Comparison of Tropical and Temperate Freshwater Animal Species' Acute Sensitivities to Chemicals: Implications for Deriving Safe Extrapolation Factors

Authors: Kwok, Kevin W. H., Leung, Kenneth M. Y., Lui, Gilbert S. G., Chu, Vincent K. H., Lam, Paul K. S., et al.

Source: Integrated Environmental Assessment and Management, 3(1) : 49-67

Published By: Society of Environmental Toxicology and Chemistry

URL: https://doi.org/10.1897/1551-3793(2007)3[49:COTATF]2.0.CO;2

Integrated Environmental Assessment and Management — Volume 3, Number 1—pp. 49–67

Comparison of Tropical and Temperate Freshwater Animal Species' Acute Sensitivities to Chemicals: Implications for Deriving Safe Extrapolation Factors

Kevin WH Kwok,† Kenneth MY Leung,† Gilbert SG Lui,‡ Vincent KH Chu,† Paul KS Lam,§ David Morritt,ll Lorraine Maltby,# Theo CM Brock,** Paul J Van den Brink,**†† Michael St J Warne,‡‡ and Mark Crane§§*

†The Swire Institute of Marine Science, Department of Ecology and Biodiversity, The University of Hong Kong, Pokfulam, Hong Kong, PR China
‡Department of Statistics and Actuarial Sciences, The University of Hong Kong, Pokfulam, Hong Kong, PR China
§Department of Biology and Chemistry, City University of Hong Kong, Tat Chee Avenue, Kowloon Tong, Hong Kong, PR China
llSchool of Biological Sciences, Royal Holloway, University of London, Egham, Surrey TW20 0EX, United Kingdom
#Department of Animal and Plant Sciences, The University of Sheffield, Sheffield S10 2TN, United Kingdom
***Alterra Centre for Water and Climate, Wageningen University and Research Centre, PO Box 47, 6700 AA Wageningen, The Netherlands*
††Wageningen University, Department of Aquatic Ecology and Water Quality Management, Wageningen University and Research Centre, PO Box 8080, 6700 DD Wageningen, The Netherlands
‡‡Centre for Environmental Contaminants Research, CSIRO Land and Water, PMB 2, Glen Osmond, South Australia 5064, Australia
§§Watts & Crane Associates, 23 London Street, Faringdon, Oxfordshire SN7 7AG, United Kingdom

(Received 5 September 2005; Accepted 1 April 2006)

Original Research

ABSTRACT

Toxicity data for tropical species are often lacking for ecological risk assessment. Consequently, tropical and subtropical countries use water quality criteria (WQC) derived from temperate species (e.g., United States, Canada, or Europe) to assess ecological risks in their aquatic systems, leaving an unknown margin of uncertainty. To address this issue, we use species sensitivity distributions of freshwater animal species to determine whether temperate datasets are adequately protective of tropical species assemblages for 18 chemical substances. The results indicate that the relative sensitivities of tropical and temperate species are noticeably different for some of these chemicals. For most metals, temperate species tend to be more sensitive than their tropical counterparts. However, for un-ionized ammonia, phenol, and some pesticides (e.g., chlorpyrifos), tropical species are probably more sensitive. On the basis of the results from objective comparisons of the ratio between temperate and tropical hazardous concentration values for 10% of species, or the 90% protection level, we recommend that an extrapolation factor of 10 should be applied when such surrogate temperate WQCs are used for tropical or subtropical regions and a priori knowledge on the sensitivity of tropical species is very limited or not available.

Keywords: Temperature Environmental quality standard Chemical hazard Ecotoxicology Climate change

INTRODUCTION

Over 75% of global biodiversity is found in tropical ecosystems, which include highly productive wetlands, freshwater systems and marine environments (Lecher and Goldstein 1997). Tropical environments occur between approximately 23.5°N and 23.5°S of the equator and are characterized by warm temperatures with little or no seasonality and heavy precipitation during at least 1 part of the year (Lecher and Goldstein 1997). Tropical aquatic environments, therefore, differ ecologically from the habitats of temperate zones in both their physicochemical and biological attributes. The biodiversity in the subtropics and tropics is substantially higher than in temperate zones; thus, the number of species potentially affected by exposure to a particular pollutant is also greater. Unfortunately, many countries in the subtropics and tropics are developing nations, heavily populated, and rapidly becoming industrialized but lack the money, infrastructure, and other resources for advanced pollution controls. Therefore, tropical aquatic ecosystems are under increasing threat of environmental degradation (e.g., from the release of toxic substances through discharge of untreated industrial effluents to the aquatic environment; Kim et al. 2001). To safeguard the important biodiversity in tropical aquatic ecosystems, the need to establish a sound framework for assessing and managing the ecological risks of an ever-increasing number of chemicals that occur in these regions is urgent (Peters et al. 1997).

The regulation of substances discharged to aquatic environments relies on data derived predominately from ecotoxicity tests (OECD 1995; Lam and Gray 2001). Most of these data are generated by developed western countries and are based on temperate and coldwater species endemic to Europe and North America (Dyer et al. 1997; Kim et al. 2001). In contrast, fewer toxicity data are available for species from tropical or subtropical regions (Lam and Wu 1999). Because of this paucity of data, many tropical water quality criteria (WQC) rely on extrapolations from temperate data. This surrogate approach assumes that tropical species respond similarly to temperate species and that the distributions of tropical and temperate species sensitivities are sufficiently similar. However, these assumptions have yet to be tested. This study is designed to investigate the extent to which the sensitivity distributions of temperate species to toxicants coincide with those of tropical species.

Useful progress can be made by comparing the sensitivities of tropical and temperate species to the same chemicals. Several parametric and nonparametric approaches now exist

* To whom correspondence may be addressed: kmyleung@hkucc.hku.hk

for estimating species sensitivity distributions (SSDs) on the basis of laboratory toxicity data (Stephan et al. 1985; Wagner and Lokke 1991; Aldenberg and Jaworska 2000; Campbell et al. 2000; Newman et al. 2000; Grist et al. 2002; Wheeler, Grist et al. 2002). Most approaches involve fitting a distribution to toxicity data for different species, which provides information about the range of species sensitivity to a particular chemical and the concentration predicted to affect only a small proportion (typically 5% or 10%) of species (Versteeg et al. 1999). The median or lower confidence limit on this parameter can be taken to represent the WQC (Aldenberg and Slob 1993; Maltby et al. 2005). When toxicity data are plotted as SSDs, the relationship between tropical and temperate data can be visualized and compared (Leung et al. 2001; Wheeler, Leung, et al. 2002; Maltby et al. 2005). If tropical and temperate toxicity data are similar or related in a systematic and predictable way, the former can be used to predict the latter with confidence. This would bring substantial socioeconomic benefits to tropical nations from significantly reduced requirements for additional toxicity testing without compromising environmental protection. The results of this study are therefore important for ecological risk assessment and environmental management in the tropical region.

METHODS

Data mining

Acute median lethality data (LC50) for freshwater animal organisms from tropical and temperate regions were found for 18 chemicals (ammonia; 9 metals: arsenic, cadmium, chromium, copper, lead, mercury, nickel, silver, and zinc; 6 pesticides: carbaryl, chlordane, chlorpyrifos, DDT, lindane, and malathion; 2 narcotics: pentachlorophenol [PCP] and phenol). Data were extracted from the US Environmental Protection Agency [USEPA] ECOTOX toxicology database (http://www.epa.gov/ecotox/), Pesticide Action Network (North America) database, European Centre for Ecotoxicology and Toxicology of Chemicals ECETOC database, peer-reviewed literature, data presented in Maltby et al. (2005), and government and consultancy reports. The original data sources were reviewed and the qualities of the data were determined according to the criteria suggested by Wheeler, Grist, et al. (2002); only data with quality 2b or above were used in the analysis. Quality 2b data were generated from moderately reliable studies, including tests based on nominal concentrations and tests without reporting the control mortality (Wheeler, Grist, et al. 2002). Multiple data for the same species were summarized as geometric means (Wheeler, Grist, et al. 2002).

To standardize the toxicity of ammonia, un-ionized ammonia concentration was used instead of total ammonia concentration for constructing the SSD. When LC50 data were expressed as un-ionized ammonia concentrations in the source literature, they were used directly for SSD construction. Otherwise, they were calculated with the equation of Erickson (1985) on the basis of the LC50 of total ammonia and testing conditions (i.e., pH and temperature).

Construction of species sensitivity distributions

Data for each substance were classified into 2 climatic region classes according to where the test species were collected. Test organisms collected between approximately 23.5°N and 23.5°S of the equator were classified as tropical, whereas those collected outside this area were classified as temperate. If the source of the test species was not mentioned in the data source, the known species distribution range was used for classification. Species sensitivity distributions were constructed on the basis of the rank of sensitivity against LC50 values (Wheeler, Grist, et al. 2002). There are many methods for fitting the SSD so that hazardous concentrations corresponding to 95% and 90% protection (HC5 and HC10) can be estimated. In this study, HC10 was chosen as an acute predicted no-effect concentration (acute PNEC) and the point for comparison between tropical and temperate species sensitivities because HC10 is derived with a higher certainty than HC5 and it has been adopted as a convenient working criterion for deriving WQC (Solomon et al. 2001). To allow consideration of variations among HC10 values derived by various SSD fitting approaches, we used the 4 most common approaches in this study, namely, 1) parametric model fitting approach (log-normal model [Wagner and Lokke 1991] or log-logistic model [Aldenberg and Slob 1993]), 2) nonparametric bootstrap approach (Newman et al. 2000), 3) bootstrap regression approach (Grist et al. 2002), and 4) the log-triangular approach suggested by Stephan et al. (1985). The 1st method applies the standard parametric model for fitting the SSD, and its accuracy is primarily dependent on the goodness of fit. Thus, in this study, we only used the best fit model (log-normal or log-logistic) to derive the HC10. Any chemical with the SSD (tropical or temperate) that could not be fit by either parametric model would not be analyzed by method 1. Although bootstrap is a nonparametric or distributional free method, it requires a relatively large sample size (e.g., $n \geq 20$ and $n \geq 10$ for deriving HC5 and HC10, respectively; Grist et al. 2002). However, it is often the case that there is very limited ecotoxicity data, especially for tropical species; thus, the conventional bootstrap approach is not applicable. The bootstrap regression approach, which is a compromise between parametric regression and nonparametric resampling, can be used to estimate any HC value, even with a small dataset (i.e., $5 \leq n \leq 9$; Grist et al. 2002). This hybrid technique also allows the calculation of the confidence limits around the point estimate. The final approach of Stephan et al. (1985) is only concerned with the lower tails of the SSD and derives the HC5 by fitting a linear regression model through 4 data points surrounding the 5% region. In this study, we applied a slight modification to this approach by employing the 4 data points of cumulative probabilities closest to the 10% region instead of the 5% region for estimating the HC10. In some cases, this could include data points of cumulative probabilities higher or lower than the 10% region.

Model fits of log-normal and log-logistic SSDs were examined by the Kolmogorov–Smirnov (KS) goodness of fit test for continuous data (Zar 1999). The best model fit was determined by comparing error root mean square (error RMS) of the 2 models. In addition, the Anderson–Darling (AD) test (Anderson and Darling 1954) was conducted for all log-normal SSDs to examine the fit of data at the lower tail of the SSDs. Species sensitivity distributions that did not pass the KS or AD test were excluded from the subsequent derivation of a temperate-to-tropical extrapolation factor. Visual inspection of model fit was also applied when the goodness of fit results were marginal.

