

Tabulated observations of the pH tolerance of marine and estuarine biota

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TABULATED OBSERVATIONS OF
THE pH TOLERANCE OF MARINE AND ESTUARINE BIOTA

by

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Abstract

Compared to the situation in fresh waters, pH in the marine environment is well-buffered and relatively stable between 7.5 and 8.4 pH units. Nevertheless, pH can be altered outside this range by natural (e.g., photosynthesis) or anthropogenic (e.g., industrial) processes. The Canadian Water Quality Guideline for the Protection of Aquatic Life recommends that the pH of marine and estuarine waters be maintained between 7.0 and 8.7 pH units. This recommendation was based on a guideline developed by British Columbia in 1991. The present document provides an updated summary of published observations of pH tolerance of organisms in marine and estuarine habitats, including numerous studies published after 1991. This tabulation of the literature confirms that most pH-related impacts on survival, growth, photosynthesis, feeding and immune response occur at pH levels outside the recommended range. Some taxa, however, are notable for their tolerance of pH conditions well outside this range. Among the taxa tolerant of extremely high pH levels ($>10-11$ pH units), and potentially contributing to or even causing elevated pH through their photosynthetic activity, are several macroalgae commonly associated with “nuisance” blooms, including the green algae *Ulva lactuca* and *Enteromorpha* sp. A separate table was produced for the effects of acetic acid on biota as mortality from acetic acid exposure appears greater than that from other acids at the same pH, possibly because of the toxic effects of the acetate ion.

Résumé

Comparativement à la situation en eau douce, le pH en mer est bien tamponné et reste relativement stable, en se maintenant entre 7,5 et 8,4. Cependant, des processus naturels (p. ex., la photosynthèse) ou anthropiques (par. ex., des activités industrielles) peuvent faire baisser ou monter le pH en dehors de cette fourchette. Les Recommandations pour la qualité de l'eau en vue de la protection de la vie aquatique préconisent un maintien du pH des eaux marines et d'estuaire à une fourchette de 7 à 8,7. Ces recommandations sont fondées sur des lignes directrices élaborées par la Colombie-Britannique en 1991. Le document constitue une compilation d'observations publiées sur la tolérance d'organismes vivant dans des habitats marins et estuariens aux variations du pH, y compris de nombreuses études publiées après 1991. Cette compilation d'articles confirme que la plupart des impacts relatifs au pH sur la survie, la croissance, la photosynthèse, l'alimentation et la réaction immunitaire se manifestent à des niveaux de pH se situant à l'extérieur de la fourchette recommandée. Cependant, certains taxons se distinguent par leur tolérance à des conditions de pH qui se situent bien en dehors de cette fourchette. Parmi les taxons qui sont tolérants à des niveaux extrêmement élevés de pH (> 10 ou 11) et qui, en raison de leur activité photosynthétique, pourraient avoir un rôle dans la hausse du pH voire même en être la cause, se trouvent plusieurs macroalgues communément associées à la prolifération nuisible d'algues, y compris des algues vertes comme l'*Ulva lactuca* et l'*Enteromorpha*. Un tableau distinct, qui présente les effets de l'acide acétique sur le biote, a été créé, puisque la mortalité attribuable à une exposition à l'acide acétique est plus grande que la mortalité attribuable à d'autres acides possédant le même pH, probablement en raison des effets toxiques de l'ion acétate qu'il contient.

Introduction

While the role of hydrogen ion concentration has been extensively studied in Canada in the context of acidification of lakes and streams (e.g., NRCC 1981), pH has generally not been considered an important determinant of pelagic processes in marine environments (Hansen 2002). In comparison to the sensitivity of some fresh waters to altered hydrogen loading, the pH of sea water is relatively stable. A pH value between 7.5 and 8.4 is typical of full salinity seawater (Sverdrup et al. 1942), although photosynthesis can increase pH to 9 and rarely even to 10 in estuaries (Hansen 2002). Nevertheless, the pH of the ocean can be affected by anthropogenic factors operating on scales ranging from global to local. Oceanic absorption of CO₂ from fossil fuels is expected to result in larger pH changes over the next several centuries than any inferred from the geological record of the past 300 million years (Caldeira and Wickett 2003). Relative to preindustrial times, the oceans had acidified by 0.1 pH units by the year 2000, and geochemical models forecast a further decrease of nearly 0.8 pH units by the year 2300 (Pelejero et al. 2005). On the local scale, the pH of water bodies can be affected by additions of acidic or alkaline materials from industrial processes or other human activities. The compilation of literature summarized in the present document was motivated by a need to examine the effects on the surrounding environment of potentially pH-altering treatments (acetic acid and hydrated lime) used in the bivalve aquaculture industry to control fouling (Locke et al., in review).

