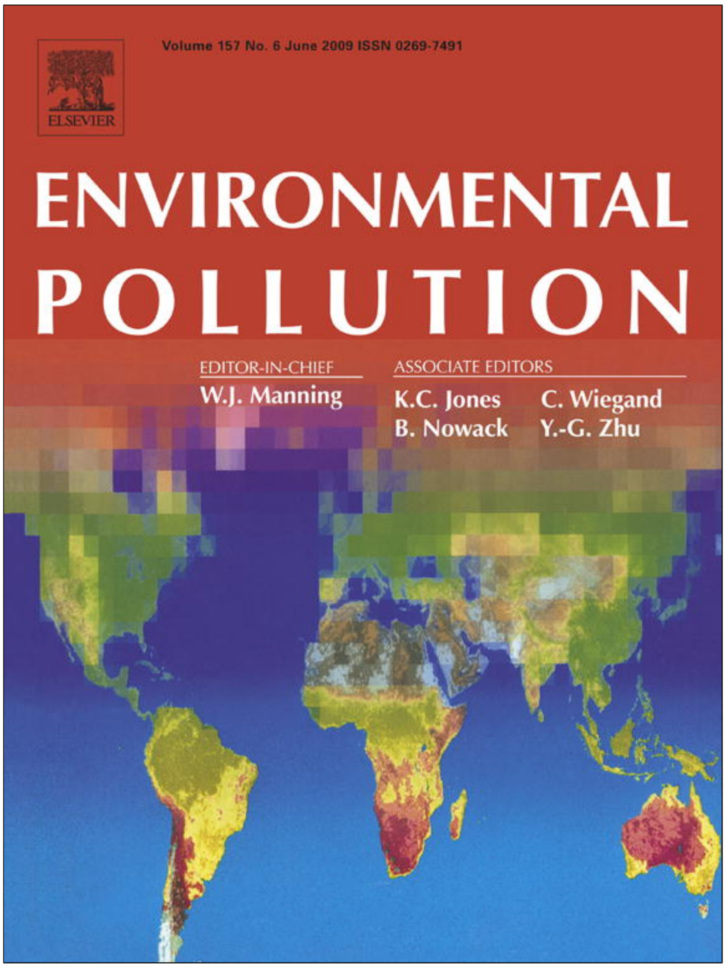

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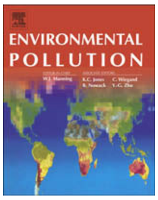

Review

Contaminants reduce the richness and evenness of marine communities: A review and meta-analysis

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Contamination substantially reduces the biodiversity of marine communities in all major habitat types and across all major contaminant classes.

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ABSTRACT

Biodiversity of marine ecosystems is integral to their stability and function and is threatened by anthropogenic processes. We conducted a literature review and meta-analysis of 216 studies to understand the effects of common contaminants upon diversity in various marine communities. The most common diversity measures were species richness, the Shannon–Wiener index (H') and Pielou evenness (J). Largest effect sizes were observed for species richness, which tended to be the most sensitive index. Pollution was associated with marine communities containing fewer species or taxa than their pristine counterparts. Marine habitats did not vary in their susceptibility to contamination, rather a ~40% reduction in richness occurred across all habitats. No class of contaminant was associated with significantly greater impacts on diversity than any other. Survey studies identified larger effects than laboratory or field experiments. Anthropogenic contamination is strongly associated with reductions in the species richness and evenness of marine habitats.

1. Introduction

Coastal marine ecosystems are amongst the most diverse and productive on earth (e.g. de Forges et al., 2000). The rich biodiversity of these systems is integral to their proper functioning and may afford them greater stability and resilience to natural and anthropogenic perturbations (Hooper et al., 2005). However, the diversity of marine ecosystems is increasingly threatened by anthropogenic stressors including over-harvesting, habitat destruction and climate change (Vitousek et al., 1997). In the scientific literature, and in the public mind, contamination from anthropogenic sources is assumed to be an additional threat to marine biodiversity (Crowe et al., 2004). However, susceptibility to contaminants varies between species and there are mechanisms (such as species replacement) that may mask the effects of contaminants on diversity *per se* (Washington, 1984). Moreover, there are many varieties of contaminant and many different marine habitats. Review articles have tended to focus upon particular marine habitats (Glover and Smith, 2003; Legendre and Rivkin, 2002), regions (He and Morrison, 2001; Lotze and Milewski, 2004; Morrison and Delaney, 1996) or contaminants (Pastorok and Bilyard, 1985; Rabalais, 2002; Wu, 1995). Consequently our general understanding of how different contaminants influence patterns of marine biodiversity across habitats is limited (Crowe et al., 2004; Oliveira and Qi, 2003). From a management perspective, key questions remain as to which marine habitats are most vulnerable to contaminants and which classes of contaminants are most likely to cause negative impacts on diversity. Reliable information regarding these key questions will greatly assist in the prioritisation of remediation efforts.

Contaminants come in many forms and there is the potential for different toxins to impact differently upon diversity. Some contaminants (such as some metals) are essential for marine life at trace concentrations, whilst many modern and artificially synthesized compounds (e.g. "emerging contaminants") may have no biological origin or function. Other potential contaminants, such as nutrients, may be limiting in marine ecosystems and their enrichment as a result of anthropogenic activities may in fact lead to enhanced resource availability with concomitant increases in species richness (Hall et al., 2000).

Similarly there is the potential for particular marine habitats to vary in their susceptibility to contamination. Some systems are inherently more diverse than others and may have greater functional redundancy allowing for species replacement rather than

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loss. Alternatively, some habitats such as seagrass meadows may comprise communities reliant upon a few, specific foundation species (or ecosystem engineers) and hence be potentially more vulnerable to habitat collapse. Habitats also typically occur in different environments that may be subject to more or less contaminant exposure. Many contaminants accumulate in sediments and may be expected to affect sediment infauna whilst the propensity for contaminants to persist in well-flushed rocky reef environments may be relatively low. Hence there are a range of reasons why we might predict differential sensitivity of habitat types and differential impact of contaminant classes.

Contaminant impacts may also be assessed in a variety of ways and within the aquatic pollution literature there are a range of biological indices that have been developed for particular types of contamination. In order to compare across habitats and contaminants, however, it is necessary to examine impacts on diversity indices which are non-specific and designed to reflect total environmental stress (Gray and Delaney, 2008; Washington, 1984). The simplest measure of diversity is the number of species per unit area or sampling effort (species richness). However, a recognized component of diversity is "evenness" or the abundance at which each species occurs within an area (Pielou, 1975). Evenness measures may be expected to respond to changes in community composition or structure even when there is no change to absolute species richness. Many commonly used diversity indices typically include a measure of both species richness, and the evenness of species distributions. If anthropogenic contamination acts to remove rare species from the system entirely then species richness should be the most sensitive indicator of impact. If contamination changes community structure, particularly by modifying the effective dominance of key species one might expect that evenness measures will be most sensitive to anthropogenic contamination.

