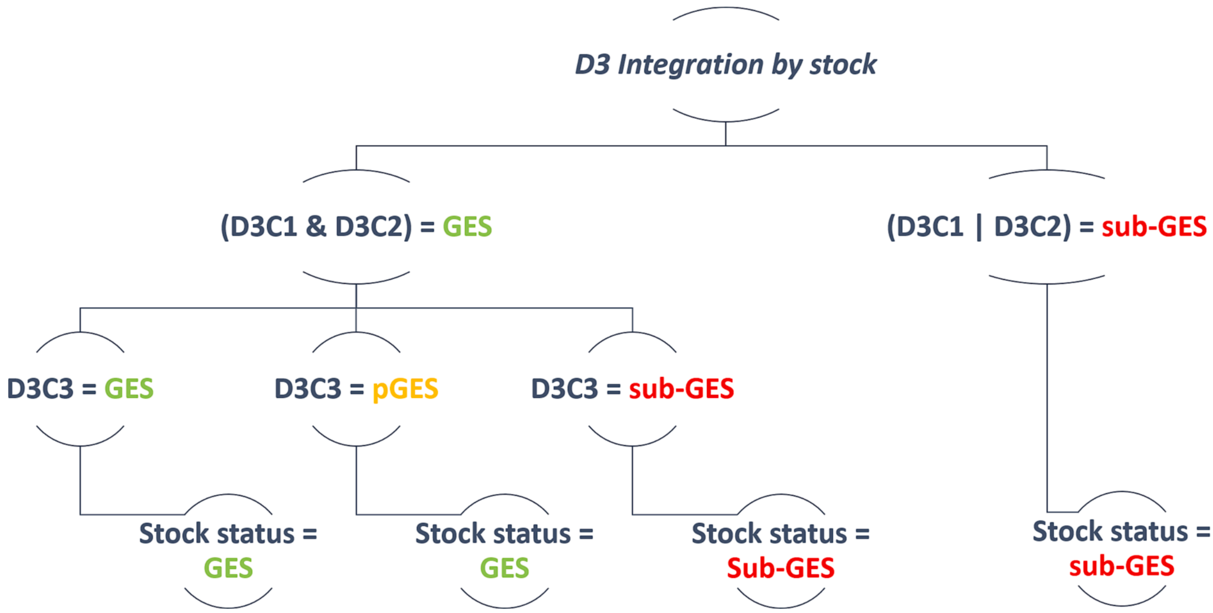

Fig. 3. Integration scheme for the assessment outcomes of the three criteria (D3C1-D3C3) for MSFD Descriptor D3. D3C1 = Fishing mortality (F), D3C2 = Spawning stock biomass (SSB), D3C3 = Recruitment (R) and SSB/R. Colour codes as in Table 3.

3. Results

3.1. Sensitivity analysis with real stock data

The RandomForest model explained 57.14 % of the variance. The most important variables based on Boruta-analysis were L_{inf}, S and stock followed by year, F_{bar} and F_{imt}/F_{bar} (supplementary material S2). All variables had higher importance than the random shadow variables.

In RandomForests, partial dependences express the relationship between single predictors and the dependent variable (Fig. 4). Thereby, SSB/R followed a monotonous, sigmoidal decline with increasing F_{bar}. For F_{imt}/F_{bar} the trajectory was similar. In contrast, SSB/R increased with increasing S. Further, SSB/R increased with increasing L_{inf}. There was also a trend by year with a decline from 1947 until 2000 and an increase from 2000 to 2021. The was also differences between stocks and SSB/R with North Sea haddock, whiting and herring and Baltic sprat having the lowest SSB/R values.

Overall, SSB/R reacted in an expected manner to all pressure indicators and hence proved to be responsive and sensitive to fishing mortality and selectivity.

3.2. Assessment of example stocks

From the 20 assessed stocks seven stocks achieved GES, 13 stocks failed GES (Table 3). No stock failed GES because of criterion D3C3, but nine stocks had lower than ever average recruitment in 2016 – 2021 and seven stocks had a lower than ever average SSB/R in 2016–2021. The two indicators D3C3 – R and D3C3 – SSB/R had equal assessment outcomes in 11 cases and differing assessment outcomes in nine cases.

