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Pollution signature for temperate reef biodiversity is short and simple

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ABSTRACT

Pollution increasingly impacts healthy functioning of marine ecosystems globally. Here we quantify concentrations of major pollutant types (heavy metals/sewage/petrochemicals/plastics) as accumulated within marine sediments on and/or immediately adjacent to shallow reefs for 42 sites spanning coastal population centres across south-eastern Australia. Gradients in pollutants were revealed, but few pollutants co-varied, while increasing wave exposure ostensibly diluted concentrations of all pollutants except microplastics. Examination of reef biodiversity indicators revealed that maximum size of fauna and flora, a key life-history parameter summarised by the *Community shortness index,* plus declining functional and species richness, were the most sensitive bioindicators of pollutants – for which heavy metals and nutrient-enrichment were most pervasive. Results indicate that assemblages of biogenic habitat formers and associated fauna collapse from "long and complicated" to "short and simplified" configurations in response to increasing pollution, and this community signature may form an effective bioindicator to track human-driven degradation.

1. Introduction

The legacy of unregulated historical pollution in combination with accelerating production of human waste and synthetic compounds poses an accumulating threat to the health of ecosystems globally (Islam and Tanaka, 2004; Vörösmarty et al., 2010; Halpern et al., 2008, 2009; Crain et al., 2009). In developing nations, unregulated pollution remains a contemporary issue, while for developed countries legacies remain (e.g. Knott et al., 2009) and/or new regulatory needs are evolving in response to increasing pollution threats and/or "viral" shifts in social–consciousness (e.g. cosmetic micro-bead plastics). Representing ultimate sinks for pollution, contemporary pollutants are continually superimposed upon past legacies in the marine environment (e.g. Halpern et al., 2009; Crain et al., 2009). However, marine pollution is generally "out-of-sight, out-of-mind" compared to pollution in either terrestrial or freshwater environments.

The general lack of visibility of marine pollution in subtidal marine environments means that mitigation for solely aesthetic reasons is seemingly unlikely. Furthermore, pollution concerns appear more likely to escalate if toxins become evident within seafood or occur at popular swimming destinations, or become highly visible via interactions (distressing/smothering/entanglement/ingestion) involving charismatic marine megafauna such as seabirds, turtles, seals or whales (e.g. Page et al., 2004; Wilcox et al., 2015). Beyond these highly visible and confronting signs, the broader impacts of marine pollution on non-seafood species, less charismatic fauna or the dynamics of marine populations, communities and broader functioning of marine ecosystems is comparatively less understood (Chapman, 2002; but see Peterson et al., 2003; Lotze et al., 2011).

Shallow reef communities are among the most visible of all subtidal marine ecosystems and also harbour the greatest concentrations of biodiversity in the ocean (Roberts et al., 2002). Furthermore, reefs in estuaries and embayments have been suggested to be amongst the habitats of greatest value to society (Costanza et al., 1997; Bennett et al., 2016). The flora and fauna on subtidal reefs are readily assessable using visual underwater census techniques in less turbid areas, and are frequently surveyed by scientific and/or citizen science divers, with sometimes longer-term > 10 year time series for particular reefs (Babcock et al., 2010; Edgar and Stuart-Smith, 2014). Particular components of subtidal reef communities are known to exhibit variable sensitivity to human impacts, with specific functional components of the reef community, beyond individual species (e.g. Stuart-Smith et al., 2013), also appearing susceptible to pollution (e.g. McLean et al., 1991; Costanzo et al., 2001; Gaston and Suthers, 2004; Airoldi et al., 2008; Lotze et al., 2011; Strain et al., 2014; Oh et al., 2015; Stuart-Smith et al., 2015, 2017).

While environmental monitoring of pollution typically focusses on the presence of chemical compounds and laboratory based toxicology

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studies, longer term population and ecologically relevant effects are less well understood (e.g. Lam and Gray, 2001; Chapman, 2002). Although management of pollution is guided by knowing levels of pollutants in the system, a seemingly powerful driver of change in management practices and public behaviour is the visible impact of pollution on biodiversity. Such a capacity to track biological signatures of impact could be useful for environmental monitoring (e.g. State-of-the-Environment reporting) and ultimately mitigation (Stuart-Smith et al., 2017). The impact of pollution on subtidal reef communities in temperate Australia has been broadly assessed (e.g. Edgar and Barrett, 2000; Edgar et al., 2003; Stuart-Smith et al., 2015; Oh et al., 2015; Kriegisch et al., 2016). However, examination of structural changes of the entire reef ecosystem (including faunal and floral components) alongside assessments of gradients in specific pollutants, as measured directly at reef sites, has not previously been undertaken.

Here we provide new insights into community-level pollution responses, and thus useful bioindicators of pollution, by examining co-located data on fishes, invertebrates and macroalgae with measurements of a suite of heavy metal, sewage and plastic pollutants taken from the benthos adjacent to 42 reef monitoring sites spanning the captial cities and marine environmental gradients in south-eastern Australia. Our aim was to explore system wide changes in reef community structure across pollution gradients common among regions, and independent of biogeographical influences. We utilised a community-trait based approach, instead of focussing on species-specific patterns, to inform the applicability of general and visually-detectable signatures of pollution-associated change for reef communities.