Here we present the results of a systematic literature review and meta-analysis in which we address five specific questions about contaminant impacts on marine biodiversity:

1) What diversity measures are most commonly used in the monitoring of contaminant impacts?
2) In which habitats are researchers typically interested in the effects of contaminants on diversity?
3) Do marine habitats vary in their susceptibility to impacts of contamination upon diversity?
4) Do specific classes of contaminant vary in their ability to impact upon marine diversity?
5) Do the results of ecological investigations depend upon the research approach used (i.e. mensurative survey studies, manipulative experiments and laboratory-based mesocosms)?

2. Methods

2.1. Search methodology

A systematic literature review was conducted to capture a representative sample of the marine pollution literature. We first used a specific list of search terms in four databases: Aquatic Sciences and Fisheries Abstracts (1971–present), Biological Abstracts (1969–2003), Current Contents (1998–present) and Web of Science (1900–present). The following search strategies were used on each database and searches were limited to English language primary studies (not reviews) published in peer-reviewed journals:

Search 1. "*pollution* AND *marine* AND (*biodiversity* OR *diversity*)"
Search 2. Results of search 1 crossed with the terms; "*hydrocarbon*, *PAH*, *metals*, *nutrient*, *sewage*, *solid waste*, *effluent*"

We read the abstracts of all of the papers that emerged in these searches ($n > 800$) and selected for review, those with a marine focus and which reported the effects of anthropogenic contamination upon the diversity of recipient communities. Studies must have measured levels of contamination. Diversity could either be studied in terms of the diversity of a community at the species level or higher taxonomic levels, or as the genetic diversity of a population of an individual species. We then examined the citation lists of papers selected in the first round in order to capture studies that had been published prior to the database selections, or that had been published in journals not indexed in the databases we searched (Hillebrand, 2002). Again, we selected articles from this group with a marine focus and which reported the effect of contamination upon biodiversity. In total 216 research articles satisfied the criteria for inclusion in the review.

From these studies we extracted qualitative background data relating to contaminant type (metals, hydrocarbons, nutrients, sewage or mixtures), habitat type (pelagic, soft sediments, seagrass meadows and intertidal, coral and subtidal reefs), and diversity measures (species richness, Shannon–Wiener, Pielou, Margalef's, Simpson's or 'other'). We then collated data on the overall finding of the research (reduced, increased or no effects on diversity) as concluded by the authors of the papers and the direction and magnitude of the change (response ratios – see details below). Some of the studies performed no formal tests of hypotheses but because they presented the effects of contamination upon marine diversity we were still able to extract the required data from these studies. Some studies identified taxa to the lowest possible level and did not necessarily report species-level diversity. However, if they reported 'species richness' then we accepted their definition of this term.

2.2. Design criteria for meta-analysis

In addition to this qualitative review, we performed a quantitative meta-analysis. We focused our meta-analysis on studies which reported the most commonly used diversity indices: species richness (S; species per unit area), the Shannon–Wiener index (H′) and Pielou evenness (J). At least one of these measures was reported in 175 papers from the initial 216 included in the literature review.

For these studies we calculated response ratios (effect sizes) attributable to pollution. We defined the response ratio as the proportional change in mean diversity from experimental controls to treatments, or between reference and impact sites in the case of observational studies (Hedges et al., 1999; Hillebrand et al., 2007). In some cases, the effect size data had to be extracted from graphs and is considered an estimate of observed effects only. Survey studies either examined species richness and evenness along gradients away from contaminant sources, or contrasted diversity at reference to potentially impacted locations. For gradient studies we calculated an effect size by contrasting diversity and evenness at the sampling location closest to the contaminant source, to reference locations furthest from the source. For designs contrasting reference and potentially impacted locations, we compared diversity at control locations to diversity at impacted locations after the onset of contamination. Field and laboratory experimental studies typically involved contrasting species richness and evenness following exposure to a range of concentrations of contaminants. For these studies we compared control communities with communities exposed to the highest level of contamination. Effect sizes were contrasted amongst marine habitats, classes of contaminants and research approaches using separate one-way analyses of variance (ANOVA).

3. Results

3.1. Community types, approaches and impacts

Of the over 800 titles and abstracts examined, a total of 216 papers fulfilled the criteria for inclusion in the review (Appendix I). The vast majority of research (~64%) was conducted in soft sediment systems (Fig. 1a). Research into hard-substrate habitats such as intertidal rock platforms and temperate and tropical subtidal reefs were comparatively rare, as were studies on pelagic vertebrate and invertebrate communities such as fish and plankton (Fig. 1a). Research predominantly took the form of field-based surveys, with field and laboratory experiments that manipulate levels of contaminants being less common (Fig. 1b). The most frequently used measures of diversity and evenness were species richness (number of species per unit area), the Shannon–Wiener index (H′) and Pielou evenness (J; Fig. 1c). Margalef's richness (Dm) and Simpson's diversity (D) were also used occasionally (Fig. 1c).

In each habitat type the vast majority of published reports concluded that there were significant negative effects of pollution upon species richness (Fig. 2b). Similarly, all contaminant types were associated with negative effects upon species richness (Fig. 2a). Occasional increases in species richness were associated with pollution (Fig. 2a). Without exception, increases in diversity were correlated with exposure to nutrient enrichment in various forms (eutrophication, sewage, hydrocarbons, or mixtures of