An interim guideline for pH in Canadian marine and estuarine waters (published in CCME 1999, after CCME 1996) is as follows:

“The pH of marine and estuarine waters should fall within the range of 7.0-8.7 units unless it can be demonstrated that such a pH is a result of natural processes. Within this range, pH should not vary by more than 0.2 pH units from the natural pH expected at that time. Where pH is naturally outside that range, human activities should not cause pH to change by more than 0.2 pH units from the natural pH expected at that time, and any change should tend towards the recommended range (CCME 1996).”

The interim Canadian guideline was based largely on the guideline published for British Columbia in 1991 (CCME 1999). The objective of the present document is to provide, in tabular form, an updated summary of published pH observations on marine and estuarine organisms.

Methods

The scientific literature was searched for information on the pH tolerances of marine and estuarine biota. Relevant data were found in 49 papers. The data were reported here as given; no attempt was made to standardize the endpoints. A few authors conducted bioassays and reported the results as toxicological standard measurements such as “EC50” (pH at which 50% of organisms were affected), but these were the

exceptions. Unless otherwise specified, the given endpoint represents the level above or below which an observational study determined 100% mortality (or cessation of reproduction, feeding, etc.) occurred. Thus, a table entry for “Tolerance of acidic pH” indicating an endpoint of “Photosynthesis” and critical pH “7.0” would indicate that the organism was unable to photosynthesize at pH levels below 7.0. Likewise, an entry under “Tolerance of alkaline pH” citing a critical pH of “8.5” for endpoint “Mortality” would indicate no survival at pH > 8.5.

The results were tabulated by taxonomic/functional groups; heterotrophic microorganisms, Plantae (algae) and autotrophic microorganisms, Plantae (vascular macrophytes), Mollusca (Bivalvia), Arthropoda, other invertebrates, Ascidiacea, and Osteichthyes. Classification followed the Catalogue of Life: 2008 Taxonomic Checklist (www.catalogueoflife.org, accessed 23 July 2008). Within each taxonomic/functional group, pH tolerances were listed from lowest to highest pH.

A separate table was produced for tolerances of organisms to acetic acid. This pH-altering chemical has been of special interest in recent years for its potential to control abundances of Ascidiacea on aquaculture structures. Acetic acid appears to be more biocidal than other acids adjusted to the same pH (Forrest et al. 2007; Locke et al. in review), possibly because at pH <6.5, acetic acid acts to uncouple cellular communication (Germain and Anctil 1996).

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Table 1. pH tolerance of marine heterotrophic microorganisms.

(a) Tolerance of acidic pH

Taxon (Phylum) or functional group	Endpoint	Critical pH	Source
Methane bacteria	50% reduced growth	5.0	Hutton and Zobell 1949
Aerobic heterotrophs	50% reduced growth	6.5	Zobell 1941

(b) Tolerance of alkaline pH

Taxon (Phylum) or functional group	Endpoint	Critical pH	Source
<i>Favella ehrenbergii</i> , <i>Rimostrombidium caudatum</i> , <i>R. veniliae</i> (Ciliophora)	Reduced growth	8.8	Pederson and Hansen 2003
<i>Favella ehrenbergii</i> , <i>Rimostrombidium caudatum</i> , <i>R. veniliae</i> (Ciliophora)	Growth	9.0	Pederson and Hansen 2003
<i>Favella ehrenbergii</i> , <i>Rimostrombidium caudatum</i> , <i>R. veniliae</i> (Ciliophora)	24 h mortality	9.3	Pederson and Hansen 2003
<i>Balanion comatum</i> (Ciliophora)	Reduced growth	9.5	Pedersen and Hansen 2003

Table 2. pH tolerance of marine algae and photosynthetic microorganisms.

(a) Tolerance of acidic pH

Taxon (Phylum, Class)	Endpoint	Critical pH	Source
<i>Ulva lactuca</i> (Chlorophyta, Ulvophyceae)	Mortality	6.0-6.5	Hampson 1967
<i>Prorocentrum</i> <i>micans</i> , <i>Peridinium</i> sp. (Dinophyta, Dinophyceae)	Growth	6.0-7.0	Barker 1935
<i>Halimeda tuna</i> (Chlorophyta, Bryopsidophyceae)	Calcification	6.5	Borowitzka and Larkum 1976
<i>Palmaria longata</i> (Rhodophyta, Florideophyceae)	Photosynthesis	6.5	Robbins 1977
<i>Coccolithus</i> <i>(Emiliania) huxleyi</i> (Haptophyta, Prymnesiophyceae)	Photosynthesis	6.7	Paasche 1976
<i>Ectocarpus</i> sp. (Ochrophyta, Phaeophyceae)	Growth	7.0	Boalch 1961
<i>Bossiella orbigniana</i> (Rhodophyta, Florideophyceae)	Calcification	7.0	Smith and Roth 1979
<i>Nitzchia</i> sp., <i>Navicula</i> sp. (Bacillariophyta)	Growth	7.0	Bachrach and Luccicardi 1932
<i>Porphyra</i> sp. (Rhodophyta, Bangiophyceae), <i>Petalonia</i> sp. (Ochrophyta, Phaeophyceae), <i>Ulva</i> sp. (Chlorophyta, Ulvophyceae)	Photosynthesis	7.0	Ogata 1966
<i>Cricosphaera</i> <i>longata</i> (Haplophyta, Prymnesiophyceae)	Growth	7.4	Swift and Taylor 1966

