Response to Manuscript Reviewers' Comments

Title:
Baseline for ostracod-based northwestern Pacific and
Indo-Pacific shallow-marine paleoenvironmental reconstructions: ecological
modeling of species
distributions

Dear Prof. Irizuki,
Thank you all for your valuable comments on my manuscript. Please find the relevant excerpts from your report reproduced below, alongside their respective responses.
Yours sincerely,
Yuanyuan Hong
(email: oocirclr@gmail.com)

1. When the relationship between ostracod distributions and environmental factors is studied, autochthonous ostracod data should be basically used. However, you did not discuss whether ostracod assemblages or specimens were autochthonous or allochthonous. For example, because Xestoleberis is phytal genus, it is basically allochthonous specimens in bottom sediments and transported from intertidal zones with Zostera beds or calcareous algae. You should add several sentences about this taphonomic problem.

We agree that a phytal genus like Xestoleberis is allochthonous, and its value in studying ostracod distribution and related environmental factors is limited. We added some sentences regarding taphonomic problems in the revised manuscript. Please see line 215–220 "A small percentage of specimens of phytal genera (e.g., Xestoleberis spp., Neonesidea spp.) were contained in each sample, which are basically allochthonous specimens in bottom sediments transported from surrounding phytal environments. The value of allochthonous species to environmental interpretation is limited, however most ostracod specimens in each sample are composed of benthic, muddy sediment dwellers which are considered autochthonous."

2. Total organic carbon content (TOC) in bottom sediment is very important for ostracod distribution (Irizuki et al., 2011, 2015a, 2018) and it is a good indicator to estimate eutrophication and dissolved oxygen (DO) in the past in case of studies based on core samples. Though you did not examine TOC in sediment, you had better discuss the importance of TOC as an environmental factor and that TOC is strongly related to eutrophication and DO. (Irizuki, T., Hirose, K., Ueda, Y., Fujihara, Y., Ishiga, H., Seto, K., 2018, Ecological shifts due to anthropogenic activities in the coastal seas of the Seto Inland Sea, Japan, since the 20th century. Marine Pollution Bulletin, 127, 637-653.

Yes, indeed, we did notice eutrophication and hypoxia can be important factors for ostracods. It's the reason why we used Chlorophyll-a and DO in our modeling. They are reliable proxy for eutrophication and hypoxia. We agree TOC is important for paleo studies, but this MS is on modern distribution, and so it's out of the scope of our MS.

3. Minor problems are directly highlighted and revised in the text. Please also note the supplement to this comment: https://www.biogeosciences-discuss.net/bg-2018-405/bg-2018-405-RC1- supplement.pdf

Please see the attached pdf file for replies. For other corrections, please see the revised manuscript.

Response to Manuscript Reviewers' Comments

Title:
Baseline for ostracod-based northwestern Pacific and Indo-Pacific shallow-marine paleoenvironmental reconstructions: ecological modeling of species distributions

Dear editor and reviewer, T. M. Cronin
Thank you all for your valuable comments on my manuscript. Please find the relevant excerpts from your report reproduced below, alongside their respective responses.
Yours sincerely,
Yuanyuan Hong
(email: oocirclr@gmail.com)

1. The results section however is awfully descriptive and redundant, each paragraph starting the same way: Relative abundance of SPECIES X was correlated only with ENVIRONMENTAL: : :. These data is given in the tables. So emphasize in discussions the key species of most utility in east Asia. The data in tables are fine, but I think the authors have to discuss the most obvious and useful species as indicators of natural [T, S DO] and human [toxics, metals] chemical and physical factors. Not just plot and chart all the data. A little variability in writing style would help too.

Thanks for pointing this out! To improve descriptive and redundant impression, we divided the discussion section into sub-sections of (a) Widespread Group, (b) Temperate Group, (c) Subtropical Group, (d) Tropical Group, and (e) Globally Distributed Group. We also revised fig 7 accordingly. We also add some variation to our writing style. We already selected potentially important species for this study and so would like to keep mentioning all the species. Regarding the most obvious and important species, we already mentioned S impressa and N delicata in the abstract.

2. Tropical not tropic?

Thanks! Now we revised the MS and consistently use "tropical" as an adjective and "tropics" as a noun.

3. Some might argue 150 microns and larger misses some smaller species.

As discussed in the method section, most specimens smaller than 150 um will be early juveniles that are rarely preserved or difficult to identify. More datailes are discussed in Yasuhara et al 2017 Journal of Biogeography. So, we revised the relevant sentence in the method section as follow: "The residue was dry-sieved over a 150 µm mesh sieve, and ostracod specimens larger than 150 µm were picked; smaller individuals are mostly early instar juveniles that are often not preserved (because their shells are usually thin and delicate) or difficult to identify (see Yasuhara et al., 2017 for more details)."

4. I wonder why most specimens were dead shells and living animals were so scarce?

We don't know why (perhaps low population density or loss of living specimens during sampling or both). But it's quite common in grab sample based studies. However, dead shells eventually become fossils, so usage of mostly dead shells for obtaining autoecological information for paleoenvironmental application is reasonable.

5. Line 289. Why if K. kloempritensis lives in deeper water is it useful for sea level reconstruction? Species that live at or mean SL are best.

We agree that species living at mean SL are very useful, but our samples don't cover intertidal environments. *K. kloempritensis* is useful for sea level reconstructions at least in qualitative sense, because it could be an indicator for deeper water and tropical species rarely have such detailed autoecological information. The presence or higher relative abundance indicates higher relative sea-level.

6. Figure 7 could be re-designed to show the distributions better, for example, in shallow water regions.

We revised Fig. 7 to address your comment 1 above. We rearranged the order of species according to their geographic distribution groups. We also vertically compressed the map a bit for better visual. But please note than primary aim of this fig is to visualize large scale geographic distributions approximately, and it's out of the scope to show detailed or fine scale distributions.

Response to Manuscript Reviewers' Comments

Title:
Baseline for ostracod-based northwestern Pacific and Indo-Pacific shallow-marine paleoenvironmental reconstructions: ecological modeling of species distributions

Dear Dr Lazaro,
Thank you all for your valuable comments on my manuscript. Please find the relevant excerpts from your report reproduced below, alongside their respective responses.
Yours sincerely,
Yuanyuan Hong
(email: oocirclr@gmail.com)

1. In order to avoid the iterative descriptions of results for all species it could be useful to underline the stronger correlations of species with environmental parameters (as positive correlations) and on the other hand, the stronger un-correlations of species/parameters (as negative correlations) to evidence the most sensitive species to environmental alterations (anthropogenic, in particular).

To address a reviewer 2's comment and to reduce iterative impression, we divide the results and discussion section into subsections by grouping the species into Widespread, Temperate, Subtropical, Tropical, and Globally Distributed Groups. We hope this works. In addition, the Table 3 already highlights significant correlations in model averaging (that are similar to "stronger correlations" in your sense).

2. Taphonomic status of individuals must be clearly noted, since only autochthonous specimens are valid to ecological modelling. In particular apply this with estuarine species that can be found in deeper waters.

The samples are mostly muddy (indicating deposition under calm condition), and so we think the faunal is mostly autochthonous, except a small percentage of phytal species included in each sample. We added some sentences regarding taphonomic problems in the revised manuscript. Please see line 215–220 "A small percentage of specimens of phytal genera (e.g., Xestoleberis spp., Neonesidea spp.) were contained in each sample, which are basically allochthonous specimens in bottom sediments transported from surrounding phytal environments. The value of allochthonous species to environmental interpretation is limited, however most ostracod specimens in each sample are composed of benthic, muddy sediment dwellers which are considered autochthonous."

3. Minor problems:
212 was strongly correlated with salinity (negative) better: strongly uncorrelated
We think the word "uncorrelated" is a bit confusing, because it can mean non-significant correlation instead of significant negative correlation. We also changed "strongly" to "significantly" for better accuracy.

Text might be somehow simplified by using: correlated (positive) as correlated, and correlated (negative) as uncorrelated.
Please refer to answer for 3.

233 Relative abundance of B. bisanensis s.l., better using the complete name of species (Bicornucythere bisanensis) at first mention, and then writing the contracted name (B.
bisanensis) in other mentions of this species. This can apply for all species.
We agree, that's why we mentioned the complete name at the beginning of **5. Results and discussions**. In addition, species names at the beginning of a sentence are not abbreviated.

240 (Bicornucythere bisanensis) we did not see a significant relation between relative abundance and metal concentration, productivity s.l., but in Table 2 it is uncorrelated with MD (-0.23; -0.29) and correlated with Pb (+0.18)

Table 2 shows the best three regression models for the relative abundance of each common species. However, Table 3 is model averaging results (of all regression models) and more conservative regarding significance. So, MD and Pb are significant in some models, but not so overall. Thus, our discussion is mostly based on Table 3 results.

419 to 426 Why all these references there?
Deleted.

Fig. 7 Bicornucythere bisanensis s.l. (dot in "l")
Revised.

Table 2. R is variable Region. How is it measured the correlation/uncorrelation of different species with this variable?
Categorical parameter like geographic region can be included in regression modeling. Correlation is based on species distribution and presence and absence of each region.

Copper (Cu) is included in the performed environmental analyses (Fig. 3; Table 1), but
after this it do not appear in any of the results and discussions. I wonder if there is not one correlation with the studied species; if so, please indicate.
We explored linear dependencies by computing variance inflation factors (VIF) (Legendre & Legendre, 1998) and pairwise correlations between predictor variables to assess whether multicollinearity was likely to influence regression results (Yasuhara et al., 2012b). The degree of freedom is more than one for the geographic region variable (see below), thus we computed generalized variance inflation factors (GVIF). For continuous variables, GVIF (Table 4) is the same as VIF, but for categorical variables, GVIF has degrees of freedom (Df) equal to the number of coefficients associated with it (Hendrickx et al., 2004). Thus, we used GVIF1/2df to make GVIF values comparable among those with different Df. VIF >20 is usually indicative of high collinearity (Legendre & Legendre, 1998). Thus we calculated an equivalent threshold of 4.47 (equal to $\sqrt{20}$) for GVIF1/2df to assess collinearity. Also, adjusted R2 >0.8 indicates a strong correlation of variables (Hoffman, 2015). In all datasets, summer temperature (ST) and copper (Cu) were highly correlated

(R^2=0.8217), and the GVIFs of ST and Cu are >20, indicating that these correlations may influence regression results. Thus, we re-ran the linear regression modeling without ST and Cu. In other words, ST and Cu were removed from our analyses and discussion.

Please also note the supplement to this comment: https://www.biogeosciences-discuss.net/bg-2018-405/bg-2018-405-RC3-supplement.pdf
Manuscript has been revised, with the comments in the supplement.

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Baseline for ostracod-based northwestern Pacific and Indo-Pacific shallow-marine paleoenvironmental reconstructions: ecological modeling of species distributions

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Abstract:

Fossil ostracods have been widely used for Quaternary paleoenvironmental reconstructions especially in marginally marine environments (e.g. for water depth, temperature, salinity, oxygen levels, pollution). But our knowledge of the autoecology of indicator species, the base of paleoenvironmental reconstructions, remains limited and commonly lacks robust statistical support and comprehensive comparison with environmental data. We analysed marginally marine ostracod taxa at 52 sites in Hong Kong for which comprehensive environmental data are available. We applied linear regression models to reveal relationships between species distribution and environmental factors, and identified indicator species of environmental parameters. For example, *Sinocytheridea impressa* and *Neomonoceratina delicata* indicate botttom-water hypoxia – eutrophication, and heavy-metal pollution - increased turbidity, respectively. Many taxa are widespread throughout the northwestern Pacific – Indo-Pacific regions, including temperate (South China Sea to Japan and Russia), subtropical (i.e., Indo-Pacific to the East China Sea), and tropical (i.e., Indo-Pacific and South China Sea) taxa. With statistical support from ecological modeling and comprehensive environmental data, These results provide a robust baseline for ostracod-based Quaternary-Anthropocene paleoenvironmental reconstructions in the tropic–extratopic northwestern Pacific and Indo-Pacific.

Key words: Autoecology, Distribution modeling, Indicator species, Ostracoda, Paleoenvironmental reconstruction, Proxy.

Key points

1. We provide a robust baseline for ostracod (microscopic Arthropods) based paleoenvironmental reconstructions from Quaternary and Anthropocene marginal marine sediments.

2. The studied species have wide distributions over the tropics and extratropics of the northwestern Pacific and Indo-Pacific.

3. Ecological modeling established reliable indicator ostracod species for paleoenvironmental reconstructions.

1. Introduction

Because of their small size, high abundance and excellent fossil record, fossil ostracods (microcrustaceans), have been widely used to reconstruct Quaternary environmental conditions including water-depth, salinity, temperature, oxygen, and pollution, especially in marginal marine sediments (Boomer & Eisenhauer, 2002; Cronin, 2015; Frenzel & Boomer, 2005; Horne et al., 2012; Ruiz et al., 2005). In the northwestern Pacific and Indo-Pacific there are numerous, widely distributed deltas (Woodroffe et al., 2006) hosting accumulated Holocene marine sediments. Many studies have reconstructed the depositional environments of these sediments (Alberti et al., 2013; Dong et al., 2012; Irizuki et al., 2015b; Tanaka et al., 2011; Yasuhara & Seto, 2006; Yasuhara et al., 2005; Zhou et al., 2015). Due to high sedimentation rates (> 1 cm per year), fossil ostracods allow high-resolution reconstructions of human-induced environmental changes (pollution, eutrophication, bottom oxygen depletion) over the past century (Irizuki et al., 2011; Yasuhara et al., 2003).

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Many have evaluated the autoecology of indicator species as the basis for the paleoenvironmental reconstructions (Hazel, 1988; Irizuki et al., 2003; Ozawa et al., 2004; Stepanova et al., 2003; Wang et al., 1988; Yasuhara & Seto, 2006; Zhao, 1984; Zhao & Wang, 1988a, 1988b). Yet these studies tend to focus on only one or few targeted environmental factor(s) and lack rigorous statistical evaluation, particularly statistical modeling, a common approach in contemporary ecology. This is probably due to the facts that comprehensive environmental dataset are often unavailable and an ecological modeling approach (especially regression modeling and model selection) has not been common in the field of micropaleontology.

Hong Kong is an ideal location for the marine ecological modeling approach valid for the northwestern Pacific and Indo-Pacific, because of its extensive and intensive marine environmental monitoring program, which provides robust datasets for ecological modeling and its subtropical location, where tropical and temperate species coexist, which allows investigations of species with different latitudinal and geographical distributions. We employed regression modeling of Hong Kong shallow-marine ostracod species to show statistical relationships between species abundance, distribution and environmental factors. This study allows the autoecology and statistical evaluation of common tropical and extratropical species, providing a baseline for ostracod-based shallow-marine paleoenvironmental reconstructions of the northwestern Pacific and Indo-Pacific regions.