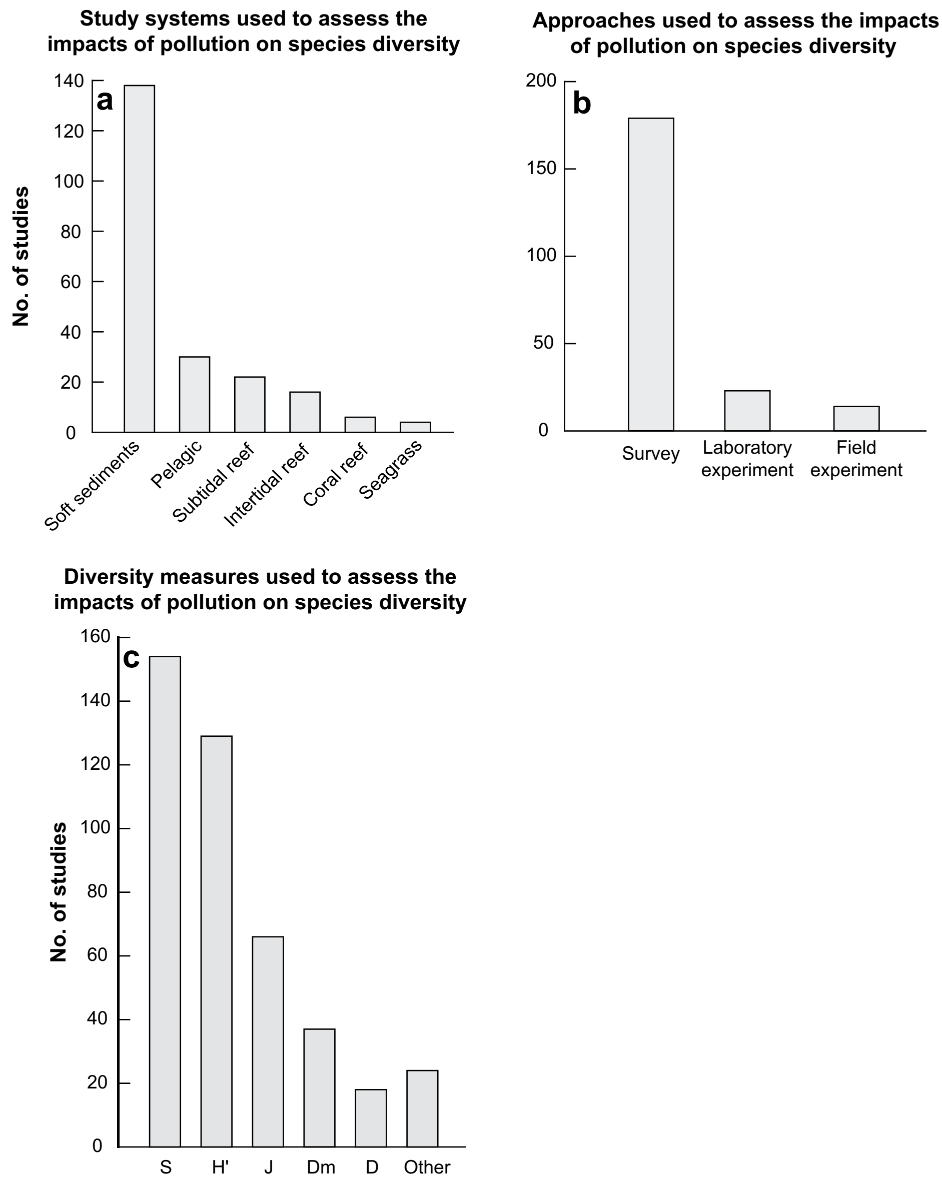

Fig. 1. Summary of a qualitative literature review examining research into the effects of marine pollution upon biodiversity. Studies are characterized by a) study systems in which research is conducted, b) research approaches used and c) biodiversity measures used to quantify impacts of pollution. Data are number of papers in each category.

nutrients and other contaminants). Of the studies reviewed, a minority (~20%) reported no detectable effects of contamination upon diversity, suggesting a possible bias towards publishing research which yields statistically significant results.

3.2. *Results of meta-analysis*

The meta-analysis supported qualitative assessments of the literature as reported above, and indicated that pollution in marine environments is correlated with clear and consistent negative impacts upon the species richness and, to a lesser extent, evenness of recipient communities. Effect sizes of pollution upon species richness (S) and Shannon–Wiener diversity (H′) tended to be greater than reductions in Pielou evenness (J). This was true when impacts were considered according to study systems, contaminants and research approaches (Fig. 3a–c).

Impacts of pollution upon species richness and evenness were remarkably similar across habitats and contaminant classes. There were no significant differences in the proportional change of species richness, Shannon–Weiner diversity or Pielou evenness across any of the study systems or contaminant classes we considered. Rather, a 30–50% reduction in species richness and diversity were identified in all habitats exposed to all contaminant types (Fig. 3a and b, Table 1). Manipulative field experiments tended to have lower effect sizes associated with contaminant impact on Shannon–Weiner diversity than did survey studies (Fig. 3c, Table 1). There were similar strong trends towards smaller effect sizes in field and laboratory experiments with respect to species richness and evenness with associated low P values (Fig. 3c, $P = 0.056$ and $P = 0.061$ respectively, Table 1).

4. Discussion

Anthropogenic contamination of marine habitats was frequently associated with a reduction in biodiversity, either as a result of reduced species richness, increased dominance of

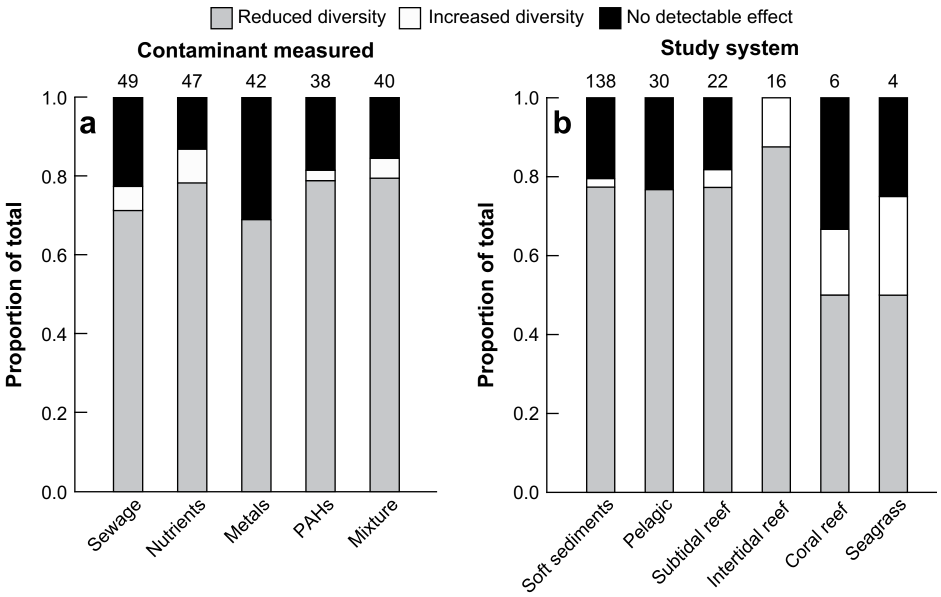

Fig. 2. Proportion of studies in the marine literature concluding that marine pollution has positive, negative and no effects upon biodiversity. Studies are characterized according to a) contaminants measured and b) study systems in which research is conducted. The number of research papers in each category is shown above each bar.

tolerant species (i.e. decreased evenness), or a combination of both factors. According to the meta-analysis, the effects of pollutants upon species richness were remarkably consistent across marine habitats resulting in an average reduction in species richness of 30–50%, although some habitat types are poorly represented. Similarly, individual pollutants were consistent in their ecological impacts, with no single pollutant having significantly greater impacts on diversity than any other.