Comparison of sensitivities of tropical and temperate species

For each SSD, HC10 values and their 95% confidence limits (CLs) were estimated from each of the 4 different approaches as mentioned above. First, they were derived from best fit parametric SSDs (log-normal or log-logistic model) that were indicated by smaller RMS error with a good model fit (as indicated by KS and AD tests). Second, the HC10 values were estimated from the conventional nonparametric bootstrap method; however, this method excluded 4 chemicals with $n < 10$ in the tropical dataset (i.e., arsenic, silver, nickel. and chlordane; Table 1). Third, the bootstrap regression was used to derive HC10 values of the 4 chemicals with $n < 10$ tropical data points, and these results were incorporated with those obtained from the conventional bootstrapping for further analysis. Fourth, for each SSD, an HC10 value was also derived following a modified method of Stephan et al. (1985) as described above.

For each chemical, an HC10 ratio between the 2 climatic regions was defined as temperate HC10/tropical HC10 for the same chemical. For HC10 values derived from parametric SSDs, the HC10 ratio and its 95% CI were generated by Monte Carlo simulation. In each simulation, 1 HC10 value was randomly selected from each of the 2 parametric distributions of the HC10 value to compute the HC10 ratio. In total, 5,000 iterations of such a simulation were applied so as to obtain 5,000 HC10 ratios, from which the ratio and its 95% CI were determined at 50 percentile and 2.5 to 97.5 percentiles, respectively. Double bootstrapping was used to estimate the 95% CI for the HC10 ratios derived from HC10 values that were generated from nonparametric bootstrap or bootstrap regression. In the 1st stage of bootstrapping, 5,000 samples were generated by resampling. In the bootstrap regression cases, residuals from fitting a parametric function were chosen, whereas in the nonparametric cases, quantiles on the SSD were chosen as parameters of the resampling. In the 2nd stage of bootstrapping, $2(5{,}000)^{1/2}$ samples (rounded to the nearest integer) were generated by bootstrapping from the 5,000 samples in the 1st stage of bootstrapping (Hall 1992). The 95% confidence limits were then determined as the 2.5 and 97.5 percentiles of the bootstrap-generated samples.

Meta-analysis for deriving safe extrapolation factors

For each of the 4 approaches, each substance was ranked and assigned percentiles according to its HC10 ratios. These HC10 ratios were then fit to the log-normal model. Subsequently, safe extrapolation factors covering 90%, 95%, and 99% of all chemicals were computed by inverse prediction (see Wheeler, Leung, et al. 2002) for tropical regions. As a consequence, 4 sets of extrapolation factors derived with the use of the HC10 values obtained from the 4 different approaches, respectively, were compared. With careful consideration of these values, a practical extrapolation factor (or assessment factor) was finally proposed.

Comparison of test temperatures

Geometric means of the test temperature of each species were taken from available data. Mann–Whitney tests were performed for each chemical to test for significant differences in the test temperature between the tropical and temperate regions. A Wilcoxon test was used to examine whether the overall test temperature, across all tested chemicals, differed between tropical and temperate ecotoxicity tests.

RESULTS

Tropical tests were conducted at a significantly higher temperature than temperate tests for 13 of the 18 tested chemicals (Table 2). Across all chemicals, a Wilcoxon test also indicated that tropical tests were in general conducted at a significantly higher temperature ($Z = 3.623$; df 1, 17; $p < 0.001$) with a median temperature difference of 5.3 °C.

The SSDs of the 18 chemicals for both temperate and tropical species are shown in Figures 1 to 3. The species composition of each SSD is also given. Regression parameters of tropical and temperate SSDs for each individual chemical are summarized in Table 1 while the chemical-specific HC10 ratios and their 95% CI values are summarized in Table 3.

SSDs and their species composition

For the parametric SSDs, the log-normal approach generally gave a better model fit than the log-logistic approach for the majority of the datasets (Table 1). However, parametric methods (log-normal and log-logistic approach) did not provide SSDs of satisfactory goodness of fit for 9 chemicals (Table 1). Only 1 SSD failed the KS test (tropical arsenic SSD) while 13 SSDs failed the AD test (Table 1).

Un-ionized ammonia—Both datasets of un-ionized ammonia contained large proportions of fish and crustacean data (Figure 1; tropical: 70% and 20%; temperate: 32% and 29% respectively). Parametric SSDs showed good fit to both tropical and temperate datasets (Table 1). In general, tropical species tend to be more sensitive to un-ionized ammonia (Figure 1).

Trace metals—For trace metals, more data were available for temperate species than for tropical species (Table 1). With the exception of the tropical arsenic dataset, most metal datasets contained data from a wide spectrum of taxa, with fish and crustaceans being the most abundant groups (Figure 2, pie charts). Parametric SSDs for 6 metals were of good fit. Temperate chromium, copper, and silver failed the AD test, whereas tropical arsenic SSD failed both the KS and AD tests (Table 1). Temperate chromium SSD failed the AD test, but that was mostly attributable to the misfit at the upper tail (Figure 2c); therefore, HC10 values of chromium were still derived and used in the subsequent meta-analysis. The majority of metals (i.e., cadmium, chromium, copper, lead, mercury, and nickel) were more toxic to temperate species than tropical species (Figure 2), but tropical species were more sensitive to zinc. For arsenic and silver, differences between temperate and tropical SSDs were somewhat less obvious, possibly because of insufficient tropical data.

Pesticides—Tropical species data for pesticides were generally limited (Table 1). Mollusk data were especially lacking because no tropical or temperate mollusk data were found for 5 pesticides (Figure 2 and Table 4). Temperate datasets were largely made up of fish, crustacean, and insect data (Figure 3, pie charts), whereas tropical datasets, except for chlorpyrifos, contained mostly fish data (Figure 3, pie charts). Many pesticide datasets did not appear to conform to shapes of common parametric distributions (Figure 3), limiting the use of parametric SSDs. Of all the pesticides, the parametric SSDs of lindane and malathion have a sufficient goodness of fit to derive HC10 values subsequently, whereas all other pesticide parametric SSDs did not show good fit (Table 1).

Table 1. Comparison of the temperate and tropical species sensitivity distributions of parametric log-normal model, $y = ax + b$, and log-logistic model, $y = 1/\{1 + \exp[-(x - \alpha)/\beta]\}$ and Stephan et al. (1985) log-triangular approach, $y = ax + b$; bold values represent best fit models on the basis of smaller error residual mean square (error RMS); KS D_{max} is the test statistic and KS Critical is the Kolmogorov–Smirnov test critical value; AD is the Anderson–Darling test statistic (critical value at $p = 0.05$ is 0.752); Model fit provides the general overall comment on the goodness of the fit. Between the 2 parametric models, the model with a better fit is indicated by bold letters for the model parameters

			Parametric model								Goodness of fit tests				Stephan et al. (1985) log-triangular approach		
			Log-normal model				Log-logistic model				KS test		AD test				
		n	a	b	R^2	Error RMS	α	β	R^2	Error RMS	D_{max}	Critical	AD	Model fit	a	b	R^2
Ammonia	Tropical	10	**1.571**	**0.329**	**0.977**	**0.00086**	2.957	0.356	0.986	0.00103	0.201	0.409	0.221	Good	1.734	–0.122	0.914
	Temperate	31	2.226	–1.97	0.973	0.00085	**3.108**	**0.257**	**0.991**	**0.00075**	0.096	0.238	—	Good	4.077	–6.937	0.927
Arsenic	Tropical	9	1.074	0.943	0.575	0.00238	**4.163**	**0.363**	**0.919**	**0.00204**	0.431	0.430	—	Poor	0.446	2.589	0.803
	Temperate	22	1.734	–2.790	0.922	0.00139	**4.492**	**0.274**	**0.983**	**0.00124**	0.139	0.281	—	Good	0.688	1.144	0.953
Cadmium	Tropical	22	0.871	1.875	0.964	0.00095	**3.587**	**0.558**	**0.986**	**0.00085**	0.103	0.281	—	Good	3.737	–4.121	0.938
	Temperate	53	**1.122**	**2.006**	**0.962**	**0.00075**	2.669	0.455	0.987	0.00091	0.129	0.183	0.637	Good	0.570	2.814	0.936
Chromium	Tropical	14	**1.225**	**–0.34**	**0.957**	**0.00181**	4.359	0.380	0.969	0.00185	0.155	0.349	0.467	Good	0.878	0.887	0.965
	Temperate	37	**0.866**	**1.42**	**0.916**	**0.00231**	4.136	0.566	0.960	0.00255	0.162	0.218	1.117	Fair	0.879	1.583	0.848
Copper	Tropical	28	1.503	1.167	0.983	0.00084	**2.231**	**0.376**	**0.992**	**0.00065**	0.085	0.250	—	Good	0.749	2.715	0.814
	Temperate	35	**0.868**	**3.327**	**0.908**	**0.00067**	1.927	0.560	0.979	0.00068	0.123	0.224	1.136	Fair	2.039	1.869	0.842
Lead	Tropical	20	0.760	1.778	0.977	0.00068	**4.064**	**0.635**	**0.989**	**0.00066**	0.120	0.294	—	Good	1.207	0.705	0.925
	Temperate	25	**0.879**	**2.07**	**0.946**	**0.00299**	3.334	0.553	0.969	0.00749	0.156	0.264	0.407	Good	0.683	2.385	0.963
Mercury	Tropical	27	1.236	1.915	0.986	0.00067	**2.536**	**0.412**	**0.992**	**0.00062**	0.100	0.254	—	Good	0.769	2.568	0.902
	Temperate	38	1.257	2.257	0.966	0.00079	**2.184**	**0.400**	**0.990**	**0.00063**	0.099	0.215	—	Good	0.474	3.264	0.732
Nickel	Tropical	9	**1.059**	**0.219**	**0.984**	**0.00079**	4.515	0.424	0.987	0.00079	0.149	0.430	0.436	Good	1.155	–0.143	0.985
	Temperate	24	1.260	0.930	0.936	0.00218	**3.23**	**0.383**	**0.964**	**0.00206**	0.155	0.269	—	Good	3.579	–4.756	0.906
Silver	Tropical	8	2.541	2.345	0.960	0.00184	**1.045**	**0.172**	**0.970**	**0.00183**	0.237	0.454	—	Good	2.040	2.728	0.863
	Temperate	20	**0.940**	**3.761**	**0.890**	**0.00339**	1.317	0.493	0.945	0.01279	0.163	0.294	0.912	Fair	1.769	3.127	0.960
Zinc	Tropical	26	**0.934**	**1.629**	**0.980**	**0.00137**	3.443	0.514	0.979	0.00152	0.136	0.259	0.563	Good	1.879	–0.425	0.985
	Temperate	42	**1.343**	**0.371**	**0.993**	**0.00037**	3.448	0.383	0.995	0.00042	0.069	0.205	0.409	Good	1.720	–0.629	0.965
Carbaryl	Tropical	36	**0.802**	**2.161**	**0.782**	**0.00118**	3.347	0.499	0.963	0.00122	0.203	0.221	1.437	Fair	1.035	2.364	0.991
	Temperate	71	**0.691**	**2.81**	**0.849**	**0.00127**	2.622	0.647	0.946	0.00139	0.126	0.159	0.857	Fair	2.857	1.140	0.909