2. Study area

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Hong Kong is situated at the southeastern corner of the Pearl River (Zhujiang) Delta, and has an area of 2500 km^2 (Fig. 1), at 22° 12.021' to 22° 33.817' N latitude, 113° 53.388' to 114° 26.920' E longitude. It is an ideal location to study natural and/or anthropogenic impacts on benthic communities due to its complex hydrology and long history of human influence. Western Hong Kong is affected by input from the Pearl River, particularly during the summer heavy rainfall (Morton & Wu, 1975), when salinity of the surface waters is strongly influenced by rainfall. Eastern Hong Kong waters are mainly marine and derived from the South China Sea. As one of the most urbanized coastal areas in the world, human activities, including rapid industrialization, sewage discharge, trawling, dredging and land reclamation have led to a deteriorated marine benthic ecosystem (Blackmore, 1998; Hodgkiss & Yim, 1995; Hong et al., 2017; Hu et al., 2008; Morton, 1996; Morton & Blackmore, 2001; Owen & Sandhu, 2000; Shin, 1977; Tanner et al., 2000).

3. Materials and Methods

3.1. Samples and laboratory procedure

In January and July of 2011 we used a Van Veen Grab to collect 100 ml of sediment from the uppermost cm of the sea floor from 52 sites in Hong Kong marine waters (Fig. 1; Supplement A), 41 of which are in open waters and 11 in typhoon shelter sites. Typhoon shelters are semi-enclosed areas of water designed to protect moored vessels in extreme weather (Environmental Protection Department, 2011). All sites are included in the Hong Kong EPD marine water and sediment quality monitoring program, which has been conducted monthly since 1986 (for water) and biannually (for sediment), providing comprehensive environmental data for all stations (see below).

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Sediments were wet-sieved over a 63 μm mesh sieve and air dried or oven-dried at 40 °C. The residue was dry-sieved over a 150 μm mesh sieve, and ostracod specimens larger than 150 μm were picked; smaller individuals were not included to avoid problems of identification in small, early instar juveniles. In samples containing fewer than 200 specimens, we picked all individuals. If there were more than 200 specimens, we picked ostracods from a split. We identified each counted specimen to species level when possible. We considered both an entire carapace or a single valve as one individual for counting.

3.2 Environmental Variables

We selected parameters from the EPD monitoring program (Table 1) for our regression modeling (see below), including surface productivity (Chlorophyll-a, Chl; Fig. 2), water depth (D; Fig. 2), bottom water dissolved oxygen (DO; Fig. 2), bottom water salinity (Sal; Fig. 2), turbidity (Tur; Fig. 2), summer bottom water temperature (ST – June to September average; Fig. 2), winter bottom water temperature (WT – November to Feburary average; Fig. 2), mud content (MD; Fig. 2), and heavy metal concentration (Cu, Zn, and Pb; Fig. 3). These parameters are known to control ostracod faunal properties (Cronin, 2015; Cronin & Vann, 2003; Hazel, 1988; Ikeya & Shiozaki, 1993; Irizuki et al., 2005; Ruiz et al., 2005; Yasuhara et al., 2007; Yasuhara et al., 2012b). We used averages over the entire monitoring period (1986–2011), because the ostracods in this study were mostly dead shells, thus the samples should be considered time averaged. Bottom water DO is the average of the summer season (June–September), due to the likely importance of summer bottom water oxygen depletion.

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4. Regression modeling

Multiple linear regression modeling was used to determine the relationship between common ostracod species (relative abundance of each species) and environmental parameters (Supplement B). All environmental parameters were log-transformed and zero centered. Salinity outliers (salinity <25: DS2 and DS3) and samples with low abundance (<50 specimens: ES5, MS7, VS21, VS5 & VS6) were removed from the models.

The best-fitting models were selected based on Akaike's Information Criterion (AICc) for small sample size, in which the lower score indicates the better model support considering both goodness-of-fit and model complexity (Anderson & Burnham, 2002). Akaike weights were used to summarize proportional support for all candidate models (Anderson et al., 2000) (Table 2). We considered parameter estimates averaged over models, proportional to the support that each model received (Anderson et al., 2000) (Table 3). This approach accounts for the uncertainty in model selection and thus leads to appropriately broader confidence intervals than obtained by relying only on the single, best-supported model. The relative importance of various predictor variables was measured by the sum of Akaike weights of models that included the variables in question (Brunham & Anderson, 2002).

We explored linear dependencies by computing variance inflation factors (VIF) (Legendre & Legendre, 1998) and pairwise correlations between predictor variables to assess whether multicollinearity was likely to influence regression results (Yasuhara et al., 2012b). The degree of freedom is more than one for the geographic region variable (see below), thus we computed generalized variance inflation factors (GVIF). For continuous variables, GVIF (Table 4) is the same as VIF, but for categorical variables, GVIF has degrees of freedom (Df) equal to the number of coefficients associated with it (Hendrickx et al., 2004). Thus, we used $GVIF^{1/2df}$ to make GVIF values comparable among those with different Df. VIF >20 is usually indicative of high collinearity (Legendre & Legendre, 1998). Thus we calculated an equivalent threshold of 4.47 (equal to √20) for $GVIF^{1/2df}$ to assess conlinearity. Also, adjusted R^2 >0.8 indicates a strong correlation of variables (Hoffman, 2015). In all datasets, summer temperature (ST) and water depth (D) were highly correlated (R^2=0.8217), and the GVIFs of ST and Cu are >20, indicating that these correlations may influence regression results. Thus, we re-ran the linear regression modeling without ST and Cu. The new GVIFs of all variables were under 4.47 (Table 4).

We considered the degree of spatial autocorrelation in model residuals by the calculation of Moran's *I* index for the five best models. The neighborhood size was set as 2, 5, 10, 20 and 50 km. We found significant spatial autocorrelation in model residuals for many cases, thus we forced the geographic region variable (R) (Water Control Zones defined by EPD) to be included in all models. After this treatment, spatial autocorrelation was detected only in a few models for *Propontocypris* spp., *Stigmatocythere roesmani*, and *Hemikrithe orientalis*.

The multiple linear regression model analyses were implemented in R programming language (R Core Team, 2016). We used 'M_UMI_N' (Bartoń, 2013) for model averaging and 'SPDEP' (Bivand & Piras, 2015) to measure spatial autocorrelation.

5. Results and discussions

The comprehensive ostracod dataset for the 52 sites and the environmental variables enabled us to elucidate distribution patterns of common ostracod taxa and their related environmental factor(s). We identified 151 species belonging to 76 genera

(Supplement A). Among them, 18 common taxa (mainly species, a few genera) of *Sinocytheridea impressa*, *Neomonoceratina delicata*, *Propontocypris* spp., *Pistocythereis bradyi*, *Bicornucythere bisanensis* s.l., *Keijella kloempritensis*, *Nipponocythere bicarinata*, *Spinileberis quadriaculeata*, *Xestoleberis* spp., *Loxoconcha malayensis, Neonesidea* spp., *Neosinocythere elongata*, *Stigmatocythere roesmani*, *Phlyctocythere japonica*, *Alocopocythere goujoni*, *Hemikrithe orientalis*, *Loxoconcha epetterseni* and *Hemicytheridea reticulata* (Supplement B) were used for regression modelling, and their relative abundances (to the total ostracod abundance in a sample) show a significant relation with environmental parameters. The best three regression models are presented in Table 2 and the model-averaged parameter estimates in Table 3.

Relative abundance of *S. impressa* [=*Sinocytheridea latiovata*; see Whatley and Zhao (1988a)] was strongly correlated with salinity (negative), dissolved oxygen (negative), mud content (positive) and productivity (positive) (Tables 2 and 3). The species is noticeably dominant in areas characterized by a muddy bottom including northern Mirs Bay, Port Shelter and coastal Southern Waters (Fig. 4). This species is also abundant in Tolo Harbour, an area known for its summer hypoxia and eutrophication (Hu et al., 2001; Sin & Chau, 1992). These results are consistent with previous studies indicating that *S. impressa* is dominant in low salinity, nutrient-rich and turbid estuaries (Irizuki et al., 2005; Tanaka et al., 2011), but we did not see a significant relation with turbidity (Tables 2 and 3). *S. impressa* is known as a euryhaline species widely distributed throughout the East and South China Seas [abundant in water depths of <20 m; Whatley and Zhao (1988a)], and the Indo-Pacific (Fig. 7).

Relative abundance of *N. delicata* (=*Neomonoceratina crispata*; see Hou & Gou, 2007) is significantly correlated with Zn (positive), salinity (positive) and turbidity (positive) (Tables 2 and 3). *N. delicata* is a nearshore species, abundant at depths less than 30 m, at relatively high salinities (>30; Zhao and Wang, 1988). *N. delicata* prefers higher salinity waters in Hong Kong (Figs. 2 and 4; Tables 2 and 3), and is likely tolerant to human-induced environmental stress such as pollution and eutrophication, in view of its positive correlation with Zn and turbidity. This species is widely known from nearshore and estuary environments in the East and South China Seas, and the Indo-Pacific (Fig. 7).

Relative abundance of *B. bisanensis* s.l. was significantly correlated with water depth (negative) (Tables 2 and 3) and this species prefers shallower environments (Figs. 2 and 4). In Chinese and Japanese coastal areas, *B. bisanensis* s.l. is abundant in brackish water (salinity: 20–30) at depths less than 10 m (Ikeya & Shiozaki, 1993; Irizuki et al., 2006; Zhao et al., 1986). Our results confirm its preference for shallow depths. *Bicornucythere bisanensis* is tolerant of anthropogenic impacts, especially eutrophication and the resulting bottom water hypoxia in Japan (Irizuki et al., 2003; Yasuhara et al., 2003; Yasuhara et al., 2012a). We did not see a significant relation between relative abundance and metal concentration, productivity, or dissolved oxygen. Possibly, the more dominant presence of *S. impressa* and *N. delicata,* that are neither dominant or distributed throughout most of Japan, could explain this difference. These species may have a higher tolerance than *B. bisanensis* s.l. Another explanation may be that different morphotypes have different ecological preferences (Abe, 1988), and only Form A is known to be tolerant to eutrophication and bottom-water oxygen depletion (Irizuki et al., 2011; Irizuki et al., 2015a; Yasuhara & Yamazaki, 2005; Yasuhara et al., 2007). Form A is less abundant in

Hong Kong, and due to the difficulty of identification of juveniles, we did not divide *B. bisanensis* into morphotypes. *B. bisanensis* s.l. is widely distributed throughout marginal marine environments around Japan and Russia, and the East and South China Seas (Fig. 7).

Relative abundance of *P. bradyi* was highly correlated with salinity (positive), water depth (negative) and Pb (negative) (Tables 2 and 3). This indicates the species prefers relatively shallow environments with high salinity (Figs. 2 and 4). In the Pearl River Delta and shallow South China Sea (Fig. 7), *P. bradyi* is dominant along the inner continental shelf at water depths <100 m (mostly common between 10–50 m), and at salinities from 30–40 (Li, 1985; Zhao & Wang, 1990; Zhao et al., 1986). *Pistocythereis bradyi* is a typical middle muddy bay species in Japan (Irizuki et al., 2006; Yasuhara & Irizuki, 2001; Yasuhara & Seto, 2006), and known from open bays such as Gamagyang Bay in Korea (Abe, 1988) and Malacca Strait (Whatley & Zhao, 1988b). In these studies, *P. bradyi* prefers relatively high salinity and deeper water in the inner continental shelf (Tables 2 and 3). Our data agree as to the preference for high salinity, but we find shallower depths, inconsistent with the literature. Maybe salinity is more important than depth, but the restricted depth range of our sites (≤35 m) may also be a reason for this inconsistency. Our results indicate that *P. bradyi* is sensitive to metal pollution. This species is widely distributed throughout the marginally marine environments of Japan, the East and South China Seas, and the Indo-Pacific (Fig. 7).

Relative abundance of *N. bicarinata* was correlated with productivity (negative) (Tables 2 and 3). This is a typical middle bay species in Japan (Irizuki et al., 2006), abundant on muddy substrates at water depths > 10 m (Yasuhara & Seto, 2006; Yasuhara et al., 2005). found *N. bicarinata* to be sensitive to eutrophication, prefering lower productivity (Figures 2, 4). This species is know from marginal marine environments around Japan and the East and South China Seas (Fig. 7).

Relative abundance of *S. quadriaculeata* is correlated to productivity (positive) and turbidity (negative). This is a typical inner muddy bay species in Japan (Irizuki et al., 2006), which prefers silty substrates in brackish waters, at salinities from 20–30, and water depths of 2–7 m (Ikeya and Shiozaki, 1993). This study shows a preference for waters with higher productivity but relatively low turbidity (Tables 2 and 3), so that the species is abundant in Tolo Harbour (higher productivity, lower turbidity) but not in Deep Bay (higher turbidity) (Figs. 2 and 4). *Spinileberis quadriaculeata* is not tolerant to seasonal anoxia or oxygen depletion (0–1 mg/L) in Uranouchi Bay, Japan (Irizuki et al., 2008), but we do not find a significant correlation with dissolved oxygen content, probably due to the relatively high bottom-water oxygen content (2.96–6.84 mg/L) in Hong Kong (Fig. 2; Supplement B). *S. quadriaculeata* is widely distributed in marginally marine environments around Japan and Russia, and the East and South China Seas (Fig. 7).

Relative abundance of *K. kloempritensis* was correlated only with water depth (positive) (Fig. 4; Tables 2 and 3). *Keijella kloempritensis* is widely known from the tropical Indo-Pacific region, and abundant along the inner continental-shelf of the South and East China Seas (Fig. 7), at water depths range from 20–50 m and salinity is close to normal marine (Zhao & Wang, 1990). Our modelling results are consistent with this showing a preference for relatively deeper water in this study (Tables 2 and 3). Thus, this species is probably useful for reconstructing past sea-level changes in the broad tropical and subtropical Indo-Pacific and northwestern Pacific regions.

Relative abundance of *L. malayensis* was correlated with dissolved oxygen (negative) and mud content (negative) (Tables 2 and 3). *Loxoconcha malayensis* is a typical tropical species known from the Indo-Pacific and the South China Sea (Fig. 7). We did not find a correlation to temperature, likely due to the small range of variation of bottom water temperatures in Hong Kong (winter temperature: 19.10–21.49°C). This species prefers coarse sediments and is resistant to low oxygen content (Table 2 and 3), as seen by its abundance in Victoria Harbour (Figs. 2 and 4).

Relative abundance of *N. elongata* was correlated only with turbidity (positive) (Tables 2 and 3). *Neosinocythere elongata* occurs along the entire coast of China (Fig. 7) in marginal marine, especially estuarine, environments shallower than 20 m (Dong et al., 2012; Hou & Gou, 2007; Liu et al., 2013; Liu et al., 2017; Zhao & Whatley, 1993) and is known from the Indo-Pacific region (Fig. 7). Our modeling results and previous studies indicate consistently that *N. elongata* prefers shallow, turbid waters like Deep Bay and the Pearl River Estuary (Figs 2 and 6).