The ecological impacts of marine pollution may be overestimated due to the tendency of journals to publish studies which find significant ecological impacts. In the present study approximately 20% of peer-reviewed papers reported no negative effect of contaminants on diversity and this proportion was relatively consistent across contaminant classes and habitat types (exceptions exist for coral reef and seagrass habitats for which there were few studies). A finding of no negative effect upon diversity could either result from species replacement or minimal (non-toxic) exposure to contaminants. There is no obvious way of standardizing the concentrations across contaminant classes (for example, comparing toxic cations with nutrient concentrations). Hence dose–response comparisons across contaminant classes are not currently feasible. We do, however, urge researchers and journal editors to publish well-designed studies that ultimately find no effects on diversity (e.g. Lu and Wu, 2003), particularly where the studies have accurately measured contaminant loads and can report on other community attributes (e.g. multivariate structure) that may indicate effects.

We observed a quite remarkable similarity of effect size across habitat and contaminant types. Pollution was never associated with the complete exclusion of life from a location and there were commonly 50–70% of species that were able to tolerate the contaminant load. The identity of pollution-tolerant and -intolerant species is therefore of great interest. Pollution-tolerant and opportunistic species have long been recognized as potential bioindicators of impacted systems (e.g. Rygg, 1985) and recent research has suggested that marine contamination may reduce endemic diversity while enhancing the dominance of invasive species (Piola and Johnston, 2007). Simple diversity indices which consider species richness, but not species identity cannot do much to elucidate these more complex ecological impacts.

A primary mechanism driving decreases in diversity as a result of exposure to contaminants is the elimination of sensitive species and the subsequent monopolization of resources by tolerant species. For example, species richness and diversity decrease along increasing sediment contamination gradients within urbanized and industrialized harbours, whilst communities become increasingly dominated by pollution-tolerant species (Je et al., 2004; Simboura et al., 1995; Thompson and Shin, 1983). Infaunal communities in metal contaminated sediments are typically dominated by metal-tolerant opportunistic deposit-feeding polychaetes (Belan, 2004; Lancellotti and Stotz, 2004). Even regions such as the Antarctic, with a relatively short history of anthropogenic contamination, have sediments which are characterized by high dominance of opportunistic polychaetes, and fewer species than nearby uncontaminated sediments (Lenihan and Oliver, 1995). In soft sediment habitats one of the indirect effects of nutrient enrichment is the release of hydrogen sulfide from sediments (Gowen and Bradbury, 1987). Thus, a reduction in diversity of infaunal communities in nutrient-enriched sediments may paradoxically be accompanied by overall increases in abundance of organisms such as deposit-feeding polychaetes and opportunistic copepods. These organisms thrive in organic-rich environments, are tolerant of high sulfide concentrations and low oxygen levels and monopolize communities under these conditions (Gao et al., 2005; Gee et al., 1985; Karakassis et al., 2000).

It has been suggested that macroalgal communities are relatively resilient to contamination (Edwards, 1975). However, substantial research has shown metal- and nutrient-impacted intertidal rocky shores to contain depauperate communities of macroalgae, and be dominated by opportunistic algal species with rapid growth rates (Abou-Aisha et al., 1995; Archambault et al., 2001; Fariña and Castilla, 2001; Littler and Murray, 1975; Soltan et al., 2001). In particular green algae including *Ulva* and *Enteromorpha*, and species of the genus *Corallina* may colonise nutrient-rich environments around intertidal sewage outfalls and replace relatively diverse communities of large perennial algae and sessile filter feeders seen in more pristine areas (Correa et al., 2000; Littler and Murray, 1975; Soltan et al., 2001). Correa et al. (1999) found macroalgal species richness declined along a gradient of increasing

