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What does impacted look like? High diversity and abundance of epibiota in modified estuaries

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ABSTRACT

Ecosystems modified by human activities are generally predicted to be biologically impoverished. However, much pollution impact theory stems from laboratory or small-scale field studies, and few studies replicate at the level of estuary. Furthermore, assessments are often based on sediment contamination and infauna, and impacts to epibiota (sessile invertebrates and algae) are seldom considered. We surveyed epibiota in six estuaries in south-east Australia. Half the estuaries were relatively pristine, and half were subject to internationally high levels of contamination, urbanisation, and industrialisation. Contrary to predictions, epibiota in modified estuaries had greater coverage and were similarly diverse as those in unmodified estuaries. Change in epibiota community structure was linearly correlated with sediment-bound copper, and the tubeworm *Hydroides elegans* showed a strong positive correlation with sediment metals. Stressors such as metal contamination can reduce biodiversity and productivity, but others such as nutrient enrichment and resource provision may obscure signals of impact.

1. Introduction

Estuaries are a nexus of human settlement and marine environments, and bear the brunt of human activities occurring on both land and water. Consequently, they are widely considered the most impacted of all marine habitats (Edgar et al., 2000; Kennish, 2002; Roy et al., 2001). At the same time there is great incentive to preserve their proper functioning, since estuaries provide key ecosystem services such as nutrient cycling, water filtration, and act as nursery grounds for economically-important species of fish (Morrisey, 1995). The task of minimising human impacts in these ecologically significant environments is one of the major challenges facing environmental managers today.

Many estuaries are subject to multiple stressors from industry, agriculture, urban and coastal development, and some are now chronically contaminated (Scanes and Scanes, 1995). Heavy metals, fertilizers, sewage, and synthetic compounds are common forms of pollution that enter the marine environment as a result of human activities. Some contaminants can bind to sediments and reside in estuaries for years or decades, periodically re-entering the water column when sediments are disturbed (Roberts, 2012). Coastal development also affects physico-chemical water quality parameters (e.g. temperature, salinity, turbidity and dissolved oxygen) by altering terrestrial run-off, hydrodynamics, dredging, or the discharge of heated effluent. The physical underwater landscape of many urban estuaries is also extensively modified through the addition of artificial structures (Dafforn et al., 2009), or by displacing sediment to accommodate shipping (Newell et al., 1998). It is vital to identify and rank the strongest drivers of human impacts, and understand their effects in order to sustainably manage and conserve these ecosystems.

Estuaries encompass a diverse range of habitats, from soft sediments to rocky reefs, seagrass beds, mangroves and open water systems (Morrisey, 1995). Past environmental management has focused on monitoring water quality alone (ANZECC, 2001), but has been criticised for lacking ecological relevance (Scanes et al., 2007). Focus is now moving towards integrated ecosystem assessments that include biotic components (Borja et al., 2008), and substantial

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research has been invested worldwide in developing estuarine health indicators. Some taxa have been identified as useful bioindicators – species whose abundance or condition reflects environmental quality (Carignan and Villard, 2002). However, most of this research has focused on soft-sediment infaunal communities (Borja et al., 2008; Hewitt et al., 2009; Hyland et al., 2003; Van Dolah et al., 1999), which are physically separated from water column disturbances and may respond differently to other ecosystem components.

Sessile invertebrates and algae, or epibiota, grow on hard substrates in estuaries and can be useful bioindicators. Most sessile invertebrates are filter feeders and are exposed to contaminants ingested as food, or absorbed in dissolved form directly from the water column. These pathways of exposure are also relevant to other ecosystem components, such as fish and plankton. Marine invertebrates require trace amounts of some metals (e.g. copper, lead and zinc) for metabolic function, but elevated concentrations interfere with metabolic processes and can cause sub-lethal impacts or mortality. Particulate matter in the water column can also physically disturb filter-feeders by clogging feeding apparatus or burying individuals (Burton and Johnston, 2010). Sediment resuspension events from dredging or vessel traffic have been shown to harm sessile invertebrates through the remobilisation of contaminants and/or increased suspended sediment (Knott et al., 2009). To assess the response of epibiota to contamination and to understand the utility of these fauna as bioindicators, we need to quantify their distributions relative to contamination at large-scales in the field.

The abundance and diversity of introduced species is another important measure of ecological integrity. Epibiota represent a large proportion of marine non-native species (Ruiz et al., 1997), primarily due to their affinity to be transported by shipping. Non-native species are frequently transported as adults on the hulls of vessels, or as larvae in ballast water. Some species can acquire tolerance to heavy-metals (Piola and Johnston, 2006), which facilitates their transport on vessels coated in anti-fouling paint and provides them a competitive advantage against less-tolerant natives in polluted environments (Piola and Johnston, 2007). Monitoring epibiota in urbanised estuaries is an essential task for understanding the spread and impacts of marine invaders.

Here we assess the distribution of epibiota relative to human modification at large scales, across multiple estuaries. We use the term 'modification' to acknowledge the multiplicity of ways that humans impact estuaries. Many anthropogenic stressors are spatially correlated so their effects cannot be distinguished without experiments, but together they represent the collective imprint of human activities. Broad-scale surveys point to likely associations between ecological and environmental patterns, and indicate whether there is real-world support for predicted trends. We conducted a survey of sessile invertebrates at 84 sites across six estuaries in south-eastern Australia, and tested for differences between communities in replicate modified and relatively unmodified estuaries. At each site we collected environmental data, including water quality measurements (e.g. temperature, salinity and turbidity), and metal and organic contamination. The modified estuaries included Port Jackson and Port Kembla, which have some of the highest concentrations of benthic sediment metals in the world (Birch, 2000; He and Morrison, 2001). For this reason we focused on metal contamination as a proxy for modification when testing for potential bioindicators, but emphasize that other stressors covary with metal contamination. We were also interested in how introduced species were distributed relative to human modification, so conducted additional analyses to examine this.