Relative abundance of *S. roesmani* was correlated with Pb (negative) (Tables 2 and 3), thus it was sensitive to metal pollution (but note the significant autocorrelation with the modeling result of this genus) and absent in areas with high metal concentrations, e.g., Tolo and Victoria Harbours (Fig. 3, 6). This species occurs in the East and South China Seas and the Indo-Pacific region (Dewi, 1997; Mostafawi, 1992; Whatley & Zhao, 1988a) (Fig. 7).

Relative abundance of *P. japonica* was correlated with water depth (positive) (Tables 2 and 3). This species is known from relatively deeper waters (>40 m) in the East China Sea (Ishizaki, 1981; Wang et al., 1988). At our sites, it has its greatest abundance at the deeper southern sites (Fig. 5). *Phlyctocythere japonica* is distributed around Japan (Yasuhara et al., 2002) and the East and South China Seas (Fig. 7).

Relative abundance of *A. goujoni* was correlated with salinity (positive) (Tables 2 and 3). It occurs not only in Mirs Bay where the salinity is higher, but also in Deep Bay and North Western Waters where the salinity is lower than in other areas (Figs 2 and 6). The Deep Bay and North Western Waters are shallow and have relatively low oxygen content. The modeling result of this species shows a marginally insignificant but negative relationship to oxygen content and water depth with moderately high relative importance (Table 3). We explain this inconsistency by considering their preference of higher salinity and shallow water depths, and also their resistance to low oxygen conditions, but further research is needed to know their autoecology with better confidence. *Alocopocythere goujoni* is known from the South China Sea and the Indo-Pacific (Fig. 7).

Relative abundance of *H. orientalis* was correlated with water depth (positive) (Tables 2 and 3; but note the significant autocorrelation with the modeling result of this genus), and it is more abundant in deeper waters including southern Mirs Bay (Fig. 5). *Hemikrithe orientalis* is known from depths of 20–50 m in the South China Sea (Zhao & Wang, 1988a), and reported from tropical Indo-Pacific marginal marine environments (Fig. 7). Our regression modeling consistently shows a positive relationship between the relative abundance and winter temperatures, with moderately high relative importance, although the correlation is marginally insignificant (Table 3).

Relative abundance of *L. epeterseni* was correlated with water depth (positive) and turbidity (negative) (Tables 2 and 3), and its occurs in the southern and eastern, deeper and less turbid parts of Hong Kong waters, but the trend is not very clear (Figs 2 and 6). This species is also known from the deeper parts of Osaka Bay, Japan (Yasuhara & Irizuki, 2001) and from marginal marine environments around Japan (Ishizaki, 1968), the East China Sea (Yang et al., 1982), and the South China Sea (Cao, 1998) (Fig. 7). This species is reported as *Loxoconcha modesta* in Hou & Gou (2007), and also has been misidentified as *Loxoconcha viva* and *Loxoconcha sinensis*

(Hou & Gou, 2007). Ishizaki (1968) described *Loxoconcha laeta* and *Loxoconcha modesta* but in our opinion, these are the females and males of the same species. Ishizaki (1981) gave the new species names *Loxoconcha epeterseni* and *Loxoconcha tosamodesta* for *Loxoconcha laeta* and *Loxoconcha modesta*, respectively, because these names were junior homonyms. Since *Loxoconcha laeta* (= *epeterseni*) appears earlier than *Loxoconcha modesta* (=*tosamodesta*) in the original description (Ishizaki, 1968), we use the name *Loxoconcha epeterseni* for this species.

Relative abundance of *H. reticulata* was correlated with Pb (negative) and water depth (negative) (Tables 2 and 3). This species is abundant in Tolo Harbour and the inner part of Mirs Bay (Fig. 5), at shallow depths, and is also consistently found in very shallow waters from the Indo-Pacific (Zhao & Whatley, 1989). Their metal-pollution sensitivity is contradictory because they occur in Tolo and Victora Harbours, both polluted regions of Hong Kong, and further research is needed to better understand these results (Figs 2 and 6). *Hemicytheridea reticulata* is distributed in the East China Sea (Gu et al., 2017), the South China Sea, and the Indo-Pacific (Fig. 7).

The relative abundance of the cosmopolitan *Neonesidea* spp. was correlated with dissolved oxygen (positive), as expected for a phytal species (Smith & Kamiya, 2002; Yamada, 2007) (Table 2 and 3; Fig 6).

The relative abundance of the cosmopolitan *Propontocypris* spp. was strongly correlated with productivity (negative) (Tables 2 and 3). This negative correlation with productivity (but note the significant autocorrelation with the modeling result of this genus) indicates that the genus prefers less eutrophic waters (Fig. 6). *Propontocypris* is a good swimmer (Maddocks, 1969), and thus may have an advantage in obtaining food in relatively food-limited environments.

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The relative abundance of the cosmopolitan phytal (Irizuki et al., 2008; Sato & Kamiya, 2007; Yasuhara et al., 2002) *Xestoleberis* spp. was correlated with turbidity (negative), mud content (negative), and dissolved oxygen (positive) (Table 2 and 3; Fig. 6). The taxon's habitats including clear water, coarse sediment, and high oxygen content are reflected in our modeling.

Summary

Benthic ostracods from Hong Kong marginal marine waters studied here include widespread (i.e., distributed throughout the northwestern Pacific – Indo-Pacific region: one species), temperate (i.e., distributed from the South China Sea to Japan and Russia: five species), subtropical (i.e., distributed from the Indo-Pacific to the East China Sea: six species), and tropical (i.e., distributed in the Indo-Paficic and South China Sea: three species) species and three globally distributed genera (Fig. 7). We provide a robust baseline of autoecology for these common ostracod taxa based on rigorous statistical modeling using comprehensive environmental data. We established reliable indicator forms for water depth, mud content, salinity, turbidity, dissolved oxygen, heavy metal pollution (Pb and Zn) and eutrophication (chlorophyll-a) (Table 5). Thus our results are applicable for future ostracod-based paleoenvironmental studies in a wide range of localities from the tropics to the extratropics, and from the Indian Ocean to the northwestern Pacific. We established pollution and eutrophication indicator species in tropical environments for the first time. Anthropocene paleoenvironmental and paleoecological studies in the tropics are urgently needed because (1) the tropics are seriously under-studied (Wilkinson et al., 2014; Yasuhara et al., 2012a), (2) tropical environments and ecosystems are vulnerable and sensitive to human influences (Jackson et al., 2001; Pandolfi et al., 2003), and (3) Indo-Pacific tropical environments have been seriously degraded by the human activity of rapidly developing countries (Bellwood et al., 2004; Jackson, 2008; Knowlton & Jackson, 2008). Our results provide useful and reliable tools for tropical Anthropocene research in the broad Indo-Pacific region.

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Captions

Fig. 1 Locality map showing the 52 sampling sites across Hong Kong, including 41 open water sites (blue dots) and 11 typhoon shelter sites (red open dots). From west to east, DS: Deep Bay; NS: North Western waters; SS: Southern waters; VS: Victoria Harbour; ES: Eastern Buffer; JS: Junk Bay; TS: Tolo Harbour; PS: Port Shelter; MS: Mirs Bay.

Fig. 2 Spatial distribution of environmental parameters in Hong Kong. Mean surface-water chlorophyll-a concentration; water depth; summer (June to September) bottom-water dissolved oxygen content; mean bottom-water salinity; mean turbidity; mean summer (June to September) bottom-water temperature; mean winter (November to February) bottom-water temperature; and mean mud content. All are averaged values of the data obtained during 1986–2013 (Table 1).

Fig. 3 Spatial distribution of environmental parameters in Hong Kong. Mean copper (Cu) concentration, mean lead (Pb) concentration, and mean zinc (Zn) concentration in surface sediments. All are averaged values of the data obtained during 1986–2013 (Table 1).

Fig. 4. Spatial distribution of the relative abundance of *Sinocytheridea impressa*, *Neomonoceratina delicata*, *Bicornucythere bisanensis* s.l., *Pistocythereis bradyi*, *Nipponocythere bicarinata*, *Spinileberis quadriaculeata*, *Keijella kloempritensis*, and *Loxoconcha malayensis* in Hong Kong. See Figure 1 for sampling stations.

Fig. 5. Spatial distribution of the relative abundance of *Neosinocythere elongata*, *Stigmatocythere roesmani*, *Phlyctocythere japonica*, *Alocopocythere goujoni*,

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Hemikrithe orientalis, *Loxoconcha epetterseni*, *Hemicytheridea reticulata* and *Neonesidea* spp. in Hong Kong. See Figure 1 for sampling stations.

Fig. 6. Spatial distribution of the relative abundance of *Propontocypris* spp., and *Xestoleberis* spp. in Hong Kong. See Figure 1 for sampling stations.

Fig. 7. Geographical distributions of the 18 taxa in the northwestern Pacific and Indo-Pacific regions, including *Sinocytheridea impressa*, *Neomonoceratina delicata*, *Pistocythereis bradyi*, *Bicornucythere bisanensis* s.l., *Keijella kloempritensis*, *Nipponocythere bicarinata*, *Spinileberis quadriaculeata*, *Loxoconcha malayensis,* *Neosinocythere elongata*, *Stigmatocythere roesmani*, *Phlyctocythere japonica*, *Alocopocythere goujoni*, *Hemikrithe orientalis*, *Loxoconcha epeterseni*, *Hemicytheridea reticulata*, *Neonesidea* spp., *Propontocypris* spp., and *Xestoleberis* spp. The following references were used mainly to determine the geographical distributions of the species: Al Jumaily and Al-Sheikhly (1999); Dewi (1997); Dong et al. (2012); Fauzielly et al. (2013); Hong et al. (2017); Hou and Gou (2007); Hussain et al. (2004); Hussain et al. (2010); Hussain and Mohan (2000, 2001); Irizuki et al. (2006); Irizuki et al. (2009); Iwatani et al. (2014); Jie et al. (2013); Li (1985); Mostafawi (1992); Nishath et al. (2017); Noraswana et al. (2014); Pugliese et al. (2006); Schornikov et al. (2014); Tanaka et al. (2009); Tanaka et al. (2011); Wang et al. (1988); Wang and Zhang (1987); Wang and Zhao (1985); Zhao (1984); Zhao and Wang (1988a, 1988b, 1990); Zhao and Whatley (1993); Zhou et al. (2015).

Table 1. Summary of marine water/sediment parameters. Note: 1. Summer: June, July, August and September. 2. Winter: November, December, January and February.

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Table 2. Best three regression models of the relative abundance of common species, including *Sinocytheridea impressa*, *Neomonoceratina delicata*, *Propontocypris* spp., *Pistocythereis bradyi*, *Bicornucythere bisanensis* s.l., *Keijella kloempritensis*, *Nipponocythere bicarinata*, *Spinileberis quadriaculeata*, *Xestoleberis* spp., *Loxoconcha malayensis*, *Neonesidea* spp., *Neosinocythere elongata*, *Stigmatocythere roesmani*, *Phlyctocythere japonica*, *Alocopocythere goujoni*, *Hemikrithe orientalis*, *Loxoconcha epeterseni* and *Hemicytheridea reticulata*. The table shows the coefficient of each term, adjusted R^2, the Akaike information criterion corrected for small sample size (AICc), and the Akaike weight (AW). Bold denotes significance at $P < 0.05$. Overall P is < 0.05 in all models. R: region. Other abbreviations are found in Table 1.

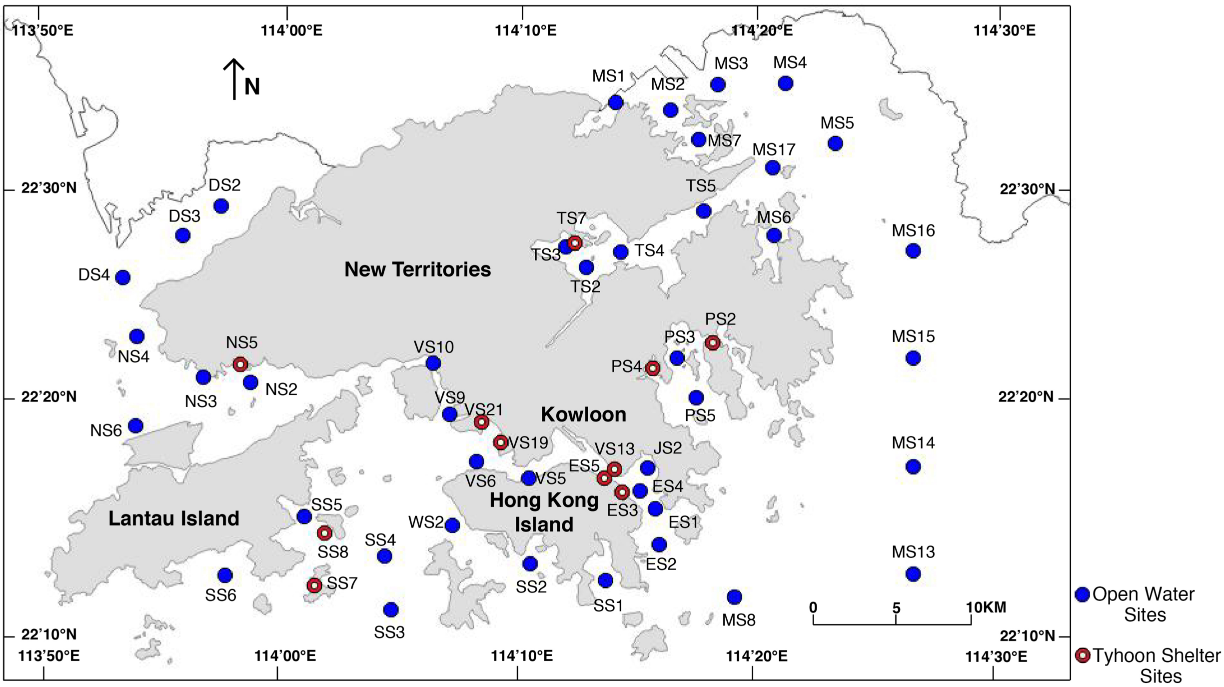
Table 3. Model-averaged parameter estimates and CIs of the relative abundance of common species, including *Sinocytheridea impressa*, *Neomonoceratina delicata*, *Propontocypris* spp., *Pistocythereis bradyi*, *Bicornucythere bisanensis* s.l., *Keijella kloempritensis*, *Nipponocythere bicarinata*, *Spinileberis quadriaculeata*, *Xestoleberis* spp., *Loxoconcha malayensis,* *Neonesidea* spp., *Neosinocythere elongata*, *Stigmatocythere roesmani*, *Phlyctocythere japonica*, *Alocopocythere goujoni*, *Hemikrithe orientalis*, *Loxoconcha epeterseni* and *Hemicytheridea reticulata*. CIs, confidence intervals; RI, relative importance (the sum of the Akaike weights of models that include the variable in question; see Materials and Methods); R, region. Other abbreviations are found in Table 1. Bold denotes CIs that exclude zero. For R, coefficient, lower CI, and upper CI values shown are averages of those for geographic regions.