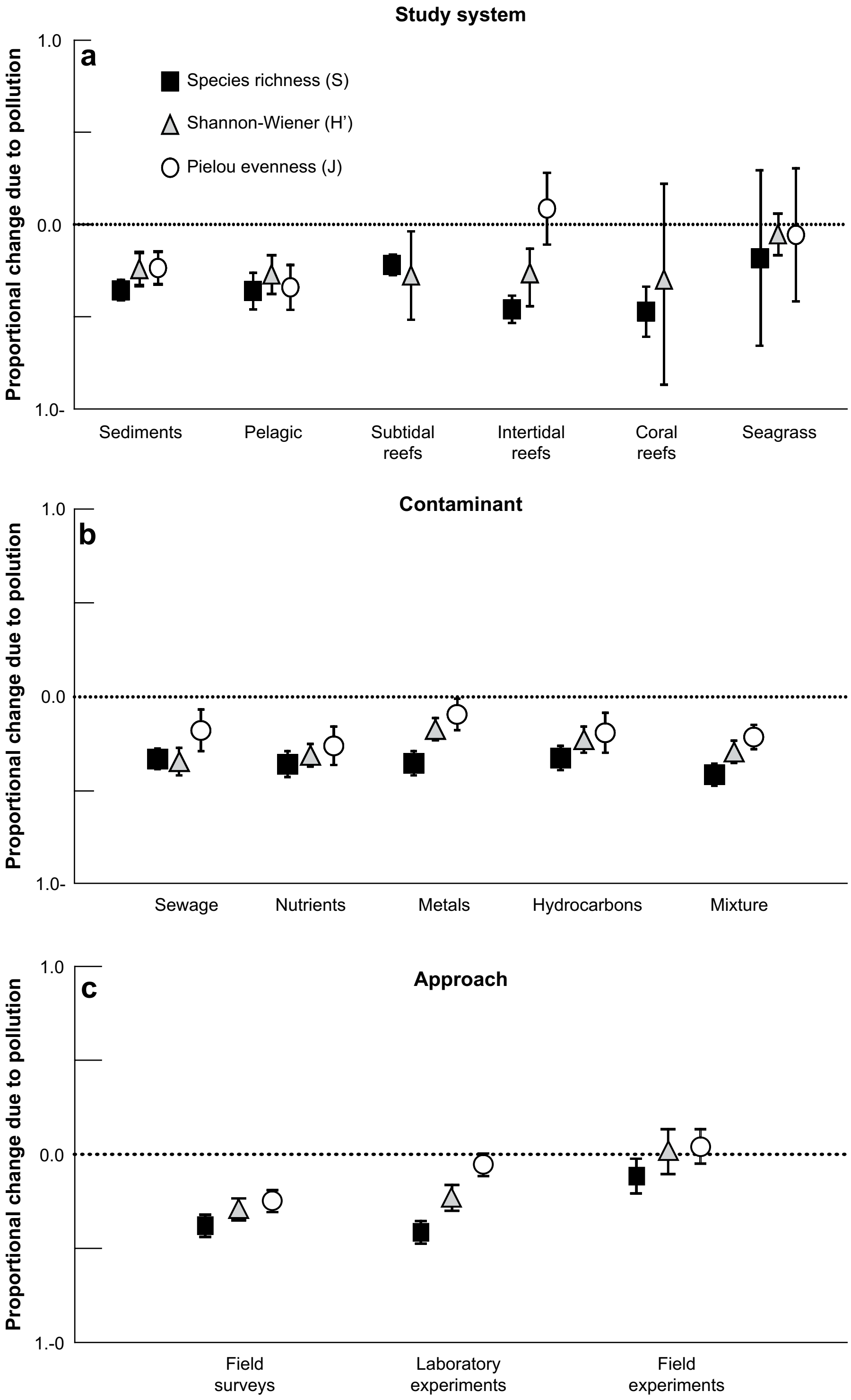

Fig. 3. Summary of a quantitative meta-analysis of marine research examining the effects of marine pollution upon biodiversity. Mean effect sizes ± SE are shown for species richness, Shannon–Weiner diversity and Pielou evenness. Studies are characterized by a) study systems in which research is conducted, b) contaminants measured and c) research approaches used.

copper contamination which later studies attributed to copper mining activities (Ramirez et al., 2005). Intertidal areas receiving mining discharges may be species poor due to a reduction in filamentous algae and sessile filter feeders, probably as a result of smothering and abrasion by mine tailings (Correa et al., 2000; Fariña and Castilla, 2001).

4.1. Impacts of pollution upon community structure

Taxa richness (i.e. number of taxa per unit area) and the Shannon–Wiener diversity index have long been popular measures of biodiversity (Costello et al., 2004). Such indices have been described as “relatively crude” (Gray et al., 1990) and “dubious”

Table 1
Analysis of variance contrasting impacts of pollution on species richness, diversity and evenness amongst experimental and survey studies, contaminant classes and marine habitats.

Source	df	Effects on species diversity						Effects on evenness		
		Species richness			Shannon–Weiner diversity			Pielou evenness		
		MS	F	*P*	MS	F	*P*	MS	F	*P*
Approach	2	0.299	2.937	0.056	0.297	3.444	**0.035**	0.238	2.947	0.061
Contaminant	4	0.036	0.342	0.849	0.102	1.146	0.339	0.043	0.479	0.751
Study system	5	0.114	1.100	0.363	0.031	0.330	0.892	0.115	1.363	0.260

df_{Error} (S, H′, J): Approach – 142, 110, 52; Contaminant – 140, 108, 50; Study system – 139, 107, 49; MS_{Error} (S, H′, J): Approach – 0.102, 0.086, 0.081; Contaminant – 0.106, 0.089, 0.090; Study system – 0.104, 0.093, 0.084.

(Hulbert, 1971) measures of ecological impact. However, in the vast majority of published studies (~80%), there were clear negative effects of contamination on the major diversity indices. In general, we found that Shannon–Weiner diversity and Pielou evenness reflected the same effect on diversity as the simpler measure of species richness. However, if sufficient sample sizes are not collected this may have the effect of excluding rarer species, leading to skewed estimates of evenness. If anything, species richness is likely to be a more sensitive indicator of impact since the response ratios were generally larger.

One criticism of the sole use of diversity indices as measures of ecological impacts is that such measures do not consider alterations to the structure of communities (Green, 1979; Johnston and Keough, 2005; Schratzberger et al., 2000) and they may therefore mask more effects than they elucidate (Olsgard and Gray, 1995; Somerfield et al., 1994). It is possible that contamination may act to strongly alter community structure, but may not have discernible effects upon diversity *per se*. For example, Johnston and Keough (2005) found the structure of fouling communities was altered following exposure to experimental copper pulses, with widespread species replacement. However, diversity as measured by both Shannon–Weiner diversity and species counts failed to detect any differences. Contamination may also prevent prolonged persistence of organisms which in turn liberates space for new recruits, resulting in communities whose species composition is in constant flux (Moran and Grant, 1989, 1991). Similarly, research has found sewage outfalls may increase the relative abundances of planktivorous and detrivorous fish around outfalls, with no alterations to species richness (Guidetti et al., 2003). Such effects would not be evident in measurements of diversity, but require multivariate analyses of community structure in space and through time.

Several studies have found indices which consider taxonomic relatedness and multivariate analyses of community structure to be more sensitive and powerful means of detecting ecological impacts than studies which consider diversity and species richness alone (Gong et al., 2005; Magurran, 2003; McRae et al., 1998; Olsgard and Gray, 1995; Schratzberger et al., 2000; Warwick and Clarke, 1991). Warwick and Clarke (1995) particularly highlight the importance of considering the relatedness of species sampled and the taxonomic level at which diversity occurs. A potential short-coming of this approach however, is that the required level of taxonomic clarity is not available in many marine ecosystems (particularly in the southern hemisphere).

4.2. Positive effects of pollution were generally associated with nutrient enrichment

Few studies identified an increase in species richness associated with anthropogenic contamination. The few studies that did find an increase in diversity were almost exclusively concerned with nutrient enrichment (via aquaculture and sewage outfalls). The bulk of experimental and observational research suggests that anthropogenic nutrient enrichment typically results in the disproportionate dominance of competitively superior species (Hillebrand et al., 2007; Pastorok and Bilyard, 1985). However, if nutrient availability is a limiting factor an increase in the availability of nutrients may result in greater primary production, greater resource heterogeneity and consequently, enhanced species diversity (Arai, 2001; Hall et al., 2000; Matthews et al., 2005). As the availability of resources (nutrients) increases in a landscape so too does spatial heterogeneity in resource distribution (Hall et al., 2000; Hillebrand et al., 2007). Such patchiness may stimulate enhanced species diversity due to the opportunity for species which exploit nutrient-rich and -poor conditions to coincide (Conlan et al., 2004; Pearson and Rosenberg, 1978). However, resources are assumed to become homogenously available when present at very high levels, and consequently species diversity decreases beyond a threshold level as competitively superior organisms are favored throughout the landscape (Hall et al., 2000; Hillebrand et al., 2007).

Nutrient enrichment may also result in the die-off of dominant species, thus liberating space available to opportunistic species. For example, enhanced algal diversity has been found in some intertidal reefs receiving excess phosphorus inputs (Abou-Aisha et al., 1995). It is suggested that the removal of dominant, fleshy macrophytes by phosphorus loading allowed for the colonisation of various species of opportunistic turf-forming algae, resulting in an overall increase in biodiversity at impacted sites (Abou-Aisha et al., 1995). Similarly, experimental spiking of beach sediments with nutrients led to short-term increases in diversity as a result of the displacement of competitively dominant species (Hockin, 1983). In many cases however, the removal of dominant species occurs via simple species replacement processes which yield little or no overall effects on species richness.