2. Methods

2.1. Field sites

Sampling of pollutants and reef communities was undertaken in coastal estuaries and embayments influenced by the major urban populations of south-eastern Australia, including the four state capital cities: Sydney (New South Wales), Melbourne (Victoria), Adelaide (South Australia) and Hobart (Tasmania). These cities have major ports and industry, and regions of substantial heavy metal pollution as a legacy from both historical industrial pollution and contemporary, but ostensibly reduced, inputs of heavy metals, organic enrichment and other pollutants from storm water runoff and effluent discharges from sub-catchments dominated by urban and agricultural land use (Birch, 2000; Gorman et al., 2009; Knott et al., 2009; Townsend and Seen, 2012). In an attempt to achieve a gradient of pollution levels, additional sampling was undertaken at sites in less densely populated areas along adjacent coastlines, where lower levels of pollutants were expected. Study sites were required to have low turbidity (i.e. > 5 m visibility) to ensure surveys of reef life using visual census was effective (see below), thus sites high within estuaries were not sampled as part of this study.

2.2. Pollutants

Concentrations of heavy metals (Antimony, Arsenic, Cadmium, Chromium, Copper, Cobalt, Lead, Manganese, Nickel, Selenium, Silver, Vanadium, Zinc and Mercury), organic (total nitrogen, nitrogen δ14:15 isotope ratio [hereafter termed δ15N], total organic content), petro-chemicals, and plastic pollution were measured on and within sediments adjacent to 42 south-eastern Australian rocky reef sites (NSW, $n = 12$; SA, $n = 6$; Vic, $n = 8$; Tas, $n = 16$). Within each south-eastern Australian state, sites were distributed across contrasting polluted and relatively pristine sub-locations of Sydney Harbour, Jervis Bay and Eden in NSW; from adjacent to the city of Melbourne towards The Heads in Port Phillip Bay, Victoria; from Port Adelaide south along the Adelaide metropolitan coast in South Australia; and from the Derwent Estuary south to the D'Entrecasteaux Channel plus more pristine sites in eastern Tasmania (Fig. 1).

Study sites were spread as evenly as practically possible across pollution gradients with a minimum separation distance of 2 km within a region. Measurements of pollutants at each site involved sampling duplicate sub-sites spread 50 m apart, which were averaged for each site for all pollutants except for micro-plastics, for which extraction and enumeration was highly time consuming and thus only a single sample per site was processed within the time-frame of the study.

At each site, subtidal marine sediment was collected from depths of 5 to 13 m using a vessel-deployed Van Veen sediment grab (30 cm by 30 cm gape) during September to November 2015, with laboratory determination of pollutant levels occurring from Oct 2015 to Dec 2016. Labile pollutants (e.g. nutrients and petro-chemical compounds) were held on ice then frozen and assessed within 2 weeks of collection, while non-labile material such as micro-plastic concentrations were processed within 12 months of sample collection.

Heavy metal and organic pollution samples (i.e. total organic carbon) were analysed by ALS Environmental Pty Ltd. Australia following all standard operating procedures avoiding contamination, e.g. the use of sterile gloves (http://www.alsenviro.com; 277-289 Woodpark Rd., Smithfield, NSW, 2164). Heavy metal concentrations were analysed for both total metals in sediments extracted by ICP-AES (ALS method code: EG005-SD), plus the bio-active fraction extracted by weak acid 1 M HCl extractable Mercury by FIMS (ALS analysis code: EG035-SDH); notably the bio-active fraction represented 38% of the total metals extractable ($R^2 = 0.97$). Analysis of nitrogen and δ15N enrichment, indicating urban sources of N (*after* Costanzo et al., 2001, 2005), was performed by Environmental Isotopes Pty Ltd., again following standard protocols (http://www.isotopic.com.au/). Micro-plastics were extracted from marine sediments using density separation by NaI and centrifuging with all plastics within the size range of 38 μm to 4 mm collected onto filter paper and enumerated under dissecting microscope (see Ling et al., 2017). Counts distinguished plastic particles from filaments such as polyesters shed from clothing made from synthetic fabrics (see detailed microplastic methodology in Ling et al., 2017). Exposure of samples to other sources of plastics was minimised and blanks run at increasing exposure times to potential sources of airborne microplastic filament contamination (i.e. 1, 3 and 6 h exposures) revealed a contamination rate of 1.02 filaments hr^{-1} ($n = 9$). This contamination rate was considered negligible as samples were exposed for < 30 min and an increase of a single filament per hour, represented only a 0.46% increase in the average microfilament count per sample.

In order to obtain signals of pollutants directly from reefs where fish, invertebrates and macroalgal data were collected, divers also sampled fine sediment layers trapped within algal turfs by suctioning with 50 ml syringes. Comparison of heavy metal pollution measurements for turf-trapped sediments on reefs and conventional Van Veen grabs of sediment from adjacent sandy/silty habitats (within 300 m of the reef site) were highly correlated (Pearson Correlation Coefficient of 0.77). Heavy metal concentration in the turf-sediment matrix on reefs, summed for all heavy metal types, was therefore used for statistical analyses as this was the most direct measure of conditions experienced by the reef community. By contrast, isotopic signals of organic pollutants, petro-chemical surrogates and micro-plastics required larger volumes of sediment than was readily obtainable from the reef surface, consequently soft-sediment habitats adjacent to reef sites were sampled by Van Veen grabs for these purposes. All pollutant/environmental data are available via: http://metadata.imas.utas.edu.au/geonetwork/srv/en/metadata.show?uuid=11075fdf-e53e-4d8c-8999-0b239a742243.

2.3. Reef communities

Reef fish and invertebrate abundances, and percent cover of biogenic habitat-forming species (e.g. macroalgae, sponges, bivalves), were sampled at all 42 south-eastern Australian sub-tidal reef sites adjacent to pollutant sampling sites, using underwater visual census.