Table 1. Continued

			Parametric model								Goodness of fit tests				Stephan et al. (1985) log-. triangular approach		
			Log-normal model				Log-logistic model				KS test		AD test				
		n	a	b	R^2	Error RMS	α	β	R^2	Error RMS	D_{max}	Critical	AD	Model fit	a	b	R^2
Chlordane	Tropical	7	**0.697**	**3.501**	**0.916**	**0.00194**	2.151	0.599	0.937	0.00967	0.145	0.483	0.622	Good	0.826	3.321	0.631
	Temperate	18	**2.324**	**1.736**	**0.850**	**0.00097**	1.542	0.253	0.891	0.00097	0.227	0.309	1.268	Fair	0.765	3.186	0.989
Chlorpyrifos	Tropical	38	**0.659**	**3.631**	**0.962**	**0.00060**	0.529	0.639	0.989	0.00524	0.090	0.215	0.762	Fair	1.013	4.526	0.971
	Temperate	69	**0.498**	**4.158**	**0.939**	**0.00061**	0.782	0.655	0.992	0.06259	0.075	0.161	0.972	Fair	0.955	4.281	0.879
DDT	Tropical	11	0.659	3.483	0.928	0.01372	**2.300**	**0.677**	**0.949**	**0.00293**	0.253	0.391	—	Good	0.813	3.271	0.863
	Temperate	23	**0.726**	**3.885**	**0.874**	**0.00715**	1.539	0.636	0.903	0.01559	0.199	0.275	1.231	Fair	1.356	3.243	0.750
Lindane	Tropical	30	**1.358**	**1.574**	**0.948**	**0.00195**	2.153	0.588	0.986	0.01098	0.092	0.242	0.674	Good	1.629	2.518	0.834
	Temperate	62	**0.849**	**3.338**	**0.918**	**0.00126**	1.805	0.482	0.994	0.00843	0.074	0.153	0.712	Good	1.975	2.451	0.921
Malathion	Tropical	12	**1.513**	**–0.328**	**0.874**	**0.00113**	3.521	0.289	0.971	0.00122	0.194	0.375	0.627	Good	0.752	1.852	0.932
	Temperate	36	**0.588**	**3.24**	**0.967**	**0.00164**	2.995	0.855	0.977	0.00181	0.145	0.221	0.611	Good	1.063	3.071	0.962
Pentachlor-ophenol	Tropical	19	**2.320**	**0.911**	**0.958**	**0.00241**	2.942	0.526	0.960	0.00242	0.144	0.301	0.644	Good	0.645	2.692	0.920
	Temperate	68	**1.958**	**1.142**	**0.855**	**0.00135**	2.664	0.446	0.974	0.00612	0.112	0.162	1.281	Fair	1.652	0.727	0.954
Phenol	Tropical	13	1.429	–1.623	0.859	0.00188	**4.393**	**0.275**	**0.975**	**0.00181**	0.360	0.361	—	Good	0.642	1.442	0.938
	Temperate	21	1.584	–2.623	0.963	0.00112	**4.813**	**0.306**	**0.976**	**0.00104**	0.151	0.287	—	Good	2.038	–4.702	0.964

Table 2. Median toxicity test temperature of temperate and tropical test data and results of Mann–Whitney test on temperature difference between the 2 groups

Chemical	Median temperature (°C)		Difference	Mann–Whitney *U*
	Tropical	Temperate		
Ammonia	27.0	21.0	6.0	31.0*
Arsenic	21.5	21.5	0.0	46.0
Cadmium	26.8	19.8	7.0	96.0**
Chromium	27.4	20.0	7.4	63.0*
Copper	25.2	21.0	4.2	102**
Lead	23.7	20.0	3.7	64.5*
Mercury	25.5	12.1	13.4	105**
Nickel	27.4	20.0	7.4	18.5*
Silver	30.0	20.7	9.3	120**
Zinc	25.8	20.0	5.8	86.0**
Carbaryl	18.2	18.0	0.2	66.5
Chlordane	23.6	19.0	4.6	5.0
Chlorpyrifos	25.8	22.5	3.3	17.0
DDT	21.0	16.8	4.2	38.0
Lindane	23.0	18.0	5.0	43.0*
Malathion	25.5	22.0	3.5	83.0*
Pentachlorophenol	24.0	18.5	5.5	45.0*
Phenol	24.0	17.0	7.0	17.5*

* Significantly different medians at $p < 0.05$.
** Significantly different medians at $p < 0.001$.

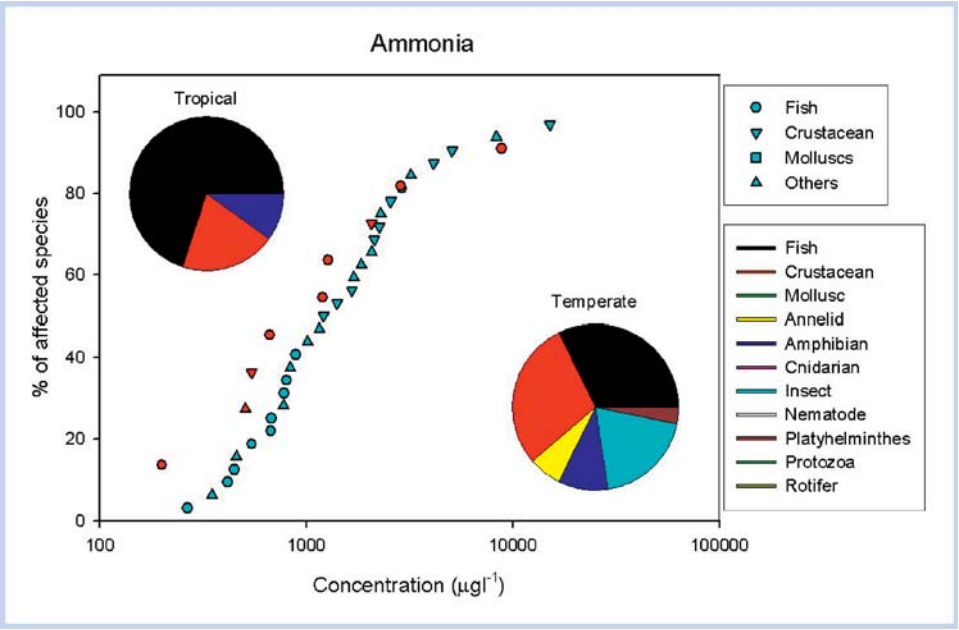

Figure 1. Tropical and temperate species toxicity data for ammonia. Red symbols indicate tropical data points whereas blue symbols indicate temperate data points. Pie charts represent the taxonomic composition of the upper tropical and lower temperate distributions. Symbols for different higher taxa composing data points in species sensitivity distribution are given in the upper key; color codes for different taxa in pie charts are given in the lower key.

Generally speaking, temperate species were more sensitive to carbaryl, DDT, and malathion, whereas tropical species were more sensitive to chlorpyrifos (Figure 3). For lindane, both temperate and tropical SSDs converge and merge at the lower tails, indicating similar species sensitivity. Because of scarcity of tropical data, the difference between temperate and tropical chlordane SSDs is less obvious.

Narcotics—More data were available for PCP than for phenol (Table 1). Fish, crustacean, and insect data contributed most of the data in the datasets of the 2 narcotics (Figure 3g and h, pie charts). Parametric SSDs of phenol were of good fit, but temperate PCP SSD failed the AD test (Table 1). For both chemicals, the patterns of the temperate and tropical species sensitivity were similar because the shapes of the data distribution were alike (Figure 3g and h; i.e., tropical species generally appeared to be slightly more sensitive at the lower tail of the distributions, whereas sensitivities of tropical and temperate species became similar at the middle of the distributions).

Derivation of HC10 values and HC10 ratios

HC10 values derived from the 4 different approaches were of comparable magnitudes (Table 3). Temperate to tropical HC10 ratios showed large variations among different chemicals, ranging from 0.013 to 16.2 (Table 3). When the HC10 ratio is larger than 1, it indicates that tropical species could be more sensitive to that chemical than temperate ones and vice versa. Eleven of the 18 chemicals had HC10 ratios smaller than 1, whereas 6 had temperate to tropical HC10 ratios larger than 1. The 1 exception was the HC10 ratio for PCP, which could be less than or greater than 1 depending on the SSD approach used (Table 3). These results suggested that the acute sensitivities of tropical and temperate freshwater organisms are different for different chemicals.

For un-ionized ammonia, a large difference was found between the HC10 values of temperate and tropical species. The HC10 ratio of un-ionized ammonia was larger than 1 from all SSD approaches, suggesting that tropical species are likely more sensitive to un-ionized ammonia than temperate ones. The temperate-to-tropical HC10 ratio ranged from 2.4 to 4.3 on the basis of the model of SSD used (Table 3). For most metals, temperate species are possibly more sensitive than tropical species, as indicated by having HC10 ratios smaller than 1. But for zinc and arsenic, their HC10 ratios were larger than 1, ranging from 2 to 16 (Table 3), indicating that tropical species are likely to be more sensitive to these 2 metals.

Among the pesticides, tropical species appeared to be more sensitive to chlorpyrifos and chlordane, as indicated by the HC10 ratios larger than 1 (Table 3). For carbaryl, DDT, lindane, and malathion, temperate species were likely to be more sensitive, as indicated by the small HC10 ratios (Table 3). Chlorpyrifos was also the most toxic chemical examined in this study, as suggested by the smallest HC10 values when compared with other chemicals. For naroctics, the HC10 ratio of phenol was larger than 1 (Table 3), suggesting that tropical species are possibly more sensitive. However, the sensitivities of tropical and temperate species to PCP was unclear because it had an HC10 ratio larger than 1 with the use of bootstrap regression and Stephan et al. (1985) approaches, but the ratio was smaller than 1 with the use of conventional nonparametric bootstrapping.

Temperate freshwater organisms are more sensitive to 7 of the 9 metals (except zinc and arsenic) and 4 of the 6 pesticides (except chlordane and chlorpyrifos; Table 3). Besides, their tropical counterparts are more sensitive to ammonia and phenol (Table 3). Across all chemicals, however, there were no consistent differences in the relative sensitivity of tropical and temperate species.

Meta-analysis for deriving appropriate temperate to tropical extrapolation factors

As described in *Methods*, extrapolation factors were derived with HC10 ratios derived from the 4 different approaches. The best fit parametric SSD model was only valid for 10 chemicals (ammonia, cadmium, chromium, lead, mercury, nickel, zinc, lindane, malathion, and phenol) with a satisfactory goodness of fit. On the basis of these 10 chemicals, an extrapolation factor of 13.8 was derived, which covers 95% of all chemicals with a 90% protection level for the aquatic species assemblage (Figure 4a). An extrapolation factor of about 9.6 (at the same protection level) was derived from 14 HC10 ratios, which were obtained from the conventional nonparametric bootstrap (Figure 4b). The extrapolation factor was slightly increased from 9.6 to 10.9 by adding the HC10 ratios of 4 more chemicals derived from the bootstrap regression to those obtained with the use of the 2nd approach (Figure 4c). Finally, the modified Stephan et al. (1985) approach yielded a comparable extrapolation factor of 13.4 (Figure 4d). The average of these 4 extrapolation factors is 11.9 ($\pm$2.0; $\pm$SD). For ease of use, we suggest that an extrapolation factor of 10 should be applied when chemicals have not been tested with tropical species and surrogate temperate WQCs (or environmental quality standards) are adopted in tropical regions. If it is decided that a less conservative approach is needed, a factor of 6 (mean 6.1 $\pm$ 0.8), covering 90% of chemicals with 90% protection level, could be used. It should be noted that the toxicity data for tropical species for 61% to 63% of chemicals would be covered (Figure 4) if no extrapolation factors were applied (i.e., a factor of 1) when adopting temperate WQCs for protecting freshwater species in tropical regions, and that an extrapolation factor of 10 could be overprotective in approximately 95% of cases.