4.3. Research approach

Survey studies examining the impacts of contamination upon marine diversity reported significantly larger differences than did laboratory- and field-based experiments. This finding is especially surprising given our conservative approach which calculated effect sizes for experiments based upon contrasts between control treatments and treatments exposed to the highest contaminant doses. Experimental studies may underestimate effects if contaminants are presented in forms or at concentrations different to those encountered in contaminated habitats. There are also typically limitations in the duration of field manipulative experiments which may prevent the establishment of a "naturally" diverse control community which would act to underestimate impacts of pollution on diversity. Furthermore, there are inherent difficulties and ethical considerations in running field-based experimental studies which typically act to limit the spatial and temporal extent of contaminant manipulation.

However, survey studies may overestimate contaminant impacts if diversity is affected by environmental factors which co-vary with contaminant load. Past research has been dominated by field-based surveys, some of which wrongly assume a cause-and-effect relationship between contamination and reduced biodiversity. Such correlative studies would be strengthened by the addition of complementary field or laboratory experiments that manipulate levels of contaminants. More recent survey studies now partition responses to multiple environmental factors simultaneously (e.g. Mucha et al., 2003). Moreover, recent advances in the design of ecological impact studies provide robust survey structures that can overcome many of the limitations of conventional contaminant surveys. The overriding advantage of performing *both* field and laboratory-based experiments is that they allow an assessment of underlying mechanisms responsible for observed ecological effects in the field. Thus, far more research is required which combines mensurative survey studies with experimental research (Chapman, 1995).

4.4. Pollution is able to reduce genetic diversity

Anthropogenic contamination is a potentially powerful agent of selection acting upon aquatic organisms (Levinton et al., 2003). Contamination clearly affects the macro-diversity and abundance of organisms, but the impact of contaminants upon genetic diversity has not been examined in detail. Perturbations in population genetics can represent an early warning of other more dramatic effects such as loss of species and alterations to dispersal (Theodorakis, 2003). In addition to research on the specific diversity of marine communities, our search terms uncovered eight papers that examined contaminant effects on genetic diversity. These studies typically found reductions in the genetic diversity of populations of marine organisms collected from contaminated regions (Kim et al., 2003; Ross et al., 2002; Street and Montagna, 1996). Genetic diversity has been found to be reduced in pelagic microbial communities in Arctic seawater samples following experimental exposures to crude oil (Atlas et al., 1991). Field monitoring studies have identified reduced genetic diversity in copepod species within 30 m of oil platforms relative to reference sites over 3 km away (Street and Montagna, 1996). Genetic diversity is inversely related to multivariate measures of sediment metal and nutrient pollution around oil rigs, described as "islands" of poor genetic diversity within areas of relatively uniform diversity (Street and Montagna, 1996).

4.5. Gaps in knowledge

Research which considers the effects of contaminants upon biodiversity has focused largely upon soft sediment ecosystems. In particular, the impact of contaminants on coral reef diversity has rarely been reported, despite reefs being subjected to a variety of anthropogenic inputs. For example, Hoffmann (2002) quantified potential sources of anthropogenic stress on four tropical islands. Many of these stresses showed negative correlations with species diversity. In particular, a strong negative correlation was found between the diversity of hard coral species on reef flats and the degree of industrialization and intensive agriculture on bordering islands. Given the well-established threats posed to coral reef communities by anthropogenic contaminants, the effects of these contaminants upon species richness and evenness in tropical reef environments should be a focus of future research.

5. Conclusions

From our review and meta-analysis it is clear that anthropogenic contamination of marine habitats is consistently associated with reductions in both species richness and evenness. It should be noted however, that some habitats are poorly represented (particularly coral reefs and seagrass habitats) and that the vast majority of research has been conducted in soft sediments at the expense of other habitats. Thus a vast body of literature attests to the potential for anthropogenic contamination to reduce the diversity and evenness of soft sediment infaunal communities, and more limited experimental and observational studies in other habitats suggest such ecological impacts are common in all major marine ecosystems. Somewhat surprisingly, no single contaminant was found to have consistently greater impacts upon diversity and evenness than any other. Together, these findings suggest the impact of contaminants upon marine diversity and evenness is remarkably consistent in the marine environment, and typically in the order of 30–50% reductions in both these measures.

This study confirms the general belief that contamination is associated with reduced biodiversity across many different marine habitats. Environmental managers and the general public are right to be concerned about the release of contaminants into marine systems and the potential for contaminants to negatively affect biodiversity. Reductions in diversity are likely to reduce the resilience of communities to other stresses common to near-shore environments such as dredging, development, invasive species and storm action (Hooper et al., 2005). Global climate change will also interact with pollution since some contaminants are predicted to increase in toxicity and bioavailability with increasing temperature (Sokolova and Lanning, 2008). Polluted systems should therefore be considered generally more vulnerable to entire ecosystem collapse and efforts should be made to reduce or ameliorate the impacts of contaminants in these systems.

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Appendix. Supplementary data

Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.envpol.2009.02.017.

References

Abou-Aisha, K.M., Kobbia, I.A., Elabyad, M.S., Shabana, E.F., Schanz, F., 1995. Impact of phosphorous loadings on macro-algal communities in the Red Sea coast of Egypt. Water, Air and Soil Pollution 83, 285–297.

Arai, M.N., 2001. Pelagic coelenterates and eutrophication: a review. Hydrobiologia 451, 69–87.

Archambault, P., Banwell, K., Underwood, A.J., 2001. Temporal variation in the structure of intertidal assemblages following the removal of sewage. Marine Ecology Progress Series 222, 51–62.

Atlas, R.M., Horowitz, A., Krichevsky, M., Bej, A.K., 1991. Response of microbial populations to environmental disturbance. Microbial Ecology 22, 249–256.

Belan, T.A., 2004. Marine environmental quality assessment using polychaete taxocene characteristics in Vancouver Harbour. Marine Environmental Research 57, 89–101.

Chapman, P.M., 1995. Ecotoxicology and pollution – key issues. Marine Pollution Bulletin 31, 167–177.

Conlan, K.E., Kim, S.L., Lenihan, H.S., Oliver, J.S., 2004. Benthic changes during 10 years of organic enrichment by McMurdo Station, Antarctica. Marine Pollution Bulletin 49, 43–60.

