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Calculation of species sensitivity values and their precision in marine benthic faunal quality indices

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ABSTRACT

A challenging aspect of benthic quality indices used for assessing the marine environment has been to compile reliable measures of the species' sensitivity to disturbances. Sensitivity values and their uncertainties can be calculated, but a problem to cope with is that the results may depend on the actual proportion of samples from disturbed and undisturbed environments.

Here we calculated sensitivity values for each species along an artificial disturbance gradient created by bootstrapping varying numbers of samples from disturbed and undisturbed environments. The values were increasing, decreasing, or more or less constant along this gradient. The lowest value with the lowest uncertainty was adopted as the species sensitivity value.

Analyses of the uncertainties indicated that the accuracy rather than the precision might be a concern. We suggest a method to exclude species for which the uncertainty is outside predefined limits as a precaution to reduce bias in the environmental status classification.

1. Introduction

Species sensitivity or tolerance values are commonly used in various indices for assessing marine environmental quality as in the EU Water Framework Directive (WFD), and more recently also within the Marine Strategy Framework Directive (MSFD). One of the most challenging aspects of benthic quality indices (e.g. AMBI: Borja et al., 2000; BQI: Rosenberg et al., 2004) has been to compile reliable measures of the species' sensitivity and tolerance to various magnitudes and different kinds of disturbances. Marine benthic fauna encompasses thousands of species and most of them occur at low densities. Scientific knowledge about the ecology of many species is limited, which makes it hard to assign sensitivity values for many species based on documented knowledge. Species and community classifications used so far is either based on literature data combined with expert knowledge (e.g. Borja et al., 2000; Teixeira et al., 2010), or empirical derivation based on number of species and their densities in various community assemblages in relation to the theoretical framework on benthic faunal succession developed by Pearson and Rosenberg (1978), Rosenberg et al. (2004), and Leonardsson et al. (2009).

Sensitivity values derived from literature or from expert knowledge have not been qualified by uncertainties in sensitivity but are rather presented as fixed values. However, the absence of uncertainties does not imply that the values are accurate, and they are not free from uncertainty. Empirically derived sensitivity values could be assigned explicit uncertainties, but so far no such analyses have been performed.

A commonly used minimum number of samples required to calculate sensitivity values for a particular species has been set to 20 (e.g. Rosenberg et al., 2004; Leonardsson et al., 2009; Rygg and Norling, 2013). As the number of samples available for assessing sensitivity values increases over time it is essential to update these values for improving their reliability. The sensitivity values used in the Benthic Quality Index (BQI) formula derived by Rosenberg et al. (2004) and further developed by Leonardsson et al. (2009), are based not only on the tolerance of a species to disturbance but also their capability to coexist with other species. A high sensitivity value means that the species occurs in a high diversity community and has a high competitive ability; it is seldom found in species-poor and disturbed environments. A low sensitivity value on the other hand means that the species has been found predominantly in species-poor environments. This implies that deriving sensitivity values based on samples from rather pristine environments alone is likely to produce higher sensitivity values than if the

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samples come from disturbed environments. On the other hand, if all samples come from disturbed environment sensitive species will typically be missing and their sensitivity values cannot be calculated. A mixture of samples from disturbed and undisturbed environments is therefore needed (Rosenberg et al. 2004), but so far there has been no attempt to evaluate which mixture of samples should be optimal. A complication is that the most proper sensitivity values for opportunists should be in samples predominantly from disturbed environments, while samples from undisturbed areas should give more reliable results for sensitive species. This means that a fixed proportion of samples from disturbed versus undisturbed areas may not be the best mixture of samples for all species.

One reason why it is important to assign uncertainties to the empirically derived sensitivity values is that it is not obvious how the samples used to calculate sensitivity values should be distributed among disturbed and undisturbed areas. Thus, obtaining samples from both disturbed and undisturbed environments could give an accurate mixture to provide the lowest observed sensitivity value, in combination with a low uncertainty, for a species. Similarly, it is not clear how many samples are needed for obtaining reliable estimates.

The aim with this investigation was to develop a method to calculate species sensitivity values that is robust against how the underlying samples are distributed among disturbed and undisturbed areas. Analysis of the uncertainties of the empirically determined species sensitivity values was important in this framework. The existing sensitivity values were based on species richness by calculating the expected number of species (ES) among 50 individuals (ES50). The most tolerant individuals of a species are likely to be associated with the lowest ES50 values, and based on the distribution of a species at a set of stations, the 5% limit of the population was assigned as the species' sensitivity value ($ES50_{0.05}$) (Rosenberg et al., 2004). However, during a recent update of the sensitivity values the ES50-approach caused problems in a number of samples with many species because of high number of juveniles of one or two species. Similar problems with the rarefaction method have been discussed also by other scientists (e.g. Peet, 1974; Labrune et al., 2006; Fleischer et al. 2007; Grémare et al., 2009). To avoid this type of problem we change the base for the sensitivity values in the Swedish index to the observed number of species rather than the expected number of species.