Table 4. GVIF value for Environmental Variables. Df, degree of freedom; R, region. Other abbreviations are found in Table 1.

Table 5. Summary of autoecology for common ostracod taxa. Chl: Chlorophyll-a; D: Water Depth; DO: Dissolved Oxygen; MD: Mud Content; Sal: Salinity; Tur: Turbidity; WT: Winter Temperature; Pb: Lead; Zn: Zinc; R: Region.

Supplement A. Ostracod faunal list.

Supplement B. Dataset used for the regression modeling.


113'50°E
114'00°E
114'10°E
114'20°E
114'30°E
22'30°N
22'20°N
22'10°N
N
New Territories
Kowloon
Hong Kong Island
Lantau Island
MS1
MS2
MS3
MS4
MS5
MS7
MS17
TS5
TS7
TS3
TS4
TS2
MS6
MS16
MS15
MS14
MS13
MS8
DS2
DS3
DS4
NS4
NS5
NS3
NS2
NS6
VS10
VS9
VS21
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PS5
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SS8
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SS6
SS4
SS3
SS2
SS1
WS2
0
5
10KM
Open Water Sites
Tyhoon Shelter Sites

Fig. 1

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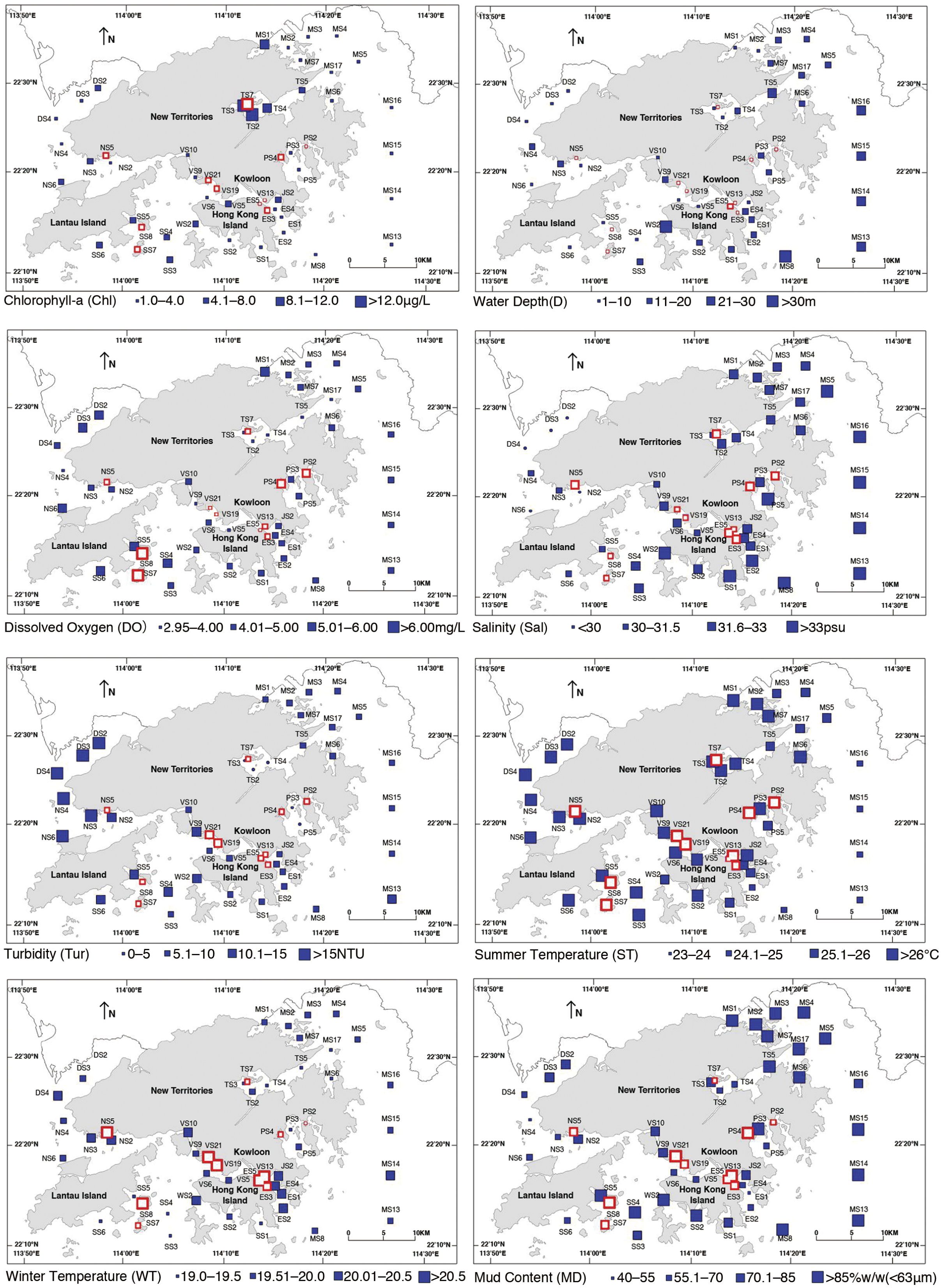

Fig. 2

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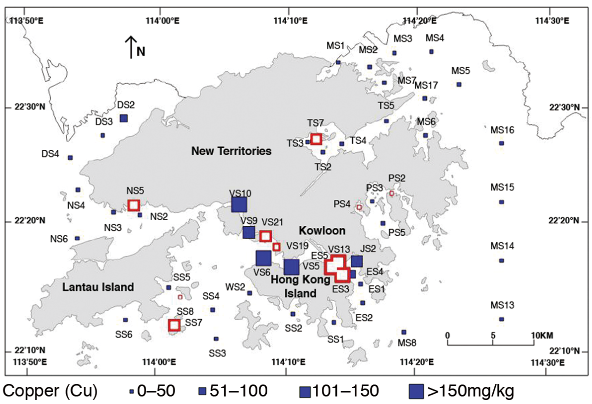

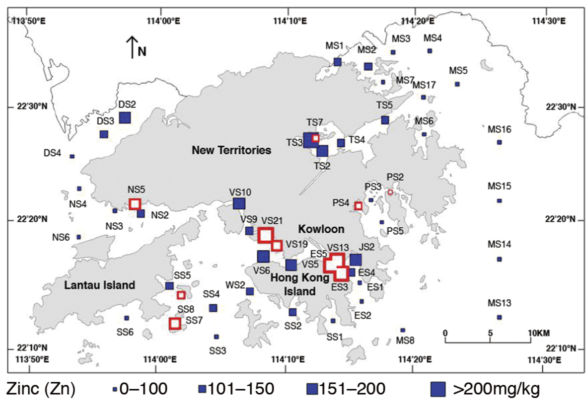

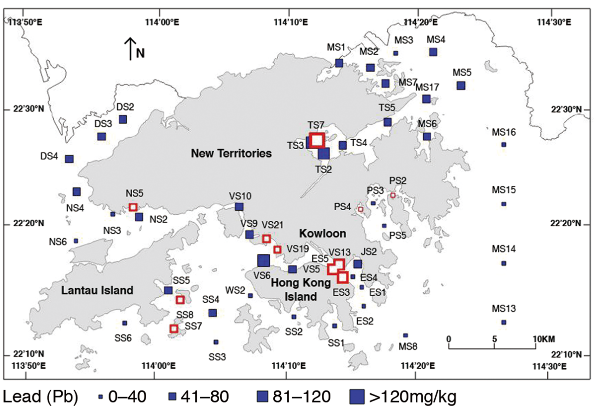

Fig. 3

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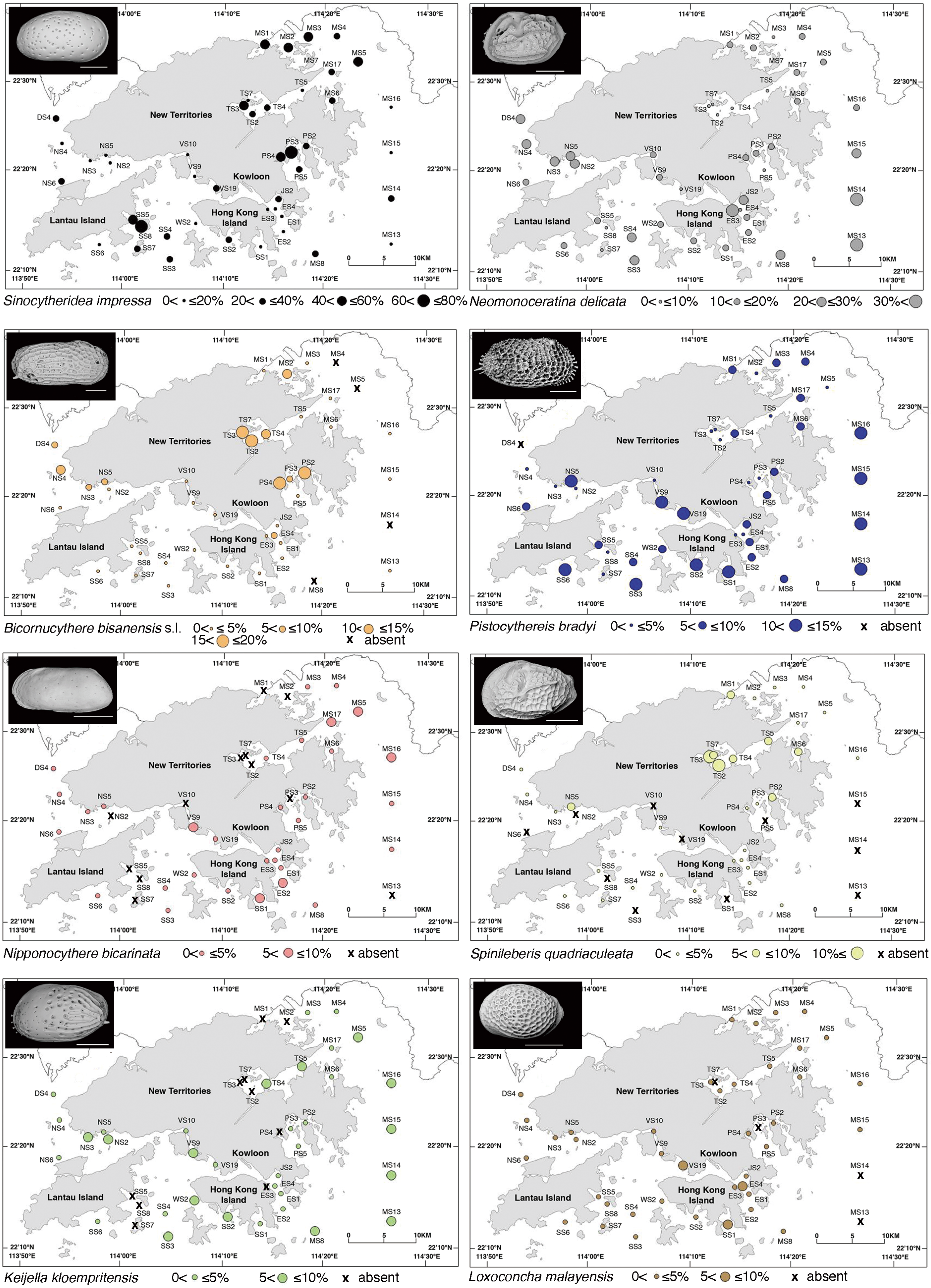

Fig. 4

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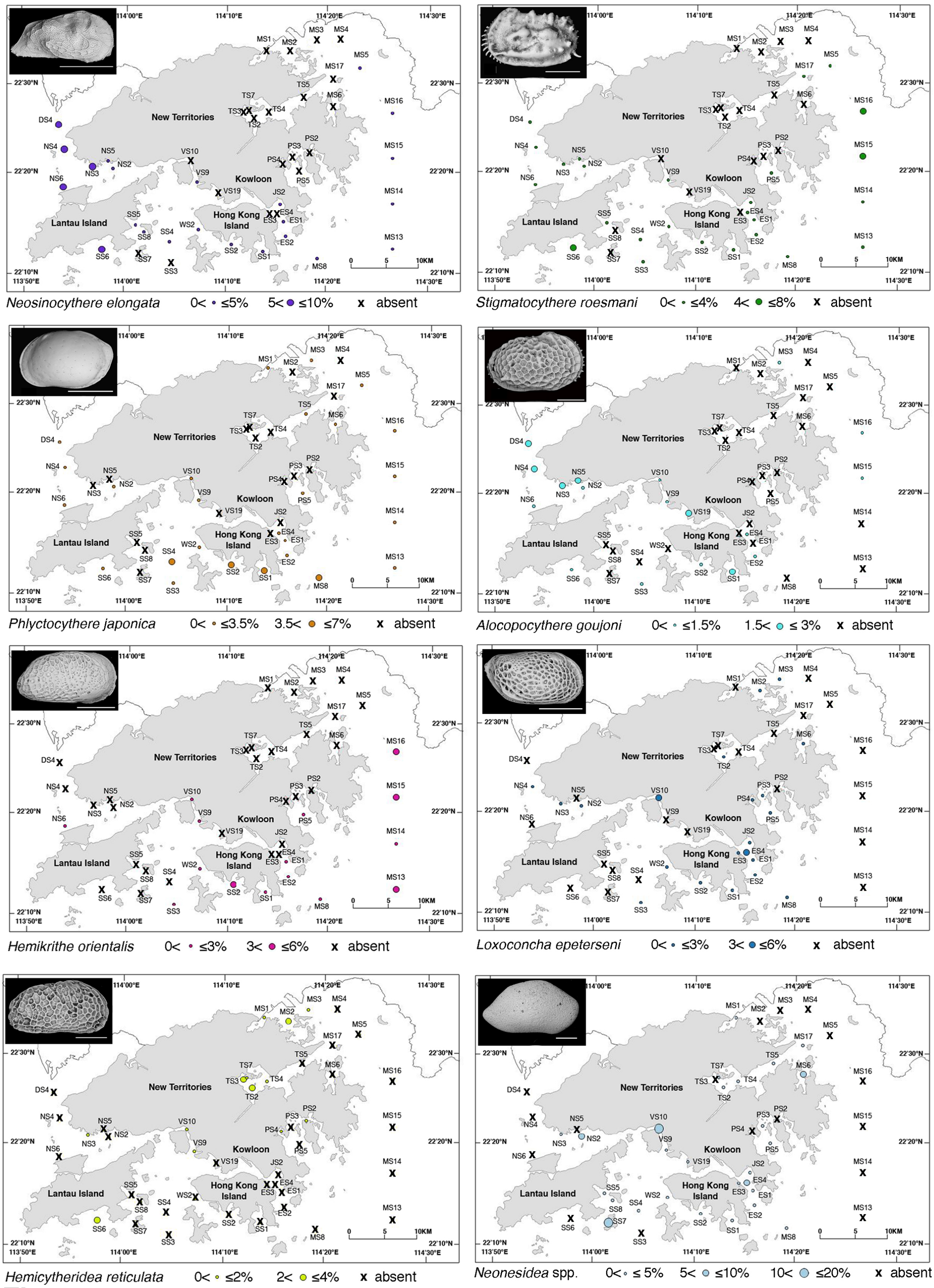

