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A simulation-approach to assess the size structure of commercially exploited fish populations within the European Marine Strategy Framework Directive

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ABSTRACT

Assessing the size structure and composition of fish stocks, as demanded by the Marine Strategy Framework Directive (MSFD), is considered to be critical for the evaluation of the health status of exploited populations. The MSFD explicitly contains the concept that many large individuals within a population are indicative of a healthy stock. To reflect the abundance of large individuals, the EU-Commission suggested several size-based indicators (SBI). Only few of these SBI have been tested within a pressure-state relationship, in which a state indicator is sensitive, responsive and specific to a given pressure. Sensitivity and responsiveness of pressure-state relationship can be validated by cross-correlating time-series of pressure and state indicators. In the real world, however, time-series of ecological indicators are not only affected by the influence of a pressure, but by natural variability, changes in the sampling method and stochasticity. Hence observed cross-correlations between pressure and state indicator time-series may not be based on a true causal link, especially if time-series are short (less than 30 years). To overcome these limitations, the performance of eight SBI was tested with a population model in which pressures (fishing mortality) and states of ecosystem components (SBI) were precisely known. We distinguished between relative SBI reflecting proportions of size-classes and absolute SBI reflecting absolute entities of the size-distribution such as the observed maximum size in a given survey year. Relative SBI were more sensitive to recruitment than absolute SBI, but not to fishing pressure, which makes relative SBI unsuitable for the assessment of the abundance of large individuals within a population. The outcomes of the model simulation were confirmed by a case study on North Sea cod, where the mean length of the largest ten individuals caught in a given survey year (L_{max10}) emerged as a promising indicator for the assessment of size structure. Exemplary, we demonstrate how the L_{max10} may be incorporated into the existing International Council for the Exploration of the Sea (ICES) assessment framework by defining target and limit values of the good environmental status.

1. Introduction

The Marine Strategy Framework Directive (MSFD; 2008/56/EC) requires the member states of the European Union (EU) to achieve good environmental status (GES) of marine waters by evaluating 11 qualitative descriptors. One of them (Descriptor 3; D3) is related to managing natural living resources in a way that “populations of all commercially exploited fish and shellfish are within safe biological limits, exhibiting a population age and size structure that is indicative of a healthy stock” (EU-COM, 2008b). This quote of Descriptor 3-GES implies the extension of the existing International council for the Exploration of the Sea (ICES) stock assessment framework used under the EU common fisheries policy regime, in which the status of an exploited fish stock is assessed against reference points for spawning stock biomass (SSB) and fishing mortality (*F*). Under the MSFD, indicators on the status of stock size- or age structure have to be included. The MSFD further demands, that the current assessments of stock status are expanded to commercial species with limited data availability, which are currently not assessed by ICES.

The implementation of an ecosystem based approach to fisheries management implies the application of ecosystem indicators (Cury and Christensen, 2005; Garcia and Cochrane, 2005). The MSFD-drafting group on D3 proposed several size-based indicators to assess the age or length structure of exploited fish populations (Piet et al., 2010), which found their way into criterion 3.3 of the EU-Commission Decision 477/2010 (EU-COM, 2010). These indicators are the proportion of fish larger than the mean size of first sexual maturation (3.3.1 of EU-COM Decision 477/2010), the mean maximum length across all species found in research vessel surveys (3.3.2), the 95%-percentile of the length distribution (L_{95}; 3.3.3) and the size at first sexual maturation (3.3.4). Whereas the indicators

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Table 1
Parameterisation of the age-based population model to simulate the development of a cod-like fish population for a period of 120 years. VBGF = von Bertalanffy-growth-function. Length–weight regression has the form $W = a \times L^b$.

Parameter	Description	Value	Source
M	Natural mortality	0.2	(Pauly, 1980)
F	Fishing mortality	0.4 (1900–1962) ICES assessment (1963–2010) 0.4 (2011–2020)	(ICES, 2011)
L_∞	Asymptotic maximum length of VBGF	106	(Daan, 1974)
K	Growth parameter of VGBF	−0.2	(Froese and Pauly, 2012)
t_0	Intersection point of X-axis from VGBF	0.2	(Froese and Pauly, 2012)
a	Regression parameter of length–weight regression of North Sea cod	0.0065	von Thünen Institute-surveys
b	Power parameter of the length–weight regression of North Sea cod	3.0982	von Thünen Institute-surveys
Simulation start	–	1900	–
Simulation end	–	2020	–
Initial population size (No.)	–	10^5	–

3.3.1 and 3.3.2 require information about the size at first maturation for a given species in a given area or show trends only at the community level, indicator 3.3.3 attempts to assess the size-distribution within a fished population or stock unit. Thus single species/stock indicators such as the L_{95} are better suited to fit into the existing F/SSB assessment framework currently used by ICES (ICES, 2011) and will be the subject of this study.

