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Can biotic indicators distinguish between natural and anthropogenic environmental stress in estuaries?

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ABSTRACT

Because estuaries are naturally stressed, due to variations in salinity, organic loadings, sediment stability and oxygen concentrations over both spatial and temporal scales, it is difficult both to set baseline reference conditions and to distinguish between natural and anthropogenic environmental stresses. This contrasts with the situation in marine coastal and offshore locations. A very large benthic macroinvertebrate dataset and matching concentrations for seven toxic heavy metals (i.e. Cr, Ni, Cu, Zn, Cd, Hg and Pb), compiled over three years as part of the UK's National Marine Monitoring Programme (NMMP) for 27 subtidal sites in 16 estuaries and 34 coastal marine sites in the United Kingdom, have been analysed. The results demonstrate that species composition and most benthic biotic indicators (number of taxa, overall density, Shannon–Wiener diversity, Simpson's index and AZTI's Marine Biotic Index [AMBI]) for sites in estuarine and coastal areas were significantly different, reflecting natural differences between these two environments. Shannon–Wiener diversity and AMBI were not significantly correlated either with overall heavy metal contaminant loadings or with individual heavy metal concentrations ('normalized' as heavy metal/aluminium ratios) in estuaries. In contrast, average taxonomic distinctness (Δ^+) and variation in taxonomic distinctness (Λ^+) did not differ significantly between estuarine and coastal environments, i.e. they were unaffected by natural differences between these two environments, but both were significantly correlated with overall heavy metal concentrations. Furthermore, Δ^+ was correlated significantly with the Cu, Zn, Cd, Hg and Pb concentrations and Λ^+ was correlated significantly with the Cr, Ni, Cu, Cd and Hg concentrations. Thus, one or both of these two taxonomic distinctness indices are significantly correlated with the concentrations for each of these seven heavy metals. These taxonomic distinctness indices are therefore considered appropriate indicators of anthropogenic disturbance in estuaries, as they allow a regional reference condition to be set from which significant departures can then be determined.

1. Introduction

Analysis of the structure and composition of benthic macroinvertebrate faunas has become one of the mainstays of environmental quality assessments and led to the development of a wide variety of indicators for assessing the ecological status of estuaries and other transitional waters, either singly or in combination as multimetrics. Two major problems with this approach are the difficulties in setting baseline reference conditions (Borja and Tunberg, 2011; Borja et al., 2004; Warwick and Somerfield, in press) and distinguishing between the responses of these indicators to natural and anthropogenic environmental stresses (Dauvin, 2007; Dauvin and Ruellet, 2009; Elliott and Quintino, 2007). This is a particular problem in estuaries since their natural environmental conditions vary both spatially and temporally (Hutton et al., 2015; Borja and Tunberg, 2011; Tweedley et al., 2012; Wetzel et al., 2012; Nebra et al., 2014; Brauko et al., 2015).

For many of these indicators there is no universal reference condition. Such indicators include those that employ data on species diversity and abundance, either alone or in combination with other metrics, e.g. M-AMBI (Muxika et al., 2007), or those involving ratios between different taxa, e.g. the BOPA index (Dauvin and Ruellet, 2007) or functional groups, e.g. the Infaunal Trophic Index (Maurer et al., 1999). In such cases there are a number of possibilities for setting reference conditions (Borja and Tunberg, 2011; Borja et al., 2004). The best-scoring samples are typically taken as indicating the most pristine state. These are then used to establish local reference conditions that act as a baseline against which temporal changes or spatial differences can be assessed and which may vary among estuaries. It has been argued, however, that it is inappropriate to use a pristine state as a reference point against which potentially impacted sites can be evaluated (ICES, 2002). This point is particularly valid with estuaries, where all sites might be impacted to some degree and no appropriate reference sites may thus

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be available. In such circumstances, Borja et al. (2004) have proposed the use of 'virtual' reference locations, i.e. those "based upon experience gained of the area and conceived as 'potential' components – biological parameters, chemical concentrations, etc. – that should be present".

Rather than comparing data, real or virtual, among times or locations, an alternative approach is to apply measures that, in some sense, have expected values that reflect differences in environmental quality. Two indices, AZTI's Marine Biotic Index, AMBI (Borja et al., 2000, 2003) and taxonomic distinctness (Clarke and Warwick, 2001; Warwick and Clarke, 2001) adopt different approaches to setting reference conditions by using global or regional, rather than local data to establish baselines.

AMBI was designed to assess the environmental quality of European coastal waters by classifying their benthic macroinvertebrate species into five ecological groups on the basis of their known sensitivity to environmental stress. The designation of a species to an ecological group is drawn from the extensive literature on species in marine and transitional waters, supplemented by the consensus judgement of experts, with the index based on the relative abundances of species in each ecological group (Borja et al., 2000; Teixeira et al., 2010). The index has become an important element for assessing the ecological status of marine and transitional waters under the European Water Framework Directive, either alone or in combination with other metrics, such as species richness and Shannon–Wiener diversity (e.g. Blanchet et al., 2008; Borja et al., 2003, 2004, 2007). Based on survey data from a large number of sites in the north-eastern Atlantic, numerical limits for AMBI have been shown to reflect differences in ecological status, so that ecological status may be assigned using single samples, the ecological condition being based on a global comparison with other areas (Tweedley et al., 2014). Furthermore, in regions of the world where the sensitivity of species to pollution and disturbance is not well documented, calculating AMBI at the family level has proven to be effective (Tweedley et al., 2014). However, AMBI is essentially an indicator of organic enrichment and associated reduction in oxygenation of the sediments, properties that vary naturally and thus potentially confound any biotic response to anthropogenic contamination or disturbance (Brauko et al., 2015; Tweedley et al., 2014; Wetzel et al., 2012). Consequently, some authors have considered it an inappropriate tool for assessing disturbance levels in estuaries (Dauvin, 2007; Escavarage et al., 2004). The BENTIX index (Simboura and Zenetos, 2002) is essentially similar to AMBI, except that the species comprise three rather than five ecological groups. It is invariably correlated with AMBI and thus suffers from the same influences of natural variability.