Correa, J.A., Castilla, J.C., Ramirez, M.A., Varas, M., Lagos, N., Vergara, S., Moenne, A., Roman, D., Brown, M.T., 1999. Copper, copper mine tailings and their effect on marine algae in northern Chile. Journal of Applied Phycology 11, 57–67.

Correa, J.A., Ramirez, M.A., de la Harpe, J.P., Roman, D., Rivera, L., 2000. Copper, copper mining effluents and grazing as potential determinants of algal abundance and diversity in northern Chile. Environmental Monitoring and Assessment 61, 265–281.

Costello, M.J., Pohle, G., Martin, A., 2004. Evaluating Biodiversity in Marine Environmental Assessments. In: Research and Development Monograph Series 2001. Canadian Environmental Assessment Agency, Ottawa.

Crowe, T.P., Smith, E.L., Donkin, P., Barnaby, D.H., Rowland, S.J., 2004. Measurements of sublethal effects on individual organisms indicate community-level impacts on pollution. Journal of Applied Ecology 41, 114–123.

Edwards, P., 1975. Assessment of possible pollution effects over a century on benthic marine algae of Durham, England. Botanical Journal of the Linnean Society 70, 269–305.

Fariña, J.M., Castilla, J.C., 2001. Temporal variation in the diversity and cover of sessile species in rocky intertidal communities affected by copper mine tailings in northern Chile. Marine Pollution Bulletin 42, 554–568.

de Forges, B.R., Koslow, J.A., Poore, G.C.B., 2000. Diversity and endemism of the benthic seamount fauna in the southwest Pacific. Nature 405, 944–947.

Gao, Q.F., Cheung, K.L., Cheung, S.G., Shin, P.K.S., 2005. Effects of nutrient enrichment derived from fish farming activities on macroinvertebrate assemblages in a subtropical region of Hong Kong. Marine Pollution Bulletin 51, 994–1002.

Gee, J.M., Warwick, R.M., Schaanning, M., Berge, J.A., Ambrose, W.G., 1985. Effects of organic enrichment on meiofaunal abundance and community structure in sublittoral soft sediments. Journal of Experimental Marine Biology and Ecology 91, 247–262.

Glover, A.G., Smith, C.R., 2003. The deep-sea floor ecosystem: current status and prospects of anthropogenic change by the year 2025. Environmental Conservation 30, 219–241.

Gong, J., Song, W.B., Warren, A., 2005. Periphytic ciliate colonization: annual cycle and responses to environmental conditions. Aquatic Microbial Ecology 39, 159–170.

Gowen, R.J., Bradbury, N.B., 1987. The ecological impact of salmonid farming in coastal waters – a review. Oceanography and Marine Biology: An Annual Review 25, 563–575.

Gray, N.F., Delaney, E., 2008. Comparison of benthic macroinvertebrate indices for the assessment of the impact of acid mine drainage on an Irish river below an abandoned Cu–S mine. Environmental Pollution 155, 31–40.

Gray, J.S., Clarke, K.R., Warwick, R.M., Hobbs, G., 1990. Detection of initial effects of pollution of marine benthos: an example from the Ekofisk and Eldfisk oilfields, North Sea. Marine Ecology Progress Series 66, 285–299.

Green, R.H., 1979. Sampling Design and Statistical Methods for Environmental Biologists. John Wiley & Sons, New York.

Guidetti, P., Terlizzi, A., Fraschetti, S., Boero, F., 2003. Changes in Mediterranean rocky-reef fish assemblages exposed to sewage pollution. Marine Ecology Progress Series 253, 269–278.

Hall, S.J., Gray, S.A., Hammett, Z.L., 2000. Biodiversity–productivity relations: an experimental evaluation of mechanisms. Oecologia 122, 545–555.

He, Z., Morrison, R.J., 2001. Changes in the marine environment of Port Kembla Harbour, NSW, Australia, 1975–1995: a review. Marine Pollution Bulletin 42, 193–201.

Hedges, L.V., Gurevitch, J., Curtis, P.S., 1999. The meta-analysis of response ratios in experimental ecology. Ecology 80, 1150–1156.

Hillebrand, H., 2002. Top-down versus bottom-up control of autotrophic biomass: a meta-analysis on experiments with periphyton. Journal of the North American Benthological Society 21, 349–369.

Hillebrand, H., Gruner, D.S., Borer, E.T., Bracken, M.E.S., Cleland, E.E., Elser, J.J., Harpole, W.S., Ngai, J.T., Seabloom, E.W., Shurin, J.B., Smith, J.E., 2007. Consumer versus resource control of producer diversity depends on ecosystem type and producer community structure. Proceedings of the National Academy of Sciences of the United States of America 104, 10904–10909.

Hockin, D.C., 1983. The effects of organic enrichment upon a community of meiobenthic harpacticoid copepods. Marine Environmental Research 10, 45–58.

Hoffmann, T.C., 2002. Coral reef health and effects of socio-economic factors in Fiji and Cook Islands. Marine Pollution Bulletin 44, 1281–1293.

Hooper, D.U., Chapin, F.S., Ewel, J.J., Hector, A., Inchausti, P., Lavorel, S., Lawton, J.H., Lodge, D.M., Loreau, M., Naeem, S., Schmid, B., Setala, H., Symstad, A.J., Vandermeer, J., Wardle, D.A., 2005. Effects of biodiversity on ecosystem functioning: a consensus of current knowledge. Ecological Monographs 75, 3–35.

Hulbert, S.H., 1971. The nonconcept of species diversity: a critique and alternative parameters. Ecology 52, 577–586.

Je, J.G., Belan, T., Levings, C., Koo, B.J., 2004. Changes in benthic communities along a presumed pollution gradient in Vancouver Harbour. Marine Environmental Research 57, 121–135.

Johnston, E.L., Keough, M.J., 2005. Reduction of pollution impacts through the control of toxicant release rate must be site- and season-specific. Journal of Experimental Marine Biology and Ecology 320, 9–33.

Karakassis, I., Tsapakis, M., Hatziyanni, E., Papadopoulou, K.N., Plaiti, W., 2000. Impact of cage farming of fish on the seabed in three Mediterranean coastal areas. ICES Journal of Marine Science 57, 1462–1471.

Kim, S.J., Rodriguez-Lanetty, M., Suh, J.H., Song, J.I., 2003. Emergent effects of heavy metal pollution at a population level: *Littorina brevicula* a study case. Marine Pollution Bulletin 46, 74–80.

Lancellotti, D.A., Stotz, W.B., 2004. Effects of shoreline discharge of iron mine tailings on a marine soft-bottom community in northern Chile. Marine Pollution Bulletin 48, 303–312.

Legendre, L., Rivkin, R.B., 2002. Pelagic food webs: responses to environmental processes and effects on the environment. Ecological Research 17, 143–149.