Table 2. Continued.

(b) Tolerance of alkaline pH

Taxon (Phylum) or functional group	Endpoint	Critical pH	Source
<i>Ceratium tripos</i> (Dinophyta, Dinophyceae)	20% reduction in growth	8.24	Schmidt and Hansen 2001
<i>Ceratium furca</i> (Dinophyta, Dinophyceae)	20% reduction in growth	8.29	Schmidt and Hansen 2001
<i>Ceratium lineatum</i> (Dinophyta, Dinophyceae)	20% reduction in growth	8.30	Schmidt and Hansen 2001
<i>Ceratium tripos</i> (Dinophyta, Dinophyceae)	Growth	8.30	Schmidt and Hansen 2001
<i>Dictyocha speculum</i> (Ochrophyta, Chrysophyceae)	20% reduction in growth	8.30	Schmidt and Hansen 2001
<i>Ceratium furca</i> (Dinophyta, Dinophyceae)	Growth	8.40	Schmidt and Hansen 2001
<i>Skeletonema costatum</i> (Bacillariophyta)	20% reduction in growth	8.49	Schmidt and Hansen 2001
<i>Cylindrotheca closterium</i> (Bacillariophyta)	Growth	8.5	Humphrey 1975
<i>Heterosigma akashiwo</i> (Ochrophyta, Raphidophyceae)	20% reduction in growth	8.52	Schmidt and Hansen 2001
<i>Pyramimonas propulsa</i> (Prasinophyta, Prasinophyceae)	20% reduction in growth	8.55	Schmidt and Hansen 2001
<i>Alexandrium ostenfeldii</i> (Dinophyta, Dinophyceae)	20% reduction in growth	8.66	Schmidt and Hansen 2001

Table 2. Continued.

Taxon (Phylum) or functional group	Endpoint	Critical pH	Source
<i>Alexandrium tamarensense</i> (Dinophyta, Dinophyceae)	20% reduction in growth	8.66	Schmidt and Hansen 2001
<i>Dunaliella tertiolecta</i> (Prasinophyta, Prasinophyceae)	Growth	8.69	Elzenga and Prins 2000
<i>Chrysochromulina polylepis</i> (Haptophyta, Prymnesiophyceae)	20% reduction in growth	8.70	Schmidt and Hansen 2001
<i>Gymnodinium mikimotoi</i> (Dinophyta, Dinophyceae)	20% reduction in growth	8.72	Schmidt and Hansen 2001
<i>Rhodomonas marina</i> (Cryptophyta, Cryptophyceae)	20% reduction in growth	8.74	Schmidt and Hansen 2001
<i>Prorocentrum micans</i> (Dinophyta, Dinophyceae)	20% reduction in growth	8.75	Schmidt and Hansen 2001
<i>Ceratium lineatum</i> (Dinophyta, Dinophyceae)	Growth	8.79	Schmidt and Hansen 2001
<i>Heterocapsa triquetra</i> (Dinophyta, Dinophyceae)	20% reduction in growth	8.8-8.9	Schmidt and Hansen 2001
<i>Emiliania huxleyi</i> (weak coccoliths) (Prymnesiophyta, Prymnesiophyceae)	Growth	8.80	Elzenga and Prins 2000
<i>Pyramimonas propulsa</i> (Prasinophyta, Prasinophyceae)	Growth	8.80	Schmidt and Hansen 2001
<i>Dictyocha speculum</i> (Ochrophyta, Chrysophyceae)	Growth	8.81	Schmidt and Hansen 2001

Table 2. Continued.