2. Materials and methods

2.1. Study design

We surveyed the distribution of sessile invertebrates in six estuaries in New South Wales (NSW), Australia (Fig. 1). Estuaries were classified as either "modified" or "unmodified" by human activities. These labels are used in relative terms – unmodified estuaries are subject to less disturbance but still accommodate some human activities. Port Kembla, Port Jackson and Botany Bay are heavily modified estuaries with 80–100 years of industrialisation and urbanisation (Birch, 1996; He and Morrison, 2001; Irvine and Birch, 1998). Port Hacking, The Clyde and Jervis Bay are estuaries that are relatively less modified by urbanisation and have no history of major industry. In addition, trawling and commercial fishing are restricted in the Marine Protected Areas of The Clyde and Jervis Bay (ANZECC, 1999). Each estuary was divided into "inner" and "outer" zones, and in each zone we selected 7 sites. Zones were determined by natural breaks in the geomorphology and water quality of estuaries, where the prevailing influence changed from predominantly oceanic to estuarine.

2.2. Sampling units

At each site we deployed a 40 × 40 cm grey PVC panel, held to the seabed with either a sand-screw (Wombat®) or 30 kg weight, depending on site suitability. A settlement plate (11 × 11 cm roughened black Perspex) was attached to each side of each panel, such that two settlement plates were deployed per site. Settlement plates were the sampling unit on which sessile invertebrate communities were censused. Panels were deployed for 3 months between November 2009 and February 2010. Upon collection, settlement plates containing assemblages were removed from panels and preserved in 7% formaldehyde buffered in seawater. Communities were censused by placing a 10 × 10 cm grid over each settlement plate, and recording taxa that occurred under 100 evenly spaced points. All organisms were identified to the lowest possible taxonomic level. The origin of each taxa (native, cryptogenic, introduced, or unidentified) was determined with reference to the literature.

2.3. Environmental variables

At each site we measured a suite of environmental variables including metal and PAH concentrations, and water quality variables. Temperature, salinity, turbidity, pH, oxygen and chlorophyll fluorescence were measured at the same depth as the settlement panels using a YSI-Sonde 6600-v2 (Yellow Springs, USA). This was done twice, as panels were deployed and retrieved.

A detailed description of methodology used to quantify contamination is given in Dafforn et al. (2012). Briefly, at each site we measured metal contamination in (i) benthic surface sediments collected with a Van Veen grab, (ii) sediments collected in sediment traps attached to each panel, and (iii) tissue of oysters (*Saccostrea glomerata*) deployed in mesh bags attached to each panel. Both sediments traps and oysters were deployed for the full 3 months of panel deployment.

Sediments and oyster tissue were acid digested and analysed for metal concentrations (Cu, Zn, Pb, As) using ICP-AES (Perkin Elmer, Optima7300DV, USA). Benthic sediments and oyster tissues were analysed for the following PAHs using Method 8260 (USEPA, 1996): naphthalene, acenaphthylene, acenaphthene, fluorene, phenanthrene, anthracene, fluoranthene, pyrene, benzo(a)anthracene, chrysene, benzo(a)pyrene, benzo(b & k)fluoranthene, indeno(1,2,3-cd)pyrene, dibenzo(a,h) anthracene and benzo(g,h,i)perylene. There was insufficient sediment in the sediment traps to analyse PAH concentrations. Individual sediment contaminants were highly correlated with one another, so we derived a single measure of toxicity by calculating a mean sediment quality guideline quotient (mSQGQ). This quotient was obtained by scaling contaminant concentrations against their guideline values and high sediment quality guidelines (Simpson et al., 2013), then summing scaled concentrations at each site (Long et al., 2006). These ANZECC/ARMCANZ sediment quality guideline values are comparable to standards by other regulatory agencies (CCME, 2002; EUWFD, 2010).

2.4. Statistical analysis

Community-level differences between samples from modified and unmodified estuaries were tested with PERMANOVA (Anderson, 2001). Data were square-root transformed and samples related by Bray–Curtis similarity. Fixed factors (levels in parentheses) were Modification (modified, unmodified) and Zone (inner, outer). Estuary ($n = 6$) and Site ($n = 84$, nested in Estuary) were random factors. Multivariate data were visualized with an nMDS ordination, using the metaMDS function in the R package `vegan` (Oksanen et al., 2012). We related environmental variables to nMDS axes with vector plots, and plotted correlations between nMDS axes and species distributions. Metal concentrations in benthic sediment, sediment trap, and oyster metal were highly correlated, so to avoid co-linearity we used benthic metal concentrations to represent metal contamination. Correlations between a key environmental variable (Cu in benthic sediment) and nMDS axes were illustrated with a surface plot.

Univariate tests for differences in response variables according to Modification, Zone, and their interaction were tested with generalized linear mixed models (Bolker et al., 2009) using the `lme4` package (Bates et al., 2011) in R v.3.0.1. Data were averaged for each Site prior to analysis. Modification and Zone were fixed factors, and Estuary was a random factor. We assumed Poisson distributions and estimated