Fig. 5

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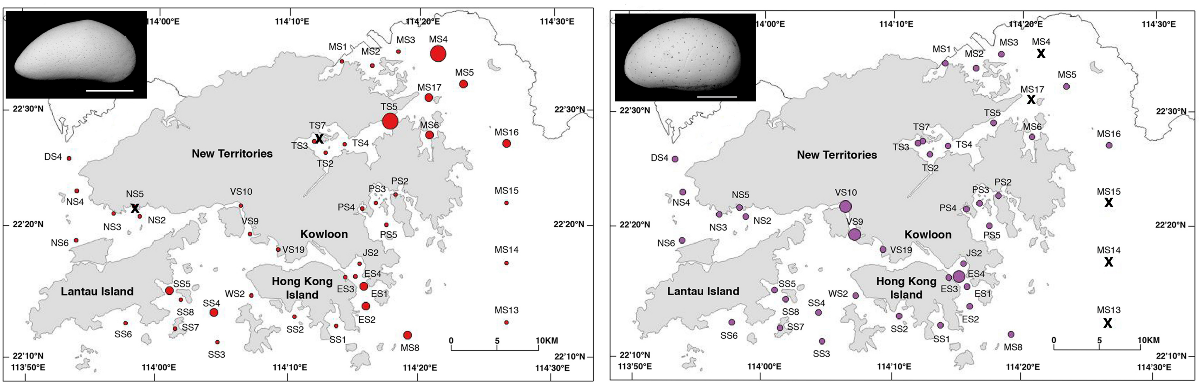

Propontocypris spp. 0< • ≤10% 10< ● ≤20% 20%< ● ≤60% **x** absent

Xestoleberis spp. 0< • ≤5% 5< ● ≤15% **x** absent

Fig. 6

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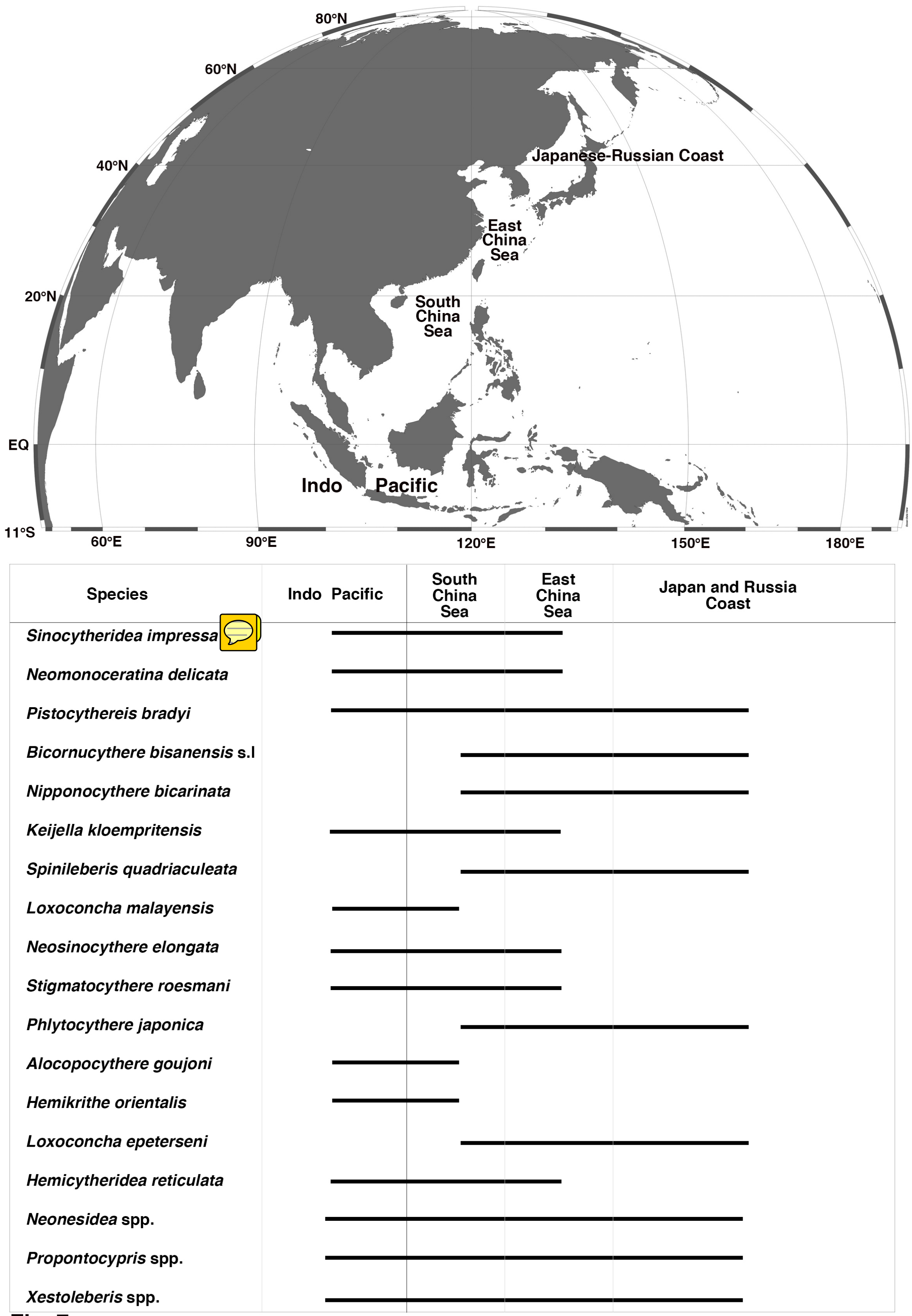

Fig. 7

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Table 1.

Parameter (Abbreviation)	Unit	Sampling Depth / Material	Season (AD. 1986-2013)
Chlorophyll-*a* (Chl)	µg/L	Surface water	All year
Water Depth (D)	m		All year
Dissolved Oxygen (DO)	mg/L	Bottom water	Summer[1]
Mud Content (MD)	%w/w (<63µm)	Bottom sediment	All year
Salinity (Sal)		Bottom water	All year
Turbidity (Tur)	NTU	Bottom water	All year
Summer Temperature (ST)	°C	Bottom water	Summer[1]
Winter Temperature (WT)	°C	Bottom water	Winter[2]
Copper (Cu)	mg/kg	Bottom sediment	All year
Lead (Pb)	mg/kg	Bottom sediment	All year
Zinc (Zn)	mg/kg	Bottom sediment	All year

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Table 2.

Model	Chl	D	DO	MD	Sal	Tur	WT	Pb	Zn	R	R^2	AICc	AW
Sinocytheridea impressa													
1	**0.33**		**-1.47**	**0.75**	**-9.13**					**0.34**	0.55	-37.29	0.27
2	**0.41**		**-1.48**		**-8.75**					**0.37**	0.50	-35.24	0.10
3			**-1.12**	**0.94**	**-10.30**					**0.44**	0.49	-34.78	0.08
Neomonoceratina delicata													
1					**3.77**	**0.34**			**0.41**	**-0.13**	0.48	-82.57	0.29
2			0.43		**5.02**	**0.31**			**0.39**	**-0.20**	0.50	-81.21	0.15
3					**3.47**	**0.33**		-0.20	**0.55**	**-0.12**	0.48	-79.32	0.06
Propontocypris spp.													
1	**-0.28**			**0.46**						**0.04**	0.20	-72.47	0.15
2	**-0.24**									**0.07**	0.13	-71.74	0.10
3	**-0.24**			**0.49**			-2.46			0.02	0.22	-70.76	0.06
Pistocythereis bradyi													
1		**-0.12**			**2.67**			**-0.21**		**-0.06**	0.61	-163.64	0.52
2		**-0.13**			**2.87**	0.04		**-0.20**		**-0.05**	0.61	-159.79	0.08
3		**-0.12**	0.07		**2.83**			**-0.21**		**-0.07**	0.60	-159.42	0.06
Bicornucythere bisanensis s.l.													
1		**-0.09**		**-0.23**						**0.02**	0.60	-137.80	0.12
2		**-0.08**								**-0.01**	0.56	-136.77	0.07
3				**-0.29**				**0.18**		0.00	0.58	-136.77	0.05
Keijella kloempritensis													
1		**0.06**						**-0.06**		**-0.02**	0.56	-202.12	0.12
2		**0.08**								**-0.02**	0.53	-201.51	0.09
3		**0.06**		0.09				**-0.08**		**-0.02**	0.58	-200.86	0.06
Nipponocythere bicarinata													
1	**-0.07**		**-0.12**							**0.03**	0.43	-200.57	0.11
2	**-0.09**									**0.03**	0.39	-200.38	0.10
3	**-0.09**	-0.03	**-0.16**							**0.04**	0.45	-199.30	0.06
Spinileberis quadriaculeata													
1	0.06					**-0.09**				**-0.04**	0.63	-183.88	0.10
2		**-0.05**								**0.02**	0.60	-182.94	0.06
3	**0.08**					**-0.09**	-0.75			**-0.04**	0.65	-182.66	0.05
Xestoleberis spp.													
1		**0.04**	**0.15**	**-0.11**		**-0.08**		**0.05**		**-0.02**	0.62	-225.55	0.09
2		**0.03**	**0.15**	**-0.09**		**-0.09**				**-0.02**	0.59	-225.29	0.08
3				**-0.09**		**-0.06**				**0.00**	0.52	-224.60	0.06

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Model	Chl	D	DO	MD	Sal	Tur	WT	Pb	Zn	R	R^2	AICc	AW
Loxoconcha malayensis													
1		**-0.03**	**-0.14**	**-0.12**						**0.03**	0.55	-229.55	0.10
2	**0.04**		**-0.13**	**-0.12**						**0.02**	0.55	-229.42	0.09
3		**-0.04**	**-0.14**	**-0.10**				-0.04		**0.03**	0.57	-228.47	0.06
Neonesidea spp.													
1	**-0.12**			**-0.25**					**0.19**	**0.05**	0.28	-149.00	0.09
2	**-0.11**		**0.33**	**-0.24**			-1.13		**0.20**	**0.05**	0.31	-147.86	0.05
3			0.21							0.02	0.08	-147.40	0.04
Neosinocythere elongata													
1	**-0.02**					**0.09**				**-0.03**	0.76	-244.70	0.09
2				**-0.06**		**0.08**				**-0.03**	0.76	-244.42	0.08
3						**0.09**				**-0.03**	0.74	-244.15	0.07
Stigmatocythere roesmani													
1								**-0.08**		**0.00**	0.23	-225.23	0.07
2					0.36			**-0.07**		**-0.02**	0.25	-224.06	0.04
3			**0.10**		**0.67**			**-0.07**		**0.30**	0.30	-224.03	0.04
Phlyctocythere japonica													
1		**0.04**								0.00	0.28	-238.60	0.19
2		**0.03**			0.33					-0.02	0.30	-237.01	0.09
3		**0.03**						-0.02		0.00	0.27	-235.62	0.04
Alocopocythere goujoni													
1					**0.21**					**-0.04**	0.68	-331.97	0.09
2		**-0.01**			**0.28**				**-0.01**	**-0.04**	0.71	-330.52	0.05
3		**-0.01**			**0.27**			**-0.02**		**-0.04**	0.71	-330.45	0.04
Hemikrithe orientalis													
1		**0.03**					**0.46**			0.00	0.19	-249.44	0.11
2		**0.03**	**0.07**							0.00	0.18	-248.67	0.07
3		**0.04**	0.06				**0.42**			0.00	0.23	-248.60	0.07
Loxoconcha epeterseni													
1		**0.03**			**-0.33**	**-0.03**				**0.01**	0.49	-288.61	0.11
2	**0.02**	**0.04**		**-0.04**	**-0.34**	**-0.04**				**0.00**	0.56	-287.76	0.07
3	0.02	**0.04**			**-0.34**	**-0.04**				0.00	0.51	-287.31	0.06
Hemicytheridea reticulata													
1		**-0.03**						**-0.04**		**0.01**	0.23	-270.79	0.14
2	0.02	**-0.02**						**-0.04**		0.01	0.26	-269.44	0.07
3	**0.03**							**-0.03**		0.00	0.19	-268.64	0.05

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Table 3.

