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Case Study

Macrobenthic–mud relations strengthen the foundation for benthic index development: A case study from shallow, temperate New Zealand estuaries

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ABSTRACT

Globally the input of sediment to coastal systems, in particular to estuaries, is predicted to increase due to anthropogenic activities. Sediment mud content is a powerful driver of ecologically important, macrobenthic taxa in estuarine intertidal flats. Accordingly, forecasting species responses to increased sedimentation is fundamental for effective ecosystem management, particularly for productive, geologically young, and sand-dominated estuaries that characterise many countries, including New Zealand (NZ). Modelling studies have highlighted the non-linear, highly variable responses of taxa to mud concentration. However, existing taxon-specific models have not adequately accounted for the full mud gradient, the influence of potentially confounding variables (e.g. organic enrichment, heavy metal concentrations), or regional differences in species responses. Furthermore, such models are often based on qualitative expert consensus of the membership of taxa in ecological groups that characterise their sensitivity to mud content. In this study, data from 25 unmodified to highly disturbed, shallow NZ estuaries, were used to develop an ecologically relevant model to relate the responses of 39 taxa to sediment mud content for use in the intertidal flats of shallow, temperate estuaries. Preliminary analyses indicated that sediment mud content was the dominant driver of macroinvertebrate community composition among sites, total organic carbon was of secondary importance and heavy metals did not explain significant variation in composition. Regression analysis revealed a significant linear relationship between sediment mud and total organic carbon content, which permitted subsequent analyses to be based on mud content alone. Generalised additive models were used to develop taxon-specific models that, according to k-fold cross validation, accurately predicted both probability of presence (up to 79% deviance explained) and maximum density (up to 96% deviance explained) along the sediment mud gradient (0.1–92.3%). Estimates of "optimal mud range" and "distribution mud range" were quantitatively-derived for each taxon and used to categorise taxa into one of five ecological groups (identical to those used in existing biotic indices), based on their individual sensitivities to increasing mud content. By removing expert consensus from the grouping process, the classification methods established herein provide strong support for the use of quantitative indices for the assessment and management of estuarine condition in response to increasing sediment mud content. The findings indicate that NZ estuarine sediments (2–25% mud) support a more diverse and abundant macroinvertebrate assemblage and exhibit low organic enrichment (<1% total organic carbon) compared to estuaries with >25% mud content.

1. Introduction

Changes in land-use and coastal development have increased rates of sediment inputs to estuaries (Thrush et al., 2004) and are expected to increase still further in many parts of the world (Halpern et al., 2008). The elevated delivery to and retention of terrigenous mud (<63 μm particle diameter) in estuarine systems

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can impair feeding, behavioural responses, larval recruitment, and trophic interactions in coastal food-webs (Norkko et al., 2002; Ellis et al., 2002; Cummings et al., 2003; Duarte et al., 2005; Jones et al., 2011; Vasconcelos et al., 2011). Consequently, quantitative models to forecast changes in macrobenthic community composition in relation to increasing mud content are important tools for estuarine monitoring and assessment programmes worldwide, including The European Water Framework Directive (WFD of the European Union 2000), New Zealand's National Estuarine Environmental Assessment and Monitoring Protocol (EMP; Robertson et al., 2002), and the United States Environmental Protection Agency National Estuary Programme (US EPA, 2009). Such information is particularly important in the context of shallow, intertidal, short water residence time (i.e. <1 day) estuaries (SSRTEs), which are vulnerable to sedimentation owing to the large area of intertidal habitat available for mud deposition and the subsequent enhancement of macroalgal blooms that affect estuaries in many countries, including New Zealand (NZ). To date, models of macrobenthic species-specific changes in abundance have established functionally variable, non-linear responses of taxa to increasing mud content (Norkko et al., 2002; Ysebaert et al., 2002; Thrush et al., 2003; Anderson, 2008; Sakamaki and Nishimura, 2009; Pratt et al., 2014). However, most taxon-specific models do not adequately account for the full mud gradient (with data often dominated by mud content <40%), for the influence of other potentially confounding variables (e.g. organic enrichment, heavy metal concentrations), or for regional differences in species responses. Accordingly, there is an urgent need for quantitative macrobenthic–mud response models that are conditioned on multi-estuary data, which represent a broad spatial scale (i.e. applicable at a national rather than regional level), comprehensive mud gradient, and more taxa with varying sensitivity across the full mud gradient.