Unlike AMBI and species richness measures, taxonomic distinctness measures of biodiversity are claimed to be relatively insensitive to natural changes in environmental conditions, but are sensitive to anthropogenic disturbance (Leonard et al., 2006). That paper included a preliminary analysis of benthic macroinvertebrate data collected as part of the United Kingdom's National Marine Monitoring Programme (NMMP), which is treated in much more detail here. Taxonomic distinctness indices, based on simple species lists (presence or absence of species, i.e. Δ^+ and Λ^+), provide a potential framework within which these measures can be tested for departure from expectation (see Warwick and Clarke, 2001). Variability in taxonomic distinctness, due to differences in natural environmental factors, generally falls within a predictable range, based on the null hypothesis that the species present are structured as if they are a random selection from the regional species pool. This expectation then becomes the baseline against which biodiversity change is determined, the concept of spatial or temporal baselines thus being replaced by the concept of a 'reference condition'. This potentially establishes a baseline in a region that is entirely impacted to some degree, and where no appropriate reference sites are available. To date, taxonomic distinctness has not been included in many papers comparing a plethora of other biotic indices employed to assess the environmental quality of estuaries (e.g. Hutton et al., 2015; Cardoso et al., 2012; Wetzel et al., 2012; Nebra et al., 2014; Brauko et al., 2015).

The aim of this study was to compare the inferences drawn from AMBI and taxonomic distinctness for a very large and extensive benthic macroinvertebrate dataset, for which corresponding sediment contaminant data (i.e. toxic heavy metal concentrations) were also available. If any of the indices are to be a useful indicator of environmental condition, they should clearly be correlated with pollution status. Although Shannon–Wiener diversity has no reference condition, the relative performance of this very widely used index is also included for comparative purposes.

2. Material and methods

2.1. Source of data

The data for benthic macroinvertebrates and metal concentrations employed in this study were obtained as part of the UK's NMMP. The NMMP benthic survey has involved a massive sampling and analytical effort by several teams of workers in the different regions. While the methodology has been standardized as far as possible, this standardization is not perfect. Five replicate samples of benthic macroinvertebrates were collected using 0.1 m^2 Day grabs or box corers at each of 67 locations in estuarine and coastal marine areas around the UK coast on one, two or three occasions between February and June in 1999, 2000 and 2001 (CEFAS, 2004). The concentrations of chromium (Cr), nickel (Ni), copper (Cu), zinc (Zn), cadmium (Cd), mercury (Hg) and lead (Pb), together with that of aluminium (Al), were measured in five replicate samples from 61 of the 67 sites. Thus, composite faunal and metal data were available for 61 sites. These sites comprised 27 subtidal sites in 16 estuaries (Forth, Tweed, Tyne, Wear, Tees, Humber, Thames, Medway, Tamar, Pool Harbour, Severn, Dovey, Mawddach, Mersey, Bann and Lough Foyle) and 34 sites in coastal areas (Fig. 1). The faunal densities and metal concentrations of the five replicate samples from

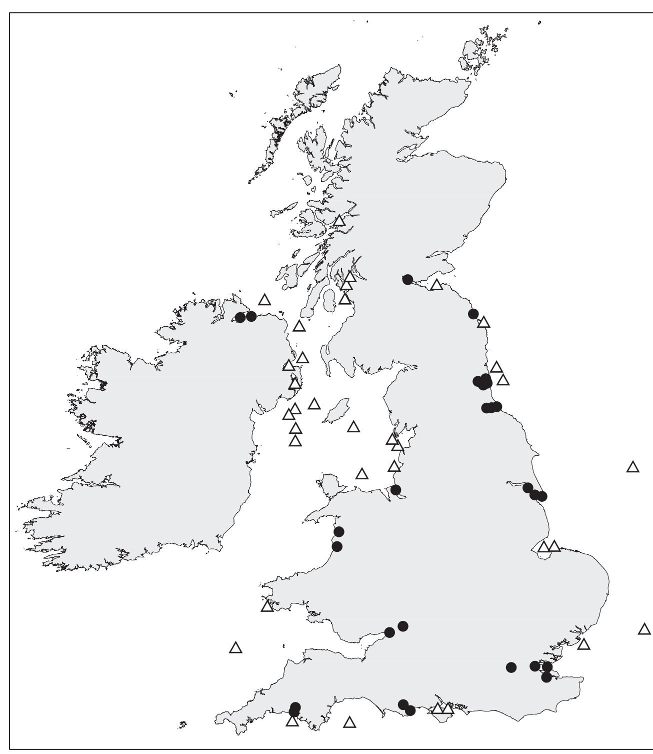

Fig. 1. Map showing the locations of the estuarine (●) and coastal areas (△) sampled in the United Kingdom during the National Marine Monitoring Programme in 1999, 2000 and 2001.