4. Discussion

The here presented approaches for assessing D3C3 and integrating D3 are simple procedures which build on existing data that are readily available for many stocks in European waters. In the North East Atlantic, working groups of the International Council for the Exploration of the Sea (ICES) are the central assessment bodies, in the Mediterranean working groups of the Scientific the Technical and Economic Committee for Fisheries (STECF) fulfil the same purpose (Vasilakopoulos et al., 2022). Thereby the here proposed assessment structure for D3 stocks should be readily applicable for a considerable number of stocks in the majority of European marine waters, as long as time series and reference values of F, SSB and R are available.

The new assessment approach of D3C3 incorporates recruitment, which is usually not assessed under the CFP (Subbey et al., 2014). In the approach presented by this study, recruitment is considered as a proxy for the stock productivity. It could be argued that the productivity of stocks is more influenced by variations in environmental drivers than by fishing. Hence changes in recruitment might rather reflect changes in the carrying capacity of the ecosystem, which may not be subject to conventional fisheries management. However, recruitment reflects the productivity of a stock, which becomes impaired at very low SSB (Myers and Barrowman, 1996; Myers et al., 1999). Hence fishing pressure can affect recruitment i.e. when stock size is decreased below a level at which the production of offspring becomes limiting. The inclusion of recruitment into an integrative indicator framework to assess the status of a stock allows therefore to screen for indications of reduced productivity and recruitment overfishing (Jennings et al., 2001; Myers et al., 1994; Quinn and Deriso, 1999).

In previous analysis, recruitment was often considered as interference to the assessment of the age structure (ICES, 2016b; Probst et al., 2013b). The novelty of the here presented approach therefore lies in combining R and ABI, the latter aiming to reflect the proportion of old individuals. Thereby-two relevant components of the stock age (and size structure) are combined into D3C3.

The here suggested indicators for D3C3 – R and SSB/R – include a certain degree of redundancy, as both indicators contain R. Further, 55 % of the assessed stocks showed equal assessment outcomes for both D3C3 indicators. However, for several stocks the outcomes for R and SSB/R differed. Therefore, both indicators can convey diverging information on different stock components that influence the age structure of the stock. For saithe and cod, average recruitment between 2016 and 2021 was below the minimum of previously observed means (identified by break point analysis), while the relative abundance of old individuals was relatively high (see supplementary material S3), suggesting that the abundance of recruits and the proportion of mature individuals is not always congruent.

Recruitment has been considered to negatively impact age based indicators i.e. the metric value decreases with increasing recruitment (ICES, 2016d; Probst et al., 2013b). This is also the case for SSB/R, which