Taxon (Phylum) or functional group	Endpoint	Critical pH	Source
<i>Alexandrium tamarensense</i> (Dinophyta, Dinophyceae)	Growth	8.85	Schmidt and Hansen 2001
<i>Alexandrium ostenfeldii</i> (Dinophyta, Dinophyceae)	Growth	8.90	Schmidt and Hansen 2001
<i>Thalassiosira punctigera</i> (Bacillariophyta)	Growth	8.90	Elzenga and Prins 2000
<i>Biddulphia aurita</i> (Bacillariophyta)	Growth	9	Humphrey 1975
<i>Chaetoceros didymus</i> (Bacillariophyta)	Growth	9	Humphrey 1975
<i>Skeletonema costatum</i> (Diatomaceae)	Growth	9.0	Rajaretnam et al. 1987
<i>Eutreptiella gymnastica</i> (Euglenozoa, Euglenida)	20% reduction in growth	9.00	Schmidt and Hansen 2001
<i>Gymnodinium mikimotoi</i> (Dinophyta, Dinophyceae)	Growth	9.00	Schmidt and Hansen 2001
<i>Gymnodinium splendens</i> (Dinophyta, Dinophyceae)	Growth	9	Humphrey 1975
<i>Monochrysis lutheri</i> (Ochrophyta, Synurophyceae)	Growth	9	Humphrey 1975
<i>Phaeocystis globosa</i> (Haptophyta, Prymnesiophyceae)	Growth	9.14	Elzenga and Prins 2000
<i>Heterosigma akashiwo</i> (Ochrophyta, Raphidophyceae)	Growth	9.15	Schmidt and Hansen 2001

Table 2. Continued.

Taxon (Phylum) or functional group	Endpoint	Critical pH	Source
<i>Chrysochromulina polylepis</i> (Haptophyta, Prymnesiophyceae)	Growth	9.20	Schmidt and Hansen 2001
<i>Chrysochromulina simplex</i> (Haptophyta, Prymnesiophyceae)	20% reduction in growth	9.20	Schmidt and Hansen 2001
<i>Gymnodinium dominans</i> (Dinophyta, Dinophyceae)	Reduced growth	9.2	Pedersen and Hansen 2003
<i>Prorocentrum minimum</i> (Dinophyta, Dinophyceae)	20% reduction in growth	9.20	Schmidt and Hansen 2001
<i>Skeletonema costatum</i> (Bacillariophyceae)	Growth	9.21	Schmidt and Hansen 2001
<i>Eutreptiella gymnastica</i> (Euglenozoa, Euglenida)	Growth	9.22	Schmidt and Hansen 2001
<i>Chrysochromulina simplex</i> (Haptophyta, Prymnesiophyceae)	Growth	9.25	Schmidt and Hansen 2001
<i>Emiliania huxleyi</i> (heavy coccoliths) (Haptophyta, Prymnesiophyceae)	Growth	9.29	Elzenga and Prins 2000
<i>Chroomonas</i> sp. (Cryptophyta, Cryptophyceae)	Growth	9.3	Humphrey 1975
<i>Gymnodinium dominans</i> (Dinophyta, Dinophyceae)	Growth	9.4	Humphrey 1975
<i>Synechococcus</i> sp. (Cyanobacteria)	Growth	9.40	Elzenga and Prins 2000
<i>Heterocapsa triquetra</i> (Dinophyta, Dinophyceae)	Growth	9.43	Schmidt and Hansen 2001

Table 2. Continued.

Taxon (Phylum) or functional group	Endpoint	Critical pH	Source
<i>Dunaliella tertiolecta</i> (Prasinophyta, Prasinophyceae)	Growth	9.5	Humphrey 1975
<i>Nitzschia closterium</i> (Bacillariophyta)	Growth	9.5	Humphrey 1975
<i>Thalassiosira fluviatilis</i> (Diatomaceae)	Mortality	9.5	Rajaretnam et al. 1987
<i>Ceramium rubrum</i> , <i>Polysiphonia linum</i> (Rhodophyta, Florideophyceae), <i>Chaetomorpha linum</i> (Chlorophyta, Ulvophyceae)	Photosynthesis	9.5-9.7	Sand-Jensen and Gordon 1984
<i>Prorocentrum minimum</i> (Dinophyta, Dinophyceae)	Growth	9.62	Schmidt and Hansen 2001
<i>Thalassiosira pseudonana</i> (Bacillariophyta)	Growth	9.77	Elzenga and Prins 2000
<i>Prorocentrum micans</i> (Dinophyta, Dinophyceae)	Growth	9.92	Schmidt and Hansen 2001
<i>Rhodomonas marina</i> (Cryptophyta, Cryptophyceae)	Growth	9.93	Schmidt and Hansen 2001
<i>Gymnodinium dominans</i> (Dinophyta, Dinophyceae)	5-day mortality	10	Pedersen and Hansen 2003
<i>Phaeodactylum tricornutum</i> (Bacillariophyta)	Growth	10	Humphrey 1975
<i>Amphidinium carterae</i> (Dinophyta, Dinophyceae)	Growth	10	Humphrey 1975
<i>Nannochloropsis</i> sp. (Ochrophyta, Eustigmatophyceae)	Growth	10.08	Elzenga and Prins 2000

Table 2. Continued.