Term	RI	Coeffiencient	Lower CI	Upper CI	Term	RI	Coeffiencient	Lower CI	Upper CI
Sinocytheridea impressa					***Keijella kloempritensis***				
R	1.00	0.36	-0.09	0.81	R	1.00	-0.02	-0.09	0.04
Sal	**0.99**	**-9.26**	**-14.61**	**-3.91**	**D**	**0.86**	**0.06**	**0.02**	**0.11**
DO	**0.91**	**-1.42**	**-2.48**	**-0.37**	Pb	0.58	-0.08	-0.17	0.01
MD	**0.75**	**0.82**	**0.07**	**1.57**	Sal	0.35	0.68	-0.21	1.58
Chl	**0.74**	**0.82**	**0.03**	**0.70**	MD	0.25	0.08	-0.05	0.21
WT	0.20	**0.82**	-2.34	8.89	Tur	0.24	0.05	-0.03	0.14
Zn	0.13	**0.82**	-0.68	0.51	Chl	0.22	-0.04	-0.11	0.03
Tur	0.11	**0.82**	-0.61	0.30	Zn	0.17	0.02	-0.11	0.14
D	0.11	**0.82**	-0.29	0.41	WT	0.14	0.33	-0.55	1.22
Pb	0.10	**0.82**	-0.62	0.46	DO	0.11	0.03	-0.14	0.19
Neomonoceratina delicata					***Nipponocythere bicarinata***				
R	1.00	-0.15	-0.42	0.12	R	1.00	0.02	-0.04	0.09
Zn	**0.94**	**0.41**	**0.11**	**0.70**	**Chl**	**0.92**	**-0.08**	**-0.14**	**-0.02**
Sal	**0.93**	**4.06**	**1.00**	**7.13**	DO	0.50	-0.14	-0.30	0.02
Tur	**0.84**	**0.33**	**0.06**	**0.59**	D	0.30	-0.03	-0.08	0.02
DO	0.33	0.45	-0.17	1.06	WT	0.25	-0.03	-0.08	0.02
Pb	0.17	-0.18	-0.67	0.30	Sal	0.24	0.51	-0.35	1.36
MD	0.14	0.25	-0.33	0.84	Tur	0.19	-0.04	-0.11	0.04
D	0.11	-0.01	-0.22	0.20	Zn	0.18	-0.04	-0.12	0.04
WT	0.11	-0.86	-4.32	2.60	Pb	0.13	-0.03	-0.11	0.06
Chl	0.09	0.00	-0.24	0.23	MD	0.10	0.00	-0.13	0.13
***Propontocypris* spp.**					***Spinileberis quadriaculeata***				
R	1.00	0.05	-0.19	0.30	R		-0.01	-0.10	0.07
Chl	**0.80**	**-0.26**	**-0.47**	**-0.04**	**Tur**	**0.66**	**-0.09**	**-0.17**	**0.00**
MD	0.58	0.50	-0.03	1.03	**Chl**	**0.54**	**0.06**	**0.00**	**0.13**
WT	0.29	-2.60	-6.48	1.28	D	0.45	-0.05	-0.10	0.01
Pb	0.19	-0.18	-0.55	0.20	WT	0.32	-0.76	-1.82	0.31
Sal	0.17	-1.48	-4.88	1.92	DO	0.19	0.10	-0.10	0.30
DO	0.15	-0.27	-0.99	0.45	MD	0.17	-0.07	-0.23	0.09
Zn	0.14	-0.03	-0.48	0.41	Pb	0.17	-0.05	-0.16	0.07
D	0.13	0.04	-0.17	0.26	Zn	0.14	0.03	-0.09	0.15
Tur	0.10	0.01	-0.29	0.32	Sal	0.13	0.11	-1.03	1.26
Pistocythereis bradyi					***Xestoleberis* spp.**				
R	1.00	-0.06	-0.15	0.04	R	1.00	-0.01	-0.06	0.05
Sal	**1.00**	**2.71**	**1.53**	**3.88**	**Tur**	**0.77**	**-0.07**	**-0.12**	**-0.01**
D	**1.00**	**-0.12**	**-0.19**	**-0.06**	**MD**	**0.66**	**-0.10**	**-0.19**	**0.00**
Pb	**0.97**	**-0.21**	**-0.32**	**-0.10**	**DO**	**0.63**	**0.13**	**0.00**	**0.26**
Tur	0.12	0.04	-0.07	0.15	D	0.42	0.03	-0.01	0.07
Zn	0.11	-0.05	-0.23	0.13	Pb	0.33	0.04	-0.02	0.11
DO	0.10	0.06	-0.18	0.31	Sal	0.27	0.46	-0.24	1.15
WT	0.10	0.33	-0.98	1.64	WT	0.19	-0.37	-1.06	0.31
Chl	0.09	0.02	-0.08	0.11	Zn	0.14	0.00	-0.09	0.08
MD	0.08	-0.01	-0.20	0.18	Chl	0.10	0.00	-0.05	0.05
***Bicornucythere bisanensis* s.l.**					***Loxoconcha malayensis***				
R	1.00	0.01	-0.11	0.12	R	1.00	0.02	-0.02	0.06
MD	0.63	-0.26	-0.52	0.00	**DO**	**0.87**	**-0.14**	**-0.25**	**-0.03**
D	**0.62**	**-0.08**	**-0.16**	**0.00**	**MD**	**0.85**	**-0.11**	**-0.20**	**-0.02**
Pb	0.38	0.14	-0.05	0.33	D	0.48	-0.03	-0.06	0.00
DO	0.20	0.17	-0.15	0.48	Chl	0.40	0.03	-0.01	0.08
Chl	0.19	0.06	-0.07	0.19	Pb	0.29	-0.04	-0.10	0.02
Tur	0.19	0.07	-0.08	0.22	WT	0.26	0.41	-0.21	1.03
Zn	0.16	-0.01	-0.28	0.25	Zn	0.20	-0.03	-0.10	0.04
Sal	0.12	-0.02	-1.86	1.82	Sal	0.15	-0.26	-0.91	0.39
WT	0.10	0.06	-1.80	1.92	Tur	0.11	-0.01	-0.07	0.05

Term	RI	Coeffiencient	Lower CI	Upper CI	Term	RI	Coeffiencient	Lower CI	Upper CI
***Neonesidea* spp.**					***Alocopocythere goujoni***				
R	1.00	0.02	-0.09	0.13	R	1.00	-0.03	-0.05	-0.02
DO	**0.72**	**0.30**	**0.02**	**0.57**	**Sal**	**0.78**	**0.22**	**0.03**	**0.41**
Zn	0.58	0.15	-0.01	0.31	D	0.46	-0.01	-0.02	0.00
MD	0.46	-0.23	-0.49	0.03	DO	0.43	-0.03	-0.07	0.01
Chl	0.42	-0.09	-0.21	0.02	Pb	0.31	-0.01	-0.03	0.01
WT	0.32	-1.13	-2.69	0.42	Zn	0.29	-0.01	-0.03	0.01
Tur	0.24	-0.09	-0.22	0.05	WT	0.24	0.13	-0.08	0.33
D	0.23	0.05	-0.04	0.15	Tur	0.18	0.01	-0.01	0.03
Pb	0.17	0.05	-0.13	0.24	MD	0.14	-0.01	-0.04	0.02
Sal	0.15	-0.60	-2.20	1.01	Chl	0.11	0.00	-0.01	0.01
Neosinocythere elongata					***Hemikrithe orientalis***				
R	1.00	-0.03	-0.07	0.00	R	1.00	0.00	-0.04	0.03
Tur	**1.00**	**0.08**	**0.04**	**0.13**	**D**	**0.77**	**0.03**	**0.00**	**0.05**
MD	0.33	-0.05	-0.13	0.02	WT	0.46	0.43	-0.07	0.93
Chl	0.30	-0.02	-0.05	0.01	DO	0.44	0.08	-0.02	0.17
WT	0.26	-0.33	-0.85	0.18	Sal	0.30	0.37	-0.17	0.90
Zn	0.21	-0.02	-0.06	0.02	Pb	0.22	-0.03	-0.08	0.02
Pb	0.19	-0.02	-0.07	0.02	Tur	0.17	0.02	-0.03	0.07
D	0.12	0.00	-0.03	0.03	Chl	0.14	-0.01	-0.05	0.03
DO	0.12	-0.02	-0.11	0.07	Zn	0.11	0.00	-0.05	0.05
Sal	0.10	0.04	-0.40	0.49	MD	0.10	-0.01	-0.08	0.07
Stigmatocythere roesmani					***Loxoconcha epeterseni***				
R	1.00	-0.01	-0.07	0.05	R	1.00	0.00	-0.02	0.03
Sal	0.61	0.62	-0.04	1.27	**D**	**0.94**	**0.03**	**0.00**	**0.05**
Pb	**0.61**	**-0.06**	**-0.12**	**0.00**	**Tur**	**0.76**	**-0.03**	**-0.06**	**0.00**
Tur	0.37	0.04	-0.01	0.10	Sal	0.53	-0.30	-0.62	0.02
Zn	0.31	-0.05	-0.11	0.02	MD	0.38	-0.04	-0.08	0.01
DO	0.31	0.09	-0.04	0.22	Chl	0.30	0.02	-0.01	0.04
MD	0.23	-0.06	-0.16	0.04	DO	0.26	0.04	-0.02	0.10
Chl	0.19	-0.02	-0.07	0.02	Pb	0.17	0.01	-0.02	0.05
WT	0.19	0.35	-0.33	1.02	WT	0.13	-0.13	-0.48	0.22
D	0.14	-0.01	-0.05	0.04	Zn	0.12	0.01	-0.03	0.04
Phlyctocythere japonica					***Hemicytheridea reticulata***				
R	1.00	-0.01	-0.05	0.03	R	1.00	0.01	-0.02	0.03
D	**0.80**	**0.03**	**0.01**	**0.06**	**Pb**	**0.67**	**-0.04**	**-0.07**	**0.00**
Sal	0.42	0.46	-0.10	1.02	**D**	**0.66**	**-0.02**	**-0.04**	**0.00**
Pb	0.21	-0.03	-0.08	0.03	Chl	0.49	0.03	0.00	0.05
Zn	0.20	-0.02	-0.07	0.03	WT	0.24	-0.24	-0.64	0.16
WT	0.15	0.22	-0.38	0.81	MD	0.23	-0.03	-0.09	0.02
DO	0.14	0.03	-0.08	0.15	Zn	0.17	-0.01	-0.06	0.05
Tur	0.12	0.00	-0.05	0.05	DO	0.13	0.02	-0.05	0.10
Chl	0.12	0.00	-0.04	0.05	Tur	0.13	-0.01	-0.05	0.03
MD	0.11	0.00	-0.09	0.08	Sal	0.11	-0.05	-0.43	0.34

Biogeosciences Discuss., https://doi.org/10.5194/bg-2018-405
Manuscript under review for journal Biogeosciences
Discussion started: 15 October 2018

Table 4.

Environmental Variables	GVIF	Df	$GVIF^{1/2Df}$
Chl	7.40	1	2.72
D	6.41	1	2.53
DO	4.49	1	2.12
MD	3.72	1	1.93
Sal	9.43	1	3.07
Tur	6.67	1	2.58
Pb	9.98	1	3.16
Zn	10.05	1	3.17
WT	2.39	1	1.55
R	1266.30	9	1.49

Biogeosciences Discuss., https://doi.org/10.5194/bg-2018-405
Manuscript under review for journal Biogeosciences
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Table 5

Taxa	Chl	D	DO	MD	Sal	Tur	WT	Pb	Zn	R
Sinocytheridea impressa	+		-	+	-					
Neomonoceratina delicata					+	+			+	
Pistocythereis bradyi		-			+			-		
Bicornucythere bisanensis s.l.		-								
Keijella kloempritensis		+								
Nipponocythere bicarinata	-									
Spinileberis quadriaculeata	+					-				
Loxoconcha malayensis			-	-						
Neosinocythere elongata						+				
Stigmatocythere roesmani								-		
Phlyctocythere japonica		+								
Alocopocythere goujoni					+					
Hemikrithe orientalis		+								
Loxoconcha epeterseni		+				-				
Hemicytheridea reticulata		-						-		
Neonesidea spp.			+							
Propontocypris spp.	-									
Xestoleberis spp.			+	-		-				

Biogeosciences

Research Paper

Baseline for ostracod-based northwestern Pacific and Indo-Pacific shallow-marine paleoenvironmental reconstructions: ecological modeling of species distributions

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[2]Swire Institute of Marine Science, The University of Hong Kong, Cape d'Aguilar Road, Shek O, Hong Kong SAR, China

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Abstract:

Fossil ostracods have been widely used for Quaternary paleoenvironmental reconstructions especially in marginal marine environments (e.g. for water depth, temperature, salinity, oxygen levels, pollution). But our knowledge of indicator species autoecology, the base of paleoenvironmental reconstructions, remains limited and commonly lacks robust statistical support and comprehensive comparison with environmental data. We analysed marginal marine ostracod taxa at 52 sites in Hong Kong for which comprehensive environmental data are available. We applied linear regression models to reveal relationships between species distribution and environmental factors for 18 common taxa (mainly species, a few genera) in our Hong Kong dataset, and identified indicator species of environmental parameters. For example, *Sinocytheridea impressa*, widely distributed euryhaline species throughout the East and South China Seas and the Indo-Pacific, indicates eutrophication and botttom-water hypoxia, *Neomonoceratina delicata*, widely known species from nearshore and estuarine environments in the East and South China Seas, and the Indo-Pacific, indicates heavy-metal pollution and increased turbidity. The 18 taxa used for this study are widely distributed geographically and divided into Widespread (throughout the northwestern Pacific and Indo-Pacific regions), Temperate [South China Sea to Russia (Sea of Japan coast) and Japan], Subtropical (Indo-Pacific to the East China Sea), Tropical (Indo-Pacific and South China Sea), and Globally Distributed Groups. With statistical support from ecological modeling and comprehensive environmental data, these results provide a robust baseline for

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ostracod-based Quaternary-Anthropocene paleoenvironmental reconstructions in the tropical–extratropical northwestern Pacific and Indo-Pacific widely.

Key words: Autoecology, Distribution modeling, Indicator species, Ostracoda, Paleoenvironmental reconstruction, Proxy.

Key points

1. We provide a robust baseline for ostracod-based (microscopic Arthropods) paleoenvironmental reconstructions from Quaternary and Anthropocene marginal marine sediments.
2. The studied species have wide distributions over the tropics and extratropics of the northwestern Pacific and Indo-Pacific.
3. Ecological modeling established reliable indicator ostracod species for paleoenvironmental reconstructions.

1. Introduction

Because of their small size, high abundance and excellent fossil record, fossil ostracods (microcrustaceans), have been widely used to reconstruct Quaternary environmental conditions including water-depth, salinity, temperature, oxygen, and pollution, especially in marginal marine sediments (Boomer & Eisenhauer, 2002; Cronin, 2015; Frenzel & Boomer, 2005; Horne et al., 2012; Ruiz et al., 2005). In the northwestern Pacific and Indo-Pacific there are numerous deltas (Woodroffe et al., 2006) hosting accumulated Holocene marine sediments. Many studies have

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reconstructed the depositional environments of these sediments (Alberti et al., 2013; Dong et al., 2012; Irizuki et al., 2015b; Tanaka et al., 2011; Yasuhara & Seto, 2006; Yasuhara et al., 2005; Zhou et al., 2015). Due to high sedimentation rates (> 1 cm per year), fossil ostracods allow the high-resolution reconstruction of human-induced environmental changes (pollution, eutrophication, bottom oxygen depletion) over the past century (Irizuki et al., 2011; Irizuki et al., 2015a; Irizuki et al., 2018; Yasuhara et al., 2003; Yasuhara et al., 2007).

Many have evaluated the autoecology of ostracod indicator species as the basis for paleoenvironmental reconstructions (Hazel, 1988; Irizuki et al., 2003; Ozawa et al., 2004; Stepanova et al., 2003; Wang et al., 1988; Yasuhara & Seto, 2006; Zhao, 1984; Zhao & Wang, 1988a, 1988b). Yet these studies tend to focus on only one or a few targeted environmental factor(s) and lack rigorous statistical evaluation, particularly statistical modeling, a common approach in contemporary ecology. This is probably due to the fact that comprehensive environmental datasets are often unavailable and an ecological modeling approach (especially regression modeling and model selection) has not been common in this field of micropaleontology.

Hong Kong constitutes an ideal location for a marine ecological modeling approach in the northwestern Pacific and Indo-Pacific regions because of extensive and intensive marine environmental monitoring program and subtropical location where tropical and temperate species coexist. This program provides robust datasets for ecological modeling, and the subtropical location allows the investigation of species with different latitudinal and geographical distributions. We employed regression modeling of Hong Kong shallow-marine ostracod species to show

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statistical relationships between species abundance, distribution and environmental factors. This study allows the autoecology and statistical evaluation of common tropical and extratropical species, providing a baseline for ostracod-based shallow-marine paleoenvironmental reconstructions of the northwestern Pacific and Indo-Pacific regions.