DISCUSSION

Differences in sensitivity to toxic chemicals of species from different climatic zones, although recognized, have not, to our knowledge, been thoroughly investigated. The Canadian protocol for derivation of water quality guidelines for protection of aquatic life and USEPA Federal Insecticide, Fungicide, and Rodenticide Act (FIFRA) guidelines recognize the potential difference between species from different climatic zones by requiring toxicity data for a coldwater fish and a warm water fish species (Canadian Council of Ministers of the Environment 1991; FIFRA 1996). Results from this study indicate that tropical and temperate species do differ in sensitivity to different chemical classes (e.g., most trace metals were more toxic to temperate species). Such differences are probably attributable to several potential factors, including differences in the modes of toxic action among the test compounds, temperature-related differences in metabolism, uptake and detoxification between tropical and temperate species, and the species composition of the SSDs.

How well the observed difference in sensitivities of tropical and temperate species reflects the true environmental picture will be influenced by 2 main factors: 1) Biological differences

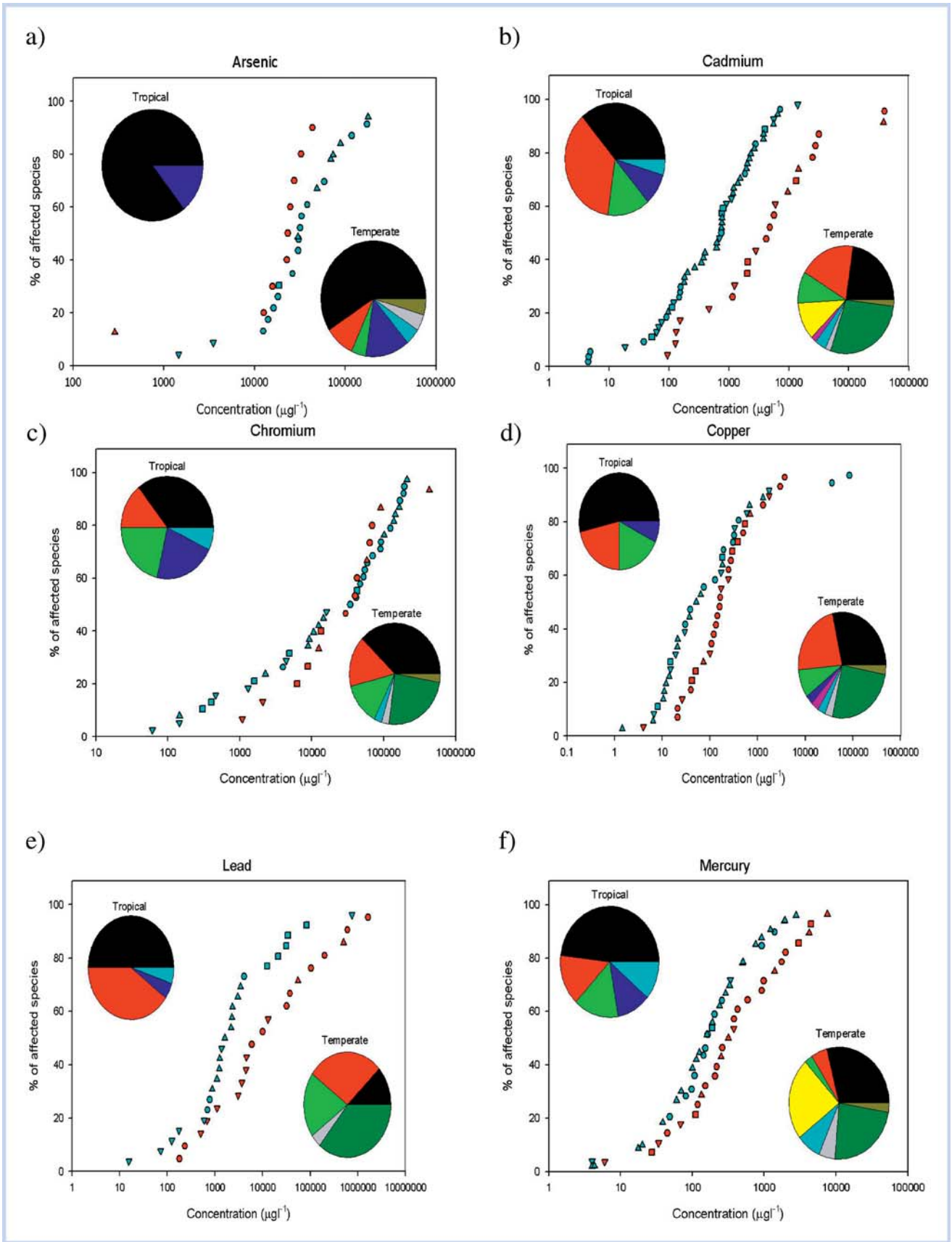

Figure 2. Tropical and temperate species toxicity data for metals. Pie charts represent the taxonomic composition of the distributions (upper tropical and lower temperate). Conventions as for Figure 1.

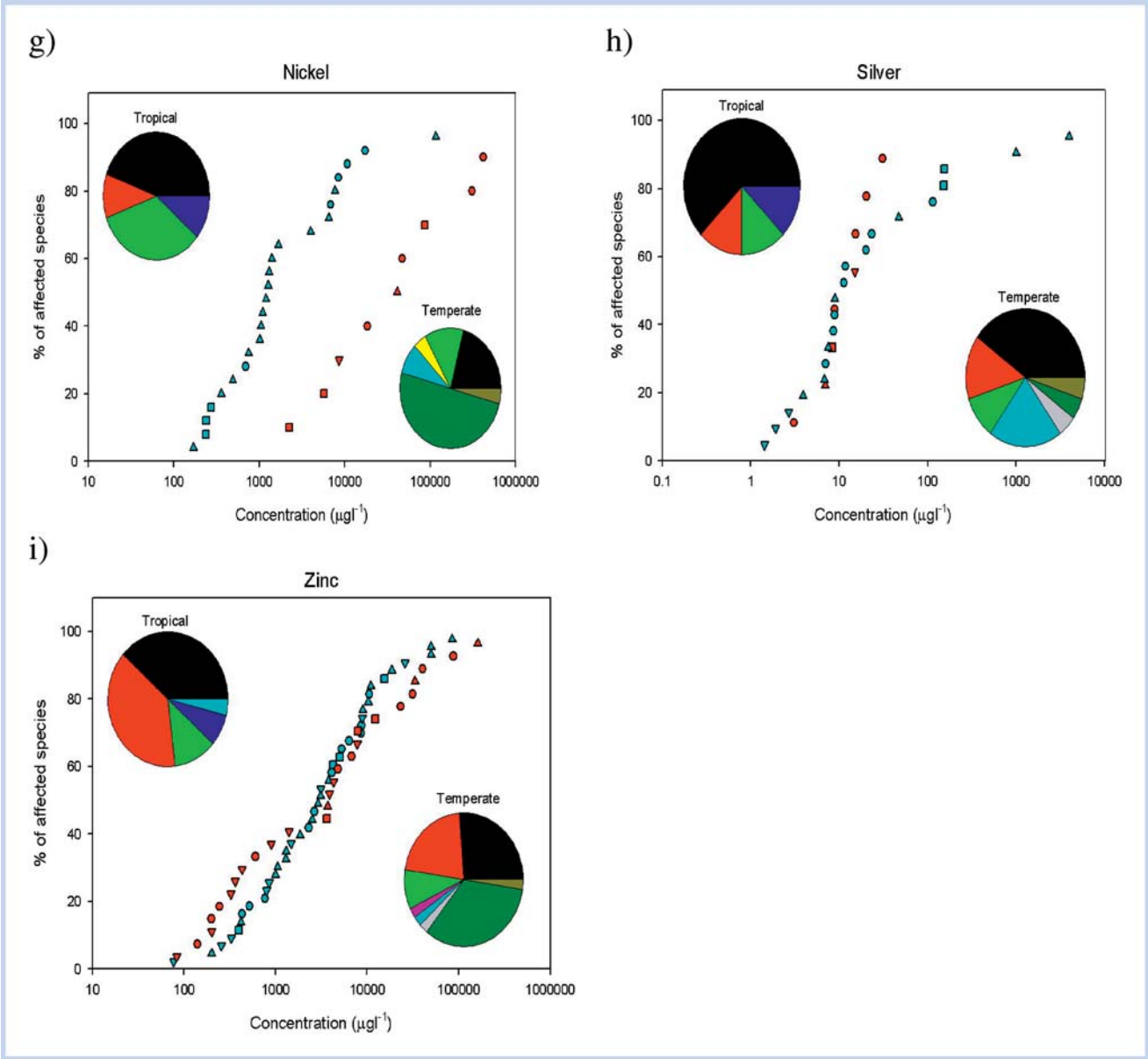

Figure 2. Continued.

between tropical and temperate organisms and 2) differences in testing methodology and conditions (e.g., temperature) that lead to systematic differences in estimates of toxicity.

Temperature–biota interactions

In this study, we confirm that most tropical ecotoxicity tests have been conducted at higher temperatures (~5.7 °C) than for temperate tests. In fact, optimal test temperatures for tropical species are about 20 to 25 °C, whereas optimum test temperatures for temperate species are about 12 to 18 °C (Doudoroff et al. 1951). Tropical and temperate aquatic invertebrates differ in their physiologies and life histories, with concomitant implications for sensitivity to toxicants. On the basis of the metabolic principle (Q_{10}), it has been hypothesized that tropical aquatic species should be more sensitive to toxic chemicals than their temperate counterparts (Castillo et al. 1997). Previous laboratory studies suggested that the risk of toxicity to an aquatic organism appears to increase with temperature (Sprague 1985; Viswanathan and Murti 1989; Brecken-Folse et al. 1994; Willis et al. 1995; Lydy et al. 1999; Kwok and Leung 2005). In general, the solubility of the toxicant in water and the rates of uptake and circulation in the test organism are higher at elevated temperatures. Indeed ectothermic aquatic organisms experience the double bind of reduced dissolved oxygen and increased metabolic rates as water temperature increases (Cairns et al. 1975; Rathore and Khangarot 2002). This might increase the amount of energy expended to meet their respiratory gas exchange requirements, which could ultimately exacerbate toxic effects. In contrast, as metabolic rate increases, biochemical detoxification and elimination of the chemical might also increase with temperature, which could eventually reduce chemical toxicity (Howe et al. 1994).