Taxon (Phylum) or functional group	Endpoint	Critical pH	Source
<i>Phaeodactylum tricornutum</i> (Bacillariophyta)	Growth	10.3	Goldmann et al. 1982
<i>Phaeodactylum tricornutum</i> (Bacillariophyta)	Growth	10.4	Nimer et al. 1997
<i>Fucus vesiculosus</i> (Ochrophyta, Phaeophyceae)	Photosynthesis	10.4	Sand-Jensen and Gordon 1984
<i>Ulva lactuca</i> , <i>Enteromorpha</i> sp. (Chlorophyta, Ulvaceae)	Photosynthesis	>10.4 (photosynthesis continued at 10.4, the highest pH tested)	Sand-Jensen and Gordon 1984
<i>Ulva lactuca</i> (Chlorophyta, Ulvophyceae)	Mortality	>11.6 (this pH is reached in floating mats in Denmark)	Sand-Jensen and Gordon 1984

Table 3. pH tolerance of marine macrophytes.

(a) Tolerance of acidic pH

Taxon	Endpoint	Critical pH	Source
<i>Zostera muelleri</i>	Reduced photosynthesis	7.8	Millhouse and Strother 1986

(b) Tolerance of alkaline pH

Taxon (Phylum) or functional group	Endpoint	Critical pH	Source
<i>Ruppia longata, Zostera marina</i>	Photosynthesis	10-10.2	Sand-Jensen and Gordon 1984

Table 4. pH tolerance of marine Bivalvia (Mollusca).

(a) Tolerance of acidic pH

Taxon	Endpoint	Critical pH	Source
<i>Crassostrea gigas</i> (~1 cm)	Mortality	6.0	Bamber 1990
<i>Venerupis longata</i>	Mortality	6.1-6.4	Bamber 1987
<i>Crassostrea virginica</i> larva	Mortality	6.25	Calabrese and Davis 1966
<i>Mercenaria mercenaria</i> larva	Mortality	6.25	Calabrese and Davis 1966
<i>Mulina lateralis</i> larva	Mortality	6.50	Calabrese 1970
<i>Ostrea virginica</i>	Pumping frequency and opening time	6.5	Loosanoff and Tommers 1947
<i>Crassostrea gigas</i>	Gaping valves	6.6	Bamber 1990
<i>Mytilis edulis</i> (<5 cm)	Mortality	6.6	Bamber 1990
<i>Mytilus edulis</i>	Gaping valves	6.6	Bamber 1990
<i>Ostrea edulis</i> (~1 cm)	Mortality	6.6	Bamber 1990
<i>Ostrea edulis</i>	Gaping valves	6.6	Bamber 1990
<i>Crassostrea virginica</i>	Normal growth	6.75	Calabrese and Davis 1966
<i>Mercenaria mercenaria</i>	Normal growth	6.75	Calabrese and Davis 1966
<i>Ostrea edulis</i> (~4 cm)	Mortality	6.9	Bamber 1990
<i>Crassostrea gigas</i>	Weight	7.0	Bamber 1990
<i>Mercenaria mercenaria</i>	Embryonic development	7.0	Calabrese and Davis 1966
<i>Mulina lateralis</i>	Larval growth	7.0	Calabrese 1970
<i>Mytilus edulis</i>	Increased heart beat	7.0	Schlieper 1955 cited in Knutzen 1981
<i>Ostrea edulis</i>	Weight	7.0	Bamber 1990
<i>Ostrea edulis</i>	Growth in length	7.0	Bamber 1990
<i>Ostrea edulis</i>	Normal larval development	7.0	Gaarder 1932
<i>Venerupis elongata</i>	Feeding	7.0	Bamber 1987
<i>Venerupis elongata</i>	Shell growth	7.0	Bamber 1987
<i>Venerupis elongata</i>	Flesh weight	7.0	Bamber 1987
<i>Crassostrea gigas</i>	Feeding rate	7.2	Bamber 1990
<i>Mytilus edulis</i>	Feeding rate	7.2	Bamber 1990
<i>Ostrea edulis</i>	Feeding rate	7.2	Bamber 1990

Table 4. Continued.