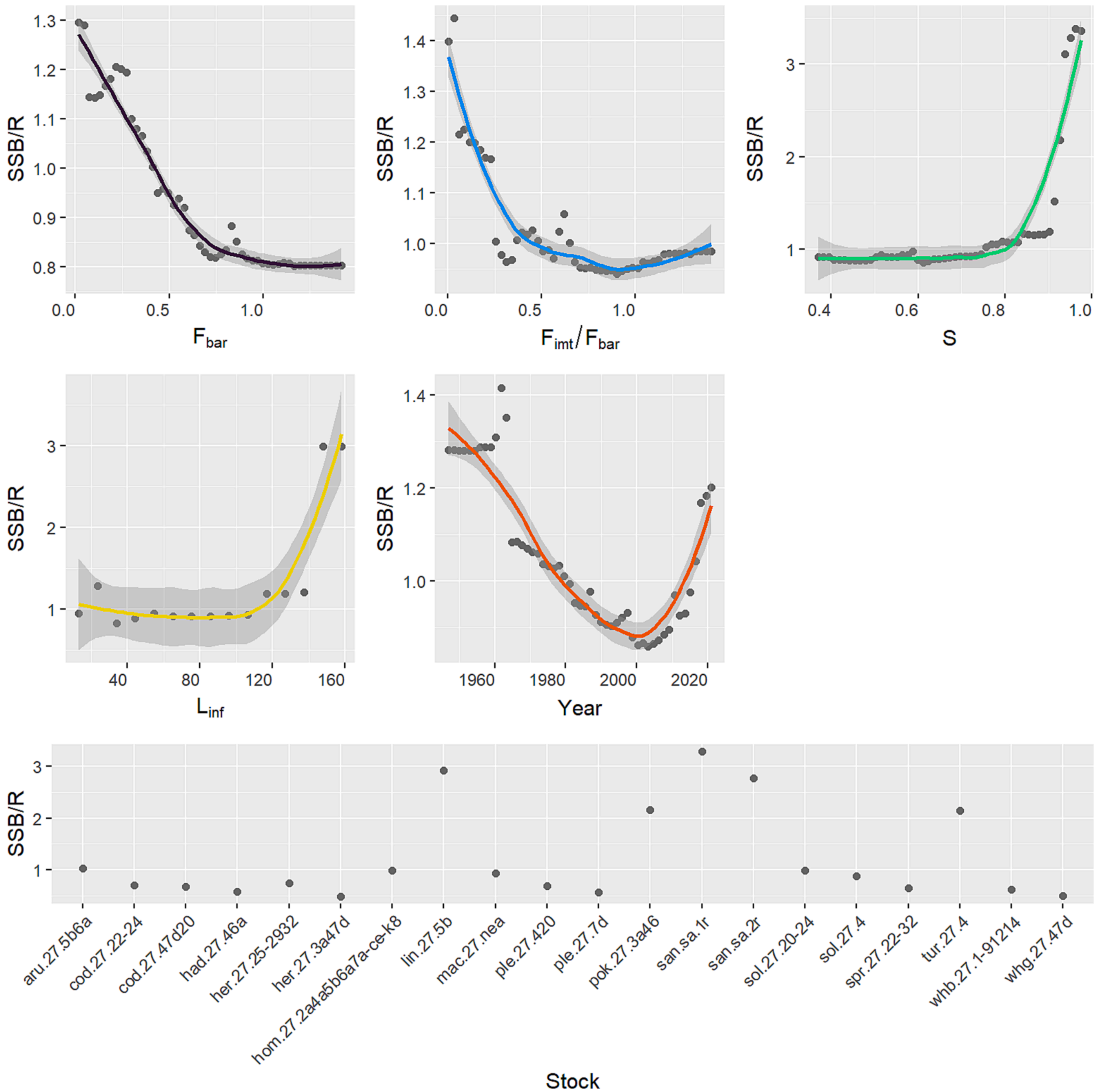

Fig. 4. Partial dependencies of a RandomForest model indicating relationships between the ratio of spawning stock biomass (SSB) over recruitment (R). Coloured lines indicate loess-smoothers applied to the points of partial dependences using the 'autoplot'-function in R.

showed a negative correlation to R (supplementary material S4). However, SSB/R was also found to be closely related to A_{mean} and hence can be considered as indicative of the relative abundance of old individuals (ICES, 2021a). Therefore SSB/R was considered to be an adequate indicator for D3C3, in spite its sensitivity to recruitment, for two reasons: i) the impacts of annual variations in R were reduced by averaging across six-year periods and ii) R is assessed independently as an additional parameter. Especially for stocks, for which the correlation between SSB/R and R was strong, namely cod and haddock, the assessment outcomes of both D3C3 indicators diverged. This provides evidence that SSB/R and R can complement each other as indicator pair within D3C3.

The assessment of D3 can be considered as work in progress for three reasons. Firstly, the aspect of assessing genetic effects of exploitation are not yet addressed (EU-COM, 2017; ICES, 2016c). Genetic effects of exploitation can result in fisheries induced evolution (Jørgensen et al., 2007) leading to earlier maturation at smaller sizes. The prime indicator for the assessment of genetic impacts by fisheries is the Probabilistic Maturation Reaction Norm (Barot et al., 2004; Heino et al., 2002), but this indicator requires extensive data on maturity ogives over time and thus may only be applicable to a limited number of data rich stocks. Alternatively, genetic effects can be assessed by mean-size-at-first-maturity, which, however, can be subject to phenotypical plasticity and hence is not as closely linked to genetic change as PMRN (ICES, 2016c). Since 2016 the conceptual implementation of indicators assessing genetic effects has not progressed and further work on their implementation is required.