An important, yet frequently overlooked, application of macrobenthic–mud models is their ability to inform various biotic indices that are commonly used to assess estuarine benthic condition (see review in Borja et al., 2012). These indices are based on the seminal research of Gray (1974), which focussed on animal-sediment relationships to describe habitat preferences of biological assemblages. These relationships were further developed to describe groups of taxa according to their different pollution tolerances (e.g. Pearson and Rosenberg, 1978; Borja et al., 2000). Despite their cost-effectiveness and apparent global application, such indices lack a strong quantitative foundation. For example, the widely used AZTI-Tecnalia marine biotic index (AMBI; Borja et al., 2000) and the more recent traits based index (TBI; Rodil et al., 2013), rely largely on qualitative expert consensus to categorise taxa into "ecological groups" (EGs), based on taxon-specific sensitivities to an increasing organic enrichment and heavy metal or mud gradient, respectively. Keeley et al. (2012) highlighted the subjective nature of expert consensus and sought to combine it with quantitative modelling approaches to assign individual taxa to EGs. However, like much of the AMBI list containing >6500 taxa, Keeley et al. (2012) assigned EGs on the basis of organic enrichment stress (i.e. specifically beneath subtidal finfish farms). Quantitative species-specific models that have focussed on sedimentation stress include the probability of occurrence and mean density (based on Generalised Linear Models; GLMs) (Ysebaert et al., 2002; Thrush et al., 2003; Sakamaki and Nishimura, 2009), and canonical analysis and quantile regression splines approach (Anderson, 2008). In the latter approach, models characterised change in assemblages using the maximum density (i.e. 95th percentile of the abundance distribution) of select species along an increasing mud gradient and allowed estimation of an optimum mud value (i.e. preferred mud content) for certain taxa. However, these models, and associated information (i.e. optimum mud values), are yet to be used to strengthen the foundation of biotic indices such as the AMBI and TBI.

The primary objective of the present study was to develop quantitative models of macrobenthic–mud relations in shallow, temperate estuaries to improve understanding of species-specific responses to increased sedimentation. Secondly, these models of ecologically relevant "ranges" (Holt, 2003) were then used to categorise taxa into EGs, rather than relying on expert consensus. Analyses were first undertaken to distinguish the mud content gradient from other environmental gradients that are known to co-vary with mud and hence synergistically influence macrofaunal assemblages. Following this, building on the approaches of Thrush et al. (2003) and Anderson (2008), we employed a two-step procedure that utilised generalised additive models (GAMs – a flexible class of a generalised linear model based on backfitting with linear smoothers; Wood and Augustin, 2002) to predict the distributions and maximum densities of 39 common macrobenthic taxa along a mud gradient. The present dataset, based on 135 intertidal sites in 25 SSRTEs distributed throughout NZ and spanning $\sim 12^\circ$ of latitude, effectively expands the regional scale, mud gradient range and the number of taxa modelled in earlier studies. Then, using GAMs, an "optimum" (i.e. preferred mud range) and "distribution" (i.e. the mud range over which a given taxa was present) mud range was derived for each taxon. These two quantitative estimates then informed membership of taxa into one of five mud-specific EGs (groupings identical to those listed in the AMBI, representing 0.1–92.3% mud content), thereby strengthening the foundation and applicability of quantitative indices for the assessment and management of estuarine condition in response to increasing sediment muddiness. It is envisaged these EG classification methodologies are globally applicable (i.e. to SSRTEs outside NZ), and also could be used to group taxa in freshwater or terrestrial systems. However, since species occurrences and species-specific responses to increasing sediment mud content likely vary on a global scale, the models developed herein should be locally validated a priori before being applied to a new country. Overall, this study provides new information fundamental to improving current conservation and management standards that aim to safeguard the environmental integrity of temperate SSRTEs.

2. Materials and methods

2.1. Study locations and sampling protocol

This study focusses on the spatial (not temporal) variability in macroinvertebrate taxa among locations. In total, 135 locations in 25 estuaries, encompassing most of NZ (Fig. 1), were selected based on the criteria outlined in the National Estuary Monitoring Protocol (NEMP) (Robertson et al., 2002). The tidal rivers, lagoons, harbours and deltas surveyed represent a range of common estuary types (Table 1), with most characterised by relatively short water residence times (<1 day) and dominated by intertidal habitat (>90%, except the Firth of Thames, a large coastal embayment, which was added because it is characterised by 85 km^2 of intertidal habitat available for mud deposition); properties common to estuaries worldwide (e.g. Nicastro and Bishop, 2013; Sutula et al., 2014). The number of sampling locations within each estuary was allocated proportionately to each estuary's size and extent of intertidal mud and sandflat habitat. Large estuaries ($\geq 30\ km^2$) were generally allocated more locations (maximum of 6), while small estuaries ($\leq 10\ km^2$) were allocated fewer locations (e.g. 2). Sampling locations were chosen and the sampling protocol itself was carried out in accordance with the National Estuary Monitoring Protocol (NEMP) (Robertson et al., 2002). All sampling was conducted during the southern hemisphere summer (January to March) over a 13 year