How these mechanisms operate and their relationship with temperature appears to be both species and chemical specific. Brix et al. (2001) provided a preliminary comparison of SSDs for acute copper toxicity between tropical and temperate freshwater fish and demonstrated that temperate fish species

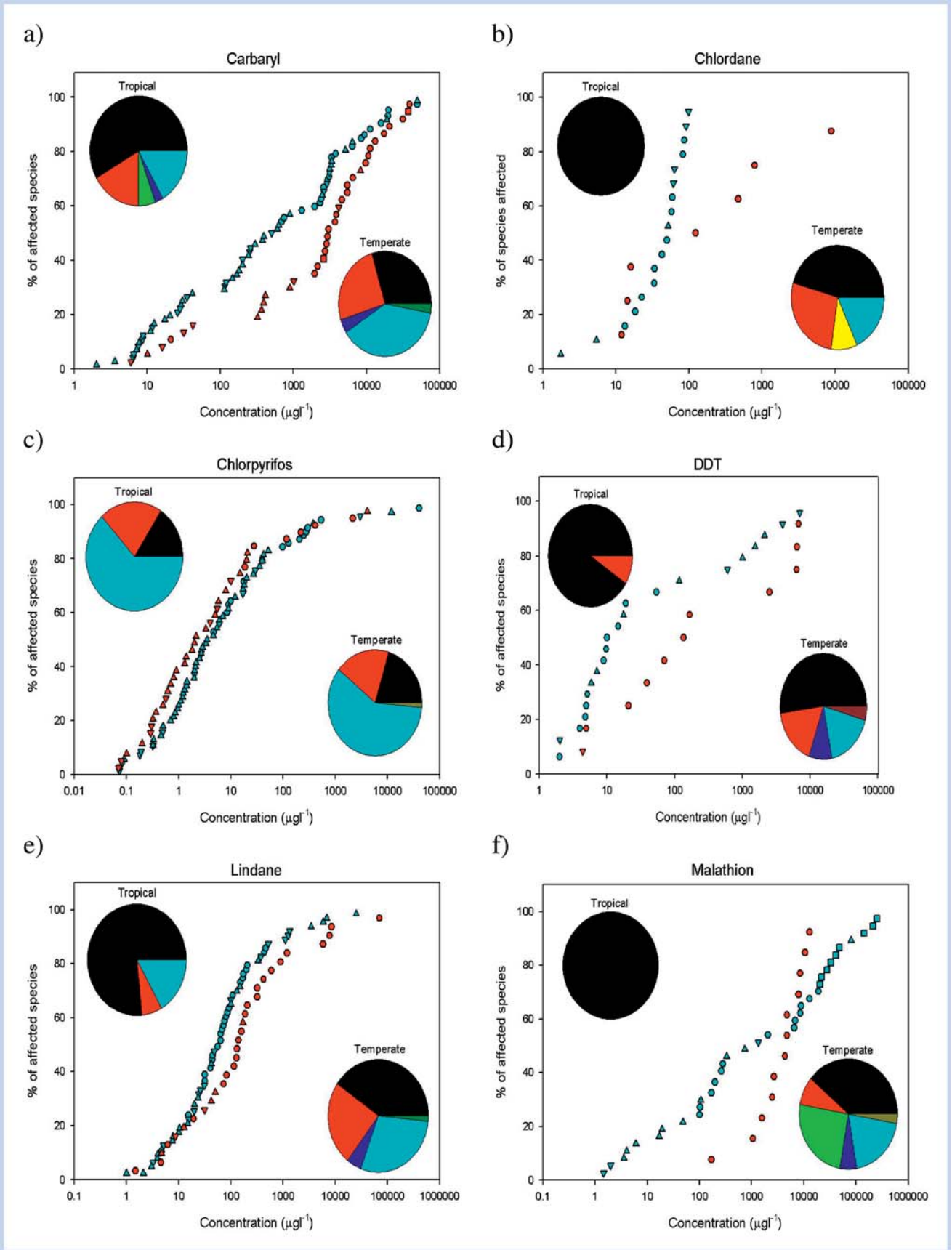

Figure 3. Tropical and temperate species toxicity data for pesticides and narcotics. Pie charts represent the taxonomic composition of the distributions (upper tropical and lower temperate). Conventions as for Figure 1.

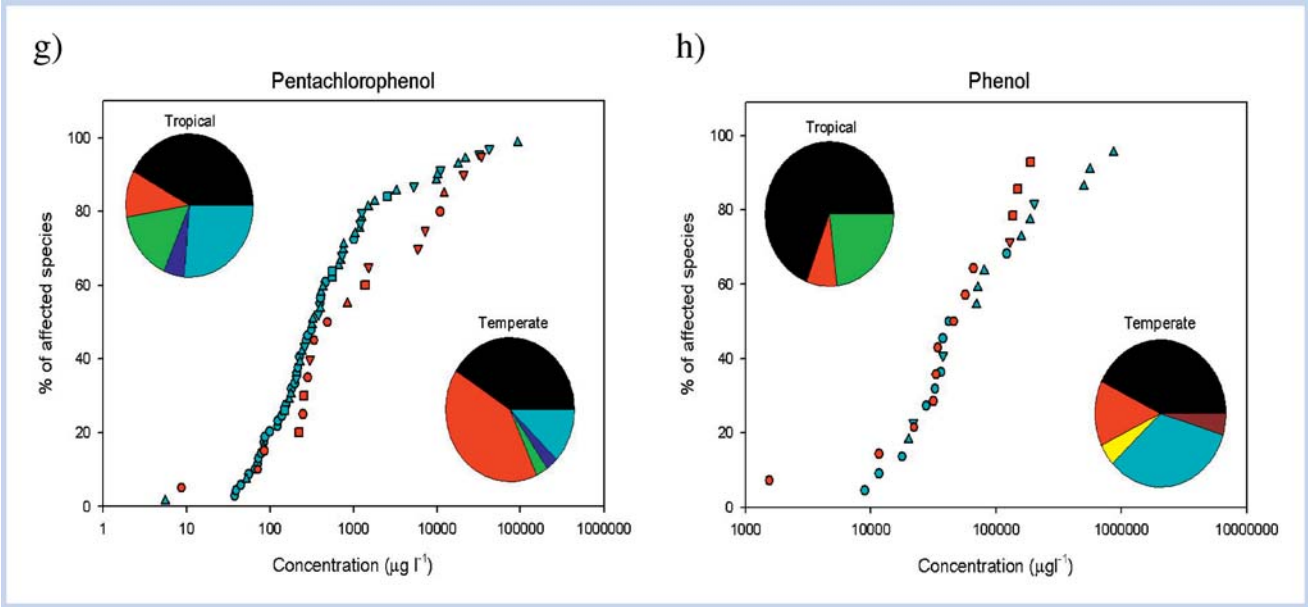

Figure 3. Continued.

appeared to be more sensitive than tropical species. In contrast, Markich and Camilleri (1997) found no difference in the sensitivity of the tropical Australian fish purple striped gudgeon (*Mogurnda mogurnda*) and the temperate US fish species to copper and uranium. Perschbacher (2005) has recently showed that the toxicity of copper to the temperate catfish *Ictalurus punctatus* also increases with decreasing temperature. Perschbacher (2005) proposed that such an increase in toxicity might be associated with reduced resistance mechanisms to copper at lower temperatures, including decreased enzyme production and rates of activity, decreased membrane transport and clearance rates from the body, and decreased mucus production (Sprague 1985; Perschbacher 2005). In zebrafish *Danio rerio* embryos, cadmium toxicity was greatest at low temperatures, then at high temperatures, and was lowest at an intermediate temperature (Hallare et al. 2005).

Temperature–toxicity relationships in invertebrates are also complex. For example, the toxicity of some trace metals to the tubificid worm *Tubifex tubifex* is greatest at intermediate temperatures, whereas toxicity generally increases with increasing temperatures (Rathore and Khangarot 2002). The toxicity of phenol to the aquatic sowbug *Asellus aquaticus* is greater at lower temperatures than at higher temperatures, with the lowest toxicity at an intermediate temperature (Cebrian et al. 1993). In contrast, the sensitivity of the red-swamp crayfish *Procambarus clarkii* toward lindane appeared to be unaffected by temperature change (Green et al. 1988). These complex and contradictory findings invite further study and validation with a wider range of chemicals and species (including more invertebrate phyla).

The influence of temperature on the chemistry of bioassay systems could be as important as, and difficult to separate from, the biological effects of temperature. Some internationally recognized test guidelines (e.g., OECD guidelines) permit considerable freedom in the way that toxicity tests are performed, analyzed, and reported. Differences between test methods for related tropical and temperate species are likely to be a major source of variability (Whitehouse et al. 1996; Worboys et al. 2002). Tropical tests were conducted at significantly higher temperatures than temperate tests for 13 of the chemicals examined in this paper (Table 2). Higher test temperatures in toxicity tests with tropical species might lead to an increase in the bioavailability of some chemicals in the test solutions, making tropical species appear to be more sensitive. The extrinsic effect of temperature because of higher test temperature of tropical species and intrinsic differences in sensitivities between tropical and temperate species are difficult to decouple. However, because tropical environments experience higher temperatures than temperate environments, the 2 effects are likely to act together in the natural environment; therefore, although decoupling the effects of these 2 parameters is scientifically interesting, it is not environmentally relevant.

Data availability and data quality

Differences in the availability of toxicity data for different taxa could also introduce bias into SSDs. We cannot, a priori, assume that an SSD with 7 to 70 species of 3 to 10 different taxonomic groups can fully represent all species present in the natural environment and thereby provide an accurate picture of underlying species sensitivity. However, this uncertainty can never be removed completely until we have toxicity data for all species that occur in an ecosystem. To deal with such extrapolation uncertainty (i.e., from a few species to the field situation), the knowledge gaps need to be filled by generating new tropical and temperate toxicity data for several chemicals for taxa currently underrepresented in, or absent from, datasets. During this study, we have also identified toxicity data gaps for these 18 selected chemicals (Table 4). As anticipated, more temperate toxicity data are available than for tropical species (e.g., tropical mollusk data were missing for almost half of the chemicals examined). Further toxicity tests are required to generate acute and chronic ecotoxicity data to fill these knowledge gaps and to increase confidence in predicting tropical WQCs.

Because of limited availability of toxicity data, especially tropical data, data from ecotoxicity tests with nominal

Table 3. Tropical and temperate hazardous concentrations corresponding to 90% protection (HC10) values and temperate/tropical HC10 ratios of each chemical and their 95% confidence limits in parentheses generated in 4 different ways on the basis of a) best fit parametric species sensitivity distributions (SSDs) (log-normal and log-logistic SSDs) with good model fit; b) nonparametric bootstrap SSD, excluding the 4 chemicals with fewer than 10 data points in the tropical; c) HC10 values of (b) plus HC10 values of bootstrap regression SSDs of the 4 chemicals with fewer than 10 tropical data points; and d) HC10 values derived with the approach proposed by Stephan et al. (1985); ND indicates not determined