Table 3
Integrated stock assessments of 20 fish stocks from the North East Altantic [including Baltic Sea] based on the integrative assessment scheme from Fig. 3. Color codes are green="good environmental status [GES], red = GES not achieved, orange = partially at GES (only applicable to D3C3).

Stock	D3C1	D3C2	D3C3 – R	D3C3 – SSB/R	D3C3	GES
aru.27.5b6a	green	red	green	red	orange	red
cod.27.22-24	red	red	red	green	orange	red
cod.27.47d20	red	red	red	green	orange	red
had.27.46a	red	green	red	red	red	red
her.27.3a47d	green	green	green	green	green	green
her.27.25-2932	red	green	red	green	orange	red
hom.27.2a4a5b6a7a-ce-k8	red	red	red	red	red	red
lin.27.5b	red	green	green	green	green	red
mac.27.nea	green	green	green	green	green	green
ple.27.7d	green	green	green	green	green	green
ple.27.420	green	green	green	green	green	green
pok.27.3a46	red	green	red	green	orange	red
san.sa.1r*	grey	green	red	red	red	red
san.sa.2r*	grey	red	red	green	orange	red
sol.27.4	red	red	red	red	red	red
sol.27.20-24	green	green	green	green	green	green
spr.27.22-32	red	green	green	red	orange	red
tur.27.4	green	green	green	green	green	green
whb.27.1-91214	red	green	green	green	green	red
whg.27.47d	green	green	red	green	orange	green

*Short-lived species are assessed based on the ICES-escapement strategy and hence no reference points for D3C1 are provided.

Secondly, the criteria of D3 may need restructuring (Probst et al., 2016). Because the pressure-state relationship between F and SSB is well established and their calculation and assessment a common procedure for many stocks, criteria D3C1 and D3C2 provide a solid foundation for D3 (Vasilakopoulos et al., 2022). By contrast, D3C3 may include a certain degree of redundancy to D3C2, as large SSB may lead to high abundances of large and old individuals and implies good recruitment. Persistently low recruitment will eventually lead to low SSB. Thereby SSB already addresses many aspects of a healthy stock. The complementary assessment of R may still be helpful, as it can help to disentangle the reasons for recruitment declines by allowing to look simultaneously at fishing pressure, stock sizes and recruitment. If recruitment in a stock is below an all-time at low fishing mortalities, then changes in the carrying capacity of the environment may be the driving forces of reductions in recruitment and stock size (Tu et al., 2018). Contrary, if stock size is low and fishing pressure is significantly above reference points, reductions in recruitment may indicate recruitment overfishing.

Thirdly, SSB/R has been demonstrated to be a good proxy for A_{mean}. A_{mean} is an ABI which requires the availability of age structured data. However, for many stocks information on age structure is not available and SBI may have to be used to assess the demographic structure of the stock (Froese et al., 2019; Tu et al., 2018). This study provides no analysis on which and how SBI can be included into D3C3 and further work on incorporating existing SBI into MSFD D3 assessments is required.

5. Conclusion

The assessment of D3 might need to be further adapted due to the aforementioned reasons. For example, the inclusion of indicators on genetic traits may require to adapt and extent the here proposed assessment framework for D3C3. Also, the assessment of the old and large stock component may build on different or new indicator metrics (e.g. A_{mean} directly) that demonstrate to capture. However, the here presented assessment approach for D3 provides a coherent and consistent framework to determine the status of exploited fish (and shellfish) stocks according to the requirements of MSFD D3. All three criteria of D3 are assessed and integrated to obtain the status of a stock. The approach is easy to implement and can be included for a wide array of stocks building on data that is readily available from analytical stock assessments.

6. Data statement

Extracted and processed data from ICES stock assessments by HAWG 2021, WGBFAS 2022, WGDEEP 2022, WGWIDE 2022 and WGNSSK 2021 are available at https://www.ices.dk. Data on time series of F, SSB and R and reference points for stock-specific F and SSB were extracted using the icesSAG package (version 1.4.0).

CRediT authorship contribution statement

W. Nikolaus Probst: Conceptualization, Methodology, Software, Validation, Formal analysis, Investigation, Data curation, Visualization, Writing – original draft, Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ecolind.2023.109899.

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