2. Study area

Hong Kong is situated at the southeastern corner of the Pearl River (Zhujiang) Delta, and has an area of 2500 km^2 (Fig. 1), at 22° 12.021' to 22° 33.817' N latitude, 113° 53.388' to 114° 26.920' E longitude. It is an ideal location to study natural and/or anthropogenic impacts on benthic communities due to its complex hydrology and long history of human influence. Western Hong Kong is affected by input from the Pearl River, particularly during the summer heavy rainfall (Morton & Wu, 1975), when surface water salinity is strongly influenced by rainfall. Eastern Hong Kong waters are mainly marine and derived from the South China Sea. As one of the most urbanized coastal areas in the world, human activities including rapid industrialization, sewage discharge, trawling, dredging and land reclamation have led to a deteriorated marine benthic ecosystem (Blackmore, 1998; Hodgkiss & Yim, 1995; Hong et al., 2017; Hu et al., 2008; Morton, 1996; Morton & Blackmore, 2001; Owen & Sandhu, 2000; Shin, 1977; Tanner et al., 2000).

3. Materials and Methods

3.1. Samples and laboratory procedure

In January and July of 2011 we used a Van Veen Grab to collect 100 ml of sediment from the uppermost centimeter of the sea floor from 52 sites in Hong Kong marine

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waters (Fig. 1; Supplement A), 41 of which are in open waters and 11 in typhoon shelter sites. Typhoon shelters are semi-enclosed areas of water designed to protect moored vessels in extreme weather (Environmental Protection Department, 2011). All sites are included in the Hong Kong EPD marine water and sediment quality monitoring program, which has been conducted monthly since 1986 (for water) and biannually (for sediment), providing comprehensive environmental data for all stations (see below).

Sediments were wet-sieved over a 63 µm mesh sieve and air dried or oven-dried at 40 °C. The residue was dry-sieved over a 150 µm mesh sieve, and ostracod specimens larger than 150 µm were picked; smaller individuals are mostly early instar juveniles that are often not preserved (because their shells are usually thin and delicate) or difficult to identify (see Yasuhara et al., 2009 and Yasuhara et al., 2017 for more details). In samples containing fewer than 200 specimens, we picked all individuals. If there were more than 200 specimens, we picked ostracods from a split. We identified each counted specimen to species level when possible. We considered both an entire carapace or a single valve as one individual for counting.

3.2 Environmental Variables

We selected parameters from the EPD monitoring program (Table 1) for our regression modeling (see below), including surface productivity (Chlorophyll-a, Chl; Fig. 2), water depth (D; Fig. 2), bottom water dissolved oxygen (DO; Fig. 2), bottom water salinity (Sal; Fig. 2), turbidity (Tur; Fig. 2), summer bottom water temperature (ST – June to September average; Fig. 2), winter bottom water temperature (WT – November to Feburary average; Fig. 2), mud content (MD; Fig. 2), and heavy metal concentration (Cu, Zn, and Pb; Fig. 3). These parameters are known to control

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ostracod faunal properties (Cronin, 2015; Cronin & Vann, 2003; Hazel, 1988; Ikeya & Shiozaki, 1993; Irizuki et al., 2005; Irizuki et al., 2015a; Irizuki et al., 2018; Ruiz et al., 2005; Yasuhara et al., 2007; Yasuhara et al., 2012b). We used averages over the entire monitoring period (1986–2011), because the ostracods in this study were mostly dead shells, thus the samples should be considered time averaged. Bottom water DO is the average of the summer season (June–September), due to the likely importance of summer bottom water oxygen depletion.

4. Regression modeling

Multiple linear regression modeling was used to determine the relationship between common ostracod species (relative abundance of each species) and environmental parameters (Supplement B). All environmental parameters were log-transformed and zero centered. Salinity outliers (salinity <25: DS2 and DS3) and samples with low abundance (<50 specimens: ES5, MS7, VS21, VS5 & VS6) were removed from the models.

The best-fitting models were selected based on Akaike's Information Criterion (AICc) for small sample size, in which the lower score indicates the better model support considering both goodness-of-fit and model complexity (Anderson & Burnham, 2002). Akaike weights were used to summarize proportional support for all candidate models (Anderson et al., 2000) (Table 2). We considered parameter estimates averaged over models, proportional to the support that each model received (Anderson et al., 2000) (Table 3). This approach accounts for the uncertainty in model selection and thus leads to appropriately broader confidence intervals than obtained by relying only on the single, best-supported model. The relative importance of various predictor variables was measured by the sum of Akaike weights of models that included the variables in question (Brunham & Anderson, 2002).

We explored linear dependencies by computing variance inflation factors (VIF) (Legendre & Legendre, 1998) and pairwise correlations between predictor variables to assess whether multicollinearity was likely to influence regression results (Yasuhara et al., 2012b). The degree of freedom is more than one for the geographic region variable (see below), thus we computed generalized variance inflation factors (GVIF). For continuous variables, GVIF (Table 4) is the same as VIF, but for categorical variables, GVIF has degrees of freedom (Df) equal to the number of coefficients associated with it (Hendrickx et al., 2004). Thus, we used $GVIF^{1/2df}$ to make GVIF values comparable among those with different Df. VIF >20 is usually indicative of high collinearity (Legendre & Legendre, 1998). Thus we calculated an equivalent threshold of 4.47 (equal to √20) for $GVIF^{1/2df}$ to assess conlinearity. Also, adjusted R^2 >0.8 indicates a strong correlation of variables (Hoffman, 2015). In all datasets, summer temperature (ST) and copper (Cu) were highly correlated (R^2=0.8217), and the GVIFs of ST and Cu are >20, indicating that these correlations may influence regression results. Thus, we re-ran the linear regression modeling without ST and Cu. The new GVIFs of all variables were under 4.47 (Table 4).

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We considered the degree of spatial autocorrelation in model residuals by the calculation of Moran's *I* index for the five best models. The neighborhood size was set as 2, 5, 10, 20 and 50 km. We found significant spatial autocorrelation in model residuals for many cases, thus we forced the geographic region variable (R) (Water Control Zones defined by EPD) to be included in all models. After this treatment, spatial autocorrelation was detected only in a few models for *Propontocypris* spp., *Stigmatocythere roesmani*, and *Hemikrithe orientalis*.

The multiple linear regression model analyses were implemented in R programming language (R Core Team, 2016). We used 'M$_{U}$MI$_{N}$' (Bartoń, 2013) for model averaging and 'SPDEP' (Bivand & Piras, 2015) to measure spatial autocorrelation.

5. Results and discussions

The comprehensive ostracod dataset for the 52 sites and the environmental variables enabled us to elucidate distribution patterns of common ostracod taxa and their related environmental factor(s). We identified 151 species belonging to 76 genera (Supplement A). Among them, 18 common taxa (mainly species, a few genera) of *Pistocythereis bradyi*, *Bicornucythere bisanensis* s.l., *Nipponocythere bicarinata*, *Spinileberis quadriaculeata*, *Phlyctocythere japonica*, *Loxoconcha epeterseni*, *Sinocytheridea impressa*, *Neomonoceratina delicata*, *Keijella kloempritensis*, *Neosinocythere elongata*, *Stigmatocythere roesmani*, *Hemicytheridea reticulata* *Loxoconcha malayensis*, *Alocopocythere goujoni*, *Hemikrithe orientalis*, *Propontocypris* spp., *Neonesidea* spp. and *Xestoleberis* spp. (Supplement B) were used for regression modelling, and their relative abundances (to the total ostracod abundance in a sample) show a significant relation with environmental parameters. The best three regression models are presented in Table 2 and the model-averaged parameter estimates in Table 3. A small percentage of specimens of phytal genera (e.g., *Xestoleberis* spp., *Neonesidea* spp.) were contained in each sample, which are basically allochthonous specimens in bottom sediments transported from surrounding phytal environments. The value of allochthonous species to environmental interpretation is limited, however most ostracod specimens in each sample are composed of benthic, muddy sediment dwellers which are considered autochthonous.

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Ostracods were divided into four groups based on their geographic distributions, including Widespread Group; Temperate Group; Subtropical Group; and Tropical Group; and Globally distributed Group (Fig. 4).

a. Widespread Group

Only one species *Pistocythereis bradyi* constitutes Widespread Group. *Pistocythereis bradyi* is widely distributed throughout the marginal marine environments of Japan, the East and South China Seas, and the Indo-Pacific (Fig. 4). Relative abundance of *P. bradyi* was highly correlated with salinity (positive), water depth (negative) and Pb (negative) (Tables 2 and 3). This indicates the species prefers relatively shallow environments with high salinity (Figs. 2 and 5). In the Pearl River Delta and shallow South China Sea (Fig. 4), *P. bradyi* is dominant along the inner continental shelf at water depths <100 m (mostly common between 10–50 m), and at salinities from 30–40 (Li, 1985; Zhao & Wang, 1990; Zhao et al., 1986). *Pistocythereis bradyi* is a typical middle muddy bay species in Japan (Irizuki et al., 2006; Yasuhara & Irizuki, 2001; Yasuhara & Seto, 2006), and known from open bays such as Gamagyang Bay in Korea (Abe, 1988) and Malacca Strait (Whatley & Zhao, 1988b). In these studies, *P. bradyi* prefers relatively high salinity and deeper water in the inner continental shelf (Tables 2 and 3). Our data agree as to the preference for high salinity, but inconsistent with the literature regarding shallower water depths. Salinity may be more important than depth, but the restricted depth range of our sites (≤35 m) may also be a reason for this inconsistency. Our results indicate that *P. bradyi* is sensitive to metal pollution.

b. Temperate Group

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Five species including *Bicornucythere bisanensis* s.l., *Nipponocythere bicarinata*, *Spinileberis quadriaculeata*, *Phlyctocythere japonica* and *Loxoconcha epeterseni* are distributed from Japan-Russian Coast to South China Sea.

Bicornucythere bisanensis s.l. is very common in most samples, the relative abundance of which was significantly correlated with water depth (negative) (Tables 2 and 3) and this species prefers shallower environments (Figs. 2 and 5). In Chinese and Japanese coastal areas, *B. bisanensis* s.l. is abundant in brackish water (salinity: 20–30) at depths less than 10 m (Ikeya & Shiozaki, 1993; Irizuki et al., 2006; Zhao et al., 1986). Our results confirm this preference for shallow depths. In Japan, *Bicornucythere bisanensis* is tolerant of anthropogenic impacts, especially eutrophication and the resulting bottom water hypoxia (Irizuki et al., 2003; Irizuki et al., 2011; Irizuki et al., 2015a; Irizuki et al., 2018; Yasuhara et al., 2003; Yasuhara et al., 2007; Yasuhara et al., 2012a). We did not see a significant relation between relative abundance and metal concentration, productivity, or dissolved oxygen. Possibly, the more dominant presence of *S. impressa* and *N. delicata,* that are neither dominant or distributed throughout most of Japan, could explain this difference. These species may have a higher tolerance than *B. bisanensis* s.l.. Another explanation may be that different morphotypes have different ecological preferences (Abe, 1988), and only Form A is known to be tolerant to eutrophication and bottom-water oxygen depletion (Irizuki et al., 2011; Irizuki et al., 2015a; Irizuki et al., 2018; Yasuhara & Yamazaki, 2005; Yasuhara et al., 2007). Form A is less abundant in Hong Kong, and due to the difficulty of juvenile identification, we did not divide *B. bisanensis* into morphotypes. *Bicornucythere bisanensis* s.l. is widely distributed throughout marginal marine environments around Japan, Russia (Sea of Japan coast), and the East and South China Seas (Fig. 4).

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Relative abundance of *N. bicarinata* correlated with productivity (negative) (Tables 2 and 3). This is a typical middle bay species in Japan (Irizuki et al., 2006), abundant on muddy substrates at water depths >10 m (Yasuhara & Seto, 2006; Yasuhara et al., 2005). We found *N. bicarinata* to be sensitive to eutrophication, prefering lower productivity (Figs 2 and 5). This species is know from marginal marine environments around Japan and the East and South China Seas (Fig. 4).

Relative abundance of *S. quadriaculeata* correlated to productivity (positive), and turbidity (negative) (Tables 2 and 3). This is a typical inner muddy bay species in Japan (Irizuki et al., 2006), which prefers silty substrates in brackish waters, at salinities from 20–30, and water depths of 2–7 m (Ikeya and Shiozaki, 1993). This study shows a preference for waters with higher productivity but relatively low turbidity (Tables 2 and 3), so that the species is abundant in Tolo Harbour (higher productivity, lower turbidity) but not in Deep Bay (higher turbidity) (Figs. 2 and 5). *Spinileberis quadriaculeata* is not tolerant to seasonal anoxia or oxygen depletion (0–1 mg/L) in Uranouchi Bay, Japan (Irizuki et al., 2008), but we do not find a significant correlation with dissolved oxygen content, probably due to the relatively high bottom-water oxygen content (2.96–6.84 mg/L) in Hong Kong (Fig. 2; Supplement B). *Spinileberis quadriaculeata* is widely distributed in marginal marine environments around Japan, Russia (Sea of Japan coast), and the East and South China Seas (Fig. 4).

Relative abundance of *P. japonica* correlated with water depth (positive) (Tables 2 and 3). This species is known from relatively deeper waters (>40 m) in the East China Sea (Ishizaki, 1981; Wang et al., 1988). At our sites, it has its greatest abundance at the deeper southern sites (Fig. 5). *Phlyctocythere japonica* is distributed around Japan (Yasuhara et al., 2002) and the East and South China Seas (Fig. 4).

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Similarly to *P. japonica*, relative abundance of *L. epeterseni* correlated with water depth (positive), and turbidity (negative) (Tables 2 and 3). It occurs in the southern and eastern, deeper and less turbid regions of Hong Kong waters, but the trend is not very clear (Figs 2 and 5). This species is also known from the deeper parts of Osaka Bay (Yasuhara & Irizuki, 2001) and marginal marine environments around Japan (Ishizaki, 1968), the East China Sea (Yang et al., 1982), and the South China Sea (Cao, 1998) (Fig. 4). This species is reported as *Loxoconcha modesta* in Hou & Gou (2007), and also has been misidentified as *Loxoconcha viva* and *Loxoconcha sinensis* (Hou & Gou, 2007). Ishizaki (1968) described *Loxoconcha laeta* and *Loxoconcha modesta*, but these are the females and males of the same species (Ikeya et al., 2003). Ishizaki (1981) gave the new species names *Loxoconcha epeterseni* and *Loxoconcha tosamodesta* for *Loxoconcha laeta* and *Loxoconcha modesta*, respectively, because these names were junior homonyms. Since *Loxoconcha laeta* (= *epeterseni*) appears earlier than *Loxoconcha modesta* (=*tosamodesta*) in the original description (Ishizaki, 1968), we use the name *Loxoconcha epeterseni* for this species (e.g., see Ikeya et al., 2003).

c. Subtropical Group

Six species including *Sinocytheridea impressa, Neomonoceratina delicata, Keijella kloempritensis, Neosinocythere elongata, Stigmatocythere roesmani* and *Hemicytheridea reticulata* are reported from the East China Sea to Indo-Pacific area.