Taxon	Endpoint	Critical pH	Source
<i>Mulina lateralis</i>	Normal embryonic development	7.25	Calabrese 1970
<i>Pintada fucata</i>	Adult mortality	7.48	Kuwatani and Nishii 1969
<i>Venerupis elongata</i>	Shell dissolution	7.5	Bamber 1987
<i>Mytilus edulis</i>	Gamete respiration	7.6	Akberali et al. 1985
<i>Pintada fucata</i>	Shell dissolution	7.66	Kuwatani and Nishii 1969
<i>Mytilus</i> spp.	Normal larval development	7.75	SFEI 1997

(b) Tolerance of alkaline pH

Taxon (Phylum) or functional group	Endpoint	Critical pH	Source
<i>Mulina lateralis</i>	Normal embryonic development	8.25	Calabrese 1970
<i>Mulina lateralis</i> larva	Growth	8.5	Calabrese 1970
<i>Crassostrea virginica</i> larva	Mortality	8.75	Calabrese and Davis 1966
<i>Crassostrea virginica</i>	Normal growth	8.75	Calabrese and Davis 1966
<i>Mercenaria mercenaria</i> larva	Mortality	8.75	Calabrese and Davis 1966
<i>Mulina lateralis</i> larva	Mortality	8.75	Calabrese 1970
<i>Mytilus</i> spp.	Normal larval development	8.75	SFEI 1997
<i>Crassostrea virginica</i>	Embryonic development	9.0	Calabrese and Davis 1966
<i>Mercenaria mercenaria</i>	Embryonic development	9.0	Calabrese and Davis 1966

Table 5. pH tolerance of marine Arthropoda.

(a) Tolerance of acidic pH

Taxon (Class, Order)	Endpoint	Critical pH	Source
<i>Themisto japonica</i> (Malacostraca, Euphausiacea)	24-h LC50	4.74	Yamada and Ikeda 1999
<i>Eucalanus bungii bungii</i> (Maxillopoda, Calanoida)	24-h LC50	4.79	Yamada and Ikeda 1999
<i>Panulirus homarus</i> (Malacostraca, Decapoda)	Impaired immune system	Between 5.0 and 8.0	Vergheze et al. 2007
<i>Metridia pacifica</i> (Maxillopoda, Calanoida)	24-h LC50	5.07	Yamada and Ikeda 1999
<i>Euphausia pacifica</i> nauplii (Malacostraca, Euphausiacea)	24-h LC50	5.22	Yamada and Ikeda 1999
<i>Neocalanus cristatus</i> (Maxillopoda, Calanoida)	24-h LC50	5.39	Yamada and Ikeda 1999
<i>Conchoecia</i> sp. (Ostracoda, Halocypriida)	24-h LC50	5.40	Yamada and Ikeda 1999
<i>Temora longicornis</i> (Maxillopoda, Calanoida)	Mortality	5.5	Grice et al. 1973
<i>Eucalanus bungii bungii</i> (Maxillopoda, Calanoida)	168-h LC50	5.53	Yamada and Ikeda 1999
<i>Pseudocalanus minutus</i> (Maxillopoda, Calanoida)	24-h LC50	5.57	Yamada and Ikeda 1999
<i>Metridia pacifica</i> (Maxillopoda, Calanoida)	72-h LC50	5.68	Yamada and Ikeda 1999
<i>Calanus pacificus</i> (Maxillopoda, Calanoida)	24-h LC50	5.83	Yamada and Ikeda 1999

Table 5. Continued.

Taxon	Endpoint	Critical pH	Source
<i>Euphausia pacifica</i> juveniles (Malacostraca, Euphausiacea)	24-h LC50	5.93	Yamada and Ikeda 1999
<i>Armases</i> spp. (Malacostraca, Decapoda)	Normal development to 2 nd larval stage	6	Diesel et al. 2000
<i>Pseudocalanus minutus</i> (Maxillopoda, Calanoida)	144-h LC50	6.02	Yamada and Ikeda 1999
<i>Euphausia pacifica</i> nauplii (Malacostraca, Euphausiacea)	120-h LC50	6.10	Yamada and Ikeda 1999
<i>Calanus pacificus</i> (Maxillopoda, Calanoida)	120-h LC50	6.14	Yamada and Ikeda 1999
<i>Neocalanus cristatus</i> (Maxillopoda, Calanoida)	24-h LC50	6.16	Yamada and Ikeda 1999
<i>Paraeuchaeta elongata</i> (Maxillopoda, Calanoida)	24-h LC50	6.23	Yamada and Ikeda 1999
<i>Conchoecia</i> sp. (Ostracoda, Halocyprida)	120-h LC50	6.44	Yamada and Ikeda 1999
<i>Acartia tonsa</i> (Maxillopoda, Calanoida)	Mortality	6.7	Rose et al. 1977
<i>Themisto japonica</i> (Malacostraca, Euphausiacea)	168-h LC50	6.70	Yamada and Ikeda 1999
<i>Paraeuchaeta elongata</i> (Maxillopoda, Calanoida)	144-h LC50	6.83	Yamada and Ikeda 1999
<i>Euphausia pacifica</i> juveniles (Malacostraca, Euphausiacea)	168-h LC50	6.84	Yamada and Ikeda 1999

Table 5. Continued.