Usually ecosystem indicators are embedded into a pressure-state-response framework (PSR) (or its extension driver-pressure-state-impact-response; DPSIR), in which indicators for ecosystem state, human pressures and management responses are distinguished (Jennings, 2005; OECD, 1993; Smith and Weterings, 1999). The PSR- classification of ecosystem indicators is not explicitly adapted within the MSFD, but at least a separation into pressure and state indicators is possible (see Borja et al., 2011 for examples). Within the pressure-state framework a statistical validation of a pressure-state relationship is necessary (Rice and Rochet, 2005) and has been performed for a couple of fish related indicators (Greenstreet et al., 2011; Probst et al., 2012). After a positive validation of the pressure-state relationship, the subsequent task for the operationalisation of an ecosystem indicators is the definition of adequate reference targets and limits for GES of the pressure and state indicator (Rice, 2009). GES is most easily defined if the relationship between pressure and state is non-linear i.e. that maxima, minima or inflection points of a curved relationship can be set as limits or targets (Samhouri et al., 2010).

Unfortunately the relationships between pressure and state indicators are not always as evident as theoretically assumed and can have time lags of years to decades (Greenstreet et al., 2011; Probst et al., 2012; Shephard et al., 2011). It is also difficult to test the specificity of state indicators to a given pressure as changes in a state indicator time-series may have multiple causes such as sensitivity to multiple independent pressures, changes in the monitoring regime or changes in environmental conditions. In many cases it is not possible to separate these influences in observation data, because multiple pressures may covary. Furthermore, a thorough understanding of pressure-state relationships may be confounded by sampling imprecision, artefacts and data misreporting (Fraser et al., 2008; Greenstreet and Piet, 2008; Greenstreet et al., 2012). The use of observation data is therefore not always a satisfying approach to establish pressure-state relationships, because it is impaired by the incomplete knowledge about the measured parameters.

The present study aims to identify an operationable SBI allowing to safely assessing the abundance of large individuals within a population as demanded by the MSFD. An age-structured population model is used to investigate theoretical principals of SBI and their dependency on fishing mortality and populations dynamics. The second part of this study compares the model results with observed SBI time-series of North Sea cod to evaluate how well the model assumptions are transferable to observed stock size structures. Finally, the best performing SBI was used to develop target and limit values for a possible definition of GES.

2. Material and methods

2.1. Population model

The advantage of using a model population instead of observed data is that all population features such as recruitment, abundance, mortality and size structure are precisely known. Multiple pressures which can influence indicator time-series of observed data (e.g. due to climate change, fishing and pollution) are excluded from the model and hence the influence of the population dynamics (mortality and recruitment) can be directly related to the SBI.

The population model simulates the size structure of a fish population with the life-history parameters derived from data on North Sea cod (Table 1). The population age and size matrices were set up to contain age classes from 1 to 20 years and length classes from 1 to 250 cm.

The initial population consisted of four age classes (age 0–3) in the first year of the simulation set to 1900. The age classes had proportions of 40%, 30%, 20% and 10%, respectively. The total population abundance was initially set to 10^5 individuals (Table 2). The simulated population was exposed to low fishing mortalities of 0.4 for the first 62 years. From 1963 until 2010 the F-values from the ICES stock assessment of North Sea cod were entered into the

Table 2
Age-based model parameters of the modelled fish population. L_i is the mean length of the age class, S_i is the selection coefficient to fishing mortality.

Age (years)	L_i (cm)	S.D. L_i (cm)	S_i
1	15.7	3.2	0.0
2	32.0	6.4	0.3
3	45.5	9.0	0.7
4	56.4	11.2	1.0
5	65.4	13.0	1.0
6	72.8	14.6	1.0
7	78.8	15.8	1.0
8	83.7	16.8	1.0
9	87.8	17.6	1.0
10	91.1	18.2	1.0
11	93.8	18.8	1.0
12	96.0	19.2	1.0
13	97.8	19.6	1.0
14	99.3	19.8	1.0
15	100.5	20.2	1.0
16	101.5	20.4	1.0
17	102.3	20.4	1.0
18	103.0	20.6	1.0
19	103.5	20.8	1.0
20	104.0	20.8	1.0