		a) Best fit parametric		b) Nonparametric bootstrap		c) Bootstrap regression		d) Stephan et al. (1985) approach	
		HC10	HC10 ratio	HC10	HC10 ratio	HC10	HC10 ratio	HC10	HC10 ratio
Ammonia	Tropical	64.91 (25.41, 135.0)	4.258 (1.602, 14.55)	200.0 (175.2,1,430)	2.380 (0.905, 3.205)	64.91 (9.218, 156.8)	4.258 (1.657, 14.34)	163.8 (87.70, 224.2)	2.507 (1.738, 4.833)
	Temperate	276.4 (207.0, 352.7)	—	476.0 (455.2, 600.3)	—	276.4 (197.7, 354.6)	—	410.7 (388.9, 429.0)	—
Arsenic	Tropical	ND	ND	ND	ND	624.3 (ND, 2,386)	8.214 (1.700, ∞)	340.3 (0.126, 1,689)	16.21 (2.762, 59,170)
	Temperate	ND	—	5,127 (3,980, 15,137)	—	5,775 (3,944, 7,209)	—	5,514 (4,142, 8,154)	—
Cadmium	Tropical	35.71 (29.61, 42.44)	0.366 (0.240, 0.556)	43.54 (26.60, 61.11)	0.297 (0.193, 0.625)	35.71 (28.95, 42.73)	0.366 (0.232, 0.558)	125.2 (118.6, 135.4)	0.310 (0.229, 0.394)
	Temperate	13.06 (9.112, 18.11)	—	12.94 (113.8, 281.3)	—	13.06 (8.463, 18.53)	—	3.440 (0.767, 6.599)	—
Chromium	Tropical	2056 (1,382, 2,800)	0.220 (0.128, 0.387)	1,497 (1,285, 8,819)	0.175 (0.078, 0.328)	2,056 (1,219, 3,160)	0.220 (0.121, 0.406)	1,677 (1,197, 2,139)	0.161 (0.088, 0.455)
	Temperate	452.7 (285.0, 666.1)	—	261.7 (195.0, 541.2)	—	452.7 (265.7, 677.2)	—	269.3 (183.9, 555.7)	—
Copper	Tropical	ND	ND	21.00 (21.00, 40.18)	0.353 (0.202, 0.598)	18.92 (16.13, 21.65)	0.149 (0.079, 0.252)	21.92 (12.73, 208.4)	0.368 (0.035, 0.750)
	Temperate	ND	—	7.421 (6.998, 11.23)	—	2.823 (1.474, 4.477)	—	8.075 (7.257, 9.556)	—
Lead	Tropical	249.6 (179.4, 333.9)	0.301 (0.165, 0.497)	251.8 (244.6, 867.7)	0.396 (0.160, 1.376)	249.6 (172.6, 339.0)	0.301 (0.163, 0.539)	313.7 (230.2, 420.5)	0.285 (0.151, 0.423)
	Temperate	75.14 (48.81, 109.9)	—	99.82 (66.55, 416.5)	—	75.14 (46.79, 117.5)	—	89.50 (62.58, 112.4)	—
Mercury	Tropical	30.85 (26.80, 35.24)	0.489 (0.388, 0.610)	32.48 (27.45, 72.83)	0.592 (0.193, 1.115)	30.85 (26.20, 35.89)	0.489 (0.390, 0.609)	31.31 (19.01, 77.47)	0.290 (0.061, 0.976)
	Temperate	15.09 (12.66, 17.69)	—	19.21 (9.982, 37.12)	—	15.09 (12.36, 17.87)	—	9.087 (4.727, 19.02)	—

Table 3. Continued

		a) Best fit parametric		b) Nonparametric bootstrap		c) Bootstrap regression		d) Stephan et al. (1985) approach	
		HC10	HC10 ratio	HC10	HC10 ratio	HC10	HC10 ratio	HC10	HC10 ratio
Nickel	Tropical	2,018 (1,440, 2,668)	0.087 (0.083, 0.210)	ND	ND	2,018 (1,231, 2,930)	0.118 (0.082, 0.180)	2,205 (1,646, 2,610)	0.106 (0.085, 0.156)
	Temperate	166.7 (119.1, 219.5)	—	238.0 (215.8, 342.2)	—	166.7 (110.3, 230.9)	—	233.4 (220.5, 247.4)	—
Silver	Tropical	ND	ND	ND	ND	3.396 (2.195, 4.228)	0.579 (0.438, 1.149)	3.058 (1.357, 4.045)	0.706 (0.486, 1.833)
	Temperate	ND	—	1.967 (1.837, 4.692)	—	0.901 (0.399, 1.679)	—	2.159 (1.932, 2.508)	—
Zinc	Tropical	128.6 (99.24, 161.6)	2.421 (1.906, 3.230)	173.4 (153.7, 285.6)	1.966 (1.336, 2.751)	128.6 (97.48, 163.1)	2.421 (1.844, 3.209)	160.4 (145.9, 173.2)	2.104 (1.843, 2.429)
	Temperate	311.2 (290.7, 332.5)	—	340.9 (297.4, 413.8)	—	311.2 (290.0, 334.8)	—	337.4 (313.5, 355.9)	—
Carbaryl	Tropical	ND	ND	19.39 (16.45, 38.08)	0.396 (0.176, 0.509)	48.25 (27.57, 76.12)	0.218 (0.137, 0.394)	20.36 (19.21, 21.72)	0.392 (0.357, 0.421)
	Temperate	ND	—	7.680 (7.451, 9.050)	—	10.51 (8.457, 13.04)	—	7.987 (7.750, 8.258)	—
Chlordane	Tropical	ND	ND	ND	ND	2.051 (0.023, 12.01)	2.354 (0.447, 16.08)	3.031 (ND, ND)	1.640 (ND)
	Temperate	ND	—	4.828 (3.234, 20.01)	—	6.356 (2.660, 10.07)	—	4.970 (4.137, 6.000)	—
Chlorpyrifos	Tropical	ND	ND	0.163 (0.119, 0.289)	1.596 (0.888, 2.799)	0.076 (0.046, 0.111)	1.836 (1.119, 3.113)	0.160 (0.134, 0.187)	1.610 (1.177, 2.183)
	Temperate	ND	—	0.259 (0.191, 0.364)	—	0.139 (0.106, 0.181)	—	0.257 (0.220, 0.305)	—
DDT	Tropical	ND	ND	4.509 (4.394, 33.52)	0.550 (0.109, 0.999)	2.096 (0.414, 6.375)	0.281 (0.062, 1.402)	3.554 (0.080, 7.310)	0.631 (0.008, 35.92)
	Temperate	ND	—	2.479 (2.011, 4.908)	—	0.589 (0.233, 1.153)	—	2.242 (0.005, 30.95)	—
Lindane	Tropical	4.319 (3.139, 5.784)	0.897 (0.656, 1.277)	4.831 (4.640, 11.79)	0.828 (0.412, 1.039)	4.319 (3.139, 5.784)	0.897 (0.632, 1.360)	5.452 (4.249, 6.824)	0.804 (0.613, 1.076)

Table 3. Continued

		a) Best fit parametric		b) Nonparametric bootstrap		c) Bootstrap regression		d) Stephan et al. (1985) approach	
		HC10	HC10 ratio	HC10	HC10 ratio	HC10	HC10 ratio	HC10	HC10 ratio
	Temperate	3.872 (3.279, 4.509)	—	4.000 (3.900, 5.017)	—	3.872 (3.280, 4.553)	—	4.384 (4.108, 4.663)	—
Malathion	Tropical	472.0 (241.0, 746.2)	0.138 (0.008, 0.056)	294.3 (170.0, 2,187)	0.013 (0.004, 0.034)	472.0 (117.3, 802.4)	0.014 (0.008, 0.058)	304.0 (144.3, 510.2)	0.013 (0.007, 0.031)
	Temperate	6.525 (4.394, 9.389)	—	3.840 (3.083, 9.121)	—	6.525 (4.185, 9.712)	—	4.067 (3.603, 4.661)	—
Pentachlor-ophenol	Tropical	ND	ND	71.75 (25.13, 233.4)	0.921 (0.400, 3.448)	34.26 (20.69, 51.09)	1.016 (0.661, 1.801)	39.15 (22.13, 78.98)	1.651 (0.796, 3.045)
	Temperate	ND	—	66.10 (57.83, 74.24)	—	34.82 (27.80, 42.76)	—	64.63 (61.42, 67.43)	—
Phenol	Tropical	5,267 (2,730, 8,264)	1.928 (1.090, 4.342)	3,484 (1,902, 31,500)	3.656 (0.682, 8.153)	5,267 (1,305, 9,321)	1.928 (1.172, 7.252)	3,505 (1,728, 5,808)	3.872 (2.215, 8.585)
	Temperate	10,151 (8,510, 12,331)	—	12,739 (11,833, 21,342)	—	10,151 (7,739, 12,453)	—	13,572 (12,198, 14,872)	—

Table 4. Missing taxonomic groups in the freshwater species sensitivity distributions (SSDs)

	Temperate SSD				Tropical SSD			
Chemical	Fish	Crustacea	Mollusca	Others	Fish	Crustacea	Mollusca	Others
Ammonia	✓	✓	—[a]	✓	✓	✓	—	✓
Arsenic	✓	✓	✓	✓	✓	—	—	✓
Cadmium	✓	✓	✓	✓	✓	✓	✓	✓
Chromium	✓	✓	✓	✓	✓	✓	✓	✓
Copper	✓	✓	✓	✓	✓	✓	✓	✓
Lead	✓	✓	✓	✓	✓	✓	✓	✓
Mercury	✓	✓	✓	✓	✓	✓	✓	✓
Nickel	✓	—	✓	✓	✓	✓	✓	✓
Silver	✓	✓	✓	✓	✓	✓	✓	✓
Zinc	✓	✓	✓	✓	✓	✓	✓	✓
Carbaryl	✓	✓	—	✓	✓	✓	✓	✓
Chlordane	✓	✓	—	✓	✓	—	—	—
Chlorpyrifos	✓	✓	—	✓	✓	✓	—	✓
DDT	✓	✓	—	✓	✓	✓	—	—
Lindane	✓	✓	—	✓	✓	✓	—	✓
Malathion	✓	✓	✓	✓	✓	—	—	—
Pentachlorophenol	✓	✓	✓	✓	✓	✓	✓	✓
Phenol	✓	✓	✓	—	✓	✓	—	✓

[a]Indicates that taxonomic group is missing.

concentrations or unreported control mortality were used in this study. The majority of tropical toxicity data was based on nominal concentrations, whereas a few data sources did not report control mortality. In general, the quality of temperate toxicity data were higher because they often consist of standard test organisms for which toxicity test procedures were highly standardized. The lower quality of tropical data could be a source of uncertainty or systematic bias in this study.

In addition, several other confounding factors, such as difference in exposure periods, water hardness, and pH (USEPA 1985) could have affected the conclusions of this study. However, because of the limited tropical data, standardization of these test conditions would have resulted in insufficient data for analysis. This also highlights the importance of conducting good quality toxicity tests with the use of tropical organisms to fill the data gaps recognized and to explain this issue more explicitly.

Species composition of SSDs

Species sensitivity distribution models assume a random selection of test species, which is rarely the case (Forbes and Calow 2002a, 2002b). Indeed, a major cause of differences between sensitivity distributions of tropical and temperate organisms could be due to differences in the taxonomic composition of the datasets. Difference in species composition between tropical and temperate SSDs were most evident for pesticides because tropical datasets contained much higher proportions of fish data whereas temperate datasets contained large proportions of fish, crustacean, and insect data (Figure 3, pie charts). Furthermore, SSDs constructed with the use of all available data from different taxa might contain several subdistributions, possibly related to taxonomic differences in sensitivity (Newman et al. 2000) that might not be adequately described by a parametric regression model. This is especially evident in the SSDs for pesticides in this study (e.g., DDT and PCP; Figure 3d and g). For instance, pesticides often exhibit a specific mode of action; thus, a single parametric SSD model might not be able to describe the sensitivity of all taxa. In such cases, Maltby et al. (2005) suggested that the SSD should be based on the most sensitive taxonomic group, for which the parametric model fit would be better.

To investigate this, SSDs could be constructed with the use of organisms from the same phylum or order with the use of crustacean or fish data only (Solomon and Sibley 2002; Maltby et al. 2005). Such taxa-specific SSD comparisons are essential to help identify the sensitive or tolerant taxonomic group(s) to the test chemical (Maltby et al. 2005), and the results are also complementary to those based on SSDs constructed with all available species.