Sinocytheridea impressa [=*Sinocytheridea latiovata*; see Whatley and Zhao (1988a)] is the most dominant species, the relative abundance of which was significantly correlated with salinity (negative), dissolved oxygen (negative), mud content (positive) and productivity (positive) (Tables 2 and 3). This species is

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noticeably dominant in areas characterized by a muddy bottom including northern Mirs Bay, Port Shelter and coastal Southern Waters (Fig. 5). It is also abundant in Tolo Harbour, an area known for its summer hypoxia and eutrophication (Hu et al., 2001; Sin & Chau, 1992). These results are consistent with previous studies indicating that *S. impressa* is dominant in low salinity, nutrient-rich and turbid estuaries (Irizuki et al., 2005; Tanaka et al., 2011), but we did not see a significant relation with turbidity (Tables 2 and 3). *Sinocytheridea impressa* is known as a euryhaline species widely distributed throughout the East and South China Seas [abundant in water depths of <20 m; Whatley and Zhao (1988a)], and the Indo-Pacific (Fig. 4).

Neomonoceratina delicata (=*Neomonoceratina crispata*; see Hou & Gou, 2007) is very common in most of the samples, and the relative abundance significantly correlates with Zn (positive), salinity (positive) and turbidity (positive) (Tables 2 and 3). *Neomonoceratina delicata* is a nearshore species, abundant at depths less than 30 m, at relatively high salinities (>30; Zhao and Wang, 1988). It prefers the higher salinity waters in Hong Kong (Figs. 2 and 5; Tables 2 and 3) and in view of its positive correlation with Zn and turbidity, is likely tolerant to human-induced environmental stress such as pollution and eutrophication. This species is widely known from nearshore and estuarine environments in the East and South China Seas, and the Indo-Pacific (Fig. 4).

The relative abundance of *K. kloempritensis* correlated only with water depth (positive) (Fig. 6; Tables 2 and 3). Widely known from the tropical Indo-Pacific region, *K. kloempritensis* is abundant along the inner continental shelf of the South and East China Seas (Fig. 4), at water depths ranging from 20–50 m and salinity close to normal marine (Zhao & Wang, 1990). Our modelling results are consistent with this, showing a preference for the relatively deeper waters in our study (Tables 2 and

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3). Thus, this species is probably useful for reconstructing past sea-level changes in the broad tropical and subtropical Indo-Pacific and northwestern Pacific regions as a deeper water indicator.

Relative abundance of *N. elongata* correlated only with turbidity (positive) (Tables 2 and 3). This species occurs along the entire coast of China (Fig. 4) in marginal marine, especially estuarine environments shallower than 20 m (Dong et al., 2012; Hou & Gou, 2007; Liu et al., 2013; Liu et al., 2017; Zhao & Whatley, 1993) (Fig. 4). Known from the Indo-Pacific region, our modeling results and previous studies indicate consistently that *N. elongata* prefers shallow, turbid waters like Deep Bay and the Pearl River Estuary (Figs 2 and 6).

The relative abundance of both *S. roesmani* and *H. reticulata* correlated with Pb (negative) (Tables 2 and 3), thus they are sensitive to metal pollution (but note the significant autocorrelation with the modeling result of *S. roesmani*) and absent in areas with high metal concentrations, e.g., Tolo and Victoria Harbours (Fig. 3, 6). Relative abundance of *H. reticulata* also correlated with water depth (negative) (Tables 2 and 3). This species is abundant in Tolo Harbour and the inner part of Mirs Bay (Fig. 6), at shallow depths, and is also consistently found in very shallow waters from the Indo-Pacific (Zhao & Whatley, 1989). Their metal-pollution sensitivity is contradictory because they occur in Tolo and Victora Harbours, both polluted regions of Hong Kong, and further research is needed to better understand these results (Figs 2 and 6). They occur in the East and South China Seas and the Indo-Pacific region (Fig. 4).

d. Tropical Group

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Three species including *Loxoconcha malayensis*, *Alocopocythere goujoni* and *Hemikrithe orientalis* are distributed from the South China Sea to the Indo-Pacific.

Relative abundance of *L. malayensis* correlated with dissolved oxygen (negative) and mud content (negative) (Tables 2 and 3). It is a typical tropical species known from the Indo-Pacific and the South China Sea (Fig. 4). We did not find a correlation with temperature, likely due to the small range of variation of bottom water temperatures in Hong Kong (winter temperature: 19.10–21.49°C). This species prefers coarse sediments and is resistant to low oxygen content (Table 2 and 3), as seen by its abundance in Victoria Harbour (Figs. 2 and 6).

Relative abundance of both *A. goujoni* and *H. orientalis* correlated with natural factors only. *Alocopocythere goujoni* correlated with salinity (positive) (Tables 2 and 3) and occurs not only in Mirs Bay where the salinity is higher, but also in Deep Bay and North Western Waters where the salinity is lower than in other areas (Figs 2 and 6). The Deep Bay and North Western Waters are shallow and have relatively low oxygen content. The modeling result of this species shows a marginally insignificant but negative relationship to oxygen content and water depth with moderately high relative importance (Table 3). We explain this inconsistency by considering their preference for higher salinity and shallow water depths, and also their resistance to low oxygen conditions, but further research is needed to know their autoecology with better confidence. Relative abundance of *H. orientalis* correlated with water depth (positive) (Tables 2 and 3; but note the significant autocorrelation with the modeling result of this genus), and it is more abundant in deeper waters including southern Mirs Bay (Fig. 6). It is known from depths of 20–50 m in the South China Sea (Zhao & Wang, 1988a), and reported from tropical Indo-Pacific marginal marine environments (Fig. 4). Our regression modeling consistently shows a

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positive relationship between relative abundance and winter temperatures, with moderately high relative importance, although the correlation is marginally insignificant (Table 3).

e. Globally Distributed Group

Propontocypris is known as a cosmopolitan genus. The relative abundance of *Propontocypris* spp. significantly correlated with productivity (negative) (Tables 2 and 3). This negative correlation with productivity (but note a significant autocorrelation with the modeling result of this genus) indicates that the genus prefers less eutrophic waters (Fig. 6). *Propontocypris* is a good swimmer (Maddocks, 1969), and thus may have an advantage in obtaining food in relatively food-limited environments.

Phytal genera including *Neonesidea* spp. and *Xestoleberis* spp. have global distribution and are correlated with various environmental factors. The relative abundance of *Neonesidea* spp. correlated with dissolved oxygen (positive), as expected for a phytal species (Smith & Kamiya, 2002; Yamada, 2007) (Table 2 and 3; Fig 7). Similarly, phytal (Irizuki et al., 2008; Sato & Kamiya, 2007; Yasuhara et al., 2002) *Xestoleberis* spp. correlated with dissolved oxygen (positive), turbidity (negative) and mud content (negative) (Table 2 and 3; Fig. 7). This taxon's habitat preference including clear water, coarse sediment, and high oxygen content are reflected in our modeling. As mentioned above, the value of allochthonous phytal species to environmental interpretation is limited, but they broadly reflect adjacent phytal environments.

Summary

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Benthic ostracods from Hong Kong marginal marine waters studied here include widespread (i.e., one species distributed throughout the northwestern Pacific Indo-Pacific region), temperate (i.e., five species distributed from the South China Sea to Japan and Russia), subtropical (i.e., six species distributed from the Indo-Pacific to the East China Sea), and tropical (i.e., three species distributed in the Indo-Paficic and South China Sea) species and three globally distributed genera (Fig. 4). We provide a robust baseline of autoecology for these common ostracod taxa based on rigorous statistical modeling using comprehensive environmental data. We established reliable indicator forms for water depth, mud content, salinity, turbidity, dissolved oxygen, heavy metal pollution (Pb and Zn) and eutrophication (chlorophyll-a) (Table 5). Thus our results are applicable for future ostracod-based paleoenvironmental studies in a wide range of localities from the tropics to the extratropics, and from the Indian Ocean to the northwestern Pacific. We established pollution and eutrophication indicator species in tropical environments for the first time. Anthropocene paleoenvironmental and paleoecological studies in the tropics are urgently needed because (1) the tropics are seriously under-studied (Wilkinson et al., 2014; Yasuhara et al., 2012a), (2) tropical environments and ecosystems are vulnerable and sensitive to human influences (Jackson et al., 2001; Pandolfi et al., 2003), and (3) Indo-Pacific tropical environments have been seriously degraded by the human activity of rapidly developing countries (Bellwood et al., 2004; Jackson, 2008; Knowlton & Jackson, 2008). Our results provide useful and reliable tools for tropical Anthropocene research in the broad Indo-Pacific region.

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Fig. 1 Locality map showing the 52 sampling sites across Hong Kong, including 41 open water sites (blue dots) and 11 typhoon shelter sites (red open dots). From west to east, DS: Deep Bay; NS: North Western waters; SS: Southern waters; VS: Victoria Harbour; ES: Eastern Buffer; JS: Junk Bay; TS: Tolo Harbour; PS: Port Shelter; MS: Mirs Bay.

Fig. 2 Spatial distribution of environmental parameters in Hong Kong. Mean surface-water chlorophyll-a concentration; water depth; summer (June to September) bottom-water dissolved oxygen content; mean bottom-water salinity; mean turbidity; mean summer (June to September) bottom-water temperature; mean winter (November to February) bottom-water temperature; and mean mud content. All are averaged values of the data obtained during 1986–2013 (Table 1).

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Fig. 3 Spatial distribution of environmental parameters in Hong Kong. Mean copper (Cu) concentration, mean lead (Pb) concentration, and mean zinc (Zn) concentration in surface sediments. All are averaged values of the data obtained during 1986–2013 (Table 1).

Fig. 4 Geographical distributions of the 18 taxa in the northwestern Pacific and Indo-Pacific regions, including *Pistocythereis bradyi*, *Bicornucythere bisanensis* s.l., *Nipponocythere bicarinata*, *Spinileberis quadriaculeata*, *Phlyctocythere japonica*, *Loxoconcha epeterseni*, *Sinocytheridea impressa*, *Neomonoceratina delicata*, *Keijella kloempritensis*, *Neosinocythere elongata*, *Stigmatocythere roesmani*, *Hemicytheridea reticulata* *Loxoconcha malayensis*, *Alocopocythere goujoni*, *Hemikrithe orientalis*, *Propontocypris* spp., *Neonesidea* spp. and *Xestoleberis* spp.. The following references

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were used mainly to determine the geographical distributions of the species: Al Jumaily and Al-Sheikhly (1999); Dewi (1997); Dong et al. (2012); Fauzielly et al. (2013); Gu et al. (2017); Hong et al. (2017); Hou and Gou (2007); Hussain et al. (2004); Hussain et al. (2010); Hussain and Mohan (2000, 2001); Irizuki et al. (2006); Irizuki et al. (2009); Iwatani et al. (2014); Jie et al. (2013); Li (1985); Mostafawi (1992); Nishath et al. (2017); Noraswana et al. (2014); Pugliese et al. (2006); Schornikov et al. (2014); Tanaka et al. (2009); Tanaka et al. (2011); Wang et al. (1988); Wang and Zhang (1987); Wang and Zhao (1985); Zhao (1984); Zhao and Wang (1988a, 1988b, 1990); Zhao and Whatley (1993); Zhou et al. (2015). Note that *Sinocytheridea impressa* is know to be distributed in Japan, but their Japanese distribution is very limited in certain areas of the southern part of Japan (Iwasaki, 1992; Tanaka et al. 2019). Thus, we did not indicate their Japanese-Russian coast distribution in this figure.

Fig. 5 Spatial distribution of the relative abundance for *Pistocythereis bradyi*, *Bicornucythere bisanensis* s.l., *Nipponocythere bicarinata*, *Spinileberis quadriaculeata*, *Phlyctocythere japonica*, *Loxoconcha epetersenі*, *Sinocytheridea impressa*, and *Neomonoceratina delicata* in Hong Kong. See Figure 1 for sampling stations.

Fig. 6 Spatial distribution of the relative abundance for *Keijella kloempritensis*, *Neosinocythere elongata*, *Stigmatocythere roesmani*, *Hemicytheridea reticulata* *Loxoconcha malayensis*, *Alocopocythere goujoni*, *Hemikrithe orientalis*, and *Propontocypris* spp. in Hong Kong. See Figure 1 for sampling stations.

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Fig. 7. Spatial distribution of the relative abundance for *Neonesidea* spp. and *Xestoleberis* spp. in Hong Kong. See Figure 1 for sampling stations.

Table 1. Summary of marine water/sediment parameters. Note: 1. Summer: June, July, August and September. 2. Winter: November, December, January and February.

Table 2. Best three regression models of the relative abundance of common species, including *Pistocythereis bradyi*, *Bicornucythere bisanensis* s.l., *Nipponocythere bicarinata*, *Spinileberis quadriaculeata*, *Phlyctocythere japonica*, *Loxoconcha epeterseni*, *Sinocytheridea impressa*, *Neomonoceratina delicata*, *Keijella kloempritensis*, *Neosinocythere elongata*, *Stigmatocythere roesmani*, *Hemicytheridea reticulata* *Loxoconcha malayensis*, *Alocopocythere goujoni*, *Hemikrithe orientalis*, *Propontocypris* spp., *Neonesidea* spp. and *Xestoleberis* spp. The table shows the coefficient of each term, adjusted R^2, the Akaike information criterion corrected for small sample size (AICc), and the Akaike weight (AW). Bold denotes significance at $P < 0.05$. Overall P is < 0.05 in all models. R: region. Other abbreviations are found in Table 1.

Table 3. Model-averaged parameter estimates and CIs of the relative abundance for common species including *Pistocythereis bradyi*, *Bicornucythere bisanensis* s.l., *Nipponocythere bicarinata*, *Spinileberis quadriaculeata*, *Phlyctocythere japonica*, *Loxoconcha epeterseni*, *Sinocytheridea impressa*, *Neomonoceratina delicata*, *Keijella kloempritensis*, *Neosinocythere elongata*, *Stigmatocythere roesmani*, *Hemicytheridea reticulata* *Loxoconcha malayensis*, *Alocopocythere goujoni*, *Hemikrithe orientalis*,

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Propontocypris spp., *Neonesidea* spp. and *Xestoleberis* spp.. CIs, confidence intervals; RI, relative importance (the sum of the Akaike weights of models that include the variable in question; see Materials and Methods); R, region. Other abbreviations are found in Table 1. Bold denotes CIs that exclude zero. For R, coefficient, lower CI, and upper CI values shown are averages of those for geographic regions.

Table 4. GVIF value for Environmental Variables. Df, degree of freedom; R, region. Other abbreviations are found in Table 1.

Table 5. Summary of autoecology for common ostracod taxa. Chl: Chlorophyll-a; D: Water Depth; DO: Dissolved Oxygen; MD: Mud Content; Sal: Salinity; Tur: Turbidity; WT: Winter Temperature; Pb: Lead; Zn: Zinc; R: Region. + and - marks indicate significant positive and negative corrlations, respectively.

Supplement A. Ostracod faunal list.

Supplement B. Dataset used for the regression modeling.

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