Taxon	Endpoint	Critical pH	Source
<i>Penaeus monodon</i> (Malacostraca, Decapoda)	Loss of physiological control over mineralization	7.4	Wickins 1984

(b) Tolerance of alkaline pH

Taxon (Phylum) or functional group	Endpoint	Critical pH	Source
<i>Panulirus homarus</i> (Malacostraca, Decapoda)	Impaired immune system	Between 8.0 and 9.5	Vergheese et al. 2007
<i>Armases</i> spp. (Malacostraca, Decapoda)	Normal development to 2 nd larval stage	8.5	Diesel et al. 2000
<i>Sesarma curacaoense</i> (Malacostraca, Decapoda)	Normal development to 2 nd larval stage	8.5	Diesel et al. 2000

Table 6. pH tolerances of marine invertebrates other than Mollusca (Bivalvia) and Arthropoda.

(a) Tolerance of acidic pH

Taxon (Phylum)	Endpoint	Critical pH	Source
<i>Procephalothrix simulus</i> (Nemertea)	Mortality	5	Zhao and Sun 2006
<i>Sagitta elegans</i> (Chaetognatha)	24-h LC50	5.91	Yamada and Ikeda 1999
<i>Sepiella inermis</i> (= <i>S. maindroni</i>) (Cephalopoda)	Larval mortality	6	Yin et al. 2005
<i>Sagitta elegans</i> (Chaetognatha)	72-h LC50	6.73	Yamada and Ikeda 1999

(b) Tolerance of alkaline pH

Taxon (Phylum) or functional group	Endpoint	Critical pH	Source
<i>Procephalothrix simulus</i> (Nemertea)	Mortality	9.20	Zhao and Sun 2006
<i>Sepiella inermis</i> (= <i>S. maindroni</i>) (Cephalopoda)	Larval mortality	9.5	Yin et al. 2005

Table 7. pH tolerance of marine chordates (Ascidia).

(a) Tolerance of acidic pH

Taxon	Endpoint	Critical pH	Source
<i>Ciona intestinalis</i>	Normal larval development	6.9	Bellas et al. 2003

(b) Tolerance of alkaline pH

Taxon (Phylum) or functional group	Endpoint	Critical pH	Source
<i>Ciona intestinalis</i>	Normal larval development	9.0	Bellas et al. 2003

Table 8. pH tolerance of marine chordates (Osteichthyes).

(a) Tolerance of acidic pH

Taxon	Endpoint	Critical pH	Source
<i>Heteromycteris capensis</i>	24 h LC50	4.48	Brownell 1980
<i>Sparus aurata</i>	24 h LC50	4.82-5.55	Parra and Yüfere 2002
<i>Solea senegalensis</i>	24 h LC50	4.88-5.76	Parra and Yüfere 2002
<i>Heteromycteris capensis</i>	24 h LC10	4.51	Brownell 1980
<i>Gaidropsarus capensis</i>	24 h LC50	4.74	Brownell 1980
<i>Gaidropsarus capensis</i>	24 h LC10	4.99	Brownell 1980
<i>Diplodus sargus</i>	24 h LC50	5.06	Brownell 1980
<i>Diplodus sargus</i>	24 h LC10	5.17	Brownell 1980
<i>Diplodus sargus</i>	24 h first-feeding EC50	5.20	Brownell 1980
<i>Gaidropsarus capensis</i>	24 h first-feeding EC50	5.22	Brownell 1980
<i>Diplodus sargus</i>	24 h first-feeding EC10	5.69	Brownell 1980
<i>Heteromycteris capensis</i>	24 h first-feeding EC50	5.90	Brownell 1980
<i>Gaidropsarus capensis</i>	24 h first-feeding EC10	5.91	Brownell 1980
<i>Atherina boyeri</i>	Avoidance	6.5	Davies 1991

(b) Tolerance of alkaline pH

Taxon	Endpoint	Critical pH	Source
<i>Gaidropsarus capensis</i>	24 h first-feeding EC10	8.39	Brownell 1980
<i>Heteromycteris capensis</i>	24 h first-feeding EC10	8.50	Brownell 1980
<i>Diplodus sargus</i>	24 h first-feeding EC10	8.52	Brownell 1980
<i>Sparus aurata</i>	24 h LC50	8.66-9.26	Parra and Yüfere 2002
<i>Gaidropsarus capensis</i>	24 h first-feeding EC50	8.67	Brownell 1980
<i>Heteromycteris capensis</i>	24 h first-feeding EC50	8.78	Brownell 1980

Table 8. Continued.