Choice of SSD approaches

The parametric approach (i.e., log-normal or log-logistic model) is mathematically simple to use and has been widely used in probabilistic risk assessments for pesticides (Solomon et al. 1996; Giesy et al. 1999; Hall et al. 2000). However, the problem of poor goodness of fit limited its use in this and other studies. Newman et al. (2000), for example, has shown that 15 of 30 datasets tested failed conformity tests for the

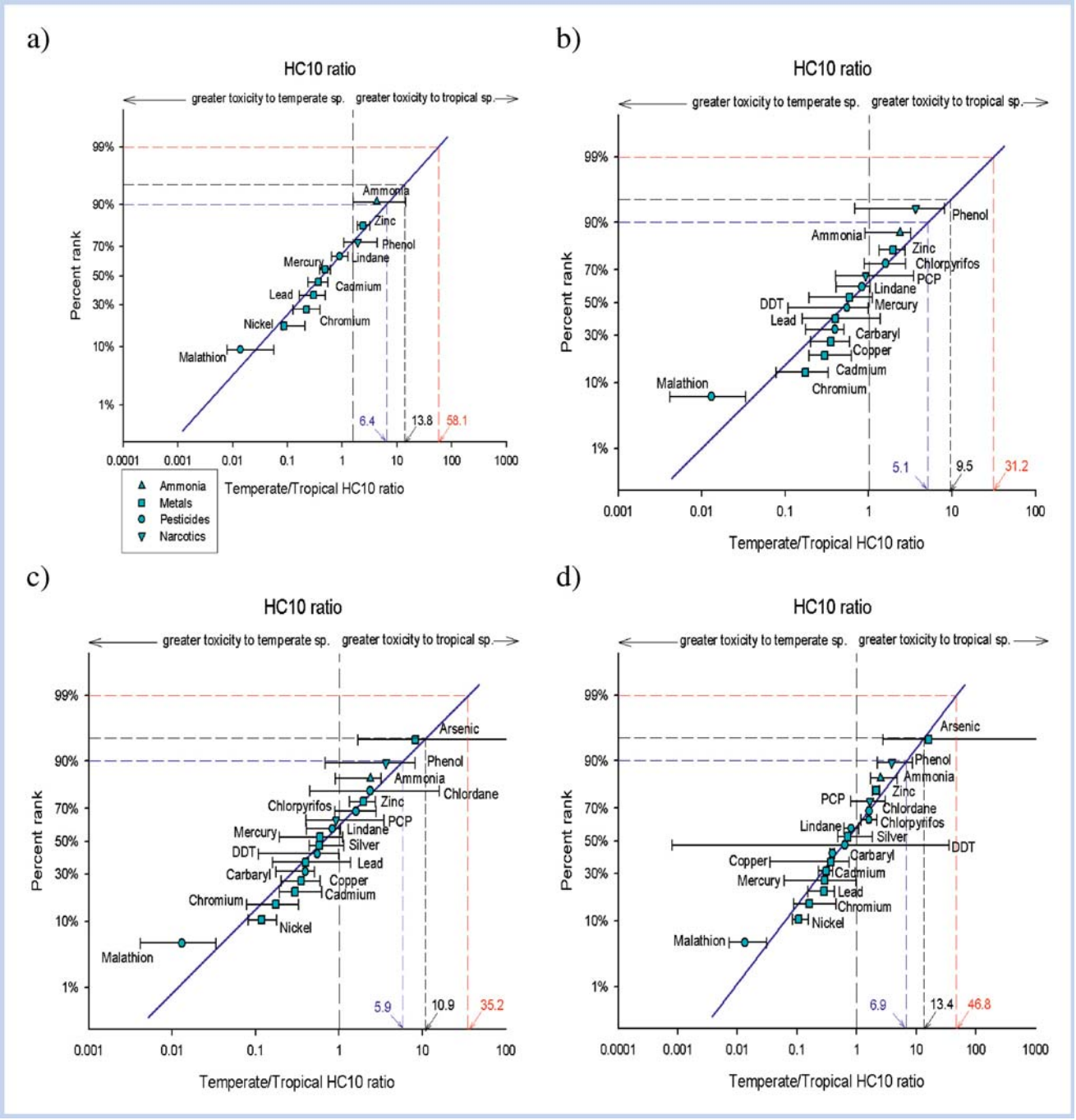

Figure 4. Relationship between temperate/tropical hazardous concentration for 10% (HC10) of species ratios and chemical classes on the basis of (**a**) best fit parametric species sensitivity distributions (SSDs) (log-normal or log-logistic SSDs) with good model fit; (**b**) nonparametric bootstrap SSD, excluding the 4 chemicals with fewer than 10 data points in the tropical; (**c**) HC10 values of (b) plus HC10 values of bootstrap regression SSDs of the 4 chemicals with fewer than 10 tropical data points; and (**d**) HC10 values derived using the approach of Stephan et al. (1985). Horizontal error bars denote the 95% confidence limits of the HC10 ratios.

log-normal distribution. Similar results were observed in this study, in which 13 of 23 datasets failed the AD goodness of fit test (Table 1). Also during the derivation of the Australian and New Zealand water quality guidelines (ANZECC and ARMCANZ 2000), it was found that the log-logistic distribution failed to fit approximately one third of the datasets (MStJ Warne, Ecotoxicology Section, Environment Protection Authority New South Wales, Australia, personal communication). The use of a nonparametric approach can avoid the problem associated with goodness of fit; however, estimation of HC*x* values might be limited by the number of data points. For instance, to estimate HC10 value of a dataset, at least 10 data points are needed. The results of this study, nonetheless, indicate that the choice of SSD approaches does not affect the overall pattern of sensitivity differences between tropical and temperate species. In general, temperate freshwater organisms are more sensitive to metals, whereas their tropical counterparts are more sensitive to ammonia, phenol, and some pesticides (Table 3). This difference in sensitivities of tropical and temperate species did not appear to be consistent (HC10 ratios varied from 0.013 to 16.2). Therefore, it would be difficult to predict tropical species

Table 5. The interspecies assessment factors for a range of different interspecies extrapolations that should protect 95% and 99% of species

Type of interspecies extrapolation	Interspecies assessment factors to protect a theoretical percentage of all species	
	95%	99%
Species within genus[a]	10.0	16.3
Genera within family[a]	11.7	16.9
Families within order[a]	99.5	145.0
Orders within class[a]	64.8	87.5
Classes within phylum[b]	1,000	
Freshwater to saltwater[c]	7.2	8.8
Temperate to tropical[d]	10	40

[a] Obtained from Calabrese and Baldwin (1993).
[b] Obtained from Sloof et al. (1986).
[c] Obtained from Leung et al. (2001).
[d] This study.

sensitivity toward a new chemical solely on the basis of temperate data.

Comparison with other similar studies

Two similar studies comparing sensitivities of tropical and temperate freshwater species on the basis of acute data of a single taxonomic group to pesticides (Dyer et al. 1997; Maltby et al. 2005) have also demonstrated some differences in species sensitivity between the 2 climate regions, although such differences are not substantial. On the basis of arthropod data, Maltby et al. (2005) compared sensitivities of tropical and temperate arthropods to 3 pesticides (chlorpyrifos, fenitrothion, carbofuran) with the use of log-normal SSD and demonstrated that tropical HC5 values were consistently smaller than the temperate HC5 values of all 3 pesticides, although these differences were not statistically significant. Dyer et al. (1997) compared medians of LC50 values of 4 pesticides (carbaryl, DDT, lindane, and malathion) and 2 narcotics (phenol and PCP) solely on the basis of fish species. They concluded that no apparent difference in sensitivity was observed between tropical and temperate fish species, but sensitivity between coldwater and temperate fish species, as well as coldwater and tropical fish species, for most of these 6 chemicals were significantly different. Some discrepancies exist between the results from this study and that of Dyer et al. (1997), which could be due to differences in the methods employed, the taxa chosen for comparison, and the number of chemicals and chemical class compared. Unlike their studies, we used a "universal" collection of species in the SSDs and also compared the species sensitivity to trace metals between tropical and temperate species.

Comparison with other extrapolation factors

On the basis of the results of objective comparisons of HC10 ratios between temperate and tropical freshwater animal species, we recommend an extrapolation factor of approximately 10 for coverage of 95% of chemicals with 90% protection level, if a priori knowledge on the sensitivity of tropical species is very limited or not available. Calabrese and Baldwin (1993) suggested extrapolation factors from 10 to 1,000 when extrapolating between different levels of the classification hierarchy (Table 5). Our suggested extrapolation factor (i.e., 10) not only fits well within the range of documented factors but is also reasonable and practical. If there is a desire to reduce the level of environmental protection offered or the magnitude of the extrapolation factor and the consequent cost of protection, regulatory authorities might consider applying a factor of 6 (covering 90% of chemicals with 90% of protection level). Even the smaller extrapolation factor will provide considerably improved protection over the current practice of using surrogate WQCs directly in tropical or subtropical regions.

CONCLUSIONS

These SSD comparisons demonstrate differences in species sensitivities to different chemicals between tropical and temperate aquatic organisms. For 6 of the 18 chemicals examined (ammonia, arsenic, zinc, chlorpyrifos, chlordane, and phenol), tropical organisms are likely to be more sensitive than temperate ones. For chemicals that have never been tested with tropical species, or when there is insufficient toxicity data for tropical species, an extrapolation factor should be applied to temperate data. The magnitude of this extrapolation should be flexible, whereas small factors of 6 (protective for 90% of species for 90% of chemicals) to 12 (protective for 90% of species for 95% of chemicals; 10 for ease of use) could greatly increase the safety margin to safeguard tropical species. Without extrapolation, a factor of 1 would protect 90% of species for more than 60% of chemicals. However, further validation of these factors is required by conducting ecotoxicity tests for currently untested chemicals with the use of both tropical and temperate species. This study also revealed some major toxicity data gaps for tropical regions—in particular, a lack of mollusk data.

With rapid population growth, industrialization, and urbanization in the tropics and subtropics, more chemicals are likely to be released into tropical aquatic systems. To protect limited freshwater resources and unique aquatic biodiversities, it is important that regulatory authorities establish legislation with appropriate water quality guidelines and effective enforcement. In this study, we provide an initial derivation of a defensible extrapolation factor for tropical countries to apply for regulatory purposes if adopting PNECs or toxicity data derived from temperate species.

Acknowledgment—This study was supported by a grant of the University of Hong Kong (project 1020-4904/5692) and the Area of Excellence Scheme under the University Grants Committee of the Hong Kong Special Administration Region, China (project AoE/P-04/2004). The authors also thank the 3 anonymous reviewers and the editors of the Journal for their valuable comments on early drafts of this manuscript.

REFERENCES

Aldenberg T, Jaworska JS. 2000. Uncertainty of the hazardous concentration and fraction affected for normal species sensitivity distributions. *Ecotoxicol Environ Saf* 46:1–18.

Aldenberg T, Slob W. 1993. Confidence limits for hazardous concentrations based on logistically distributed NOEC toxicity data. *Ecotoxicol Environ Saf* 25:48–63.

Anderson TW, Darling DA. 1954. A test of goodness of fit. *J Am Stat Assoc* 49:765–769.

[ANZECC and ARMCANZ] Australian and New Zealand Environment and Conservation Council and the Agriculture and Resource Management Council of Australia and New Zealand. 2000. Australian and New Zealand guidelines for fresh and marine water quality. Canberra (AU): ANZECC and ARMCANZ.