Lenihan, H.S., Oliver, J.S., 1995. Anthropogenic and natural disturbances to marine benthic communities in Antarctica. Ecological Applications 5, 311–326.

Levinton, J.S., Suatoni, E., Wallace, W., Junkins, R., Kelaher, B., Allen, B.J., 2003. Rapid loss of genetically based resistance to metals after cleanup of a Superfund site. Proceedings of the National Academy of Sciences of the United States of America 100, 9889–9891.

Littler, M.M., Murray, S.N., 1975. Impact of sewage on the distribution, abundance and community structure of rocky intertidal macro-organisms. Marine Biology 30, 277–291.

Lotze, H.K., Milewski, I., 2004. Two centuries of multiple human impacts and successive changes in a North Atlantic food web. Ecological Applications 14, 1428–1447.

Lu, L., Wu, R.S.S., 2003. Recolonisation and succession of subtidal macrobenthic infauna in sediments contaminated with cadmium. Environmental Pollution 121, 27–38.

Magurran, A., 2003. Measuring Biological Diversity. Blackwell Publishing, Massachusetts.

Matthews, A., Grenfell, H.R., Hayward, B.W., Horrocks, M., 2005. Foraminiferal record of sewage outfall impacts on the inner Manukau Harbour, Auckland, New Zealand. New Zealand Journal of Marine and Freshwater Research 39, 193–215.

McRae, G., Camp, D.K., Lyons, W.G., Dix, T.L., 1998. Relating benthic infaunal community structure to environmental variables in estuaries using nonmetric multidimensional scaling and similarity analysis. Environmental Monitoring and Assessment 51, 233–246.

Moran, P.J., Grant, T.R., 1989. The effects of industrial pollution on the development and succession of marine fouling communities. II. Multivariate analysis of succession. Marine Ecology 10, 247–261.

Moran, P.J., Grant, T.R., 1991. Transference of marine fouling communities between polluted and unpolluted sites: impact on structure. Environmental Pollution 72, 89–102.

Morrison, R.J., Delaney, J.R., 1996. Marine pollution in the Arafura and Timor seas. Marine Pollution Bulletin 32, 327–334.

Mucha, A., Teresa, M., Vasconcelos, S., Bordalo, A., 2003. Macrobenthic community in the Douro estuary: relations with trace metals and natural sediment characteristics. Environmental Pollution 121, 169–180.

Oliveira, E.C., Qi, Y.B., 2003. Decadal changes in a polluted bay as seen from its seaweed flora: the case of Santos Bay in Brazil. Ambio 32, 403–405.

Olsgard, F., Gray, J.S., 1995. A comprehensive analysis of the effects of offshore oil and gas exploration and production on the benthic communities of the Norwegian continental shelf. Marine Ecology Progress Series 122, 277–306.

Pastorok, R.A., Bilyard, G.R., 1985. Effects of sewage pollution on coral-reef communities. Marine Ecology Progress Series 21, 175–189.

Pearson, T.H., Rosenberg, R., 1978. Macrobenthic succession in relation to organic enrichment and pollution of the marine environment. Oceanography and Marine Biology: An Annual Review 16, 229–311.

Pielou, E.C., 1975. Indices of diversity and evenness. In: Pielou, E.C. (Ed.), Ecological Diversity. John Wiley & Sons, New York, pp. 5–18.

Piola, R.F., Johnston, E.L., 2007. Pollution reduces native diversity and increases invader dominance in marine hard-substrate communities. Diversity and Distributions 14, 329–342.

Rabalais, N.N., 2002. Nitrogen in aquatic ecosystems. Ambio 31, 102–112.

Ramirez, M., Massolo, S., Frache, R., 2005. Metal speciation and environmental impact on sandy beaches due to El Salvador copper mine, Chile. Marine Pollution Bulletin 50, 62–72.

Ross, K., Cooper, N., Bidwell, J.R., Elder, J., 2002. Genetic diversity and metal tolerance of two marine species: a comparison between populations from contaminated and reference sites. Marine Pollution Bulletin 44, 671–679.

Rygg, B., 1985. Distribution of species along pollution induced diversity gradients in benthic communities in Norwegian Fjords. Marine Pollution Bulletin 16, 469–474.

Schratzberger, M., Gee, J.M., Rees, H.L., Boyd, S.E., Wall, C.M., 2000. The structure and taxonomic composition of sublittoral meiofauna assemblages as an indicator of the status of marine environments. Journal of the Marine Biological Association of the United Kingdom 80, 969–980.

Simboura, N., Zenetos, A., Panayotidis, P., Makra, A., 1995. Changes in benthic community structure along an environmental pollution gradient. Marine Pollution Bulletin 30, 470–474.

Sokolova, I.M., Lanning, G., 2008. Interactive effects of metal pollution and temperature on metabolism in aquatic ectotherms: implications of global climate change. Climate Research 37, 181–201.

Soltan, D., Verlaque, M., Boudouresque, C.F., Francour, P., 2001. Changes in macroalgal communities in the vicinity of a Mediterranean sewage outfall after the setting up of a treatment plant. Marine Pollution Bulletin 42, 59–70.

Somerfield, P.J., Gee, R.M., Warwick, R.M., 1994. Soft sediment meiofaunal community structure in relation to a long-term heavy metal gradient in the Fal estuary system. Marine Ecology Progress Series 105, 79–88.

Street, G.T., Montagna, P.A., 1996. Loss of genetic diversity in Harpacticoida near offshore platforms. Marine Biology 126, 271–282.

Theodorakis, C.W., 2003. Establishing causality between population genetic alterations and environmental contamination in aquatic organisms. Human and Ecological Risk Assessment 9, 37–58.

Thompson, G.B., Shin, P.K.S., 1983. Sewage pollution and the infaunal benthos of Victoria Harbour, Hong Kong. Journal of Experimental Marine Biology and Ecology 67, 279–299.

Vitousek, P.M., Mooney, H.A., Lubchenco, J., Melillo, J.M., 1997. Human domination of earth's ecosystems. Science 277, 494–499.

Warwick, R.M., Clarke, K.R., 1991. A comparison of some methods for analysing changes in benthic community structure. Journal of the Marine Biological Association of the United Kingdom 71, 225–244.

Warwick, R.M., Clarke, K.R., 1995. New 'biodiversity' measures reveal a decrease in taxonomic distinctness with increasing stress. Marine Ecology Progress Series 129, 301–305.

Washington, H.G., 1984. Diversity, biotic and similarity indices: a review with special relevance to aquatic ecosystems. Water Research 18, 653–694.

Wu, R.S.S., 1995. The environmental impact of marine fish culture: towards a sustainable future. Marine Pollution Bulletin 31, 159–166.