2. Material and methods

Samples of benthic fauna were obtained from the Skagerrak and Kattegat areas between Denmark, Norway and Sweden over the period 1965–2013. In total 1411 stations and 9492 samples from depths between 5 and 456 m were analyzed (Fig. 1).

Benthic experts from Denmark, Norway and Sweden pointed out coastal areas that at some point in time had been exposed to anthropogenic disturbance as demonstrated in benthic fauna composition. These disturbed areas were not always but at least some time exposed to hypoxia, physical disturbance or toxic substances. Fishing pressure was not included in our analysis since we, at present, lack suitable data for this pressure and its effects. Samples from these areas were also enclosed. The analyzed benthic communities ranged from the phase of increasing environmental degradation to early successional stages in disturbed environments to more mature successional stages in comparatively undisturbed conditions.

2.1. Sensitivity values

Initially the procedure described by Rosenberg et al. (2004) and Leonardsson et al. (2009) was used to calculate the sensitivity values: ES50-values (estimated number of species among 50 individuals, rarefaction following Hurlbert (1971)) for each sample and the sensitivity values for each species. Samples with fewer than 50 individuals were assigned the observed number of species. However, a number of samples obtained very low ES50-values despite the fact that the observed number of species ranged between 10 and 20. As an example, we have recorded juveniles of recently recruited bivalves (*Angulus tenuis*) and polychaetes (*Galathowenia oculata*) in numbers exceeding 3000 per 0.1 m^2, and these species were not listed in e.g. AMBI or earlier by Rosenberg et al. (2004) and Leonardsson et al. (2009) as tolerant species. When recorded in such high numbers they will contribute to low ES50-values for those samples, and consequently all species associated with those samples will be assigned the same low ES50-values. Their high abundances are unlikely to remain for any longer time as they are time and site specific. If sampling was made at the same site weeks later, the ES50-value would most likely have been significantly higher. This problem of low "species" number, calculated by the rarefaction method when one or a few dominating species, mask the occurrence of the other less common species has been discussed by others (e.g. Peet, 1974; Labrune et al., 2006; Fleischer et al., 2007; Grémare et al., 2009). For the same reason we now abandon the ES50-approach that we used earlier in the calculation of the sensitivity values (Leonardsson et al., 2009) and instead use the observed number of species in each sample. The new species sensitivity value, $S_{0.05}$, is defined as the 5th percentile of the number of species each individual of the species encounter in the samples where the species occur. One way to find the sensitivity value is to select all samples where the species is present, sort the sample's number of species in ascending order, divide each sample's number of species with the sum of all selected sample's number of species and multiply by 100 to have the percentile, and finally locate the sample which holds the 5th percentile. The sensitivity value is then the number of species found in that sample.

Only species occurring in at least 20 samples from each of the two disturbed and undisturbed environments were analyzed for an optimum mixture of samples. In order to find the optimum mixture of samples, i.e. with the lowest sensitivity value in combination with the lowest uncertainty, with each species from disturbed and undisturbed areas a range of sample proportions from the two environments were assigned from 0 to 1 in steps of approximately 0.05 when possible. The lowest proportions were found by keeping all samples from the undisturbed areas and varying the number of samples from the disturbed areas. Similarly, the highest proportions were found by keeping all samples from the disturbed areas and varying the number of samples from the undisturbed areas. Hence, each proportion corresponded to a fixed number of samples from the undisturbed and the disturbed areas respectively. For convenience we call this approach the stratification method. During the resampling with replacement for each proportion, the specified fixed number of undisturbed samples were drawn at random from all the undisturbed samples, and the specified fixed number of disturbed samples were drawn at random from the all the disturbed samples. Thereafter the sensitivity value was calculated and stored following Leonardsson et al. (2009) but now using the number of species for each sample rather than the ES50-values. This procedure was repeated 10,000 times for each proportion and species, and the 2.5th and the 97.5th percentiles of the sensitivity values were derived as measures of uncertainty. The optimum proportion of samples from the disturbed areas was found for each species by allowing a range of sensitivity values from the lowest sensitivity value to one unit above this minimum. This range was arbitrarily chosen to keep the sensitivities low but at the same time allowing for a range of sensitivity values with potentially different uncertainties. In this