Brecken-Folse JA, Mayer FL, Pedigo LE, Marking LL. 1994. Acute toxicity of 4-nitrophenol, 2,4-dinitrophenol, terbufos and trichlorfon to grass shrimp (*Palaemonetes* spp.) and sheepshead minnows (*Cyprinodon variegates*) as affected by salinity and temperature. *Environ Sci Technol* 13:67–77.

Brix KV, DeForest DK, Adams WJ. 2001. Assessing acute and chronic copper risk to freshwater aquatic life using species sensitivity distributions for different taxonomic groups. *Environ Toxicol Chem* 20:1846–1856.

Cairns J Jr, Heath AG, Parker BC. 1975. The effects of temperature upon the toxicity of chemicals to aquatic organisms. *Hydrobiologia* 47:135–171.

Calabrese EJ, Baldwin LA. 1993. Performing ecological risk assessments. Boca Raton (FL): Lewis.

Campbell E, Palmer MJ, Shao Q, Warne MStJ, Wilson D. 2000. BurrliOZ: A computer program for the estimation of the trigger values for the ANZECC and ARMCANZ water quality guidelines. In: National water quality management strategy, Australian and New Zealand Guidelines for fresh and marine water quality. Canberra (AU): Australian and New Zealand Environment and Conservation Council and Agriculture and Resource Management Council of Australia and New Zealand.

Canadian Council of Ministers of the Environment 1991. A protocol for the derivation of water quality guidelines for the protection of aquatic life (April 1991). In: Canadian Environmental Quality Guidelines. Canadian Council of Resource and Environment Ministers, 1987. Appendix 9. Prepared by the Task Force on Water Quality Guidelines. Updated and reprinted with minor revisions and editorial changes in Canadian environmental quality guidelines. Chapter 4. Canadian Council of Ministers of the Environment, 1999. Winnipeg (CA).

Castillo LE, Fruz EDL, Ruepert C. 1997. Ecotoxicology and pesticides in tropical aquatic ecosystems of central America. *Environ Toxicol Chem* 16:41–51.

Cebrian C, Moliner EA, Gamon M. 1993. The effect of time, concentration and temperature on bioaccumulation in the gill of crayfish *Procambarus clarkii* induced by organochlorine pesticides, lindane and endosulfan. *Comp Biochem Physiol C Comp Pharmacol* 104:445–551.

Doudoroff P, Anderson BG, Burdick GE, Galsoff PS, Hart WB, Patrick R, Strong ER, Surber EW, Horn WMV. 1951. Bio-assay methods for the evaluation of acute toxicity of industrial waters to fish. *Sewage Ind Wastes* 23:1380–1397.

Dyer SD, Belanger SE, Carr GJ. 1997. An initial evaluation of the use of Euro/North American fish species for tropical effects assessments. *Chemosphere* 35:2767–2781.

Erickson RJ. 1985. An evaluation of mathematical-models for the effects of pH and temperature on ammonia toxicity to aquatic organisms. *Water Res* 19:1047–1058.

[FIFRA] Federal Insecticide, Fungicide, and Rodenticide Act. 1996. Federal Insecticide, Fungicide, and Rodenticide Act. 7 U.S.C. s/s 136 et seq. USA.

Forbes VE, Calow P. 2002a. Extrapolation in ecological risk assessment: Balancing pragmatism and precaution in chemical controls legislation. *Bioscience* 52:249–257.

Forbes VE, Calow P. 2002b. Species sensitivity distributions revisited: A critical appraisal. *Human Ecological Risk Assessment* 8:473–492.

Giesy JP, Solomon KR, Coates JR, Dixon KR, Giddings JM, Kenaga EE. 1999. Chlorpyrifos: Ecological risk assessment in North American aquatic environments. *Rev Environ Contam Toxicol* 160:1–129.

Green DWJ, Williams KA, Hughes DRL, Shaik CAG, Pascoe D. 1988. Toxicity of phenol to *Asellus aquaticus* (L.)—Effects of temperature and episodic exposure. *Water Res* 22:225–231.

Grist EPM, Leung KMY, Wheeler JR, Crane M. 2002. Better bootstrap estimation of hazardous concentration thresholds for aquatic assemblages. *Environ Toxicol Chem* 21:1515–1524.

Hall LW, Scott MC, Killen WD, Unger MA. 2000. A probabilistic ecological risk assessment of tributyltin in surface waters of the Chesapeake Bay watershed. *Human Ecological Risk Assessment* 6:141–179.

Hall P. 1992. The bootstrap and Edgeworth expansion. New York (NY): Springer-Verlag.

Hallare AV, Schirling M, Luckenbach T, Köhler H-R, Triebskorn R. 2005. Combined effects of temperature and cadmium on developmental parameters and biomarker responses in zebrafish (*Danio rerio*) embryos. *J Therm Biol* 30:7–17.

Howe GE, Marking LL, Bills TD, Rach JJ, Mayer FL. 1994. Effects of water temperature and pH on toxicity of terbufos, trichlorfon, 4-nitrophenol and 2,4-dinitrophenol to the amphipod *Gammarus pseudolimnaeus* and rainbow trout *Oncorhynchus mykiss*. *Environ Toxicol Chem* 13:51–66.

Kim YH, Cowan CE, Sanchez-Osuna M, Kimerle R. 2001. Environmental risk assessment and management of chemicals in Asia/Pacific countries. In: Proceedings of the UNIDO/SETAC Regional Symposium and Workshop,held at Seoul, Republic of Korea, April 20–24, 1998; United Nations Industrial Development Organization; Seoul (KR): Hanrimwon.

Kwok KWH, Leung KMY. 2005. Toxicity of antifouling biocides to the intertidal harpacticoid copepod *Tigriopus japonicus* (Crustacea, Copepoda): Effects of temperature and salinity. *Mar Pollut Bull* 51:830–837.

Lam PKS, Gray JS. 2001. Predicting effects of toxic chemicals in the marine environment. *Mar Pollut Bull* 42:169–173.

Lam PKS, Wu RSS. 1999. Developing ecotoxicity tests for coastal protection and management in Hong Kong. In: Conference Proceedings 12/PEMSEA: Challenges and opportunities in managing pollution in the East Asian seas; MPP-EAS. Quezon City (PH): PEMSEA. p 410–418.

Lecher TE, Goldstein MI. 1997. Tropical ecotoxicology: Status and needs. *Environ Toxicol Chem* 16:100–111.

Leung KMY, Morritt D, Wheeler J, Whitehouse P, Sorokin N, Toy R, Holt M, Crane M. 2001. Can saltwater toxicity be predicted from freshwater data? *Mar Pollut Bull* 42:1007–1013.

Lydy MJ, Belden JB, Ternes MA. 1999. Effects of temperature on the toxicity of *m*-parathion, chlorpyrifos, and pentachlorobenzene to *Chironomus tentans*. *Arch Environ Contam Toxicol* 37:542–547.

Maltby L, Blake N, Brock TCM, Van den Brink PJ. 2005. Insecticide species sensitivity distributions: Importance of test species selection and relevance to aquatic ecosystems. *Environ Toxicol Chem* 24:379–288.

Markich SJ, Camilleri C. 1997. Investigation of metal toxicity to tropical biota: Recommendations for revision of the Australian water quality guidelines. Report 127, Supervising Scientist. Canberra (AU): Department of the Environment and Heritage.

Newman MC, Ownby DR, Mezin LCA, Powell DC, Christensen TL, Lerberg SB, Anderson BA. 2000. Applying species-sensitivity distributions in ecological risk assessment: Assumptions of distribution type and sufficient numbers of species. *Environ Toxicol Chem* 19:508–515.

[OECD] Organization for Economic Cooperation and Development. 1995. Guidance document for aquatic effects assessment. Paris (FR): OECD Environment Monograph 92, Environment Directorate.

Perschbacher PW. 2005. Temperature effects on acute copper toxicity to juvenile channel catfish *Ictalurus punctatus*. *Aquaculture* 243:225–228.

Peters EC, Gassman NJ, Firman JC, Richmond RH, Power EA. 1997. Ecotoxicology of tropical marine ecosystems. *Environm Toxicol Chem* 16:12–40.

Rathore RS, Khangarot BS. 2002. Effects of temperature on the sensitivity of sludge worm *Tubifex tubifex* Müller to selected heavy metals. *Ecotoxicol Environ Saf* 53:27–36.

Sloof W, Van Oers JA, De Zwart D. 1986. Margins of uncertainty in exotoxicological hazard assessment. *Environ Toxicol Chem* 5:841–852.

Solomon KR, Baker DB, Richards RP, Dixon KR, Klaine SJ, La Point TW, Kendall RJ, Weisskopf LW, Giddings JM, Giesy JP, Hall LW, Williams WM. 1996. Ecological risk assessment of atrazine in North American surface waters. *Environ Toxicol Chem* 15:31–76.

Solomon KR, Giddings JM, Maund SJ. 2001. Probabilistic risk assessment of cotton pyrethroids: I. Distributional analyses of laboratory aquatic toxicity data. *Environ Toxicol Chem* 20:652–659.

Solomon KR, Sibley P. 2002. New concepts in ecological risk assessment: Where do we go from here? *Mar Pollut Bull* 44:279–285.

Sprague JB. 1985. Factors that modify toxicity. In: Rand GM, Petrocelli SR, editors. Fundamentals of aquatic toxicology. Bristol (UK): Taylor & Francis. p 124–163.

Stephan CE, Mount DI, Hansen DJ, Gentile JH, Chapman GA, Brungs WA. 1985. Guidelines for deriving numerical national water quality criteria for the protection of aquatic organisms and their uses. Washington DC: USEPA Report PB-85-227049.

[USEPA] US Environmental Protection Agency. 1985. Ambient water criteria for copper. Washington DC: EPA-440/5-84-31.

Versteeg DJ, Belanger SE, Carr GJ. 1999. Understanding single-species and model ecosystem sensitivity: Data-based comparison. *Environ Toxicol Chem* 18:1329–1346.

Viswanathan PN, Murti KCR. 1989. Effects of temperature and humidity on ecotoxicology of chemicals. In: Bourdeau P, Haines JA, Klein W, Krishna Murti CR, editors. Ecotoxicology and climate. Chichester (UK): John Wiley & Sons. p 139–154.

Wagner C, Lokke H. 1991. Estimation of ecotoxicological protection levels from NOEC toxicity data. *Water Res* 25:1237–1242.

Wheeler JR, Grist EPM, Leung KMY, Morritt D, Crane M. 2002. Species sensitivity distribution: Data and model choice. *Mar Pollut Bull* 45:192–202.

Wheeler JR, Leung KMY, Morritt D, Whitehouse P, Sorokin N, Toy R, Holt M, Crane M. 2002. Freshwater to saltwater toxicity extrapolation using species sensitivity distributions. *Environ Toxicol Chem* 21:2459–2467.

Whitehouse P, Crane M, Redshaw CJ, Turner C. 1996. Aquatic toxicity tests for the control of effluent discharges in the UK—The influence of test precision. *Ecotoxicology* 5:155–168.

Willis KJ, Ling N, Chapman MA. 1995. Effects of temperature and chemical formulation on the acute toxicity of pentachlorophenol to *Simocephalus vetulus*. *N Z J Mar Freshw Res* 29:289–294.

Worboys MA, Leung KMY, Grist EPM, Crane M. 2002. Time should be considered in developmental ecotoxicity tests. *Mar Pollut Bull* 45:92–99.

Zar JH. 1999. Biostatistical analysis. Upper Saddle River (NJ): Prentice Hall. p 478–481.