Taxon	Endpoint	Critical pH	Source
<i>Diplodus sargus</i>	24 h LC10	8.89	Brownell 1980
<i>Heteromycteris capensis</i>	24 h LC10	8.92	Brownell 1980
<i>Gaidropsarus capensis</i>	24 h LC10	8.99	Brownell 1980
<i>Diplodus sargus</i>	24 h LC50	9.04	Brownell 1980
<i>Diplodus sargus</i>	24 h LC50	8.82	Brownell 1980
<i>Solea senegalensis</i>	24 h LC50	8.94-9.57	Parra and Yüfere 2002
<i>Heteromycteris capensis</i>	24 h LC50	9.21	Brownell 1980
<i>Gaidropsarus capensis</i>	24 h LC50	9.24	Brownell 1980

Table 9. Effects of exposure to acetic acid on marine organisms.

(a) Algae

Taxon	Endpoint	% Acetic acid	Immersion time (min)	Source
<i>Cladophora</i> sp. (Chlorophyta, Ulvophyceae)	Mortality	2%	3 min	Forrest et al. 2007
<i>Cladophora</i> sp. (Chlorophyta, Ulvophyceae)	Mortality	4%	1 min	Forrest et al. 2007
Green alga (Chlorophyta)	Mortality	5%	15 sec	Sharp et al. 2006
<i>Undaria pinnatifida</i> (Ochrophyta, Phaeophyceae) gametophyte and plantlet	Mortality	<1%	1 min	Forrest et al. 2007
<i>Undaria pinnatifida</i> (Ochrophyta, Phaeophyceae) sporophyte	Mortality	4%	1 min	Forrest et al. 2007

(b) Bivalvia (Mollusca)

Taxon	Endpoint	% Acetic acid	Immersion time (min)	Source
<i>Mytilus edulis</i> spat	>60% unattached or gaping open 24 h after exposure	5%	20 sec	Sharp et al. 2006
<i>Mytilus edulis</i> spat	Death or lack of growth	5%	Repeated 15 sec immersion	Sharp et al. 2006
<i>Mytilus edulis</i>	74% reduction in sock weight after 7 mo	5%	30 sec	LeBlanc et al. 2007
<i>Mytilus edulis</i>	86% reduction in sock weight after 7 mo	5%	2 min	LeBlanc et al. 2007

Table 9. Continued.

Taxon	Endpoint	% Acetic acid	Immersion time (min)	Source
<i>Perna canaculus</i>	Attachment >95% after 1 mo	4%	2 min, rinsed	Forrest et al. 2007
<i>Perna canaculus</i>	Attachment <57% after 1 mo	4%	2 min, not rinsed	Forrest et al. 2007
<i>Perna canaculus</i>	Attachment <26% after 1 mo	8%	2 min, not rinsed	Forrest et al. 2007

(c) Invertebrates other than Bivalvia

Taxon	Endpoint	% Acetic acid	Immersion time (min)	Source
<i>Bugula neritina</i> (Bryozoa)	Mortality	4%	1 min	Forrest et al. 2007
<i>Watersipora subtorquata</i> (Bryozoa)	Mortality	4%	1 min	Forrest et al. 2007
<i>Hydroides elegans</i> (Polychaeta)	Mortality	4%	4 min, air-dried, transported 24 h	Forrest et al. 2007
Terebellidae (Polychaeta)	Mortality	2%	3 min	Forrest et al. 2007
Terebellidae (Polychaeta)	Mortality	4%	2 min	Forrest et al. 2007

(d) Ascidea

Taxon	Endpoint	% Acetic acid	Immersion time (min)	Source
<i>Botrylloides leachi</i>	Mortality	4%	1 min	Forrest et al. 2007
<i>Botryllus schlosseri</i>	Mortality	4%	1 min	Forrest et al. 2007
<i>Ciona intestinalis</i>	Mortality	2%	1 min, air-dried	Forrest et al. 2007
<i>Ciona intestinalis</i>	Mortality	4%	4 min	Forrest et al. 2007

Table 9. Continued.

Taxon	Endpoint	% Acetic acid	Immersion time (min)	Source
<i>Cnemidocarpa bicornuata</i>	Mortality	2%	1 min, air-dried	Forrest et al. 2007
<i>Corella eumyota</i>	Mortality	2%	1 min, air-dried	Forrest et al. 2007
<i>Corella eumyota</i>	Mortality	4%	4 min	Forrest et al. 2007
<i>Styela clava</i>	66% mortality after 1 wk	1%	5 min	Coutts and Forrest 2005
<i>Styela clava</i>	100% mortality after 1 wk	1%	10 min	Coutts and Forrest 2005
<i>Styela clava</i>	100% mortality after 1 wk	2%	5 min	Coutts and Forrest 2005
<i>Styela clava</i>	100% mortality after 1 wk	4% and 5%	1 min	Coutts and Forrest 2005